Computer interpretation of pediatric orthogonal electrocardiograms: statistical and deterministic classification methods

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ABSTRACT Statistical multivariate and conventional deterministic methods of computerized interpretation of the electrocardiogram (ECG) were compared in the analysis of 1711 pediatric orthogonal ECGs validated by nonelectrocardiographic criteria on the basis of clinical and anatomic diagnoses. Among 642 children catheterized for the evaluation of congenital heart disease, there were 140 patients with left ventricular hypertrophy, 299 with right ventricular hypertrophy, and 203 with biventricular hypertrophy. A group of 1069 obviously healthy school children was studied as a control. The overall accuracy of multigroup ECG diagnosis was 85% and 79% for the statistical and deterministic methods, respectively. The diagnostic performances of both methods expressed in terms of sensitivity and predictive value were the highest for normal children and those with right ventricular hypertrophy and lowest for children with biventricular hypertrophy. The statistical method was more sensitive in the diagnosis of left ventricular hypertrophy (74% vs 64%), right ventricular hypertrophy (86% vs 83%), and biventricular hypertrophy (62% vs 50%). Mutual agreement for a correct diagnosis by the two methods was 83% for normal children and 82% for those with right ventricular hypertrophy but only 61% for children with left ventricular hypertrophy and 39% for those with biventricular hypertrophy. In conclusion, better classification results are obtained with statistical multivariate techniques as compared with conventional deterministic analysis, but both methods of ECG interpretation are complementary and their combination in the same electrocardiographic computer program can improve diagnostic accuracy.


COMPUTER-ASSISTED interpretation of electrocardiograms (ECGs) or vectorcardiograms (VCGs) is especially useful in the pediatric age group. The important variations of ECG/VCG parameters in childhood and the complexity of abnormalities produced by congenital heart disease make mandatory a more quantitative approach to ECG analysis in children. A new computer program for analysis and interpretation of pediatric Frank orthogonal ECGs has been developed and evaluated in our center.1 This program includes extensive age- and sex-dependent criteria based on

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tables of normal limits for numerous VCG parameters. The diagnostic classification follows the deterministic method, i.e., a decision-tree logic in which the cardiologist’s method of analyzing VCGs is simulated. We reported with this pediatric program an overall diagnostic accuracy ranging from 75% to 89% for type A diagnostic categories such as left ventricular hypertrophy (LVH), right ventricular hypertrophy (RVH), biventricular hypertrophy (BVH), and normal. In an attempt to further improve this accuracy rate, we decided to apply another type of diagnostic classification by using multivariate statistical analyses.

Pipberger et al.2 and Cornfield et al.3 have strongly advocated the interest of such multivariate classification techniques with the aim of reducing the number of misclassifications as compared with the conventional method of ECG analysis. These authors classified the two approaches — deterministic and statistical — into first- and second-generation electrocardiographic computer programs.2 More recently, Zywietz et al.4
also developed a pediatric vectorcardiographic-computer program that uses alternative multivariate classification techniques. Our own statistical model of multivariate analysis of pediatric VCGs combines dichotomous and continuous parameters selected by various sequential stepwise procedures. The purpose of this study was to undertake a formal comparative evaluation of the two methods of diagnostic classification, statistical vs deterministic, with a common data base of pediatric orthogonal ECGs validated by ECG-independent means.

Materials and methods

Vectorcardiographic pediatric computer program: signal processing and analysis. The data acquisition, signal conditioning and processing parts of our vectorcardiographic computer program have been previously described. Briefly, 10 sec of activity from X, Y, and Z Frank leads are sampled simultaneously at 500/sec with 12-bit resolution. After removal of baseline drift and selective beat averaging, a noise-free “averaged” P-QRS-T complex is submitted to wave recognition by threshold-crossing methods applied to filtered spatial velocity curves. Rhythm analysis, parameter extraction, and production of high-resolution vectorcardiographic loop displays are performed before the automatic interpretation of the QRS-T contours.

Automatic interpretation by the deterministic method. From the 260 scalar, planar, and spatial parameters computed by the measurement program, about 80 are actually used for the diagnostic classification. More emphasis is placed on specific vectorcardiographic parameters better able to quantify the severity of ventricular hypertrophy. Not only continuous variables such as wave durations and linear or angular values of amplitude and area parameters, but also dichotomous variables such as direction of inscriptions (clockwise or counterclockwise) of QRS loop in frontal, sagittal, and transverse planes are used in the diagnostic process. Most criteria take into account the normal limits according to the patient’s age and sex, established from our local population. The diagnostic classification is based on the deterministic or heuristic method, i.e., by applying the cardiologist’s expertise through Boolean algebra and decision-tree logic. To avoid a common pitfall of this approach, namely the excessive dependence of diagnostic flow on small variations of discrete parameters, a multiparameter-multithreshold approach was used. Each diagnostic criterion is generally composed of several interrelated parameters, some of which have several thresholds, and several criteria are being used to arrive at a given diagnosis. For instance, the diagnosis of LVH and the assessment of its severity rely mainly on the actual value of the left maximal spatial voltage and its distance from the upper normal limit for age and sex, using several successive thresholds. But LVH could also be diagnosed on the basis of other criteria by scalar or planar QRS vectors or even morphologic features of QRS-T loops. Since these various parameters and thresholds are being sequentially used along the paths of the decision-tree rather than simultaneously and in combination as in statistical methods, we did not call this diagnostic procedure “multivariate.” The diagnostic criteria were carefully designed to reach the maximum sensitivity with an acceptable level of specificity according to the clinical characteristics of our hospital population of children referred to the Department of Pediatric Cardiology mainly for the evaluation of congenital heart disease. A learning set of 112 VCGs was used to test the program’s interpretation and to optimize some diagnostic criteria.

The results were then verified on a large testing set consisting of 616 VCGs obtained from catheterized patients and 1165 VCGs from normal children.

Diagnostic classification by multivariate statistical techniques. The development and testing of a new statistical model for the multivariate classification of pediatric VCGs have been described in detail in another publication. The problem was to assign each pediatric VCG to one of four mutually exclusive categories — LVH, RVH, BVH, and normal — on the basis of the discrimination provided by linear combinations of vectorcardiographic parameters. First, a large data base of 1893 pediatric VCGs was subdivided into various age/sex-stratified subgroups depending on the number of pathologic cases available, with adequate statistics used to find the maximal differences of individual linear and angular parameters. Six subgroups were considered: youngsters from birth to 6 months and from 6 months to 2 years, boys 2 to 5 and 6 to 19 years, and girls 2 to 7 and 8 to 19 years. Then, of the 233 parameters initially considered, a subset of discriminant variables was selected to reduce the redundancy and to make the number of variables compatible with the number of cases in the smallest category (in general n variables ≤N/20 cases).

The selection procedure was performed by means of stepwise iterative methods, taking into account correlations between individual continuous variables at various significant levels of dichotomous variables. First, we applied the Lachin procedure, which is a stepwise incremental method in which the selection is determined by the capability of the dichotomous variables, i.e., counterclockwise or clockwise rotation of QRS loop in horizontal plane, to differentiate among the four diagnostic categories. Then, we used the Goldstein-Dillon procedure, which reexamined these variables relative to the discriminant power generated not only by the combinations of the variables themselves but also by their various levels. It is also a stepwise incremental method, in which, at each step, the level of the examined variable is selected only if it leads to a significant increase of discrimination for conditional levels of other previously selected variables. Finally, the continuous variables were introduced in the discrimination process after linear transformation of angular data and a two-by-two Friedman test of homogeneity to verify the hypothesis of equal variance-covariance matrices. By a sequential stepwise procedure, a certain number q of discriminant variables out of a total of p parameters was progressively selected. Depending on the size of each particular age/sex subgroup, from six to 13 variables were finally selected for the discrimination process (see appendix A). This subset of q variables would then maximally influence the decision function.

At the end of the discrimination process, misclassification matrices were built for each age/sex subgroup and at each level of dichotomous variables. The mixed Krzanowsky model, allowing us to use both dichotomous and continuous variables, was applied to these tables. It was then possible to estimate from the observed distribution frequencies of selected levels of dichotomous variables in the four diagnostic categories the conditional probabilities of belonging to one of these categories (see appendix B). As with the deterministic program, we adjusted the selection and discrimination procedures to obtain in each pathologic category the maximum sensitivity corresponding to an acceptable level of specificity in the normal group. A learning set of 1506 VCGs, subdivided according to the age/sex categories and the selected levels of dichotomous variables, was used to establish a linear discriminant function in each subgroup. By applying this discriminant function to the learning set, we obtained a general classification table and, in each case, the results were assessed with respect to the true clinical and anatomic diagnoses. The results were then verified by applying
the linear discriminant function to an independent testing set of 387 VCGs. Since there was no significant deterioration between the learning and testing sets, they were eventually pooled to simplify the presentation of results.

Statistical vs deterministic classification/evaluation method. The deterministic and statistical classification methods were compared in the analysis of a large common set of 1711 pediatric Frank ECGs. This data base included only well-validated vectorcardiographic records without bundle branch blocks or other types of major ventricular conduction defects. It consisted of all the cases in which both deterministic and statistical procedures had been applied, pooling the learning and testing groups that had been used separately in the development and evaluation of the multivariate classification strategy and of the deterministic program. Table 1 shows the distribution of the various diagnostic categories in the two main age groups in this study population. Of the 714 records of children under 2 years of age, 323 were provided by Zyweitz from the medical school of Hannover. The remaining 391 records of youngsters as well as the 997 records of older children all came from our center. The hospital population consisted of 642 children who had undergone cardiac catheterization and vectorcardiographic recording, no more than 3 weeks apart, for the diagnosis or evaluation of congenital heart disease. Their conditions represented a very large spectrum of congenital heart disease with various types of ventricular overloading. On the basis of the hemodynamic and angiographic criteria we defined a pathologic group that included 140 patients with isolated LVH, 299 with isolated RVH, and 203 with combined ventricular hypertrophy or BVH.

To this hospital population we added a group of 1069 records that had been collected from obviously healthy children attending nurseries, day-care centers, and elementary and secondary schools. All these children had been carefully screened; they had normal histories and no evidence of organic heart murmur on complete physical examination. This out-of-hospital ambulatory population represented the normal control group. Thus in each individual the vectorcardiographic diagnosis generated by both the statistical and the deterministic classifiers was assessed with reference not to the electrocardiographer’s opinion but to objective, ECG-independent reference derived from clinical evidence and catheterization data. Classification matrices were built to compare the vectorcardiographic diagnosis with the true clinical diagnosis with respect to the group population. For each diagnostic category, we computed the numbers of true positives (TP), true negatives (TN), false positives (FP), and false negatives (FN). From these figures we derived various indexes of diagnostic performance by means of usual formulas:

\[
\text{sensitivity} = \frac{TP}{TP + FN}, \quad \text{specificity} = \frac{TN}{TN + FP}, \quad \text{predictive value of positive diagnosis} = \frac{TP}{TP + FP}, \quad \text{predictive value of negative diagnosis} = \frac{TN}{TN + FN}, \quad \text{and diagnostic accuracy} = \frac{(TP + TN)}{\text{Total population}}.
\]

Differences between the classification rates by the two methods were assessed by means of McNemar chi-square test (statistically significant at \( p < .05 \)). Figure 1 shows typical data from a patient with BVH whose VCG was analyzed by both methods.

### TABLE 1

<table>
<thead>
<tr>
<th>Age</th>
<th>LVH</th>
<th>RVH</th>
<th>BVH</th>
<th>Normal</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;2 yr</td>
<td>36</td>
<td>172</td>
<td>165</td>
<td>341</td>
<td>714</td>
</tr>
<tr>
<td>≥2 yr</td>
<td>104</td>
<td>127</td>
<td>38</td>
<td>728</td>
<td>997</td>
</tr>
<tr>
<td>Total</td>
<td>140</td>
<td>299</td>
<td>203</td>
<td>1069</td>
<td>1711</td>
</tr>
</tbody>
</table>

aExpressed as number of subjects.

Results

The overall diagnostic accuracy computed as the sum of correctly classified cases was 79% for the statistical method and 85% for the deterministic method. Of the 140 patients with LVH, 101 (72%) and 71 (51%) were correctly diagnosed by the statistical and deterministic classifiers, respectively, with false-negative classifications of LVH represented by seven and 17 diagnoses of RVH, 12 and 24 diagnoses of BVH, and 20 and 28 diagnoses of normal. Considering a diagnosis of BVH as also correct for LVH, the correct classification rate was 81% (113/140) and 68% (95/140) for the statistical and deterministic methods, respectively. The LVH cases misclassified as normal were generally patients with mild or moderate LVH. Those misclassified as RVH usually had a rightward maximal QRS vector as in special cases of LVH secondary to coarctation of the aorta or aortic stenosis.

Of the 299 patients with RVH, about the same numbers were correctly classified by the two methods: 247 by the statistical classifier (83%) and 241 by the deterministic classifier (81%). Among the 52 false-negative classifications of RVH by the statistical method, there were seven erroneous diagnoses of LVH, 20 of BVH, and 25 of normal. Corresponding numbers for the deterministic method were six diagnoses of LVH, 18 of BVH, and 34 of normal. Considering a diagnosis of BVH as also correct for RVH, the correct classification rates were 89% (267/299) and 87% (259/299) for the statistical and deterministic methods, respectively. The RVH cases misclassified as normal were either patients with mild RVH or newborns in whom the predominant right ventricular forces were considered physiologic.

BVH was the most difficult diagnosis for both methods. Of the 203 patients with BVH, only 127 (63%) and 102 (50%) were correctly classified by the statistical and deterministic methods, respectively. Among the false-negative classifications of BVH, 26 cases were misdiagnosed as normal by both classifiers. They represented cases with either mild BVH or exact cancellation of increased left and right spatial voltages resulting in apparent normalization of the VCG. The other misclassifications by the statistical and deterministic classifiers, respectively, consisted of 12 and 22 diagnoses of LVH and 38 and 53 diagnoses of RVH.

The specificity of the two classification methods was indicated by the proportion of normal cases correctly recognized. Of 1069 normal records, 981 (92%) and 943 (88%) were correctly diagnosed by the statisti-
FIGURE 1. VCG of a 3-year-old boy with BVH secondary to a large ventricular septal defect (Qp/Qs = 1.6; pulmonary arterial pressure = 86/22, mean 57 mm Hg; important RVH and left ventricular dilatation at angiography). Clockwise from bottom right are shown: the averaged P-QRS-T complex in X, Y, and Z leads; the QRS-T loops in horizontal plane (H), frontal plane (FR), and right sagittal plane (SD); the P loop in frontal (PF), sagittal (Ps), and horizontal (Ph) planes. The QRS loops are interrupted every 2 msec (dashes) with arrows (10 msec apart), indicating the direction of inscription. In this case, the statistical classification was BVH, whereas the deterministic diagnosis was “minor right ventricular conduction defect, pattern compatible with right ventricular hypertrophy (type C).”

cal and deterministic classifiers, respectively. Among the false-positive classifications there were 49 and 44 cases misdiagnosed as LVH, 25 and 64 as RVH, and 14 and 18 as BVH.

Table 2 presents the results expressed in terms of various indexes of diagnostic performance. In this part of the evaluation, the LVH and RVH cases were counted twice, once as isolated LVH and RVH and a second time as individual components of BVH. This method allows one to test the ability of the classifiers in more challenging situations, e.g., when both LVH and RVH are present and partially cancel each other. Thus a case of BVH diagnosed as either LVH or RVH was considered as correct for LVH or RVH but as incorrect for BVH. A case of LVH classified as BVH was considered as correct for LVH but represented a false-positive diagnosis of RVH. A case of RVH classified as BVH was considered as correct for RVH but represented a false-positive diagnosis of LVH. Table 2 shows that figures of diagnostic accuracy were slightly higher, ranging from 89% to 93%, for the statistical classifier than for the deterministic one (range 88% to 91%). The sensitivity of the statistical method was higher than that of the deterministic one in the three pathologic groups: LVH (74% vs 64%), RVH (86% vs 83%), and BVH (62% vs 50%).

The figures of specificity were similar between the two classifiers in the categories of LVH and BVH but they were higher for the statistical classifier in the category of RVH (95% vs 90%). The predictive values of a positive diagnosis were similar in the category of LVH (74% vs 72%) but they were about 10% higher for the statistical classifier in the categories of RVH (88% vs 77%) and BVH (73% vs 63%). The predictive values of a negative diagnosis were about equal between the two methods for all three pathologic groups. In the normal group the “sensitivity” and predictive value of a normal diagnosis, indicating the ability to correctly recognize a normal pattern, were higher for the statistical classifier: 92% vs 88% and 93% vs 92%,
TABLE 2
Statistical vs deterministic methods: diagnostic performance indexes

<table>
<thead>
<tr>
<th>Groups</th>
<th>Method</th>
<th>SE (%)</th>
<th>SP (%)</th>
<th>PV(+) (%)</th>
<th>PV(-) (%)</th>
<th>DA (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LVH (n = 343)</td>
<td>Deterministic</td>
<td>64</td>
<td>94</td>
<td>72</td>
<td>91</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td>Statistical</td>
<td>74</td>
<td>93</td>
<td>74</td>
<td>93</td>
<td>89</td>
</tr>
<tr>
<td>RVH (n = 502)</td>
<td>Deterministic</td>
<td>83</td>
<td>90</td>
<td>77</td>
<td>93</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td>Statistical</td>
<td>86</td>
<td>95</td>
<td>88</td>
<td>94</td>
<td>93</td>
</tr>
<tr>
<td>BVH (n = 203)</td>
<td>Deterministic</td>
<td>50</td>
<td>96</td>
<td>63</td>
<td>94</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>Statistical</td>
<td>62</td>
<td>97</td>
<td>73</td>
<td>95</td>
<td>93</td>
</tr>
<tr>
<td>Normal (n = 1069)</td>
<td>Deterministic</td>
<td>88</td>
<td>86</td>
<td>92</td>
<td>82</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td>Statistical</td>
<td>92</td>
<td>89</td>
<td>93</td>
<td>87</td>
<td>91</td>
</tr>
</tbody>
</table>

SE = sensitivity; SP = specificity; PV(+) = predictive value of a positive diagnosis; PV(-) = predictive value of a negative diagnosis; DA = diagnostic accuracy.

respectively. Furthermore, the "specificity" and predictive value of a "nonnormal" diagnosis were higher for the statistical method: 89% vs 86% and 87% vs 82%, respectively.

Figures 2 to 5 show the results of the comparative evaluation of the two classification methods in the various diagnostic categories. In the diagnosis of isolated LVH (figure 2) the correct classification rate was 13% higher for the statistical classifier than for the deterministic one (81% vs 68%; p < .005) and the mutual agreement between the two methods for a correct diagnosis was 61%. Twenty-eight cases of LVH missed by the deterministic method were correctly diagnosed by the statistical method, whereas 10 of the cases missed by the latter were recognized by the former.

In the diagnosis of isolated RVH (figure 3) the correct classification rates were nearly identical for the two methods: 89% and 87% for the statistical and deterministic classifiers, respectively, with a high mutual agreement rate of 82%. Only 6% of the RVH cases were missed by both classifiers.

By contrast, in the diagnosis of BVH (figure 4) the mutual agreement for a correct diagnosis was only 39%. The superiority of the statistical classifier over the deterministic one was statistically significant: 62% vs 50% of correct classifications (p < .005), although still 27% of the BVH cases were missed by both methods. However, the complementary nature of the two approaches was demonstrated by the fact that of the

FIGURE 2. Determination of accuracy for LVH by statistical and deterministic classification methods. C = correct, i.e., LVH diagnosed as LVH and BVH; I = incorrect, i.e., LVH diagnosed as RVH or normal. Data in parentheses indicate numbers of cases. A definite improvement is noted with the statistical classifier (p < .005).

FIGURE 3. Determination of accuracy for RVH. C = correct, i.e., RVH diagnosed as RVH and BVH; I = incorrect, i.e., RVH diagnosed as LVH or normal. Differences between the two classifications are not significant. Mutual agreement on a correct diagnosis reaches 82%.
101 cases missed by the deterministic classifier, 47 were correctly diagnosed by the statistical classifier and, inversely, of the 76 cases missed by the latter, 22 were recognized by the former. Figure 1 shows a typical example of BVH, illustrating the potential advantage of the statistical multivariate approach over the conventional deterministic method. In this case, the deterministic diagnosis was correct for RVH. Indeed, there was an important rightward displacement of the maximal (179 degrees) and mean (141 degrees) QRS vectors in horizontal plane and increase of the magnitude of the right maximal spatial vector (2.52 mV). However, it missed the diagnosis of concomitant LVH because the left maximal spatial voltage (2.15 mV) was still within normal limits for age and sex. The statistical program made a correct diagnosis of BVH. The decision was presumably influenced by the presence of a counterclockwise inscription of the QRS loop in horizontal plane, which is unusual in case of isolated RVH in congenital heart disease, and by the values of three combined parameters: MAX S_X, 4/8 MAX QRS_XYZ, and 0.02 STy, which showed the smallest distance to the mean value of the BVH group.

In the 1069 normal children (figure 5), the correct classification rate reached 92% for the statistical classifier and 88% for the deterministic classifier, a statistically significant difference (p < .005). The agreement rate was high (83%), and in only 3% of these normal subjects did both classifiers make a false-positive diagnosis.

**Discussion**

In this study we performed a comparative evaluation of two methods of diagnostic classification in the computer interpretation of pediatric orthogonal ECGs. A statistical multivariate analysis and the more conventional deterministic method were compared in the multigroup classification of the four most relevant categories related to heart disease in childhood: LVH, RVH, BVH, and absence of cardiac lesion. The study population included a large set of 642 unselected in-hospital patients who had been catheterized for the diagnosis or evaluation of congenital heart disease and a control group of 1069 healthy young subjects. In each patient the computer diagnosis by each classifier was assessed with respect not to the cardiologist’s interpretation of the ECG, but to a standard represented by clinical, hemodynamic, and angiographic data. The results were expressed in terms of various indexes of diagnostic performance, not only sensitivity and specificity, which represent intrinsic characteristics of a test, but also the predictive value, which is related to the particular conditions of testing, especially the prevalence of the diagnostic categories in the population analyzed. Although predictive values based on the Bayesian approach do not provide any additional information not contained in determinations of sensitivity and specificity, they are very useful in expressing the

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**FIGURE 4.** Determination of accuracy for BVH. C = correct, i.e., BVH diagnosed as BVH; I = incorrect, i.e., BVH diagnosed as LVH, RVH, or normal. The correct recognition rate of the statistical method is higher than that of the deterministic method (p < .005). Mutual agreement on a correct diagnosis is only 39%.

**FIGURE 5.** Classification of the normal subjects. C = correct, i.e., normal diagnosed as normal; I = incorrect, i.e., normal diagnosed as LVH, RVH, or BVH. The difference in correct diagnosis favors the statistical classification (p < .005).

<table>
<thead>
<tr>
<th></th>
<th>DIAGNOSIS OF BVH (n =203)</th>
<th>DIAGNOSIS OF NORMAL (n =1069)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>STATISTICAL</td>
<td>STATISTICAL</td>
</tr>
<tr>
<td></td>
<td>C: 39% (80)</td>
<td>C: 83% (887)</td>
</tr>
<tr>
<td></td>
<td>I: 23% (47)</td>
<td>I: 9% (94)</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>62%</td>
<td>92%</td>
</tr>
<tr>
<td></td>
<td>38%</td>
<td>8%</td>
</tr>
</tbody>
</table>
performance of a diagnostic method in a given clinical setting. In this study comparing two classification methods, only sensitivity, specificity, and predictive values were used, although it is recognized that other evaluation procedures, such as those computing cost of misclassification, are possible.

The overall diagnostic accuracy computed as the total percentage of correct classifications over all four diagnostic categories was higher for the statistical classifier than for the deterministic one (85% vs 79%). The diagnostic accuracy computed in each category ranged from 88% to 91% for the deterministic method and from 89% to 93% for the statistical method (table 2). The sensitivity was the highest in the diagnosis of RVH, with little difference between the two classifiers, whereas differences were more important in the diagnosis of LVH and BVH. In the diagnosis of RVH the specificity of the statistical classification was 5% higher than that of the deterministic method (95% vs 90%), while the figures were about equal in the categories of LVH and BVH. The statistical classification led to higher positive predictive values in the categories RVH (88% vs 77%) and BVH (73% vs 63%). The diagnostic indexes in the normal category were also slightly higher for the statistical classifier.

Although the statistical classifier had a better overall diagnostic accuracy than the deterministic method, the complementary nature of the two approaches was demonstrated by the percentages of cases misclassified by one method and correctly diagnosed by the other (figures 2 to 5). The mutual agreement for a correct diagnosis was the highest in the categories RVH and normal: 82% and 83%, respectively. Only 6% of the RVH cases and 3% of the normals were missed by both methods. In contrast, in the categories LVH and BVH the differences between the performances of the two classifiers and the independent contribution of each to a correct diagnosis were statistically significant.

Willems23 has reviewed the relative advantages and drawbacks of both the multivariate statistical analysis and decision-tree conventional analysis in computerized ECG interpretation. These considerations essentially have been confirmed when we compared the two approaches in the clinical interpretation of orthogonal ECGs in adults.29 More recently, Zywietz has developed a new vectorcardiographic computer program for children using an alternative multivariate classification.4 In their approach the classification is performed in two steps: first, by testing for the presence or absence of each pathologic entity and the normal vs the total pathologic group and second, by testing for the definite assignment to a diagnostic category. Our own statistical model for the diagnostic classification of pediatric VCGs differs from these previous experiences in several respects. First, since in children the four type A diagnostic categories were exhaustive and mutually exclusive, we applied a multigroup classification scheme from the outset. This was also necessary because of the differences observed between the covariance matrices of the normal group and of the total pathologic group. Second, the influence of such important constitutional variables such as age and sex were specifically taken into account in the statistical model. Third, we used several sequential stepwise procedures for the selection of discriminant variables without assumption of multinormality but with assumption of equal covariance matrices of the four groups and the classification was performed by using dichotomous and continuous variables in a hierarchical order. In this manner we took advantage of the statistical information present, not only in the correlation between individual variables but also between various levels of these variables. The model also utilized the diagnostic information related to the rotational characteristics of the QRS loop in the reference planes, which has long been used in clinical vectorcardiography.

Notwithstanding the definite advantages of multivariate diagnostic classification, the deterministic approach remained attractive and presented several complementary features. This interpretative approach includes the electrocardiographer’s or vectorcardiographer’s experience and the rationale derived from cardiac electrophysiology, which are specifically excluded in the statistical model. The correction of existing criteria and introduction of new criteria are more easily performed and the set of criteria can be adjusted to the type of population analyzed. The multi-threshold-multilevel approach in the design of the diagnostic criteria avoided an excessive dependence of the diagnostic flow on small discrete variations in the values of single parameters. Finally, the deterministic approach allows one to consider a large number of diagnostic categories and to differentiate between various degrees of severity in the pathologic entities.1

In conclusion, the combination of both methods of diagnostic classification as in our vectorcardiographic
pediatric program is feasible and contains the potential for a higher diagnostic accuracy.

We gratefully acknowledge the collaboration of Christoph Zywietz from the Dept. f. Biometrie u. Med. Informatik, Med. Hochschule Hannover, who kindly provided a part of the pediatric vectorcardiographic data base used in this study.

References

APPENDIX A
Selection of discriminant variables in each sex/age subgroup according to various levels of dichotomous variables

<table>
<thead>
<tr>
<th>Age/sex group</th>
<th>Dichotomous variable</th>
<th>Continuous variablesa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Babies, birth-6 mo</td>
<td>AQRS loop XZ plane: CCW (counterclockwise rotation)</td>
<td>0.06 STXYZH°, VENTR. GRAD. AZIMUTH, AQRSx, 0.04 STXYH°, 0.02 STXYZH°, 0.08 STXYZYH°, 0.03 QRS spatial velocity, STX, Rx at end of Qx, MAX QRSiT, 3/8 QRSXYZ.</td>
</tr>
<tr>
<td></td>
<td>AQRS loop XZ plane: CW (clockwise rotation)</td>
<td>AQRSxYz, 0.01 QRSXYZ. AQRSxyz, AQRSxyzV°, QRSXYZ0.06, AQRSxyz, AQRSxyz, 0.02 STXYZH°, Sx duration, AQRSAT spatial angle, VENTR. GRAD. ELEVATION, MAX QRX.</td>
</tr>
<tr>
<td>Babies, 6-24 mo</td>
<td>AQRS loop XZ plane: CCW</td>
<td>MAX QRSXYZ, MAX QRSxT, MAX TXYH°, 0.03 QRSXYZ, 0.03 QRS spatial velocity, QRSXYZ 0.05 H°, VENTR. GRADIENT, 0.02 STZ, AQRSxz.</td>
</tr>
<tr>
<td></td>
<td>AQRS loop XZ plane: CW</td>
<td>MAX QRSXYZ, 7/8 QRSXYZ, 0.08 STY, STYZ, 0.04 STY, MAX TXYZF°, STXYZ°, STY.</td>
</tr>
<tr>
<td>Males, 2-5 yr</td>
<td>AQRS loop XZ plane: CCW</td>
<td>Sx, 4/8 QRSXYZ, 0.02 STx, 0.02STx, ATx, ATXYZ, 0.06 QRSXYZV°, 6/8 STXYZH°.</td>
</tr>
<tr>
<td>Males, 6-19 yr</td>
<td>AQRS loop XZ plane: CCW</td>
<td>MAX QRSXYZ, RMSV, 0.02 STY, 0.06 STXYZV°, 6/8 STXYZH°.</td>
</tr>
<tr>
<td>Females, 2-7 yr</td>
<td>AQRS loop XZ plane: CCW</td>
<td>AQRSx, RMSV, 3/8 QRSXYZ, 0.06 STX, STXZ.</td>
</tr>
<tr>
<td>Females, 8-19 yr</td>
<td>AQRS loop XZ plane: CCW</td>
<td>MAX QRSXYZ, MAX QRSxT, 3/8 QRSXYZ, 5/8 QRSXYZ, 0.05 STXYZ, 0.06 STX, 0.04 STXYZH°, 4/8 STXYZH°, 0.03 QRSXYZ, ATXH°.</td>
</tr>
</tbody>
</table>

Abbreviations are those recommended by the Committee on Electrocardiography of the American Heart Association (Circulation 52: 11, 1975).

Appendix B
The Krzanowski model. Let us suppose a multiparameter vector obtained from the VCG:

\[ W = (X, Y) \]

where X is a vector of dichotomous parameters and Y is a vector of continuous parameters.

Let us suppose Dj is a diagnosis. According to Bayes theorem:

\[ P(Dj|W) = \frac{P(W|Dj) \cdot P(Dj)}{\sum_{i=1}^{4} P(W|Di) \cdot P(Di)} \]

where P(Dj) is the prior probability of belonging to diagnostic category Dj, P(W|Dj) is the conditional probability of having a vector of parameters W given the diagnostic category Dj, and P(Dj|W) is the posterior probability of belonging to diagnostic category Dj given the vector of parameter is W.

However, the conditional probability of the vector W can be rewritten as:

\[ P(W|Dj) = P(Y|X, Dj) \cdot P(X|Dj) \]

The distribution of Y, the part with the continuous variables of the vector W, is thus considered after (or when) X, the dichotomous part of the vector W, is known. In this application, P(Dj) was ¼, i.e., the prior probabilities of belonging to one of the four diagnostic categories were equal.
Computer interpretation of pediatric orthogonal electrocardiograms: statistical and deterministic classification methods.
C R Brohet, A Robert, C Derwael, R Fesler, M Stijns, A Vliers and L A Braasseur

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