KARDIO-E — an expert system for electrocardiographic diagnosis of cardiac arrhythmias

Abstract: *KARDIO-E is an expert system for the electrocardiographic diagnosis of heart arrhythmias. At the present stage the system can be used as a helpful diagnostic tool in the routine assessment of ECG recordings in preventive or systematic examinations as, by cardiologist's estimation, its performance is equivalent to that of a specialist of internal medicine (non-cardiologist) highly skilled in the reading of ECG recordings. The system is also useful for instruction of electrocardiography in education of all medical profiles. This paper presents the ECG diagnosis problem, the automatic generation of the system's knowledge base and a detailed description of the system. Results of an assessment study are also presented.*

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Introduction

In general a system for the diagnosis analysis of electrocardiograms consists of four substantial parts:

(a) registration of the ECG signal and estimation of noise level

(b) detection of heart beats or QRS complexes in each beat

(c) classification of beats into regular and irregular ones

(d) recognition and interpretation of diagnostic parameters

Commercially-available systems exist that efficiently deal with all these problems attaining up to 90% recognition accuracy of diagnostic parameters (shapes and time relations of QRS complex, T wave, ST segment and more rarely also the P wave) [1].

Normally these systems deal only with a very limited repertoire of diagnostic alternatives (of the order 10). This limitation stems from two reasons. One is the difficulty in the recognition of the P wave which causes the system to deal only with elementary cardiac arrhythmias for which no information about the P wave is needed. And the other reason is the lack of knowledge of what is the set of all diagnostic alternatives and what are the characteristic values of their diagnostic parameters (the characteristic ECG features). This knowledge can not be explicitly found in medical literature and as to its complexity it is impossible to extract it from a specialist's knowledge.

The KARDIO-E expert system for the interpretation of electrocardiograms represents a complement to the existing ECG analysis systems. The KARDIO-E does not accept an actual electrical ECG signal but its description in terms of qualitative features such as the rate or the shape of the QRS complex of a heart beat.

For such an ECG description possible diagnoses are selected from a repertoire of 587 arrhythmias. These arrhythmias represent the physiologically possible combinations of twenty-five elementary arrhythmias that the system deals with. The knowledge base (called the arrhythmia knowledge base) consists of 587 rules relating each arrhythmia with an ECG pattern, representing all its alternative ECG descriptions. Generation of the knowledge base was done automatically using a model of the electrical heart activities [2, 3].

We know of only one other attempt of building a similar expert system [4] which does not seem to be operational due to its computational inefficiency.

The KARDIO-E expert system is one of the results in the development of a complex expert system KARDIO for the diagnosis and treatment of cardiac arrhythmias [2, 3, 5]. The system is implemented in Prolog on DEC-10 [6] including graphic facility for presentation of ECG diagrams which is most useful for instruction. In an evaluation study several deficiencies in the knowledge base were found. This led to a new, slightly modified ECG description language, consideration of five other elementary arrhythmias and some corrections in the model of the heart. The new, second version of the arrhythmia knowledge base was generated. This knowledge base consists of 8,314 rules, relating 2,419 arrhythmias to 140,966 corresponding ECG descriptions. By cardiologists' estimation [7] this second version of the knowledge base is sufficient for correctly handling 95% of patients suffering from arrhythmias. KARDIO-E at present uses the earlier version of the knowledge base (the one with 587 arrhythmias) so the rest of this paper refers to this version.

The ECG diagnosis problem in KARDIO-E

To interpret a given electrocardiogram means to identify those disorders in the patient's heart which caused this ECG. Disorders in the heart's activity are called cardiac arrhythmias. Typical such disorders are: abnormalities in the rate of the heart beats, abnormal origin of generation of electrical heart impulses, and abnormal conduction of impulses from the atria to the ventricles. Our system is limited to disorders in the electrical activity of the heart and does not include mechanical failures (thus excluding diagnoses like myocardial infarction).

Each electrocardiogram can be described in terms of features that are indicative of a diagnosis. In KARDIO-E as well as in medical literature [8] these features are of a qualitative, rather than quantitative nature. A specification of such features for a given ECG will be called a qualitative ECG description. In KARDIO-E the ECG diagnosis problem is then: for a given ECG description find those arrhythmias which correspond to such an ECG.

Choice of a language for qualitative description of ECG's

The language for the qualitative ECG description consists of seven attributes for the description of regular heart beats and three attributes for ectopic heart beats. Each of the attributes has two–five possible values. We will not list all the possible values of attributes but rather present an informal description of a normal electrocardiogram (representing a normal sinus rhythm) and of a combination of sinus bradycardia and ventricular ectopic beats, which is one of the heart arrhythmias (Figure 1):

sinus rhythm	*sinus bradycardia and ventricular ectopic beats*
rhythm: regular	rhythm: ectopic-beats
regular-P: normal	regular-P: normal
rate-of-P: between-60-100	rate-of-P: under-60
relation-P-QRS: after-P-always-QRS	relation-P-QRS: after-P-always-QRS
regular-PR: normal	regular-PR: normal
regular-QRS: normal	regular-QRS: normal
rate-of-QRS: between-60-10	rate-of-QRS: under-60
	ectopic-P: absent
	ectopic-PR: no-P-before-QRS
	ectopic-QRS: wide

Figure 1. *Two ECG diagrams and their qualitative ECG descriptions*

Automatic generation of the system's knowledge base

KARDIO-E deals with a repertoire of twenty-five 'elementary disorders', also called simple arrhythmias. Each of these arrhythmias corresponds to a functional state (either normal or abnormal) of some part of the electrical system of the heart. The problem of specifying the relation between these simple arrhythmias and their corresponding ECG descriptions is relatively simple and was done manually. However, complications arise from the combinatorial nature of arrhythmias: several disorders present in the heart at the same time give rise to a combined arrhythmia. In general, a combined arrhythmia is a combination of one or more simple arrhythmias. In principle, the number of combined arrhythmias grows exponentially with the number of constituent simple arrhythmias. But in fact not all combinations of simple arrhythmias are physiologically possible.

In our project an alternative to manual construction of the arrhythmia knowledge base was used. We developed a model of electrical activities of the heart. The model can be thought of as an electrical network. However, signals that circulate in this network are represented by symbolic descriptions, rather than by voltage *vs* time relations. Such descriptions specify signals qualitatively in terms of their forms, rates, regularity and mutual relationships. So these descriptions appear very similar to the electrical processes in the heart and the way these processes are affected by disorders in the heart. To our knowledge this is the first attempt of the qualitative modelling approach on a substantial physiological problem, while other related works deal with relatively simple problems in physics [9, 10, 11].

The model was effectively executed on all mathematically possible combinations of simple arrhythmias. The majority of these combinations were eliminated by constraints over the states of the heart. An interesting result of such elimination is also that the most complex arrhythmias are combinations of seven simple arrhythmias. For the physiologically possible combinations their ECG descriptions were derived by qualitative simulation based on the model. In this way, a complete arrhythmia knowledge base was synthesized automatically.

The causal model of the heart represents 'deep knowledge' of underlying electrical processes in the heart in contrast to the 'shallow' level of the generated arrhythmia knowledge base. The model specifies the causal relations between events in the heart. A causal sequence of such events represents a qualitative simulation of electrical processes in the heart. For a given arrhythmia such a simulation produces its corresponding ECG descriptions. The model of the heart is completely documented elsewhere [2].

". . this is the first attempt of the qualitative modelling approach on a substantial physiological problem . . ."

Description of the system

The arrhythmia knowledge base specifies the relation between 587 arrhythmias and their corresponding ECG patterns. These relations are represented by 587 rules of the form:

$$A \rightarrow E$$

where A is an arrhythmia (simple or combined), and E is an ECG pattern. The rule is read as:

<u>if</u> arrhythmia is A <u>then</u> its ECG pattern is E

where E is described by a list of attribute:value pairs. Each ECG pattern represents a set of alternative ECG descriptions E1, E2,..., En that correspond to the arrhythmia A. So the rule can also be read as

<u>if</u> arrhythmia is A <u>then</u> E1 or E2 or ... or En

To obtain this compact representation of several ECG descriptions by a single ECG pattern the logic interpretation of the rule is the following: attribute:value pairs are connected conjunctively for different attributes and disjunctively for the same attribute.

KARDIO-E uses these rules not for confirming but rather for disconfirming candidate arrhythmias: if the patient's ECG does not match any of the ECG descriptions Ei in the pattern E then arrhythmia A is rejected by the rule:

not E1 and not E2 and ... and not En $\rightarrow$ not A

The inference mechanism compares the input patient's ECG with ECG patterns in the knowledge base. From the set of all possible diagnoses it eliminates the diagnoses whose ECG patterns never match the patient's ECG description. An ECG description matches an ECG pattern if for each attribute it has at least one common disjunctive value. At first there are all 587 arrhythmias in the set of candidate diagnoses. By the described elimination mechanism (implementing the generate and test strategy) the set of candidate diagnoses shrinks until only diagnoses compatible with the patient's ECG are left in the set.

The menu-driven communication module leads the user when choosing among functions of the system. We will only mention the most important functions of the system namely the input of the patient's ECG data, diagnosis, explanation and instruction of arrhythmias.

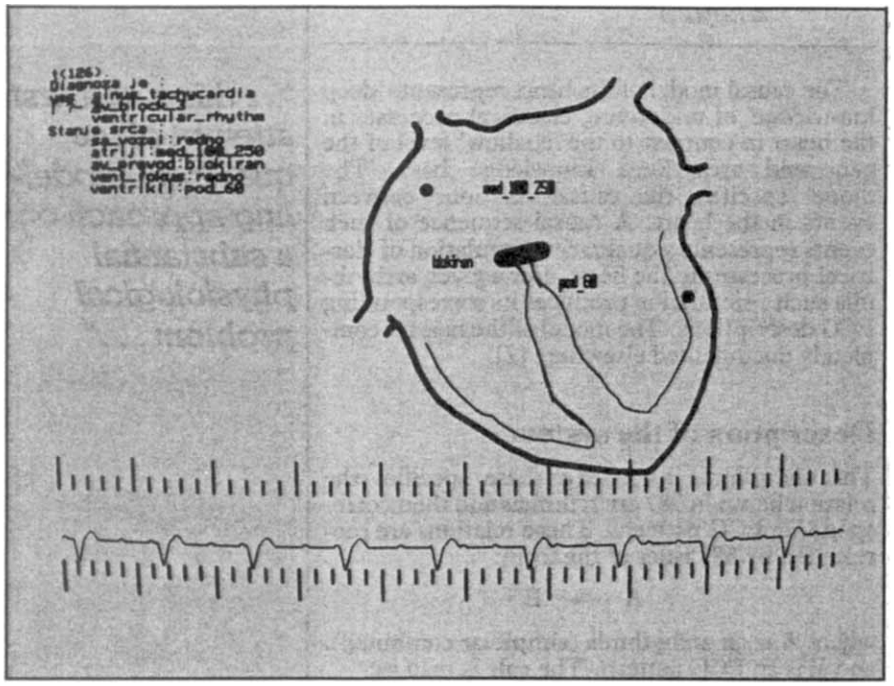

Figure 2: *The graphics facility in KARDIO: a schematic illustration of the heart failures and an automatically generated ECG signal (below) that corresponds to this arrhythmia (in this case the arrhythmia is the combination of sinus tachycardia, av block 3 and ventricular rhythm).*

Normally the user first enters the patient's ECG data. The user is helped by the system's queries for specifying for each attribute its value from a menu of all its possible values. For any attribute the user can select also the value 'unknown'. User's choice of this value is interpreted as if all the values for the attribute were possible (so no arrhythmia gets eliminated on the basis of this attribute). Once the patient's ECG has thus been specified the user may request the diagnosis.

If the system's diagnosis contradicts the user's opinion he can ask the system for an explanation why a certain diagnosis (the one that he considered to be correct) was excluded. The system then outputs the values of attributes which eliminated the user's hypothesis from the set of possible arrhythmias. If such an arrhythmia is even theoretically impossible regardless of the patient's ECG the explanation consists of those constraints in the model of the heart that eliminated this arrhythmia from the initial set of all candidate diagnoses.

The instruction function generates problems for the user so that a user is asked to interpret a randomly chosen ECG description. This function is supported by a graphic facility for generating and displaying of ECG curves. These ECG diagrams are synthetically generated from their ECG descriptions. Figure 2 shows an example.

Results of an assessment study

The testing of the system's correctness and completeness was performed by three cardiologists. The testing was made on thirty-six cases from clinical practice for which the patients' electrocardiograms with all the twelve leads were available. The evaluation was based on comparing the system's diagnoses with the diagnoses given by the cardiologists. The evaluation showed several deficiencies which prompted the development of an improved, substantially more complex second version of the arrhythmia knowledge base (consisting of 8314 rules, relating 2419 arrhythmias to 140,966 corresponding ECG patterns) [2].

An assessment study of the applicability of the KARDIO-E expert system was performed by two specialist, cardiologists [7]. By their estimation the system using the second version of the knowledge base is sufficient for correctly handling 95% of patients suffering from arrhythmias. More precisely: The system is estimated to be able to correctly identify about 95% of rhythm disturbances which can be noted on ECG recordings of a non-selected population, e.g. in preventive or systematic check-ups. In a selected population (e.g. patients referred to the cardiologists by their family doctors on the account of underlying anamnestic data, clinical examinations or preliminary ECGs) the identification capability would be 75% of arrhythmia cases.

Thus one conclusion of the cardiologist's estimation is that the performance of KARDIO-E is equivalent to that of a specialist of internal medicine (non-cardiologist) highly skilled in reading of ECG recordings. Therefore it would be appropriate to introduce the system in the routine assessment of ECG recordings in preventive or systematic examinations, e.g. before surgery or in general medical practice. The KARDIO-E expert system would enable the medical staff to select the patients on the basis of their ECG recordings and it also could suggest different diagnostic possibilities. The system is reliable in excluding ECG tracings which are not in need of attention from the cardiologist and thus enhancing the possibility of patients needing cardiological treatment to get it as soon as possible.

In the diagnosis of arrhythmia, the clinical condition of the patient as well as his anamnestic data are always taken into account in addition to the

ECG recording, so that the final diagnosis should be made by the cardiologist before initiating therapy. The diagnostic alternatives suggested by KARDIO-E are a valuable asset in the cardiologist's work.

The cardical studies of arrhythmia are time and effort-consuming therefore KARDIO-E has already achieved an important role in the education of all medical profiles. Operating the system is interesting and broadening the medical knowledge owing to the possible combinations. It is more useful in practice as it better resembles real assessment of the ECG than classical ECG studies. Its particular advantage is the shortened educational time. KARDIO-E is of particular interest in the education of (a) nurses and medical technicians (taking routine ECG recordings or those working in coronary units), (b) students of medicine and general practitioners wanting to improve their understanding of cardiac arrhythmias, and (c) specialists in internal medicine and specialists of non-internal branches of medicine to up-date their knowledge.

Concluding remark

Using the improved version of the knowledge base the KARDIO-E expert system would already be interesting for practical use in routine ECG diagnosis and in instruction. Our plan is to connect the KARDIO-E system to one of the diagnostic analysis systems thus obtaining a powerful automatic diagnostic tool.

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RECENT ARTICLES

• **Les systèmes experts (III): des noyaux qui ont la pêche.** J. Ferber, *Micro-Systèmes*, 43, Juin 1984, pp. 68–73.

Examines an essential part of expert systems — the interference engine and looks at the elements making this up. Describes a number of tools for building expert systems such as Emycin, KAS, OPSS, Tango, Snark, Hearsay-III, RLL and Mering.

• **Expert vs. management support systems: semantic issues.** Ronald M. Lee, *Cybernetics and Systems,* 14, 2–4, April– Dec. 1983, pp. 139–157.

Expert systems hold great promise for technical application areas such as medical diagnosis or engineering design. They are, we argue, less promising for management applications. The reason is that managers are not experts in the sense of possessing a formal body of knowledge which they apply. The limitations of artificial intelligence approaches in managerial domains is explained in terms of semantic change, motivating attention toward management (decision) support systems.

• **Les systèmes experts.** Marie-Odile Cordier, *La Recherche,* 15, 151, Janvier 1984.

A basic summary of 'what is an expert system,' with a list of examples of actual systems from the USA and from France.

• **The machine as partner of the new professional.** F. Hayes-Roth, *IEEE Spectrum,* 216, June 1984, pp. 28–31.

Today's instruments are providing more data than the mind can process — expert systems are coming to the rescue but may soon usurp human roles. Milestones — past and predicted — in knowledge engineering are also given.

• **Les premiers systèmes experts en CFAO.** Michael Rueher, *Electronique Industrielle,* 70, May 1984, pp. 55–58.

An article by Michael Rueher of INSA detailing a number of expert systems developed in France in the area of computer-aided design (CAD). Discusses systems such as Tropic, Carter, Peace, Gari and Argos II.

• *MIAI-Micro Systems,* XVII, 9, July 1984, pp. 89, 91.

Microsoft Corp. (USA) is expected to offer expert-system construction software within the next two years based on Expert-Ease, a package that can generate decision-making rules from information entered in a form similar to a spreadsheet. Microsoft will collaborate on the venture with Expert Software International Ltd., (Scotland). Nixdorf (FRG) is offering expert-system "spells" requiring a Unix host and Digital Research Inc. (USA) is also preparing expert-system products for the home consumer market.

• **Les systèmes experts (fin): du mythe à la realité,** J. Ferber, *Micro-systèmes,* 44, Juillet–Août 1984, pp. 112–114.

Looks at the practical side of expert systems, their selection and difficulties encountered in their development.

• **Why computers can't outthink the experts.** T. Alexander, *Fortune,* 110, 4, 20 Aug. 1984, pp. 105, 106, 108, 112, 114–116, 118.

Contends that expert systems have no special claim to "intelligence" and display fewer of the attributes classically associated with intelligence. A major weakness of medical ES programs is that they don't learn medicine the way doctors do and are instead programmed with rules of thumb. Article discusses these and other aspects, describes the applications for which ESs are best suited and gives a few examples.

• **Artificial intelligence for engineering design.** M.K. Simmons, *Computer-Aided Engineering,* 1, April 1984, pp. 75–83.

Looks first at engineering design and then considers what AI could contribute to it. Reviews some engineering projects involving AI techniques as well as related AI design projects. Among the potential benefits of the use of AI techniques is the packaging of human expertise into expert system software.