On the Clinical Value of Calibrated Displacement Apexcardiography

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SUMMARY
A new type of displacement transducer for recording the calibrated left apexcardiogram (QLAC) has been evaluated in 69 normal subjects and 99 cardiac patients. Total displacement of QLAC (TD), its peak first derivative (peak dD/dt) and the normalized value (dD/dt/Dt) max were measured as well as the time interval from the upstroke of QLAC to peak dD/dt (t-peak dD/dt). A strong correlation exists between peak dD/dt and TD in normal subjects (r = 0.95) and the deviation from the normal relationship allows a separation between normal and abnormal ventricular function. In normal subjects (dD/dt/Dt) max averaged 34.2 ± 5.7 sec⁻¹; it was significantly lower in patients with congestive cardiomyopathy (26.5 ± 6.3 sec⁻¹, P < 0.005). This index correlates with left ventricular end-diastolic pressure (LVEDP) (r = -0.69) and with ejection fraction (r = 0.66) and behaves as expected during positive and negative inotropic interventions. The index (dD/dt/Dt)(max is superior to TD and peak dD/dt, being less variable, independent of thorax circumference and better correlated with hemodynamic parameters. The index t-peak dD/dt was 53.9 ± 9.5 msec in normal subjects and 81.6 ± 18.9 msec in patients with congestive cardiomyopathy (P < 0.001). This time-interval correlates weakly with LVEDP (r = 0.40) and with ejection fraction (r = -0.66).

It is concluded that the normalized first derivative of QLAC provides useful information on left ventricular function.

Additional Indexing Words:
Contractile state of the heart  First derivative of the left apexcardiogram  Left ventricular function
Mecanocardiography  Normalized velocity of apical displacement  Noninvasive cardiology

In recent years, methods have been developed for calibration of the left apexcardiogram1-8 and of its first derivative.2 4 By using calibrated tracings, the left apexcardiogram appeared to be related to left ventricular function, and its height, expressed in mm Hg, has been shown to correlate significantly with left ventricular systolic pressure.5 A relationship between the first derivative of the left apexcardiogram and left ventricular dp/dt has also been demonstrated.2,4,6,7 Inter- and intrarecorder variation and extrinsic factors such as thoracic wall thickness, physical characteristics of the recording device and its coupling to the thoracic wall, are the major limitations to the clinical application of calibrated apexcardiography.

Recently, some investigators have introduced the concept of normalized derivative3 in apexcardiography by using indices derived from the instantaneous relationship between the first derivative of the left apexcardiogram and its amplitude.4,7,8 These normalized indices were found to correlate significantly with the indices of contractility derived from left ventricular pressure and its first derivative, experimentally in dogs,4,7 as well as in human subjects.8

A new recording device for calibrated apexcardiography has now been developed in order to obtain an immediate electronic calculation of the first derivative and the normalized first derivative of the apexcardiogram.

It is the purpose of this study to evaluate the clinical usefulness and limitations of the calibrated left apexcardiogram (QLAC), its first derivative, and the normalized first derivative in the assessment of left ventricular function.

Material and Methods
1. Material of the Study

Left apexcardiogram tracings were obtained in 175 individuals: 69 normal subjects ranging in age from 18 to 58 years (mean age: 30 ± 13 years) and 99 patients with heart disease, ranging in age from 17 to 79 years (mean age 47 ± 14 years). In seven additional subjects the effect of pharmacological agents with positive and negative inotropic action was studied. Before registration, a physical examination was performed and height, weight, blood pressure and thorax circumference in maximum inspiration and expiration were measured.

The group of normal subjects consisted of 39 young (age
range: 18–25 years) and 30 middle-aged men (age range: 34–58 years). No previous history of heart disease was present and a complete physical examination, 12 lead electrocardiogram and chest X-ray were normal.

The cardiac patients were divided into five subgroups: 1) left ventricular systolic overload: 26 patients (IHSS: 6; dominant valvular aortic stenosis: 8; moderate systemic hypertension: 12); 2) left ventricular diastolic overload (aortic and/or mitral regurgitation): 23 patients; 3) dominant mitral stenosis: 9 patients; 4) congestive cardiomyopathy: 14 patients; 5) ischemic heart disease: 27 patients. The diagnosis of the underlying cardiac disease was confirmed in the large majority of the patients by cardiac catheterization and appropriate angiographic studies.

Pharmacological interventions were performed in seven volunteers in order to study the effect of positive and negative inotropic drugs on QLAC and derived indices. Isoproterenol (Isuprel-Winthrop), infused intravenously at a rate of 0.05 μg/kg/min, and propranolol (Inderal-ICI), 5 mg IV, were given in order to obtain the appropriate effect. In two cases only one drug was given. Informed consent was obtained from the subjects prior to the examination.

Interobserver variation was studied in 25 subjects in whom QLAC was recorded consecutively by two experienced investigators, each unaware of the other’s findings.

Intraobserver variation was studied in 23 subjects in whom the left apexcardiogram was recorded twice by the same investigator within an interval of at least one week. All subjects were middle-aged, did not take cardioactive drugs and were instructed to avoid smoking and drinking coffee or alcohol for at least four hours before the recording session. All tracings were recorded after a 10 min. rest period. Heart rate and blood pressure were measured before, during and after recording the apexcardiogram.

Paired t-test analysis on the data revealed a slight increase in heart rate during the second observation period (+3 beats/min, P < 0.05). For systolic and diastolic blood pressure, however, no statistically significant difference existed between the two observation periods.

2. Methods

The nomenclature used throughout the paper to define the different parts and reference points of QLAC is indicated on figure 1.

Pulse-Phono Transducer

The recording device is a new type of pulse-phono microphone (Elema Schonander) which allows simultaneous pick-up of precordial pulsation and heart sounds in the same area of the chest wall. An electrode ring permits the recording of a precordial ECG lead, which is helpful in distinguishing between a right and left apexcardiogram. The pick-up system consists basically of an air-coupled crystal microphone with a single sensing crystal. The diameter of the capsule is 21 mm and the air chamber has a volume of ± 1640 mm. The generated electrical signal is divided and amplified for recording of pulse and phono. A selection permits varying the time constant from 0.3 to 1.64 or 7 sec. All apexcardiograms in the present study were recorded with a time constant of 4 sec. With a time constant of 4 sec the upper and lower limit (-3 dB attenuation) is at 1000 Hz and 0.04 Hz, respectively. This time constant, chosen for the actual recording of the QLAC, gives an undistorted reproduction of the real physical event. The resonance frequency of the microphone is about 1500 Hz.

The pulse signal passes through a third degree low-pass Bessel filter with an upper frequency limit (-3 dB attenuation point) of 50 Hz and an attenuation slope of -18 dB per octave for frequencies greater that 50 Hz. Frequencies higher than 50 Hz in the apexcardiogram are generally generated by events which, although present in the pressure tracing, have only a very low energy content (sounds due to opening or closing of valves). In rare cases, however, these higher frequency artifacts dominate the time course of the first derivative of the QLAC, because its amplitude is directly proportional to frequency. Moreover, practically all the energy content of the apexcardiogram is contained in its first 10 harmonics.14 The time lag caused by the filter is constant (6 msec) for frequencies below 20 Hz.

Calculation of the First Time Derivative of QLAC (dD/dt)

Since the pulse signal passes through the Bessel filter before differentiation, there is no delay between the filtered signal and its first time derivative. The differentiator permits true differentiation for frequencies < 75 Hz (+ 6 dB/ octave).

Calculation of the Normalized First Derivative of QLAC

By means of automatic zero-clamping, the O point of the apexcardiogram is always held at a constant level. This is necessary because the floating O point of the QLAC serves as the zero-reference level for D1 in the calculation of dD/dt/D1. This clamping at a constant level is affected by rapid discharge of a condenser during the descending part of the QLAC. With the O point of the QLAC as reference zero-level, dD/dt/D1 is calculated with the aid of a logarithmic amplifier and differentiator (fig. 2).13 14

Calibration of the Signals

The pulse signal and its first time derivative are calibrated by means of a constant ramp-signal with a slope of 4 V/sec, an amplitude of 1 V and a frequency of 2 Hz. This ramp-signal passes the same differentiating circuit as the pulse-wave and both signals are recorded on paper (fig. 3). The height of the ramp signal in mm serves as a calibration factor (1 ×) and the height of the apexcardiogram is expressed

Figure 1

Nomenclature used to define the different parts and reference points of the QLAC. A: diastolic A wave; C: intersection of the downslope of the A wave and the fast rising systolic wave; E: highest early systolic point; O: nadir of the QLAC curve; TD: total displacement of QLAC, i.e., the vertical distance between the O point and the highest systolic point; a: one-third of the vertical distance between C and E point; a': corresponding value of dD/dt; QLACf: filtered QLAC tracing.
CALIBRATED APEXCARDIOGRAPHY

Figure 2

Example of a registration of the calibrated left apexcardiogram (QLAC) and derived indices. Top tracing: the precordial ECG recorded at the same area of the chest wall as the QLAC; second tracing: unfiltered QLAC signal; third tracing: filtered QLAC signal with the O point clamped at a constant level necessary for the calculation of dD/dt/Di (see methods); bottom tracing: first derivative (dD/dt) and normalized first derivative (dD/dt/Di) of the QLAC. The peak value of the dD/dt/Di curve was called (dD/dt/Di) max.

as a factor of ×. By using the time (t) from the nadir to the top of the ramp signal (in fig. 3, t equals 93 msec), the calibration signal for the first time derivative can be expressed as a value of ×/sec (in fig. 3, the height of the calibration factor equals 10.75 ×/sec). As can be seen on fig. 3, a calibration signal exists also for dD/dt/Di. It is calibrated in such a way that when the output is 15 mm on the paper, 1 mm equals 1 unit dD/dt/Di sec⁻¹ (Elema-Schönander, patents pending).

In 24 cases the electronic calculation of dD/dt/Di has been controlled manually on simultaneous high speed tracings (500 mm/sec) of QLAC and dD/dt by using an XY digitizing table which is connected to a desk computer ( Hewlett Packard 9810A calculator). An excellent agreement between both methods was found (r = 0.924).

Registration Technique

QLAC was recorded at the site of the maximal apical impulse during mild expiratory apnea with the patient in the left recumbent position. Subsequently QLAC and dD/dt and QLAC and dD/dt/Di were recorded, together with a precordial ECG lead.

All tracings were recorded on an ink-jet direct-writing four-channel recorder (Elema Mingograf 34) at paper speeds of 100 and 500 mm/sec.

Measurements

The indices derived from QLAC and its first derivative are indicated on figure 1.

The vertical distance between the O point and the highest systolic point of the QLAC curve represented its total displacement (TD) and was expressed as a factor of ×.

The maximum value of the first derivative of QLAC during the pre-ejection period (peak dD/dt) was expressed in ×/sec.

The normalized first derivative of QLAC (i.e., the instantaneous relationship between first derivative and amplitude of apical displacement) was calculated using both the instantaneous total (D1) and developed (D2) displacement of QLAC. The value of D1 is measured with the O point, and of D2 with the C point as reference zero-level. The normalized first derivative using total displacement was calculated electronically (see above) and its peak value is called the index (dD/dt/D1) max. The index (dD/dt/D2) was calculated manually at one-third of developed displacement, i.e., the distance CE of QLAC. The index dD/dt/D2 was calculated in order to be independent of both the zero-level and of the OC amplitude of QLAC (fig. 1). In three of 175 subjects, the OC amplitude was near or equal to zero and thus (dD/dt/D2) max could not be measured since it tended to become infinite.

The time-interval between the C point and the peak of the first time derivative of the QLAC (t-peak dD/dt) was measured at a paper speed of 500 mm/sec. In 20 of 175 subjects this time interval could not be measured due to the presence of multiple peaks in the derivative tracing.

The mean of at least five consecutive beats was taken. All values are expressed as mean ± 1 sd. Differences between mean values were assessed by the Student’s t-test for independent and nonindependent samples.

Reproducibility of QLAC and Derived Indices

The standard deviations of the mean differences (sd Δ) between the values of TD and peak dD/dt found by two independent observers (interobserver variation), expressed as a percentage of the mean (sd, relative standard deviation) were 28 and 31%, respectively. Similar percentage differences were even higher for observations made by one observer in the same patient at an interval of at least one week (intraobserver variations: 44% and 42%, respectively).

For the normalized first derivative of QLAC (dD/dt/D2) max however, inter and intraobserver variations were much smaller (sd: 11% and 15%, respectively) (table 1).

Hemodynamic Data

The relationship between the indices derived from QLAC and some parameters of left ventricular performance, obtained during heart catheterization, was only studied in 42 patients in whom the hemodynamic investigations were performed within 48 hours before or after registration of the apexcardiogram.

Standard catheterization techniques were used. Pressures were recorded with saline-filled catheters connected to an Elema EMT 34 strain gauge. The reference level for all pressures was 5 cm below the angle of Louis.
Table 1

Inter and Intraobserver Variation of QLAC and Derived Indices

<table>
<thead>
<tr>
<th></th>
<th>m</th>
<th>Δ</th>
<th>SDΔ</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interobserver variation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TD (X)</td>
<td>3.44</td>
<td>-0.28</td>
<td>0.97</td>
<td>28%</td>
</tr>
<tr>
<td>Peak dD/dt (X/sec)</td>
<td>47.5</td>
<td>-2.6</td>
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<td>31%</td>
</tr>
<tr>
<td>(dD/dt/Dt) max (sec⁻¹)</td>
<td>31.1</td>
<td>-0.8</td>
<td>3.6</td>
<td>11%</td>
</tr>
<tr>
<td>Intraobserver variation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TD (X)</td>
<td>2.39</td>
<td>+0.14</td>
<td>1.06</td>
<td>44%</td>
</tr>
<tr>
<td>Peak dD/dt (X/sec)</td>
<td>32.5</td>
<td>+1.4</td>
<td>13.6</td>
<td>42%</td>
</tr>
<tr>
<td>(dD/dt/Dt) max (sec⁻¹)</td>
<td>33.0</td>
<td>+0.2</td>
<td>5.1</td>
<td>15%</td>
</tr>
</tbody>
</table>

For explanation of calculations see text. Abbreviations: m, Δ, sd Δ: mean, mean difference and standard deviation of the mean difference between the values found by two independent observers (interobserver variation) and by one observer in the same patients at an interval of at least one week (intraobserver variation); sn: standard deviation of the mean difference (sdΔ), expressed as a percentage of the mean (m).

Left ventricular end-diastolic pressure (LVEDP) was measured at the intersection of the desnsosome of the a wave and the onset of the rapid rise of left ventricular pressure. Measurements were made from high gain tracings recorded at a paper speed of 50 mm/sec. The mean of 5 consecutive beats was taken.

Left ventricular cineangiograms were performed during maximal inspiratory apnea with the patient in a 30° right anterior oblique position. Urographine 76%, 0.7 cc/kg, was injected in 2-3 sec and film speed was 40 frames/sec. Left ventricular ejection fraction (EF) was determined by the area-length method of Dodge et al.17 Two consecutive beats were analyzed and the mean value was taken. Only beats preceded by at least two normally conducted ventricular contractions were analyzed. In our laboratory the lower limit of normal for the ejection fraction (i.e., mean normal value minus 2 sn) is 0.64. This value is based on cineangiographic studies in a series of 29 patients with normal hemodynamics in whom a mean value of 0.76 ± 0.06 was obtained.

Results

1. Total Displacement of QLAC (TD) and Its
Peak First Derivative (Peak dD/dt)

Normal Subjects

Figure 4 shows the mean value (± 1 sd) of the total displacement of QLAC (TD) and of peak dD/dt in the total group of normal subjects and also in the young and middle-aged subgroups. In the whole group the mean values for TD and peak dD/dt were 2.7 ± 1.7 X and 37.9 ± 24.3 X/sec, respectively. The variation coefficients of TD and peak dD/dt were large, reaching 62.2 and 64.2%, respectively.

The mean values of TD and peak dD/dt were significantly lower in middle-aged than in younger subjects (P < 0.001). Mean body weight and maximal expiratory thorax circumference were definitely higher in the middle-aged group (P < 0.02 and P < 0.001). In the total group of subjects, a negative association was found between maximal expiratory thorax circumference and TD (r = -0.41) and also peak dD/dt (r = -0.41). Multiple regression analysis did not reveal any significant effect of systolic blood pressure and heart rate on TD and peak dD/dt.

Patients with Heart Disease

TD and peak dD/dt were compared with the middle-aged normal group since mean age in the group of cardiac patients was 47 ± 14 years.

TD was significantly elevated in systolic (P < 0.02) and diastolic overload (P < 0.001) but normal values were found in the other subgroups (Table 2). Peak dD/dt exceeded normal values only in diastolic overload (P < 0.005) (Table 2). In the subgroup of systolic overload, patients with idiopathic hypertrophic subaortic stenosis (IHSS) and valvular aortic stenosis but not with systemic hypertension showed a rise of TD (3.77 ± 2.28 X, P < 0.02 and 3.81 ± 2.0 X, P < 0.01). Only in IHSS was peak dD/dt above normal values (56.5 ± 28.3 X/sec, P < 0.01).

Multiple regression analysis with TD and peak dD/dt as dependent variables and thorax circumference, heart rate, cardiothoracic ratio and left ventricular systolic and end-diastolic pressure as independent variables revealed a significant correlation only with thorax circumference (N = 42, r = -0.48 and r = -0.56). TD and peak dD/dt were also not significantly correlated with left ventricular ejection fraction.

Important differences in anthropometric data existed between the normal group and the various subgroups of cardiac patients, e.g., body weight and thorax circumference were 76.4 ± 9.3 kg and...
Table 2
The Calibrated Left Apexcardiogram and Derived Values in Middle-aged Normal Subjects and in Patients with Heart Disease.

<table>
<thead>
<tr>
<th></th>
<th>TD (X)</th>
<th>Peak dD/dt (X/sec)</th>
<th>(dD/dt/Dt) max (sec^-2)</th>
<th>dD/dt/Dt (sec^-3)</th>
<th>t-peak dD/dt (msec)</th>
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<tbody>
<tr>
<td>Normal subjects</td>
<td>1.95</td>
<td>27.1</td>
<td>33.8</td>
<td>44.8</td>
<td>56.9</td>
</tr>
<tr>
<td>(N = 30)</td>
<td>±1.48</td>
<td>±22.6</td>
<td>±7.0</td>
<td>±10.0</td>
<td>±7.6</td>
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<tr>
<td>Systolic overload</td>
<td>3.06</td>
<td>38.9</td>
<td>34.5</td>
<td>49.2</td>
<td>49.8</td>
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<tr>
<td>(N = 26)</td>
<td>±1.77</td>
<td>±22.3</td>
<td>±10.0</td>
<td>±10.8</td>
<td>±8.3</td>
</tr>
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<tr>
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<td>NS</td>
<td>NS</td>
<td>P &lt; 0.005</td>
<td></td>
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<tr>
<td>Diastolic overload</td>
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<td>52.1</td>
<td>29.8</td>
<td>36.7</td>
<td>62.2</td>
</tr>
<tr>
<td>(N = 23)</td>
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<td>±30.1</td>
<td>±12.2</td>
<td>±8.7</td>
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</tr>
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<td>Mitral stenosis</td>
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<td>39.2</td>
<td>39.3</td>
<td>70.1</td>
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<tr>
<td>(N = 9)</td>
<td>±1.09</td>
<td>±17.3</td>
<td>±10.3</td>
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<tr>
<td>t = 0.07</td>
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<tr>
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<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>P &lt; 0.001</td>
<td></td>
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<tr>
<td>Congestive cardiomyopathy</td>
<td>2.59</td>
<td>29.9</td>
<td>26.5</td>
<td>32.6</td>
<td>81.6</td>
</tr>
<tr>
<td>(N = 14)</td>
<td>±1.45</td>
<td>±21.9</td>
<td>±6.3</td>
<td>±8.9</td>
<td>±18.9</td>
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<tr>
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<td>t = 3.58</td>
<td>t = -5.66</td>
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<tr>
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<td>NS</td>
<td>P &lt; 0.005</td>
<td>P &lt; 0.001</td>
<td>P &lt; 0.001</td>
<td></td>
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<tr>
<td>Ischemic heart disease</td>
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<td>27.6</td>
<td>30.1</td>
<td>37.4</td>
<td>69.1</td>
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<tr>
<td>(N = 27)</td>
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<td>±16.6</td>
<td>±11.2</td>
<td>±9.4</td>
<td>±16.0</td>
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<td>NS</td>
<td>NS</td>
<td>P &lt; 0.02</td>
<td>P &lt; 0.005</td>
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</table>

94.1 ± 5.9 cm in the normal group and 61.4 ± 8.4 kg and 87.4 ± 5.1 cm in the group with congestive cardiomyopathy. Both differences were significant at the P < 0.005 level.

Pharmacological Interventions

During isoproterenol infusion a significant increase was observed in heart rate (+15 beats/min, t = -5.57, P < 0.001); TD (+0.71 X, t = -2.71, P < 0.05) and peak dD/dt (+53.8 X/sec, t = -3.61, P < 0.02).

Mean heart rate decreased by 11 beats/min (t = 3.63, P < 0.02) after intravenous administration of propranolol. TD and peak dD/dt fell in all but one case, but the changes were statistically significant only for peak dD/dt (-9.8 X/sec, t = 2.89, P < 0.05).

2. Relationship between Total Displacement of QLAC (TD) and Its Peak First Derivative (Peak dD/dt)

In the total group of normal subjects, the linear correlation between peak dD/dt and TD was highly significant (r = 0.95) (fig. 5). This relationship is mathematically expressed by the regression equation peak dD/dt = 13.8 TD + 0.86.

Strong correlations between peak dD/dt and TD were also present in the different subgroups of patients with heart disease (r = 0.81, 0.86, 0.97, 0.94.

Circulation, Volume 51, March 1975

Figure 5
Relationship between the total displacement of QLAC (TD) and its peak first derivative (peak dD/dt) in normal subjects.
and 0.91 for subgroups 1–5, respectively).

The regression line relating peak dD/dt to TD obtained in patients with a low ejection fraction (< 0.64) was markedly different from those obtained in normal subjects and in patients with a normal ejection fraction (≥ 0.64) (fig. 6).

3. The Normalized First Derivative of QLAC

Normal Subjects

In the total group the mean value for (dD/dt/Dt) max was 34.2 ± 5.7 sec\(^{-1}\) whereas dD/dt/Dt had a mean value of 44.7 ± 9.2 sec\(^{-1}\).

The variation coefficient for the normalized first derivative was definitely lower than for TD and peak dD/dt and attained, respectively, 16.6% for (dD/dt/Dt) max and 20.6% for dD/dt/Dt. For these indices no difference existed between young and middle-aged subjects (fig. 4) and no correlation was found between (dD/dt/Dt) max and thorax circumference. A positive association was present between (dD/dt/Dt) max and heart rate (r = 0.31).

Patients with Heart Disease

The normalized first derivative of QLAC was definitely lower in patients with congestive cardiomyopathy (P < 0.005 for (dD/dt/Dt) max and P < 0.001 for dD/dt/Dt. Lower mean values were also found in patients with ischemic heart disease (P < 0.02 for dD/dt/Dt) whereas normal values were found in the remaining subgroups (table 2).

Multiple regression analysis with (dD/dt/Dt) max as dependent variable and thorax circumference, heart rate, cardiothoracic ratio and left ventricular systolic and end-diastolic pressure (LVEDP) as independent variables revealed a positive association only for LVEDP (N = 42, r = 0.54).

In patients with mitral stenosis and atrial fibrillation, the index (dD/dt/Dt) max varies inversely with the length of the preceeding diastole whereas dD/dt/Dt remains constant (fig. 7).

Hemodynamic Correlation

Over a wide range of values, a weak correlation was found between (dD/dt/Dt) max and LVEDP (N = 42, r = −0.54) (fig. 8). When not including the patients with IHSS, the correlation coefficient was −0.69. The relationship between dD/dt/Dt and LVEDP was statistically not significant (table 3).

All but four patients with a value of (dD/dt/Dt) max ≥ 34 sec\(^{-1}\) (i.e., the mean value of this index obtained in normal subjects) had a normal LVEDP (i.e., < 12 mm Hg). Three of the four patients had IHSS (fig. 8).

Contrary to the findings for TD and peak dD/dt, the normalized first derivative of QLAC correlated

![Figure 6](http://circ.ahajournals.org/)

**Figure 6**

*Relationship between the total displacement of QLAC (TD) and its peak first derivative (peak dD/dt) in normal subjects and in cardiac patients with a normal and with an impaired left ventricular function.*
significantly with the left ventricular ejection fraction (EF) (table 4). All but one patient with a value of \( (dD/dt/D_t) \) max \( \geq 34 \text{ sec}^{-1} \) had a normal EF (i.e. \( \geq 0.64 \)). On the contrary, all but one patient with a value of \( (dD/dt/D_t) \) max \( \leq 23 \text{ sec}^{-1} \) (i.e., normal mean value minus 2 sd) had an EF below the lower limit of normal (< 0.64).

**Pharmacological Interventions**

During isoproterenol infusion the normalized first derivative of QLAC markedly increased in all cases (+ 14.9 sec\(^{-1}\) for \( (dD/dt/D_t) \) max, \( t = -5.19, P < 0.001 \) and + 25.3 sec\(^{-1}\) for \( dD/dt/D_d \) t = -3.97, \( P < 0.02 \)). After intravenous administration of propranolol, these indices decreased significantly (-5.8 sec\(^{-1}\) for \( dD/dt/D_d \) max, \( t = 3.99, P < 0.02 \) and -8.4 sec\(^{-1}\) for \( dD/dt/D_d \) t = 5.00, \( P < 0.001 \)). In one case, both TD and peak \( dD/dt \) increased after propranolol administration whereas \( (dD/dt/D_t) \) max and \( dD/dt/D_d \) decreased.

**4. Time to Peak \( dD/dt \) of the Left Apexcardiogram**

In the total group of normal subjects t-peak \( dD/dt \) had a mean value of 53.9 ± 9.5 msec and a variation coefficient of 17.6%. In middle-aged subjects, the mean value of this time interval was 56.9 ± 7.6 msec which was slightly higher than in younger subjects (51.5 ± 10.8 msec, \( P < 0.05 \)). Mean heart rate was definitely lower in the middle-aged group (\( P < 0.001 \)). A weak correlation was present between t-peak \( dD/dt \) and heart rate \( (r = -0.33) \).

Among cardiac patients, t-peak \( dD/dt \) was markedly increased in patients with congestive cardiomyopathy (81.6 ± 18.9 msec, \( P < 0.001 \)). Significantly higher mean values were also obtained in the group with ischemic heart disease (\( P < 0.01 \)) and

**Table 3**

**Relationship Between QLAC and Left Ventricular End-diastolic Pressure**

<table>
<thead>
<tr>
<th>( X )</th>
<th>( Y )</th>
<th>( N )</th>
<th>( r )</th>
<th>( P )</th>
<th>Regression equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>LVEDP</td>
<td>TD</td>
<td>42</td>
<td>-0.02</td>
<td>NS</td>
<td>—</td>
</tr>
<tr>
<td>LVEDP</td>
<td>peak ( dD/dt )</td>
<td>42</td>
<td>-0.18</td>
<td>NS</td>
<td>—</td>
</tr>
<tr>
<td>LVEDP ( (dD/dt/D_t) ) max</td>
<td>42*</td>
<td>-0.54*</td>
<td>&lt;0.001*</td>
<td>Y = -0.54X + 40.95*</td>
<td></td>
</tr>
<tr>
<td>LVEDP ( (dD/dt/D_d) ) max</td>
<td>39†</td>
<td>-0.69†</td>
<td>&lt;0.001†</td>
<td>Y = -0.72X + 42.85†</td>
<td></td>
</tr>
<tr>
<td>LVEDP</td>
<td>( dD/dt/D_d )</td>
<td>37</td>
<td>-0.30</td>
<td>NS</td>
<td>—</td>
</tr>
</tbody>
</table>

* Patients with idiopathic hypertrophic subaortic stenosis (IHSS) included.
† Patients with IHSS not included.

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in patients with mitral stenosis ($P < 0.001$) (table 2). In patients with IHSS, t-peak dD/dt was significantly shorter than normal (46.5 ± 8.5 msec, $P < 0.01$). In patients with diastolic overload, t-peak dD/dt was not significantly altered.

The interval t-peak dD/dt correlated weakly with the ejection fraction ($N = 17$, $r = -0.655$). A positive association existed between t-peak dD/dt and left ventricular end-diastolic pressure ($N = 30$, $r = 0.40$).

During isoproterenol infusion t-peak dD/dt significantly decreased in all cases (-8.7 msec, $t = 4.08$). After intravenous administration of propranolol, t-peak dD/dt increased in all but one case, but the changes were statistically not significant.

In the total group of normal subjects and cardiac patients, t-peak dD/dt correlated weakly with the normalized first derivative of QLAC (dD/dt/Dt) max ($N = 117$, $r = 0.34$).

Multiple regression analysis with ejection fraction as dependent variable and all the indices derived from QLAC and its first derivative (the normalized indices and the index, t-peak dD/dt) as independent variables, revealed a significant $t$-value only for (dD/dt/Dt) max (table 5).

**Discussion**

Essentially, two different methods exist to record the apexcardiogram. The first method can be described under the term displacement apexcardiography: it records the free movement of the apical impulse in relation to the rim of the recording device. The second method records the apical impulse while counter-pressure is exerted on the thoracic wall in order to render displacement as minimal as possible: this method can be described under the term pressure apexcardiography. A close relationship exists between the two methods. We have preferred to use calibrated displacement apexcardiography in view of its inherent simplicity and because it is more closely related to the findings obtained during clinical examination.

Lack of calibration has undoubtedly hampered the clinical application and usefulness of apexcardiography, and until now attempts at calibration have been rare. Clinicians, however, have long been aware that the quality and amplitude of the apical impulse was not similar in patients with different types of heart disease. Calibrated apexcardiography has now enabled the clinician to substantiate these impressions (table 2).

### Table 4

**Relationship Between QLAC and Derived Indices and Left Ventricular Ejection Fraction in a Group of Cardiac Patients Without Valvular Insufficiency.**

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>N</th>
<th>r</th>
<th>P</th>
<th>Regression equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>EF</td>
<td>TD</td>
<td>25</td>
<td>0.06</td>
<td>NS</td>
<td>—</td>
</tr>
<tr>
<td>EF</td>
<td>peak dD/dt</td>
<td>25</td>
<td>0.35</td>
<td>NS</td>
<td>—</td>
</tr>
<tr>
<td>EF</td>
<td>(dD/dt/Dt)</td>
<td>25</td>
<td>0.66</td>
<td>$&lt;0.001$</td>
<td>$Y = 32.80X + 12.73$</td>
</tr>
<tr>
<td>EF</td>
<td>dD/dt/Dt</td>
<td>22</td>
<td>0.62</td>
<td>$&lt;0.01$</td>
<td>$Y = 34.35X + 22.69$</td>
</tr>
</tbody>
</table>

### Table 5

**Multiple Regression Equation and Multiple and Partial Correlation Coefficients between Left Ventricular Ejection Fraction, the Normalized Derivative Indices of QLAC and the index t-peak dD/dt**

\[
\text{EF} = -0.238 + 0.016 \text{(dD/dt/Dt)} + 0.007 \text{dD/dt/Dt} + 0.0004 \text{(t-peak dD/dt)}
\]

$N = 17^*$

$\rho = 0.89 (P < 0.001)$

$\rho_{11} = 0.85, t = 4.22$

$\rho_{12} = 0.71, t = 1.27$

$\rho_{13} = -0.66, t = 0.10$

*The relationship with EF has been studied in all patients without valvular insufficiency and in whom peak dD/dt could be measured (see methods).
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the QLAC in different patient groups. The differences in body build, present in the various subgroups of the present study, are probably responsible for the lack of difference in total amplitude of QLAC between normal subjects and patients with cardiomyopathy.

Although the total displacement of QLAC (TD) significantly differs from normals when large numbers of patients are studied, the clinical value of this index is limited since TD is largely dependent on extrinsic factors such as thorax circumference and inter and intraobserver variation.

2. The First Derivative of Apical Displacement

Several authors have studied the time interval from the onset of ventricular depolarization to the peak of the first derivative of the left apexcardiogram. Our data are generally in agreement with the findings of Reale and of Vetter et al. who reported a significant correlation between this time interval and several indices of left ventricular contractility. The interval between the upstroke of the QLAC and the peak of its first derivative (t-peak dD/dt), used in the present study was, however, less dependent on heart rate.

Difficulties in calibration are the main reason for the scarcity of studies analyzing the peak first derivative of the left apexcardiogram. During acute hemodynamic interventions in the canine, the absolute value of the peak first derivative of the QLAC correlates significantly with left ventricular peak dP/dt. In the present study, peak dD/dt increased during positive and decreased during negative inotropic interventions. Peak dD/dt was significantly increased in patients with IHSS which is in agreement with previous findings. The clinical value of this index, however, is limited since peak dD/dt does not correlate significantly with LVEDP and ejection fraction and is mainly determined by extrinsic factors such as thorax circumference.

An important finding was the excellent correlation in normal subjects between the peak first derivative of the QLAC (peak dD/dt) and its total displacement (TD) (r = 0.95, fig. 5) A highly significant correlation between peak dD/dt and TD was also found in the subgroups of cardiac patients. The slope of the regression line, however, was definitely lower in patients with a low ejection fraction (<0.64) whereas in the group with a normal ejection fraction it was nearly identical to normals (fig. 6). The relation between peak dD/dt and TD appears to be an expression of the functional state of the heart and further work in this field is certainly warranted.

3. The Normalized First Derivative of Apical Displacement

When the velocity of apical displacement (dD/dt) is normalized for its instantaneous amplitude (index (dD/dt/Dd) max and dD/dt/Dd), the spreading of the values found in normal subjects is substantially reduced (fig. 4). Moreover, inter and intraobserver variations decrease (table 1). Contrary to the findings for TD and peak dD/dt, the normalized value (dD/dt/Dd) max does not correlate significantly with the thorax circumference.

Throughout the paper normalization of dD/dt is done both by using total (index (dD/dt/Dd) max) and developed displacement of QLAC (index dD/dt/Dd). The index dD/dt/Dd is independent of the OC amplitude, i.e., the vertical distance between the O point and the upstroke of the QLAC. In some cases of mitral stenosis, the diastolic part of the QLAC continues to rise, making the OC amplitude and thus the index (dD/dt/Dd) max dependent on the length of the preceding diastole (fig. 7); in rare cases the OC amplitude may be near zero, so that the index (dD/dt/Dd) max tends to become infinite. This discrepancy can be avoided by using developed displacement for the normalization of dD/dt (fig. 7).

Contrary to the findings for TD and peak dD/dt, (dD/dt/Dd) max significantly correlates with left ventricular end-diastolic pressure and with ejection fraction (EF). It is widely accepted that LVEDP is not a reliable index of left ventricular contractility since LVEDP is altered by changes in loading and by variation in diastolic compliance. Moreover, LVEDP can be normal in patients with impaired left ventricular contractility, for instance in cases with congestive cardiomyopathy. It is of interest that the value (dD/dt/Dd) max was low in some patients with congestive cardiomyopathy despite a normal LVEDP, whereas this index was normal and even supranormal in patients with IHSS with a markedly raised LVEDP (fig. 8).

The index dD/dt/Dd did not correlate significantly with LVEDP (table 3). Developed displacement of the QLAC does not contain the OC amplitude, which has been shown to correlate well with LVEDP and this probably explains the discrepancy between indices derived from total and developed displacement. On the contrary, the normalized first derivative of QLAC correlates significantly with EF both by using total and developed displacement (table 4).

The index (dD/dt/Dd) max and dD/dt/Dd increases by positive inotropic and decreases by negative inotropic interventions. Recently some investigators have demonstrated that the normalized first derivative of the QLAC is only influenced by inotropic interventions and not by changes in heart rate, nor by changing afterload with drugs selectively altering the peripheral vascular resistance. This is in agreement with the present observation that (dD/dt/Dd) max is only slightly dependent on heart rate and does not
significantly differ from normal in patients with mild systemic hypertension and with aortic valvular stenosis with a normal left ventricular function at rest.

Although these observations demonstrate that the various indices obtained by amplitude normalization of $dD/dt$ are highly influenced by the contractile state of the heart, we prefer at this stage to consider them as normalized indices of velocity of displacement rather than as indices of contractility. Moreover, the normalized first derivative of $dD/dt$ derived from the isovolumic period, has only been correlated with isotonic indices of left ventricular performance such as ejection fraction because clinical judgment was based on these indices and indices of contractility were not available in this group of patients.

For this reason the relationship between the normalized first derivative of $dD/dt$ and left ventricular ejection fraction was only studied in a group of patients without valvular insufficiency. It should be noted, however, that previous work from our laboratory has shown that in the dog the normalized first derivative of the left apexcardiogram is highly significantly correlated with indices of contractility derived from left ventricular dp/dt and instantaneous isovolumic pressure.

In order to evaluate the relative importance of the normalized indices derived from QLAC and the index $t$-peak $dD/dt$, multiple regression analysis has been performed including all measured indices and using $EF$ as the dependent variable. Only $(dD/dt/Dt)_{max}$ had a significant $t$-value, demonstrating its superiority on the index $t$-peak $dD/dt$ (table 5).

In view of the inherent simplicity of measuring the time interval $t$-peak $dD/dt$, which obviates the need for calibration, this time interval remains highly interesting for the evaluation of the hemodynamic state of the heart, although peak $dD/dt$ could not always be measured due to the presence of multiple peaks in the derivative tracing.

The independence of the normalized indices of QLAC from the thorax circumference and the significant correlation that exists between these indices and other parameters of ventricular function, e.g., ejection fraction and LVEDP, clearly demonstrate their superiority on the nonnormalized indices. This superiority is further enhanced by the lesser variability of the normalized index in normal subjects and by the reduced inter and intraobserver variation. It can be concluded that the normalized first derivative of QLAC is of great value for the clinical evaluation of the hemodynamic state of the heart.

Acknowledgments

The authors gratefully acknowledge the skilled assistance of Mrs. M. T. Geurts-Stassen and Miss N. Vangeel.

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Circulation. 1975;51:541-551
doi: 10.1161/01.CIR.51.3.541

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

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