COMPUTERS AND BIOMEDICAL RESEARCH 4, 493–508 (1971)

A PVC Detection Program

JOHN S. GEDDES* AND HOMER R. WARNER†

Department of Biophysics and Bioengineering, Latter-day Saints Hospital, Salt Lake City, Utah 84103

Received January 4, 1971

INTRODUCTION

Existing knowledge concerning the relation between premature ventricular complexes (PVCs) and prognosis in patients with acute myocardial infarction indicates that the detection of PVCs and their elimination, the main therapeutic endeavor of coronary care units, is highly rewarding (*1*).

Much additional information is required concerning the significance of such characteristics of PVCs as frequency of occurrence, relation to heart rate, timing in relation to the preceding *QRS* complex, repetitive occurrence in runs and variation in frequency. Recent observations (Pantridge, Scott and Geddes, unpublished) have shown that serious haemodynamic effects may result from arrhythmias, including PVCs previously thought haemodynamically benign. Such haemodynamic effects may adversely affect prognosis, by increasing infarct size.

To the clinician the dependable separation of normal *QRS* complexes from PVCs by digital computer would be an attractive proposition. The alternative system of giving adequate coronary care is expensive but only semiquantitative. A nurse or technician must constantly observe a monitoring oscilloscope, on which the ECGs of 8 or even more patients are displayed, and attempt to count the PVCs of all patients.

The variability of the "normal" *QRS* complexes, against which PVCs must be detected, and of the regularity of the basic heart rhythm, together with the frequent transient superimposition of skeletal muscle artifact on the ECG waveform, render simple hardware devices unsuitable for the task of reliable PVC detection. This is especially true since the drugs used to control PVCs are themselves toxic and occasionally produce adverse effects, so that the false detection of normal complexes as PVCs is as serious an error as failure to detect genuinely abnormal complexes.

PVCs may differ from normal complexes in that they are usually detectably premature, are usually of increased duration, and are invariably of abnormal shape.

* Support by a grant from the Northern Ireland Hospitals Authority.
† Supported by a grant from the National Institutes of Health, RR-00012.

In defining criteria for their detection the variable presence of prematurity and duration must be considered, together with limitations in the accurate assessment of duration and shape imposed by the logic employed. The need to identify premature atrial complexes as normal further complicates the logical manipulation of parameters as criteria for detecting PVCs. These inconsistencies of the parameters are summarized in Table 1.

TABLE 1

COMPLICATING FACTORS IN SELECTION OF PARAMETERS FOR PVC DETECTION

Parameter	"Abnormal" in non-PVC	"Normal" in PVC
Prematurity	PACs, atrial fib.	End-diastolic PVCs, atrial fib.
Duration	A–V dissociation, skeletal artifact	Basic rhythm bundle branch block
		isoelectric portions of *QRS*
Shape		—

Owing to the overlap in frequencies of the waveform arising from skeletal muscle potentials and *QRS* complexes, the former are not amenable to exclusion by filtering techniques. A method of detecting this artifact is therefore required such as permits the automatic rejection of computer decisions when it is present.

The program to be described was written in order to facilitate development of the best logic for measuring the parameters and to find the optimum combination of parameters which would detect PVCs reliably without giving an unacceptable number of false positive decisions. The program will sample four beds simultaneously and display the results in real time at a remote station in a Coronary Care Unit. Up to 11 stations may be active at any one time.

METHODS

Using the MEDLAB time-sharing computer system (*2*), the ECG is sampled 200 times per second and each sample is converted to digital units on an octal scale of 0–2000. The samples are stored in a 512 word circular buffer. A flow chart summarizing the steps by which the data is processed is shown in Fig. 1.

Two seconds of ECG (400 points) is sampled at a time. After the 400th point the data is searched for a *QRS* complex. The maximum absolute derivative between any two points in the first 400 samples is found and half this number is employed as a derivative tolerance to detect subsequent *QRS* complexes. The position of the first *QRS* in the data is indexed using this tolerance. The *ST* segment of the first *QRS* is examined for artifact and if none is found the position of the second *QRS* in the data is indexed, its shape and duration are determined and compared with the standard. The *ST* segment of the second complex, too, is searched for artifact. The cycle length between the first and second *QRS*s in the data is now tested for prematurity

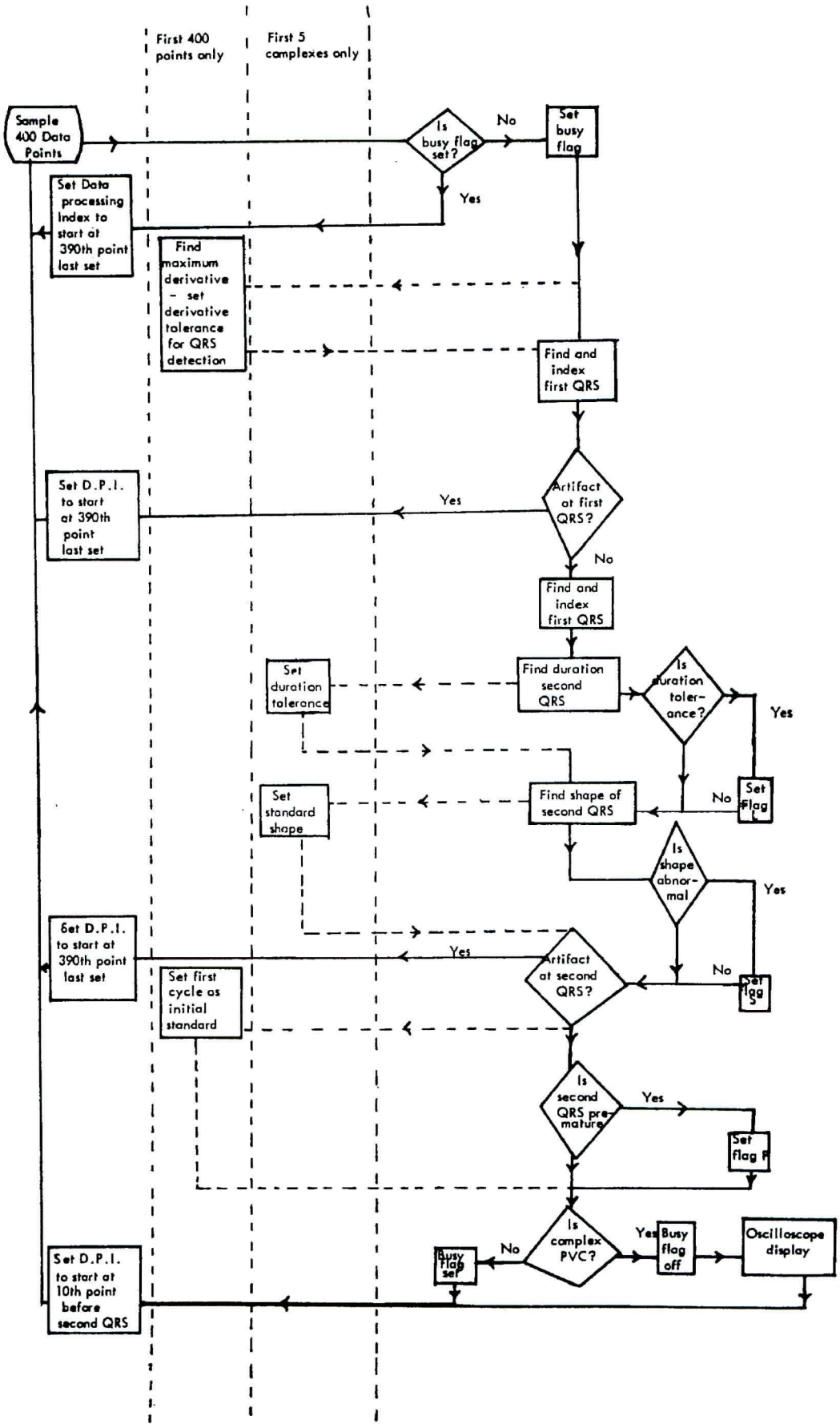


FIG. 1. Flow diagram summarizing logic of test program.

The logical steps in the diagnosis of the complex are then executed. If the complex is labeled a PVC, its waveform is displayed. Finally, the index for the start of the next 400 points is set at 10 before the index of the second *QRS* which becomes the first *QRS* in the next set of data.

During the processing of the 400 data points, a flag is set which prevents the commencement of processing of the next set of data until the first set has been completed. Should processing the next set be attempted, this set results is omitted so that a backlog cannot be built up even when many other programs are active in the time-sharing computer system. When artifact is detected following the first or second complexes in a set, the entire 400 points of data are rejected.

The parameters used for PVC detection and muscle artifact are measured and standardized in the following way:

1. *R–R interval.* The number of samples between the indices of the first and second complex is measured. For regular rhythms the standard R–R interval is conveniently calculated as

$$\frac{2(R\text{–}R\,\mathrm{AVE}) + (R\text{–}R\,\mathrm{LST})}{3}$$

where (R–RAVE) is the previous standard, and (R–RLST) is the R–R interval immediately preceding the cycle under consideration. A complex falling at the end of an R–R interval of less than 90% of the standard is considered premature. The first R–R interval after starting the program serves as the initial standard.

2. *Duration.* Using a derivative tolerance of ±3 A–D units starting at the point at which the QRS complex is indexed, the data is searched forward and backwards until the beginning and end of the complex are reached. To allow for notches and flat portions of the *QRS*, up to 5 derivative "misses" are allowed before the forward search is complete. The number of consecutive "misses" at the beginning or end is then trimmed to define the limits of the actual *QRS* complex. This logic is shown diagramatically in Fig. 2. The standard duration is the median of the durations of the first 5 complexes, and a tolerance of 5 points above the normal is allowed.

3. *Shape.* The up and down slopes and level portions of the *QRS* are assigned the codes 1, 3, and 2, respectively. In order to define only the steeper slopes, a derivative tolerance of 8 A–D units between consecutive points is employed, greater than that for duration measurement. The codes for the differences between sequential pairs of samples are stored using character addressing, 4 codes to a word, in an 8-word array. The codes from the 6th sample before to the 25th after the indexing sample are saved. The shape is thus recorded over a period of 160 msec. An example of the codes derived for a hypothetical *QRS* complex are shown in Fig. 3.

At the start of the program, the shape is saved for 5 consecutive complexes in a 40-word array. The most commonly occurring code in each character is then stored as the standard.

The shape of each subsequent complex is tested against the standard. Because of

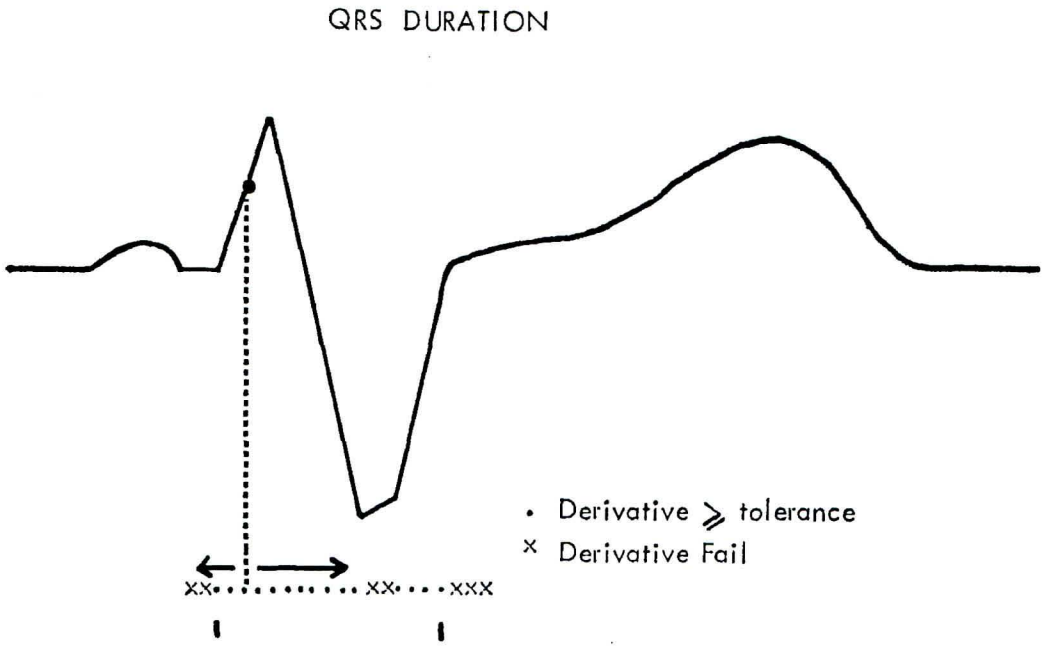


FIG. 2. *QRS* duration determination.

uncertainty that the indexing sample falls at the same point in each complex only the middle 24 characters (120 msec) of the test shapes are used. These 24 characters are compared first with the first 24 characters of the standard and are then right-adjusted one character, compared again, and so on until they are finally compared with the right-most 24 characters of the standard. At each comparison the arithmetic differences between each standard and test character are summed to give a numerical expression of the dissimilarity of the waveforms. An upslope (code 1) contrasting with a downslope (code 3) gives a difference of 2, greater than the difference between

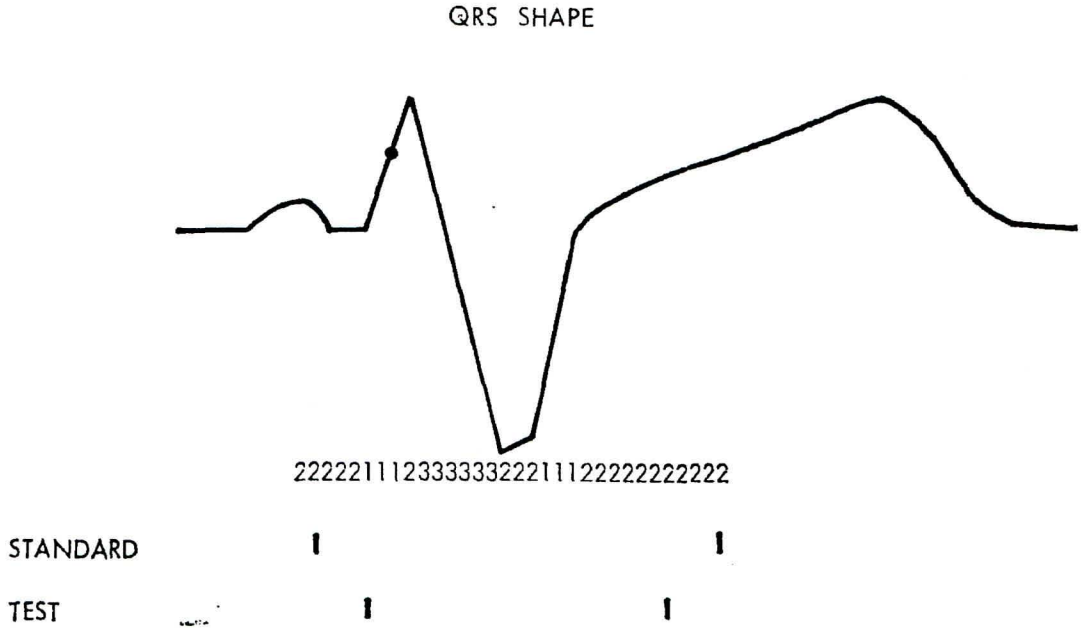


FIG. 3. *QRS* shape coding.

either slope and a level region 1. When all the comparisons are complete, the least numerical difference between standard and test complexes is taken as a measure of the abnormality of shape of the test complex. Under test conditions with mono or biphasic *QRS* complexes, the measured difference between normal complexes and the standard was usually 1–4, and seldom exceeded 6.

It is inevitable that the determination of shape just described is influenced by the duration of the complex. Thus a complex of above average duration must infringe upon the buffer of 2*s* surrounding the representation of the normal complex in the standard. It was felt, however, that the value of the parameter would be impaired by restricting the comparison to a specific part of the complex (e.g., first 80 msec) because considerable portions of the shapes of normal and abnormal complexes may be similar (Fig. 4).

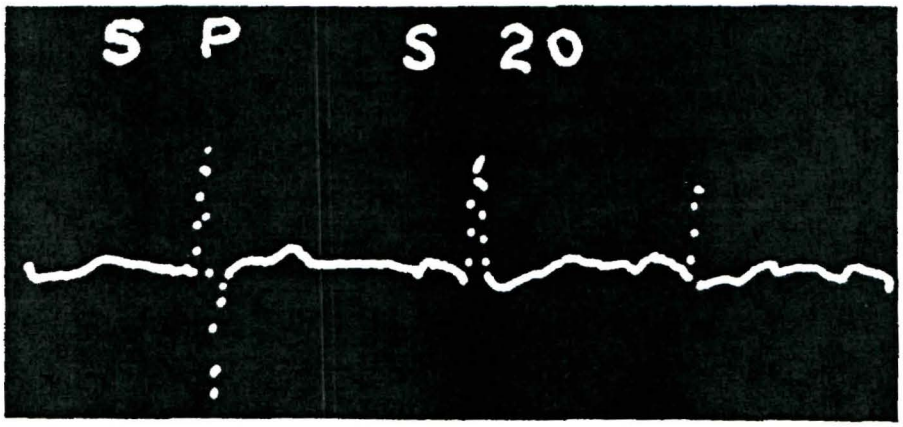


FIG. 4. Similarity of shapes of normal *QRS*s and of early part of PVC waveform.

4. *Artifact Recognition.* Artifact due to skeletal muscle movement may be of sufficient intensity to simulate *QRS* complexes, or may interfere with duration and shape determination of genuine complexes. In order to detect artifact when it occurs, a portion of the ECG waveform which is normally smooth is searched for irregularity. So that genuine *QRS* complexes might not be falsely interpreted as artifact, the part of the cycle chosen was the *ST* segment, at which time the heart is in a refractory state and a new *QRS* complex is impossible. The area of search extends from the 20th point after the indexing samples of a *QRS* complex to the 50th point.

Although the contour of the *ST* segment is smooth, without high frequency components, its slope varies from patient to patient, and within the same patient according to the origin of the complexes. The presence of steep slopes was not, therefore, a sufficient criterion for the detection of artifact. However, if the second derivative is computed at each point in the search area and compared with a tolerance slightly exceeding the derivative tolerance, e.g., 5–10 A–D units, sensitive artifact detection is obtained. The result is independent of the slope of the *ST* segment (Fig. 5).

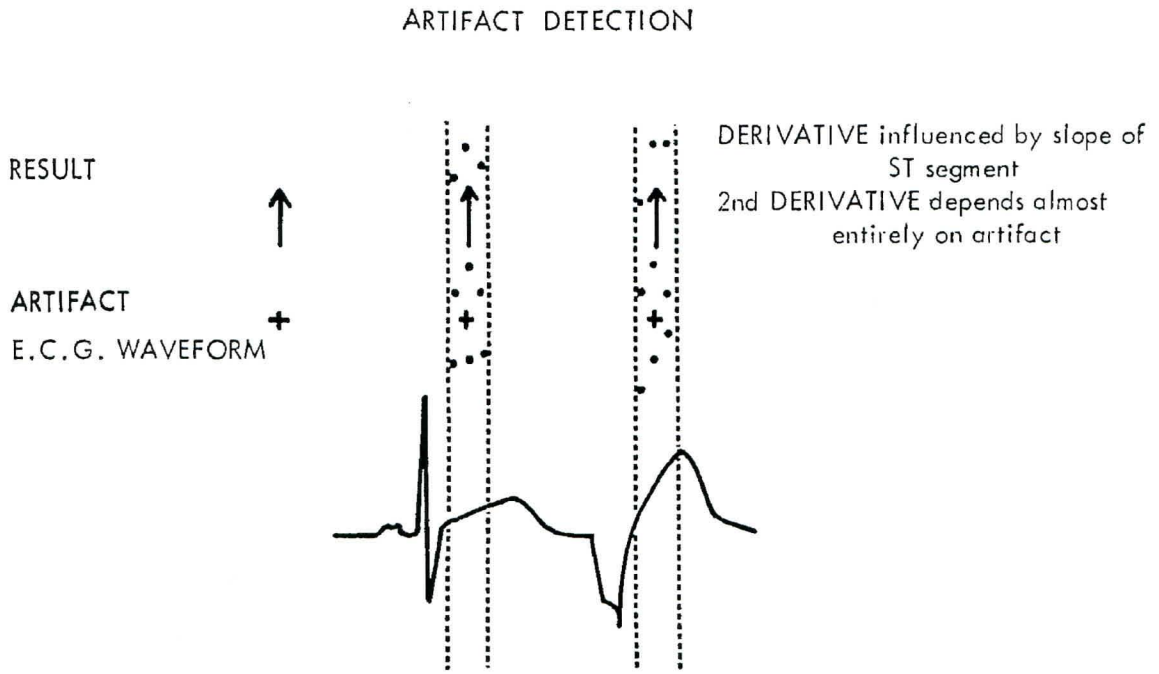
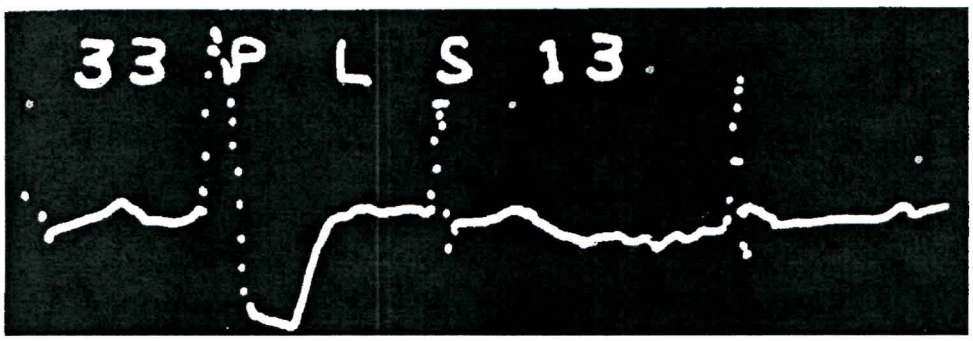


FIG. 5. Logic of artifact detection. First derivative of samples in *ST* segment varies more than second derivative in absence of artifact.

When the program is running, the computer decision on a complex is considered liable to error if artifact is detected during the preceeding or subsequent *ST* segments. Artifact sufficient to interfere with beat recognition is detected unless it is of brief duration and is absent from the search areas. Such artifact is only occasionally seen and may be due to coughing or sneezing.

Oscilloscope Displays

Display for selecting criteria. The parameters of prematurity, duration and shape were labelled *P*, *L*, and *S*, respectively. When a complex is considered to be an extrasystole according to the criteria under test, the waveform, derived from the digital samples stored in the circular buffer, is displayed on the oscilloscope at the computer terminal (Fig. 6). The labels of the parameters detected as abnormal are also displayed along with the % of all complexes since the previous extrasystole which the present complex represents. Additional numerical data concerning the



degree of abnormality of a parameter may also be displayed. A minor modification of the program enables all complexes to be displayed and the assessment of the frequency of occurrence of abnormalities not satisfying the criteria for the diagnosis of an extrasystole.

In order to standardize the conditions of test, ECG waveforms from ten patients which included normal and varying patterns of abnormal complexes were recorded on magnetic tape.

In addition permanent records were made of computer decisions using an oscillograph to record a digital-to-analog signal from the computer alongside the ECG

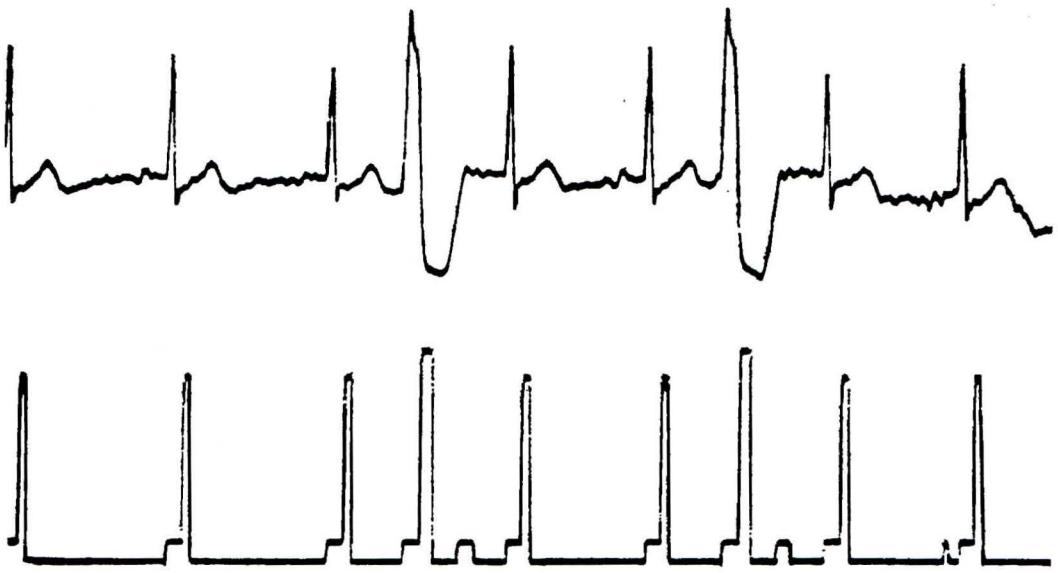


FIG. 7. Coded analog channel (lower trace) indicating computer decisions on *QRS* complexes (upper trace). Commencement of possible *QRS* indicated by small deflections. Recognition of normal *QRS* results in large deflection of fixed duration and height. Small deflections not culminating in *QRS* recognition signal are due to *P* or *T* waves and are excluded on basis of short duration. Detection of PVCs results in tall deflection of different height from normal. If criteria for PVC recognition are increased duration or combination of increased duration and prematurity the tall deflections are wider than normal (as in this record).

signal (Fig. 7). A small step is recorded at the beginning of each *QRS*-like complex. When the program senses the end of the complex or when the duration exceeds the limits for normal *QRS* duration for this patient, one of the following occurs: (1) If the waveform did not meet the criteria for a true *QRS* complex, the signal returns to the base line. (2) If the waveform is classified as a normal *QRS* for this patient, an additional step in voltage occurs. (3) If the waveform is classified as an abnormal *QRS* based on prematurity, duration, and/or shape, a step somewhat taller or shorter will be recorded. This technique was employed to evaluate a prototype version of the program from which the circular buffer was omitted, the onset of a *QRS* complex being sensed by the occurrence of a slope exceeding the derivative tolerance, and in which an arbitrary logic was used to detect extrasystoles (Fig. 8).

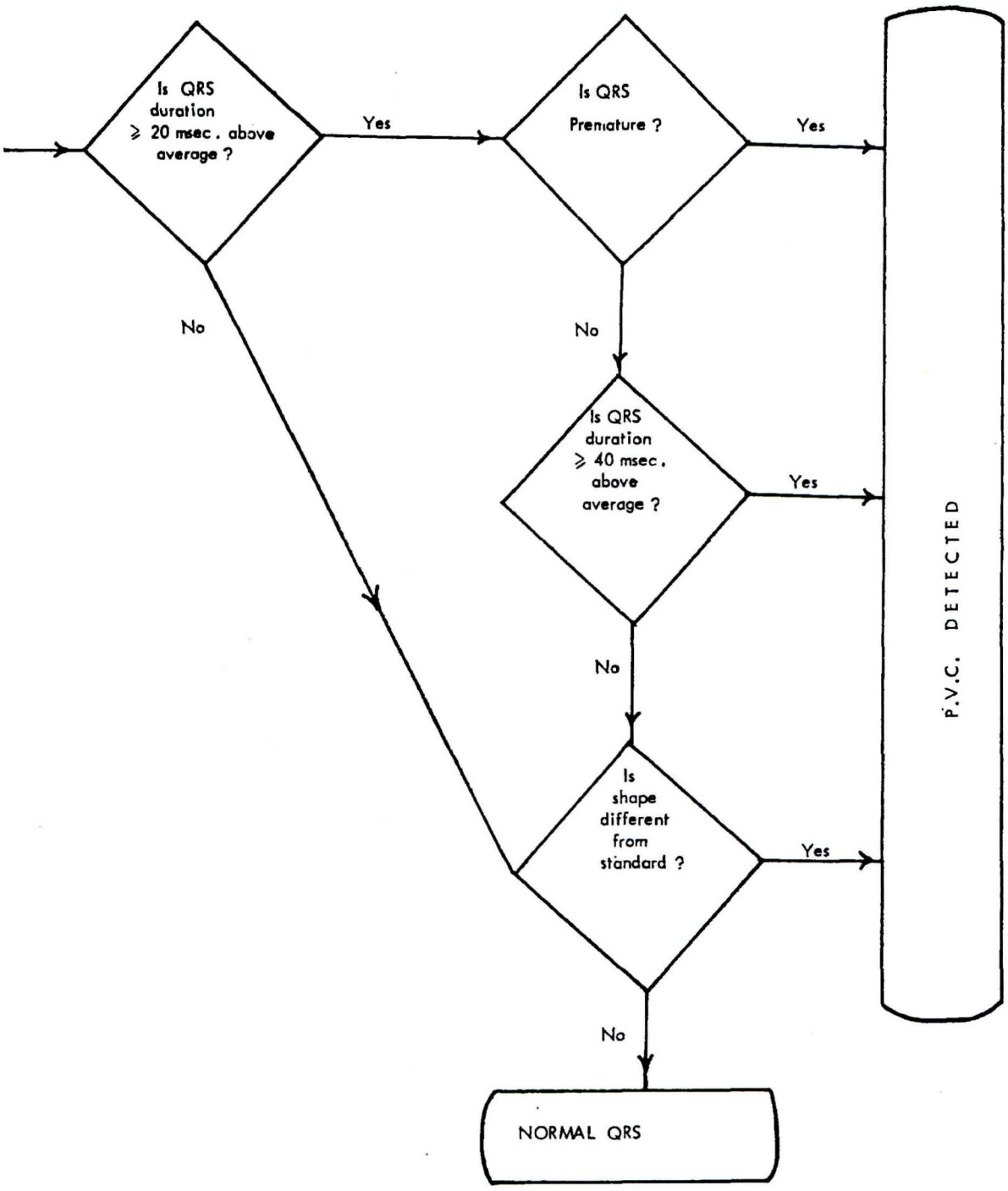


FIG. 8. Flow diagram of arbitrary logic tested.

RESULTS AND DISCUSSION

The following figures illustrate some of our results using the prototype program:

Fig. 9 shows the detection of extrasystoles using different criteria according to coupling interval. The first PVC is markedly premature, which weighted a moderate prolongation in duration and resulted in detection of the PVC. The second PVC is only slightly premature, and duration is not sufficiently prolonged to qualify the

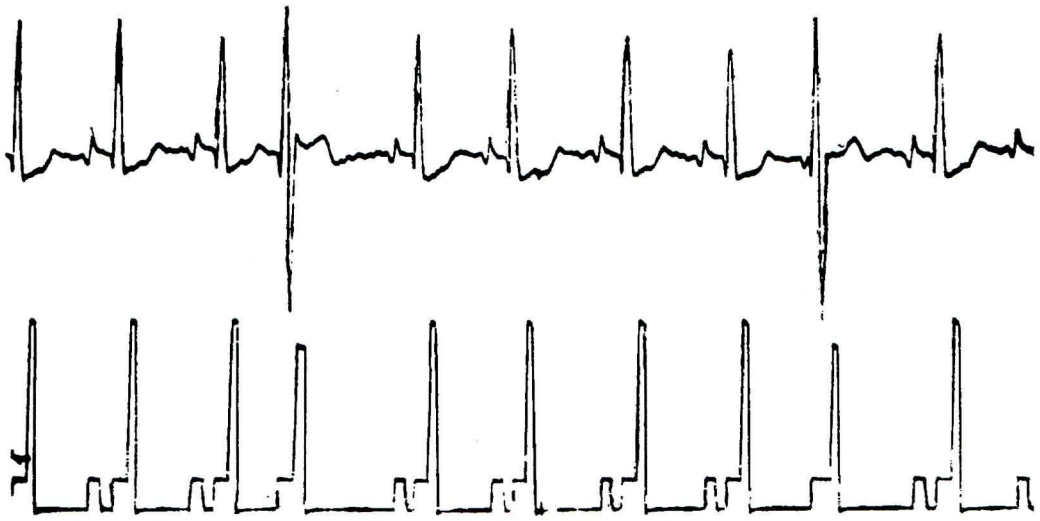


FIG. 9.

complex as a PVC on this criterion alone. However, the diagnosis of a PVC was made correctly on the basis of abnormal shape.

Fig. 10. On this cardiogram runs of supraventricular tachycardia were followed by single PVCs. In the sequence shown the PVC was correctly detected because of prematurity and increased duration. However, the second supraventricular complex following the PVC was incorrectly detected as a PVC on the basis of a slightly abnormal shape, presumably due to a minor degree of aberrant conduction.

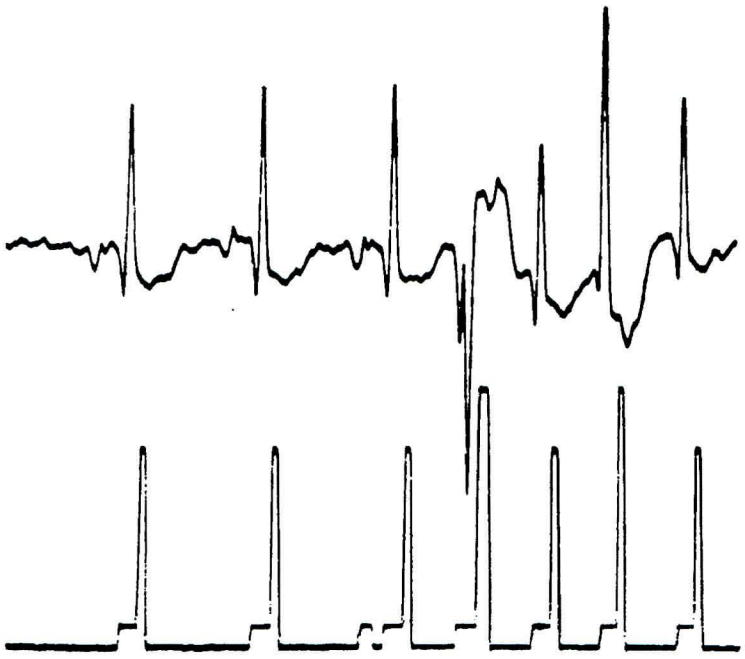


FIG. 10.

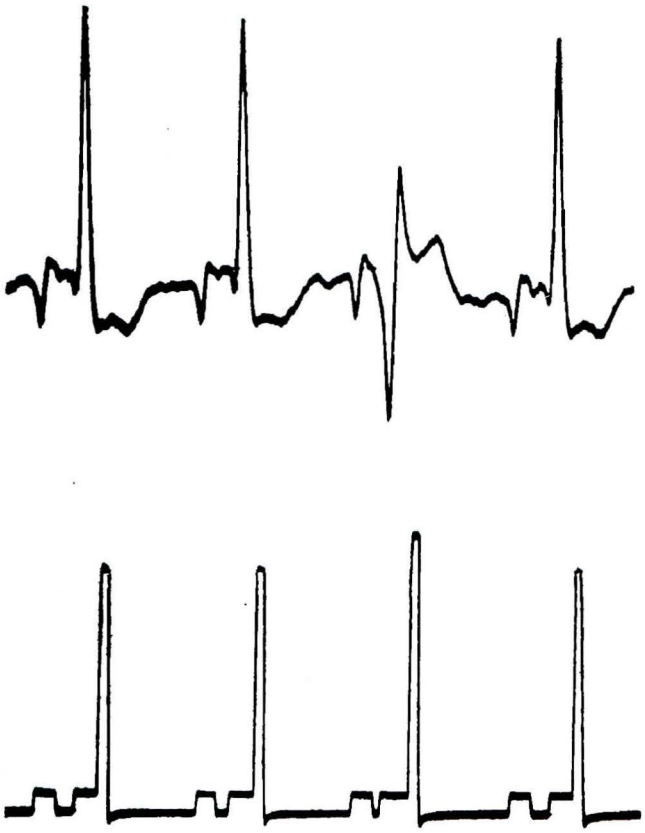


FIG. 11.

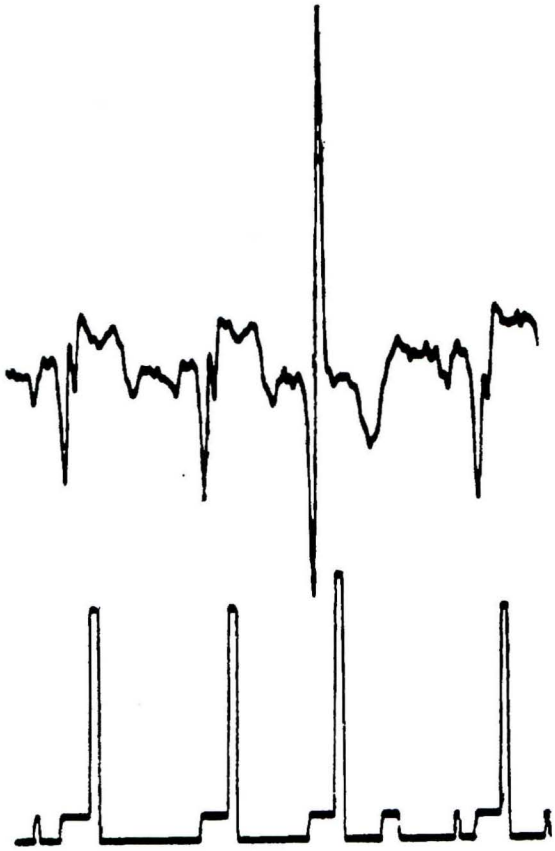


FIG. 12.

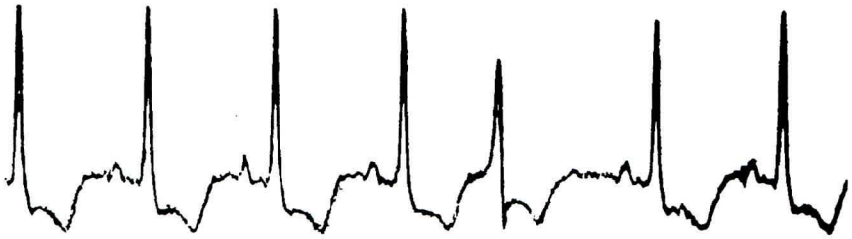
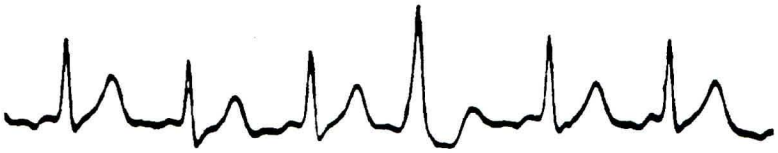


FIG. 13.

Fig. 11. In this cardiogram the abnormal complexes are of the preexcitation type. They were labelled as PVCs because of abnormal shape since the increase in duration was not sufficiently great to exceed the duration tolerance for nonpremature beats.

Fig. 12. PVC detection in bundle branch block. Although the PVC is premature, its duration is not greater than expected for this patient; so correct diagnosis here was based on abnormal shape.



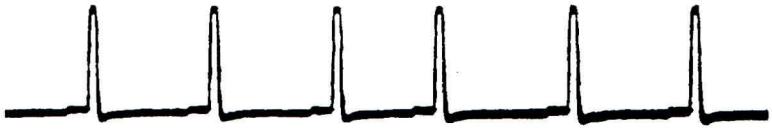


FIG. 14.

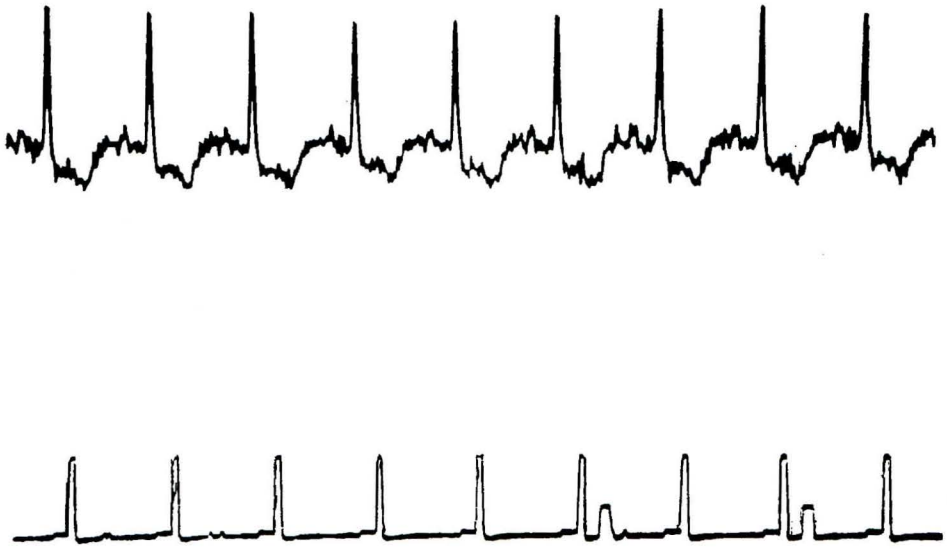


FIG. 15.

Fig. 13. Premature supraventricular complexes are detected as normal despite their prematurity. Prematurity cannot be more than a weighting factor in the evaluation of other parameters.

Fig. 14. Some PVCs are not detectable by the logic employed. The abnormal complex is almost certainly a PVC, yet the method of determining shape did not differentiate it from normal complexes.

Fig. 15. Artifact recognition. Skeletal muscle potentials are just sufficient to result in detection of artifact (indicated by a second signal after two of the *QRS* recognition signals). The artifact was insufficient to interfere with the recognition of normal complexes, as no "false positive" PVCs were detected.

Fig. 16. Detection of more severe artifact. Two *QRS* complexes are incorrectly labelled as PVCs and artifact itself is falsely recognized as an additional PVC. The artifact is recognized (again shown as a second signal) after all 3 complexes and also after the last of the normally detected *QRS* complexes before the artifact begins. A true PVC is detected to the right of the figure.

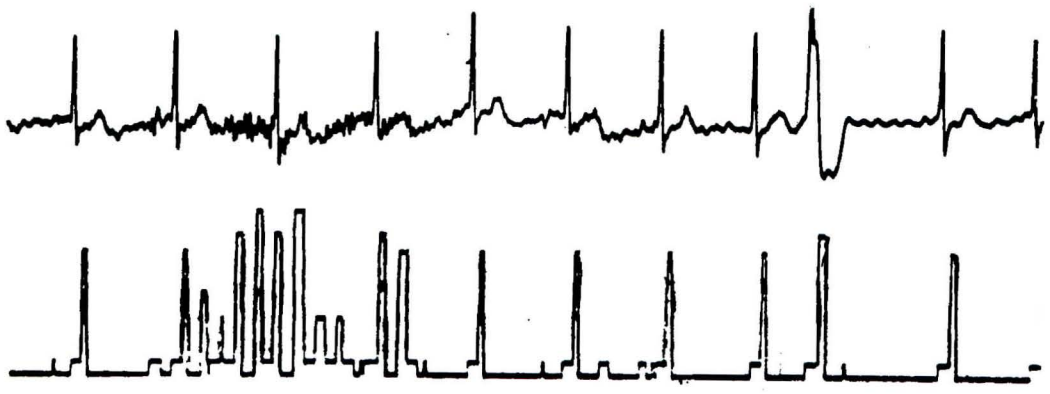


FIG. 16.

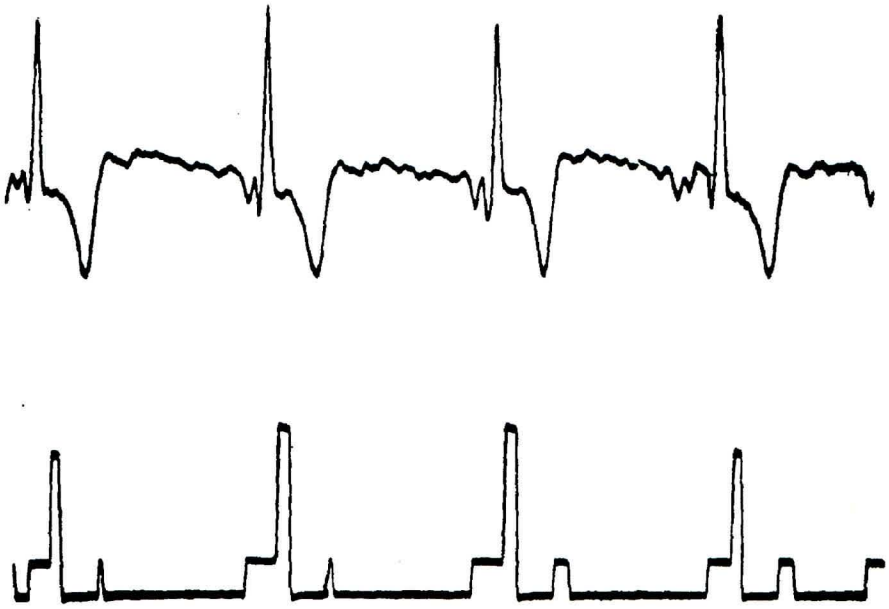


FIG. 17.

Fig. 17. AV Dissociation. The sharp *P* waves of large amplitude cause apparent increase in *QRS* duration sufficient to label the normal complexes as PVCs.

Fig. 18. AV Dissociation. Same patient as Fig. 17. Here the *P* waves coincide with the *T* waves, and because of their sharp contour produce "false" artifact.

These results indicate that it is possible to detect the majority of PVCs using a criteria of prematurity, duration, and shape. Occasionally, supraventricular complexes are labelled as PVCs using the logic tested, due to slightly abnormal shape or to superimposition of *P* waves upon the beginning or end of the *QRS* complex. The latter problem may be largely overcome by selecting a lead for monitoring in which the deflections due to *P* waves are not prominent. The test program described will be employed in further studies to devise a logic associated with an even higher degree of accuracy in PVC detection together with the maximum of economy of computer time.

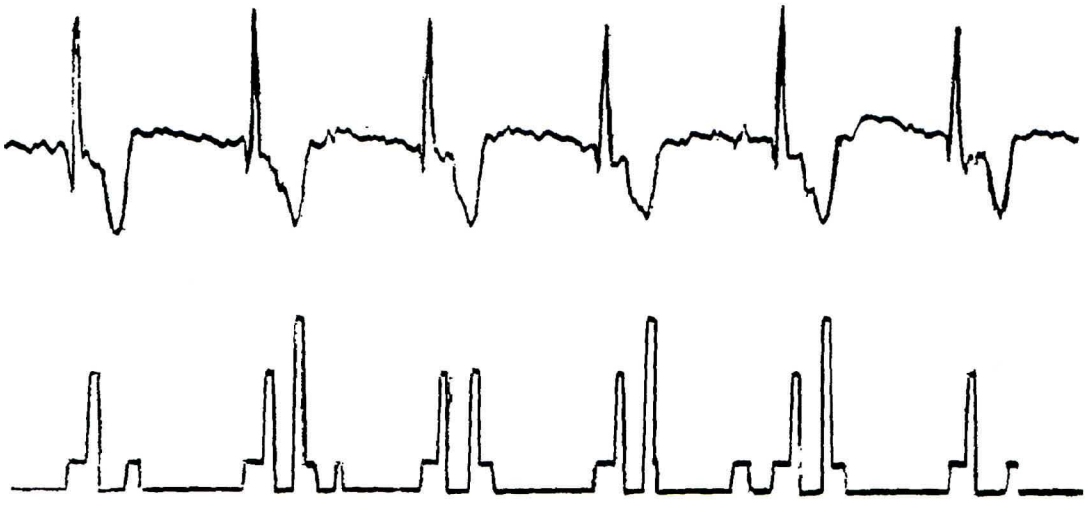


FIG. 18.

Statistical Summary

Each 20 seconds the numbers of *QRS* complexes, PVCs, runs of 2 or more PVCs, and the prematurity of the most premature PVC as a fraction (×10) of the average cycle length may be displayed on the oscilloscope for two patients (Fig. 19). For this display the occurrence of artifact causes a zero to be inserted before the number of complexes, indicating that the reliability of the result is in doubt on bed 2.

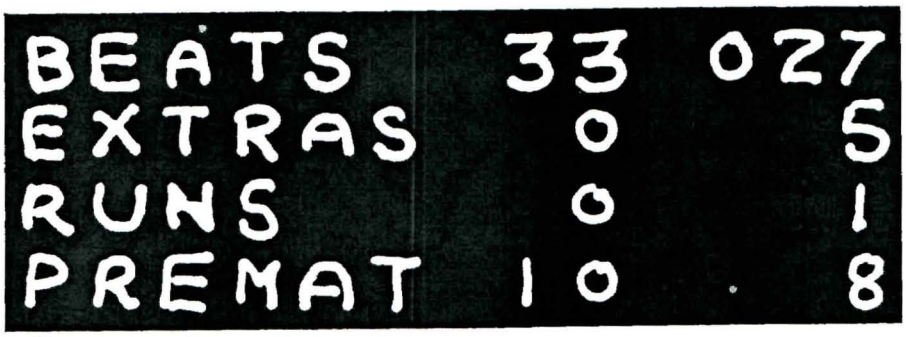


FIG. 19. Oscilloscope display of results of 20 seconds of ECG monitoring. During the monitoring interval shown on the right artifact was detected, so that the reliability of the results is in doubt. A zero is inserted before the number of "beats" in this event.

When 30 of these 20-second units of valid data have accumulated, a statistical summary is prepared (Fig. 20). This summary shows the average heart rate per minute, the maximum and minimum rates among the 20-second units, the average number of PVCs per minute, the number of 20-second units in which PVCs occurred, the maximum and minimum numbers of PVCs in any of the 20-second units, the heart rates at the time of the maximum and minimum numbers of PVCs, the composite heart rates from all cycles preceding normal cycles and from all cycles preceding cycles in which PVCs occurred, the prematurity of the most premature PVC and the maximum number of runs of PVCs in any 20-second unit.

TIME	AVE HR	MAX HR	MIN HR	AVE EX	WITHEX	MAX EX	MIN EX	HR MXX	HR MNX	NRM HR	EXT HR	MINPRE	MAXRUNS
20. 11	75	78	72										
20. 30	77	84	75	0	3	1	0	78	78	77	79	5	0
20. 43	77	81	72	1	5	1	0	78	75	77	78	5	0
20. 57	53	87	28	0	4	1	0	81	28	82	88	5	0
21. 11	88	91	84	1	4	2	0	87	87	87	87	5	0

FIG. 20. Format of statistical summary of results for clinical use. For explanation of headings, see text.

One of these summaries is saved on disc approximately every 10 minutes if artifact is slight, and they therefore accumulate at a rate of about 6 per hour. The amount of data to be reviewed by the clinician at the end of 24 hours is thus not excessive.

SUMMARY

A program is described which enables parameters of prematurity, duration and shape to be tested as criteria for PVC detection. A method of detecting artifact has been developed and found reliable. Results using a prototype program tested with tape recorded ECG tracings and using an arbitrary logic are encouraging. The test program will be used to further refine the logic. A method of summarizing the accumulating data has been devised for clinical use.

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