
A New Method to Determine Left Ventricular Pressure-Volume Loops in the Clinical Setting

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Left ventricular pressure-volume (P-V) loops provide a complete definition of cardiac performance but have been difficult to obtain in the clinical setting. Accordingly, we have developed a new technique for acquiring P-V loops during and after cardiac surgical procedures using portable first-pass radionuclide angiocardiology coupled with intraventricular micromanometer catheters. Using this technique 35 serial left ventricular P-V loops were acquired in 12 patients during and after coronary artery bypass grafting. Dynamic radionuclide left ventricular volume and micromanometer pressure were acquired simultaneously to generate the P-V loops. Moreover, simultaneous measurement of both volume and pressure allowed comparison of the timing of end diastole (ED) and end systole (ES) defined by each of the two cardiac parameters. For 208 EDs and 243 ESs analyzed volume-defined ED occurred 8 ± 27 msec (s.d.) later in the cardiac cycle than pressure-defined ED while volume-defined ES occurred 29 ± 27 msec (s.d.) earlier than pressure-defined ES. It is concluded that measurement of cardiac P-V loops with this new technique is clinically feasible and that a close agreement has been demonstrated between the timing of cardiac events defined either by volume or pressure criteria.

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Cardiac pressure-volume loops are graphic representations of intraventricular pressure and volume which completely define cardiac pump function at all points in the cardiac cycle. The standard method for obtaining ventricular P-V loops in man requires cardiac catheterization with contrast cine fluoroscopy (1,2). Cardiac catheterization is invasive and the planimetry necessary to estimate the multiple ventricular volumes required for a single P-V loop is time-consuming. Ultrasonic crystals or radio-opaque markers implanted in the myocardium provide high-fidelity measurements of dynamic myocardial segment length (3,4), but assessment of dynamic regional segment length does not always reflect global ventricular function. Moreover, these techniques are applicable in only limited clinical settings.

This report describes the first use of radionuclide techniques to determine P-V loops of the left ventricle in the clinical setting. Serial P-V loops were obtained in patients undergoing cardiac surgical procedures using first-pass radionuclide angiocardiology (RNA) to measure true ventricular volume and high-fidelity micromanometer catheters to simultaneously record ac-

curate intraventricular pressure. Moreover, the data acquired from these studies allowed beat-to-beat comparison of the timing of ED and ES as determined from ventricular volume and ventricular pressure. This report describes the feasibility of determining P-V loops in the clinical setting and compares the two methods of cardiac event timing.

MATERIALS AND METHODS

Subjects and Equipment

Thirty-five P-V studies were performed in 12 patients undergoing elective coronary artery bypass grafting using the Scinticor, a portable, multicrystal gamma camera (5). Each patient was studied either in the operating room while undergoing their surgical procedure or in the Acute Care Unit immediately afterwards. No patient was studied more than 24 hr after leaving the operating room. Ten millicuries of technetium-99m pertechnetate were used for each initial transit radionuclide angiogram with a 20-msec count interval and a 24-sec total acquisition time. Each 20×20 pixel radionuclide image was stored on high-speed magnetic disk as the first 400 elements of a 512-word digital array with each data word being 16 bits in length. A complete study was comprised of 1200 serial arrays for a total of 1.2 megabytes of data storage per study. Data stored on magnetic disk conformed to the standards of the Fortran computer language

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and was readily retrieved using standard Fortran input/output commands (Appendix).

Intraventricular pressure was recorded using high-fidelity, disposable Millar micromanometer catheters inserted into the left ventricle via the aortic or mitral valve. The amplifier gain of a Hewlett-Packard 8805D pressure conditioner was adjusted to provide a voltage-to-pressure ratio of 0.01 V per 1 mmHg pressure (Fig. 1). The amplifier baseline was adjusted to produce -1 V output at atmospheric pressure. These adjustments provided a usable dynamic range of 200 mmHg.

The amplifier output was relayed via shielded coaxial cable to an integral, eight bit resolution, analog-to-digital converter available on the Scinticor. Analog voltages were digitized at ~1,000 Hz. The maximal value digitized in each acquisition interval was recorded simultaneously with the radionuclide count data for that interval. The digitized pressure value was stored as the 410th element in the 512-word digital storage array.

Data Analysis

Ventricular P-V loops were constructed in three steps. In the first step EDs and ESs were established for each beat in the study as precisely defined points of the pressure waveform. ED was defined as 40 msec before the first derivative of pressure with respect to time (dP/dt) exceeded the arbitrary threshold of 500 mmHg/sec (6). ES was defined as the maximal negative dP/dt of the pressure waveform (7-9). With each acquisition interval, or frame, sequentially numbered, a table was constructed of the frame numbers of ED and ES for each cardiac cycle comprising the study.

The second step toward creating P-V loops involved generating a background subtracted cardiac cycle which represented the cumulative average of the several beats comprising each study. First-pass radionuclide angiography algorithms typically define the endpoints of these beats as the maxima and minima of the ventricular time-activity curves. These criteria have been proven adequate in studies comparing ejection fraction, end-diastolic volume, and end-systolic volume obtained with first-pass methods versus those obtained with cardiac catheterization. However, they are not suitably accurate for identifying ED and ES on the pressure curve because ventricular pressure changes very rapidly at these points in the cardiac cycle while ventricular volume changes very little (Fig. 2). One or two frame (20 msec to 40 msec) variations in identifying ED and ES from beat to beat produces

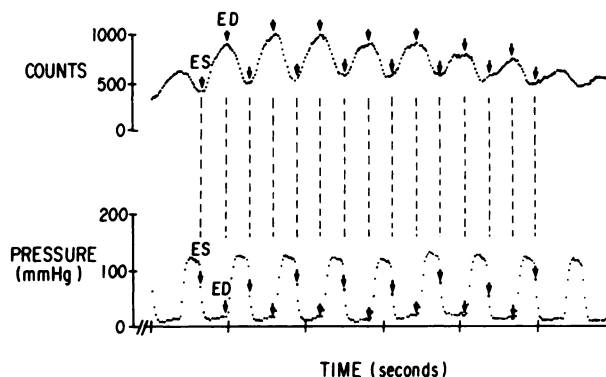


FIGURE 2

The relationship between left ventricular counts and intra-ventricular pressure. ES = end systole, ED = end diastole.

averaged pressure cycles which are not truly representative of their constituent beats. Moreover, the precision and accuracy of pressure-defined cardiac endpoints is known from previous studies (6-9). The representative cardiac cycle was, therefore, created using the pressure-defined EDs and ESs taken from the table previously described. Ejection fraction, end-diastolic volume, and end-systolic volume computed using the pressure-defined cardiac endpoints did not differ significantly from the same parameters computed from volume-defined endpoints. A histogram representing ventricular volume versus time was determined from this representative cycle using computer algorithms identical to those used in the Scinticor's predecessor, the System 77 (Fig. 3). These algorithms have been shown to give results comparable to cardiac catheterization (10).

The final step generated a representative pressure cycle. The raw pressure data, representative volume cycle and EDV were electronically transferred to an IBM personal computer using RS-232 serial communication. The table of pressure derived from ED and ES frame numbers was entered manually. All systolic phases were normalized to the longest systole, and all diastolic phases were normalized to the longest diastole using linear interpolation. Systolic and diastolic phases were averaged separately, then joined (systole followed by diastole) to produce an average ventricular pressure cycle (Fig. 3). This average ventricular pressure cycle was plotted

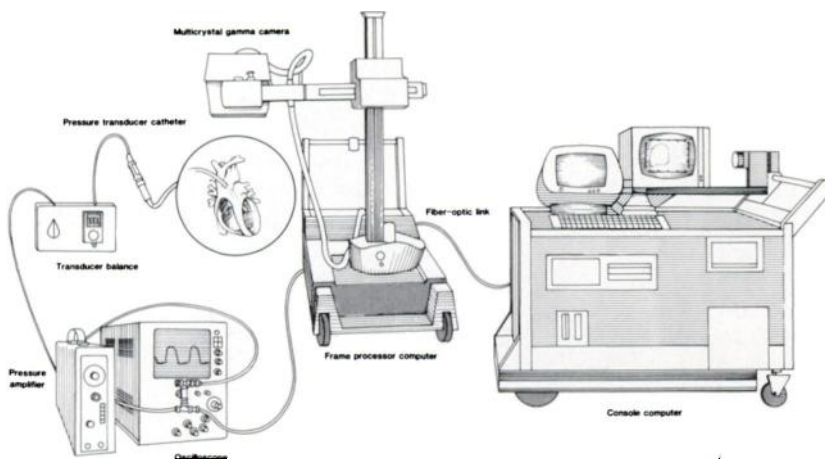


FIGURE 1

Schematic of the equipment used to obtain ventricular P-V loops at the bedside and in the operating room.

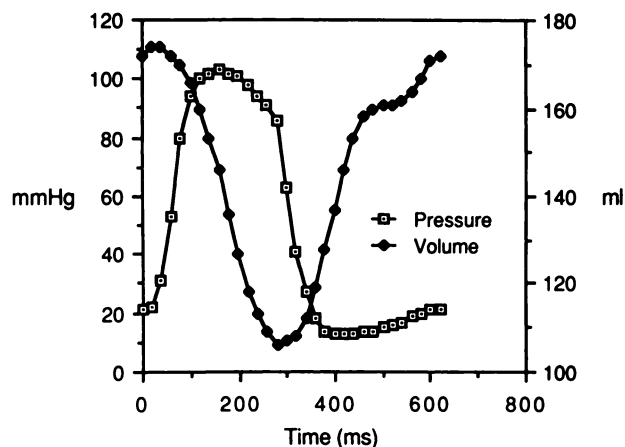


FIGURE 3
Simultaneous left ventricular volume and pressure versus time obtained by portable first-pass RNA and an intraventricular micromanometer catheter in a typical patient after undergoing coronary artery bypass grafting.

against the average ventricular volume cycle to produce the P-V loop (Fig. 4).

The difference between volume and pressure-defined timing of ED and ES was calculated for all cardiac cycles of the 35 P-V studies. For each beat the frame number of ED defined from the pressure waveform was subtracted from the frame number of ED defined as the maximum of the ventricular time-activity curve. Similarly, the frame number of each ES defined as the maximum negative dP/dt of the pressure waveform was subtracted from the frame number of ES defined as the minimum of the time-activity curve. Means and standard deviations of these differences were calculated without patient specific weighting.

RESULTS

Thirty-five P-V loops were generated from 12 patients. Two serial P-V loops were obtained from both of two patients, three loops from each of nine patients,

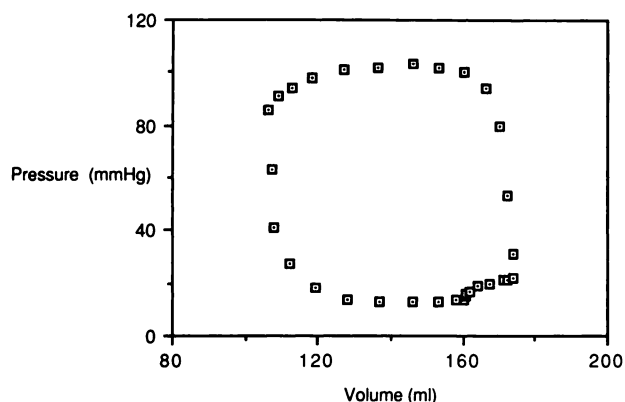


FIGURE 4
Ventricular P-V loop constructed from the data in Figure 3. The effect of atrial contraction is seen in the lower right quadrant.

and four loops from one patient. The mean EF for the group was 0.57 (range 0.28–0.90) with a mean end-diastolic volume index of 79 ml/m² (range 26–186 ml/m²). The mean cardiac index was 3.4 l/min/m² (range 1.1–5.7 l/min/m²), and the mean stroke work index was 4.6 erg 10⁶/m² (range 1.3–8.2 erg 10⁶/m²).

A representative series of P-V loops for a single patient is shown in Figure 5. The patient was a 44-yr-old male who was undergoing five-vessel coronary artery bypass grafting. The first P-V loop was acquired intraoperatively immediately prior to the initiation of cardiopulmonary bypass. The second loop was acquired 5 min later after the rapid intravenous administration of 500 ml of normal saline. The response to the fluid challenge was an increase in cardiac preload, stroke work and EF, while afterload remained essentially unchanged. The third P-V loop was acquired on the patient's arrival in the Acute Care Unit after operation. While EF decreased from 0.77 to 0.64 versus the previous study, stroke work increased from 9.75 erg 10⁶ to 12.07 erg 10⁶ as cardiac function continued to improve after successful revascularization.

The mean number of beats per patient study was 5.9 (s.d. = 1.2) yielding a total of 208 EDs and 243 ESs for analysis. When defined by ventricular volume criteria, ED occurred an average of eight msec later in the cardiac cycle than when defined by pressure criteria (s.d. = 27 msec). Volume-defined ES occurred an average of 29 msec earlier than pressure-defined ES (s.d. = 27 msec). The differences between pressure and volume-defined EDs and ESs are depicted graphically in Figure 6.

DISCUSSION

The P-V loop, first described in the animal model by Frank nearly a century ago (11), provides the most complete description of cardiac pump performance (12,

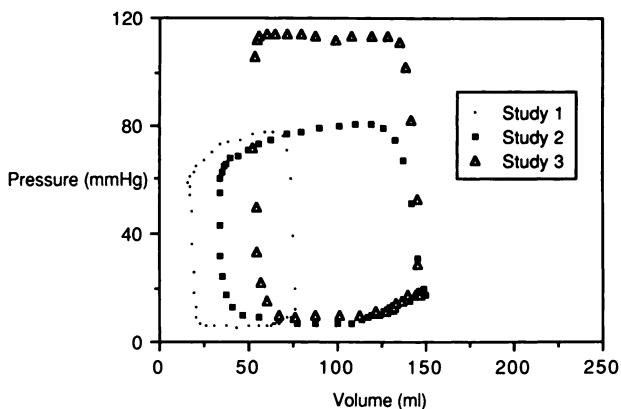


FIGURE 5
Serial pressure-volume loops in a 44-yr-old male after successful coronary artery bypass grafting.

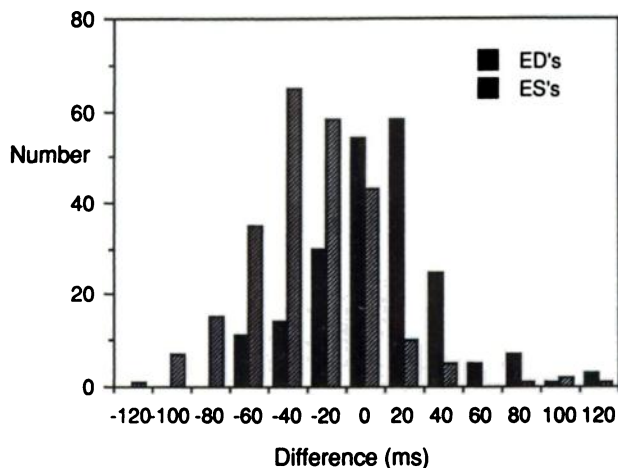


FIGURE 6
Bar graph demonstrating the frequency with which volume-defined EDs and ESs led (negative values) and lagged (positive values) those defined by pressure criteria.

13). Ejection fraction, stroke volume, end-diastolic pressure and volume, end-systolic pressure and volume, and stroke work can be readily computed from the P-V loop. When coupled with heart rate, computation of cardiac output, minute work and stroke power is possible. Moreover, current interest in defining an index of cardiac contractility independent of preload, afterload and heart rate relies on the P-V loop (6,9). This interest focuses especially on the end-systolic and end-diastolic P-V relationships, relationships easily and accurately available using the technique this paper describes.

The P-V studies comprising this investigation were performed solely on patients undergoing cardiac surgical procedures. The current standards for patient care after cardiac surgical procedures include the estimation of cardiac output using thermodilution techniques and end-diastolic pressure using the Swan-Ganz catheter. However, these measurements provide an incomplete and occasionally misleading assessment of cardiac status. In contrast, P-V loops determined by the method described in this study provide the most accurate definition of cardiac status now possible and thus have the

potential of adding to the quality and objectivity of postoperative care.

Rapid modulations of cardiac dynamics routinely occur after cardiac procedures as a result of intravascular volume changes and pharmacologic interventions. First-pass radionuclide angiography (RNA), which requires four to nine beats to complete a single study, may be the technology of choice in clinical investigations which require the ability to resolve these dynamics. In the future, algorithms which correct for the nonconstant radionuclide concentration resulting from bolus injection may make beat-to-beat P-V loops possible.

The added risk to the patient of micromanometer catheter placement is small. These catheters have routinely been used for the monitoring of left atrial pressure after cardiac surgical procedures with placement techniques similar to those used in this study. The risk of bleeding upon removal of the catheter is insignificant. The use of these catheters has not resulted in complications in this series. Therefore, it is felt this small risk is outweighed by the utility of the information the catheters provide.

This new method is especially suited to the monitoring of patients after cardiac procedures since open exposure of the heart facilitates direct placement of the pressure transducer catheters. Although not explored in this study, it is conceivable that percutaneous retrograde insertion of micromanometer catheters through the aortic valve would produce similarly acceptable results. An especially interesting application would be the use of this technique to study cardiac dynamics before and after coronary artery recanalization by percutaneous coronary artery angioplasty.

In summary, a new technique is described for the determination of cardiac P-V loops by employing non-invasive measurement of ventricular volume by portable first-pass RNA coupled with direct measurement of ventricular pressure by high-fidelity micromanometer catheters. This method has clinical application in the monitoring of patients after cardiac operations both for management and research purposes. With minor modification this technique may be adapted for use during coronary catheterization as well.

APPENDIX

```

C * * * * *
C
C Title: VOLPRESS
C Purpose: This program will retrieve and display the following:
C
C 1) Patient STUDYNUMBER, COUNT INTERVAL, EF, HR, BSA, EDV
C     ESV, PBV, AND CO from a Scinticor INFO file.
C 2) Pressure data from the postamble of the Scinticor RAW DATA
C     (F1) file.
C 3) LV REP CYCLE COUNTS from the INFO file.
C
C     FILES READ: F1, INFO (RANDOM)
C * * * * *
C
C     DIMENSION IPRESS(512),IPARM(256),IREPCYC(512)
C --- READ PATIENT SUMMARY DATA AND LV REP CYCLE COUNTS
C
C     CALL OPEN(7,"INFO",2,IER)           ;OPEN THE GENERAL INFO FILE
C     CALL RDBLK(7,18,IPARM,1,IER)        ;READ THE SCINT BLOCK
C     CALL RDBLK(7,104,IREPCYC,1,IER)      ;READ LV REP CYCLE COUNTS
C     CALL CLOSE(7,IER)                   ;CLOSE GENERAL INFO FILE
C     CALL OPEN (5, "$TTO", 2, IER)       ;OPEN THE CRT PORT
C
C     DO 10 I=11,17
C       WRITE (5,1000) IPARM(I)           ;WRITE STUDYNUM TO CRT
10  CONTINUE
C     WRITE (5,1000) IPARM(10)            ;COUNT INTERVAL
C     WRITE (5,1000) IPARM(18)            ;EF
C     WRITE (5,1000) IPARM(19)            ;HR
C     WRITE (5,1000) IPARM(134)           ;BSA
C     WRITE (5,1000) IPARM(136)           ;EDV
C     WRITE (5,1000) IPARM(138)           ;ESV
C     WRITE (5,1000) IPARM(142)           ;PBV
C     WRITE (5,1000) IPARM(144)           ;CO
C
C --- READ AND PRINT LV PRESSURE DATA
C
C     TYPE "NOW READING PRESSURE DATA FROM RAW DATA FILE...<15>"
C     CALL OPEN (2,"F1",2,IER)           ;OPEN THE RAW DATA FILE
C     N=0
C     DO 100 I=1,1200
C       CALL RDBLK (2,N,IPRESS,2,IER)    ;READ 2 BLOCKS (512 WORDS)
C       N = N + 2
C       WRITE (5,1010) I,IPRESS(410)     ;ECHO TO THE CRT
100  CONTINUE
C     CALL CLOSE (2, IER)                 ;CLOSE THE RAW DATA FILE
C
C --- PRINT REP CYCLE VOLUME COUNTS

```

APPENDIX CONT.

```

TYPE "<15>"
TYPE "LV REP CYCLE COUNTS...<15>"
DO 200 I=1,60
    IF(IREPCYC(I).EQ.0) GO TO 210      ;JUMP OUT IF COUNT=0
    WRITE (5,1010) I,IREPCYC(I)      ;ECHO TO THE CRT
200  CONTINUE
210  CONTINUE
    CALL CLOSE (5, IER)                ;CLOSE THE CRT PORT

```

C --- FORMAT STATEMENTS

```

1000  FORMAT (I6)
1010  FORMAT (I6,I6)

```

```

STOP VOLPRESS
END

```

ACKNOWLEDGMENTS

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