Computer-Aided Systematized Approach to Pediatric ECG Analysis

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Background: In pediatric electrocardiography (ECG), the correct classification of segments in the medical record is subjected to various components. A conventional analysis based either on the cardiologist's skills or a quick reference to a standard normality table may lead to mistakes and to an incorrect final medical diagnosis. In this study, the evaluation of 12 specific ECG segments (ES) is defined as segmental analysis (SA). We hypothesized that a computer-aided SA can provide better results for a correct classification of pediatric ECGs, compared to the conventional analysis. This study aims to evaluate the accuracy of a computer-aided SA ECG diagnosis of pediatric patients by cardiologists.

Methods: To validate the software, we selected four normal and one altered ECG as references, all with concordant reports given by two cardiologists using manual planimetry. Nineteen cardiology experts independently examined each of the five standard pediatric ECGs twice. First, the ECG was analyzed in the conventional form. Subsequently, the participants evaluated ECGs with our proposed computer-aided AS, by measuring the 12 specific ES in the grid paper and having their values entered into a custom-made software, in order to compare them with normality standards.

Results: The computer-aided SA reduced ECG misreading or ECG misinterpretation errors by 83%. It also showed a more uniform, high-quality analysis of all ES (minimum of 92% correctly reviewed segments from normal pediatric ECGs) by all the participant cardiologists.

Conclusions: We consider the computer-aided SA for ECG evaluation in pediatric cardiology an efficient and safe complementary method.

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pediatric electrocardiography; computer-aided electrocardiography; complementary diagnostic techniques

As an outstanding piece of the routine cardiological evaluation, the centennial electrocardiogram (ECG), a simple, low cost, quick diagnostic approach that is sensitive to the majority of cardiopathies,¹ is a substantial source of information and experience for the cardiology practitioner, who, as a rule, provides specialized medical advice for adult people, most frequently affected by acquired heart diseases, but who also are often called to analyze ECGs performed on patients under 16 years of age.²

From birth to the time a human being is fully grown-up, his/her normal ECG recordings will show alterations resulting from changes in physiological development, body size, shifts of heart positioning in relation to the body, and variations in the size and relative positioning of both heart chambers.³

The transition from fetal to neonatal blood flow responds for the great hemodynamic, respiratory, and the consequential electrocardiographic changes that occur in a newborn (NB).^{4,5} After

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birth, the cardiac structural development does not cease, but the rhythm of its alterations progressively diminishes. Those intrinsic changes, mainly observed during the very first days in life, are reflected in the normal ECG as some vectorial alterations. Thus, the diagnostic criteria for pediatric ECG interpretation are age-dependent and present increasingly more difficulties than those of an adult patient.^{6,7}

Since 1913, many reports have consolidated the knowledge about the cardiac development in pediatric electrocardiology,^{8,9} but it was not until 1957 that Nadas et al.¹⁰ pointed out the "serious mistakes" that may arise from pediatric ECGs misinterpretation. In 1978, another extensive and consistent revision of the normal pediatric ECG was published by Liebman, Plonsey et al.¹¹ However, it was only in 1979 that André Davignon et al.⁷ analyzed 2141 ECGs of white American children, aged 1 day to 16 years old, subjecting all measurements in their extensive database to computerized analysis and distributing them across percentiles built for every age group, in 37 different data sheets corresponding to the electrocardiographic segments analyzed. From the time it was first published, that seminal study based all the main revisions published later,^{8,12-14} and served as a rule for important guidelines issued on this subject.^{3,15}

At present, computerized data processing brings increased accuracy and diagnostic sophistication to the field of electrocardiography, especially in what refers to complex pediatric recordings.^{16,17} However, the recent recommendation by the European Society of Cardiology, to evaluate in a manual form the ECG segments of NB³ and children of younger age, is proof of one of the limitations of this auxiliary technological tool. The lack of gold-standard algorithms for electrocardiographic evaluation defines a set of strict limits to the use of computer software for diagnostic purposes.^{18,6,19} However, should this type of software be used to discipline (or systematize) ECG analysis, adding to the cardiologist's own skills and experiences, we would profit from better consistency to the final result of the test, with improved quickness and safety.

This study was designed to evaluate the accuracy of computer-aided segmental analysis (SA) of ECGs of under-16 pediatric patients, using a computer program, as compared with conventional ECG analysis based only on the physician's experience and the possible use of a reference normality table.

METHODS

Study Participants Selection

We invited 19 cardiology experts currently working in the Heart Institute of the University of São Paulo Medical School (InCor-FMUSP), all with daily clinical practice and engaged in (or finished) PhD studies to take part in this study: 14 pediatric cardiologists, 3 emergency cardiologists, and 2 cardiologists from the Electrocardiology Service of InCor-FMUSP. On the basis of the (straightforward) reasoning that pediatric cardiologists are more prone to analyze pediatric ECG recordings and, hence, the evaluation of their performance would be more critical compared with other cardiology practitioners, we included a higher number of pediatric cardiologists (79%) in our sample.

Material

The ECGs were randomly selected, following two prerequisites: among all five records, there would be three ECGs recorded from patients under 2 years of age, one of which would be an ECG with alterations. The age under 2 years of age is the period when the most variation from normality is usually found. The final set was then composed of four normal ECGs (ages: 6 months, 1 year and 6 months, 12 years, and 13 years, respectively), and one altered ECG (age: 1 day). The pathological ECG presented the following alterations: increased heart rate (174 bpm), presence of Q wave in V₁, short R wave in V₁ (0.1 mV), and tall S wave in V₆ (1.3 mV), an unusual but not rare ECG among the altered pediatric ones in our hospital routine.

Twelve specific electrocardiographic segments were picked out according to the literature^{7,11,14,15}: rhythm, heart rate, PR interval in D_{II}, QRS complex width in V₅, Q wave in V₁, R wave in V₁, S wave in V₁, T wave in V₁, Q wave in V₆, R wave in V₆, S wave in V₆, and QRS angle.

Two types of questionnaire were prepared for interviewing the participant physicians: the first containing subjective or qualitative questions, and the other with systematized or quantitative questions. The subjective questionnaire was presented in printed format, with 12 YES/NO questions about the normality of the segments previously described. The quantitative type, also in printed format, was composed of 12 questions that required metric measurement/evaluation or vectorial analysis for an

answer to be given (heart rate; PR interval in D_{II}; QRS complex width in V₅; amplitude of waves: Q in V₁, R in V₁, S in V₁, T in V₁, Q in V₆, R in V₆, and S in V₆; rhythm and QRS complex axis).

A printed normality table for pediatric ECG,¹⁵ indicated by the Association of Cardiology of the State of São Paulo and issued before the publication of the first Brazilian Guidelines on Resting ECG, was available for the subjective evaluation.

We considered as (gold standard) control measurements the metric and vectorial concordant values of 12 selected electrocardiographic segments of the five selected ECGs, as assessed by two independent cardiologists with the use of manual planimetric evaluation, and based on the normal values from the tables provided by Davignon.

Software

A computer program (software) was built using Excel (Microsoft Corporation, Redmond, WA) macros and data sheets to analyze the 12 electrocardiographic segments selected, in accordance with the normality reference values established at the time of the study. For this purpose, a database was created, putting together the current (at the time of the study) normality limits for every age group. Following the interview, each collected answer was then automatically compared with the programmed normality table, thus defining the normal or abnormal character of all the study variables. Those answers were later compared with the control values. The creation of an Excel macro-based database software attended four criteria: widespread availability, high user-friendliness, reliability, and sufficiency for the purposes of this study.

Data Collection and Processing

The order in which the questionnaires were introduced was defined in accordance with the routine that would be the most natural in the daily practice of a cardiologist, and therefore was less likely to have any bias on the results of the subsequent method (exercising a disciplined answering of the systematized questionnaire might affect the performance of the subjective analysis which came next).

Everyone of the 19 interviewed cardiologists performed both analyses of the same five ECGs on separate occasions. In the first, or subjective evaluation, we sought to simulate a daily professional

setting, with emphasis on the experience of the physician. For this purpose, the normal or abnormal character of each of the 12 electrocardiographic segments was questioned, with the possibility (entirely up to the practitioner's choice) of reference to a normality table based on Davignon's data.

During the second or systematized evaluation, the participant was required to evaluate metrically and vectorially (according to the segment under analysis) the same electrocardiographic segments subjectively analyzed earlier.

Data obtained from each subjective interview were directly compared with the control values. Data obtained by the systematized evaluation were fed into the custom-made software, which classified every electrocardiographic segment as normal or abnormal. This classification was then compared with the control values.

Criteria of Analysis

Results of the comparison with the control values were classified as concordant or discordant. Those classified as discordant were denominated "mistakes." Those mistakes carrying potential damage to the ECG diagnostic report were further classified as Important Errors (IE). These include misvaluations of heart rate, PR interval, Q wave in V₁, QRS angle, R wave in V₁, and S wave in V₆. The latter two variables were only taken into account for the analysis of the altered ECG.

Time

To assess whether the systematized analysis would be more time consuming than the conventional one, we computed and compared the time spent to answer all questions in both questionnaires. The time spent to feed the software with the systematized questionnaires results was not taken into account in the global times comparison.

Statistical Analysis

This study was designed to analyze the frequency of evaluation errors, especially those defined as IE, during the electrophysiological analysis of pediatric ECG segments. Therefore, common measures of tendency (such as mean value), or dispersion to the mean (standard deviation, standard error), would not be descriptive of the data for the purposes of this study.

Figure 1. ECG segments errors found in the analysis of all ECG recordings, with and without the aid of the software.

The nonparametric Wilcoxon’s signed-rank exact significance test was used to calculate the precise statistical significance, given the asymmetry found in the tables of frequency (which did not fulfill the prerequisites for the usually adopted chi-square test).

RESULTS

Figure 1 shows that, with the computer-aided systematized evaluation, the overall number of incorrect analyses of ECG segments was reduced

from 8.2% down to 4.2% ($P < 0.01$). The number of IE was reduced in the same proportion, from 1.4% down to 0.7% ($P < 0.01$).

Table 1 gives a detailed description of the nature and amount of errors of SA found in each one of the approaches (with and without software aid). It is noteworthy that, while the frequency of most errors was reduced with the systematized approach, the measurement of heart rate (whether subjectively performed or calculated on the grid paper) responded for nearly 50% of all the IE recorded.

Table 1. Description of All Errors Found in ECG Segments Sorted by Method of Analysis

Segments Analyzed	Important Errors		All Errors	
	With Software	Without Software	With Software	Without Software
Rhythm	*	*	*	2 (2%)
Heart rate	4 (50%)	21 (43%)	4 (25%)	21 (22%)
PR interval	4 (50%)	5 (10%)	4 (25%)	5 (5%)
QRS V ₅	*	*	8 (50%)	*
Q V ₁	*	5 (10%)	*	5 (5%)
R V ₁	*	*	*	2 (2%)
R V ₁ abnormal	*	3 (6%)	*	3 (3%)
S V ₁	*	*	*	9 (9%)
T V ₁	*	*	*	12 (13%)
Q V ₆	*	*	*	10 (11%)
R V ₆	*	*	*	7 (7%)
S V ₆	*	*	*	3 (3%)
S V ₆ abnormal	*	8 (16%)	*	8 (8%)
AQRS	*	7 (14%)	*	7 (7%)
Total	8 (100%)	49 (100%)	16 (100%)	94 (100%)

*No value.
The sum of individual errors percentages are not equal to 100 due to roundoff effects.

Table 2. Effects of the Computer-Aided Systematized Analysis on the Performance of Cardiologists with Pediatric ECGs Recorded in Different Age Groups

Type of Analysis	Cardiologists with at Least 1 Important Error* in 12 ECG Segments from				
	13 Years Old (Normal)	1 Year and 6 Months Old (Normal)	6 Months Old (Normal)	12 Years Old (Normal)	1 Day Old (pathological)
Without software	1 (21%)	5 (37%)	5 (32%)	3 (16%)	16 (84%)
With software	2 (10.5%)	2 (10.5%)	0 (0%)	2 (10.5%)	2 (10.5%)
P†	1000	0.453	0.063	1000	<0.001

†Wilcoxon signed-rank exact significance test; †*Error leading to misdiagnosis.

The best improvements of the computer-aided systematized approach on the ability of participant cardiologists to correctly identify the 12 segments in each of the pediatric ECGs recorded in patients from different age groups (and the most significant decreases in IE) were seen precisely in the ECGs recorded in patients at the youngest ages (normal ECG, 6 months old: $P = 0.063$; and pathological ECG, 1 day old: $P = 0.001$) (Table 2).

The systematized evaluation did not show a statistically significant improvement in the number

of cardiologists with 100% correct judgments of normal pediatric ECGs. However, a significant improvement was obtained with this approach in the performance of the pathological ECG analysis: 16 (84%) of them correctly identified 100% of the ECGs, as compared with 3 (16%) using the conventional analysis ($P < 0.001$) (Figs. 2 and 3).

The use of the software-aided systematized approach improved the quality of analysis of normal pediatric ECGs, resulting in a minimum of 92% correct identifications, among the overall number

Figure 2. Percentage of physicians with 100% correct evaluation of pediatric ECG segments from different age groups, with and without software aid.

Figure 3. Comparison of the number of correctly evaluated ECG segments of a pathological pediatric ECG, by all the cardiologists, in both analyses.

of segments analyzed by all participants (Table 3). With respect to the altered recordings, there were at least 83% of segments correctly identified (Fig. 3).

Table 4 summarizes the results for both approaches (systematized and conventional) sorted

by normal and pathological pediatric ECG recordings. The impact of the systematized approach on the performance of the 19 participant cardiologists is clearly shown, also highlighting the occurrence of IE in the analysis of a given pediatric ECG.

Table 3. Number of Segments Correctly Evaluated in Each of the Normal Pediatric ECGs, Sorted by Method of Analysis

		Cardiologists (N = 19) Grouped According to Their Overall Performance on the Analysis of Normal Pediatric ECG Recordings					Total
Normal Pediatric ECG Recording	Software Aid	8 (66.7%) Correct	9 (75%) Correct	10 (83%) Correct	11 (92%) Correct	12 (100%) Correct	
13 year	Without	2	*	*	2	15	19
	With	0	*	*	3	16	19
12 year	Without	*	1	1	1	16	19
	With	*	0	0	5	14	19
1 year/6 month	Without	*	1	1	6	11	19
	With	*	0	0	2	17	19
6 month	Without	*	1	1	4	13	19
	With	*	0	0	2	17	19

*No value.

Table 4. Number of Cardiologists with at Least 1 Important Error during Analysis of Each Pediatric ECG Recording, Using Both Methods

			Number of Cardiologists (n = 19) with Important* Errors in All Pediatric ECG Records		
Pediatric ECG Record		Type of Analysis	No mistakes	At least one error	Total
Normal	13 years old	Without software	18	1	19
		With software	17	2	19
	12 years old	Without software	16	3	19
		With software	17	2	19
	1 year and 6 months old	Without software	14	5	19
		With software	17	2	19
Pathological	6 months old	Without software	14	5	19
		With software	19	0	19
	1 day old	Without software	3	16	19
		With software	17	2	19

*Potentially leading to misdiagnosis.

The time spent on fulfilling the quantitative questionnaire (systematized approach) was 5% longer than for the qualitative questionnaire (conventional analysis): 137 seconds/ECG to 131 seconds/ECG.

DISCUSSION

Although the rate of NB children with a congenital cardiopathy seems to be small, a cardiologist will be seeing many children and adolescents during his professional career. Moreover, the progressive incidence of metabolical disorders, occasionally in association with a malignant genetic background, favors an increasingly more investigative and interventionist clinical attitude. Therefore, the performance of an electrocardiographic assessment is useful before, during, and often after treating a child or adolescent. The guidelines on electrocardiography of the NB³ issued by the European Society of Cardiology confirm the importance of the pediatric ECG, indicating that such evaluation should be performed as early as during the first month of life. However, the diagnostic criteria for interpreting pediatric ECGs are age-dependent and involve greater difficulties than those of ECGs from adult patients.^{7,20}

Zhou et al.¹⁹ reported that certain visual patterns may not be easily identifiable and may require the use of complementary tools for better diagnostic elucidation. Another study by Wathen et al.¹⁶ demonstrated a high rate of discordance among physicians on analyzing clinically important ECGs (in their study, they were specifically emergency

pediatricians and pediatric cardiologists). Snyder et al.¹⁷ also observed a reduced visual sharpness during the human interpretation of ECGs of higher complexity, and also accredited the software with better performance. However, the expected aid from computer programs to electrocardiographic diagnosis may not be confirmed. The lack of gold-standard algorithms for electrocardiographic assessment poses strict limits to the use of software for diagnostic purposes.⁶ Thus, the correct electrocardiographic analysis may be hindered especially in highly complex ECG recordings, regardless of the use of computational tools.

In the present study, the systematized approach contributed with a significant, absolute decrease from 8.3% to 1.4% of ECG segment errors (95 to 16 erroneously identified segments). However, the ratio of IE to the total number of errors remained nearly stable, around 50% (50 IE out of 95 errors with the subjective approach; 8 IE out of 16 errors with the systematized evaluation).

The detailed description of the errors (either defined as important or not) computed by any of the two approaches (see Table 1) evidences the relevance of correctly analyzing heart rate and PR interval, regardless of being subjectively evaluated or calculated on the grid paper. Crossover tabulation also evidenced that seven of the eight IE determined by the systematized evaluation (errors of either PR interval or HR) had been correctly evaluated in the qualitative questionnaire. We believe this is due to minor misreading in the grid paper.

Some points should be noted on the amount of deviation of heart rate and PR-interval errors in

the systematized evaluation, in which the practitioners were asked to evaluate metrically the segments. Heart rate was overestimated by 23.45% on average (range 13.39–44.19%) and the deviation on PR-interval errors was much higher: 93.94% on average, range 81.82–100%. Although heart rate and PR-interval errors were both originally classified as IE according to their nature, the latter were far more relevant clinically regarding the amount of deviation. These calculations could not be repeated for the subjective analysis errors because these data were not available on this type of questionnaire (practitioners were just inquired a NORMAL/ABNORMAL answer about both heart rate and PR-interval).

Our findings clearly state the benefits of a computer-aided systematized evaluation such as the one presented in this study; basically, it ensures that a uniform, high-quality electrocardiographic analysis will be obtained. All normal and pathological pediatric ECG segments of various age groups were analyzed with a uniform high accuracy, which differed from the great variability found among the cardiologists with the subjective analysis (minimum of 92% correct segments in normal ECGs, Table 3; minimum of 84% in pathological ECG, Fig. 3).

Regarding the pathological ECG, the difference between the two methods (subjective and systematized) was highly significant ($P < 0.001$); the number of physicians who had at least one IE (error that could lead to misdiagnosis), went down from 16 (84%) with the subjective analysis to only 2 (10.5%), as shown in Table 4 and Figure 3.

It should be noted, though, that a computer program of this type could be satisfactorily replaced by a disciplined, careful attitude toward the ECG interpretation. On this rationale, the electrocardiographic analysis was intentionally and pedagogically denominated a systematized evaluation, the custom-made software originally intended for greater comfort and operational agility.

The development of methods to improve the cardiologists' skills opens novel and attractive frontiers in their own field of specialization, but it often steers away from the available methods that are already fully consecrated. We often notice the use of some sophisticated, expensive tests, usually performed in facilities far away from the practitioner's office, instead of inexpensive, easily available diagnostic resources such as the ECG, which are of quick use and can provide the expected response.

These facts pervade in countries like Brazil, with a large population of poor individuals who can precariously cope with the expenses of a medical treatment. As a result, there is a large burden placed on the already deficient budget of the national health-care system.

In this scenario, the ECG emerges as an instrument with many important qualities. However, the benefits of the ECG are proportional to the knowledge and training of the practitioner who analyzes it, especially on occasions when all help provided is the aid of simple tools such as a magnifying glass and a normality database.

On the limitations of this study, some may argue about the errors defined as "important errors" in this study protocol. Our definition of important errors was restricted to those mistakes with greater potential to lead to an incorrect medical ECG report.

We may have underestimated the errors observed in the conventional analysis, as QT interval was not evaluated in this study. Should the design of study participants have included cardiologists not involved in research activities, we believe we would have found a better picture not only of the average cardiologist practitioner profile (knowledge and training) but also an increase in the number of computed errors.

Currently, the incorporation of an electrocardiographic evaluation of NB children is being increasingly considered in European countries.³ However, most cardiologists are not familiar with pediatric ECGs (a reality that, notwithstanding its limitations, this study helped to demonstrate). This makes the search for software and new methods of analysis more and more demanding, provided that they could be easily incorporated into the routine evaluation, like the one proposed in this report. Our findings indicate that the use of a simple, nondiagnostic software for analyzing pediatric ECGs is a safe and efficient complementary tool.

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