Comparison Between Apexcardiographic and Angiographic Indexes of Left Ventricular Performance in Patients with Aortic Incompetence

Jan Manolas, M.D., and Hans Peter Krayerbeuhl, M.D.

SUMMARY Left ventricular (LV) apexcardiogram (ACG) and its first derivative (dA/dt) was obtained in 104 normal subjects and 34 patients with chronic aortic incompetence (AI). In the patients with AI the ACG was recorded simultaneously with LV pressure (tipmanometer). The systolic upstroke time (SUT), the time to peak dA/dt (t-dA/dt) and the a wave percentage amplitude (a/H) of the ACG were measured. In normal subjects SUT averaged 99 ± 17 (SD) msec. In 17 patients with AI and normal ejection fraction (EF) (group 1) SUT was within normal limits; in 17 patients with AI and decreased EF (group 2) it was prolonged (142 ± 19 msec) (P < 0.001). The SUT was closely correlated with EF (r = −0.85) and less with contractile indexes derived from pressure curves. The indexes t-dA/dt and a/H were not significantly different in groups 1 and 2; they were weakly correlated only with the time to peak rate of LV pressure rise (r = 0.56) and the LV end-diastolic pressure (r = 0.59), respectively.

These results demonstrate the superiority of SUT over the other apexcardiographic parameters. The measure provides another means of noninvasive assessment of the LV performance in patients with AI.

THE EVALUATION OF THE LEFT VENTRICULAR PERFORMANCE in patients with aortic regurgitation remains an important clinical problem. Firm criteria to indicate the point in time at which myocardial failure develops have not been set. Many authors favor the ejection fraction as one of the best single measures of cardiac performance in patients with aortic incompetence (AI). The maximal rate of left ventricular pressure rise and the peak measured velocity of shortening of the contractile elements have also been proposed, despite the influence preload and afterload have on these measures. The clinical application of all of these indexes is limited by the need for direct left ventricular catheterization.

It is the purpose of the present study to evaluate the clinical usefulness and limitations of apexcardiographic parameters in the assessment of left ventricular performance in patients with chronic aortic regurgitation by 1) comparing the value of these indexes in separating patients with normal from those with decreased ejection fraction; 2) identifying the interrelations between indexes derived from pressure tracings and the relationship between these indexes and the ejection fraction; and 3) comparing the correlations between invasive and apexcardiographic parameters.

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Supported partly by a grant from the Swiss National Science Foundation. Presented at the 49th Annual Meeting of the American Heart Association, November 1976.

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Received July 21, 1977; revision accepted November 14, 1977.
Group 2
The second group was composed of 17 patients with AI, an EF of less than 0.60 and an \( f_a \) between 0.30 and 0.80. Six patients had no accompanying valvular disease. Six patients showed a slight aortic stenosis combined with a slight mitral incompetence, three mitral incompetence, and two slight aortic stenosis. It must be emphasized that in all patients of groups 1 and 2 the pressure gradient measured by planimetry did not exceed 30 mm Hg and the mitral regurgitation was less than 0.30. Furthermore, there was no clinical or angiographic sign of coronary artery disease in any of these patients.

Apex and Carotid Pulse Tracings
The ACGs were recorded at the site of maximal impulse of the heart beat during mild expiratory apnea with the patient in the left decubitus position, usually at an angle of 20–45°. In healthy persons the ACGs were obtained with the subject in several positions; we also varied the axis of the transducer in relation to the chest wall as well as the amount of pressure with which the transducer was held against the chest in order to evaluate the possible effects of these factors on the value of the apexcardiographic parameters. The CPs were recorded simultaneously with the ACG and phonocardiogram, as shown in figure 1, by holding an identical pulse transducer at the point of maximal excursion of the carotid impulse. These transducers have been constructed in our laboratory and are described in our previous studies.\(^7,\,12,\,14\) They have an infinite time constant,\(^17\) an airtight construction,\(^18\) and no measurable time delay.\(^17-19\)

Left Heart Catheterization
This was performed using the percutaneous transfemoral technique. Pressure curves were obtained by Statham SF\(_1\) or Millar tip manometers in all patients for the left ventricle and in 29 patients for the ascending aorta; an 8F pigtail catheter was used in five patients for recording the latter. The catheters were introduced into the left ventricle by the

**Figure 1.** Simultaneous records in a normal subject of left apexcardiogram (ACG), its first derivative \((dA/dt)\), carotid pulse (CP), external apical phonocardiogram (PCG\(_H\) = high frequencies, PCG\(_L\) = low frequencies) and lead II of electrocardiogram (ECG). SUT = systolic upstroke time; ESUT = ejectional systolic upstroke time; IVCT = isovolumic contraction time; \(HR\) = heart rate; paper speed = 200 mm/sec.

**Figure 2.** Simultaneous recordings of left apexcardiogram (ACG), left ventricular pressure (LVP) and their first derivatives \((dA/dt\) and \(dP/dt\), respectively), instantaneous quotient \([\{dP/dt\}/P]\), external apical phonocardiogram (PCG) and lead II of the electrocardiogram (ECG) from a patient with severe aortic regurgitation and normal ejection fraction (EF). \( f_a \) = aortic regurgitation fraction. The systolic upstroke time (SUT) of the ACG is within normal limits (93 msec).
retrograde or transseptal approach and into the ascending aorta by the retrograde route.

**Left Ventricle Cineangiography**

This procedure was carried out in the right anterior oblique position about one hour after recording the ACG. The patient was instructed to hold his breath in mid-inspiration. Filming rate was 75 frames/sec; 25 to 45 ml of Urografin 76% (Schering) were delivered by an electrocardiogram-triggered power injector (Contrac, Siemens) into the left ventricle at a rate of 10 to 15 ml/sec. At the end of the procedure a calibration grid with 1 cm squares was filmed at the level of the center of gravity of the left ventricle. This level was estimated from a chest roentgenogram in the left anterior oblique projection. Further, selective coronary arteriography was carried out according to the Judkins technique.

For determination of the EF the cineangiograms were viewed at the Tage-Arnø projector. The largest (end-diastolic) and the smallest (end-systolic) left ventricular silhouette could be identified using machine replay. The silhouettes were traced at their outermost endocardial border on paper affixed to the frosted glass screen. Volumetric analysis was performed according to the area-length method. In the end-diastolic and end-systolic silhouettes the long ventricular axis (L) was drawn from the mitral-aortic juncture to the apex. The transverse axis (T) was obtained from areas (A), as determined by planimetry, and L (T = 4A/π · L). Volumes were calculated assuming an ellipsoid-shaped ventricle. They were corrected for image magnification and pincushion distortion by using a calibration factor derived from the grid filmed at the level of the gravitational center of the left ventricle. The EF was calculated according to the formula $E F = (E D V - E S V) / E D V$ where $E D V$ = end-diastolic volume. The EDV was corrected for body surface area and expressed as index in millimeters per square meter (EDVI).

**Analysis of the Simultaneous Tracings**

All tracings were recorded on an 8 or 16-channel Electronics for Medicine oscillograph (DR-8 and DR-16, respectively) at a paper speed of 200 mm/sec with timelines of 20 msec. In normals the ACG and $dA/dt$ were recorded simultaneously with the external apical phonocardiogram and lead II of the electrocardiogram; further, the carotid pulse was simultaneously registered in 34 of the normal subjects (fig. 1). In the catheterized patients the following tracings also were obtained: left ventricular pressure (LVP), its first derivative (dP/dt), ascending aorta pressure and the instantaneous quotient of dP/dt to total LVP [(dP/dt)/P], which was obtained by an analog computer along with dP/dt (figs. 2 and 3). The time constant of the computer for calculating dP/dt and dA/dt was 0.8 msec, whereas that for calculating (dP/dt)/P was 1.1 msec. The (dP/dt)/P was also calculated manually. The peak measured velocity of shortening of the contractile elements (Vₚₚₚ) was determined according to the maximal value of (dP/dt)/(P · 28) in muscle lengths (ML) per second, where 28 is the coefficient of series elasticity. Further, the time interval from the onset of left ventricular contraction to the peak of dP/dt (1-dP/dt) was measured.

The following four parameters were measured in the apex tracing:

1) The a wave percentage amplitude (a/H), which is the a wave amplitude (a) in percent of the total height (H) of the apex tracing.

2) The systolic upstroke time (SUT), measured from the onset (C point) to the protosystolic summit (E point) of the upstroke of the apex tracing, as shown in figures 1 and 3. In the absence of sharp C and/or E points the SUT can accurately be measured by the use of the first derivative of the ACG as the time from the point where $dA/dt$ ascends from the zero line to the point where it reaches this line again after having reached its maximal peak(s), as demonstrated in figure 2.

3) The ejectional systolic upstroke time (ESUT), measured in the catheterized patients from the crossover of left ventricular and aortic pressure curves to the E point or to the end of SUT as determined using the $dA/dt$ (fig. 3). This time interval was measured in normal subjects noninvasively using the simultaneous apex and carotid pulse tracings as well as the external phonocardiogram according to the formula:

$$ESUT = SUT - IVCT$$

where IVCT (isovolumic contraction time) is given by the following table:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a/H (%)</td>
<td>10 ± 4</td>
<td>3–19</td>
</tr>
<tr>
<td>t-dA/dt (msec)</td>
<td>50 ± 12</td>
<td>25–83</td>
</tr>
<tr>
<td>SUT (msec)</td>
<td>99 ± 17</td>
<td>61–133</td>
</tr>
<tr>
<td>ESUT (msec)</td>
<td>36 ± 9</td>
<td>20–51</td>
</tr>
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</table>

Abbreviations: a/H = a wave percentage amplitude; t-dA/dt = time from the onset to the peak of the first derivative of the apex tracing; SUT = systolic upstroke time; ESUT = ejectional systolic upstroke time.
<table>
<thead>
<tr>
<th>Pt/Ages/Sex</th>
<th>Diag.</th>
<th>HR (min⁻¹)</th>
<th>SUT (msec)</th>
<th>ESUT (msec)</th>
<th>t-dA/dt (msec)</th>
<th>α/H (%)</th>
<th>LVSP/LVEDP (mm Hg)</th>
<th>AoP (mm Hg)</th>
<th>t-dP/dt (mm Hg/sec)</th>
<th>max dP/dt (mm Hg/sec)</th>
<th>Voes (ml/sec)</th>
<th>EF (ml/m²)</th>
<th>tₙ</th>
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<td>23</td>
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<td>126/65</td>
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<td>1690</td>
<td>1.46</td>
<td>0.63</td>
<td>177 0.54</td>
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<td>9</td>
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<td>116</td>
<td>77</td>
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<td>171/23</td>
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<td>29</td>
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*Table 2. Summary of Patient Data*

*Listed are mean values ± sd. The P values were obtained from the unpaired Student's t-test. NS = not significant (P > 0.05).
Abbreviations: α/H = relative amplitude of the a wave to the total height of the apexcardiogram; AI = aortic incompetence; AoP = aortic pressures (systolic/diastolic); AS = aortic stenosis; EDVI = end-diastolic volume index; EF = ejection fraction; ESUT = ejection systolic upstroke time of the apexcardiogram; F = {female}; tₙ = aortic regurgitation fraction; HR = heart rate; LVEDP = left ventricular end-diastolic pressure; LVSP = left ventricular systolic pressure; M = male; max dP/dt = maximal rate of left ventricular pressure rise; MI = mitral incompetence; P = probability; t-dA/dt = time to peak of first derivative of the apexcardiogram; t-dP/dt = time to peak of the first derivative of the left ventricular pressure; Voes = peak measured velocity of shortening of the contractile elements.*

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tracting the carotid pulse transmission time from the interval between the onset of the ACG and CP upstroke, as shown in figure 1.

4) The time to peak dA/dt (t-dA/dt), measured from the onset of the apexcardiographic systolic upstroke to the peak of dA/dt. For each hemodynamic and apexcardiographic measurement 3 to 5 separate heart cycles were averaged.

Results

Table 1 summarizes the apexcardiographic data in normal subjects with means and standard deviations and table 2 the data obtained for hemodynamic, cineangiographic, and apexcardiographic measurements in the catheterized patients. These patients have been divided into two groups for the purpose of analysis based on the value of the ejection fraction: the patients of group 1 had normal and those of group 2 a decreased ejection fraction of the left ventricle. The mean values of the following indexes of myocardial performance were significantly different in the two groups: the peak measured velocity of shortening of the contractile elements (V$_{pm}$) ($P < 0.001$), the maximal rate of left ventricular pressure rise (max dP/dt) ($P < 0.01$), and the end-diastolic volume index (EDVI) ($P < 0.02$). In contrast, there was no significant difference between the two groups in the mean value of the resting heart rate, age, left ventricular systolic (LVSP) and end-diastolic (LVEDP) pressures as well as of systolic and diastolic aortic pressures, the time from the onset to peak of the left ventricular pressure rise (t-dP/dt) and the aortic regurgitation fraction ($f_a$).

Interrelations Between Hemodynamic and Angiographic Indexes

A moderately strong inverse linear correlation was present between LVEDP and V$_{pm}$ ($r = -0.77$); a weaker association was evident between LVEDP and max dP/dt ($r = +0.55$). Furthermore, there was a strong positive correlation between max dP/dt and V$_{pm}$ ($r = +0.88$). In contrast, the index t-dP/dt showed no significant correlation with LVEDP, max dP/dt, or V$_{pm}$.

There was a weak correlation between ejection fraction (EF) and EDVI ($r = -0.48$), and no correlation between EF and $f_a$. Table 3 shows the correlation coefficients of the regression equations between pressure- and angiographically-derived indexes of ventricular performance as well as $f_a$. The LVEDP and t-dP/dt were associated with $f_a$. All but LVEDP indexes derived from pressure tracings were weakly correlated with $f_a$. Moreover, the indexes max dP/dt and V$_{pm}$ were related to EDVI.

Apexcardiographic Systolic Upstroke Time

The systolic upstroke time (SUT) of the apex tracing is defined as the interval from the onset (C point) to the end (E point) of the protosystolic wave of the ACG (figs. 1 and 3). Using the first derivative (dA/dt) of the apex tracing, SUT could be measured accurately in all normal subjects and patients of both groups (figs. 1, 2 and 3). The value of SUT was influenced only slightly, if at all, by differences in the position of the body, the axis of the pulse transducer, or the amount of pressure between the transducer and the thoracic wall. A weak correlation was observed between SUT and resting heart rate in normals ($r = -0.40$) over a range from 49 to 119 beats/min; there was no correlation between SUT and age over a range from 17 to 57 years.

The onset of SUT occurred in all catheterized patients almost simultaneously with the onset of the rise of left ventricular pressure, the former following the latter by only 1 ± 5 msec (figs. 2 and 3). Further, the SUT ended after the crossover of left ventricular and aortic pressure curves in all patients; the interval following crossover varied widely. Thus, SUT was divided into two parts (figs. 1, 2 and 3): the first corresponds with isovolumic contraction time; the second represents the ejection phase of SUT, called in this study ejectional systolic upstroke time (ESUT).

The SUT averaged 99 ± 17 msec in normals; it was significantly prolonged (142 ± 19 msec) in group 2, and within normal limits in group 1 (table 2). The ESUT averaged 36 ± 9 msec in 34 normals, as determined by simultaneous recordings of apexcardiogram and carotid pulse (fig. 1); it was significantly prolonged in group 1 (47 ± 14 msec) and in group 2 (85 ± 26 msec), and the difference between groups 1 and 2 was also significant ($P < 0.001$), as indicated in table 2.

Correlation coefficients were calculated for the total cohort of patients using SUT as the independent variable and angiographically-determined indexes of myocardial performance as well as hemodynamic measures as dependent variables (table 4). The strongest correlation was found with EF ($r = -0.85$) (fig. 4). Less strong inverse correlations were present between SUT and V$_{pm}$ ($r = -0.73$) as well as max dP/dt ($r = -0.69$) (fig. 5); only weak correlations were found between SUT and LVEDP as well as EDVI (table 4). Similar correlation coefficients were obtained when ESUT and the dependent variables were analyzed, as shown in table 4. In contrast, neither SUT nor ESUT were correlated with LVSP nor with systolic and diastolic aortic pressures.

| Table 3. Correlations Between Internally Derived Indexes |
|----------------|----------------|----------------|----------------|
|                | LVEDP           | t-dP/dt         | max dP/dt       | V$_{pm}$      | EF             | EDVI            |
| EF             | -               | -0.45           | +0.61           | +0.71         |                |                 |
| EDVI           | -               | -               | -0.60           | -0.46         |                |                 |
| $f_a$          | +0.42           | -                | -0.35           | -              |                |                 |
|                |                 |                 |                 |                |                |                 |

Abbreviations as in table 2.

| Table 4. Correlations between Apexcardiographic and Internally Derived Indexes |
|----------------|----------------|----------------|----------------|
|                | LVEDP           | t-dP/dt         | max dP/dt       | V$_{pm}$      | EF             | EDVI            |
| SUT            | +0.47           | -               | -0.69           | -0.73         | -0.85          | +0.46           |
| ESUT           | +0.62           | -               | -0.63           | -0.73         | -0.71          | +0.42           |
| t-dA/dt        | -               | +0.56           | -              | -0.51         |                |                 |
| a/H            | +0.59           | -               | -              | -              |                |                 |

Abbreviations as in tables 2 and 3.
Other Apexcardiographic Parameters

Time to Peak $dA/dt$

This measure, termed t-DA/dt, averaged in normals 50 ± 12 msec. The mean values of this time interval in groups 1 and 2 were not significantly different (table 2). It should be mentioned that t-DA/dt could not be defined in 30 of the 104 normals (29%) and six of the 34 patients (18%) with aortic regurgitation due to the presence of multiple peaks (fig. 3). Comparing the relations of t-DA/dt with other indexes (table 4), we found only one association: a relatively weak correlation with t-dP/dt ($r = +0.59$).

A Wave Percentage Amplitude

$a/H$ averaged 10 ± 4% in normals. There was no significant correlation between $a/H$ and resting heart rate or age in normal persons. The mean values of $a/H$ were within normal range in both groups of patients with aortic regurgitation (table 2). There was a positive correlation between $a/H$ and LVEDP and a negative correlation between $a/H$ and $V_{pm}$, both weak, however ($r = +0.59$ and $r = -0.51$, respectively).

Discussion

Appraisal of Angiographic Indexes

The ejection fraction has been frequently described as the most useful index for assessing impaired left ventricular performance in patients with aortic regurgitation. Miller et al. stated that in these patients low values for ejection fraction may truly be considered to be examples of high-output failure of the left ventricle. Our present results confirm the ejection fraction as the most valuable index of cardiac performance in patients with chronic aortic incompetence.

In this study, we assessed the validity of indexes of left myocardial performance derived from pressure tracings in the presence of aortic regurgitation by comparing them with the ejection fraction (table 3). Our data indicate that LVEDP is dependent on the severity of the aortic regurgitation and is not correlated with EF. These findings are similar to those of Rackley et al. who reported that LVEDP is altered by changes in loading and by variation in diastolic compliance. Other authors disagree with this interpretation.

Apexcardiographic Parameters

The most important finding to emerge from this study is the close correlation between SUT and indexes of left ventricular performance derived from angiography and left ventricular dP/dt. The closest correlation was present between SUT and EF ($r = -0.85$), as shown in figure 4. Furthermore, all patients with values over 130 msec for SUT had a decreased EF (table 2, fig. 4). The SUT was less closely related with max dP/dt and $V_{pm}$ (fig. 5). In contrast, there was only weak correlation between SUT and indexes LVEDP and EDVI (table 4); and no correlation between SUT and $f_a$, LVSP, and systolic and diastolic aortic pressures.

These data indicate that SUT is mainly determined by the myocardial performance and is only slightly influenced by
the extent of preload and chronic volume overload in patients with aortic incompetence. We have previously shown that SUT is a useful measure in patients with coronary artery disease and nonobstructive cardiomyopathy. 12 The index SUT has the further advantage of being relatively unaffected in normal subjects by resting heart rate and age.

We have considered reasons for the close relationship between SUT and left ventricular performance. While our present study does not provide direct evidence, our findings suggest that the early systolic events (volume ejected into the aorta and early ejection rate), measures that have been found to be closely related to left ventricular performance, 27 are reflected in the apexcardiographic recording in the following way. SUT did not correlate with isovolumic contraction time of the left ventricle. Instead SUT ended after the crossover of the left ventricular and aortic pressure curves. This interval after crossover we called ESUT, the ejectional systolic upstroke time. Since both SUT and ESUT show similar relationships to angiographic indexes of myocardial performance, the ESUT portion of SUT must be the main determinant of SUT's correlation with myocardial performance. ESUT was significantly longer than normal (39 msec) in both groups with aortic incompetence. It also was significantly longer in patients with a depressed ejection fraction. Thus, since we find SUT strongly reflective of early aortic ejection and early ejection rate, values mentioned above as closely related to left ventricular performance, we have a reasonable explanation for the strong correlation of SUT with ejection fraction. Future research is needed to test the validity of this hypothesis.

We compared the strength of SUT with other apexcardiographic measures and found that it correlated more closely with ejection fraction, as demonstrated in table 4. Vetter et al. 10 found significant correlations between the interval from the onset of ventricular depolarization to the peak of the first derivative of the apex tracing and hemodynamic as well as angiographic indexes of myocardial performance. We found no significant correlations other than a weak association between the interval from the onset to the peak dA/dt to the time to peak dP/dt (table 4). Moreover, the noninvasive index SUT is significantly more closely correlated to the ejection fraction than the internally derived indexes V1m and max dP/dt, as evident from tables 3 and 4.

It can be concluded that the systolic upstroke time of the left apexcardiogram provides a valuable noninvasive assessment, relative to other patients, of left ventricular performance in patients with pure or predominant chronic aortic regurgitation. However, this temporal parameter must be tested further before its application in 1) serial studies in individual patients; 2) assessment of changes in myocardial state; and 3) the presence of moderate to severe aortic stenosis or other valvular disease can be known.

Acknowledgment

The authors express their appreciation to Dr. Joerg Grimm, Miss Oddveig Toennesen and Miss Kali Doxiadis for their contributions in the performance of this study.

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Comparison between apexcardiographic and angiographic indexes of left ventricular performance in patients with aortic incompetence.

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Circulation. 1978;57:692-698
doi: 10.1161/01.CIR.57.4.692

Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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