Quantification of Segmental Wall Motion by Length-Based Fourier Analysis

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A new method for evaluating segmental wall motion by length-based Fourier analysis is described. Fourier analysis is performed on a series of lengths from a center to edges of the ventricle, generating parameters of percent length shortening (%LS) and phase of the segment (length-based phase). The reproducibility of the result was good, since the algorithm was automatic except for the setting of the ventricular region as a mask image to exclude surrounding blood pools. This program can be applied for quantification of ventricular wall-motion abnormalities in gated blood-pool studies, and for analysis of the timing of ventricular contraction in gated blood-pool emission computed tomography to detect the site of an accessory conduction pathway in patients with Wolff-Parkinson-White syndrome.

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Wall-motion analysis, as well as ejection fraction (EF), in gated blood-pool studies is of importance for the evaluation of patients with various cardiac diseases. In gated blood-pool studies, segmental wall motion has been assessed by cine-mode display of gated images (*1,2*), superimposition of end-diastolic (ED) and end-systolic (ES) perimeters of the ventricle, regional ejection fraction (*3*), functional images such as EF image (*4*), and phase and amplitude images (*5–8*). Phase analysis has a unique parameter that indicates the sequence of contraction and synchrony of the ventricular movement. Phase images, as well as other functional images of cardiac wall motion, have an advantage in that they contain three-dimensional information; however, correspondence between ventricular segments in contrast ventriculography (LVG) and functional images in radionuclide studies has been difficult to interpret in some cases. Superimposition of blood-pool perimeters has also been utilized for quantification of wall motion.

In this study we applied Fourier analysis to distances from a center to the edges of the ventricle. This method provides the parameters of length shortening and the sequence of contraction of perimeters. We applied this length-based phase analysis to routine gated blood-pool studies and gated emission computed tomography (ECT) in patients with coronary artery disease or a conduction anomaly. The method of length-based Fourier analysis and some clinical applications are described.

METHODS

The gated blood-pool studies were performed after equilibration of ~20 mCi (740 MBq) of Tc-99m red blood cells, labeled by the in vivo method. The scintillation camera, equipped with either a high-sensitivity parallel-hole collimator or an all-purpose slant-hole, was positioned in a modified left anterior oblique (LAO), a best septal, a right anterior oblique (RAO), or a left lateral projection. The data were acquired in 64 × 64 matrices, 24 frames per cardiac cycle, and were stored in a nuclear medicine computer system.

The gated ECT was also performed. The ECT system consisted of dual scintillation camera heads and a nuclear medicine minicomputer system. Projection data were collected for 2 min at every 10° around a patient. Each cardiac cycle was divided into 12 frames. Using a reconstruction algorithm based on filtered back-projection supplied by the manufacturer, short-axis, horizontal and vertical long-axis images were reconstructed.

Phase analysis was performed in two ways. Conventional phase analysis used the programs originally developed by us (*8*), which are essentially the same as those already introduced by others (*5,6*). Phase and amplitude of the fundamental frequency of the Fourier transform is mapped on the functional images. In this paper we call this the count-based phase analysis, since the change of counts in each pixel is analysed by Fourier transform. The new method, length-based phase analysis, was based on the changes of length from a center in the ventricle to the edges of its blood pool. Figure 1 shows the length-based method schematically. First, a mask image is made to eliminate the surrounding structures around the left ventricle, and the count of background is set to zero. The region of interest (ROI) for masking is determined manually by light pen, using ED, ES, and stroke-count images as references. The center of gravity within the ROI is calculated and defined as the center. If this center is outside of the ES blood pool-images, it is changed to the point of maximum count. If this new center is still exterior to the ES blood pool, it is changed manually by the light pen to approximately the center of ES blood pool. We used this center point for all images in the sequence. In each frame, the distance between center and edge is calculated. The edge is defined

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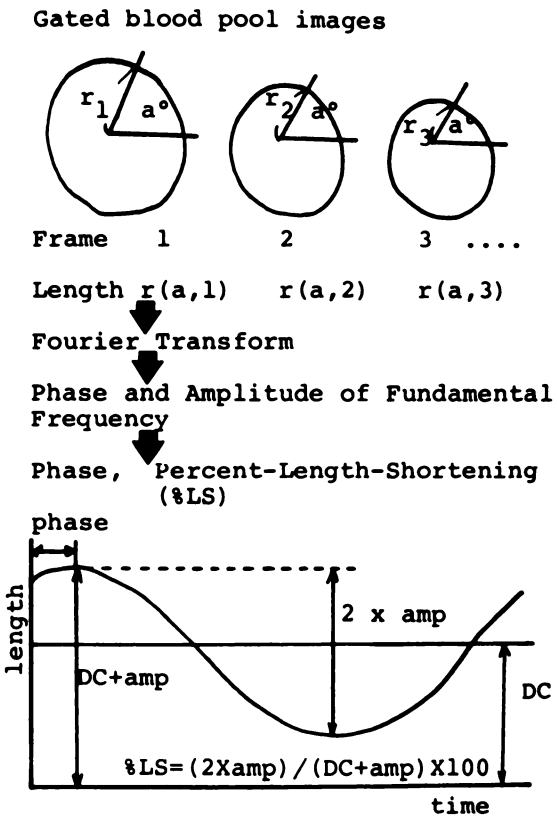

FIG. 1. Method for length-based phase analysis. Series of r(a,i), distance from center to ventricular edge, is computed by discrete Fourier transform. Phase and %LS are calculated for each angle.

by a threshold method: we assume that the edge is where the count falls to 65% of the mean for the center and the four pixels adjacent to it. A series of lengths, r(a,i), from center edges, where a is the radial angle in degrees, and i designates the i-th frame, is computed by Fourier transform, and phase and amplitude of the first harmonic are calculated for each radial direction. The step of the radial angle can be selected from 10° to 90°, and we usually use 22.5° (360/16). The amplitude is converted to a percent length-shortening (%LS) using the following equation:

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

where DC is the direct-current component of the Fourier transform (Fig. 1). The zero degree is defined as the right horizontal position from the center (3 o'clock), and the angle increases counterclockwise. The result is displayed in polar coordinates; the angle denotes the direction of a vector and the length shows the value of the phase or %LS as shown in Figs. 2 and 3. Therefore, the direction of a vector directly corresponds to the direction in the original images. We exclude the directions of valves and the segments where blood-pool overlap occurs. When %LS is less than 5%, the phase is not calculated, because it is unreliable when the amplitude is very low. Each circle of the polar display represents scale; 90 degrees for phase display and 25% for %LS. The color of the vector is changed from blue to red (from white to black on x-ray film) as the value increases.

Length-based and count-based analyses were performed in patients with ischemic heart disease or Wolff-Parkinson-White (WPW) syndrome. The diagnosis of myocardial infarction was confirmed by clinical findings, electrocardiography, coronary arteriography, and contrast LVG. In a patient with WPW syndrome, who later underwent surgical division of the accessory conduction pathway (ACP), the site of the ACP was confirmed by epicardial mapping and surgery (*8,9*).

RESULTS

Examples of the results of this program are shown in Figs. 2 and 3. Figure 2 shows phase analysis of a patient with an old myocardial infarction. By count-based phase analysis, marked delay of phase in the apical region is noted. In the LAO and RAO projections, superimposition of ED and ES perimeters, based on the isocount method, shows paradoxical movement in the apical segment. Length-based phase analysis shows decreased %LS to <25%, indicating hypokinesis, and apparent delay of phase in the apical segment. Since the segment of 270° in the LAO view, apical segment, has less than 5% length shortening, indicating akinesis, both phase and %LS are not displayed. Figure 3 is a length-based phase analysis of the left ventricle in a patient with WPW syndrome. Short-axis images of the left ventricle at a level near the base of heart were analyzed. In length-based analysis the value of phase is low in the segments from posterior to posterolateral. The septal segment is not displayed, as the %LS is <5%. An ACP was confirmed in the posterior wall, and the site of initial phase is shown also in the posterior segment.

Regarding the method of establishing a center, the center of gravity was valid in almost all cases. However, when ES blood pool was very small (for example, in a patient with hypertrophic cardiomyopathy), the center of gravity was out of the ES perimeter and manual setting was necessary.

Reproducibility of length-based phase analysis depends on the setting of the center of ventricle, a center of gravity. Therefore, it is influenced by the ROI for the mask image. When the processing was repeated by two operators, the center of gravity changed less than two pixels. The changes of phase and %LS when a center is displaced one pixel from the center of gravity in a patient with normal contraction (EF = 79%) are shown in Table 1. For the lateral segment (a = 0°), the phase was 134.2 ± 1.2 and %LS was 58.8 ± 3.8; for the apical segment (a = 270°), the phase was 133.8 ± 4.4 and %LS was 68.4 ± 3.7. For the septal segment (a = 225°), the phase was 123.6 ± 2.9, while %LS was 31.4 ± 7.7 and the CV value is relatively high (24.6%). However, the variation was generally small. The reproducibility was good, since the processing apart from the setting of the mask image, which influences the center of gravity, was completely automatic.

DISCUSSION

Segmental wall motion can be evaluated noninvasively by echocardiography and radionuclide ventriculography. In nuclear cardiology, functional images such as EF images, paradox images, and phase and amplitude images have also been attempted, and good correlation has been observed when the findings are compared with those of conventional studies (*1-7*). However, it is not always easy to evaluate the relationship between the functional images and the segments of heart. Previously we compared the result of contrast LVG in RAO and LAO planes with the regional EF images (*10*). The ventricular perimeter was divided into five segments in the RAO view and two segments in the LAO view, while functional images were divided into three regions: anteroseptal, inferoapical, and postrolateral regions. We concluded that anterolateral, apical, and septal segments of LVG correspond to inferoapical and/or anteroseptal regions on the EF images. However, it was difficult to differentiate these two regions with functional images. Apical and diaphragmatic segments correspond to the inferoapical regions, and postrobasal and posterolateral segments correspond to the posterolateral region. On the other hand, in perimetric display, all segments except for basal segments can be

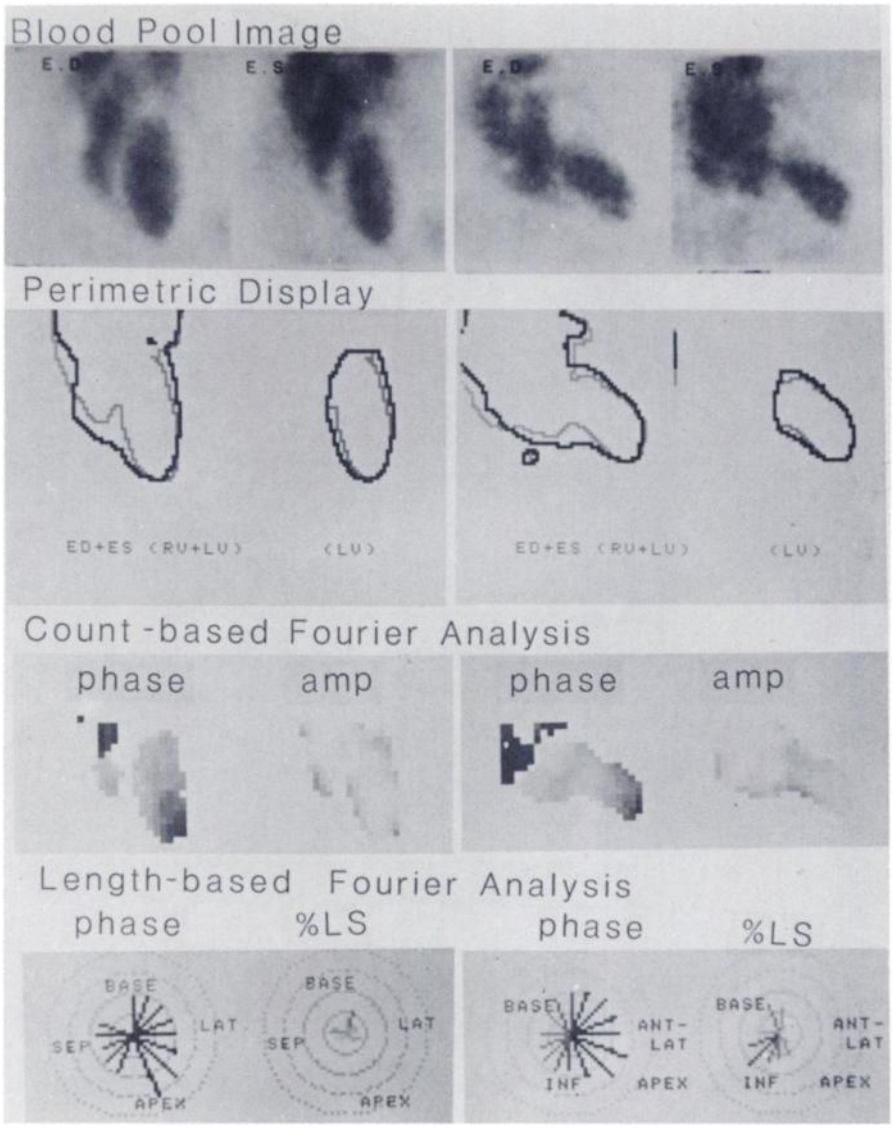

FIG. 2. Patient with old myocardial infarct. Blood-pool images and perimetric display show diffuse hypokinesis and akinesis. On apical segment, dyskinesis is represented. Count-based phase analysis indicates delayed phase in apical region both in LAO and RAO views. Length-based Fourier analysis showed delayed phase in apical segment and reduced %LS to <25% in septal, lateral, and apical segments. Each circle denotes 90° in phase and 25% in %LS.

evaluated if multiple projections are selected appropriately. Percent length shortening is sometimes utilized as a measure of ventricular movement, and we added the information of the sequence of contraction to a perimetric display in this program.

Length-based phase analysis can be also applied to gated blood-pool tomography. We have studied the detection of ACPs in patients with WPW syndrome using gated ECT and count-based phase analysis (*8*,*11*). Tomographic phase imaging was more useful for the analysis of movement of the edge, compared with conventional planar phase imaging. However, application of length-based phase analysis is thought to be more reasonable to study the movement of the edge. Because the edge of the blood pool is meaningful in tomographic blood-pool images, phase should be calculated based on the movement of an edge. When count-based phase analysis is applied to the tomographic blood-pool images, time-activity curves in pixels interior to the ES perimeter are meaningless and confusing. Further clinical study will be needed to clarify the validity of the length-based method in the tomography.

Length-based phase analysis has the following advantages. In radionuclide studies, the edge of the blood pool is not sharp, even if we use some filtering to restore edges. Particularly when the acquired count is limited due to short acquisition times (as in exercise studies), the original blood-pool images contain excessive noise, which cause irregularity in the perimeter. However, in length-based phase analysis, the %LS was affected not by the ED and ES perimeters directly but by the whole time-length curve. Reproducibility of the result was also good, since operator interaction was necessary only when the mask image was set. Regarding the mask image, automatic setting is preferable, to increase the reproducibility of the result, but it was sometimes difficult on basal and septal segments. Other parts of the algorithm are completely automatic, and no background selection is required. By the introduction of length-based phase analysis, severity of asynergy (especially dyskinesis) will be well differentiated. Contractility is evaluated quantitatively by parameters of %LS, a segment being considered hypokinetic when %LS is less than 25%. When the vector is not displayed, the %LS is less than 5% and akinesis is

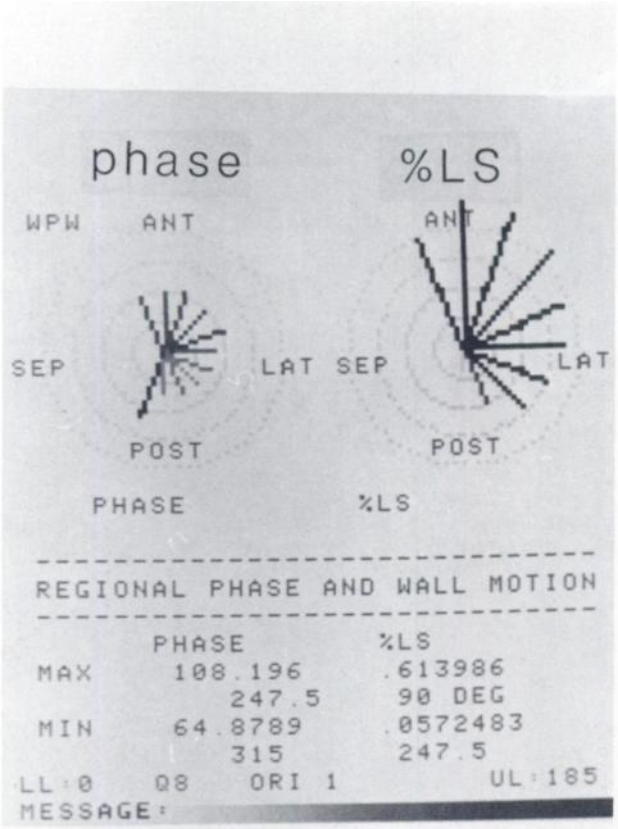

FIG. 3. Length-based Fourier analysis was applied to gated short-axial blood-pool tomography of left ventricle in patient with WPW syndrome. His accessory conduction pathway was confirmed on posterior wall and initial phase was also on posterior segment. In this case, one circle indicates 45° in phase display and 12.5% in %LS.

diagnosed. However, it may be necessary to determine the normal ranges in each projection. There is a possibility that the same program can be applied to the LVG using contrast media, but we have no experience in this area.

No complete algorithm to delineate the true ventricular edge was available, although we used thresholding for edge detection because of the simple algorithm. However, it may be ineffective in some patients, particularly for finding a septal edge. As an alternative edge-detection method, a gradient or differentiation technique is possible. But our preliminary data showed that it failed to track the ventricular perimeter, particularly when the acquired count was low. Some preprocessing filtration to reduce the noise and to enhance the edges will be required. Selection of an appropriate edge-detection algorithm is necessary, although we could not offer the best method in this paper. Nevertheless, length-based Fourier analysis can be a potentially useful approach, since it can be applied to any edge-detection algorithm.

This approach contains the following drawbacks. If the movement of the ventricular edge is several pixels but not more than 20 pixels in 64 × 64 matrices, statistical variation is greater compared with count-based method. This may be improved by applying larger matrices or by zooming the original image. In a segment of akinesis where a series of r(a,i) has the same value in a certain angle, phase cannot be calculated theoretically. The case is rare in the count-based method. Whether the length-based method is superior has not yet been determined, and utility must be studied clinically in various cardiac diseases.

In conclusion, we have developed a length-based Fourier analysis, which is based on the change of the distance from a center to the edge of the ventricle. This method provides information on

TABLE 1. CHANGES OF PHASE AND %LS WHEN CENTER IS DISPLACED ONE PIXEL

Angle	Center	x y	x + 1 y	x − 1 y	x y − 1	x y + 1	Mean ± s.d.	(CV %)
0°	phase (°)	136	134	133	135	133	134.2 ± 1.2	(.87)
(lateral)	%LS	64	55	54	61	60	58.8 ± 3.8	(6.4)
225°	phase (°)	126	124	126	118	124	123.6 ± 2.9	(2.4)
(septal)	%LS	27	20	43	35	32	31.4 ± 7.7	(24.6)
270°	phase (°)	130	129	141	133	136	133.8 ± 4.4	(3.3)
(apical)	%LS	68	68	62	72	72	68.4 ± 3.7	(5.4)

(x,y) = center of gravity.

length shortening as well as the phase of the perimeter, and the reproducibility of the result was good. Length-based Fourier analysis will be useful to quantify segmental wall motion.

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