Left Ventricular Ejection Time by Densitometry in Patients at Rest and During Exercise, Atrial Pacing and Atrial Fibrillation

Comparison with Central Aortic Pressure Measurements

By Raul Chirife, M.D., James M. Foerster, M.D., and Oscar H. L. Bing, M.D.

SUMMARY
A comparison of left ventricular ejection time (LVET) measured directly from the central aortic pressure tracing (CAPT) and a densitogram recording was carried out in 39 patients during diagnostic cardiac catheterization. The correlation coefficient between the LVET derived from the CAPT and densitogram of 32 patients while at rest was 0.974 with a standard deviation from regression (SDR) of 6.2 msec. Sequential LVETs were analyzed in two patients during atrial pacing, three patients during exercise and three patients with atrial fibrillation. Correlation coefficients were 0.981, 0.951 and 0.974 with SDRs of 5.3, 6.2 and 6.7 msec respectively. Assuming LVET from the CAPT to be error free, the over-all error of estimating LVET by densitogram was less than 5% for over 95% of the measurements. The largest mean difference between CAPT and densitogram derived LVETs was present during atrial pacing and corresponds to an error of less than 2% of the average LVET for the group. We conclude that densitometry is a practical and reliable noninvasive method for LVET measurements in a variety of physiological and pathological conditions.

Additional Indexing Words:
Systolic time intervals
Noninvasive techniques

While left ventricular ejection time (LVET) is of value in assessing cardiac performance, previous noninvasive methods for determining this interval have been of limited practical use. The external carotid pulse tracing, for example, is difficult to obtain for prolonged periods and particularly during physiological stress such as exercise. Densitometry is a simple noninvasive procedure by which pulsatile blood flow in tissues can be recorded and LVET measured.

In previous publications, it was demonstrated that the LVET obtained from densitogram recordings correlates well with intervals measured from the external carotid pulse tracing. It was further shown that the densitogram is superior during upright exercise, since it is largely free from motion artifacts. Since the external carotid pulse tracing provides only an indirect measure of left ventricular ejection time and is by itself subject to error, a definitive validation of this new technique is carried out in the present study. Correlations of densitogram-derived and directly measured LVETs were obtained in patients undergoing cardiac catheterization at rest, during exercise and atrial pacing, and in patients with atrial fibrillation.

Materials and Methods

Patient Population
Thirty-nine patients of both sexes, undergoing diagnostic cardiac catheterization were studied. The group included subjects with normal cardiac hemodynamics as well as patients with cardiomyopathy, mitral valve disease, and coronary artery disease.

All subjects were fasting and recumbent. Under fluoroscopic control, a #7 or 8 F arterial catheter was placed in the ascending aorta, just above the aortic valve. Thirty-two patients were evaluated while at rest. Seven patients were studied under one or more of the following conditions: atrial fibrillation (3 patients), exercise (3 patients) and atrial pacing (2 patients).

Pressure Recordings
Arterial pressure was obtained through a P23Db Statham...
transducer and recorded at a paper speed of 75 mm/sec on an Electronics for Medicine DR12 photographic recorder.

Since artifacts tend to obscure the visualization of the dicrotic notch of the aortic pressure tracing when fluid-filled catheters are used, signals above 15 Hz were attenuated at 6 dB per octave. These artifacts are demonstrated in figure 1A and can be reduced without significant loss of signal resolution by the use of a low-pass filter (fig. 1B). A similar high frequency attenuation system has been shown to provide satisfactory fidelity in recording physiologic pressures and derivatives over a wide range of heart rates.1

**Densitometry**

The densitogram is a graphic display of changes in tissue optical density during the cardiac cycle. The tracing resembles an arterial pressure recording in shape, but is significantly damped. The rapid upstroke and the sharpness of the dicrotic notch, as seen in central aortic pressure tracings, are relatively indistinct, although they can be clearly located through the use of a differentiator or appropriate filter (fig. 2), both of which exaggerate the high frequency components of the signal (fig. 3).

The densitograph,1 which can be line or battery operated, contains a photoelectric transducer designed to fit snugly over the pinna of the ear. This is a small, lightweight device with a 5 volt light source and a photoconductive cadmium selenide cell. Variations in light transmission due to fluctuations in tissue blood flow are received by the photocell. Resistance changes are transformed to voltage variations which are amplified and filtered (time constant of filter: 12 msec) or differentiated (time constant = 1 msec) (fig. 3). The LVET was measured with equal accuracy whether a filter or a differentiator was used to locate the upstroke and dicrotic notch of the densitogram.

A warm-up period of several minutes was allowed to permit full dilatation of the ear vessels before recordings were obtained. Vasodilatation, induced by heat generated by the light bulb of the ear piece, increases phasic tissue flow and improves the signal-to-noise ratio of the recordings.1

**Methods of Measurements**

**Method I.** The beginning and end of left ventricular ejection are located on the unfiltered, undifferentiated densitographic tracing, as follows: the points of departure of a tangent drawn to the most rapidly rising and declining components of the densitographic curve are determined. The upstroke is termed "u" and at the end of left ventricular ejection, the downstroke of the tracing is designated "d." The left ventricular ejection period is the interval, in milliseconds, between the points "u" and "d" (fig. 3).1,4,5

**Method II.** The differentiated or filtered densitographic signal requires no graphic extrapolation as described above for the determination of LVET. The "u" and "d" points are directly determined from the tracing (fig. 4). In view of its greater simplicity, this method was used for most of the densitographic determinations in this study.

The ejection periods were calculated indirectly by measuring the time from the onset of ventricular depolarization (ECG lead II) to the "u" (time a) and "d" (time b) points of the densitogram recordings. Calculations of LVET in milliseconds were made by subtracting time "a" from "b." To avoid observer bias, densitographic measurements were made independently and without knowledge of the aortic systolic intervals.

**Statistical Analysis of the Data**

Densitographic methods I and II were compared to directly measured LVETs from the central aortic pressure tracing. Differences were statistically tested for significance using the paired t-test. Correlation coefficients and regression equations between densitogram-derived and directly measured LVETs were also obtained.

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*Available from Warren E. Collins, Inc., Braintree, Massachusetts.*

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**Figure 1**

A) A recording of a square pressure wave generated at the tip of a standard fluid-filled catheter. Paper speed is 75 mm/sec. B) After the introduction of a filter, resonance artifacts are considerably diminished with relatively little distortion of the original pressure signal.

**Figure 2**

Block diagram of the densitograph. The pinna of the ear is introduced between a photocell (a) and light source (b). The output signal of the preamplifier may be differentiated or the low frequency components filtered prior to recording on a polygraph.
Ear densitograms recorded simultaneously from the same subject illustrating the effect of a filter (B) and differentiator (C) to emphasize points used for the determination of left ventricular ejection time. (A) is the unmodified tracing.

Results

Left ventricular ejection times determined from the densitogram and central aortic pressure tracings were compared during the physiological states listed below. Table 1 presents the findings of the study in summary form.

Patients at Rest

Thirty-two patients, in sinus rhythm, were studied at rest, in the recumbent position. Five measurements of LVET by densitographic methods I and II were made in each subject. These intervals were averaged and plotted against the mean LVET obtained from five simultaneous cycles from the central aortic pressure tracing. The relationship between the LVET determined from the central aortic pressure tracing and by method I and method II are shown in figure 5. The heart rate range was 54 to 105 beats/min. The correlation coefficients and regression equations were:

Method I: \( r = 0.976, y = -0.8 + 0.99x, SDR = 6.2 \) msec; method II: \( r = 0.974, y = 23.8 + 0.91x, SDR = 6.0 \) msec.

The mean difference between central aortic pressure tracing and densitogram-derived LVETs was \(-4.0 \pm 6.1 \) msec \((P < 0.01)\) for method I and \(-0.4 \pm 6.4 \) msec \((NS)\) for method II.

Table 1

<table>
<thead>
<tr>
<th>Patient status</th>
<th>Number of beats analyzed</th>
<th>Heart rate range (beats/min)</th>
<th>Relationship between LVETA and LVETD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean difference*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(msec) ± SD</td>
</tr>
<tr>
<td>Rest (method I)</td>
<td>160</td>
<td>54 to 105</td>
<td>(-4.0 \pm 6.1)</td>
</tr>
<tr>
<td>Rest (method II)</td>
<td>160</td>
<td>54 to 105</td>
<td>(-0.4 \pm 6.4)</td>
</tr>
<tr>
<td>Atrial pacing</td>
<td>55</td>
<td>65 to 135</td>
<td>2.33 ± 5.2</td>
</tr>
<tr>
<td>Atrial fibrillation</td>
<td>92</td>
<td>40 to 120</td>
<td>0.66 ± 7.2</td>
</tr>
<tr>
<td>Exercise</td>
<td>95</td>
<td>66 to 115</td>
<td>1.66 ± 6.2</td>
</tr>
</tbody>
</table>

*The mean difference between LVET derived from the central aortic pressure tracing (LVETA) and from the densitogram (LVETD) was calculated by averaging individual beat-to-beat differences.

†SDR is the standard deviation from regression.

Simultaneous central aortic pressure tracing (top) and filtered densitogram (bottom) during exercise. Body motion produces artifacts seen in the pressure tracing. The left ventricular ejection period was measured from a to b in the pressure tracing and from u to d in the densitigraph recording. The systematic delay in the densitogram relative to the aortic pressure tracing is due to the longer distance for the pulse wave to travel. Paper speed is 75 mm/sec.
Atrial pacing
Two patients underwent atrial pacing at 10 beats/min increments. Cardiac rate increased from 65 to 115 beats/min in one patient and from 80 to 135 in the other. At each heart rate the LVET was measured in five consecutive beats from the central aortic pressure tracing and the densitogram (method II) and was then plotted (fig. 6). The correlation coefficient was 0.981 and the regression equation: y = 2.5 + 1.00x; sdr = 5.3 msec. The mean difference between central aortic pressure tracing and densitogram-derived LVETs was 2.33 ± 5.2 msec (P < .01).

Atrial Fibrillation
In three patients with atrial fibrillation, a total of 92 beats with varying cycle intervals (from 505 to 1500 msec) were analyzed. The relationship between direct and densitogram-derived LVETs is demonstrated in figure 6. The correlation coefficient was 0.975 and the regression equation, y = 21.6 + 0.91x; sdr = 6.7 msec. The mean difference between the central aortic pressure tracing and densitogram-derived LVET was 0.66 ± 7.2 msec (NS).

Exercise
Three patients performed supine leg exercise during cardiac catheterization. The heart rate range was from 66 to 115 beats/min. LVET was measured from the central aortic pressure tracing and the densitogram (method II) in a total of 95 beats at differing heart rates. The correlation coefficient was 0.951 and the regression equation, y = 13.6 + 0.96x; sdr = 6.2 msec (fig. 6). The mean difference was 1.66 ± 6.2 msec (P < 0.05).

The error in the estimation of LVET by densitometry, assuming aortic-derived measurements to be error-free, was less than 5% in 31 and 30 out of 32 patients by methods I and II, respectively (97% and 94%). In the beat-to-beat determinations, the error was less than 5% in 95% of all the measurements during atrial pacing, atrial fibrillation and exercise.

Discussion
Prior noninvasive methods for measuring left ventricular ejection time required the use of either a carotid pulse tracing or an apexcardiogram, with heart sound recordings.1-3 Both of these pulse wave record...
ing techniques are of little value during physiologic stress such as exercise. These difficulties are overcome by densitometry, which provides low noise tracings despite intense body activity and labored breathing by the subject.

The usefulness of ear densitometry as a substitute for the carotid pulse tracing has been previously suggested. The present study provides definitive validation of this new technique by a comparison with intervals derived directly from the central aortic pressure tracing, during exercise, atrial pacing, in the presence of atrial fibrillation and in a heterogeneous group of patients at rest.

Although both densitographic methods used in this study gave satisfactory results, method II was considered more practical. In addition, the discrete points provided by this method for measuring LVET were less subject to error or observer bias. A small systematic error in the assessment of LVET was found (table 1). These errors of 4.0, 2.3 and 1.7 msec are less than 2% of an average ejection time and considered too small to be of practical significance. Some minor discrepancies occasionally found between aortic and densitogram LVET's might be attributed to the fact that the aortic-derived measurements were considered to be error-free, which may not necessarily be the case.

The use of densitometry for the determination of systolic time intervals during exercise testing permits an analysis of dynamic cardiovascular adjustments during and immediately following ergometry. This technique also affords the opportunity for prolonged patient monitoring without the need of transducer repositioning and might thus be useful in the setting of coronary or intensive care units. Numerous other possible applications of this noninvasive technique for measuring LVET include the monitoring of individuals during experimental weightlessness and space exploration.

We conclude that densitometry is a reliable method for measuring LVET in a variety of physiological states. The technique appears particularly suited for noninvasive studies during exercise and long-term monitoring.

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RAUL CHIRIFE, JAMES M. FOERSTER and OSCAR H. L. BING

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