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Phase plane (volume to volume-time function loop) display of data from radionuclide ventriculography obtained by single cardiac probe system

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To assess the left ventricular (LV) performance more sensitively, a new display method of phase plane (PP), displaying volume and volume-time function (dV/dt) in a single image, was applied to radionuclide ventriculography obtained by a single cardiac probe system. The sampling interval was 10 msec and the data acquisition time was 60 sec. The LV volume curve was smoothed by fitting a fourth order polynomial curve of Fourier's analysis. Then the dV/dt was calculated. In this single image PP display, the width of the horizontal axis indicates relative LV volume, and the height of the vertical axis indicates dV/dt. The direction of the rotation of this loop is clockwise. We classified 126 patients with various heart diseases into seven groups, according to the configuration of the loop. The most interesting finding was that the distortion of the loop during diastole was frequently seen in patients with hypertension and angina pectoris, whereas their ejection fraction was within normal limits. We concluded that the single image PP display is a sensitive method for assessing the abnormality of the LV function, not only by evaluating the conventional parameters, but also by analyzing the configuration of the volume to volume-time function loop.

Key words: Phase plane, Radionuclide ventriculography, Single cardiac probe system, Ejection fraction, Atrial contribution

INTRODUCTION

RADIONUCLIDE VENTRICULOGRAPHY (RNVG) is widely used for noninvasive assessment of cardiac functions.[1–3] Many parameters derived from the time-activity curve (TAC) of the left ventricle (LV) are proposed for evaluating the LV performance.[4,5] These parameters include ejection fraction (EF), first-third EF (1/3 EF), peak ejection rate (PER), peak filling rate (PFR), ejection rate (ER), first-third filling fraction (1/3 EF), time to PER, time to PFR, etc. However, it is very difficult to evaluate these parameters simultaneously because of the complex relationships between them. Therefore, to assess the LV performance more sensitively and easily, a new display method of phase plane (PP), in which volume and volume-time function (dV/dt) was displayed in a single image, was applied to RNVG. The aims of this study are to describe this new method for displaying the PP, and to present the results of some clinical applications.

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MATERIALS AND METHODS

Subjects studied were 126 patients with various heart diseases (19 females and 107 males), ranging in age from 19 to 83 years (mean age 54.4) (Table 1). All patients had normal sinus rhythm when this study was done.

Red blood cells were labeled with 740 MBq of ^{99m}Tc pertechnetate by the *in vivo* method. An equilibrium-gated blood pool study was performed using a single cardiac probe system (OMNISCOPE, Aloka Co., Ltd., Tokyo) in the ECG multi-gated mode.[4,6–8] The sampling interval was 10 msec and

Table 1 Subjects of present study

	Number (female: male)	Age (mean)
Control (C)	9 (3: 6)	20–68 (38.9)
Mitral Stenosis (MS)	2 (0: 2)	47 (47.0)
Mitral Regurgitation (MR)	4 (0: 4)	38–61 (47.8)
Aortic Regurgitation (AR)	4 (2: 2)	31–81 (47.8)
Hypertrophic Cardiomyopathy (HCM)	3 (1: 2)	19–60 (46.0)
Dilated Cardiomyopathy (DCM)	3 (0: 3)	46–52 (48.0)
Hypertension (HT)	24 (4: 20)	34–75 (55.5)
Angina Pectoris (AP)	12 (0: 12)	38–82 (57.3)
Old Myocardial Infarction (OMI)	65 (9: 56)	36–83 (56.6)
Total	126 (19: 107)	19–83 (54.4)

the data acquisition time was 60 sec. RNVG data obtained by OMNISCOPE were transferred to a microcomputer (LSI-11/23, DEC Co., Ltd., Tokyo) through RS-232c cable, and recorded on a magnetic floppy disk.

The LV volume curve was smoothed by fitting a fourth order polynomial curve of Fourier's analysis. Using this reconstructed volume curve, the dV/dt was calculated and the dV/dt curve was constructed. From these two curves, the PP display was presented by plotting the volume on the horizontal axis, and the dV/dt on the vertical axis. The PP display shows a closed loop, and the rotation of this loop is clockwise (Fig. 1). This loop demonstrates three separate periods of the cardiac cycle: systole, diastole and atrial contraction. The width of the horizontal axis indicates relative stroke volume (SV) or EF. The loop

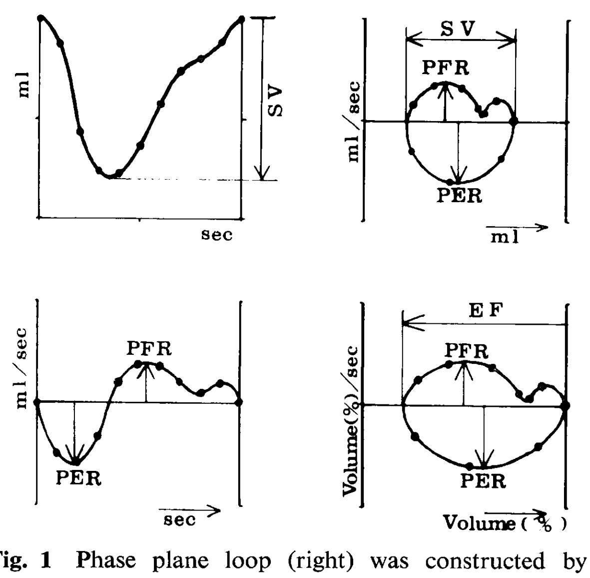

Fig. 1 Phase plane loop (right) was constructed by combining left ventricular volume curve and dV/dt curve (upper, lower left, respectively). In this study, we used the display shown in the right lower corner of this figure.

is wider in the horizontal direction when the EF or SV is greater (Fig. 2). The height of the vertical axis indicates dV/dt. When the dV/dt becomes greater, the loop is wider in the vertical direction (Fig. 3). Therefore, in a single image the PP display shows four parameters, namely EF or SV, PER, PFR and atrial contribution (AC), and the relationship between these parameters.

Figure 4 shows an example of the PP display of the data from a normal control. Phase plane-1 is a display of the absolute value of EF, PER and PFR, and phase plane-2 is a display of their relative value.

We divided the patterns of the PP display into seven groups according to the configuration of the loop. The patterns are listed in Table 2, and examples of each pattern are shown in Fig. 5. Type N is the normal pattern, which has no distortion during any of the three periods of a cardiac cycle. Type S has distortion of the loop during the systolic phase, and type D during the diastolic phase. Type M has distortion both in the systolic and diastolic phase. Type SS is a peculiar pattern of type S and type M, and has two peaks in the systolic phase. Type DD is a peculiar pattern of type D and type M, and has three peaks in the diastolic phase. Type NAC has no atrial contribution. The distribution of these patterns amont the 126 patients was determined. The seven patterns of the PP display were compared with the following conventional parameters: EF, PER, PFR and the ratio of AC to SV (AC/SV).

RESULTS

The distribution of the patterns of the phase plane is summarized in Table 3. Out of the 126 patients, type N patterns were seen in 64 patients (50.8%), type S in 21 patients (16.7%), type D in 24 patients (19%), type M in 17 patients (13.5%) and type N included all 9 normal controls. Type SS was seen in 19 patients (15.1%), type DD in 17 patients (13.5%) and type NAC in 7 patients (5.6%). The distribution of these patterns among the various heart diseases was as follows: Type S was found in 10 patients (15.4%) with myocardial infarction (OMI), in 2 patients (50%) with mitral regurgitation (MR), in 2 patients (66.7%) with hypertrophic cardiomyopathy (HCM), in 2 patients (66.7%) with dilated cardiomyopathy (DCM), in 3 patients (12.5%) with hypertension (HT) and in 2 patients (16.7%) with angina pectoris (AP). Type D was seen in 13 patients (20%) with OMI, in 2 patients (50%) with aortic regurgitation (AR), in 6 patients (25%) with HT and in 3 patients (25%) with AP. Type M was found in 12 patients (18.5%) with OMI, in 1 patient (50%) with mitral stenosis (MS), in 1 patient (25%) with AR, in 1 patient (33.3%) with DCM and in 2 patients (8.3%) with HT. Type SS

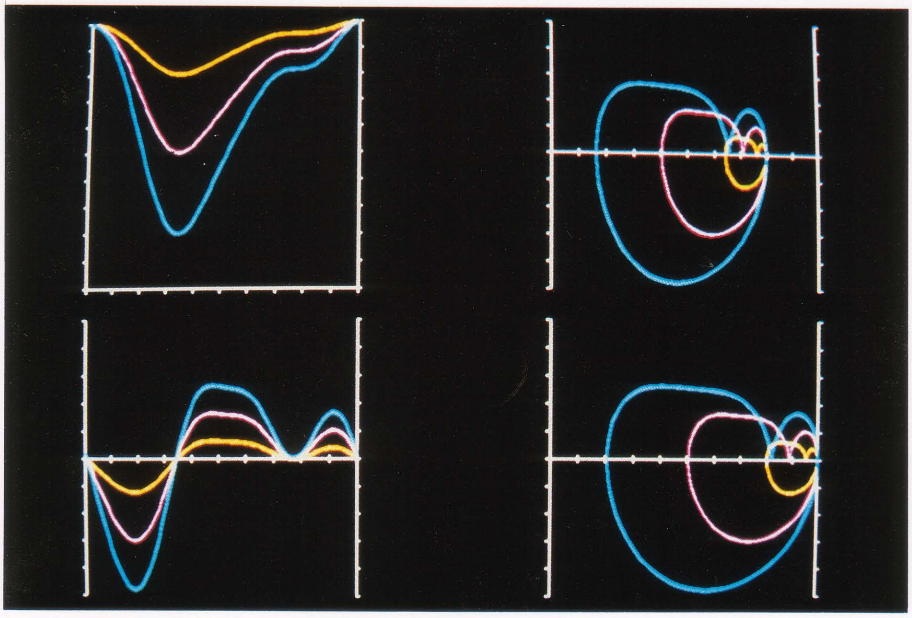

Fig. 2 Effect of ejection fraction on PP loop. The loop is wider in the horizontal direction when the ejection fraction is greater.

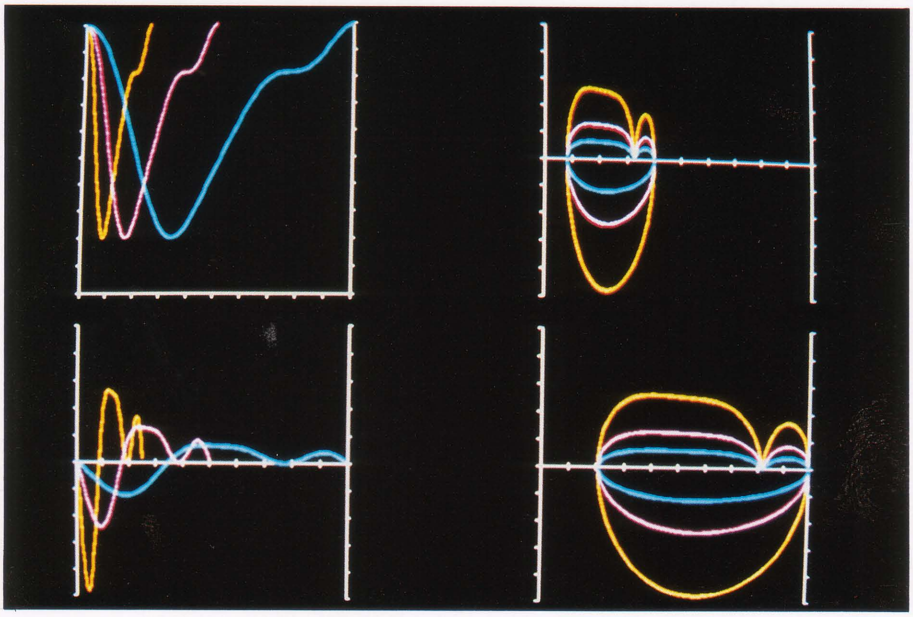

Fig. 3 Effect of heart rate on PP loop. When the heart rate becomes higher the loop is wider in the vertical direction.

were seen in MR (1 patient), HCM (1 patient), DCM (2 patients) and OMI (15 patients). Type DD were found in AR (2 patients), HT (3 patients) and OMI (12 patients), and type NAC were seen in DCM (1 patient) and OMI (6 patients).

Table 4 shows a comparison of the four parameters in the seven patterns of the PP loop. EF in types M, SS and DD were smaller than in type N ($p<0.05$). PFR in type DD was smaller than in the type N ($p<0.05$). The ratio of AC/SV was larger in types M, S, D, SS and DD, than in type N ($p<0.05$).

DISCUSSION

So-called phase plane (PP) display had been applied first to cine-ventriculography[9,10] and to RNVG ob-

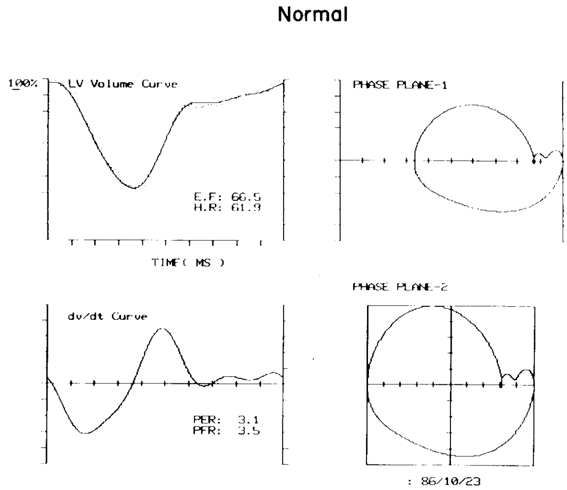

Fig. 4 Example PP display of data from normal control.

Table 2 Patterns of PP loop

N:	normal
S:	systolic type
D:	diastolic type
M:	mixed type
SS:	peaks in systole
DD:	3 peaks in diastole
NAC:	without atrial contribution

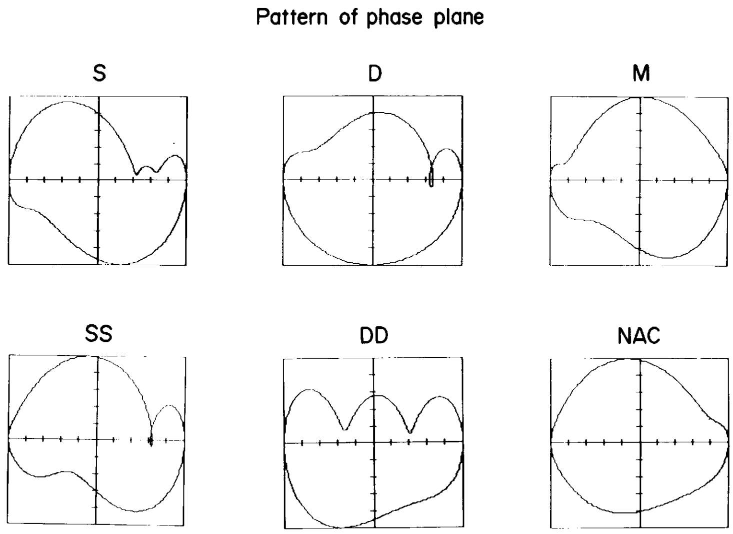

Fig. 5 Examples of PP loop patterns. See Table 2 and text for explanation of types.

Table 3 Distribution of PP loop patterns among various diseases

	C	MS	MR	AR	HCM	DCM	HT	AP	OMI	Total
N	9	1	2	1	1	0	13	7	30	64
S	0	0	2	0	2	2	3	2	10	21
D	0	0	0	2	0	0	6	3	13	24
M	0	1	0	1	0	1	2	0	12	17
Total	9	2	4	4	3	3	24	12	65	126
SS	0	0	1	0	1	2	0	0	15	19
DD	0	0	0	2	0	0	3	0	12	17
NAC	0	0	0	0	0	1	0	0	6	7

Table 4 Comparison of four parameters among seven patterns of PP loop

	EF	PER	PFR	AC/SV
N	61.5± 7.9	2.96±0.70	2.71±0.82	23.8± 7.9
S	51.5±23.1	2.64±1.05	2.68±1.26	29.2±13.5*
D	57.8±15.6	3.13±0.87	2.43±0.84	28.2± 7.1*
M	46.8±17.1*	2.76±1.13	2.14±0.92	30.3± 6.9*
SS	42.9±19.7*	2.49±1.12	2.34±1.21	30.3±11.5*
DD	48.3±15.8*	2.71±1.01	1.95±0.72*	30.4± 7.3*
NAC	48.6±17.2	3.23±1.21	2.66±1.10	—

*$p<0.05$

tained by a scintillation camera-computer system.[11] Concerning these studies, however, there was controversy over whether that sufficient points of data to construct smooth loops had been obtained by their methods. Therefore, it was thought that the distortion of the loops could not be evaluated precisely.

In our study, this problem was overcome by using a cardiac probe system made with sodium iodide, which has a high temporal resolution.[4–8] Therefore, a LV-TAC which was accurate enough to construct smooth loops was obtained. Another reason for the smooth configuration of our PP loops was our ECG gating method, which was performed bi-directionally, forward and backward, from the peak of the R wave of the ECG signals. This bi-directional gating method is a useful way to analyze the late diastolic phase of the cardiac cycle, including the period of the atrial contraction.[12,13] The counting efficiency of our system was high enough to collect sufficient data in 60 sec.

Our PP display method shows the values of EF or SV, PER, PFR and AC/SV simultaneously, and the relationships between these parameters. In this display, the changes in each parameter and their relationships are easily recognized as a distortion in a particular portion of the loop. The advantages of our PP display over the other methods are the easy detection of the changes in each LV parameter and the recognition of the relationships among them as indicated by their patterns. Another advantage of this method is that the values of the four conventional parameters can be printed out whenever those values are needed.

Concerning the distribution of the PP display patterns, the distortion of the loop in the systolic phase (type S and/or type M) was found in patients with MS (50%), AR (25%), HCM (66.7%), DCM (100%), HT (20.8%), AP (16.7%) and OMI (33.8). Similarly, the distortion of the loop in the diastolic phase (type D and/or type M) were seen in patients with MS (50%), AR (75%), DCM (33.3%), HT (33.3%), AP (25%) and OMI (38.5%). Most of these findings are easily explained by their hemodynamic derangements. From these findings, type S may represent systolic impairment of the left ventricle and type D diastolic LV impairment. Although there were some exceptions, especially in HCM, our method for classification of the PP loop seemed reliable. However, further evaluation will be needed to explain the reason for the distortion of the loop that was observed.

An interesting finding was that in 8 patients (33.3%) with HT and 3 patients (25%) with AP, whose EF, PER and PFR were within normal limits, the distortion of the PP loop was noted in the diastolic phase (type D). Moreover, in most cases, the distortion was found in the early phase of the diastolic. These findings are probably explained by increased stiffness of the left ventricular muscle.[10] From this standpoint, the PP loop is a sensitive method for displaying the data or RNVG.

The EF of type SS pattern patients was lower than that of type S patients, whereas the PER was almost in same range (Table 4). Similarly, the EF and PER of type DD pattern patients were smaller than those of type D patients. Therefore, the LV function of the type SS patients was thought to be worse than that of the type S patients in the systolic phase; and the LV function of the type DD patients was thought to be worse than that of the type D patients in the diastolic phase.

Conventional LV parameters such as EF, PER and PFR are widely used in nuclear cardiology. These indices, however, are essentially limited to the peak value. On the other hand, the PP display described in this paper shows the continuous changes in the relationships between EF or SV and dV/dt during the cardiac cycle. Therefore, this method may be more sensitive to detect abnormalities in both the early systolic and diastolic phases. In this study, we only used the qualitative method for classifying the abnormality in the PP display, but quantitative analysis may offer more useful information. Such study is now in progress in our department.

CONCLUSION

This two-dimensional display of the volume-dV/dt relationship may be helpful in assessing the LV function because this display presents the continuous changes in LV performance which can be easily evaluated.

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