P Wave Analysis in 2464 Orthogonal Electrocardiograms from Normal Subjects and Patients with Atrial Overload

By Kyozo Ishikawa, M.D., P. Manohar Kini, M.D., and Hubert V. Pipberger, M.D.

SUMMARY
The purpose of this study was to establish limits of normal for P wave measurements, and to propose criteria for routine electrocardiographic readings and for multivariate analysis to recognize left atrial overload (LAO) and right atrial overload (RAO) in the orthogonal electrocardiogram (ECG). Frank ECG's were obtained from 2464 subjects, including 580 normals, 164 patients with mitral valve disease (MVD) forming the LAO group, and 623 with chronic lung disease (CLD) as the RAO sample. Each group was divided into training and test sets. Using a digital computer, 120 different P wave measurements were computed for each ECG to find optimal discriminators between normal (N), LAO, and RAO.

In the training set of MVD, using three scalar measurements, LAO was recognized in 57% with 3% false positives. These criteria diagnosed LAO in 70% of the test cases of MVD. Four discriminators identified RAO in 30% and 37% of training and test cases of CLD with 11% false positives.

A set of 15 measurements obtained by multivariate analysis was used in a classification in which the three groups, N, LAO, and RAO were considered simultaneously. Ninety-four percent N, 74% LAO, and 45% RAO in the training sets, and 95%, 71%, and 24% in N, LAO, and RAO test sets were correctly identified. An attempt was made to correlate the rate of recognition of LAO with the degree of LAO estimated by cardiac catheterization. Data reported in the present study can serve as standard for P wave analysis in the Frank ECG.

Additional Indexing Words:
Computer analysis Left atrial overload Multivariate analysis Right atrial overload

RELIABLE ELECTROCARDIOGRAPHIC evidence of atrial abnormality and the precise differentiation of right and left atrial overloading can be extremely useful in the differential diagnosis of cardiac lesions. In more recent years, several criteria have been proposed for the conventional 12-lead electrocardiogram (ECG).1-3 The terminal P forces in the right precordials leads4 have been widely accepted as indicative of left atrial overload (LAO). New criteria have been proposed for the recognition of right atrial overloading (RAO) in children,5 and some previously proposed criteria for RAO such as "P pulmonale" or the Macruz index6 have been found to be lacking in sensitivity or specificity or both.5,10

In the orthogonal ECG, however, no comprehensive analysis of P wave abnormalities has so far been performed, although several investigations of the normal P wave have been reported.11-15 The widespread use of the Frank lead system in more recent years makes a detailed P wave study in this lead system imperative.

We present here an analysis of the P wave on large numbers of ECG's recorded with the Frank lead system in normal subjects as well as in patients

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with heart disease. Our major goals were, (1) to establish limits of normal ranges for P wave measurements, (2) to propose criteria for the recognition of LAO and for RAO in routine reading of the Frank ECG, and (3) to select a separate set of measurements for multivariate analysis that would give an optimum separation of normal (N), LAO, and RAO records. We have used the term overloading to include hypertrophy and/or dilatation.

A digital computer was used for evaluation of large numbers of measurements including tests of their sensitivity and specificity. A classification procedure was used in which the three groups, N, LAO, and RAO, were considered simultaneously and each record was classified into one of the three groups.

**Materials and Methods**

A total number of 2,464 ECG’s recorded by Frank’s corrected orthogonal leads were used for analysis. Of these, 2,138 records were collected from eight VA Hospitals in the framework of a cooperative study for cardiovascular data processing. Selection criteria of the cases were based on non-ECG information. In addition, 326 ECG’s recorded from coal miners in Belgium with severe pneumoconiosis and sent to us for analysis were used in this study.

ECG’s from 580 normal subjects were used to compute limits of normal for P wave measurements and also to serve as controls. History and physical examination did not reveal any signs or symptoms of past or present cardiovascular and/or pulmonary disease in these subjects. The 580 records were divided at random into two groups. Three hundred and eighty-seven ECG’s (two-thirds of the total) were used as the training set and the remaining 193 (one-third of the total) comprised a group for testing repeatability of results.

One hundred and sixty-four ECG’s from patients with mitral valve disease were available as prototype for LAO. The diagnosis was based on clinical manifestations including cardiac auscultation and radiologic examination in all patients. One hundred and one of these records (82 from patients with mitral stenosis and 19 from patients with mitral regurgitation) were used as the training set and ECG’s from 63 patients with isolated mitral stenosis were used as the test set. All the 63 patients in the test group and 40 patients with mitral stenosis in the training group had cardiac catheterization. Left atrial mean pressure (LAP) was estimated from the pulmonary wedge pressure, and varied between 6 and 40 mm Hg with a mean of 21 mm Hg in the 40 training cases and between 6 and 36 mm Hg with a mean of 19 mm Hg in the test set. The catheterized patients in the training and test sets were further subdivided into mild (LAP ≤ 13 mm Hg), moderate (LAP 14 to 23 mm Hg), and severe (LAP ≥ 24) groups.

Furthermore, 1,097 patients with heart disease predisposing to left ventricular hypertrophy (LVH) were used as an independent sample to test for the incidence of LAO by the criteria derived from the training set. These included 901 patients with hypertension and 196 patients with aortic valve disease. The 1,097 patients were divided into three groups according to clinical severity of their heart disease. Group 1 consisted of 455 patients who had no cardiomegaly by chest X-ray, nor signs or symptoms of present or past congestive heart failure. Three hundred and eighteen patients with roentgenographic evidence of cardiomegaly but without history of cardiac failure formed the second group. Group 3 was composed of 324 patients who had radiologic cardiomegaly as well as clinical history of congestive heart failure.

As training set for RAO, 326 records from Belgian miners with severe pneumoconiosis were used. Clinical situations associated with chronic right atrial overloading are relatively rare among patients in VA Hospitals, and hence this sample was used for establishing criteria for RAO. Ninety of these patients had undergone cardiac catheterization. The mean pulmonary artery pressure (PAP) was within the normal range (< 20 mm Hg) in 69% of them and in the remaining 31% PAP was moderately elevated. These 90 patients may be considered to be representative of the whole group and it seems reasonable to assume that about 30% of the total patients had pulmonary hypertension predisposing to RAO. To test for repeatability of results, records from 297 patients with pulmonary emphysema from the VA Hospitals were employed. In the majority of these patients, the emphysema was of moderate severity.

Tracings were recorded on FM magnetic tape and then converted into digital form for further processing by a CDC 3200 digital computer. Recording techniques and computer methods have been reported previously. The sampling rate in the process of A-D conversion was 500 per second per lead. Subsequently, these digitized records were filtered in order to minimize noise problems. Filtering was especially desirable in patients with chronic lung disease in whom, in addition to the small amplitudes, overactivity of the respiratory muscles often resulted in noisy records. The filter used was of a moving average type, with standard digital techniques, using 17 sample points. Figure 1 shows the frequency characteristics of this filter. As can be seen in this figure, the frequency response at the upper end is down by 3dB at 27 Hz. Since the main frequencies of the P wave are in the range below 20 Hz, P wave amplitudes are not significantly altered. No phase shifts occur with these digital filters. Major noise artifacts including power line frequency were effectively eliminated from ECG tracings without losing main characteristics of the P wave.

One hundred and twenty different electrocardiographic measurements on the P wave were computed for each record. Details are listed in table 1. This large number comprised practically all spatial vector and

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*We are grateful to Dr. R. Bernard, Hôpital Universitaire St. Pierre, Brussels, Belgium, for permission to use these records for analysis.
ELECTROCARDIOGRAM IN ATRIAL OVERLOADING

The filter used in this study is a moving average type, and was synthesized digitally to minimize noise problems as well as phase shift effects in the range of frequencies of interest. Frequency response is attenuated to 70% (3dB down) at 27 Hz. Almost no attenuation occurs below 15 Hz. Since the main P wave component lies in the 1-10 Hz range, P wave amplitudes are not significantly altered.

Scalar parameters that have ever been proposed for P wave analysis as well as several new ones. No general agreement exists on optimal electrocardiographic and vectorcardiographic P wave measurements for separation of normal from abnormal and for differentiation of LAO from RAO. We found it necessary, therefore, to include in the present study as many measurements as possible.

A search for the best diagnostic discriminators between normal, LAO, and RAO groups was made by the following method. At first, 96 percentile ranges were computed for each measurement on the normal training set. Such ranges were used in preference to means and standard deviations as many electrocardiographic measurements are not normally distributed. The number of cases of LAO and RAO which exceeded the limits of normal ranges for each of these measurements was determined. The best discriminators were then compared to test their efficiency in the separation of the different groups. Care was taken to eliminate redundant measurements and to keep the percentage of false positives to a minimum with the use of methods described previously. A small number of scalar and vector measurements which can be obtained easily, by hand, were set apart for use in routine ECG analysis.

For computer usage, a set of 42 candidate measurements was selected. Using these measurements, a sequential stepdown procedure was applied where at each stage the measurement that added the least amount to the multivariate distance between the groups was eliminated. Misclassification matrices for the three groups were computed each time a measurement was eliminated. As expected, the percentage of correct classification declined progressively with the elimination of more and more measurements. We decided to use the 15 most important measurements for the final analysis as further elimination of measurements resulted in a rapid fall in the percentage of records correctly classified. Furthermore, with 15 measurements, the number of misclassifications both for normal and atrial overloading records appeared satisfactory.

These 15 measurements were then used for a simultaneous three-group analysis utilizing a Bayesian likelihood ratio. Each record was classified into one of the three categories, N, LAO, or RAO, based on the diagnosis for which its posterior probability was greatest. In electrocardiographic classification it is customary to consider two groups at a time. However, in a clinical setting, all diagnostic categories have to be considered simultaneously. Efficient statistical methods can be utilized where several diagnoses are taken into consideration at the same time and each record classified into one of the diagnostic groups. The main advantage of these procedures is that adjustment for sensitivity and specificity need be made only once. Our classification method considers the three groups, N, LAO, and RAO, simultaneously.

The 15 measurements selected for multivariate analysis were first used to classify the training sets. To test repeatability of results, these were applied to the

Table 1

<table>
<thead>
<tr>
<th>List of Scalar and Vectorial P wave Measurements Computed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. P duration, P-R interval and P-R segment</td>
</tr>
<tr>
<td>2. For the positive and the negative P wave:</td>
</tr>
<tr>
<td>(a) Peak amplitudes and durations</td>
</tr>
<tr>
<td>(b) Sum of positive and negative amplitudes</td>
</tr>
<tr>
<td>(c) Time interval between these two peaks</td>
</tr>
<tr>
<td>3. Vector measurements in three planes—frontal, transverse, and left sagittal:</td>
</tr>
<tr>
<td>(a) Magnitude and orientation of maximal P vector</td>
</tr>
<tr>
<td>(b) Time interval from the onset to the maximal P vector</td>
</tr>
<tr>
<td>4. Spatial magnitude and orientation of the maximal P vector</td>
</tr>
<tr>
<td>5. Magnitude of scalar and spatial components and spatial orientation of four instantaneous vectors by time-normalizing the P wave into four equal parts (1/4, 2/4, 3/4, and 4/4)</td>
</tr>
<tr>
<td>6. Product of the peak amplitude and the duration of the positive wave in lead Z (&quot;P terminal force&quot;)</td>
</tr>
<tr>
<td>7. P duration/PR segment ratio (Macruz Index)¹</td>
</tr>
<tr>
<td>8. For the twin peak P wave:</td>
</tr>
<tr>
<td>(a) Amplitudes of the first and second peaks</td>
</tr>
<tr>
<td>(b) Time interval between peaks</td>
</tr>
<tr>
<td>(c) Time interval between the beginning and the first peak and between the beginning and second peak</td>
</tr>
<tr>
<td>9. P wave area:</td>
</tr>
<tr>
<td>(a) Total, positive and negative area in each scalar lead</td>
</tr>
<tr>
<td>(b) The area divided in time into four equal parts (1/4, 2/4, 3/4, and 4/4) for each scalar lead</td>
</tr>
<tr>
<td>10. Time interval from the beginning to its peak and from the peak to the end, and the ratio of the former time interval to the latter</td>
</tr>
<tr>
<td>11. Magnitude of the end of P wave in the three scalar leads</td>
</tr>
</tbody>
</table>

Circulation, Volume XLVII, September 1973
independent test samples of the normal, LAO, and RAO records. The LAO measurements were tested a second time on the large sample of ECG's obtained from patients with hypertension and aortic valve disease.

Prior probabilities in the ratio of 50:25:25 for the N, LAO, and RAO groups, respectively were used in the classification of records. Prior probabilities are estimates of appropriate relative frequencies of the various diagnostic categories in the population being studied. They are required to achieve minimum classification error in the population. These probabilities were not precisely known for our study as the cases were collected from a variety of sources. In order to keep the specificity at a high level (94%) the prior probability of the normal group was assumed to be double that of each of the abnormal groups. It should be realized that classification errors may be significantly altered by changing prior probabilities according to the estimated prevalence of different types of atrial overloading in the population to be tested.

**Results**

Mean values, standard deviations, and 96 percentile ranges of commonly used P wave parameters for normal subjects and patients with LAO and RAO are shown in table 2.

**ECG and VCG Configuration.** The mean P configuration of the scalar X, Y, and Z leads and the vector loop projections in the frontal, left sagittal, and transverse planes for the three groups are shown in figure 2. These means were derived from the training set of cases for each group. The mean amplitude was calculated at 20 msec intervals until the end of the P wave and then used for display of averaged scalar leads and vector loops.

The P in LAO shows prolongation in duration, delayed peaking, a slight increase in the amplitude in lead X, and a marked increase in amplitude of the positive component in lead Z when compared to the normal P. The posterior displacement of the major part of the P loop is well displayed in the sagittal and transverse planes. In RAO the P in lead Y is of greater amplitude than normal and the magnitude of the maximum P vector is increased in

**Table 2**

| Commonly Used P Measurements in Scalar Orthogonal Leads and in Vectorial Displays* |
|---------------------------------|-----------|-----------|
|                                 | Normal    | LAO       | RAO       |
| P amplitude in Lead X (mV)      | 0.058 ± 0.020 | 0.091 ± 0.046 | 0.063 ± 0.037 |
| P amplitude in Lead Y (mV)      | 0.025→ 0.106 | 0.023→ 0.213 | 0.023→ 0.170 |
| P negative amplitude in Lead Z (mV) | -0.030 ± 0.012 | -0.041 ± 0.019 | -0.041 ± 0.024 |
| P positive amplitude in Lead Z (mV) | -0.056→ -0.015 | -0.059→ -0.019 | -0.103→ -0.015 |
| P duration (sec)                | 0.095 ± 0.012 | 0.113 ± 0.018 | 0.101 ± 0.016 |
| PR segment (sec)                | 0.072→ 0.120 | 0.084→ 0.160 | 0.076→ 0.132 |
| PR interval (sec)               | 0.056 ± 0.017 | 0.054 ± 0.028 | 0.051 ± 0.021 |
| Magnitude of spatial maximal P-vector (mV) | 0.126 ± 0.041 | 0.158 ± 0.073 | 0.171 ± 0.107 |
| Magnitude of maximal P-vector in the frontal plane (mV) | 0.060→ 0.220 | 0.047→ 0.301 | 0.054→ 0.500 |
| Angle of maximal P-vector in the frontal plane (°) | 66° | 56° | 72° |
| Magnitude of maximal P-vector in the sagittal plane (mV) | 0.122 ± 0.045 | 0.159 ± 0.072 | 0.168 ± 0.107 |
| Angle of the maximal P-vector in the sagittal plane (°) | 76° | 55° | 88° |
| Magnitude of maximal P-vector in the transverse plane (mV) | 0.072 ± 0.022 | 0.123 ± 0.051 | 0.080 ± 0.045 |
| Angle of the maximal P-vector in the transverse plane (°) | 330° | 313° | 325→ 131 |
| P duration/PR segment ratio     | 1.89 ± 0.90 | 2.91 ± 3.28 | 2.41 ± 1.42 |

*The mean and standard deviation of each measurement are shown on the upper line. The second line indicates the limits of 96 percentile range. For angular measurements, only mean and 96 percentile range are shown,
the frontal and sagittal planes. The P frontal angle is more vertical than normal.

Classification by Hand Measurements

Left Atrial Overloading vs Normal. The most efficient discriminators between LAO and normal records are listed in table 3, together with limits and cumulative results of classification. Using three measurements, 57% of the training set of LAO cases were correctly identified with 3% of the normals being misclassified (false positives). Vector measurements did not contribute to any further separation of LAO cases from normal.

To test for repeatability of results, these criteria were tested on the 63 test records from patients with mitral stenosis. Seventy percent of these were classified as having LAO confirming the sensitivity of the measurements. These criteria were further applied on 1,097 records obtained from patients with hypertension and aortic valve disease. The recognition rate of LAO for these latter test records was 19% with 9, 17, and 34% being identified in Group 1, Group 2, and Group 3, respectively.

Right Atrial Overloading vs Normal. Criteria that were found to differentiate between the groups are given in table 3. Three scalar and one vectorial measurements led to the recognition of RAO in 30% of the cases in the training set, with 11% false positives. These measurements, when tested on the independent sample of 297 records, identified 37% of them as having RAO.

Classification by Multivariate Analysis. The 15 measurements selected for multivariate analysis are listed together with their means and standard deviations for the different groups in table 4. These were used for a simultaneous three-group analysis with prior probabilities in the ratio of 50:25:25 being assigned to the N, LAO, and RAO groups, respectively. The results are shown in table 5A. Ninety-four percent of the normal, 74% of LAO records and 45% of the RAO sample were correctly classified. On the test sets, the results for normal and LAO were 95% and 71% respectively, whereas the rate of recognition of RAO was 24%.

To test the sensitivity of the proposed criteria in detecting the severity of LAO, the number of cases

Figure 2

Mean scalar leads and vector loops of the P, based on 387 records from normal subjects (solid lines), 101 patients with mitral stenosis (broken lines), and 326 patients with chronic lung disease (broken lines with periods). The average configurations are based on mean amplitudes computed at 20 msec intervals until the end of the P wave in each category. Note the increased duration of the P and prominent positive component in lead Z in LAO. Posterior displacement of the loop is evident in the sagittal and transverse planes. The averaged P in RAO closely resembles the normal P except in lead Y in which its amplitude is greater than in the normal.
recognized in the mild, moderate, and severe groups of LAO were computed. In the training sample of 40 patients with catheterization data, 10 had mild, 12 moderate, and 18 severe degrees of LAO. The rate of recognition for these groups was 50%, 75%, and 83% respectively. The test sample of 63 was comprised of 17 mild, 29 moderate, and 17 severe, cases of LAO. Fifty-three percent, 80%, and 80% of these three groups were recognized as having LAO by the criteria obtained by multivariate analysis.

The analysis was repeated on the 1,097 records obtained from patients with hypertension and aortic valve disease (Table 5B). Twenty-two percent of the tracings were classified into the LAO category. The percentage of patients in whom LAO was identified, increased with advancing severity of heart disease; 11% in Group 1 had LAO as compared to 21% in Group 2, and 39% in Group 3.

### Discussion

Many different criteria have been proposed and used for the electrocardiographic diagnosis of atrial overloading. However, no data on sensitivity and specificity of these criteria have been reported. To avoid some of the inadequacies of the studies in the past, and to set up new criteria for P wave analysis on the orthogonal ECG, we collected a large number of normal and abnormal records. The data were obtained on the basis of strict study protocols and uniform recording techniques. Large numbers of records were analyzed to offset the shortcomings of drawing conclusions on the basis of small numbers of cases and controls. Available computer facilities allowed a great variety of comparisons and correlations in order to arrive at optimal criteria for diagnostic discrimination. The present study required testing and comparing 120 ECG variables on over 2,000 ECG’s.

One of the difficulties in P wave analysis is the low amplitude of the signal. Since the P wave has a smaller amplitude compared to the QRS, superimposed noise is particularly critical when accurate measurements are made. Although high amplification can be used, this in itself does not improve the ability to discriminate between signal and noise. If noise components lie in a frequency range outside the P wave signal, a properly designed filter can improve the signal to noise ratio by accepting signal and rejecting noise frequencies.

Brody and coworkers demonstrated the presence of multiple notching of the P wave in normal subjects with the use of high fidelity recording methods and averaging procedures. The highest frequencies estimated in such recordings are close to 90 Hz. The significance of these small notchings is unknown. However, frequencies of greater than 20 Hz have not been shown so far to be of importance in P wave analysis. With the use of a filter which had a cut-off (3dB down) at 27 Hz, we

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*We gratefully acknowledge the records made available to us by Dr. Daniel Brody, Division of Clinical Physiology, University of Tennessee, Memphis, Tennessee.
ELECTROCARDIOGRAM IN ATRIAL OVERLOADING

Table 4

<p>| Measurements for Multivariate P wave Analysis with Means and Standard Deviations** |
|---------------------------------|----------------|----------------|----------------|----------------|</p>
<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Normal</th>
<th>S.D.</th>
<th>Mean</th>
<th>LAO</th>
<th>S.D.</th>
<th>Mean</th>
<th>RAO</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>P amplitude Y*</td>
<td>0.107</td>
<td>0.048</td>
<td></td>
<td>0.130</td>
<td>0.074</td>
<td></td>
<td>0.160</td>
<td>0.108</td>
<td></td>
</tr>
<tr>
<td>3/4 P area Zt</td>
<td>0.725</td>
<td>0.597</td>
<td></td>
<td>1.881</td>
<td>1.349</td>
<td></td>
<td>0.752</td>
<td>0.825</td>
<td></td>
</tr>
<tr>
<td>P total area Z†</td>
<td>0.856</td>
<td>1.499</td>
<td></td>
<td>2.427</td>
<td>2.484</td>
<td></td>
<td>0.662</td>
<td>1.832</td>
<td></td>
</tr>
<tr>
<td>P duration†</td>
<td>195.3</td>
<td>11.7</td>
<td></td>
<td>112.9</td>
<td>17.9</td>
<td></td>
<td>101.0</td>
<td>15.6</td>
<td></td>
</tr>
<tr>
<td>2/4 P elevation (°)</td>
<td>60</td>
<td>15</td>
<td></td>
<td>40</td>
<td>28</td>
<td></td>
<td>65</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>2/4 P area Z†</td>
<td>-0.042</td>
<td>0.582</td>
<td></td>
<td>0.480</td>
<td>0.957</td>
<td></td>
<td>-0.281</td>
<td>0.686</td>
<td></td>
</tr>
<tr>
<td>Time to P maximal</td>
<td>51.3</td>
<td>10.7</td>
<td></td>
<td>67.3</td>
<td>20.8</td>
<td></td>
<td>51.0</td>
<td>13.4</td>
<td></td>
</tr>
<tr>
<td>1/4 P amplitude Y</td>
<td>0.063</td>
<td>0.025</td>
<td></td>
<td>0.067</td>
<td>0.041</td>
<td></td>
<td>0.094</td>
<td>0.065</td>
<td></td>
</tr>
<tr>
<td>3/4 P amplitude X</td>
<td>0.044</td>
<td>0.022</td>
<td></td>
<td>0.061</td>
<td>0.048</td>
<td></td>
<td>0.037</td>
<td>0.034</td>
<td></td>
</tr>
<tr>
<td>P positive area Z†</td>
<td>1.586</td>
<td>1.148</td>
<td></td>
<td>3.548</td>
<td>2.350</td>
<td></td>
<td>1.596</td>
<td>1.423</td>
<td></td>
</tr>
<tr>
<td>P max transverse plane magnitude</td>
<td>0.072</td>
<td>0.022</td>
<td></td>
<td>0.124</td>
<td>0.051</td>
<td></td>
<td>0.079</td>
<td>0.045</td>
<td></td>
</tr>
<tr>
<td>4/4 P amplitude X</td>
<td>-0.004</td>
<td>0.016</td>
<td></td>
<td>-0.023</td>
<td>0.033</td>
<td></td>
<td>-0.008</td>
<td>0.023</td>
<td></td>
</tr>
<tr>
<td>Spatial P max mag:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Y component</td>
<td>0.113</td>
<td>0.047</td>
<td></td>
<td>0.110</td>
<td>0.095</td>
<td></td>
<td>0.156</td>
<td>0.111</td>
<td></td>
</tr>
<tr>
<td>4/4 P amplitude Y</td>
<td>-0.022</td>
<td>0.026</td>
<td></td>
<td>-0.032</td>
<td>0.034</td>
<td></td>
<td>-0.035</td>
<td>0.043</td>
<td></td>
</tr>
<tr>
<td>P xy angle§</td>
<td>-0.005</td>
<td>0.092</td>
<td></td>
<td>-0.048</td>
<td>0.125</td>
<td></td>
<td>0.029</td>
<td>0.097</td>
<td></td>
</tr>
</tbody>
</table>

*Amplitudes and magnitudes are expressed as millivolts
†Millivolts x milliseconds
‡All durations are in milliseconds
§Cosine differences
**Measurements labelled 1/4, 2/4, and so on, are derived from time-normalized P waves obtained by dividing the P in time into four equal parts.

The failure rate of recognition of P waves by this method was less than 1% as judged by an analysis of the P on 501 independent records. The heart rate does not usually influence the rate of recognition, as the frequency content of the wave does not change with heart rate. However, records in which the P wave is superimposed on the end of the preceding T wave causes identification problems for the computer. The failure rate of less than 1% is within the acceptable range in the present state of the art of computer wave recognition.

Table 5

Results of Multivariate Analysis

A. Classification results with measurements selected for multivariate analysis

<table>
<thead>
<tr>
<th></th>
<th>Training Set</th>
<th>LAO (101)</th>
<th>RAO (326)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>Normal</td>
<td>94</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>LAO</td>
<td>20</td>
<td>74</td>
<td>6</td>
</tr>
<tr>
<td>RAO</td>
<td>52</td>
<td>3</td>
<td>45</td>
</tr>
</tbody>
</table>

B. Multivariate classification of P waves in 1097 cases of LVH

<table>
<thead>
<tr>
<th>Group</th>
<th>Normal</th>
<th>LAO</th>
<th>RAO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1 (455)</td>
<td>84</td>
<td>11</td>
<td>5</td>
</tr>
<tr>
<td>Group 2 (318)</td>
<td>73</td>
<td>21</td>
<td>6</td>
</tr>
<tr>
<td>Group 3 (324)</td>
<td>53</td>
<td>39</td>
<td>8</td>
</tr>
<tr>
<td>Total (1097)</td>
<td>72</td>
<td>22</td>
<td>6</td>
</tr>
</tbody>
</table>

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depth of the terminal negative deflection and its
duration\(^1\) (Morris index), are widely utilized as an
index of left atrial enlargement. We obtained a
similar index from the product of the peak
amplitude and duration of the positive P in lead Z
and tested its efficiency in the diagnosis of LAO in
the Frank ECG. Thirty-five percent of the cases of
the training and test sets of mitral valve disease
exceeded the 96 percentile limit for normal, a
sensitivity rate substantially smaller than the 86%
reported by Morris et al.,\(^4\) in the 12-lead ECG. This
discrepancy in results is difficult to explain.
However, two of the three hand measurements we
used for the diagnosis of LAO include the positive
component of the P wave in lead Z which
coincides with the negative deflection of the P in
lead V\(_1\), thus confirming the usefulness of the
terminal posterior shift of the P vector in the
diagnosis of LAO.

It has long been appreciated that a twin peak (P
mitrale) in limb leads I and II is highly suggestive
of LAO, especially mitral valve involvement.
However, along with increasing evidence that a
normal P wave may contain one or more
notches,\(^19, 21, 22\) the diagnostic usefulness of twin
peaks was found to be limited. In our study, the
difference in the incidence of twin peaks between
normal and abnormal P waves was not large
enough to be of diagnostic significance.

Electrocardiographic signs of atrial abnormality
are frequently found in conditions producing left
ventricular overloading. The incidence of these
changes has been variously estimated in different
studies,\(^23-25\) and the significance of these changes is
not clearly understood. Tarazi et al.,\(^25\) reported left
atrial abnormality in 45 of 76 (59\%) patients with
hypertension. Seventeen of these patients had
normal heart size and no evidence of cardiac failure
but had abnormal P waves. In our study, 19\% of the
total 1,097 cases of LVH (hypertension and aortic
valve disease) satisfied the proposed criteria for
LAO. There was a progressive increase in the rate
of recognition of LAO with increasing severity of
cardiac involvement. As expected, the incidence of
LAO in patients in Group 1 without cardiomegaly
and without history of heart failure was very low
(9\%). When cardiac enlargement became evident,
the recognition rate increased to 17\%. For Group 3,
with a history of one or more episodes of cardiac
failure, the recognition rate increased further to
34\%. Multivariate analysis gave results slightly
better than those obtained by hand measurements.

Autopsy studies on patients with LVH by
Romhilt et al.,\(^26\) and Morris et al.,\(^27\) showed P
terminal forces indicative of left atrial abnormality
in 44\% and 46\%, respectively. These figures, how-
ever, cannot be directly compared to our results
because material obtained at autopsy would only
include severe forms of LVH, whereas our cases
comprised a wide spectrum of severity of cardiac
involvement.

The most severe forms of RAO are generally
observed in patients with congenital heart disease.
Such patients, however, are rarely seen in VA
Hospitals and hence we used patients with chronic
lung disease (CLD) to set up criteria for RAO.
Using three scalar and one vectorial criteria, 30\% of
the training set and 37\% of the test set were found to
have RAO. Several other measurements tested did
not improve results. Simultaneous three-group
analysis by the computer led to the classification of
4\% and 24\% of the training and test cases of CLD
into the RAO group. The degree of RAO in these
groups could not be ascertained with certainty by
independent criteria. However, in order to obtain
numbers of cases adequate for multivariate analysis
we had to include cases in which clear-cut evidence
of RAO was not available. Presumably, many of the
patients with CLD had normal P waves. The
averaged P configurations (fig. 2) show the close
resemblance between the normal P and the P in the
RAO group.

Comparison of our results with those of other
studies of P wave analysis in emphysema is difficult.
The reported incidence of P wave changes in
emphysema has been extremely variable.\(^28-31\) This
may be explained by the differences in the severity
of the disease process in the patients analyzed in
different studies. A high amplitude P wave, often
termed "P pulmonale," has been observed by
several investigators in the ECG of patients with
RAO. More recently Chou and Helm\(^9\) stressed the
nonspecificity of this P pattern in the diagnosis of
RAO and noted that in a significant number of
patients it represented left instead of right atrial
enlargement. In our study, a high amplitude P wave
above the normal range in lead Y was observed in
14\% of CLD cases as well as in 10\% in the mitral
stenosis group and 4\% in the LVH group. Thus it
would appear that "P pulmonale" has limited value
for the assessment of right atrial overloading.

Use of a digital computer allows a great number of
comparisons and correlations in order to arrive at
optimal criteria for diagnostic discrimination.\(^32-34\)
Complex statistical methods can be tested in an
attempt to improve diagnostic ECG classifications.
ELECTROCARDIOGRAM IN ATRIAL OVERLOADING

In the present study we at first started differentiating between normals and the two abnormal groups, considering two groups at a time. Linear discriminant function analysis was used in a previously described manner. The most useful 42 measurements were then used for a sequential stepdown procedure. In this scheme a measurement would be eliminated if it contributed the least amount to the multivariate distance between the mean vectors of the different groups. The total number of measurements used in multidimensional analysis should not exceed 1/20th of the number of cases under study if the results are to be duplicated on new and independent case material with similar results.34

The sequential stepdown procedure is helpful in selecting, from a large number of variables, the best possible measurements for classification.

Using the most important measurements, a simultaneous three-group analysis was performed in preference to a consideration of two groups at a time. Differentiation between two groups is useful in a situation where clinical information is available to aid in the classification of the record. The question might be asked, for example, in a patient with mitral stenosis, whether there is evidence of LAO, and a simple "yes" or "no" answer is expected from the ECG. However, when little or no clinical information is available, all ECG diagnoses have to be considered simultaneously. In our laboratory, a method has been developed for a seven-group analysis for the QRS using a Bayesian procedure to compute posterior probabilities.18 A similar method was used for the simultaneous analysis between normal, LAO, and RAO. Each record was assigned to the category for which its posterior probability was greatest.

The 15 criteria we have suggested may be used for routine computer analysis of the P wave in the orthogonal ECG. However, the prior probabilities for the three different groups may need adjustment according to the estimated prevalence of atrial overloading in the population to be tested. Changes in prior probabilities lead to changes in posterior probabilities, and specificity and sensitivity can be adjusted at will. The use of prior probabilities lends itself to great flexibility in routine clinical application of these criteria.

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P Wave Analysis in 2464 Orthogonal Electrocardiograms from Normal Subjects and Patients with Atrial Overload

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