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CONTENT

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EXPERT SYSTEM APPLICATION IN SUPPORT OF AUTOMATED ECG DIAGNOSIS

Roman Golubovski and Gjorgji Markoski

Abstract. An expert system (ES) is software that uses a knowledge base of human expertise for problem solving, or clarify uncertainties where normally one or more human experts would need to be consulted. Expert systems are commonly used in a specific problem domain, and traditionally are an application subfield of artificial intelligence (AI). Expert systems may or may not have learning components, and are based on the propositional logic. One of the fundamental implementation areas is the medical diagnostics, specifically the automated ECG diagnostics since the ECG morphology is completely determined. The proposed ES relies on the standard 12-lead ECG set of relevant voltage deflections and time segments and intervals. Preliminary testing on ECG records shows accuracy consistent with diagnostic opinions of expert cardiologists.

1. Introduction to propositional logic

A common and acceptable definition of the Expert System (ES) is that it is a special type of system built upon detailed experience and knowledge acquired by human brain, and formatted in such a way that it allows a computer to solve problems from within a specific domain that normally need human expertise. In the context of this paper, the "problem" is the ECG diagnosis and the "expert" is a skilful cardiologist.

The mathematical background of the ES formalism is the propositional logic. Propositional logic may be viewed as a representation language which allows expression and reasoning with statements that are either true or false. Statements like these are called propositions and are usually denoted in propositional logic by uppercase letters. Simple propositions such as P and Q are called atomic propositions or atoms for short. Atoms can be combined with the so-called logical connectives to yield composite propositions. In the language of propositional logic, the following five connectives are at disposal as illustrated in the explanatory Table 1:

- negation: $\neg$ (not)
- conjunction: $\wedge$ (and)
- disjunction: $\vee$ (or)
- implication: $\rightarrow$ (if then)
- bi-implication: $\leftrightarrow$ (if and only if)

Table 1. *The meanings of the connectives*

F	G	$\neg F$	$F \wedge G$	$F \vee G$	$F \rightarrow G$	$F \leftrightarrow G$
true	true	false	true	true	true	true
true	false	false	false	true	false	false
false	true	true	false	true	true	false
false	false	true	false	false	true	true

In propositional logic, atoms are the basic constituents of formulas that are either true or false. A limitation of propositional logic is the impossibility to express general statements concerning similar cases. First-order predicate logic is more expressive than propositional logic, and such general statements can be specified in its language. In predicate logic, the following symbols are used: Predicate symbols, Variables, Function symbols, logical connectives, quantifiers and auxiliary symbols.

Logical deduction is a method for establishing the validity of propositional type arguments. Rules of inference are well-established arguments that help in proving complex arguments through a process of logical deduction.

In general, an inference rule is given as a schema in which a kind of meta-variables occur that may be substituted by arbitrary formulas. An example of such a schema is:

$$\frac{A, A \circledR \quad B}{B}$$

The formulas above the line are called the premises, and the formula below the line is called the conclusion of the inference rule. The above-given inference rule is known as modus ponens, and when applied, it removes an implication from a formula. Another example of an inference rule, in this case for introducing a logical connective, is the following schema:

$$\frac{A, B}{A \grave{U} B}$$

Rules of inference are the following:

Modus ponens $\frac{P, P \to Q}{Q}$	Modus tollens $\frac{P \to Q, \neg Q}{\neg P}$
Hypothetical syllogism $\frac{P \to Q, Q \to R}{P \to R}$	Disjunctive syllogism $\frac{P \vee Q, \neg P}{Q}$
Conjunction elimination $\frac{P, Q}{P}$	Disjunctive introduction $\frac{P}{P \vee Q}$
Conjunction introduction $\frac{P, Q}{P \wedge Q}$	Constructive dilemma $\frac{(P \to Q) \wedge (R \to S), P \vee R}{Q \vee S}$
Destructive dilemma $\frac{(P \to Q) \wedge (R \to S), \neg Q \vee \neg S}{\neg P \vee \neg R}$	Contrapositive $\frac{P \to Q}{\neg Q \to \neg P}$
Reductio ad Absurdum $\frac{P \to (Q \wedge \neg Q)}{\neg P}$	Double negation $\frac{\neg\neg P}{P}$

Theoretical details on how ES can be built based on propositional logic are widely available [1]. Applications of ES are common as attempts to predict (for example earthquakes [2]) or diagnose (for example medical conditions [3, 4, 5, 6, 7]).

2. Introduction to expert systems

The fundamental concept behind the ES is mimicking human reasoning, which is still impossible to achieve in full. The human mental process is for now too complex to be understood and represented as an algorithm. However, most experts are able to solve problems within their domain by expressing their knowledge in the form of rules. The term rule in AI, which is the most commonly used type of knowledge representation, can be defined as an IF-THEN structure that relates given information or facts in the IF part (the condition) to some action in the THEN part (the action). A rule describes how to solve a problem. Rules are relatively easy to create and understand. Rules represent relations, recommendations, directives, strategies and heuristics. In the context of this paper, rules test ECG parameters with threshold values in their conditional part and draw partial diagnostic conclusions. The foundation of the modern ES is the ***production*** rule system model proposed by Newell & Simon (Figure 1).

The production model solves problems by applying the corresponding knowledge expressed as production rules, assuming that problems are represented by problem-specific information. The ***knowledge base*** contains the domain-specific knowledge useful for solving the problem. A rule is said to ***fire*** when its condition part is satisfied, after which its action part is executed. The ***database*** (*working memory*) includes a set of facts used to match against the IF (condition) parts of rules stored in the knowledge base. The ***inference engine*** implements the reasoning by which the expert system reaches a solution. It links the rules defined in the knowledge base with the facts formatted in the database. The ***explanation facilities*** provide the user with details on ***how*** the expert system reached a particular conclusion and ***why*** a specific fact is needed. An expert system is expected to explain its reasoning and justify its advice, analysis or conclusion. A user looking for a solution to a problem communicates with the expert system through a ***user interface***.

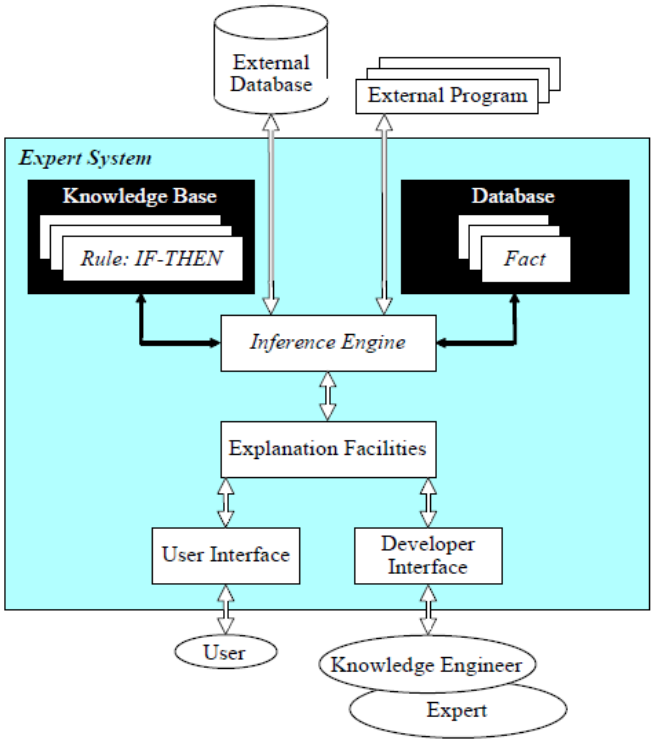

Figure 1. *Complete structure of a rule-based ES*

Modern ECG devices widely implement ES, but it is still just a helping tool to assist physicians in ECG interpretation (which as unverified must not be used as diagnostic source). So, being able to explain the deductive reasoning (forward or data-driven inference chaining) helps physicians in validating their conclusions.

3. Data definition and implementation

The standard 12-lead ECG consists of the six limb leads in the vertical plane - aVR, aVL, aVF, DI, DII and DIII (figure 2), and the six precordial leads in the horizontal plane - V1, V2, V3, V4, V5 and V6 (Figure 3).

ECG records provide non-invasively obtained data usable for assessment of a patient's heart condition. ECG features, when recognized by simple observations, and combined with heart rate, can lead to a fairly accurate and fast diagnosis.

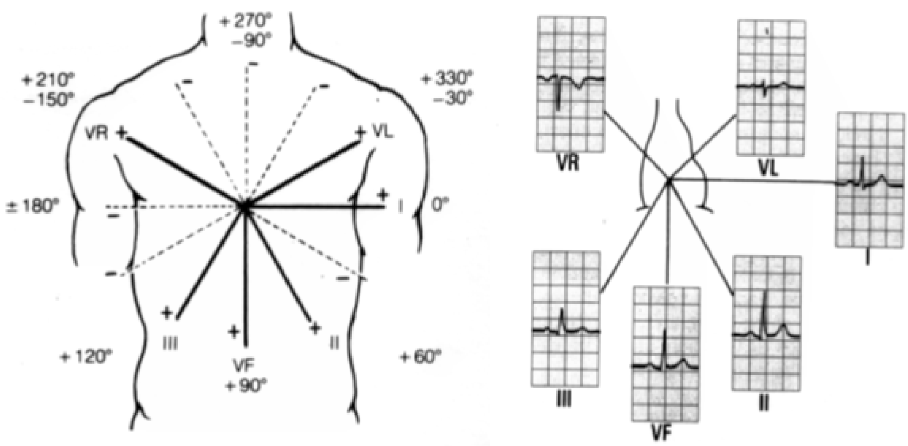

Figure 2. The limb leads

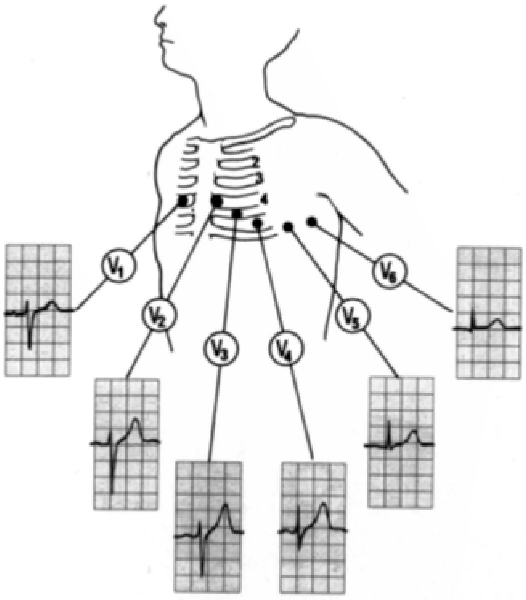

Figure 3. *The precordial leads*

So far, there have been a number of successful developments in the automated diagnosis domain. Like the ES for ECG analysis [3] that works by hierarchically organizing the knowledge in a context tree, where diseases are recognized by traversing the tree having symptoms as nodes and diseases as leafs. Others [4] have used time and frequency domain parameters and correlation constants derived from ECG signals as inputs for their expert system. A software for ECG beat detection and classification [5] had been developed and made available as an open source system for use by researchers. A technique for analysing ECG signals using hidden Markov models for beat segmentation and classification [6] had also been proposed. The use of neural networks for automatic ECG analysis for the classification of different cardiac abnormalities [7] had also been explored.

Typical ECG morphology is presented in Figure 4. The proposed expert system concept/algorithm is a rule-based decision support system that aids physicians in the diagnosis of possible heart diseases. The set of extracted ECG parameters of all 12 leads is related to voltage deflections and time segments/intervals:

- P wave
- QRS complex (Q, R and S strokes)
- ST segment
- T wave
- PR interval
- QRS duration
- QT interval
- RR interval
- PP interval

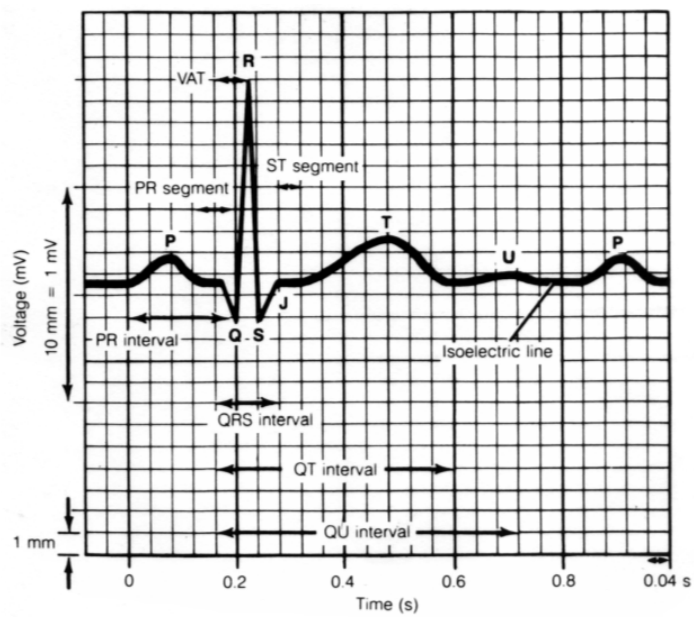

Figure 4. *Typical ECG morphology*

4. The expert system algorithm

The proposed ES is based on the concept shown in Figure 1. The framework of the rule based ES consists of:

- Facts - input obtained from derived parameters of the 12-lead ECG
- Knowledge Base - a set of rules developed in consultation with experts based on heart rate and ECG wave characteristics (parameters)
- Inference Engine - matches the input (facts) with a rule in the rule-base to identify the abnormality
- Database - stores the patient's personal details, inputs, diagnosed results and user's comments (suggestions)
- Explanation Facilities - provide the forward inference chaining in support of the proposed diagnosis

After thorough and systematic analysis of the available relations between the diagnostic conclusions and the corresponding sets of input values, all proposed ECG diagnoses are divided into the following list of groups, which are chained in an evaluating order. Each group (listed below) consists of *familiar* diagnostic statements:

- Preliminaries
- Conduction Abnormalities
- Hypertrophy
- Myocardial Infarct
- ST Elevation
- ST Depression
- T Wave Abnormalities
- Rhythm Statements

The algorithm (Figure 5) passes through the chain of groups performing strictly ordered lists of tests. After a group is evaluated (tested), the results are passed to the next group of tests. Prior to effectively evaluating a group, ***skip tests*** are performed. Skip tests decide whether group's evaluation is feasible or the available data is insufficient (the latter resulting in skipping the current group).

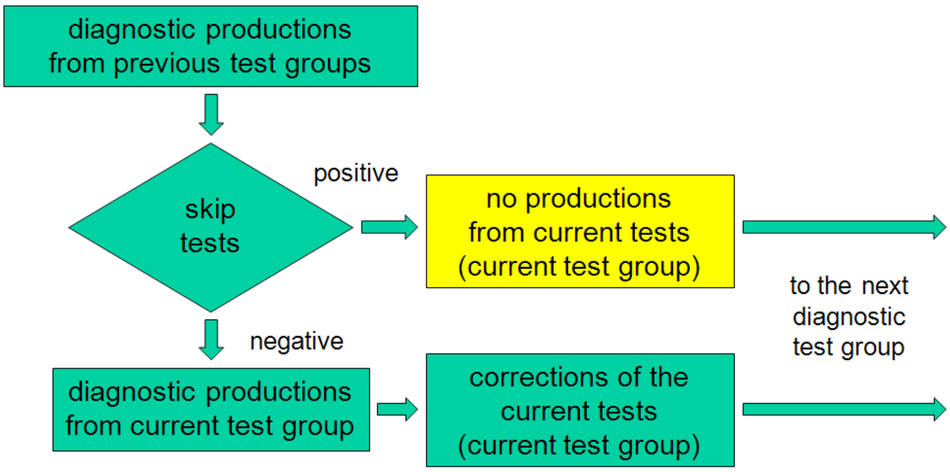

Figure 5. *Algorithm of diagnostic chain*

A condition statement follows each interpretive statement. Conditions and their meanings are listed in Figure 6.

Condition	Meaning
Normal ECG	Normal
Atypical ECG	An unusual pattern has been observed but has no specific significance.
Borderline ECG	Criteria have limited specificity or prognostic significance or where only minimal criteria are met.
Abnormal ECG	Abnormal
Abnormal Rhythm ECG	Abnormal Rhythm
No Further Interpretation Possible	Upon detecting the phenomenon in question, no further useful interpretation of the record is possible.
No Condition Associated	Used with statement prefixes and suffixes.

Figure 6. *General condition statements and explanation*

The ***Preliminaries*** group identifies the following conditions: Arm Lead Reversal and Dextrocardia; Wolff-Parkinson-White (WPW); Atrial Enlargement; Axis Deviation; Low Voltage; S1-S2-S3 Pattern; Pulmonary Disease.

The ***Conduction Abnormalities*** are: Right Bundle Conduction; Left Bundle Conduction; Non Specific Conduction Abnormality.

The ***Hypertrophies*** are: Right Ventricular Hypertrophy; Left Ventricular Hypertrophy.

The ***Myocardial Infarctions*** are: Anterior Infarct; Septal Infarct; Anteroseptal Infarct; Lateral Infarct; Anterolateral Infarct; Inferior Infarct; Inferior Infarct with Posterior Extension; Infarct Suppressions.

The ***ST Elevation*** diagnoses are: ST Segment Elevation; Early Repolarization; Pericarditis; Anterior and Septal Epicardial Injury; Lateral Epicardial Injury; Inferior Epicardial Injury.

The ***ST Depression*** diagnoses are: ST Depression; T Wave Abnormality and Ischemia.

The ***T Wave Abnormalities*** are: T Wave Abnormality, Nonspecific.

Rhythm Statements: Sinus-, Atrial-, Junctional-, Supraventricular- (Tachycardia / Rhythm / Bradycardia); Undetermined (regular) rhythm; Atrial fibrillation; Atrial flutter; Electronic ventricular pacemaker. Known modifiers are also used for recognized specific condition details.

5. Illustration of some ES production tests

First tests are the Preliminaries that check whether leads are correctly positioned and measurements are generally within the physiological ranges. The test for possible lead reversal is given in Figure 7:

IF	THEN
No Q in lead I and R amplitude < 150uV in lead I **or** Q amplitude > 0 in lead I and P axis > 90 and PR duration >= 110 ms and QRS axis > 90	PRINT "Arm leads reversed" **REASON**: *Inverted P & QRS in lead I*
If above criteria are met and R amplitude < 500 uV in lead V6 and Maximum S amplitude > Maximum R amplitude in lead V6 and P amplitude < 20 uV in lead V6 and P' amplitude < -20 uV in lead V6	PRINT "Dextrocardia" **REASON**: *Inverted P & QRS in V6*

Figure 7. *Test for Arm Lead Reversal and Dextrocardia*

Figures 8 and 9 show the amount of processing needed for incomplete and complete LBBB determination respectively. Figure 10 shows the ***skip*** tests for the Right Ventricular Hypertrophy. Figure 11 shows the test for Septal Infarct:

IF	THEN
QRS duration > 105 ms and QRS net amplitude < 0 in V1 & V2 S duration >= 80 ms in V1 & V2 and no Q is present in 2 leads of I/V5/V6 and R duration >= 60 ms in 2 leads of I/aVL/V5/V6	PRINT Incomplete left bundle branch block **REASON**: *105+ ms QRS duration, 80+ ms Q/S in V1/V2* *no Q and 60+ ms R in I/aVL/V5/V6*
QRS axis < = -45 and R amplitude > Q amplitude in I & aVL and a Q is present in I and S or S' amplitude > R amplitude in II	PRINT Left anterior fascicular block **REASON**: *QRS axis < -45, QR in I, RS in II*
The test for S1-S2-S3 is negative, and the test for Pulmonary Disease is negative and QRS axis >= 110 and R amplitude > Q amplitude in III & aVF and a Q is present in III & aVF	PRINT Left posterior fascicular block **REASON**: *QRS axis > 109, inferior Q*

Figure 8. *Left Bundle Conduction test for Incomplete Block*

IF	THEN
The test for Incomplete Left Bundle Branch Block is positive and QRS area ratio > 0.25 in I or V6 and R duration >=100 ms in 1 lead of I/aVL/V6 and QRS duration >= 160 ms **or** QRS duration >= 140 ms and the average R duration > 85 ms in I/aVL/V6 **or** QRS duration >= 120 ms and the average R duration > 85 ms in I/aVL/V6 and QRS area ratio > 0.4 in 2 leads of I/aVL/V6	PRINT Left bundle branch block **REASON**: *120+ ms QRS duration, 80+ ms Q/S in V1/V2, 85+ ms R in I/aVL/V6*

Figure 9. *Left Bundle Conduction test for Complete Block*

SKIP TEST IF
The test for Right Bundle Branch Block is positive
or the test for Left Bundle Branch Block is positive
or age < 16
or S amplitude < 250 uV in I
or S amplitude > 1000 uV in V1
or QRS axis < 60
or QRS duration > 140 ms and net QRS amplitude < 0 in V1
or Q amplitude > S amplitude and R exists in I

Figure 10. *Skip test for Right Ventricular Hypertrophy*

SKIP TEST IF
The test for left bundle branch block is positive **or** the test for anterior infarct is positive and Q amplitude > 0 in V1 **or** QRS duration > 140 ms and net QRS amplitude < 0 in V1

IF	THEN
STM and STE amplitude > 200 uV in V2 and alternate T amplitude >= 0 in V2	New septal infarct is present
STM and STE amplitude > 50 uV in V2 and alternate T amplitude < 0 in V2	Recent septal infarct is present
Septal infarct is not new or recent and STM amplitude < 50 uV in V2 and alternate T amplitude >= 0 in V2	Septal infarct is old
The criteria for a septal infarct have been met and it is neither new, recent, or old	Qualifier age undetermined will be used
Equivalent Q duration >= 30 ms in V2 **or** the test for Right Bundle Branch Block is positive and Equivalent Q duration > 20 ms in V2	PRINT Cannot rule out septal infarct **REASON**: *30 ms Q wave in V1/V2*
Equivalent Q duration >= 35 ms in V2 and left ventricular hypertrophy flag is not set	PRINT Possible septal infarct **REASON**: *35 ms Q wave in V1/V2*
Equivalent Q duration >= 40 ms in V2 and the left ventricular hypertrophy flag is not set	PRINT Septal infarct **REASON**: *40+ ms Q wave in V1/V2*

IF	THEN APPEND
Septal infarct is new	possibly acute
Septal infarct is new	probably recent
The age of the septal infarct is undetermined	age undetermined
Septal infarct is old	probably old

Figure 11. *Testing for Septal Infarct*

6. Conclusion

Expert Systems are a successful implementation of the propositional logic in the Artificial Intelligence (AI) domain. The depicted ES application conceptualizes standard cardiologists' reasoning, following the standard ambulatory cardiology expertise, supported by the established clinical ECG experience. The data-chaining of the parameters tests follows the well-established ECG diagnostic procedures, therefore high accuracy and reliability is expected upon thorough clinical performance investigation.

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