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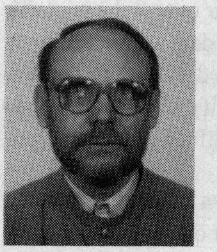
J. Clément was born in Brussels, Belgium, in 1933. He received the M.D. degree from the Université Libre de Bruxelles, Brussels, Belgium, in 1958.

He is an Assistant in the Pulmonary Function Laboratory and an Associate Professor at the Katholieke Universiteit, Leuven, Belgium.

H. Franken was born in Gent, Belgium, in 1955. He received the B.S. degree in electrical engineering from the Katholieke Universiteit, Leuven, Belgium, in 1978.

He is currently working as a Ph.D. candidate in the Pulmonary Function Laboratory, Department of Internal Medicine, University of Leuven.



K. P. Van de Woestijne was born in Waregem, Belgium, in 1930. He received the M.D. degree from the Katholieke Universiteit, Leuven, Belgium, in 1955.

He is Professor of Medicine and Head of the Pulmonary Function Laboratory in the same University.

Automated High-Speed Analysis of Holter Tapes with Microcomputers

MARK L. AHLSTROM, MEMBER, IEEE, AND WILLIS J. TOMPKINS, SENIOR MEMBER, IEEE

***Abstract*—We have developed an automated Holter scanning system based on two microcomputers. One is a preprocessor that detects *QRS* complexes and measures the *QRS* durations using computations of first and second derivatives. This microcomputer interfaces to a second microcomputer that does arrhythmia analysis, logging, and reporting using *R-R* intervals and *QRS* durations. This system can process Holter tapes at 60 times real time and produce printed summaries and 24 h trend plots of several variables including heart rate and PVC count.**

Introduction

HOLTER technology produces a continuous 24 h recording of the electrocardiogram (ECG) of an ambulatory patient using a special tape recorder. A trained technician replays this Holter recording at high speed on a separate device called a Holter scanner, detects the various arrhythmias in the ECG signal, and then generates a report for the physician. Since the manual scanning of Holter tapes is a boring task and prone to errors from operator fatigue, there have been numerous attempts to automate this process. Some of these automated systems use a template-based approach to which each *QRS* complex is compared to one or more idealized *QRS* waveforms [1], [2]. Others measure the duration, height, offset, and area of each *QRS* complex to detect abnormal beats [3].

Most of these systems have been implemented on relatively expensive and powerful minicomputers such as Digital Equipment Corporation's PDP-11 family. One system even requires both a PDP 11/40 and a PDP 11/50 and is still only able to process ECG tapes at 30 times real time [4]. Another does only a preliminary analysis to extract data for storage on disk and requires a second pass to produce the final results [5]. While our system may be less sophisticated than many of these mini-

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M. L. Ahlstrom is with Honeywell Military Avionics Division, Minneapolis, MN.

W. J. Tompkins is with the Department of Electrical and Computer Engineering, University of Wisconsin, Madison, WI 53706.

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computer-based systems, it is an automated system which uses two inexpensive microcomputers and processes Holter tapes at 60 times real time.

Overview of the System

The development of our system was motivated primarily by the need to evaluate the performance of a portable arrhythmia monitor which is being developed in our laboratory [6]-[8]. The portable arrhythmia monitor is a microcomputer-based device which is intended to replace the Holter recorder. Rather than record all ECG data, the monitor analyzes the signal in real time and captures several seconds of the ECG in RAM when an alarm condition occurs. This ECG segment and the reason for the alarm can be phoned directly to a computer in the physician's office. The need for the patient to come to the physician's office to return tapes and the need for Holter tape scanning are thus eliminated. The alarm condition may be a single, serious event such as an R-on-T phenomenon or a multiple-beat event, such as a premature ventricular contraction (PVC) rate of greater than 10 per min. Since we desire to test the portable monitor by comparing its performance to data simultaneously recorded from a patient with a Holter recorder, we need a scanning system which allows us to easily identify alarm conditions on the Holter tape. This need strongly influenced the output format of our Holter scanning system.

We use the *R-R* interval and *QRS* duration to detect arrhythmias. These two features are plotted against one another in two-dimensional space, and the resulting plane is divided into several regions using boundaries which are calculated relative to the position of the normal beats in the plane. Each new beat is classified as being either normal or abnormal by its position in the plane, and abnormal beats are further divided into specific types of arrhythmias based on the region of the plane in which their features fall. The features of the previous beats are considered in the classification of an abnormal beat. We maintain a count of each kind of arrhythmia for every minute in the 24 h period. After playing the entire tape into the system at 60 times real time, we print a summary of total counts, data for each minute in which a threshold for any selected arrhythmia was exceeded, or a trend plot of any selected arrhythmia.

Fig. 1 shows a block diagram of our system hardware. A Holter scanner which serves only as a playback device plays the tapes at 60 times real time (Avionics Research Products Corporation Model 650 Electrocardioscanner). An amplifier increases the output of the scanner to give a peak-to-peak voltage for normal beats of about half the full range of the 8 bit analog-to-digital converter (ADC). Only half the converter range is used for normal beats so that an abnormal beat such as premature ventricular contraction (PVC) that typically has a larger amplitude than a normal *QRS* complex can be properly digitized. The signal then passes through a bandpass filter with corner frequencies at 73 and 1600 Hz in order to minimize baseline drift and to prevent aliasing. This corresponds to a real-time frequency range of 1.2-26.7 Hz, so the important frequency components of the *QRS* complex are retained.

The preprocessor microcomputer then samples this signal at 5500 samples/s (sps) and filters it digitally to produce a pulse

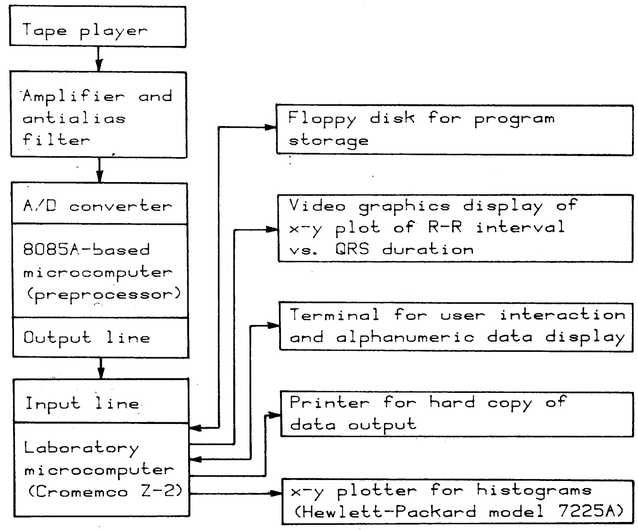

Fig. 1. Block diagram of Holter tape analysis system.

for each *QRS* complex. The width of each pulse is proportional to the corresponding *QRS* duration. Through an input port, the second microcomputer, a laboratory microcomputer system (Cromemco Model Z-2), detects these pulses and measures the *R-R* intervals and the *QRS* durations. It then analyzes these values for arrhythmias, incrementing the appropriate arrhythmia counters in its RAM as they are detected.

During processing, in addition to the actual arrhythmia analysis, the microcomputer produces for the operator a dynamically changing video graphics display of the plot of *R-R* interval versus *QRS* duration as new beats are measured, and it displays an elapsed-time clock referenced to real time. This display gives the user feedback that the system is working properly. By inspection the operator can see clusters develop in the various normal, abnormal, and noise regions of the display. After on-line processing is complete, this system enters an interactive mode that enables the user to produce formatted outputs of selected results.

ECG Preprocessor

Fig. 2 shows a block diagram of the *QRS* width-detection preprocessor that is implemented as a single-board microcomputer based on the 8085A microprocessor. The necessary components are a microprocessor, an analog-to-digital converter, one digital output line, at least 200 bytes of ROM for program storage, and about 20 bytes of RAM for use as a scratch pad and stack area. An 8085A microprocessor with an effective clock frequency of 3 MHz permits processing 60 times real time ECG signals.

The first and most difficult step in the automated analysis of ECG signals is reliable detection and characterization of *QRS* complexes. Differentiation [9] or bandpass filtering [10] is frequently used to derive a signal which can be thresholded to detect the *QRS* complex. However, these techniques do not directly provide information on the *QRS* duration or any other morphological feature of the *QRS* complex. *QRS* duration can

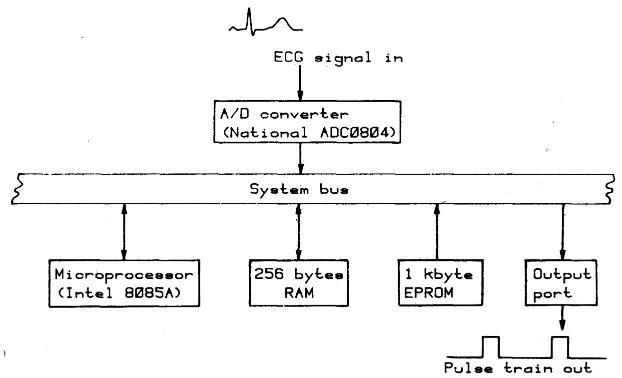

Fig. 2. Block diagram of the preprocessor microcomputer system.

be very useful in detecting ventricular arrhythmias because it varies with changes in *QRS* morphology.

The preprocessor applies several digital filters to the ECG and produces a pulse for each *QRS* complex. Our *QRS* width detector is similar to but simpler than a method developed by the Hewlett-Packard Company for use in their computerized arrhythmia monitoring system for the intensive care unit [11]. We make use of the empirical observation that the first and second derivatives of the ECG signal, when rectified and properly combined, give a pulse for each *QRS* complex. This pulse has a width proportional to the *QRS* duration.

The pulse produced by simply summing the rectified first and second derivatives together tends to have a notch near the center of the *QRS* complex. In order to produce a single continuous pulse for each complex, our software removes this notch by smoothing the derivatives with a moving average filter. The complete processing algorithm is: 1) calculate, rectify, and smooth the derivative of the original ECG signal; 2) calculate, rectify, and smooth the derivative of step 1); 3) sum the results of steps 1) and 2); and 4) threshold the waveform from the summing process with hysteresis to produce square pulses. Fig. 3 shows both the intermediate and the final results for two different *QRS* complexes.

Fig. 4 shows a flowchart of the program. After low-pass filtering the ECG signal to prevent aliasing, the preprocessor samples it at 5500 sps with 8 bit amplitude resolution. The subroutine for calculating the derivatives is based on the three-point central difference method and the smoothing subroutine is a weighted moving-average (Hanning) filter [8]. After the rectified and smoothed first and second derivatives are added together, a third subroutine thresholds the sum with hysteresis to produce the square-pulse result. The processed waveform is amplitude hardlimited to prevent arithmetic overflow errors. The preprocessor's firmware that is stored in ROM consists of about 100 assembly language instructions.

Arrhythmia Analysis Logic

The laboratory microcomputer contains a Z80 microprocessor (Zilog) with a clock frequency of 4 MHz. The microprocessor is interrupt driven to sample the pulse train produced by the preprocessor at 5500 sps providing a time-base resolution of about 0.2 ms. Fig. 5 shows a stripchart of an ECG and the corresponding *R-R* intervals and *QRS* durations for two different beats. Fig. 6 shows how these values are plotted against one another in the x-y plane and the numbers assigned to the various regions. The *R-R* interval and *QRS* duration of each beat give the coordinates a point in the plane, and we use the locations of the points to detect arrhythmias. We use general principles of ECG arrhythmia analysis to determine the normality or abnormality of beats based on their *R-R* intervals and *QRS* durations [12], [13].

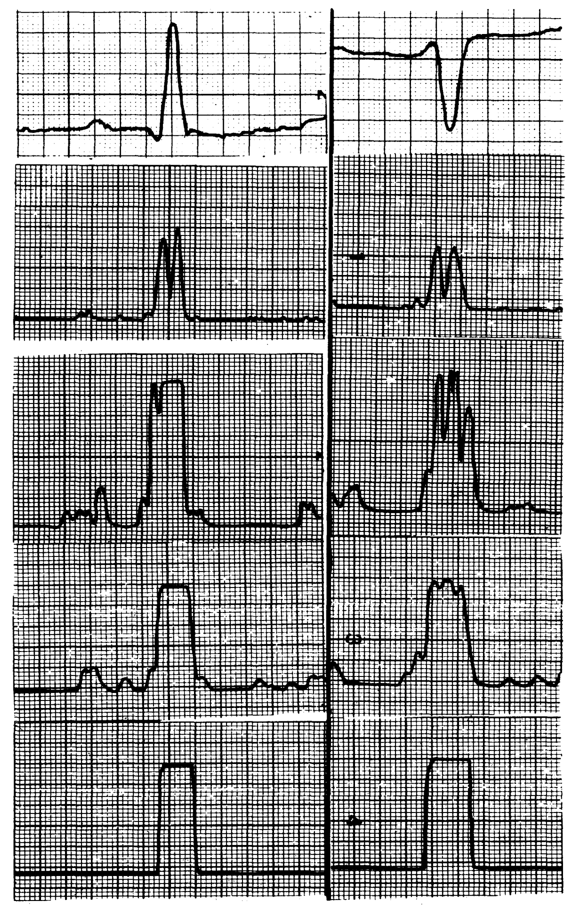

Fig. 3. Stripcharts of two *QRS* complexes showing (a) original ECG, (b) smoothed and rectified first derivative, (c) smoothed and rectified second derivative, (d) sum of the derivatives, and (e) square pulse output.

A rectangle on the video display surrounds the region of beats which are classified as normal. This fixed-size "normal" box locks onto the normal beats as the system initializes. The boundary of this region is determined by approximately a 14 percent *R-R* interval deviation and a 20 percent *QRS* duration deviation from the midpoint of the normal box. After a new beat classified as normal falls within the normal box, the program calculates the average of the *R-R* and *QRS* values for the eight most-recent "normal" beats, and then moves the box defining the normal region so that its midpoint coincides with this new average midpoint. Thus, the box drifts with the normal beats as gradual changes in heart rate occur within normal limits. Boundaries of the additional rectangular regions shown in Fig. 6 for abnormal beats and noise are established relative to the current position of the normal box. Due to their long *R-R* intervals,

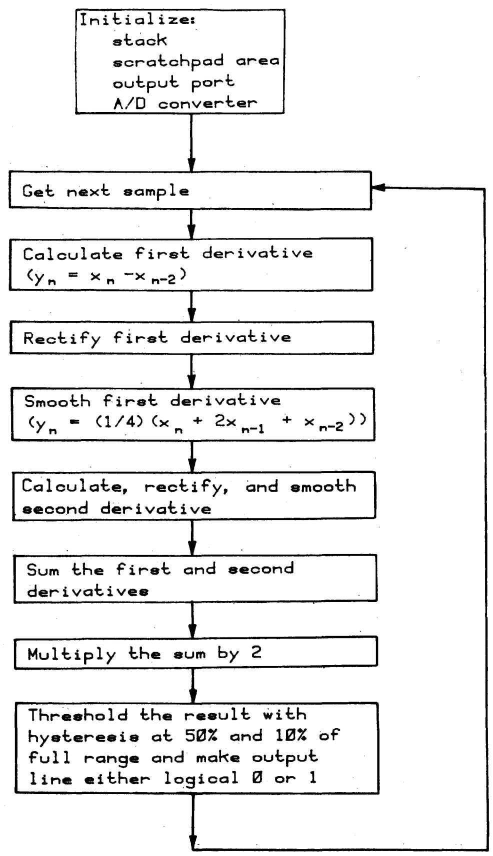

Fig. 4. Flowchart of the firmware for the preprocessor that analyzes ECG signals at 60 times real time.

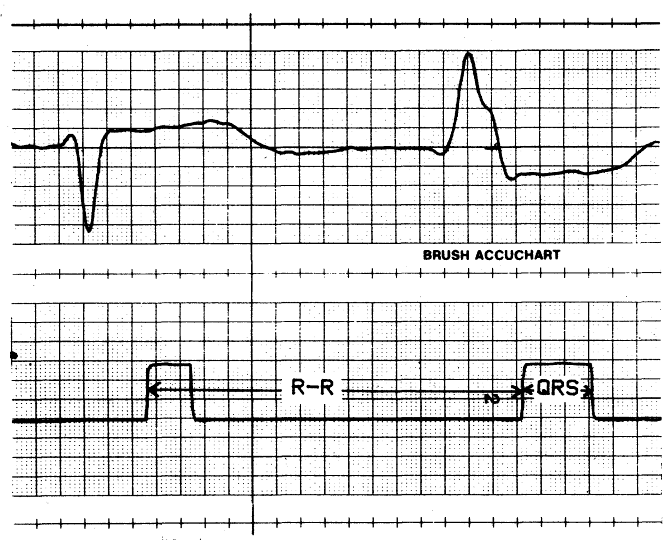

Fig. 5. Stripchart showing the measurements of R-R interval and QRS duration. The top trace is the input to the preprocessor. The bottom trace is the output of the preprocessor that goes to the laboratory microcomputer. Chart speed: 125 mm/s.

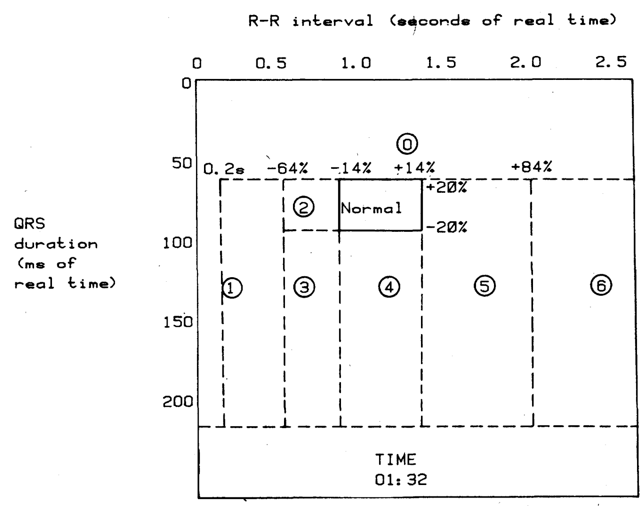

Fig. 6. Plot of R-R interval versus QRS duration. The normal box and a digital clock display appear on the video screen in real time.

dropped beats fall to the right of the line shown at 84 percent of the current normal R-R interval (Region 6). R-on-T beats fall to the left of the −64 percent line because of their short R-R interval (Region 2).

A compensated PVC produces a point in Region 3 (because it is premature and wide) followed by a point in Region 5 (because it is followed by a full compensatory pause and thus is characterized by a long R-R interval together with a normal QRS duration). A point in Region 3 followed by a point in the normal region represents an uncompensated PVC. A point in Region 3 followed by a point in either Region 1 or 2 and a subsequent point in the normal region defines an interpolated PVC since this pattern signifies an extra beat which occurs between two normal beats without upsetting the ongoing normal rhythm. Two consecutive points in Region 3 followed by a point in either Region 5 or the normal region is the pattern for a couplet (two consecutive PVC's).

A point in Region 1 followed by a point in Region 5, 6, or the normal region is the characteristic result for an R-on-T beat due to its unusually short *R-R* interval. An APB produces a point in Region 2 (since it is premature) followed by a point in Region 5 or in the normal box (because it is followed by a partial compensatory pause). The characteristic of paroxysmal bradycardia is at least three consecutive points in Region 5 (due to the slow heart rate, and thus long *R-R* interval), while paroxysmal tachycardia gives several consecutive points in Region 1, 2, or 3 (due to the short *R-R* interval). Fusion beats fall in Region 4 due to their wide *QRS* durations, while escape beats produce points in Region 5 due to their delayed (and probably wide) *QRS* complexes. A dropped beat gives a point in Region 6.

It is also desirable to detect slow-onset bradycardia and tachycardia. Since the normal box drifts with a slowly-changing heart rate, the points for these types of bradycardia and tachycardia fall within the normal box. To detect them, we check the *R-R* interval of each new point that falls in the normal box, and identify "slow-onset" bradycardia and tachycardia when this value corresponds to consistent heart rates below 40 or above 140 beats/min.

Any beat that falls in the region to the left of the boundary line at an absolute *R-R* value of 200 ms or above the line at a *QRS* duration of 60 ms (Region 0) is an artifact produced by noise since no physiological beat should fall in this region. We also ignore the beat which follows a noise point since the occurrence of a noise pulse invalidates the next *R-R* interval measurement. Normal processing resumes with the following beat.

Software Implementation

A 24 h ECG contains about 100 000 *QRS* complexes. We keep a count of total beats and arrhythmias for each minute in the day. A total of 22 separate beat counters are maintained for each minute, requiring a total of about 31 kbytes of RAM to store 24 h of data. The program, scratch pad, and stack area require another 12 kbytes of RAM, bringing the total memory requirement to about 43 kbytes.

Processing starts by locking the normal box onto the normal beats. To do this requires the assumption that most of the beats are normals. The size of the box defining the normal region is initially very large so that all of the first few beats fall within it. As each new beat is processed, the program reduces the size of the normal region, calculates a new midpoint for the box defining the region from the average of the eight most recent points which fell in the box, and moves the normal region boundaries to this new location. This process continues until the normal region reaches its standard size. If the program fails to keep tracking the normal beats during processing (detected if no point falls within the box for 256 consecutive beats), this procedure automatically repeats to locate the normal beats again.

```
****Menu for off-line processing: ****
        ALL     Dump all data minute by minute
        MENU    Print the menu
        PLOT    Go into plotting mode for x-y plots
        TIME    Print data around a time you choose
        TOTAL   Print total beat
        TYPE    Select type of display desired
        ^P      Echo to the printer
        ^C      Return to CP/M
*** Threshold routines *** Print only the data for which the count
    exceeds a threshold which you enter.
        PVC     Total PVC       /  BEATS   Beats per min
        FOC     Multifocal PVC  /  PTAC    Parox tachy
        RONT    R-on-T          /  PBRA    Parox brady
        COUP    Couplets        /  STAC    Slow-onset tachy
        INTP    Interp PVC      /  SBRA    Slow-onset brady
        PWC     PVC w/ comp     /  DROP    Dropped beats
        PNC     PVC w/o comp    /  FUSE    Fusion beats
        APB     Atrial PB       /  ESC     Escape beats
        PRE     Total beats     /  NOISE   Noise cnt
 ** During a dump
         Z    Zap function       /   H       New heading
         ^S   Stop/restart output
```

Fig. 7. The menu of options presented by the console display after the tape has been played into the system.

In practice, relocking almost never is needed. The operator can easily see on the video graphics display if the processor fails to lock onto a normal signal.

To ensure timing accuracy, the microcomputer measures the *R-R* interval and *QRS* duration within an interrupt-driven routine. Each newly computed point is displayed in its proper position on the screen and placed in a first-in-first-out buffer. This buffer ensures the ability to process relatively short episodes of extreme tachycardia without any points being skipped since new points can be buffered until all previous points have been processed. The screen updates occur at a rate of about 60 points/s (i.e., 60 times the real-time heart rate of about 1/s). The processor also counts the interrupts to determine when a minute of real time has elapsed and then changes to a new block of counters and adds a minute to the real-time clock display on the video screen.

In the extra time between interrupts, the microprocessor takes points out of the FIFO buffer and examines their coordinates to determine the regions into which they fall. If they are within the normal box, the program checks for slow-onset bradycardia and tachycardia, calculates a new midpoint for the box, and moves the box to this new location. If the points are outside the normal box the program determines the type of arrhythmia and updates the proper flags and counters. All this processing is possible without ignoring any beats for sustained heart rates of greater than 150 beats/min.

After playing the entire Holter tape into the analysis system, the user may extract specific information from the mass of 24 h data gathered. Fig. 7 shows the menu of options. Hard copy of any alphanumeric output can be easily obtained by echoing the console display to the printer.

Fig. 8 shows displays obtained by executing menu options. The "TOTAL" command prints the total counts of beats, PVC's, and APB's for the 24 h period. The "PVC" command selects a data display of PVC count. The user may enter a threshold to receive a listing of all minutes in which that threshold was exceeded, thus episodes of an arrhythmia are very easy to locate. Data around a specific time may be examined using the "TIME" command.

```
TOTAL
TOTAL BEAT COUNT =                    117475
TOTAL APB COUNT =                     00201
TOTAL INTERPOLATED PVC COUNT =        00370
TOTAL COMPENSATED PVC COUNT =         02075
TOTAL UNCOMPENSATED PVC COUNT =       00631
TOTAL PVC COUNT =                     03076
```

*PVC
MINUTES IN WHICH TOTAL PVC COUNT EXCEEDED THRESHOLD (TWO DIGITS) OF: 30

TIME	BEATS	PVC	FOC	APB	RONT	PTAC	PBRA	STAC	SBRA	DROP	FUSE	ESC	NOISE
07:59	093	31	5	0	0	0	0	0	0	0	9	0	2
08:01	102	34	6	1	0	7	0	0	0	0	2	0	3
08:39	103	31	6	0	0	0	0	1	0	0	7	0	2
10:50	096	35	9	1	0	0	0	0	0	0	0	0	0
10:51	094	41	11	6	0	0	0	0	0	0	1	0	6

*TIME
DISPLAY OF 9 MINS AROUND SELLCTED TIME:
ENTER THE TIME (IN THE FORM 05:35): 03:53

TIME	BEATS	PVC	FOC	COUP	PWC	PNC	INTP	APB	RONT	DROP	FUSE	ESC	NOISE
03:49	095	0	0	0	0	0	0	0	0	0	29	0	2
03:50	093	0	0	0	0	0	0	0	0	0	41	2	2
03:51	097	3	2	0	1	2	0	0	0	0	27	1	4
03:52	097	0	0	0	0	0	0	0	0	0	19	1	18
03:53	070	0	0	0	0	0	0	0	0	5	3	0	9
03:54	090	0	0	0	0	0	0	0	0	1	26	1	5
03:55	080	3	2	0	0	2	1	3	0	1	23	3	11
03:56	089	2	1	0	1	1	0	1	0	1	22	1	11
03:57	090	0	0	0	0	0	0	0	0	1	27	2	1

Fig. 8. Examples of displays generated by executing commands from the menu. The "TOTAL" command shows the sums of various beat counts. The "PVC" command shows a beat summary for each minute that the PVC count exceeded a threshold specified by the operator (in this case, 30 PVC's per min). The "TIME" command shows beat summaries for minutes before and after any specified time (in this case, 03:53).

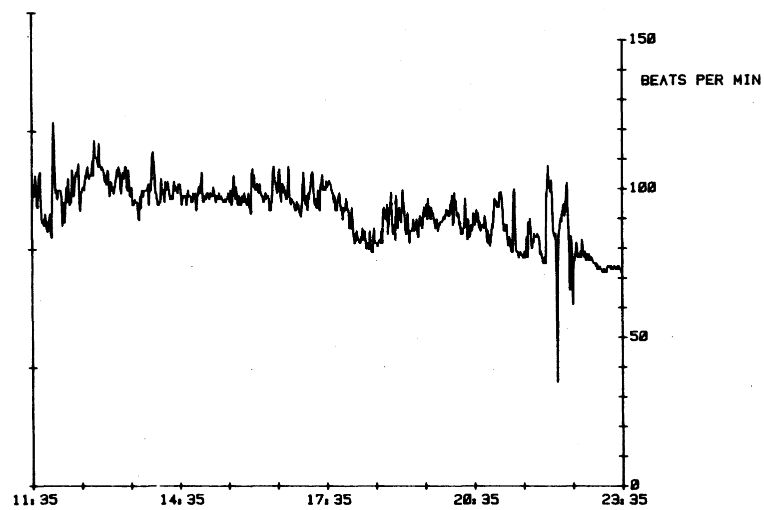

Fig. 9. Example of a trend plot of total beats per minute. The user entered 11:35 as the starting time of the tape. An optional label may be printed on the top of any plot.

Figs. 9 and 10 show examples of plots that the user can make for any of the counters. These give minute-by-minute trend plots of the selected arrhythmias over a 12 h period. The user selects either the first or second 12 h period of the day for plotting and may freely switch between the plotting mode and the numeric mode previously described.

Conclusion

We have developed a fast and reasonably sophisticated automated Holter scanning system using only inexpensive 8 bit microcomputers. Our 60 times real time *QRS* width detection algorithm, when implemented as a preprocessor using a single-board microcomputer, is an efficient method for deriving approximate *R-R* and *QRS* interval information from an ECG signal. Since the preprocessor converts the signal to a convenient form, we have ample computing time on a second microcomputer to analyze the intervals and count a large variety of arrhythmias. We believe that this is a reasonable approach for low-cost automated Holter scanning.

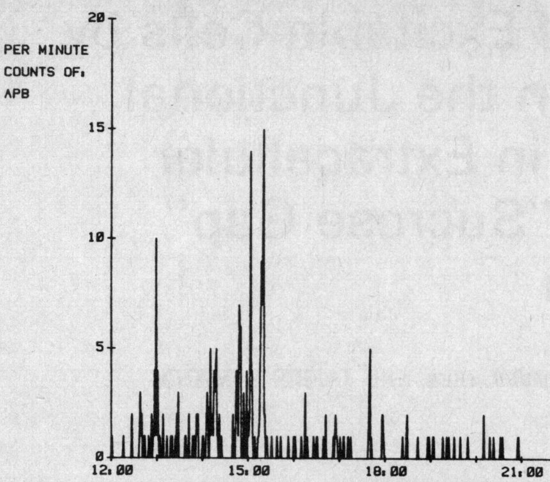

Fig. 10. Example of an APB trend plot.

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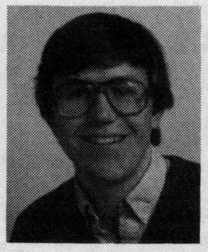

Mark L. Ahlstrom (S'79–M'81) received the B.S. degree in biochemistry and the M.S. degree in biomedical engineering from the University of Wisconsin, Madison, in 1979 and 1981, respectively.

He is now a Computer Applications Engineer at Honeywell Military Avionics Division, Minneapolis, MN. He is currently involved in software development for engineering database management systems and algorithm development for real-time image processing. His interests include programming languages, interactive programming environments, and relational database management systems.

Mr. Ahlstrom is a member of the IEEE Computer Society.

Willis J. Tompkins (S'61–M'66–SM'77) received the B.S. and M.S. degrees in electrical engineering from the University of Maine, Orono, in 1963 and 1965, respectively. He received the Ph.D. degree in biomedical electronic engineering from the University of Pennsylvania, Philadelphia, in 1973.

From 1965 to 1968, he was an Electrical Engineer at Sanders Associates, Inc., where he worked on research and development of data storage systems. He was employed from 1973 to 1974 at the Hospital of the University of Pennsylvania as a Biomedical Engineer. Since 1974, he has been on the Faculty of the University of Wisconsin, Madison, where his teaching specialty is on the topic of computers in medicine, an area in which he has developed two new courses. His research interests include on-line biomedical computing applications. He is coeditor, with John G. Webster, of the textbook, *Design of Microcomputer-Based Medical Instrumentation* (Englewood Cliffs, NJ: Prentice-Hall, 1981).

Dr. Tompkins is a member of the IEEE Engineering in Medicine and Biology Society (currently Region IV Administrative Committee Representative), the IEEE Computer Society, the Association for the Advancement of Medical Instrumentation, and the Biomedical Engineering Society. He is a Registered Professional Engineer in Wisconsin.