The Clinical Value of the Calibrated Apical A Wave and its Relationship to the Fourth Heart Sound

Boudevijn Denef, M.D., Hilaire De Geest, M.D., and Hugo Kesteloot, M.D.

SUMMARY The amplitude of the calibrated apical A wave (A), its first derivative (dA/dt), its normalized first derivative ([dA/dt]/A) and its value expressed as a percentage of the total systolic deflection (A/H) were derived from calibrated left apexcardiograms in 64 normal subjects and in 150 patients with heart disease. A is significantly increased in patients with pressure and volume overload of the left ventricle, in idiopathic hypertrophic subaortic stenosis, in congestive cardiomyopathy and in ischemic heart disease in the presence of left ventricular asynergy (p < 0.001). In aortic stenosis, A is more sensitive to changes in left ventricular compliance than the A/H ratio. Highly significant correlations exist between A and peak dA/dt in normals (r = 0.98) and in patients with heart disease (r = 0.81-0.99); at an identical A, patients with a dilated left ventricle have lower values for peak dA/dt and a lower index (peak dA/dt)/A (p < 0.001). As a result, A and peak dA/dt are considered to be primarily determined by the resistance to ventricular filling during atrial systole. In the presence of a fourth heart sound (S₄), A and peak dA/dt were significantly increased (p < 0.001). A peak dA/dt value > 6X/sec is always associated with an S₄. To a certain degree peak dA/dt can differentiate between a physiologic and pathologic S₄. The intensity of S₄ depends more on the rate of rise of the A wave than on its total amplitude.

THE LEFT APEXCARDIOGRAM (LAC) is widely used to record low-frequency precordial vibrations over the left precordium, and its value in assessing the mechanical behavior of the left ventricle has been repeatedly emphasized. The A wave of the LAC reflects the late diastolic response of the left ventricle to atrial systole. The height of the A wave expressed as a percentage of the total systolic deflection of the LAC has been proposed as an index for the noninvasive assessment of left ventricular end-diastolic pressure and left ventricular end-diastolic compliance. An abnormal increase of the A-wave ratio has been found in several types of heart disease, but some patients did not have large A waves despite severe heart disease, and normal A-wave ratios have been reported in patients with critical aortic stenosis. A relationship between the height of the apical A wave and the presence of a fourth heart sound (S₄) has also been shown. Some patients with a definite S₄, however, do not have an abnormal A-wave ratio, and the reason for this remains unexplained. Using calibrated apexcardiography and a previously described method, we attempted to clarify these problems and investigate the clinical value of A-wave calibration and its relation to S₄.

Materials and Methods

Calibrated left apexcardiogram tracings (QLACs) were obtained in 25 normal young subjects (mean age 25 ± 4 years), in 39 normal middle-aged subjects (mean age 42 ± 9 years) and in 150 patients with heart disease (mean age 50 ± 12 years). The presence or absence of an S₄ was established prospectively in 103 subjects by means of phonocardiography. In the normal groups, the absence of heart disease was based on cardiac catheterization and coronary arteriography in 14 subjects and on clinical evidence in the remainder (i.e., no previous history of heart disease, normal  

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physical examination, 12-lead ECG and chest x-ray). The patients with heart disease were divided into five subgroups based on cardiac catheterization and appropriate angiographic studies.

Group 1 (left ventricular pressure overload) consisted of 21 patients with isolated valvular aortic stenosis (AS) with a resting peak left ventricular aortic systolic pressure gradient > 50 mm Hg in 18 and < 50 mm Hg in three.

Group 2 (left ventricular volume overload) consisted of 23 patients with isolated severe aortic insufficiency (AI).

Group 3 consisted of 11 patients with idiopathic hypertrophic subaortic stenosis (IHSS).

Group 4 (congestive cardiomyopathy) consisted of 14 patients with an angiographic ejection fraction below the lower limit of normal in the absence of valvular, hypertensive, congenital or atherosclerotic heart disease (ASHD).

Group 5 consisted of 81 patients with ASHD. The diagnosis of ASHD was established in all 81 patients by selective coronary arteriography. These patients were divided into five subgroups based on the pattern of left ventricular contraction, which was assessed by the method of Hamilton et al.:

1) ASHD without left ventricular asynergy (n = 26); 2) ASHD with borderline abnormal left ventricular contraction (less than 25% of ventricular end-diastolic border) (n = 13); 3) ASHD with local left ventricular hypokinesia or akinesia (diminished or no contraction in more than 25% but less than 75% of the ventricular end-diastolic border) (n = 14); 4) ASHD with diffuse left ventricular hypokinesia (diminished contraction in more than 75% of the left ventricular end-diastolic border) (n = 12); 5) ASHD with left ventricular aneurysm, including only patients with paradoxic systolic outward motion of the left ventricular anterolateral and/or apical segments (n = 16).

No patient in the acute stages of a myocardial infarction was included in the study. All patients were in sinus rhythm, and none had severe hypertension (diastolic blood pressure ≥ 110 mm Hg) or obvious signs of congestive heart failure (i.e., pulmonary edema, gross hepatomegaly or peripheral edema).

The QLAC was recorded at the site of the maximal apical impulse with the patient in the left recumbent position. A detailed description of the registration apparatus and the calibration procedure has been reported elsewhere. Briefly, the apical displacement was calculated as a factor of the height (X) of a ramp signal with a constant slope and amplitude (fig. 1). A calibration factor for the first time derivative of the QLAC (dX/dt) was obtained by differentiating the ramp signal. The calibration factor could be calculated using the time (t) from the beginning to the top of the ramp signal and equals 1X/t sec. The pulse transducer had a time constant of 4 seconds and was linear up to 50 Hz, which was adequate for an undistorted recording of the low-frequency apical impulse. The differentiator permitted true differentiation for frequencies up to 75 Hz. On a four-channel, ink-jet, direct-writing recorder (Elema Mingograf 34), simultaneous recordings were made of the ECG, the phonocardiogram (PCG) at the fourth intercostal space, the QLAC and dX/dt. In 103 of the 214 subjects studied, the PCG was registered and studied prospectively for the presence or absence of an S4. The PCG was obtained using a dynamic microphone (Elema) placed at the apical region with the patient in the left recumbent position during maximal expiratory apnea. We used octave phonocardiographic filters according to Mannheimer with a nominal frequency of 25, 50, 100, 200 and 400 Hz and a logarithmic filter. The frequency band was situated between the nominal frequency plus or minus its value divided by \(\sqrt{2}\), with an attenuation slope in both directions of −12 dB per octave.

An S4 was considered to be present whenever characteristic presystolic vibrations of more than 10% of the height of the first heart sound (S1) were present in the 25-Hz filter band. We used a percentage value because an absolute amplitude quantification of the PCG is not available. The 10% value was selected in order to eliminate noise; in our series the baseline noise in the 25-Hz filter band (measured before the P wave) was 0.6–10% of the amplitude of S1 (mean 5.4 ± 2.4%). The lowest percentage value of S4 compared with S1 was 10.2% (mean 36.3 ± 23.9%); to calculate this mean value, we omitted one patient with a percentage value of 550%. The frequency band of 25 Hz was selected because S4 was always best visualized in this frequency band, although in most cases S4 was also visible on the 50-Hz frequency band.

Pressures were recorded with saline-filled catheters connected to an Elema EMT 34 strain gauge. The zero pressure level was at the mid-thoracic level. Left ventricular end-diastolic pressure was measured at the intersection of the downslope of the A wave and the onset of the rapid rise of left ventricular pressure.

Single-plane left ventriculography was performed with the patient in a right oblique position after power injection of 76% Urographin (0.7 ml/kg) into the left ventricular chamber. The end-diastolic and end-systolic ventriculographic silhouettes were traced with the apex and the mid-aortic valve as fixed reference points.

Measurements and Calculations

Calculations on the calibrated apical A wave were performed on high-gain tracings recorded at a paper speed of 250 mm/sec. The following measurements were made:

1) Total amplitude of the A wave (A) expressed as a factor of X and calculated as the vertical distance between the beginning and the top of the A wave.
2) The A-wave ratio (A/H), i.e., expressed as a percentage of the total systolic deflection of the LAC.
3) The peak first derivative of the A wave (peak dA/dt) expressed as a factor of X/sec.
4) The normalized first derivative of the A wave calculated as the ratio (peak dA/dt)/A. This ratio was
TABLE 1. The Apical A Wave in Normal Subjects (n = 39)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>sd</th>
<th>Variation coefficient (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/H(%)</td>
<td>7.5</td>
<td>2.9</td>
<td>39</td>
</tr>
<tr>
<td>A (X)</td>
<td>0.13</td>
<td>0.10</td>
<td>77</td>
</tr>
<tr>
<td>Peak dA/dt (X/sec)</td>
<td>3.9</td>
<td>3.3</td>
<td>85</td>
</tr>
<tr>
<td>Peak dA/dt</td>
<td>29.6</td>
<td>6.6</td>
<td>22</td>
</tr>
</tbody>
</table>

Abbreviations: A(X) = total A-wave amplitude expressed as a factor of X; A/H(%) = A-wave amplitude expressed as a percentage of the total systolic deflection of the left apexcardiogram; peak dA/dt = peak first derivative of the A wave.

measured in order to normalize peak dA/dt for A, and it eliminates to a great extent the influence of obesity, thoracic circumference and other external factors in the amplitude of the measured parameters.

All measurements were made on tracings recorded during relaxed expiratory apnea. Each measurement was the mean of five consecutive tracings. Standard statistical methods were used. The results obtained in the patients with heart disease (mean age 50 ± 12 years) were compared with those in the control group of 39 normal middle-aged subjects who were of comparable age (mean age 42 ± 9 years).

Results

The A Wave in Normal Subjects

The mean values, standard deviation and variation coefficients for the different parameters derived from the apical A wave in middle-aged normal subjects are summarized in table 1. The index (peak dA/dt)/A has the lowest variability. A highly significant correlation is present between A and peak dA/dt (fig. 2) (r = 0.98; p < 0.001) despite the large range of values found for these indices. This indicates that for given A, the rate of rise of the A wave is fairly constant in normal subjects.

The A Wave in Patients with Heart Disease

The results for A and A/H obtained in patients with heart disease are summarized in table 2. Both A and A/H are significantly increased in patients with AS, severe AI, IHSS and congestive cardiomyopathy. As indicated by the r value, A is a better index of abnormality than A/H in patients with AS, severe AI and congestive cardiomyopathy. In severe AS, A/H is frequently within normal limits despite a very high A wave on the left ventricular pressure curve (fig. 3). Only six of the 18 patients with severe AS have an A/H value above the upper limit of normal (i.e., 13.2%), while in 15 patients, A is above the upper limit of normal (i.e., 0.33X).

In ASHD, A and A/H gradually increase with progression of left ventricular dysfunction. However,
in patterns with minor left ventricular contraction abnormalities and local left ventricular hypokinesia, both indices are frequently within normal limits. In ASHD, the A/H ratio is more sensitive to left ventricular dysfunction than A, as indicated by the higher t values obtained for this index. As in normal subjects, a highly significant linear correlation is present between A and peak dA/dt in the subgroups of patients with heart disease (table 3). However, for an identical A, patients with a dilated left ventricle have a lower peak dA/dt than normals (fig. 2), as indicated by the lower regression coefficients obtained in these groups (table 3).

Table 4 summarizes the mean values for peak dA/dt and (peak dA/dt)/A in the subgroups of patients with heart disease. Significantly higher mean values are found for peak dA/dt than for A in patients with heart disease. However, in patients with a dilated left ventricle, as in severe AI, congestive cardiomyopathy or advanced stages of ASHD, peak

**TABLE 2. The Apical A Wave in Patients with Heart Disease**

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>n</th>
<th>A/H(%)</th>
<th>A(X)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal group</td>
<td>39</td>
<td>7.5 ± 2.9</td>
<td>0.13 ± 0.10</td>
</tr>
<tr>
<td>LV pressure overload (AS)</td>
<td>21</td>
<td>13.5 ± 7.6‡</td>
<td>0.54 ± 0.27</td>
</tr>
<tr>
<td>LV volume overload (AI)</td>
<td>23</td>
<td>12.7 ± 8.1‡</td>
<td>0.48 ± 0.14‡</td>
</tr>
<tr>
<td>IHSS</td>
<td>11</td>
<td>16.9 ± 5.3‡</td>
<td>0.61 ± 0.42‡</td>
</tr>
<tr>
<td>Congestive cardiomyopathy</td>
<td>14</td>
<td>10.5 ± 6.0*</td>
<td>0.43 ± 0.51†</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t = -2.5</td>
<td>t = -3.4</td>
</tr>
<tr>
<td>ASHD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Without LV asynergy</td>
<td>26</td>
<td>10.0 ± 5.3*</td>
<td>0.14 ± 0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t = 2.4</td>
<td>t = -0.4</td>
</tr>
<tr>
<td>Borderline abnormal LV contraction</td>
<td>13</td>
<td>12.5 ± 5.3‡</td>
<td>0.19 ± 0.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t = -4.3</td>
<td>t = -1.7</td>
</tr>
<tr>
<td>Local LV hypokinesia</td>
<td>14</td>
<td>8.3 ± 5.3</td>
<td>0.18 ± 0.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t = -0.7</td>
<td>t = -1.2</td>
</tr>
<tr>
<td>Diffuse LV hypokinesia</td>
<td>12</td>
<td>15.5 ± 5.8‡</td>
<td>0.38 ± 0.26‡</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t = -6.3</td>
<td>t = -4.7</td>
</tr>
<tr>
<td>LV aneurysm</td>
<td>16</td>
<td>16.8 ± 6.7‡</td>
<td>0.41 ± 0.29‡</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t = -7.2</td>
<td>t = -5.4</td>
</tr>
</tbody>
</table>

Values are mean ± sd. The t and p values represent comparison with the normal group.
* p < 0.05.
† p < 0.01.
‡ p < 0.001.

Abbreviations: A/H(%) = A-wave amplitude expressed as a percentage of the total systolic deflection of the left apexcardiogram; A(X) = total A-wave amplitude expressed as a factor of X; LV = left ventricular; AS = aortic stenosis; AI = aortic insufficiency; IHSS = idiopathic hypertrophic subaortic stenosis; ASHD = atherosclerotic heart disease.
dA/dt is rather low compared with A, resulting in significantly lower mean value for (peak dA/dt)/A. In patients with IHSS and AS, peak dA/dt is markedly higher than in patients with a dilated non-hypertrophic left ventricle, as in congestive and ischemic cardiomyopathies (fig. 4).

The coefficient of variation for (peak dA/dt)/A in the subgroups of patients with heart disease is markedly lower than for the other indices studied.

Relation Between the A Wave and S₄

Figure 5 shows the values for A/H and the A wave, expressed in absolute value (A[X]) in subjects with and without an S₄. Only subjects in whom S₄ was prospectively looked for are included. For A/H, a large degree of overlapping is present between patients with and without an S₄. An A/H value ≥ 15% is always associated with an S₄. An S₄ is frequently present despite a normal A/H, especially in cases with AS. A(X) discriminates better between subjects with and without an S₄: a value ≥ 0.23X is always accompanied by an S₄.

Figure 6 relates peak dA/dt to the presence of an S₄ and shows that a peak dA/dt value > 6X/sec is always associated with an S₄. In the presence of an S₄, peak dA/dt is higher in patients with heart disease, except those with ASHD, than in normal subjects. In

Table 3. The Apical A Wave in Patients with Heart Disease Relationship Between Total Amplitude and Peak First Derivative

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Linear regression equation</th>
<th>n</th>
<th>r</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal group</td>
<td>Peak dA/dt = 30.3 A - 0.04</td>
<td>39</td>
<td>0.98</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>LV pressure overload (AS)</td>
<td>Peak dA/dt = 34.7 A - 2.7</td>
<td>21</td>
<td>0.81</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>LV volume overload (AI)</td>
<td>Peak dA/dt = 12.0 A + 2.9</td>
<td>23</td>
<td>0.87</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>IHSS</td>
<td>Peak dA/dt = 24.2 A + 2.8</td>
<td>11</td>
<td>0.85</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Congestive cardiopathy</td>
<td>Peak dA/dt = 18.3 A + 0.6</td>
<td>14</td>
<td>0.99</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>ASHD</td>
<td>Peak dA/dt = 19.7 A + 0.7</td>
<td>81</td>
<td>0.90</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Abbreviations: peak dA/dt = peak first derivative of the apical A wave; A = total amplitude of the apical A wave; LV = left ventricular; AS = aortic stenosis; AI = aortic insufficiency; IHSS = idiopathic hypertrophic subaortic stenosis; ASHD = atherosclerotic heart disease.

Figure 3. The calibrated left apexcardiogram (QLAC) and its first derivative (dX/dt) in severe aortic stenosis. PCG = phonocardiogram; LVP = high-gain left ventricular pressure tracing; LVEDP = left ventricular end-diastolic pressure; LVP-AoP = peak systolic left ventricular pressure gradient across the aortic valve; A/H = the apical A-wave amplitude expressed as a percentage of the total systolic deflection of the left apexcardiogram; S, A = calibrated amplitude of the systolic wave and A wave of the left apexcardiogram expressed as a factor of X; N = mean normal values ± SD.
Table 4. The Apical A Wave in Patients with Heart Disease

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>n</th>
<th>Peak dA/dt (X/sec)</th>
<th>(Peak dA/dt)/A (sec⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal group</td>
<td>39</td>
<td>3.9 ± 3.3</td>
<td>29.6 ± 6.6</td>
</tr>
<tr>
<td>LV pressure overload (AS)</td>
<td>21</td>
<td>16.9 ± 10.7†</td>
<td>29.1 ± 9.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t = -6.9</td>
<td>t = 0.2</td>
</tr>
<tr>
<td>LV volume overload (AI)</td>
<td>23</td>
<td>11.5 ± 11.8‡</td>
<td>20.5 ± 6.7‡</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t = -3.7</td>
<td>t = 4.6</td>
</tr>
<tr>
<td>IHSS</td>
<td>11</td>
<td>17.6 ± 11.9‡</td>
<td>30.8 ± 8.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t = -6.4</td>
<td>t = -0.5</td>
</tr>
<tr>
<td>Congestive cardiomyopathy</td>
<td>14</td>
<td>7.3 ± 9.5</td>
<td>17.2 ± 4.5‡</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t = -1.9</td>
<td>t = 6.5</td>
</tr>
<tr>
<td>ASHD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Without LV asynergy</td>
<td>26</td>
<td>4.4 ± 2.8</td>
<td>28.5 ± 7.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t = -0.6</td>
<td>t = 0.6</td>
</tr>
<tr>
<td>Borderline abnormal LV contraction</td>
<td>13</td>
<td>5.6 ± 4.2</td>
<td>29.1 ± 7.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t = -1.5</td>
<td>t = 0.2</td>
</tr>
<tr>
<td>Local LV hypokinesia</td>
<td>14</td>
<td>5.0 ± 5.6</td>
<td>24.0 ± 4.6†</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t = -0.8</td>
<td>t = 2.8</td>
</tr>
<tr>
<td>Diffuse LV hypokinesia</td>
<td>12</td>
<td>6.9 ± 4.6*</td>
<td>18.6 ± 2.0‡</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t = -2.3</td>
<td>t = 5.2</td>
</tr>
<tr>
<td>LV aneurysm</td>
<td>16</td>
<td>7.3 ± 6.1†</td>
<td>17.7 ± 3.8‡</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t = -2.7</td>
<td>t = 6.7</td>
</tr>
</tbody>
</table>

Values are mean ± sd. The p values represent comparisons with the normal group.

* p < 0.05.
† p < 0.01.
‡ p < 0.001.

Abbreviations: peak dA/dt = peak first derivative of the A wave; (peak dA/dt)/A = normalized first derivative of the A wave; LV = left ventricular; AS = aortic stenosis; AI = aortic insufficiency; IHSS = idiopathic hypertrophic subaortic stenosis; ASHD = atherosclerotic heart disease.

Figure 4. A typical registration of the calibrated left apexcardiogram (QLAC), its first derivative (dX/dt) and the phonocardiogram (PCG, Ph1, Ph3 and Ph5) in a patient with severe aortic stenosis (1) and with an aneurysm of the left ventricular anterior wall (2). In spite of a nearly identical total A-wave amplitude in both patients, the rate of rise of the A wave is markedly different (peak dA/dt indicated with an arrow on the figure equals 38 X/sec in case 1 and 7 X/sec in case 2). This is closely related to the presence and relative intensity of the fourth heart sound (S₄), which is very pronounced in case 1 but hardly visible in case 2.
Normal subjects

AS

AI

IHSS

ASHD I-II

ASHD III-IV

Figure 5. The apical A wave in cases with (+S₄) and without (−S₄) a fourth heart sound. The values are tabulated for the A/H ratio and for the calibrated A-wave amplitude (A). AS = aortic stenosis; AI = aortic insufficiency; IHSS = idiopathic hypertrophic subaortic stenosis; ASHD = atherosclerotic heart disease.

Table 5. Relation Between the Apical A Wave and the Fourth Heart Sound (S₄)

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>A/H (%)</th>
<th>A(X)</th>
<th>Peak dA/dt (X/sec)</th>
<th>(Peak dA/dt)/A (sec⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S₄ absent</td>
<td>30</td>
<td>5.5 ± 4.3</td>
<td>0.09 ± 0.07</td>
<td>3.0 ± 1.4</td>
<td>26.5 ± 7.3</td>
</tr>
<tr>
<td>Physiologic S₄</td>
<td>20</td>
<td>7.9 ± 3.1</td>
<td>0.21 ± 0.11</td>
<td>5.8 ± 2.9</td>
<td>28.2 ± 7.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>p &lt; 0.05</td>
<td>p &lt; 0.001</td>
<td>p &lt; 0.001</td>
<td>NS</td>
</tr>
<tr>
<td>S₄ in heart disease</td>
<td>56</td>
<td>15.7 ± 6.9</td>
<td>0.49 ± 0.26</td>
<td>13.0 ± 10.0</td>
<td>26.5 ± 10.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>p &lt; 0.001</td>
<td>p &lt; 0.001</td>
<td>p &lt; 0.001</td>
<td>NS*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>p &lt; 0.001†</td>
<td>p &lt; 0.001†</td>
<td>p &lt; 0.01†</td>
<td>NS†</td>
</tr>
</tbody>
</table>

Values are mean ± SD.

*S₄ in heart disease vs S₄ absent.
†S₄ in heart disease vs physiologic S₄.

Abbreviations: A/H (%) = A-wave amplitude expressed as a percentage of the total systolic deflection of the left apexcardiogram; A(X) = total A-wave amplitude expressed as a factor of X; peak dA/dt = peak first derivative of the A wave; (peak dA/dt)/A = normalized first derivative of the A wave.
normal subjects with an $S_4$, A and peak $dA/dt$ are significantly higher than in normal subjects without an $S_4$, while $A/H$ is only slightly increased (table 5). In patients with heart disease and an $S_4$, A/H, A and peak $dA/dt$ are higher than in patients without $S_4$ or in normal subjects with or without an $S_4$ (table 5). There is no significant difference in (peak $dA/dt$)/A between patients with and without an $S_4$.

**Discussion**

**Clinical Value of A-wave Calibration**

The A wave of the LAC reflects the late diastolic response of the left ventricle to atrial systole, as well as the "atrial kick" recorded in the left ventricle.²⁶,²⁷ The height of the A wave has usually been expressed as the ratio of its height to the total amplitude of the LAC ($A/H$ ratio), but only a few investigators using calibrated tracings³¹,³²,³³ analyzed the A wave in absolute values. This $A/H$ ratio has been studied in several types of heart disease, and a significant increase has been reported in AS,¹⁹ AI,²⁰ cardiomyopathy,¹⁹ IHSS³¹ and systemic hypertension.³⁴ An abrupt increase of an apparently normal A wave at rest has been observed during exercise in patients with coronary artery disease.³³ Several investigators have correlated the $A/H$ ratio with hemodynamic data; a weak but significant correlation was found between $A/H$ and left ventricular end-diastolic pressure.¹¹ The correlation was better when only the height of the left ventricular A wave was compared with the $A/H$ ratio.¹⁵ More recently, a better correlation was found between the $A/H$ ratio and an index of left ventricular end-diastolic stiffness calculated from a combined echocardiographic and hemodynamic technique.¹⁷ These data suggest that the height of the apical A wave depends partially on left ventricular late diastolic compliance.

Despite the clinical usefulness of the $A/H$ ratio in assessing left ventricular diastolic function, some controversies remain. Kavalier et al.²¹ reported that in severe AS a large A wave may be absent, and 55% of their cases had a normal $A/H$ ratio. In the study of Gibson et al.,¹² five of 13 patients with a normal $A/H$ ratio had an elevated left ventricular end-diastolic pressure. In the present investigation only six of 18 patients with severe AS had an abnormal $A/H$ ratio. From calibrated tracings, the reason for this discrepancy is obvious: In patients with severe pressure or volume overload, a simultaneous increase in the amplitude of the systolic wave and of the A wave occurs frequently and the $A/H$ ratio remains normal (fig. 3).

In severe AS or AI, most patients with a normal $A/H$ ratio have an increased A (table 2). Previous studies using calibrated apexcardiography have shown a significant increase in the amplitude of the systolic wave of the LAC in patients with systolic and diastolic overload of the left ventricle.²²,²⁴,²⁵ The A wave calculated in absolute values shows a significant degree of variability in normal subjects and in patients with heart disease (tables 1 and 2). This is mainly a consequence of differences in thoracic circumference and body build. Nevertheless, the absolute height of the A wave is increased to such an extent in various forms of severe heart disease that a discrimination between normal and abnormal remains possible. In patients with severe AS, AI or congestive cardiomyopathy, the absolute height of the A wave is an even more sensitive index of abnormal left ventricular diastolic function than the $A/H$ ratio, as indicated by the higher $t$ values; the reverse is found in patients with ASHD (table 2). This can be explained by the increase in amplitude of both the A wave and the systolic wave of the LAC (H) in patients with systolic and diastolic overload of the left ventricle and congestive car-
diomyopathy that is not present in patients with ASHD, in whom only the A wave is elevated.

Not only A, but also its rate of rise of the A wave, as expressed by dA/dt, differs markedly between normal subjects and patients with heart disease (table 4 and fig. 4). In patients with a noncompliant hypertrophic left ventricle, as in severe AS or IHSS, the rate of rise of the A wave is frequently high. In contrast, when the left ventricle is dilated and contracts poorly, as in congestive or ischemic cardiomyopathy, the speed of the A wave is low relative to A. (table 4 and fig. 4). This is indicated by the significantly lower mean values for (peak dA/dt)/A in patients with severe aortic regurgitation, congestive cardiomyopathy and severe left ventricular dysfunction due to ASHD (table 4). This rate of rise of the apical A wave is fairly constant for a given A in normal subjects, as shown by the marked linear relationship between both variables (fig. 2 and table 3). As a consequence, the normalized index (peak dA/dt)/A has a much lower variability and the variation coefficient for this index in normals and in the subgroups of patients with heart disease is lower than for the A/H ratio (tables 1 and 4).

The hemodynamic determinants of the rate of rise of the A wave need further clarification. In previous experimental studies in the dog we have shown that the first derivative of the apical A-wave correlates significantly with the rate of left ventricular pressure rise during atrial systole. This rate of left ventricular pressure rise can be influenced by the preload and afterload conditions of left ventricular contraction, as well as by the contractility of the left atrium. Both premature mitral valve closure in aortic regurgitation and presence or absence of mitral regurgitation in severe left ventricular dilatation as a determinant of left atrial volume during atrial contraction can influence the force and the speed of left atrial contraction. Our results indicate that analyzing the calibrated apical A wave in terms of total amplitude and velocity enhances the assessment of left atrial and left ventricular diastolic function.

Relation of the Apical A Wave to S4

The genesis of the S4 is still controversial. A close association has been shown between a large apical A wave and the presence of an S4. Our results, however, indicate that an S4 frequently occurs despite a normal A/H ratio (fig. 5), especially in patients with severe AS or AI. This discrepancy has been also mentioned by other investigators. We conclude from our data that a major reason for this observation is a proportional increase in the amplitude of both the systolic wave and the A wave, resulting in a normal A/H ratio. Calculating the A wave in absolute values discriminates better between patients with or without an S4. An A > 0.23X or a peak dA/dt value > 6X/sec is always associated with an S4 (figs. 5 and 6). To a certain degree, peak dA/dt can differentiate between physiologic and pathologic S4' s, except in patients with ASHD (fig. 6).

It has been shown by other investigators that S4 audibility and its occurrence in normal subjects vs age-matched patients was not related to the PCG ratio S4/S3. In our normal subjects, the occurrence of S4 was not related to the A/H ratio (fig. 5). The amplitude of an S4 seems to be more dependent on the rate of rise of the A wave than on A. This is readily apparent in figure 4. The A waves in both patients are of comparable amplitude when expressed as a A/H ratio as well as in absolute values. In the patients with severe AS, the A wave rises rapidly and is associated with a distinct S4, while the reverse is found in the patient with severe left ventricular dysfunction and dilatation due to ASHD. In spite of a very high A wave in the latter, an S4 is nearly absent.

This paradox — an absent or a soft S4 despite severe left ventricular dysfunction in patients with ASHD — has been mentioned by other investigators. In our patients with ASHD, (peak dA/dt)/A decreases as left ventricular dysfunction progresses (table 4) and, although difficult to express quantitatively, the amplitude of the S4 seems to follow the same direction. This rate of rise of the apical A wave has been shown to be closely related to the rate of left ventricular pressure rise during atrial systole. Our results support the concept of the interrelationship between heart sounds, pressure and thoracic wall displacement, and specifically that the higher derivatives of the LAC and the left ventricular pressure tracing gradually transform these tracings into the PCG. Part of the controversy surrounding the clinical importance of an S4 undoubtly results from the impossibility of calibrating this sound in the PCG. The fact that A and dA/dt can be expressed quantitatively emphasizes their superiority for the study of diastolic heart function.

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