ภาคผนวก ก.

ตัวอย่างกฎและความจริงในฐานความรู้

ความจริงเริ่มต้นในฐานความรู้ของระบบ

```
Fact 1
((logo system)(ready)=(atomic true))

Fact 2
((input_sound system)(ready)=(atomic true))

Fact 3
((run_spec system)(start)=(atomic true))

Fact 4
((fit_spec system)(start)=(atomic true))
```

กฎในฐานความรู้ของระบบ

```
identify 1 logo
if
((logo system)(ready)=(atomic true))
((input_sound system)(ready)=(atomic true))
then
(@logo)
((menu system)(loaded)=(atomic true))
end-of-rule
#-----------------------------
identify 2 select_menu
if
((menu system)(loaded)=(atomic true))
then
(@menu)
((select menu)(select_menu)=(atomic true))
end-of-rule
#-----------------------------
identify 3 insert_info
if
((select menu)(select_menu)=(atomic true))
then
(@patient_info)
((insert patient)(info)=(atomic true))
end-of-rule
#-----------------------------
identify 4 insert_heart_sound
if
((select menu)(select_menu)=(atomic true))
((insert patient)(info)=(atomic true))
then
((heart_sound patient)(loaded)=(atomic true))
end-of-rule
#-----------------------------
identify 5 run_spec
if
((heart_sound patient)(loaded)=(atomic true))
((run_spec system)(start)=(atomic true))
then
(@run_spec)
((run_spec system)(finished)=(atomic true))
end-of-rule
#-----------------------------
identify 6 fit_spec
if
((select menu)(select_menu)=(atomic true))
```

```
((heart_sound patient)(loaded)=(atomic true))
((run_spec system)(finished)=(atomic true))
((fit_spec system)(start)=(atomic true))
then
(@fit_spec)
((fit_spec system)(finished)=(atomic true))
end-of-rule
#-----------------------------
identify 7 diag_sound
if
((run_spec system)(finished)=(atomic true))
((fit_spec system)(finished)=(atomic true))
then
(@diag_sound)
((diag heart_sound)(checked)=(atomic true))
end-of-rule
#-----------------------------
identify 8 diag_heart
if
((diag heart_sound)(checked)=(atomic true))
then
((sample heart_sound)(ask_lub)=(atomic true))
((sample heart_sound)(ask_dub)=(atomic true))
;((sample heart_sound)(ask_lub&dub)=(atomic true))
end-of-rule
#-----------------------------
identify 9 diag_heart
if
((sample heart_sound)(has_lub)=(atomic true))
((sample heart_sound)(no_dub)=(atomic true))
then
(@menu_diag_error)
(@menu)
((diag system)(finished)=(atomic true))
end-of-rule
#-----------------------------
identify 10 diag_heart
if
((sample heart_sound)(no_lub)=(atomic true))
((sample heart_sound)(has_dub)=(atomic true))
then
(@diag_error)
(@menu)
((diag system)(finished)=(atomic true))
end-of-rule
#-----------------------------
identify 11 diag_heart
if
```

```
((sample heart_sound)(no_lub)=(atomic true))
((sample heart_sound)(no_dub)=(atomic true))
((sample heart_sound)(no_lub&dub)=(atomic true))
then
(@diag_error)
(@menu)
((diag system)(finished)=(atomic true))
end-of-rule
#-----------------------------
identify 12 diag_heart
if
((sample heart_sound)(has_lub)=(atomic true))
((sample heart_sound)(has_dub)=(atomic true))
((sample heart_sound)(has_lub&dub)=(atomic true))
then
((diag patient)(alive)=(atomic true))
((symptom patient)(ask_symptom)=(atomic true))
end-of-rule
#-----------------------------
identify 13 diag_heart
if
((diag patient)(alive)=(atomic true))
((symptom patient)(tried)=(atomic true))
then
((sample heart_sound)(ask_other_sound)=(atomic true))
((sample heart_sound)(ask_murmur)=(atomic true))
end-of-rule
#-----------------------------
identify 14 diag_heart
if
((diag patient)(alive)=(atomic true))
((sample heart_sound)(has_other_sound)=(atomic true))
((sample heart_sound)(no_murmur)=(atomic true))
then
(@diag_error)
(@menu)
((diag system)(finished)=(atomic true))
end-of-rule
#-----------------------------
identify 15 diag_heart
if
((diag patient)(alive)=(atomic true))
((sample heart_sound)(has_other_sound)=(atomic true))
((sample heart_sound)(has_murmur)=(atomic true))
then
((sample heart_sound)(ask_quiet)=(atomic true))
((sample heart_sound)(ask_silent)=(atomic true))
end-of-rule
```

```
#-----------------------------
identify 16 diag_heart
if
((diag patient)(alive)=(atomic true))
((sample heart_sound)(has_lub)=(atomic true))
((sample heart_sound)(has_quiet)=(atomic true))
((sample heart_sound)(has_dub)=(atomic true))
((sample heart_sound)(has_silent)=(atomic true))
then
(@diag_normal)
((diag system)(finished)=(atomic true))
end-of-rule
#-----------------------------
identify 17 diag_heart
if
((diag patient)(alive)=(atomic true))
((sample heart_sound)(has_lub)=(atomic true))
((sample heart_sound)(has_dub)=(atomic true))
((sample heart_sound)(has_quiet)=(atomic true))
((sample heart_sound)(no_silent)=(atomic true))
then
((sample heart_sound)(diastolic)=(atomic true))
end-of-rule
#-----------------------------
identify 18 diag_heart
if
((sample heart_sound)(diastolic)=(atomic true))
then
((sample heart_sound)(ask_sissss)=(atomic true))
((sample heart_sound)(ask_urrrr)=(atomic true))
end-of-rule
#-----------------------------
identify 19 diag_heart
if
((sample heart_sound)(diastolic)=(atomic true))
((sample heart_sound)(has_lub)=(atomic true))
((sample heart_sound)(has_quiet)=(atomic true))
((sample heart_sound)(has_dub)=(atomic true))
((sample heart_sound)(has_sissss)=(atomic true))
then
(@diag_AI)
((diag system)(finished)=(atomic true))
end-of-rule
#-----------------------------
identify 20 diag_heart
if
((sample heart_sound)(diastolic)=(atomic true))
((sample heart_sound)(has_lub)=(atomic true))
```

```
((sample heart_sound)(has_quiet)=(atomic true))
((sample heart_sound)(has_dub)=(atomic true))
((sample heart_sound)(has_urrrr)=(atomic true))
then
(@diag_MS)
((diag system)(finished)=(atomic true))
end-of-rule
#------------------------------
identify 21 diag_heart
if
((diag patient)(alive)=(atomic true))
((sample heart_sound)(has_lub)=(atomic true))
((sample heart_sound)(has_dub)=(atomic true))
((sample heart_sound)(no_quiet)=(atomic true))
((sample heart_sound)(has_silent)=(atomic true))
then
((sample heart_sound)(systolic)=(atomic true))
end-of-rule
#------------------------------
identify 22 diag_heart
if
((sample heart_sound)(systolic)=(atomic true))
then
((sample heart_sound)(ask_siss)=(atomic true))
((sample heart_sound)(ask_sssurr)=(atomic true))
end-of-rule
#------------------------------
identify 23 diag_heart
if
((sample heart_sound)(systolic)=(atomic true))
((sample heart_sound)(has_lub)=(atomic true))
((sample heart_sound)(has_siss)=(atomic true))
((sample heart_sound)(has_dub)=(atomic true))
((sample heart_sound)(has_silent)=(atomic true))
then
(@diag_MI)
((diag system)(finished)=(atomic true))
end-of-rule
#------------------------------
identify 24 diag_heart
if
((sample heart_sound)(systolic)=(atomic true))
((sample heart_sound)(has_lub)=(atomic true))
((sample heart_sound)(has_sssurr)=(atomic true))
((sample heart_sound)(has_dub)=(atomic true))
((sample heart_sound)(has_silent)=(atomic true))
then
(@diag_AS)
```

```
((diag system)(finished)=(atomic true))
end-of-rule
#------------------------------
identify 25 diag_heart
if
((diag patient)(alive)=(atomic true))
((sample heart_sound)(has_lub)=(atomic true))
((sample heart_sound)(has_dub)=(atomic true))
((sample heart_sound)(no_quiet)=(atomic true))
((sample heart_sound)(no_silent)=(atomic true))
then
((sample heart_sound)(continuous)=(atomic true))
end-of-rule
#------------------------------
identify 26 diag_heart
if
((sample heart_sound)(continuous)=(atomic true))
then
((sample heart_sound)(ask_siss)=(atomic true))
((sample heart_sound)(ask_sissss)=(atomic true))
end-of-rule
#------------------------------
identify 27 diag_heart
if
((sample heart_sound)(systolic)=(atomic true))
((sample heart_sound)(has_lub)=(atomic true))
((sample heart_sound)(has_siss)=(atomic true))
((sample heart_sound)(has_dub)=(atomic true))
((sample heart_sound)(has_sissss)=(atomic true))
then
(@diag_PDA)
((diag system)(finished)=(atomic true))
end-of-rule
#------------------------------
identify 28 modify
if
((select menu)(select_menu_modify)=(atomic true))
then
(@modify)
((select menu)(select_menu)=(atomic true))
end-of-rule
#------------------------------
identify 29 help
if
((select menu)(select_menu_help)=(atomic true))
then
(@help)
(@menu)
```

```
((select menu)(select_menu)=(atomic true))
end-of-rule
#------------------------------
identify 30 report
if
((diag system)(finished)=(atomic true))
then
(@report)
((diag system)(returned)=(atomic true))
end-of-rule
#------------------------------
```

ภาคผนวก ข.

บทความทางวิชาการที่นำเสนอใน

การประชุมวิชาการ

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Feature Extraction from Phonocardiogram for Diagnosis based on Expert System

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Abstract— **This paper describes a method for extracting features from a phonocardiogram to be used by an expert system for diagnostic purposes. The key issue is to choose features which match with the doctor's (expert's) diagnostic approach. Only in that way can the knowledge of the expert be effectively coded into rules within an expert system.**

I. INTRODUCTION

The phonocardiogram contains information historically proven of value in the diagnosis of heart disease. The conventional method for processing this information is auscultation, in which the doctor listens to the signal directly and makes an interpretation of the heart's condition based on the sound of the signal.

The interpretation is highly subjective. It is therefore difficult to achieve results which are consistent at any one time amongst any group of practitioners, or stable over time for any single practitioner. In addition, it is difficult to pass hard won knowledge from the expert practitioner on to the medical student.

It is reasonable to suppose that a higher level of diagnostic consistency and educational efficacy can be achieved if an effective system can be devised which either replaces or complements the subjective method with a formalized, documented, fully objective technique.

Various approaches to develop such a system have been reported. These fall largely into two categories: artificial neural networks [1], [2], [3], [4], and expert systems [5], [6], [7]. In both cases the method is to first extract some parameters from the phonocardiogram, and then determine a diagnosis based on those parameters. In the first case a neural network is used to make the determination. In the second case an expert system is used.

In principle the expertise of the doctor can be coded as rules directly into an expert system [8]. The system is not a static one, in the sense that the doctor and system can interchange information – the system by reporting in language that the doctor can understand why it makes any particular diagnosis, and the doctor by modifying the rules to account for new cases not envisaged at the outset. Such an interaction helps to improve both the expert system and the expertise of the doctor.

On the other hand, the neural network encodes the expertise of the doctor by the way of example diagnoses. The neural network is unable to tell the doctor why it makes any particular diagnosis. If a bad diagnosis is made there is no direct path by which the doctor can either understand the problem or rectify it. More training data (examples) can be given – but there is no certitude in this approach and the additional examples can in principle bias the system so as to make other examples, for which the diagnosis was formerly correct, fail. It is possible to get trapped into a never ending loop of providing additional examples without significantly improving the system.

Regardless of whatever method is used to determine the diagnosis, the overall effectiveness of the entire system depends crucially on the parameters chosen to represent the phonocardiogram. Two things can go wrong if the parameters are not chosen carefully. The first is that information can be destroyed, and valuable diagnostic clues lost. The second is that the information can be cast into a form entirely foreign to the expert. This renders it impossible to make direct use of the expert's knowledge to process the information.

It is our impression that the systems reported in the literature concentrate primarily on the detailed technical issues, and fall somewhat short in regard to these more fundamental issues. It is our contention that the neural network approach, perhaps admirably suited to many problems, is poorly suited to this particular application. In addition, it is out feeling that a greater deal of thought needs to be put into the selection of parameters that closely parallel the way in which the expert analyses the phonocardiogram. In this paper we focus on these ideas, and seek an approach which leads to an effective system.

II. APPROACH

The approach adopted here is to extract features from the phonocardiogram on the basis of what we perceive as the chain of signal processing operations occurring inside the head of the expert practitioner, with the aim of encoding the knowledge of the expert into an expert system using rules that operate with reference to those very features.

A. Philosophy

We first note at a mechanistic level that the phonocardiogram as recorded electronically and as arriving at the ear is a one-dimensional function of time, *i.e.* a waveform. Within the inner ear this signal is separated into different frequencies – each a function of time. At this stage of the processing the signal is in the form of a two-dimensional function of frequency and time, *i.e.* a spectrogram (*cf.* [9], [10]).

The details of the signal processing at a mechanistic level beyond this stage are unknown to us. However we note that at a perceptual level musical sounds can be interpreted in the form of a melody, and that at an abstract (intellectual) level a melody can be written as a musical score. The musical score is in the form of a two dimensional function of frequency and time, and can certainly be represented as a spectrogram.

We now note the link (indeed, direct correspondence) between the spectrogram at the mechanistic level and the melody at *both* the perceptual and intellectual levels.

The doctor makes his diagnosis at the perceptual level. In order to encode the doctor's knowledge (at the intellectual level) into an expert system requires that the rules within the expert system operate in a corresponding domain. For sounds, such as the phonocardiogram, the most appropriate domain to adopt seems to be the domain of the spectrogram or musical score.

B. Features

Within the domain of the spectrogram the features which correspond at the intellectual level to the notes on the musical score, are isolated regions of energy localized both in frequency and time. We therefore adopt these bursts of energy as the features which should be passed in the form of some kind of parameters to the expert system. By adopting this approach, the expert system can be "aware" of the melody within the phonocardiogram.

C. Parameters

Five parameters are used to represent the bursts of energy:

- the intensity,
- the duration (temporal width),
- the bandwidth (frequency range),
- the central frequency and
- the temporal center.

In order to extract these five parameters each burst is fitted (in a least squares sense) by a two-dimensional third order Butterworth function. The intensity and location parameters are taken from the height and position of the function at its center, and the width parameters are taken from the 3 dB points in the time and frequency directions. For every burst of energy these five parameters are passed to the expert system.

D. Rules

Within the domain of the expert system the rules are written in a form to recognize different melodies (patterns of notes) as associated with different cardiac conditions. The key point is that the choice of features from the spectrogram and parameters passed to the expert system readily admit (as opposed to exclude) rules in the form of melody. For example, Table I gives a hypothetical rule-set for detecting an arrhythmia.

TABLE I

HYPOTHETICAL RULE-SET FOR DETECTING ARRHYTHMIA FROM MELODY.

if :	$?x$	is high intensity short duration narrow band low frequency followed by a short pause
then :	$?x$	is *lub*
if :	$?x$	is high intensity short duration narrow band low frequency followed by a long pause
then :	$?x$	is *dub*
if :	$?x$	is high intensity short duration narrow band low frequency
then :	$?x$	is *bum*
if :	$?x$	is low intensity long duration wide band high frequency
then :	$?x$	is *titty*
if :	$?a$ $?b$ $?c$ $?d$ $?e$ $?f$ $?g$	is *lub dub lub dub lub dub lub*
then :	the heart sounds normal	
if :	$?a$ $?b$ $?c$ $?d$ $?e$ $?f$ $?g$	is *bum titty bum titty bum bum bum*
then :	the heart has an arrhythmia	

III. Details

A. Signal Processing

The spectrogram was calculated by sampling the phonocardiogram at 1.47 kHz and breaking the signal into epochs of 36.7 ms, each containing 54 samples. Each epoch was then subjected to a FFT, yielding its spectral content at a resolution of 27.2 Hz.

B. Feature Extraction

Features were extracted from the spectrogram sequentially in order of decreasing energy content. The process involved three steps:

1) locating the largest feature,
2) finding parameters to describe it, and
3) eliminating the energy associated with it.

The three steps were repeated until the remaining data seemed to have no more features containing a significant amount of energy.

The second step involved fitting a two-dimensional third order Butterworth function to the data. An iterative least square fitting algorithm was employed, using a quadratic (Newton) method whenever possible, and a linear (gradient) method whenever the quadratic method failed.

IV. Results

Fig. 1 shows the spectrogram over two heart beats for a patient with an aortic insufficiency. The horizontal scale represents time in units of seconds, and the vertical scale represents frequency in units of Hertz. The height of the spectrogram is depicted using 25 contour lines, distributed on a linear scale from zero to the maximum value.

The repetitive pattern of high intensity short duration narrow band low frequency pulses of energy are the $S1$ and $S2$ sounds as heard from any normal heart. The low intensity long duration wideband high frequency burst of energy (following $S2$ and preceding $S1$) is the sound generated as blood leaks under high pressure in the reverse direction through the aortic valve (aortic insufficiency).

The rectangles drawn on the spectrogram show the temporal and frequency parameters into which each burst is

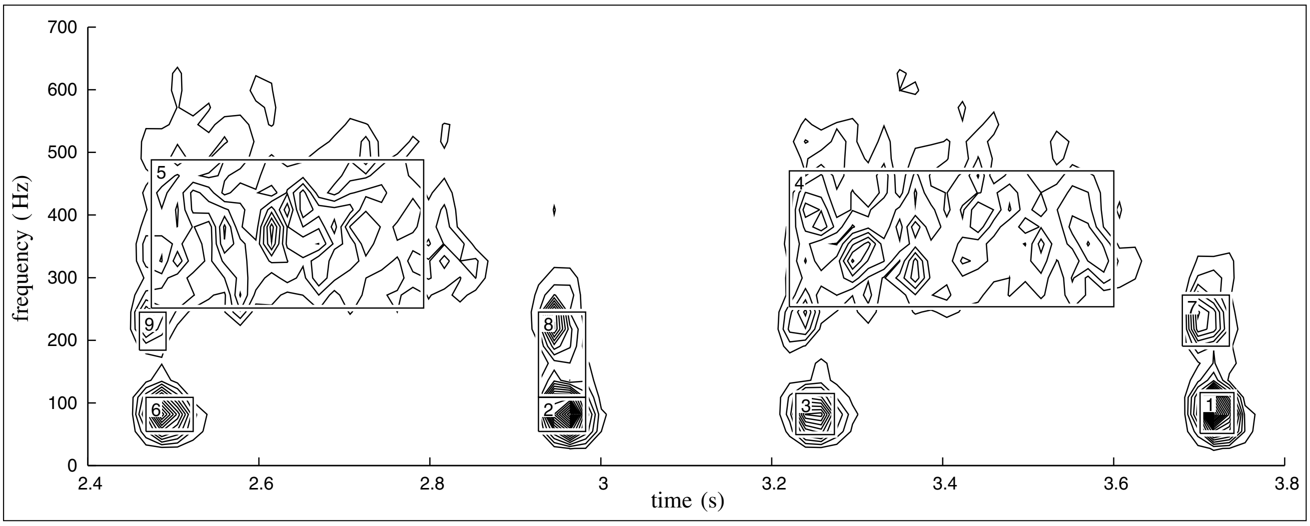

Fig. 1. Spectrogram of patient with aortic insufficiency.

converted, for communication to the expert system. The numbers near the top left corner of each rectangle indicate the order in which the data has been processed. The numerical values of the parameters are listed in Table II.

Fig. 2 shows the energy (RMS value of amplitude) within the partially processed spectrogram as features are extracted in sequence. Typically each feature accounts for less energy than the previous one, so that the curve behaves in a fashion somewhat reminiscent of an exponential decay.

TABLE II
NUMERICAL VALUES OF PARAMETERS EXTRACTED FROM SPECTROGRAM.

feature	intensity (–)	duration (s)	bandwidth (Hz)	central frequency (Hz)	temporal center (s)
1	0.655	0.040	65.22	84.00	3.721
2	0.389	0.056	54.44	81.67	2.955
3	0.383	0.046	65.66	82.27	3.251
4	0.107	0.380	216.88	362.04	3.410
5	0.117	0.318	236.58	369.69	2.634
6	0.296	0.056	54.44	81.67	2.496
7	0.181	0.056	81.66	231.39	3.708
8	0.127	0.056	136.12	176.94	2.955
9	0.126	0.032	60.76	214.53	2.476

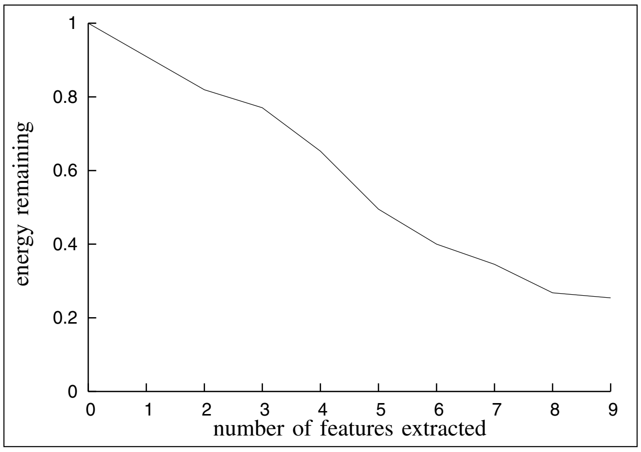

Fig. 2. Energy in spectrogram as features are extracted in sequence.

Fig. 3 shows for comparison the spectrogram (a) before and (b) after the entire process. At the termination of the process the features extracted account for 75% of the energy within the original spectrogram. The remaining energy is assumed to be insignificant (in terms of diagnosis) or to be noise.

V. DISCUSSION

The results here demonstrate in the case of aortic insufficiency that the method employed to extract the parameters is eminently practical. The method has also been successfully applied to phonocardiograms from patients with other cardiac conditions: normal heart, aortic stenosis, mitral insufficiency, and mitral stenosis. In all of these cases the spectrogram is seen to exhibit the same general form consisting of isolated bursts of energy.

The efficiency by which the data is represented as parameters can be determined by comparing the the size of the data set to the size of the set of parameters. For the spectrogram in Fig. 1 the data is recorded in the form of $38 \times 28 = 1064$ real numbers, whereas the parameters extracted from it are recoded as only $5 \times 9 = 45$ real numbers. In effect, each parameter plays the role of 23 data points.

The efficiency observed here results primarily from the technique being highly focussed in nature – designed specifically to match the general form of the data. It would also be possible to use the same method for data which, unlike the spectrogram, does not contain isolated bursts of energy. In this case one expects that, although the results would be technically correct, the efficiency by which the data is represented as parameters would be lower.

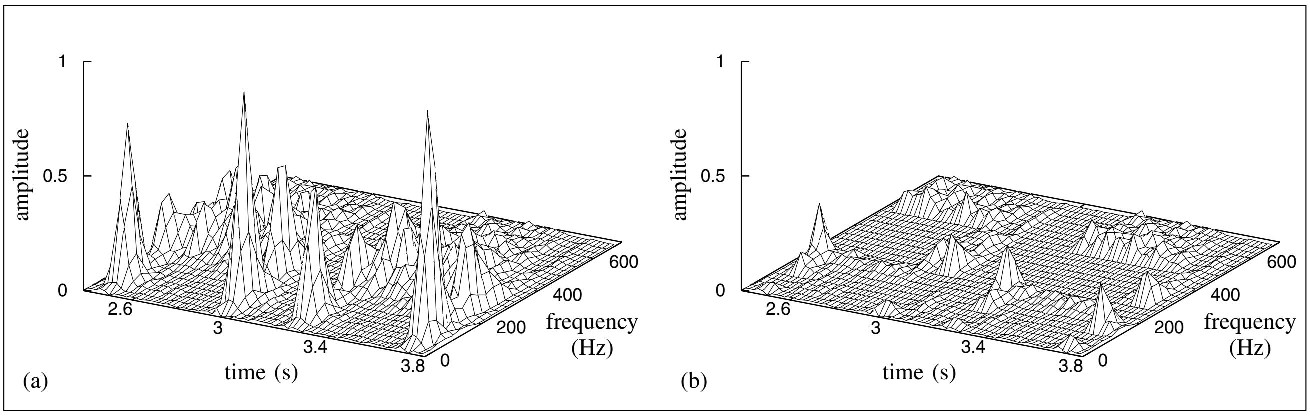

Fig. 3. Spectrogram (a) before and (b) after extraction of features.

Looking forward it now remains, on the basis of the features extracted here and with the collaboration of our medical colleagues, to complete the construction of the rules for a diagnostic expert system.

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ภาคผนวก ค.

บทความทางวิชาการที่นำเสนอใน
การประชุมวิชาการ

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SINGAPORE

HIERARCHICAL RULE BASE FOR DIAGNOSIS BASED ON MELODY OF HEART SOUNDS

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Abstract: This article describes the design of a set of rules to diagnose the heart's condition based on the sounds it generates (*i.e.* the phonocardiogram). The rules are organised in a hierarchical structure, with different layers representing different levels of intellectual abstraction. At the highest level they are written in terms of the melodies which are recognised by the expert practitioner as symptomatic of each of the heart's pathological and non-pathological conditions. At the lowest level the rules are written in a language which matches the parameters extracted from the phonocardiogram. Those parameters have been chosen especially to conform as far as possible to the abstract concept of melody employed at the highest level.

Introduction

The conventional method for interpreting the condition of the heart based on the sounds it generates is for an expert practitioner (doctor) to apply set of diagnostic rules which have been learned gradually over many years of clinical experience. Although the doctor's expertise is normally never documented in any formal way, it is in principle possible to do so, as for example by coding it as rules within some kind of diagnostic expert system [1].

Systems reported which use this approach [2, 3, 4] generally differ in the way that the doctor's expertise is formally documented, prior to being incorporated into the system. A common method is to simply use the doctor to provide diagnoses for a certain set of data, and for the engineer to statistically identify parameters which correlate with those diagnoses and then to design rules to give the same diagnoses when presented with the chosen parameters. Such an approach fails to make effective use of the full depth of the doctor's expert knowledge.

In principle this expert knowledge can be utilised and documented more fully by promoting the role of the doctor to writing rules for diagnosis for direct inclusion into the expert system. The engineer takes a complementary role: extracting the parameters from the signal in a form that provides the information required by the doctor's rules.

In this paper we focus on the idea that an effective system can be created only if both medical and engineering expertise are fully utilised, and endeavour to develop a system which does so.

Approach

The approach adopted here is to develop a system in which the function is determined by medical and engineering experts acting each at the full depth of their own separate areas of expertise in complementary and interlocking roles.

The design philosophy aims at meeting two objectives:
1. to accommodate the perceptual form with which the doctor makes his diagnosis, and
2. to ensure a common interface between the expertise of engineers and doctors which is equally intelligible to both.

The former objective is based on a belief that the knowledge of the expert practitioner (the doctor) can only be recovered in the form in which it exists. This in turn dictates that the system admits whatever chain of signal processing operations is followed by the doctor inside his head.

The latter objective is based on a need to incorporate in the system both medical and engineering expertise in an orderly progression from some kind of technical description which is largely unintelligible to the doctor, to an abstract symptomatological description of a patient's condition which is largely unintelligible to the engineer. The totality of a single unbroken progression in turn dictates at least one level of abstraction in common to both doctor and engineer.

The system developed here to meet the design objectives has the architecture shown in Figure 1. Parameters are extracted from the signal and then used to generate facts (assertions) as input to the data base of an expert system. The inference engine within the expert system interprets the facts in the data base according to rules in a rule base in order to produce a diagnosis and treatment.

The system incorporates engineering expertise at the levels of signal acquisition, signal processing and within some parts of the signal analysis, along with medical expertise at the levels of signal acquisition and other parts of the signal analysis.

At the perceptual level the doctor makes an interpretation on the basis of a temporal sequence of certain distinctly different sounds. To mimic this process in accordance with the first design objective the system is designed at all levels to operate in terms of melody.

At the level of parameter extraction (see [5] for details), melody is encapsulated as a set of localised regions of energy isolated in the spectrogram

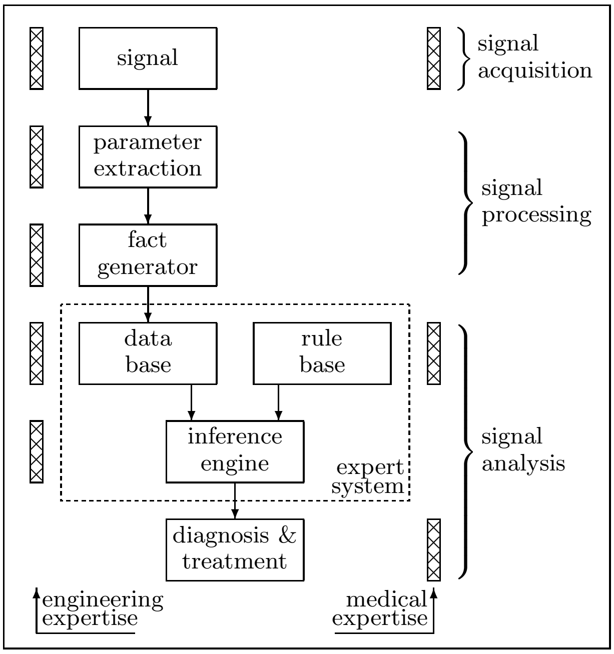

Figure 1: System architecture.

(*cf.* [6, 7]) in both time and frequency. The energy in each region is described by intensity, duration, bandwidth, and time-frequency coordinates. The sound created by every such burst of energy is viewed as a separate 'musical' note, which together in sequence produce some melody.

At the level of diagnosis the technical description of the spectrogram in terms of parameters is hidden from view, and rules are written directly in terms of the melodies perceived by the doctor.

Within the rule base of the expert system an interface between engineer and doctor in accordance with the second design objective is encapsulated in the form of a commonly agreed set of 'musical' notes. On one side the notes lead back via the realm of the engineer to parameters and signal. On the other side the notes lead on through the realm of the doctor to melody and diagnosis.

Expert System

The facts in the data base and the rules in the rule base are organised into different groups according to their role.

In the data base there are five groups of facts:

1. a technical description of notes extracted from the spectrogram, *e.g.* note2 is short interval
note2 is zero amplitude
2. a description of the temporal relationship between notes, *e.g.* note1 is before note5
note5 is before note3
3. a description of the spectral relationship between notes, *e.g.* note5 is above note3
note6 is above note1
4. a description of the intensity relationship between notes, *e.g.* note6 is louder than note4
note7 is louder than note2
5. a description of the notes observed for each patient, *e.g.* john has note1 note2 note3 note4
trevor has note1 note5 note3 note4

The facts in the data base are generated by the fact generator, which essentially translates the parameters extracted from the signal into a form compatible with the expert system.

In the rule base there are five groups of rules:

1. rules for associating names with technical descriptions of notes, *e.g.* if (?note) is low frequency
and (?note) is short interval
and (?note) is narrow band
and (?note) is high amplitude
...then (?note) is lub
2. rules for creating chords from combinations of notes, *e.g.* if (?note) is siss
and (?note) is urr
...then (?note) is sssurr
3. rules for identifying melodies as sequences of notes and chords, *e.g.*
if (?note1) is before (?note2)
and (?note2) is before (?note3)
and (?note3) is before (?note4)
...then (?note1) (?note2) (?note3) (?note4) is a melody
4. rules for making diagnosis based on melody, *e.g.*
if (?patient) has (?note1) (?note2) (?note3) (?note4)
and (?note1) (?note2) (?note3) (?note4) is a melody
and (?note1) is lub and (?note2) is sssurr
and (?note3) is dub and (?note4) is silent
...then (?patient) has (aortic stenosis)
5. rules for determining treatment based on diagnosis, *e.g.* if (?patient) has (aortic insufficiency)
...then (?patient) needs (a valve transplant)

The groups are arranged in a layered hierarchy, with a systematic progression from the lowest layer at the level of the technical description, through to the highest layer at the level of the treatment. Rules in layers 1 and 2 are the responsibility of the engineer. Rules in layer 3 and above are the responsibility of the doctor. The common interface is in the names of the notes such as 'lub', 'dub' and 'siss', which are found in the rules of layers 1,2 and 4.

It is necessary for the doctor and engineer to identify and name the sounds the doctor hears and uses in the diagnosis. The engineer can then identify their characteristics and write rules for the lower layers which tie the names back to the signal. For the higher layers the doctor can similarly write rules which tie the names to a diagnosis and treatment. There is no need for the engineer to understand the intricacies of the diagnosis, nor for the doctor to understand the inner workings of the signal processing.

Test System

A simple expert system has been implemented to make use of the heart sounds S1 (lub) and S2 (dub) as shown in Figure 2, along with any other sounds due to leaking closed valves (insufficiency) or obstructed open valves (stenosis). The system produces any of five diagnoses: aortic stenosis, mitral insufficiency, no disease, aortic insufficiency, or mitral stenosis. The diagnoses are not exclusive, so that a multiplicity of causes leads to multiple diagnoses.

The implementation is written in the LISP computer programming language using forward and backward chaining algorithms based on those in Winston [8]. Since the system has been developed for use in Thailand, a custom modified version of the

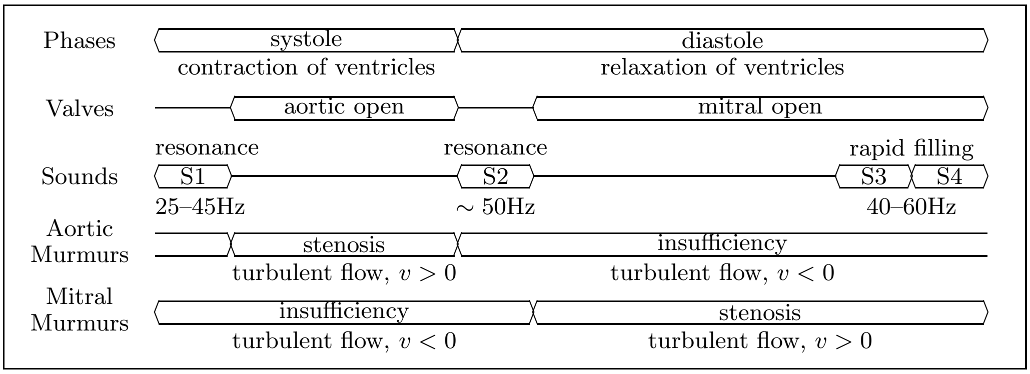

Figure 2: Timing diagram for left heart sounds.

Table 1: Names of notes in terms of their technical descriptions.

technical description	names of notes: lub	quiet	siss	urr	silent	sissss	urrrr
high amplitude	•						
narrow band	•			•			•
low frequency	•			•			•
wide band			•			•	
high frequency			•			•	
zero amplitude		•			•		
short interval	•	•	•	•			
long interval					•	•	•

LISP language which simultaneously accommodates both the Roman and Thai scripts has been used [9]. For the benefit of the international audience the rules are presented here in Anglicised form, rather than in the original Thai.

The system uses the rules shown in Table 1 to assign the names of notes to their technical descriptions, and the rules depicted in Figure 3 for making a diagnosis based on melody. The names are chosen as far as is possible in an onomatopoeic form of the sounds they represent. Direct connections between the 'lub' and 'dub' sounds and the five diagnostic melodies are omitted from the figure for the sake of clarity. Both 'lub' and 'dub' sounds are used in all melodies.

Table 2 shows a sample of a set of 41 facts about the heart sounds of five patients. The notation used is in the form of the LISP language, with 'remember-fact' as the name of a procedure which stores facts in the data base.

Results

Sample deductions are shown in Table 3 for the forward chaining algorithm, and in Table 4 for the backward chaining algorithm.

For the system implemented the forward chaining algorithm makes 45 deductions spanning all five groups in the layered hierarchy of rules.

For the backward chaining algorithm the doctor interactively interrogates the fact and rule base by invoking the 'backward-chain' procedure with any desired hypothesis. The system either confirms the hypothesis (Yes), rejects the hypothesis (No), or returns all cases which match the hypothesis (→).

Table 2: A sample of facts in the test system.

```
(remember-fact '(note2 is short interval))
(remember-fact '(note2 is zero amplitude))
(remember-fact '(note3 is low frequency))
(remember-fact '(note3 is short interval))
(remember-fact '(note3 is narrow band))
(remember-fact '(note3 is high amplitude))
(remember-fact '(note1 is before note8))
(remember-fact '(note2 is before note3))
(remember-fact '(note8 is before note3))
(remember-fact '(note3 is before note4))
(remember-fact '(tim has note1 note2 note3 note6))
(remember-fact '(albert has note1 note2 note3 note7))
(remember-fact '(george has note1 note8 note3 note4))
```

Table 3: Deductions produced by forward chaining algorithm.

Rule Name1 →(Note1 Is Lub)
Rule Name2 →(Note2 Is Quiet)
Rule Name3 →(Note4 Is Silent)
Rule Name4 →(Note5 Is Siss)
Rule Chord1 →(Note3 Is Dub)
Rule Chord2 →(Note8 Is Sssurr)
Rule Seq1 →(Note1 Is Before Note3)
Rule Seq1 →(Note2 Is Before Note4)
Rule Seq2 →(Note1 Note2 Note3 Note4 Is A Melody)
Rule Seq2 →(Note1 Note2 Note3 Note6 Is A Melody)
Rule Melody1 →(John Has (No Disease))
Rule Melody2 →(Tim Has (Aortic Insufficiency))
Rule Melody3 →(Albert Has (Mitral Stenosis))
Rule Treat1 →(John Needs (No Treatment))
Rule Treat2 →(Tim Needs (A Valve Transplant))
Rule Treat3 →(Trevor Needs Medication)

Discussion

The hierarchical structure is key to the success of the method. It supports an orderly progression in a sequence of steps from a technical description of the signal to an abstract symptomatological description of the patient's condition. Every step is small enough that it can be reviewed, and if necessary revised, without any need for expertise at all levels in the hierarchy. In this way the engineer and doctor can each incorporate in the system their own expert

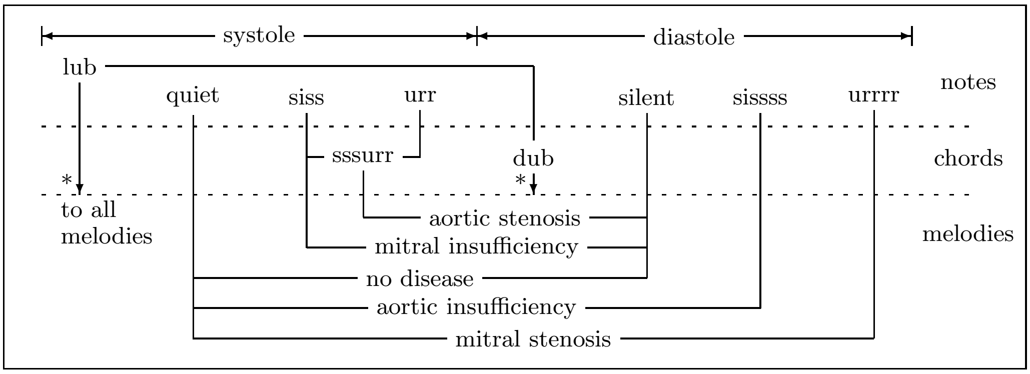

Figure 3: Rules for diagnosis from melody.

Table 4: Deductions produced by backward chaining algorithm.

(backward-chain '(albert has (? a) (? b) (? c) (? d)))
→A=NOTE1, B=NOTE2, C=NOTE3, D=NOTE7
(backward-chain '(note7 is (? x) (? y)))
→X=LOW, Y=FREQUENCY
→X=LONG, Y=INTERVAL
→X=NARROW, Y=BAND
(backward-chain '(note7 is (? what)))
→WHAT=URRRR
(backward-chain '(albert has (? disease)))
→DISEASE=(MITRAL STENOSIS)
(backward-chain '(albert needs medication))
NO
(backward-chain '((? who) needs medication))
→WHO=TREVOR
→WHO=GEORGE
(backward-chain '(albert needs (? what)))
→WHAT=(A HOLIDAY)
(backward-chain '(albert needs (a holiday)))
YES
(backward-chain '((? who) has (? disease)))
→WHO=JOHN, DISEASE=(NO DISEASE)
→WHO=TIM, DISEASE=(AORTIC INSUFFICIENCY)
→WHO=ALBERT, DISEASE=(MITRAL STENOSIS)
→WHO=GEORGE, DISEASE=(AORTIC STENOSIS)
→WHO=TREVOR, DISEASE=(MITRAL INSUFFICIENCY)
→WHO=GEORGE, DISEASE=(MITRAL INSUFFICIENCY)

knowledge at their own levels of abstract thinking, leaving for the other expert those parts where their own expertise is inferior.

Within the hierarchy one level of abstraction is common to both doctor and engineer. Reaching this level requires some critical thought, analysis and learning for each doctor and engineer. This helps to provide feedback in two directions, thereby improving rules at both higher and lower levels.

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