## PRELIMINARY NOTES

# Patterns of Ventricular Emptying by Fourier Analysis of Gated Blood-Pool Studies

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**Temporal Fourier analysis was applied to the processing of ECG-gated cardiac blood-pool studies on a pixel-by-pixel basis, to yield information about the pattern of ventricular emptying in normal hearts and in others with conduction abnormalities. The transform data at the fundamental frequency (the heart rate) were used to construct two types of display: (a) a distribution histogram of the pixel phase values, and (b) a cinematic display of the wave of emptying as it spread over the cardiac chambers. Preliminary results indicate that temporal Fourier analysis permits visualization of the pattern of ventricular emptying, which may prove useful in the study of motion abnormalities and asynergies, including those resulting from myocardial hypertrophy or conduction abnormalities, and as an aid in the optimum placement of pacemakers.**

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Fourier analysis is a mathematical technique by means of which any periodic function can be represented as the sum of sine and cosine waves of different frequencies, each frequency characterized by a specific amplitude and phase (*1*). The periodic nature of ventricular contraction seems ideally suited for the use of temporal Fourier analysis, as first proposed by Adam (*2*), and further extended by Verba (*3*). Such an analysis can be used to transform the average cardiac cycle obtained from an ECG-gated blood-pool study into its various temporal frequency components. In a gated blood-pool study, most of the changes in activity within the heart occur at the fundamental frequency, the heart rate (*4,5*). Thus, to a first approximation, the amplitude of the fundamental frequency is proportional to stroke volume, and the phase is related to the time in the cardiac cycle at which emptying begins. We have developed a new method of temporal Fourier analysis of gated blood-pool studies to obtain cinematic displays of the pattern of ventricular emptying.

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## METHODS

Normal persons and patients with conduction abnormalities underwent ECG-gated cardiac blood-pool imaging. After blood-pool equilibration of 20–25 mCi Tc-99m red blood cells, labeled in vivo, 16-frame gated studies in 64 × 64 matrix were acquired with a standard Anger camera in the 40° left anterior oblique projection, and stored in a commercial nuclear medicine computer system. The temporal Fourier transform at the fundamental frequency (the heart rate) was obtained on a pixel-by-pixel basis as follows: The discrete Fourier transform of the function f at the frequency K is given by:

$$F_K(f) = \sum_{t=1}^{N} f(t)e^{-2\pi iKt/N} \quad (1)$$

$$= \sum_{t=1}^{N} f(t)[\cos(2\pi Kt/N) - i\sin(2\pi Kt/N)] \quad (2)$$

where $F_K(f)$ is the transform of the function f at the frequency K, t is the sampling index, N is the total number of samples, and f(t) is the value of function f at sample t. We calculated the real (cosine) and imaginary (sine) parts of the transform separately, and then determined the amplitude and phase. The value of the real part of the transform is given by:

$$R_K(f) = \sum_{t=1}^{N} f(t) \cos(2\pi Kt/N), \qquad (3)$$

and of the imaginary part by:

$$I_K(f) = \sum_{t=1}^{N} f(t) \sin(2\pi Kt/N), \qquad (4)$$

where $R_K(f)$ and $I_K(f)$ are the real and imaginary values, f(t) is the value of pixel f in frame t, N is the total number of frames in the study (16 in our case), and K is the frequency (i.e, K = 1 for the fundamental frequency, K = 2 for the second harmonic, etc.). The amplitude of the transform is given by:

$$A_K(f) = (R_K(f)^2 + I_K(f)^2)^{1/2}, \qquad (5)$$

and the phase by:

$$P_K(f) = \text{arctangent}\,(I_K(f)/R_K(f)), \qquad (6)$$

where $A_K(f)$ and $P_K(f)$ are the amplitude (in "counts") and phase (in radians).

The transform data were used to construct two types of display: (a) a distribution histogram of the pixel phase values, and (b) a continuous-loop cinematic display of the wave of emptying as it spread over the cardiac chambers. Histograms of the pixel phase values were obtained as follows. The number of pixels whose phase was in a given 10° range (i.e., 0-9, 10-19°, etc.) was determined. Only those pixels whose amplitude at the fundamental frequency was above a certain threshold (usually 10-15% of the maximum amplitude) were counted, so that background pixels did not contribute to the histogram. A histogram was then constructed with

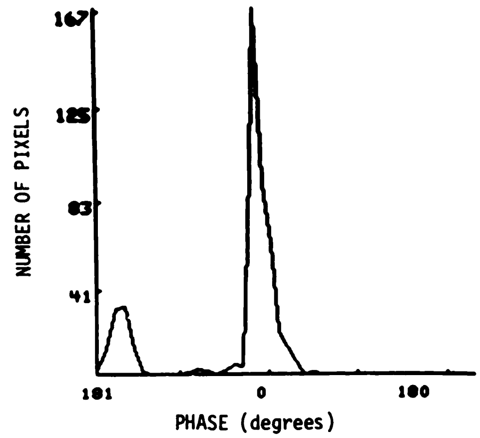


**FIG 1.** Phase histogram from normal person. Y axis is in units of number of pixels within 10° range; *x* axis is in units of phase in degrees, with phase of 0° in center of histogram.

phase in degrees on the abscissa, and number of pixels within each 10° range on the ordinate. The abscissa was right-shifted 180°, so that a phase of 0° was in the center of the histogram. From the way the transform was obtained, a pixel whose fundamental frequency curve was maximally positive in the first frame of the gated study was taken to have a phase of 0°. Thus, those pixels representing the ventricles had phases around 0°. Pixels that represented the atria, which beat out of phase with the ventricles, had phases around 180°.

The cinematic display of the wave of emptying was obtained as follows. From the phase of each pixel, the frame in which that pixel's fundamental frequency curve is maximally positive is given by:

$$F = R\left(1 + \frac{N-1}{360} P\right) \qquad (7)$$

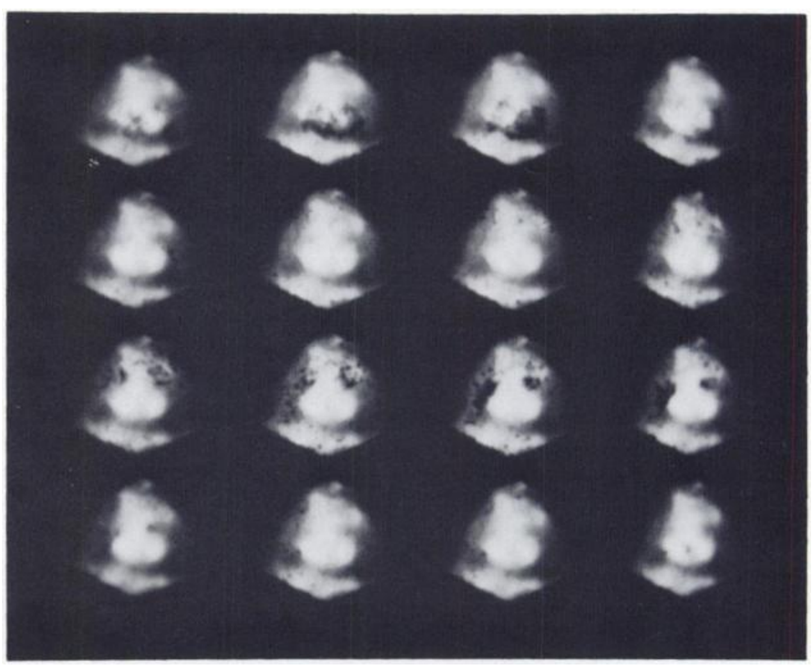

**FIG. 2.** Wave of emptying from normal person of Fig. 1, displayed as wave of black pixels traveling over end-diastolic plus end-systolic composite image. See text for pattern.

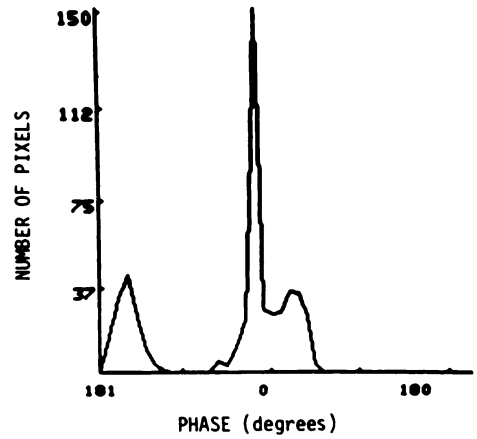


**FIG 3.** Phase histogram from patient with left bundle branch block. Axes as in Fig. 1.

where F is the frame number, R is a rounding-off function used to make F an integer, N is the total number of frames desired for the cinematic display (16 in our case), and P is the phase in degrees. A 16-frame study was created in which each pixel was blacked out in its appropriate frame F. Only those pixels whose amplitude at the fundamental frequency was above a certain threshold (again, usually 10–15% of the maximum amplitude) were displayed in this manner, so that background pixels never blackened during the cycle. This 16-frame study, representing the wave of emptying, was displayed over either the cinematic display of the original gated study of the beating heart, or over a static image formed by adding the end-diastolic and end-systolic frames, to serve as an anatomical guide. At the last stage before the display, a weighted temporal smooth was performed, using a ½-1-½ smoothing function.

## RESULTS AND DISCUSSION

In normal persons, the phase histogram had two peaks, one centered around a phase of 0°, representing ventricular pixels, and the other centered around 200°, representing those pixels corresponding to the parts of the atria lying beyond the ventricular borders (Fig. 1). In the cinematic display, the wave of emptying appeared first in the region of the interventricular septum, and then spread over each ventricle (Fig. 2). In patients with left bundle branch block, the phase histogram had the usual atrial peak around 200°, but showed a double-peaked distribution around 0° (Fig. 3). This indicated that the ventricles were not beating in phase. In the cinematic display, the wave of emptying appeared first in the region of the septum, spread over the right ventricle, and then over the left ventricle (Fig. 4). In a patient with a pacemaker at the right-ventricular apex, the phase histogram had essentially no atrial peak around 200°, and a multi-peaked distribution around 0° (Fig. 5). This indicated not only that the two ventricles were out of phase, but that parts of the same ventricle were also out of synchrony. One of the peaks could be due to atrial contraction. In the cinematic display, the wave of emptying seemed to start at the right-ventricular apex, travel up the right-ventricular side of the septum, and then spread over both ventricles (Fig. 6).

Since each pixel's time-activity curve is represented by one cycle of a single-frequency sine wave, the latter is not an exact representation of the time-activity curve. In normal persons at rest, in whom cardiac filling occurs primarily during the middle third of the cardiac cycle, isovolumetric diastole ("diastasis") accounts for most of the last third of the cycle. In such cases, the point at which the fundamental frequency curve is maximally

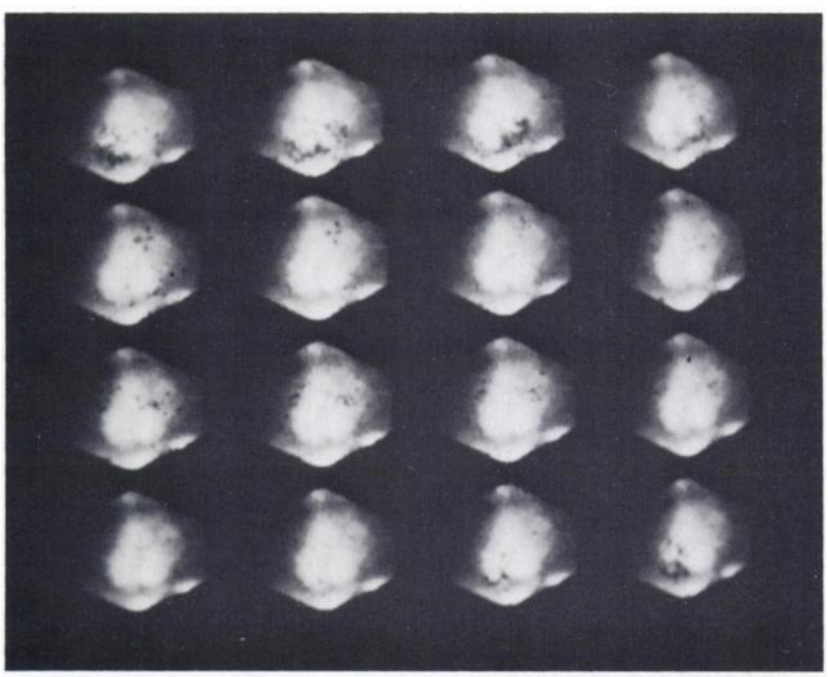

**FIG. 4.** Wave of emptying from patient of Fig. 3, with left bundle branch block, displayed as in Fig. 2. See text for pattern.

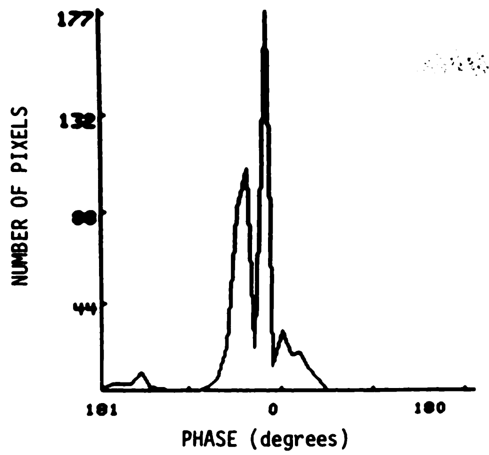


**FIG. 5.** Phase histogram from patient with right ventricular pacemaker. Axes as in Fig. 1.

positive does not correspond exactly with end-diastole, but may even occur before the start of ventricular emptying. In persons without a clear diastasis (e.g., in patients with tachycardia), there is usually close agreement between the fundamental frequency curve and the time-activity curve. Studies of the frequency spectra of ventricular volume curves—obtained either by cineradiography of surgically implanted metallic clips on the ventricle (*4*) or by contrast ventriculography (*5*)—have shown that, at a 72-bpm heart rate, approximately 75% of the total frequency content is at the fundamental frequency (1.2 cycles/sec). Approximately 95% of the frequency content is below 5 cycles/sec.

These same studies have shown the effects of varying the acquisition framing rate (number of frames per cardiac cycle) on the accuracy of left-ventricular time-volume curves. Since each pixel's time-activity curve is represented by a sine wave, there is no apparent difference in the results obtained with 64 frames per cardiac cycle compared with 16 (F. Deconinck, personal communication). The cinematic display of the wave of emptying can be composed of any desired number of frames. Increasing the number of frames would increase temporal resolution.

The use of a cinematic display of the spread of the wave of emptying was introduced by Verba (*3*). Our method differs in that the phase of the fundamental frequency (i.e., the Fourier information itself), rather than the first derivative of a Fourier-filtered time-activity curve, was used to determine the point in the cardiac cycle at which emptying began in each pixel. A practical advantage of our method is that it can be implemented on the small computer systems readily available in nuclear medicine departments. With Verba's method, one must take the total Fourier transform of each pixel, multiply the transform by a filter function, and then take the inverse transform. This requires a large computer to perform the operation within acceptable time limits. With our method, one need only obtain the value of the transform at the fundamental frequency. Our preliminary results indicate that temporal Fourier analysis permits visualization of the pattern of ventricular emptying, which may prove useful in the study of asynergies or other motion abnormalities—including those resulting from myocardial hypertrophy or conduction abnormalities—and as an aid in the optimum placement of pacemakers.

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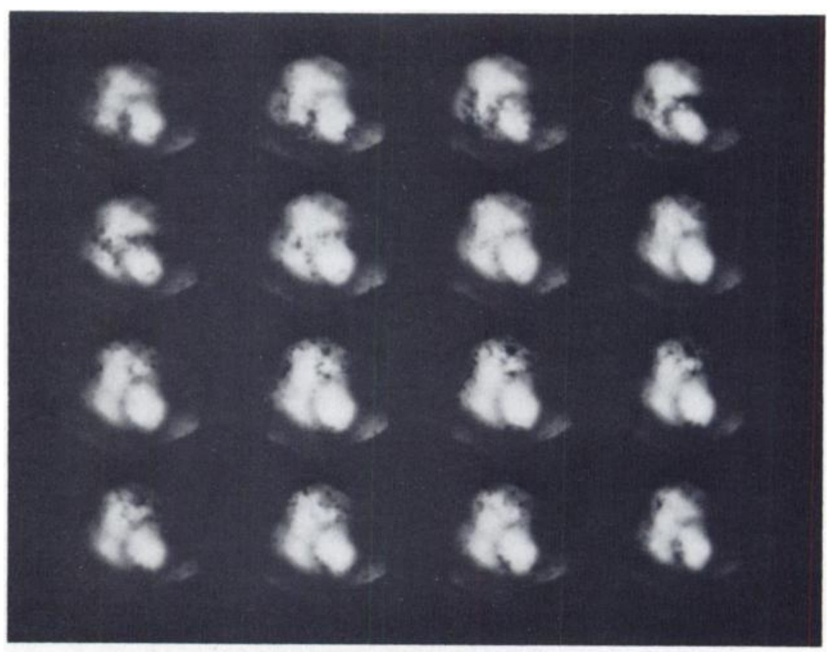

**FIG. 6.** Wave of emptying from patient of Fig. 5, with right ventricular pacemaker, displayed as in Fig. 2. See text for pattern.

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