Reconstruction of Fourier Coefficients: A Fast Method to Get Polar Amplitude and Phase Images of Gated SPECT

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Gated SPECT (GASPECT) during radionuclide ventriculography (RNV) is a time-consuming procedure requiring extended hard- and software. Furthermore, the procedure suffers from poor count statistics. Our method tries to overcome these difficulties by exploiting the count summation effect of Fourier analysis. The sine and cosine coefficients of the first harmonic are extracted from the gated views and reconstructed. This, in fact, results in an improvement of the count statistics by a factor of four combined with a tremendous reduction of disc space requirements. Using short-axis slices, bull's-eye plots of the amplitude and phase of the left ventricle are calculated. Cardiac functions and localization and extent of any malfunction are documented three-dimensionally without superposition.

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ECG gated radionuclide angiography with single-photon emission computed tomography. (GASPECT) was first applied in 1980 by Moore et al. (*1*). The technique of data collection, processing, and presentation has been refined by subsequent groups (*2–13*). However, no advantages could be noted regarding shortening of acquisition or processing time. Consequently, GASPECT did not develop into routine clinical investigation. The purpose of this study is to present a new method of data processing in gated SPECT. The information from gated projection studies will be condensed before reconstruction by computing the Fourier coefficients of the first harmonic. This technique results in a considerable shortening of processing time, a stabilization of the statistics, and offers bull's-eye plots of Fourier amplitudes and phases.

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FLASH-SPECT

Preceeding experiences with planar phase analysis (*14–19*) have shown that Fourier amplitude (FA) and phase (PH) scans of radionuclide ventriculography (RNV) contain clinically relevant information about heart motion. Definition of heart ventricles and regional wall motion abnormalities is possible utilizing FA and PH of the basal Fourier harmonics in a simple way taking into account only four fundamental rules:

1. All pixels with significant FA belong to the heart.
2. All pixels with paradox PH belong to the atria and great vessels.
3. Pixels of the heart with decreased FA belong to hypokinetic wall regions.
4. All pixels with delayed PH belong to dyskinetic regions.

The same is true for GASPECT with two variations: (a) replace *pixel* by *voxel* and (b) modify rule one (above) to "all *voxels* with significant amplitudes belonging to the *diastolic-systolic heart motion volume.*"

The full information about regional wall motion is also then included in amplitude and phase scans of GASPECT. All additional data processing to build other parametric scans (like regional ejection fraction or systolic-diastolic differences, etc.) are effectively replaced because those scans could not add significant information to clinical routine investigations. However, the concentration on PH and FA shortens the data acquisition and simplifies the processing significantly: during Fourier analysis the gated projection views are transformed and only the Fourier coefficients are reconstructed.

The theoretical basis for the new algorithm is the linearity of the Fourier transform and backprojection procedures. This allows one to perform the harmonic mathematical decomposition operations on the gated sequence of n images per view before reconstruction, rather than perform Fourier transforms on the results of n reconstructions (*14,16,20–24*). This procedure not only avoids the need for as many reconstructions as the n images of the gated interval but also gives a square root of n signal to noise improvement.

FLASH-SPECT METHOD

Data Acquisition

The patient's red cells are labeled with 720 MBq of technetium-99m (^{99m}Tc) by the modified in vivo technique. Images are recorded with a round field of view gamma camera using a low-energy all-purpose, parallel-hole collimator. Data are acquired at 32 angles over 180° rotation for 30 sec/angle. Images are collected in a 64 × 64 matrix on a dedicated nuclear medicine computer. A 20% window centered on the 140-keV photon peak of ^{99m}Tc is used. Camera nonuniformity is corrected with the camera's digital flood correction. A circular orbit with minimal radius of rotation close to the patient's thorax is used.

Each cardiac cycle is divided into eight frames with fixed interval gating of the R-R interval and rejection of all beats that do not fall within a timing window of ±20% of the average heart rate. For each projection angle, a single-window buffered-beat gated dynamic acquisition is done with forward/backward framing by thirds. (The gated image sequence is performed by combining the first two-thirds of the R-R interval with forward framing and the last one-third with backward framing.) This will avoid the count dropoff at the end of the cycle, due to heart rate variations, and will keep the R-R interval constant. Normalization to correct any variation in active acquisition time per view and to eliminate the influence of radioactive decay will be performed prior to Fourier-transforming the gated image sequences of all angle steps (Fig. 1).

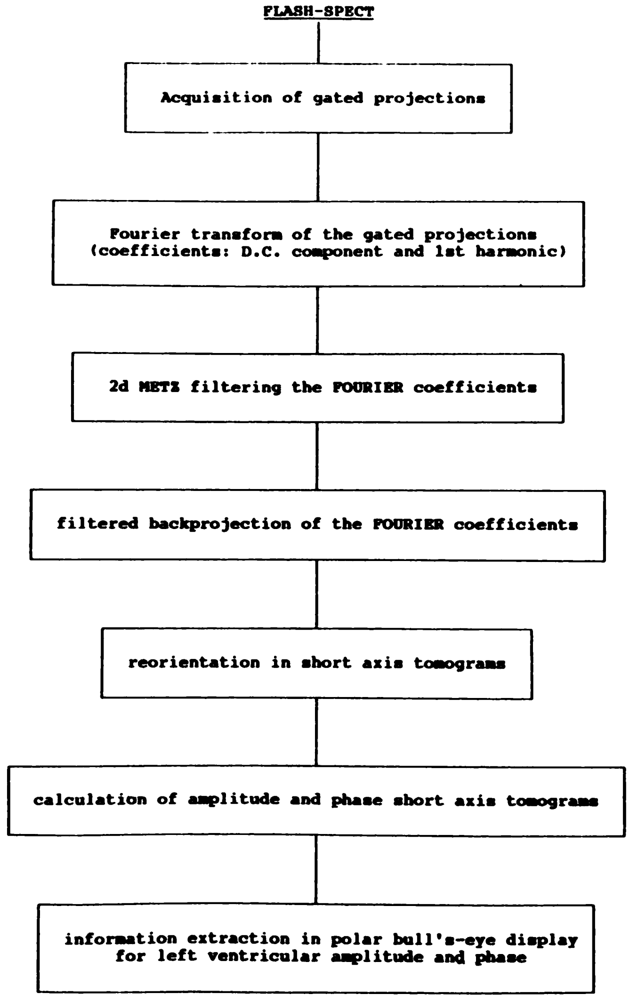

FIGURE 1
A flow-chart presentation of all FLASH-SPECT algorithms involved.

Data Processing

The Fourier transform results in the time independent mean level (D.C.) of the R-R interval, which looks like an ungated heart study, and the cosine and sine matrices of the first harmonic. These parametric Fourier projection data are two-dimensionally filtered with a count-dependent METZ-filter (*25–29*), center of rotation correction, and each parametric data set reconstructed by filtered backprojection using a Ramp filter without attenuation correction.

The slice thickness is equivalent to the pixel length of 0.6 cm by a 64 × 64 matrix size and 39 cm UFOV (useful field of view) gamma camera. Short-axis parametric views are reconstructed from the parametric transverse slices, where the mean level (D.C.) Fourier coefficient enables good recognition of anatomic structures for reorientation and definition of the left ventricular long axis. The cosine and sine matrices are identically reoriented. Last, the short-axis amplitude and phase slices are calculated from the cosine and sine parametric slices (Fig. 2).

Data Processing for Amplitude and Phase Extraction and Bull's-eye Presentation

To document left ventricular heart function by its amplitude and phase, the multiple parametric short-axis slices are difficult to compare and to evaluate. Established documentation modes are the polar bull's-eye display of thallium-201 myocardial SPECT (*30–32*) and the hemispheric display, also called unfolded map (*12*). The parametric extraction is processed semiautomatically by masking the left ventricle in all short-axis slices (Fig. 2). The left ventricular size from the apex to the mitral valve is determined in a specially generated thick vertical long-axis slice, representing a lateral projection to ease further processing in respect to the bull's-eye transformation (Fig. 3). The marked left ventricular regions of interest (ROIs) are divided into 64 sectors. The maximum amplitudes in all sectors together with their according phases are extracted and stored in a rectangular buffer's row corresponding to the slice number. The rectangular buffers for amplitude and phase build the interface to the construction algorithm for the polar bull's-eye display or the hemispheric display of left ventricular amplitudes and phases.

RESULTS

FLASH-SPECT was applied in eight patients (two females, six males) ranging in age from 45 to 78 (59.8 ± 12.0, mean ± 1 s.d.) with a history of myocardial infarction. Four anterior and four posterior wall infarctions could be localized, with the development of myocardial aneurysm in one patient.

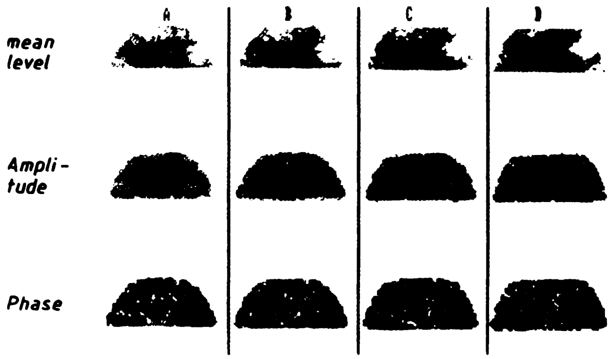

FIGURE 2
Serial short-axis tomograms of the heart from apex (column A) to base (column D). Tomograms of FOURIER average value (top line) equivalent to a nontriggered heart study and the amplitudes (second line) and phases (bottom line). The maximum amplitudes are localized in the enddiastolic-endsystolic difference area of the left ventricle.

The control group comprised eight patients (three females, five males), in which left ventricular wall motion abnormalities could be excluded by previously performed examinations. The patients of the control group ranged in age from 19 to 74 (44.6 ± 22.8). In four patients, hypertrophic cardiomyopathy was diagnosed and in two patients Wolff-Parkinson-White (WPW) syndrome. Two patients were suspected to have coronary heart disease, which could not be proved by cardiac catheterization.

The amplitudes in the bull's-eye plots of the patients of the control group without significant left ventricular wall motion abnormality showed a homogeneous distribution (Fig. 4, top). Small lesions could be detected in two patients in the area of the apex. An asymmetrical distribution of the amplitudes with a maximum in the anterolateral region and slightly reduced amplitudes in the septal region could be registered in all patients of the control group.

The amplitude bull's-eyes of the patients with a history of myocardial infarction revealed significant differences from the typical distribution of the control group (Table 1). Four patients showed reduced amplitudes corresponding to the infarcted area. In three cases, the expansion of the amplitude lesions extended the expected zone. This group additionally demonstrated a hypokinesia in the posterior wall following anterior wall infarction. Only a small area of reduced amplitudes in the anterolateral area could be registered in one patient with a small posterior infarct. The aneurysm of another patient could be outlined clearly by the help of the phase bull's-eye (Fig. 4, bottom).

DISCUSSION

Tomographic gated blood-pool imaging is a natural extension of the technologies of gated planar blood-pool scintigraphy and SPECT with rotating Anger camera (*33*). FLASH-SPECT may be seen as a functional extension of GASPECT (*2,4,5,11,34,35*) in the usage of Fourier transform immediately after data acquisition to minimize the number of reconstructions. FLASH-SPECT presents high quality bull's-eyes of three-dimensional distribution of Fourier amplitude and phase.

An important benefit of FLASH-SPECT is the reduction of the root mean square (rms) statistical uncertainty (*20,36*) of the reconstructed short-axis tomograms of amplitude and phase. Because of the summa-

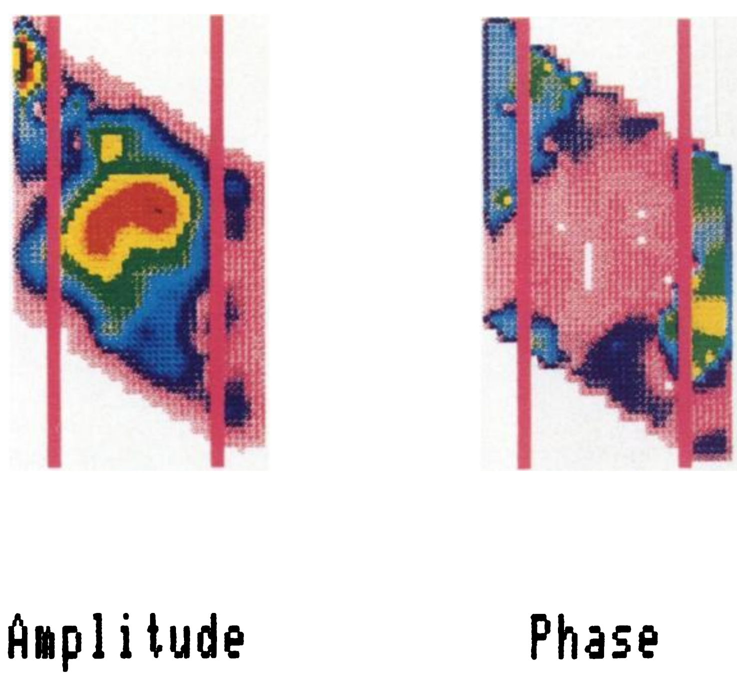

FIGURE 3
Amplitude (left) and phase (right) vertical long-axis tomograms including the whole heart. The vertical lines are part of the operator interaction to document the chosen left ventricular slices for the radial transformation (bull's-eye) from the apex (left line) to the mitral valve plane (right line).

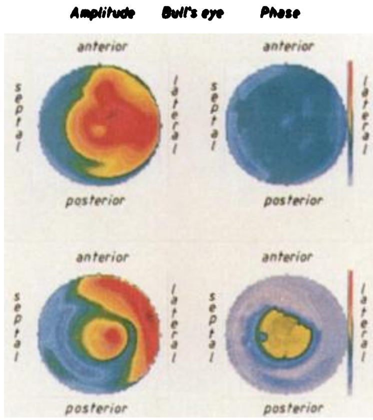

FIGURE 4
(Top) Normal heart with typical amplitude (FA) distribution. Reduction of the amplitudes in the septum is normal. The phase scan demonstrates the homogeneous time of contraction. (Bottom) Patient with anteroseptal myocardial infarction and apical aneurysm—normal amplitudes in the anterobasal and posterolateral area. The amplitudes of the apex correspond to the dyskinesia with phase delay in the phase bull's-eye plot. The reduced amplitudes anteroseptal correspond to the previous infarction.

tion effect of the Fourier transform over the whole R-R interval, the counting statistics are determined by the sum of all counts registered. Compared with conventionally reconstructed gated SPECT studies with 16 images per cycle, FLASH-SPECT offers a decrease of rms uncertainty by the factor four. Further procedures of noise reduction are generally not necessary (*3,6,7*), therefore the presented functional images represent the maximal achievable geometric resolution of the SPECT camera.

A difficult problem by the computer implementation of gated SPECT algorithms is the enormous disc space requirement. A traditional gated SPECT study with all of its projection data and gated transversal and oblique slices, requires up to 10 MBytes of disc storage which could make routine handling tedious (*8,33*). FLASH-SPECT reduces data from each projection to only three parametric images of Fourier coefficients, therefore the disc space requirement is reduced to about 4 MBytes.

Reconstruction is performed on only three parametric projectional images, which makes FLASH-SPECT considerably faster than traditional procedures. The effective processing time saved certainly depends on computer hardware. A MicroVAX computer needs, for example, 30 min for reconstruction, data processing, and bull's-eyes presentation.

Clinical Results

The phenomenon of reduced amplitudes in the whole septal region which we observed in our normal group may result from the lack of any attenuation correction routine and the use of a 180° orbit instead of 360° (*37*). However, more likely seems to be a small translation of the left ventricular center during systole towards the right ventricle, resulting in hypokinetic amplitudes in septal and hyperkinetic amplitudes in lateral regions (*38*). A possible solution of this translation artifact has not been established in clinical practice (*15,39*). Fourier resynthesis including higher spectral components to moving slices might be helpful to visualize the translatory and rotatory heart motion.

The polar bull's-eye presentation of FLASH-SPECT for amplitude and phase belongs to the group of *first-order functional imaging* (mechanical pump function) (*15,39*). *Third-order functional imaging* (metabolism) of the myocardial perfusion (thallium-201-ECT) usually is presented in the same manner. This facilitates the comparison between heart motility and perfusion (*38,40*) (Fig. 5).

CONCLUSION

FLASH-SPECT may help to bring gated SPECT into the clinical routine. Using this technique, the time for acquisition and reconstruction is acceptable and the assessment of cardiac function in patients with significant cardiac rotation or other anatomic abnormalities will be relatively simple (*33*). More precise evaluation

TABLE 1
Localization of Left Ventricular Wall Motion Abnormalities in Patients wity Myocardial Infarction

Patient no.	Polar amplitude defect localization: Antero-lateral	Anterior	Antero-septal	Inferior	Infero-septal	Infero-lateral	Infarct localization by ECG	Agreement between ECG and amplitude defect
1	—	yes	yes	yes	yes	yes	anterior	partial
2	—	—	—	yes	yes	yes	posterior	good
3	—	—	—	yes	—	yes	posterior	good
4	—	—	yes	yes	yes	—	anterior	partial
5	—	—	yes	—	—	—	anterior	good
6	yes	—	—	—	—	—	posterior	none
7	—	—	—	yes	—	yes	posterior	good
8	—	—	yes	yes	yes	—	anterior	partial

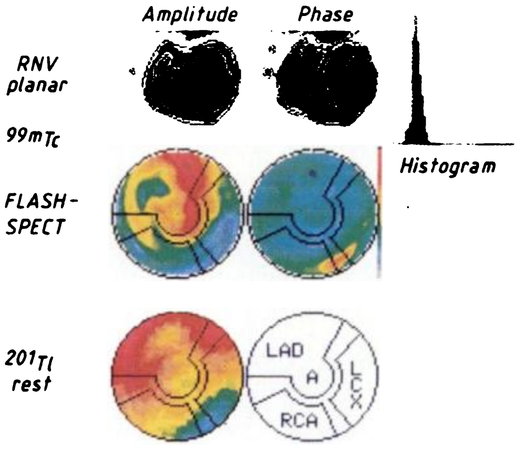

FIGURE 5
Comparison of the FLASH-SPECT to planar RNV and myocardial-ECT at rest in a 56-yr-old male with a history of coronary bypass surgery [grafts to the left anterior descending artery (LAD), to the circumflex artery (CX) and to the right coronary artery (RCA)], severe coronary three-vessel disease with obstructions of LAD, and ramus circumflexus and subtotal stenosis of the RCA. Stenosis of all three bypass grafts. The scheme of assigning vascular territories is used from Cedars-Sinai myocardial program (*41*). Planar RNV (LAO 30° projection): Posterolateral amplitude shortening with slight phase delay and hypokinesia of the posterior wall. FLASH-SPECT of the LV: Significant reduced amplitudes in the whole posterior and lateral wall and in the subaortal anterior wall. The phase bull's-eye plot shows delayed contraction with a small area of dyskinesia in the submitral posterior wall. Myocardial ECT of the LV: Perfusion deficit of the posterolateral wall.

of the size and extent of aneurysms and other regional wall motion abnormalities can be achieved.

In the present state, these results are preliminary and a larger patient population is needed before their clinical significance may be established.

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