REAL-TIME AMBULATORY ARRHYTHMIA ANALYSIS WITH A MICROCOMPUTER

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SUMMARY

We have developed a portable instrument based on the Intel 8085 microprocessor which is capable of real-time ECG analysis on the ambulatory patient. The 16K byte ECG analysis program uses feature extraction as the basis for morphologic classification. Up to 500 seconds of diagnostic quality ECG waveforms are selected and stored in digital memory to document ectopic beats and arrhythmias. When these conditions are recognized, the patient may be interviewed using a 20-character LED display and pushbuttons. Hourly summary tables, R-R interval and feature histograms, and rate trends are also collected for transmission to a base station. Transmissions may be made at any time without interrupting analysis.

INTRODUCTION

Tape recording and subsequent analysis of the ECG for long periods (typically 24 hours) has become a widely used technique for the assessment of cardiac arrhythmias. Certain problems inherent in high-speed scanning of these tapes by humans have motivated the development of computer programs suited to the task:

1. Human interpretation is time-consuming (1-1/2 to 2 hours per tape).

2. There is a risk of fatigue-induced error, due to the tedious nature of the work.

3. Reports are semi-qualitative in nature.

4. The cost is high, due to the requirement for highly skilled technicians.

The use of computers for high-speed tape analysis, while addressing these problems, still suffers from certain instrinsic limitations of the recording process:

1. Turn-around time is still in excess of one day, making management of unstable rhythms and drug therapy difficult.

2. Data are inaccessible during the recording procedure.

3. Correlations among symptoms, activities, and arrhythmias are difficult to establish reliably.

Real-Time ECG Analysis on Ambulatory Patients

A portable instrument capable of real-time ECG rhythm analysis and patient interaction has the potential to provide the physician with readily available, quantitative reports at low cost. We have developed a prototype of such an instrument. It is a general-purpose microcomputer, with specialized peripherals, powered by batteries, and packaged for use by ambulatory patients. The 16K byte ECG analysis program is currently loaded into RAM in the instrument from a microprocessor base station at set-up time. ECG analysis is performed while the patient carries the device. Results are available at any time, without interruption of ongoing analysis, by transmitting the data via telephone or hard-wired connection to the base station.

Hardware

Microcomputer

Figure 1 is a block diagram of the hardware. The design uses the Intel 8085 microprocessor and about 70 integrated circuits, combining NMOS for density, CMOS for low power, and LSTTL for speed. The 8085 is an 8-bit CPU which has an address space of 64K bytes. We have included 1K bytes of programmable read-only memory and 48K bytes of read/write memory.

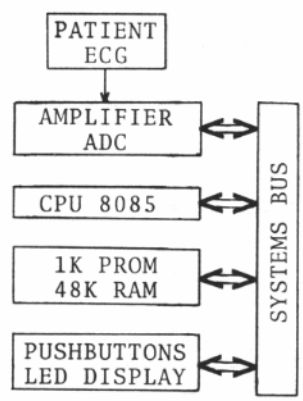

Figure 1: Hardware Organization

Peripherals

Ten-bit samples of the ECG are taken at 300 Hz by a hybrid A/D converter. An eight-channel analog multiplexer permits multichannel ECG analysis and software testing of battery and other system voltages. (Only one ECG channel is currently used.)

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Patient interaction is handled with a display consisting of twenty 16-segment starburst LED characters, a buzzer, and five pushbuttons. Communication with the base station takes place via an optically isolated serial port at switch-selectable rates up to 9600 baud. The implementation of the serial port approximates the EIA RS-232C standard.

Power

Two lithium-sulfur dioxide "D" cells supply power to the instrument. In a test using an early version of the prototype which consumed three watts, the instrument ran for 13.5 hours on one set of cells. Current power requirement is 1.9 watts, and future designs are expected to lower power consumption still further, making 24 hour operation quite feasible.

Packaging

The current prototype, although not packaged for ambulatory use, fits into about 1500 cm^3. Prototypes under construction will permit ambulatory use. The use of hybrid circuits and other technologies which become practical in commercial applications should permit a size comparable with that of Holter recorders.

Software

The real-time ECG analysis program identifies beats, detects and records clinically significant episodes, maintains statistics, conducts interviews with the patient, and responds to requests for information via the serial port. Figure 2 is a block diagram of the software.

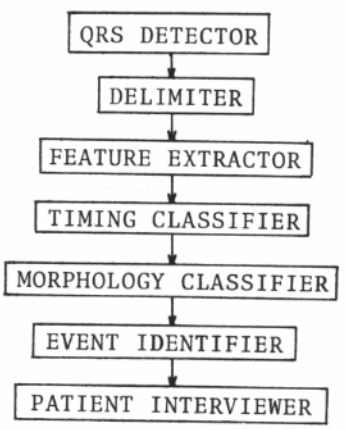

Figure 2: Software Organization

QRS Detection

QRS detection has been implemented in software. We have favored sensitivity over specificity, since the computational cost of rejecting falsely detected events later on is considerably less than that of searching for missed events. The detector requires only that the variation in amplitude exceed a threshold within a sliding time window. Provision is made for dynamic adjustment of these parameters. The detector is disabled for a short time, ΔT, after each event to avoid multiple triggering. This lock-out period is terminated when the end of the presumed QRS complex is defined by the event delimiter, or after 200 milliseconds, whichever comes first. This scheme for detector lockout thus avoids the worst shortcoming of both analog and digital detectors with fixed lockout periods: rejection of QRS complexes during the lockout periods following artifacts which trigger the detector.

Delimiting the QRS Complex

A three-pass delimiter performs the tasks of finding the beginning and end of the QRS complex. The first pass estimates the amplitude of the baseline preceding the event. The next two passes delimit the event by seeking relatively flat sections of the signal. In no case does the search extend further than 100 msec before or 200 msec after the sample on which the detector triggered.

Morphologic Feature Extraction

We regard the feature extraction process as a means of data compression. From a representation of the event as ten-bit amplitudes (requiring about 1000 bits), the program derives an event vector $\vec{E}$ comprised of seven morphologic features (requiring about 100 bits). Data compression reduces both storage requirements and computational load. In selecting features we have used these criteria:

1. value as descriptor
2. ease of computation
3. minimal sensitivity to measurement error and noise.

The last criterion implies that integral measures should be favored over differential measures. Note that physiologic significance is not a criterion. We use only one feature--width--which carries even moderately unambiguous physiologic information, and that feature is highly sensitive to measurement error. We have attempted to select an ensemble of features which taken together suffice to distinguish physiologically different beats. Currently, these features are:

QRS width
QRS absolute area
QRS signed area
QRS peak-to-peak amplitude
QRS width estimate (absolute area divided by peak-to-peak amplitude)
QRS offset
A T-wave parameter

The QRS width, absolute area, peak-to-peak amplitude, and offset are features which have been used by Cox[1] and others. The method of Lovelace et al.[2] is used to calculate the T-wave parameter. Neither the choice of features nor the number of features is definite at this time.

Classification of Timing

The event timing classifier uses a prediction based on the predominant rhythm and on the mean absolute deviation of normal R-R intervals to categorize each event as on time, premature, following a compensatory pause, or late. The timing classifier also rejects certain suspicious events and searches for missed events. There is no advantage in performing these tasks earlier since analysis is simplified by appropriate use of contextual information derived at this stage.

A software "filter" tags suspicious events (i.e., events which may not be QRS complexes), using these criteria:

1. An event which has a width considerably less than that of a normal event is probably not a cardiac event.

2. If the difference between the incoming and outgoing baseline amplitudes exceeds three-fourths of the event amplitude, the event is probably baseline shift.

3. If the event is very premature and interpolated, it may be a T-wave.

Premature, suspicious events are rejected unless followed by compensatory pauses; other suspicious events are rejected if nearby, non-suspicious events can be found which fit well into the rhythmic pattern.

If an unexpectedly long pause occurs between detected events, the timing classifier activates a secondary search for possible missed events using lower thresholds than the original detector.

Classification of Morphology

Morphologic classification is based on the event vector $\vec{E}$ mentioned above. The morphology classifier maintains statistics on up to ten active clusters of events. Each event is assigned to the cluster $(\vec{C}_i, \vec{\sigma}_i)$ which is closest to it, provided that the distance to this closest cluster does not exceed some arbitrary value.

The metric used is an approximation of the n-dimensional Mahalanobis distance

$$M_i = \{ \sum_{j=1}^{n} \left(\frac{r_{ij}}{\sigma_{ij}} \right)^2 \}^{1/2}$$

where r_{ij} is the jth component of $\vec{C}_i - \vec{E}$, and σ_{ij} is the standard deviation of members of $(\vec{C}_i, \vec{\sigma}_i)$ in dimension j.

The approximations used are these:

1. Sample mean absolute deviation is used as an approximation for standard deviation:

$$\sigma_{ij} \simeq \frac{1}{m_i} \sum_{k=1}^{m_i} \left| \bar{x}_{ij} - x_{ijk} \right|$$

where m_i is the number of events in cluster i and x_{ijk} is the jth component of the kth event vector in cluster i.

2. Cluster statistics are updated for each event until 20 events have been assigned to the cluster; thereafter, statistics are updated for every tenth event. Only the 20 events most recently assigned to the cluster are used for computation of cluster statistics.

3. A full-width search of all active clusters is not always performed. If an event is found to be closer (by the metric described above) to a cluster mean than ten of the twenty events most recently assigned to that cluster, it is assumed that a good match has been found and the search is aborted.

To increase the probability of an abbreviated search, the morphology classifier maintains a list of active clusters, and the search proceeds according to list order. When an event is assigned to an existing cluster, that cluster is moved to the head of the list. The cluster at the end of the list is deleted when room for a new cluster is needed. The order of the list is not modified when a new cluster is created; this tends to reduce proliferation of clusters due to variation in one or two morphologic features induced by noise or measurement error.

A cluster may be split into two clusters if its statistics drift sufficiently far from their initial values that the prototype event appears not to belong in the cluster. In this case the "scion" cluster is treated as a new cluster. It has not been found necessary to coalesce clusters when they drift together. The slight cost of maintaining some redundant clusters appears to be less than the cost of recognizing and coalescing them, a task which may be performed at the base station.

Cluster Identification

Morphology clusters are classified as a) "supraventricular" (normally conducted), b) "ventricular", or c) "unknown". A cluster is judged "supraventricular" if the mean width estimate of events in the cluster is less than 60 milliseconds and either:

1. at least four of the six most recent events belong to the cluster, or

2. events in the cluster are similar in morphology to previously recognized supraventricular clusters.

A cluster is classified "ventricular" if it fails the tests for supraventricular clusters and either:

1. the mean width estimate for the cluster is at least one and one-half times the largest mean width estimate observed for a supraventricular cluster and the event most recently added to the cluster is premature, or

2. the event most recently added to the cluster is premature and the events in the cluster are similar in morphology to previously recognized ventricular clusters.

Clusters falling into neither of the above two classes are labeled "unknown". Each time a new event is added to an "unknown" cluster, reclassification of the cluster is attempted. On the other hand, "supraventricular" and "ventricular" classifications, once assigned, are permanent. Future

versions of the program will provide additional cluster labels to explicitly handle events such as paced beats, ventricular escape beats and bundle branch block rhythms.

Event Identification

Individual events are identified on the basis of their rhythmic context and the type of cluster to which they belong:

1. Normal events belong to supraventricular clusters and are not usually premature.

2. APCs belong to supraventricular clusters; the ratio between the R-R intervals preceeding and following an APC is less than 0.9.

3. PVCs belong to ventricular clusters and are not late.

4. Ventricular escape beats belong to ventricular clusters and are late.

Once events have been identified, the remaining tasks are statistical summarization, and identification of sequences of events and other conditions likely to be of particular clinical interest.

Episode Detection

The program detects the following conditions:

1. Asystolic pause: a pause longer than one and one-half normal R-R intervals in the presence of a regular rhythm, or a pause longer than two normal R-R intervals following a premature beat.

2. Sudden bradycardia: an instantaneous rate decrease signalled by at least three consecutive late beats.

3. Sudden tachycardia: an instantaneous rate increase signalled by at least three consecutive premature beats.

4. PVC rate change: a PVC rate exceeding a threshold which is set to twice the current rate whenever this condition is detected, and periodically reset to zero.

5. Couplet: two consecutive ventricular beats.

6. Ventricular tachycardia: three or more consecutive PVCs.

7. Bigeminy: alternating ventricular and non-ventricular beats.

8. Trigeminy: a repetitive pattern of two non-ventricular beats followed by a ventricular beat.

9. Identification of a new cluster of abnormal beats.

10. Patient symptoms: detected when the patient indicates symptoms by pressing one of the buttons on the instrument.

Protocols for action to be taken on detection of each of these conditions have been defined; they may be redefined by the user. Normally, the protocols include update of summary statistics, and one or both of the following actions may be taken as well:

1. A sample ECG strip may be stored.

2. A patient interview may be initiated.

There are usually lockout times defined for these actions so that not every occurrence of each condition will be documented by a sample strip or an interview.

Sample ECG Strips

ECG rhythm strips normally consist of ten seconds of stored data, including five seconds preceding detection of the condition of interest. Sample ECG strips may be extended (e.g., to document prolonged episodes of ventricular tachycardia). Strips of less than ten seconds may be recorded to document new ectopic morphologies.

A compression scheme which preserves signal extrema uses only 400 bits of storage per second of ECG, thus permitting over 500 seconds of ECG to be stored in the instrument's memory. The scheme is an extension of the turning point compressor described by Mueller[3]. We have found that a compression ratio of 6:1 from 300 Hz input, storing each sample as an eight-bit amplitude, retains sufficient information to be clinically acceptable.

Patient Interviews

A number of different interviews have been defined; the choice depends on the condition detected. We have chosen intially to use non-branching interviews consisting of questions to be answered "yes" or "no" by the patient. The questions (presented on the 20-character LED display) and answers (entered using the pushbuttons) are coded and recorded in the patient log, along with the time of day, an indication of the condition which prompted the interview, and a cross reference to a sample ECG strip taken concurrently.

Interaction with patients in real-time has the potential to:

1. increase the probability of correlating patient symptoms with specific arrhythmias;

2. reveal factors in the patient's behavior or environment which precipitate arrhythmias (e.g., physical stress, anxiety, meals);

3. increase the precision of patient compliance during drug trials by providing reminders to take prescribed doses at correct times;

4. increase the safety of anti-arrhthymic drug trials by detecting dangerous trends in cardiac rhythm and then by requesting the patient to call the clinic immediately;

5. make possible the use of behavior modification therapy triggered by specific rhythm trends.

Output

Data accumulated by the portable monitor are transmitted via hard-wire or telephone link to a base-station where final report generation takes place. Quality control and editing by a technician are performed at this stage. The final report includes the following items:

1. a table providing hourly summaries of normal and ectopic activity;

2. trend plots of heart rate and rates of atrial and ventricular ectopic beats and runs;

3. histograms of R-R intervals, PVC coupling intervals, and event features;

4. the patient log;

5. sample ECG strips selected to document significant arrhythmias.

EVALUATION

At Beth Israel Hospital, we have selected one-hundred 30-minute exerpts from a library of over 3500 24-hour ECG recordings made using Avionics model 445 2-channel recorders. About half of the recordings have been gathered from in-patients. Each excerpt has been digitized at 360 Hz with 11-bit resolution, and contains two channels of ECG from nearly orthogonal chest leads. Fifty of the excerpts were selected randomly; the remainder were selected to include both representative and unusual events of clinical interest.

These digitized tapes are marked, beat by beat, by two independent experts. The annotations are compared, discrepancies are resolved and digitized tapes containing both the sampled ECG and consensus annotations of each event are produced.

The digitized tapes are used as input for a version of the ECG analysis program which can mark its own beat-by-beat annotations. The program's annotations are compared with human annotations and discrepancies can be displayed with the waveforms on a CRT or on annotated 2-channel strip chart recordings. Summary statistics for 30 minutes of data are compiled and tabulated. Figure 3 shows results from three tapes. Tape 4 has classical PVCs, tape 208 has high grade VEA and fusion beats, and tape 214 has left bundle branch block (designated normal in the figures). Agreements are entries along the diagonal, and the types of disagreements are easily identified. Subsequent reference to the annotated strip chart recording aids identification of specific problems. Excerpts from the strip chart records of tapes 4 and 208 are shown in Figure 4.

Clinical evaluations will be divided into at least two phases. During the first stage long-term analog Holter tape recordings are played into the portable instrument. The reports obtained from the base station are compared with the standard Holter reports prepared by arrhythmia laboratory technicians.

During the final stage of clinical evaluations, patients will wear both the portable monitor and Avionics recorder, using the same set of leads. Reports will be compared as above.

Acknowledgement

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4

human \ program	-	N	PVC	APC	?	T
-	-	1	5	-	-	5
N	2	3866	6	-	4	1
PVC	2	-	580	-	4	-
FUS	-	-	-	-	-	-
APC	-	-	-	-	-	-
ARTFCT	-	-	-	-	-	-

208

human \ program	-	N	PVC	APC	LEAR N	?	T
-	-	-	13	-	1	7	16
N	2	1461	25	1	23	61	5
PVC	3	36	878	2	17	51	-
FUS	-	79	135	-	5	145	-
APC	-	-	-	-	-	-	-
ARTFCT	3	1	2	-	-	-	-

214

human \ program	-	N	PVC	APC	?	ARTFCT	LEAR N	T
-	-	5	5	1	6	9	-	15
N	3	1906	18	1	25	-	45	-
PVC	-	24	159	55	6	1	3	5
APC	-	-	-	-	-	-	-	-
?	-	6	-	-	-	-	-	-
ARTFCT	2	-	-	-	-	-	-	-

Figure 3: Comparator Results

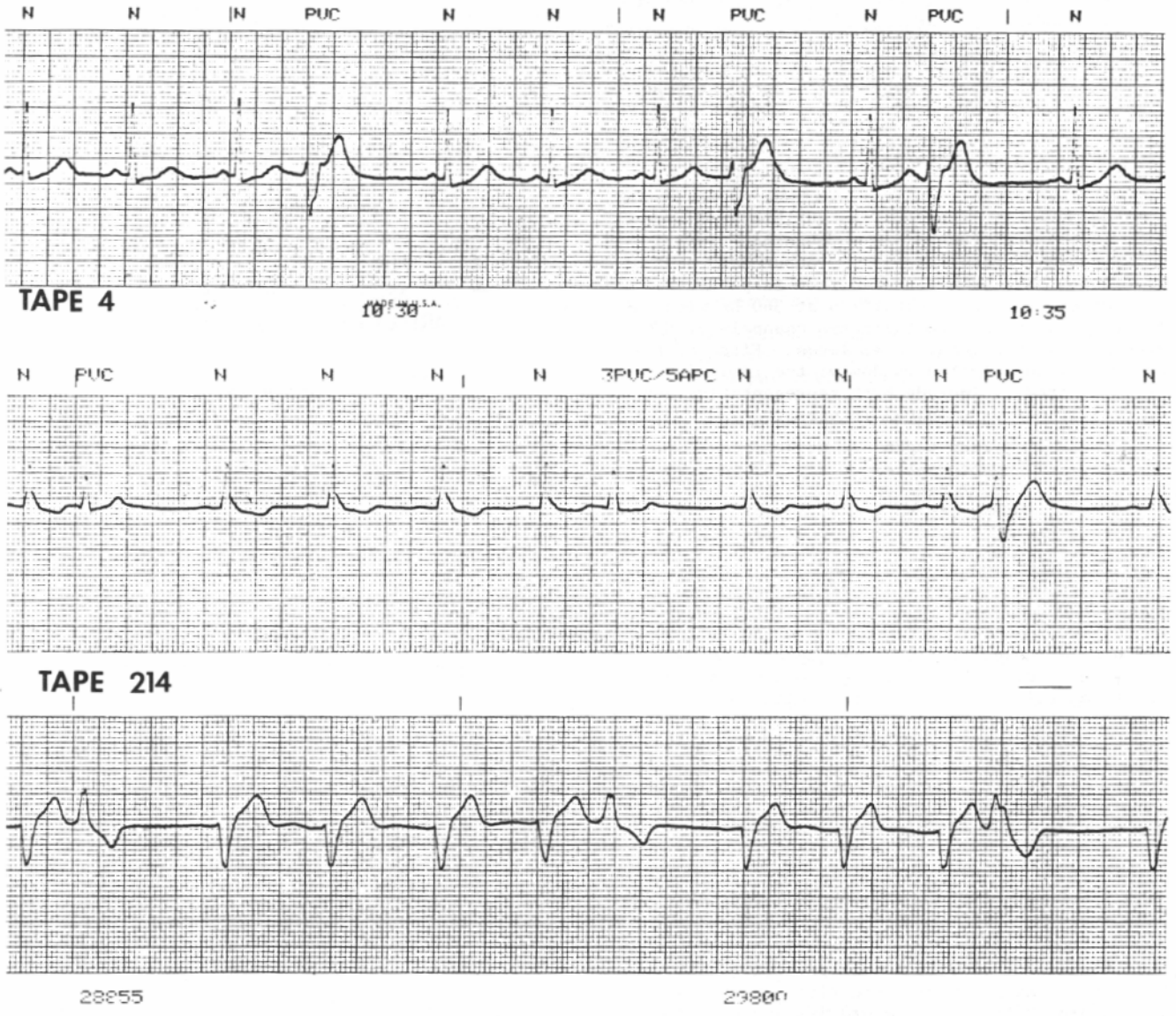

Figure 4: Annotated strips. The upper strip shows no disagreements. In the lower strip, the program (channel 5) disagrees with the cardiologist (channel 3) on the seventh beat, a PVC which appears quite similar to the normal beats in the upper channel. The lower channel (not analyzed by the program) shows the nature of the beat more closely.

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