Length-Based Fourier Analysis in the Pre-Excitation Syndrome

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Length-based Fourier analysis (LFA) was applied to tomographic gated blood-pool study, and phase and percent-shortening diagrams were generated. In 22 patients with pre-excitation syndrome and ten control subjects, the most basal short-axis section was used for tomographic analysis. When the initial abnormal phase was considered as the location of accessory conduction pathway (ACP), correct diagnosis for the localization of ACP was given in 19 of 22 patients. In ten control subjects, no specific segments of initial phase were noted, although six patients had initial phase in the septal or paraseptal segments. The tomographic LFA was more effective for pinpointing the segment of the earliest phase than tomographic count-based phase analysis. The LFA provided objective three-dimensional information for contraction sequence. Because movements of ventricular edges are essential in tomography, the LFA was considered to be a reasonable approach for the analysis of tomographic gated blood-pool study.

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Application of nuclear medicine techniques to conduction anomalies has been studied through the use of gated blood-pool studies (*1–12*). Functional imaging, in particular, is a unique approach used in nuclear cardiology, where specific parameters are extracted and displayed as maps. Phase analysis, one of the functional imaging techniques, provides a parameter that corresponds to the sequence of contraction. Although phase imaging does not directly assess electrical excitation, generally good agreement between excitation and mechanical contraction has been described (*3–11*). Since conventional phase image in planar gated blood-pool studies is based on the time-activity curve that is based on the movement of the blood pool, three-dimensional overlap of radioactivity cannot be avoided, and therefore there is a limitation to tracing the exact contraction sequence.

Tomography seems to be a more reasonable technique for the three-dimensional evaluation of contraction patterns (*12*). We have developed a length-based Fourier analysis (LFA) for the analysis of contraction and excitation using tomographic gated blood-pool studies (*13*). The purpose of this study is to evaluate the utility of the LFA for the detection of the accessory conduction pathway (ACP) in the pre-excitation syndrome (Wolff-Parkinson-White (WPW) syndrome).

METHODS

Study Group

The study group consisted of 22 patients with pre-excitation syndrome who were considered for the surgical division of the ACP because of frequent episodes of tachycardia, a history of heart failure, and/or loss of consciousness. As preoperative studies, all patients underwent routine 12-lead ECGs, electrophysiologic studies using i.v. catheters, radionuclide studies, and epicardial mapping. The final diagnosis for the location of the ACP was confirmed by the epicardial mapping and the result of surgery. The patients were classified into four groups according to the location of ACP, including five right cardiac types, three right septal types, ten left cardiac types, and four with multiple ACPs. Of the four with multiple ACPs, three had an ACP on each side, one had two ACPs on the right side. In a patient with two ACPs, ECG showed right cardiac type in the first study, and left type in the second study soon after a pacing study. A control group consisted of

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ten patients who had neither conduction anomalies nor ventricular contraction abnormalities. Associated cardiac diseases were: Ebstein's anomaly (n = 1), coronary artery disease with 75% narrowing of the left anterior descending artery (n = 1), and corrected transposition of the great arteries (n = 1). The remaining patients had no other cardiac complications. In this study, the differentiation of pre-excitation and normal conduction was based on the ECG and electrophysiologic data. No nuclear medicine criteria was used to separate the groups.

Gated Blood-Pool Studies and Gated Emission Computed Tomography

Routine gated blood-pool studies (GBPS) and gated emission computed tomography (GECT) were performed using technetium-99m (^{99m}Tc) red blood cells by an in vivo labeling method. Fifteen minutes after injection of stannous pyrophosphate solution, 25 mCi of [^{99m}Tc]pertechnetate were injected intravenously. ECG-gated blood-pool data were acquired in 64 × 64 matrices with 24 frames/cardiac cycle in modified (10° caudal tilt) left anterior oblique (LAO) 35°, right anterior oblique (RAO) 35°, and left lateral views. The data acquisition time was 10 min for LAO view and 5 min for the latter two views. The GECT system consisted of dual-headed scintillation cameras* equipped with high resolution collimators interfaced to a minicomputer†. Thirty-six projection data with 12 frames/cardiac cycle were stored on magnetic disk. Each projection datum was collected for 1 min. Since dual cameras were employed, actual acquisition time was 18 min. Serial short-axis images perpendicular to the long axis of the heart were reconstructed using a filtered backprojection algorithm supplied by the manufacturer. Full width at half maximum of the system was 15 mm at the center of rotation when the rotation radius was 23 cm. Attenuation correction was not performed.

Tomographic Count-Based Phase Analysis

The same algorithm of phase analysis that has been applied to the conventional planar GBPS was utilized for tomographic images (*1,12*). Phase and amplitude of the fundamental frequency calculated from the time-activity curve in each pixel were mapped as functional images. When we consider the nature of tomographic images, the phase data interior to the end-systolic perimeters are meaningless. Therefore, we only evaluated the periphery of the phase images, that was outside of the end-systolic boundaries. We assumed that pre-excitation was associated with the earliest inward movement of the edges. The segment of the earliest phase identified on the serial short-axis phase images were judged as the site of ACP.

Length-Based Fourier Analysis

The algorithm of the length-based Fourier analysis was (LFA) described (*13*). This algorithm was made up of five parts as follows.

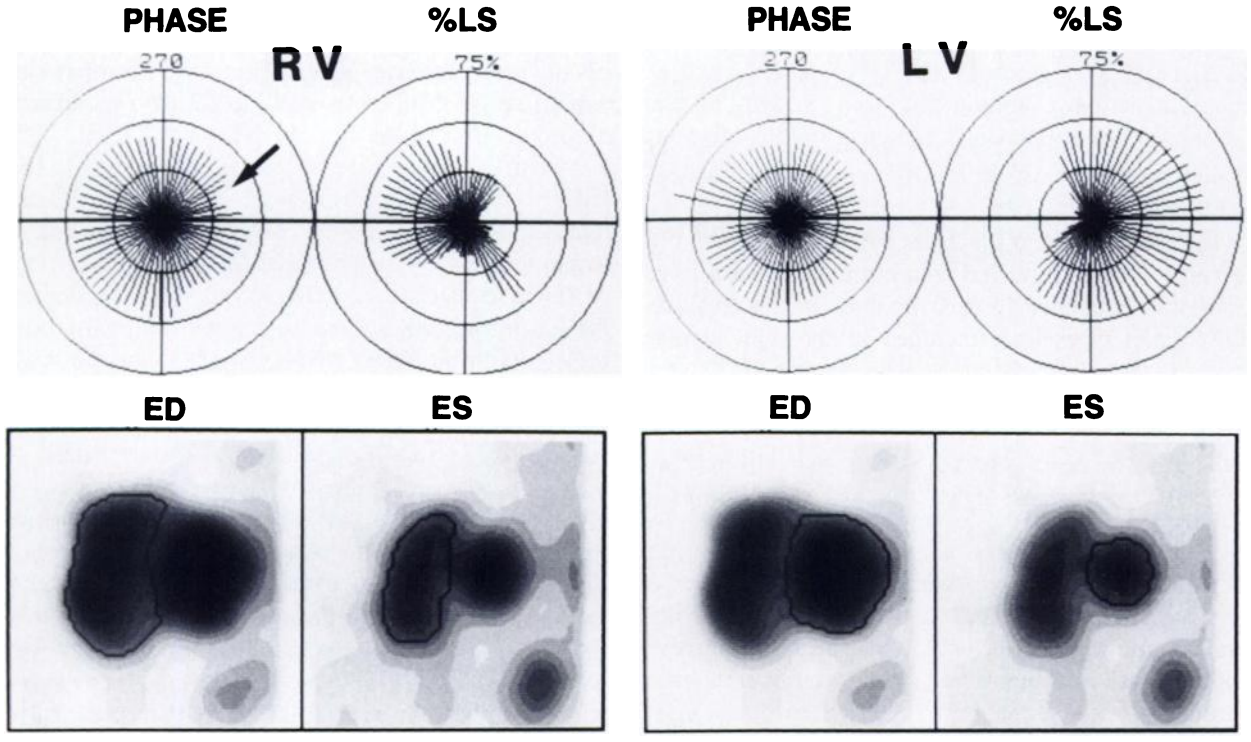


FIGURE 1
Length-based Fourier analysis (LFA) in normal subject. LFA was performed in most basal slice on both sides of ventricles. Each concentric circle denotes 90° in phase and 25% in %LS. In this diagram, minimal phase is found in right anterior septal region (arrow). Left septal segments are excluded because %LSs are < 5%

1. Isolation of chambers. In order to exclude surrounding structures, a region of interest (ROI) was set using a track-ball. With the use of this ROI as a mask, the background outside the ROI was set to 0.

2. Determination of the center. A center of gravity was determined by weighting the amount of activity in each pixel inside of a certain threshold count (usually 60% of the maximum count). This fixed point in the first frame was defined as a center throughout a whole cardiac cycle. If this center was out of end-systolic perimeter, it was set inside manually.

3. Calculation of time-length curve (TLC). The lengths from a center to ventricular edges were measured and TLCs were generated in 60 radial directions.

4. Calculation of length-based phase. Phase and amplitude of the discrete Fourier transform based on the first harmonic. Percent length-shortening (%LS) was defined as:

$$\%LS = 2 \times \text{amplitude} \times 100/(DC + \text{amplitude}),$$

where DC is a direct current component of the Fourier transform. This analysis was performed in 60 segments (6° step).

5. Display of the result. Length-based phase and %LS in 60 radial directions were displayed using polar coordinates as shown in Fig. 1. Segment zero is defined as the right horizontal direction (3 o'clock) from the center and the segment numbers increase counterclockwise.

Only the basal, short-axis slices were analyzed by the LFA. Although eight short-axis slices may have been selected, only the most basal section was used. The earliest length-based phase was considered to be the location of ACP in the WPW syndrome. The segments that showed %LS < 5% were excluded, because the reliability of phase was low in the segments of reduced contractility.

The range of length-based phase, defined as the difference of maximum and minimum phase in a basal slice, was calculated in each patient. In this analysis, right septal types were included in the right cardiac types. In the left cardiac types, a patient with transposition of the great arteries was excluded, because the shape of right and left ventricles were reversed in this anomaly. The ranges of length-based phase in the control patients were also calculated in both sides of the ventricles.

Epicardial Mapping and Surgery

The location of ACP was investigated by epicardial mapping during surgery (*14*). Using electrode catheter with six pairs of bipolar electrodes, activation on a cardiac surface was analysed by computerized recorder. The earliest epicardial activation on the cardiac surface was determined. The retrograde atrial activation was analyzed during reciprocating tachycardia or ventricular pacing. In this way, the localizations of the ACPs were determined. After the site of ACP was surgically transected, the ECG changed to the normal conduction pattern in all patients. If the distance between a segment of the earliest phase and the actual site of the ACP was within one eighth of an atrioventricular ring, it was judged as a correct diagnosis.

TABLE 1
Detectability of Site of ACP by LFA

Site of ACP	No. of patients (No. of ACP*)	Detection by LFA† (No. of ACP)
Right	5	5
Right septal	3	3
Left	10	8
Multiple	1 (2, right and left)	1 (2)
	1 (2, right and left)	1 (1)
	1 (2, right and left)	1 (1)
	1 (2, right and left)	0 (0)

* ACP = Accessory conduction pathway.
† LFA = Length-based Fourier analysis.

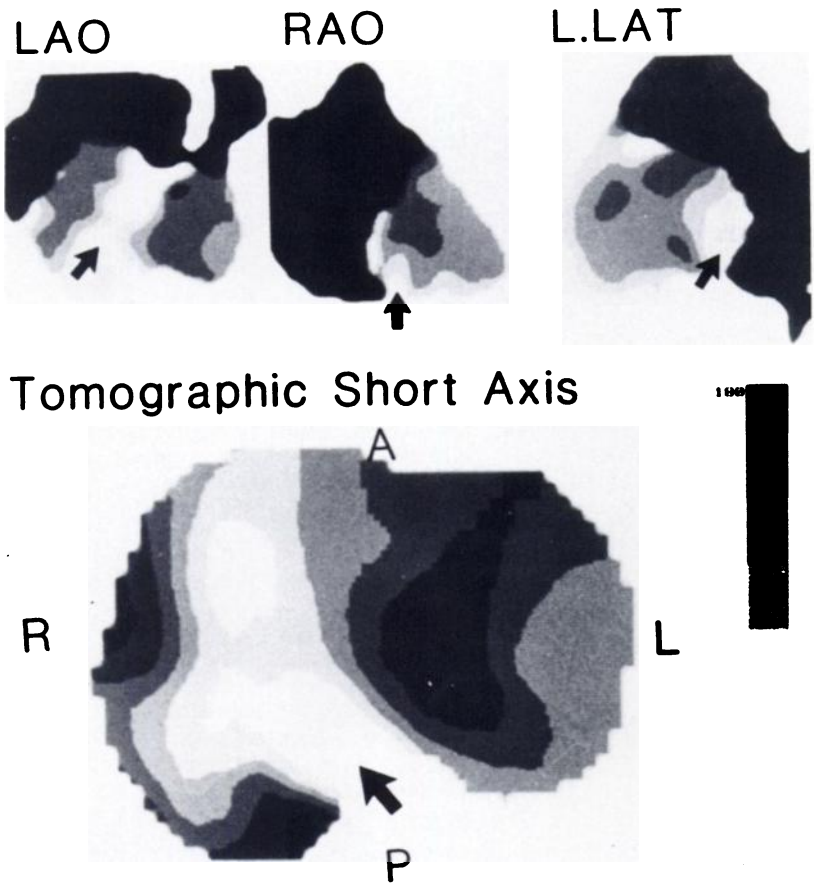
Statistical Analysis

The results of the range of length-based phase were described as mean ± s.d. The significance of the difference among the mean values was assessed with an analysis of variance and Student's t-test.

RESULTS

Detectability of the site of ACP was summarized in Table 1. Five of five patients with right cardiac type and three of three with septal ACPs were correctly diagnosed. In ten ACPs with left cardiac type, eight were correctly identified on the LFA. An ACP that failed to be detected was located on the left posterolateral segment; however, the earliest length-based phase was in segment 16 (anterior wall). The other undetected ACP was located on the left posterior segment, whereas the earliest phase was in segment 1 (lateral). Four patients with multiple ACPs were included in our study group. In a patient with an ACP on each side, ECG showed right cardiac type in the first study, and the LFA demonstrated the earliest phase in segment 43 (right posterior). After an intracavitary pacing study in this patient, ECG showed left type, then radionuclide study with GECT was repeated. At this time, the earliest phase was identified at segment 54 (left posterolateral) in the left heart. These locations were in agreement with the ACP sites surgically confirmed. One of two ACPs was detected in two patients, and none of the two were identified in a patient. Overall diagnostic sensitivity for detecting the sites of ACPs was 19 of 22 patients (86%). Regarding the ACP sites, 77% (20 of 26 ACPs) were detected.

Tomographic count-based phase analysis had the



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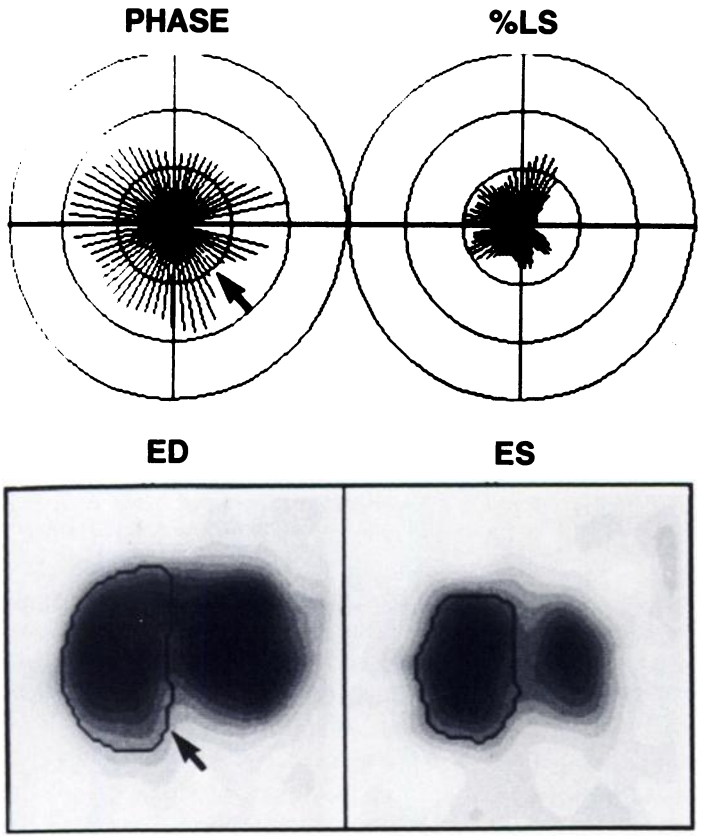

B

#	PH	%LS	#	PH	%LS
1	0	0	31	164	22
2	0	0	32	158	20
3	180	5	33	147	20
4	160	7	34	136	21
5	145	7	35	131	24
6	128	7	36	130	24
7	114	8	37	133	22
8	111	12	38	138	19
9	114	18	39	143	17
10	116	25	40	146	15
11	117	30	41	144	13
12	117	33	42	140	13
13	116	33	43	137	12
14	115	31	44	138	13
15	113	28	45	144	14
16	113	26	46	153	16
17	115	24	47	160	18
18	118	22	48	165	18
19	124	20	49	165	16
20	133	19	50	156	12
21	141	19	51	126	9
22	148	21	52	94	11
23	152	23	53	84	15
24	155	23	54	86	16
25	159	22	55	95	15
26	163	21	56	108	14
27	166	21	57	123	11
28	166	22	58	136	9
29	166	24	59	150	6
30	165	24	60	0	0

FIGURE 2

A: Planar and tomographic count-based phase images. B: LFA in patient with right posterior paraseptal ACP. Phase images are displayed in isocount display with gray scales, and earliest phase corresponds to white region. Earliest phase was noticed in midportion of right ventricle in LAO view and in posterolateral region in RAO view (above). Tomographic short-axis phase image apparently showed earliest contraction in right posterior paraseptal segment (arrow). In LFA, earliest segment was No. 53, that was in agreement with surgically confirmed location of ACP

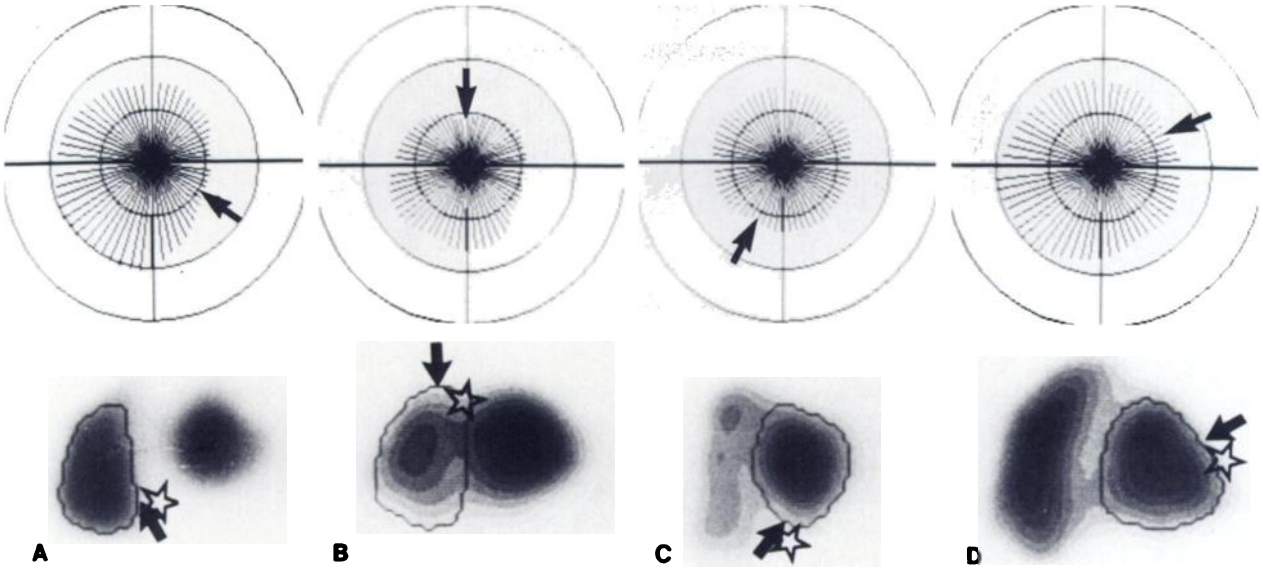

FIGURE 3
Results of length-based phase in patients with posterior and anterior septal ACPs (A and B) and left posterior and lateral ACPs (C and D). Arrows in polar coordinate displays indicate segments of earliest phase and those in lower short-axis blood-pool images correspond to location of earliest segments. Stars are sites of surgically confirmed ACPs. Note close correlations between length-based phase and site of ACP

same detectability for localizing the ACPs. However, in tomographic phase images, the earliest region was extended to several segments, sometimes more than one-fourth of an atrioventricular ring. The point of initial activation demonstrated by the LFA was in good agreement with one or several earliest segments shown in the count-based phase image. However, we think tomographic length-based presentations would make localizations simpler than with the count-based method.

In ten control subjects, no specific segments of the earliest contraction were found. The earliest segments were: two in the right free wall, four in the right septal or paraseptal, two in left free wall, and two in the left septal or paraseptal regions. Six of ten patients had initial phase in the septal or paraseptal segments. An example of LFA in a normal subject is shown in Fig. 1.

Table 2 shows the range of phase in each group. The ranges of phase (deg) in the WPW syndrome and control subjects were 69.8 ± 33.9 and 58.2 ± 14.3 in the right ventricular basal slice, and 46.8 ± 21.7 and 33.6 ± 10.2 in the left ventricular slice. The ranges of phase were larger in the WPW syndrome than in control subjects; however, the differences were not statistically significant. The range of phase distribution of the right ventricle showed significantly larger values than that of left ventricle in control patients ($p < 0.05$).

TABLE 2
Range of Length-Based Phase in Basal Slice

Group	No.	mean (°)	s.d. (°)
WPW right type	RV 8	69.8	33.9
left type	LV 9	46.8	21.7
Control	RV 10	58.2	14.3*
	LV 10	33.6	10.2†

*vs.
† $p < 0.05$.

A patient with right posterior paraseptal ACP was shown in Fig. 2. Some examples of the LFA and the locations of ACPs confirmed by epicardial mapping and surgery were indicated in Fig. 3.

DISCUSSION

Gated blood-pool study and phase images have been applied to conduction anomalies and pacing studies to analyze the relations of electrical excitation and mechanical movement (*2–11*). Although the propagation pattern of the phase is not the conduction pathway itself, it has been applied to conduction disorders because sequence of motion is generally parallel with that of conduction. In the WPW syndrome, we have attempted to detect the location of accessory conduction pathway with the use of phase image analysis. However, the planar phase analysis was considered to be unsatisfactory for localizing the precise sites of ACPs even by multiple projections (*8,12*). Tomographic gated blood-pool study with count-based phase analysis improved the diagnostic accuracy for localization of ACP (*12*). But tomographic count-based phase analysis (TCP) had some methodological problems as described later.

Therefore, we developed the algorithm, length-based Fourier analysis (*13*).

Tomographic Count-Based Phase Analysis

One of the advantages of the TCP is that the same program that has been utilized for phase analysis is available in many nuclear medicine computer systems. In a previous study, we divided the most basal section into eight segments on each side and the identification of initial phase in the segment in which the ACP was located, or adjacent to it, was judged as the correct diagnosis (*12*). With these lax diagnostic criteria, the detectability of ACP was 12 of 14 (86%) patients. However, it was difficult to indicate an earliest segment, or to pinpoint the location. Another methodological problem is in the use of count-based phase analysis for the tomographic images. Considering the characteristic of tomography, the theoretical time-activity curves inside of the end-systolic boundary must be flat. Actually they are not flat because of the effect of spatial filtering and reconstruction process. When we observe only the periphery of cardiac chambers, however, the TCP could be an effective method because of the movements of the edges reflected on the phase value in the border of the cardiac chambers.

Length-Based Fourier Analysis

Analyses of time-length curves from a center to ventricular edges are considered to be appropriate, because the information of edges is essential in tomographic images. Pinpointing of the earliest segment was easily performed by the LFA automatically. Generally, the difference between the surgically confirmed site of ACP and the earliest segment of length-based phase was at most one-eighth of an atrioventricular ring. In TCP, the septal or paraseptal segment is usually inside of the phase image, and we must be careful in the interpretation of these regions. On the other hand, in the LFA, the movement of septal border was easily recognized. However, if the percent shortening in the septal segment is small (we defined $< 5\%$ as akinetic), they are not interpreted. As shown in this study, the LFA can be a reliable diagnostic method for the localization of ACPs. Initial site of contraction and its sequence were objectively assessed. Moreover, this approach can be applied to the other cardiac contraction abnormalities as well as conduction disorders, because three-dimensional information is available without overlap of blood pools.

LFA in Normal Subjects

There were no specific segments of initial phase in normal subjects when the basal sections were analyzed. However, six of 10 patients had initial contraction in septal or paraseptal regions. This finding was consistent with the planar phase analysis (*6,9*). Therefore, in order to differentiate the conductions with normals and bypass tracts, the difference of phase between right and left ventricles is important. This differentiation can be achieved even by the planar gated blood-pool study in the LAO view. Additionally, the ECG patterns during radionuclide study were useful to confirm the presence of delta waves, short PR intervals, and wide QRS complexes. If the ECG did not show the pre-excitation pattern, the earliest segment of the phase in a chamber did not indicate the location of ACP.

Range of Phase in WPW Syndrome and Normals

The range of the length-based phase in the pre-excitation showed larger values than that of normal atrioventricular conduction, although they were not significant. This finding can be explained by the fusion of excitation through an ACP and normal conduction pathway. However, the separation of the WPW syndromes from normal patients were not good. This is due in part to the fact that the LFA was performed only in the basal slice, whereas actual contraction spreads over the whole myocardium. Therefore, the LFA should be carried out over the whole cardiac surface on both sides of heart. To overcome this limitation, a new program for making phase maps over the whole cardiac surface will be required. However, in definite WPW syndrome with characteristic ECG patterns and significant phase difference of both ventricles in planar phase image, the LFA can provide reliable information on the ACP sites.

The phase distribution of right ventricular basal slice was significantly larger than that of left ventricle. As shown in Figs. 1, 2, and 3, the phase diagrams in the left ventricle was more circular than in the right ventricle. The shape of the right ventricular basal slice had a semilunar shape and right ventricular outflow tract was sometimes included. A larger distribution of phase in the right ventricle may be explained by the complexity of right ventricular shape and motion.

Factors Affecting LFA

Three major factors can influence the result of the LFA. First, the LFA reflects the motion abnormality. Myocardial ischemia or fibrosis, for example, may affect the wall motion, that causes an abnormal length-based phase. A patient with low ejection fraction or low percent-shortening must be carefully interpreted. Secondly, certain conduction anomalies other than pre-excitation, such as bundle branch block, may affect the phase pattern. Even in the WPW syndrome, the degree of pre-excitation is different in each patient. The contraction sequence of the WPW syndrome is the fusion of multiple conduction pathways. If the patients are concealed types with only retrograde conduction or intermittent types without delta waves, they will show normal contraction patterns. The third factor is in technical problems. Although the spatial resolution in our system was 15 mm in full width at half maximum and temporal resolution for acquisition was 12 frames

in a cardiac cycle, they were practically effective as shown in this study. As is seen in planar gated blood-pool study, arrhythmia during data acquisition, the shape of the time-length curve; and order of harmonics all affect the result of phase analysis. The overlap of blood pool, however, which is one of the major causes of inaccuracy, was avoided in tomography.

CONCLUSION

The LFA in gated blood-pool tomography detected the site of ACP in 86% (19/22) of patients with WPW syndrome, and was effective for pinpointing the earliest segment. It will also be helpful for analyzing three-dimensional pattern of contraction sequence with various cardiac diseases.

FOOTNOTES

* Shimadzu Corporation (ZLC 75), Tokyo, Japan.
† Shimadzu Corporation (Scintipac 2400), Tokyo, Japan.

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