Three-Dimensional Presentation of the Fourier Amplitude and Phase: A Fast Display Method for Gated Cardiac Blood-Pool SPECT

Eörs Máté, János Mester, László Csernay, Attila Kuba, Shahram Madani and Árpád Makay

Department of Nuclear Medicine, Albert Szent-Györgyi Medical University, Szeged; Kalmár Laboratory, József Attila University, Szeged, Hungary

The routine clinical use of gated SPECT is inhibited by sophisticated, time-consuming processing techniques. The present paper describes a new technique for the simultaneous three-dimensional presentation of the amplitude and phase of the first Fourier harmonics, with the aim of obtaining detailed information about the ventricular motion in a relatively short time, from each angle of view of three-dimensional space. The method is simple and robust, and processing is automatic. It does not need carefully elaborated techniques for surface determination, because the cardiac surface is merely used as a reference skeleton onto which the functional information of amplitude and phase is mapped. The Fourier analysis before reconstruction results in running times shorter than 15 min and may further open the way for the routine use of gated SPECT.

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Since its first application by Moore et al. (*1*), ECG gated cardiac blood-pool tomography has been an alternative method in nuclear cardiology for investigation of the contractility of the myocardium and for determination of the hemodynamic parameters of the ventricles (*2–6*). However, sophisticated, time-consuming data acquisition and processing techniques have inhibited its routine use (*7*).

Recently, an interesting method of gated SPECT data processing was presented by Graf et al. (*8*). The raw data set of projections were considerably reduced to projectional matrices of sine and cosine coefficients and the average blood pool. The results were presented as polar maps (bull's-eyes) of the amplitude and phase (*8*).

The present paper can be regarded as an extension of the work of Graf et al. with the incorporation of a three-dimensional display. It describes a new technique for the simultaneous three-dimensional presentation of the amplitude and phase of the first Fourier harmonics, with the aim of obtaining detailed information about the ventricular motion in a relatively short time, from each angle of view of three-dimensional space. The method is simple and robust, and processing is automatic. It does not need carefully elaborated techniques for surface determination because the cardiac surface is merely used as a reference skeleton onto which the functional information of amplitude and phase is mapped.

METHODS

Data Acquisition

Red blood cells of the patients were labeled in vivo with 740 MBq of ^{99m}Tc. Planar radionuclide ventriculography was then performed from the best septal left anterior and from the 70° left anterior view, using a large field of view gamma camera equipped with a general-purpose low-energy collimator at a software zoom factor of 50%.

With the position of the patient kept unchanged, gated projection images were collected at 6° intervals over 180° from right anterior 45° to left posterior 45°, with 16 frames per cardiac cycle for each projection. Images were acquired at a digital resolution of 64^2, without zoom. Data on 60 representative cardiac cycles were collected for each projection. Bad beats were automatically rejected. Acquisition time was about 30 min and 12–15 million counts were collected.

Data Processing

Projection data sets were smoothed by standard nine-point smoothing. The smoothed data were reduced by Fourier analysis to three images (sine and cosine coefficients of the first harmonic and the average blood pool). The images were reconstructed to 1-pixel (6 mm) thick transaxial sections by filtered backprojection using a Hamming filter. After reconstruction of the coefficients, transaxial sections of the Fourier amplitude and phase were computed.

Construction of the Three-Dimensional Surface

The transversal section of the average blood pool with the maximum left ventricular diameter was centered for subsequent magnification. A software zoom by a factor of two in each direction resulted in an interpolate three-dimensional expansion of the voxel size for optimum image presentation. The endocardial surface of the heart was reconstructed on the basis of the set of transaxial average blood pool sections. Separation from the background was achieved with an arbitrary background cut-off

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For reprints contact: L. Csernay MD, DSc, Department of Nuclear Medicine, Albert Szent-Györgyi Medical University, Korányi fasor 8, H-6721 Szeged, Hungary.

of 50% of the maximum voxel activity. In the next step, the coordinates of the borderline voxels of the transversal blood pool sections were determined. These voxels are considered to represent the endocardial border of the heart. For each borderline voxel, the values of the amplitude and phase were taken from the corresponding points of the transversal amplitude and phase sections (Fig. 1).

Presentation of Three-Dimensional Amplitude and Phase

The three-dimensional display was based on the borderline amplitude and phase voxels. The computer screen displayed only those points of the cardiac surface which could be seen from the actual angle of view (Fig. 2). For the reconstructed three-dimensional surface of the amplitude and phase, two different display facilities are offered. First, the rotating three-dimensional heart is displayed and the patient is observed from a view perpendicular to the long-axis of his body.

Following analysis of the rotating amplitude and phase, it is possible to display selected images from an operator-determined angle of view (Fig. 2), in which a coordinate network is presented on the screen below the parametric surface images. This network represents three-dimensional space with all possible angles of view. The upper part of the network corresponds to views of the anterior surface of the heart, and the lower part to views of the inferior surface.

Running Time of the Clinical Program

The flow chart of the clinical program with the corresponding processing time is shown in Table 1. The overall processing time in a study with 17 transversal sections is about 12 min on an Amiga-3000-based nuclear medicine computer.

Clinical Applications

Patients. The method was tested in 16 patients (6 females, 10 males, mean age 49.5 yr, range 27–69). The patients were separated into two groups.

Control Group. The control group consisted of six patients with atypical chest pain, but with normal resting ECG and without any evidence of myocardial infarction (three females, three males, mean age 43.8 yr, range 34–54). Two-dimensional echocardiographic investigation documented a normokinetic left ventricle in each patient. Heart failure was excluded by Doppler echocardiography.

Myocardial Infarction Group. The myocardial infarction group consisted of 10 patients (3 females, 7 males, mean age 50.1 yr, range 27–69). Eight patients exhibited an old Q-wave posterior, and two patients an old Q-wave anterior myocardial infarction. Q-waves were present on the current resting ECG in each patient. Furthermore, in all patients there was a regional wall motion abnormality corresponding to the infarcted area, as documented by two-dimensional echocardiographic investigation.

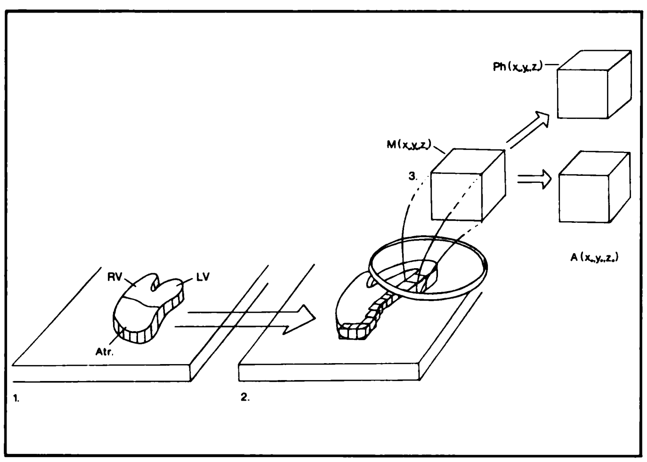

FIGURE 1. Construction of a three-dimensional surface. 1. Separation of the transversal sections of the average blood-pool from the background. 2. Determination of the borderline voxels of the heart. 3. Replacement of the values of the borderline voxels ($M(x_0, y_0, z_0)$) with the corresponding values of amplitude (A) and phase (Ph).

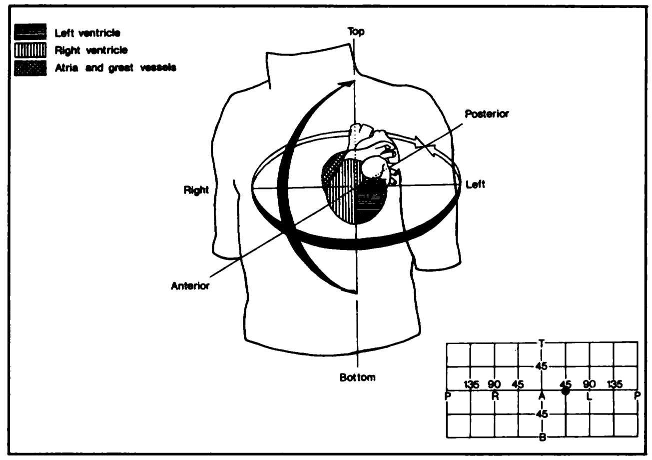

FIGURE 2. Display of the amplitude and phase on the surface of the heart from operator-determined angles of view. The figure represents the left anterior 45° view looking at the patient perpendicular to his body axis (see the circle on the coordinate network). T = top, B = bottom, A = anterior, P = posterior, R = right, L = left.

RESULTS

The results of the clinical investigations are summarized in Table 2.

Control Group

The three-dimensional display of the amplitude showed homogeneously high amplitudes of the left ventricle from each angle of view in five of the six patients (Figs. 3–5).

TABLE 1
Three-Dimensional Presentation of Fourier Coefficients

Handling	Time
Acquisition of gated projections	30–35 min
Nine-point smoothing	
Fourier transform of gated projections (sine and cosine coefficients, average blood pool)	9.5 min
Filtered backprojection of Fourier coefficients	
Determination of three-dimensional cardiac surface (surface rendering)	
Mapping of amplitude and phase onto surface	2.5 min
Presentation of results	

TABLE 2
Clinical Results

Patient no.	Gender	Age	ECG	RNV EF	RNV movie	Three-dimensional surface display defect localization amplitude	Three-dimensional surface display defect localization phase
1	Male	53	PI	55	I	I	I
2	Male	55	PI	61	I	IS	—
3	Male	58	PI	43	I	I	I
4	Male	46	PI	46	I	IB	IB
5	Female	48	PI	56	—	—	—
6	Female	51	PI	43	I	I	I
7	Male	63	PI	52	I	—	—
8	Male	27	PI	46	I	I	I
9	Female	69	A	33	A	A	A
10	Male	60	AS	57	A	A	—
11	Male	50	neg	62	—	—	—
12	Female	47	neg	59	PL	—	—
13	Male	43	neg	65	—	—	—
14	Female	54	neg	64	—	—	—
15	Male	35	neg	56	IB	—	—
16	Female	34	neg	53	—	AS	—

I = inferior; IB = inferobasal; A = anterior; AS = anteroseptal; and PL = posterolateral.

However, in one case relatively low amplitudes were observed on the septal part of the ventricle. The three-dimensional display of the phase revealed a homogeneous spread of the ventricular contraction in each patient (Figs. 3–5).

Myocardial Infarction Group

In the myocardial infarction patients, the three-dimensional amplitude display identified the ventricular hypokinesia corresponding to the ECG localization of the myocardial infarction in 8 of the 10 patients (Figs. 6–8). In two patients with posterior myocardial infarction, no hypokinetic myocardial areas were observed. The three-dimensional phase display demonstrated a phase delay of varying severity, corresponding to the infarcted area in 6 of the 10 patients (Figs. 6–8). Typical dyskinetic phases were identified, corresponding to a left ventricular aneurysm in two of the six patients with phase delay (Figs. 7 and 8).

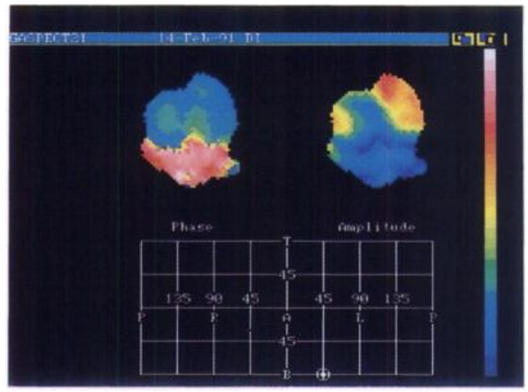

FIGURE 4. Three-dimensional surface display of the Fourier phase (top left) and amplitude (top right) of a healthy person from the left anterior 45°, bottom 90° position.

DISCUSSION

Several attempts have been made to reconstruct and display gated cardiac blood-pool tomography three-dimensional data sets (*9–12*). The first methods visualized only the cardiac blood pool at end-diastole and end-systole from different angles, but mostly only perpendicular to the long-axis of the body (*4–6,13,14*). The problem of overlap of different cardiac structures was compensated by depth-dependent shading to obtain a pseudo-three-dimensional impression (*9–11*). Miller et al. presented the free availability of any orientation selected by the observer (*12*). These techniques were very helpful in the identification and localization of wall motion abnormalities of the left ventricle, but the long processing time inhibited their routine acceptance.

An exact, partially interactive determination of the cardiac contour on transversal sections is very important, when various parameters of the cardiac function (e.g., left

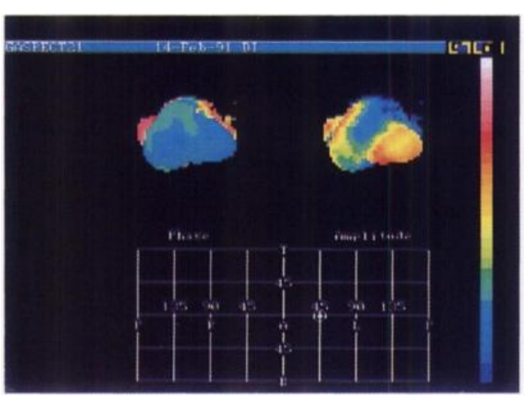

FIGURE 3. Three-dimensional surface display of the Fourier phase (top left) and amplitude (top right) of a healthy person from the left anterior 45° position.

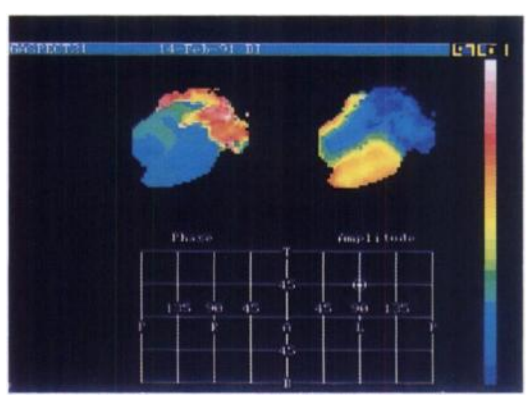

FIGURE 5. Three-dimensional surface display of the Fourier phase (top left) and amplitude (top right) of a healthy person from the left lateral, top 45° position.

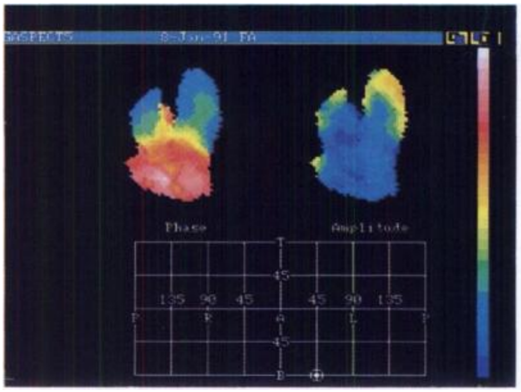

FIGURE 6. Three-dimensional surface display of the Fourier phase (top left) and amplitude (top right) of a patient with an inferior myocardial infarction from the left anterior 45°, bottom 90° position. Note the low inferior amplitudes with minimal phase delay.

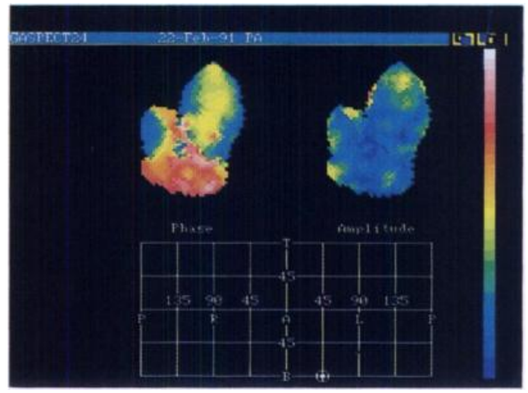

FIGURE 8. Three-dimensional surface display of the Fourier phase (top left) and amplitude (top right) of a patient with an inferior myocardial infarction from the left anterior 45°, bottom 90° position. Note the extensive areas with paradox pulsation on the inferior wall.

and right ventricular ejection fractions, left and right ventricular volumes, and regurgitant fraction) are to be determined (*4–6,9,13,14*). It is of considerably less importance and can be performed automatically, using an arbitrary threshold, when the blood-pool slices are merely used to determine a cardiac surface as a skeleton for the presentation of amplitude and phase values. In the presented technique of surface rendering, the border of the cardiac blood pool was determined by simple thresholding using a level of 50% of the maximum voxel activity. The arbitrarily chosen threshold is higher than that usually used for volume determination in gated SPECT (*4,13,15,16*), and it therefore probably results in an underestimation of the extent of the ventricle. On the other hand, this fairly high threshold seemed necessary for relatively complete background elimination. With lower values, extracardiac regions with relatively high blood content, such as the spleen, liver, etc., will not always be sufficiently eliminated and may disturb the analysis of the images. Underestimation of the ventricular extent due to the high background

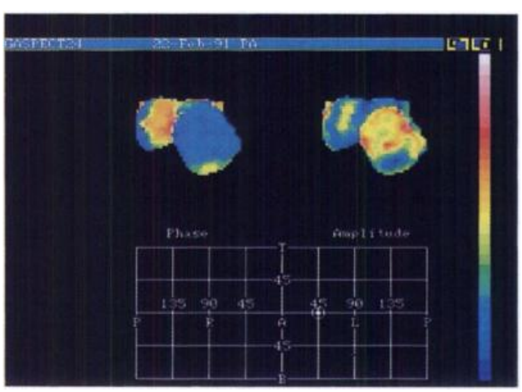

FIGURE 7. Three-dimensional surface display of the Fourier phase (top left) and amplitude (top right) of a patient with an inferior myocardial infarction and a left ventricular aneurysm from the left anterior 45° position. Note the small apical area with paradox phase.

cut-off, however, does not affect the identification and localization of regional wall motion abnormalities and the acquisition of qualitative impressions regarding their extent.

Fourier analysis of gated blood-pool data is widely accepted in nuclear cardiology. The Fourier analysis of slices of gated blood-pool scintigrams was first performed by Biersack et al. (*17*), who computed and presented the Fourier amplitude and phase on transversal, sagittal and coronal slices without double angulation. Interesting results of phase analysis to reconstruct gated blood-pool SPECT data were presented by Nakajima et al. They attained an excellent localization of abnormal left ventricular conduction pathways (*18,19*). Similarly, excellent results were presented on a modified Fourier analysis technique based on the time sequence of circumferential shortening (length-based Fourier analysis) (*20*). All these methods have the common technical shortcoming that Fourier analysis is performed after reconstruction of the whole set of raw data. The handling of the overall projectional data set prolongs processing time considerably.

Recently, a special method of Fourier analysis of gated blood-pool data before reconstruction was employed by Graf et al. (*8*). This method involves a considerable reduction of the raw data before reconstruction. The results are presented as polar maps of the amplitude and phase (bull's-eyes). Our method can be regarded as a second step. The set of transversal slices of the mean blood pool, the amplitude and the phase are computed similarly as by Graf et al. The results are not displayed as polar maps, as by Graf et al., but on the three-dimensional cardiac surface. This solution results in very short processing times, even on an Amiga-3000 PC-based nuclear medicine computer system. The mapping of information about an organ function onto the reconstructed organ surface is not new. In gated SPECT, it was first employed by Faber et al., who displayed color-coded information on the circumferential shortening onto the reconstructed cardiac surface presented by a wirenetwork (*2*). Another approach for PET data was described by Miller et al., who mapped the regional myocardial oxygen consumption onto the cardiac surface (*21*). The presentation of the amplitude and phase on the three-dimensional cardiac surface is described in this paper.

A problem in Fourier analysis of gated blood-pool data is that the combination of the regional contraction and motion of the heart as a whole within the thorax may cause artifacts on the phase and amplitude images, as documented earlier (*23*). This is probably the reason why investigation of the regional contraction of the right ventricle remains problematic. Furthermore, in one patient of the control group, we observed small paradox areas on the upper part of the septum, which can also be explained by the translatory motion of the heart and therefore considered to be an artifact.

As regards data acquisition, we considered the 30-min acquisition time to be acceptable for patients. In our work, we preferred good counting statistics, and therefore we did not try to shorten data acquisition. However, this acquisition time is too long for the investigation of some groups of patients, e.g., those with ventricular tachyarrhythmias. As documented by Clausen et al. in the technique for reconstructing Fourier coefficients, acquisition times of 8 min and shorter seem to be possible (*22*). We found the possibility of viewing the heart as a three-dimensional object of great clinical importance. The bottom views, looking at the inferior cardiac surface, were especially helpful in the identification of inferior wall motion abnormalities.

CONCLUSIONS

The method presented here is the first to allow three-dimensional consideration of Fourier amplitude and phase of the cardiac blood pool mapped onto the cardiac surface determined by surface rendering. Fourier analysis before reconstruction results in clinically acceptable running times and may open the way to the routine use of gated SPECT. Through the free availability of arbitrarily selected angles of view, on-face presentation of problematic areas, e.g., the inferior wall, is readily possible. Simultaneous three-dimensional presentation of amplitude and phase increases confidence in identifying wall motion abnormalities.

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