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ABSTRACT

The utilization of computers in the interpretation of electrocardiograms (EKG's) and vectorcardiograms is the subject of this report. A basic introduction into the operations of the electrocardiograms and vectorcardiograms is provided via an illustrated text. A historical development of the EKG starts with the 1950's with the first attempts to use computers in their interpretation. Programs intended for this purpose are described, with attributes and weaknesses of each mentioned. The current status of computer interpretation is evaluated as being generally more reliable than human interpretive methods. Another important use of the computer in patient monitoring is also described. Again, in the area of electrocardiography, the computer can detect ventricular fibrillation, an interruption of the heart's electrical stability. The computer has proven to be very effective in the detection of preliminary symptoms of ventricular fibrillation, thus lessening the demand on medical personnel to constantly monitor patients. (CP)

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# COMPUTERS IN CARDIOLOGY

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## COMPUTERS IN ELECTROCARDIOGRAPHY

Of all the areas of medicine in which computers have made an impact, perhaps the most important - and certainly the best publicized - is in electrocardiography. The reasons for this are technical, medical, and economic. Technically, the use of computers in cardiology is very exciting and challenging, primarily because it is one of the few areas of computer useage in which there is direct interface between the computer and the patient. Medically, the area is important because of its great potential for impacting the life of large numbers of people - heart disease is the single, most significant cause of death in the U.S. population, taking the lives of over a million people a year and seriously effecting the lives of five to ten times that many people. Economically, the importance of computers in cardiology becomes evident when one realizes that the total bill for electrocardiograms taken in the United States is about one billion dollars while an approximately equal amount is spent caring for patients in electrocardiographically monitored hospital beds.

To understand the use of computers in electrocardiography, it is first essential to have some grasp of the clinical uses of the electrocardiogram. The best known uses of the electrocardiogram are the conventional diagnostic electrocardiogram and the vectorcardiogram. The 12-lead cardiogram consists of 12 short recordings - usually about five seconds apiece - of the electrical activity of the heart sampled at different places on the torso. These 12 leads are depicted diagramatically in Figure 1 with the typical electrocardiogram presented in Figure 2. The vectorcardiogram, which is generally considered the diagnostic equivalent of the electrocardiogram uses only

three orthogonal leads and usually presents the results as vector loops as in Figure 3.

The electrocardiogram (or vectorcardiogram) is used for diagnostic purposes, generally to detect abnormalities which either do not vary with time or only vary slowly. An obvious example is in the detection of the acute myocardial infarction which generally produces a definitive pattern of electrocardiographic changes, indicating the existence of the myocardial infarction, a rough estimate of its size, and some indication of the location of the infarcted area. A typical pattern of a fresh anterior wall myocardial infarction shows elevated ST segments in the anterior leads. Another example of the utility of the electrocardiogram might be left ventricular hypertrophy - the abnormal growth of the left ventricular muscle - resulting from overwork of the left ventricle because of either a stenotic aortic valve or systemic hypertension. On the other hand, a giant P wave produced by atrial hypertrophy is an indication that the mitral valve is abnormal.

In the late 1950's, several groups, more or less independently, came to the conclusion that the electrocardiogram and vectorcardiogram were ideal candidates for computerization. Their conclusions were based partly on economic considerations - they realized that the cost of computer analysis would certainly be much less than the cost of having a physician read an electrocardiogram - and partly on medical-technical considerations. It appeared that since human readers of the electrocardiogram used what appeared to be fairly simple, heuristic techniques for analyzing the electrocardiogram, a straightforward translation of these techniques to machine

code should provide similar accuracy. Accordingly, several groups worked for some years through the late 1950's to develop independent programs for analysis of electrocardiograms. The best known work probably was that of Caceres et al at the U.S. Public Health Service.[1] The original PHS program sampled each of the 12 standard ECG leads at 500 times a second for approximately five seconds and measured various parameters of the ECG (e.g., height of the R-wave, P-Q interval, etc.). These data were then used in an extensive decision tree, based on conventional criteria, to produce an ECG diagnosis. This program has been through many revisions and is currently in common use as ECAN Version E. Two other groups working in the early days both utilized the vectorcardiogram. These were Pipberger's group at the VA Hospital in Washington[2] and Smith's group at Mayo Clinic.[3] Towards the end of the 1960's, a fourth group led by Pordy and Bonner[4] made a significant impact with a 12-lead ECG program that was similar in concept to its three major competitors but probably performed a little bit better at the time it was introduced. The original Pipberger program is not in current use. The Smith program and the Pordy/Bonner programs are used in somewhat updated versions.

Of course, each of the current versions of the various programs has its own proponents who feel strongly about its strength compared to its competitors weaknesses. In general, the performance of these programs is not too different. They are almost all excellent screening devices, allowing only a small number of false negatives to slip through. On the other

hand, they tend to have some fair number of false positives. Furthermore, for those ECG's diagnosed as abnormal, the specific abnormality is often inconsistent with the abnormality as judged by physicians reading the same record. In practice, where these programs are in use, they are used as screening devices. All negative readings are generally accepted as being negatives, whereas positive readings are reread by a human interpreter. In general, the number of true abnormals read as negatives is probably of the order of 5% or less, whereas 20% or more false positives are typical.

In recent years, these programs have been joined by two major proprietary programs. One is a new effort by Bonner[5] and is marketed by IBM. The other is available from a time-share ECG processing corporation known as Telemed. These programs have the same heuristic bases as the ones mentioned above but are of more recent vintage and probably somewhat more accurate. In common with the earlier ones, they have more trouble with real positives than real negatives and they are prone to problems when arrhythmias - abnormalities in the heart rhythm - are present. In this last regard, they are probably better than the earlier programs since they require that at least three leads be gathered simultaneously rather than looking for all leads in a sequential manner.

In practical terms, all these programs are available, along with a variety of their deriyatives, on either dedicated small computers or time-

shared large computers. Software is made available by the government, by computer manufacturers on an unbundled basis, and by sellers of complete systems. The complete systems usually involve a data acquisition system, some kind of magnetic storage, and a minicomputer. The time-share systems, on the other hand, gather most of their data over telephone lines using modems and offer fairly complete services in terms of physician over-reading of positive results. Further, to ease the entry of ECG into the computers, several companies offer ECG carts which contain, in addition to the ECG amplifiers, appropriate switches for entering patient data, e.g., number, automatically sequencing and coding of leads, and appropriate modulation devices.

In summary, conventional reading of the electrocardiogram for pattern indicated abnormalities such as acute myocardial infarction, has been moderately successful. The programs that are available are adequate to reduce the work load in many institutions which do large amounts of screening of routine ECG's but need assistance with more complex abnormalities. Companies engaged in the ECG processing business have had mixed success with a few companies - both selling equipment or time-sharing services - having done fairly well but many others having gone out of business. Of equal significance to the current state of the art is what the future appears to hold. No doubt people will continue to improve already extensive programs but it seems likely that major improvements may well come from new approaches such as that being pioneered by Pipberger.[6]

The essence of the latest V.A. approach is to accept that there will always be a difference between computer readings of an ECG and human reading of that same ECG. They depart from conventional wisdom in ascribing much of the difference to errors in human reading. Their approach has been to gather a large number of vectorcardiograms from well-studied patients and to document these patients' diseases with independent information such as that obtained from cardiac catheterization or autopsy. They then make 66 independent measurements of each vectorcardiogram. Using half of the well documented data, they performed a multi-variate analysis to relate the ECG measurements to independently documented abnormalities. On the other half of the data, they were then able to show that the computer, making use of multi-variate analysis, could do a better job than human readers. Indeed, in their latest paper, Pipberger's group showed that the current version of the computer was accurate in 86% of over a thousand cases while physicians reading 12-lead cardiograms of these same patients had an accuracy of only 68%.

The other major use of the computer in electrocardiography is for patient monitoring. For many years, people recognized that one of the primary dangers of acute myocardial infarction is sudden death of the patient through ventricular fibrillation. Often the injury caused the heart by a "heart attack" is not sufficient to have a major detrimental effect on the pumping action of the heart but can seriously interrupt the heart's electrical stability. The result is an erratic, ineffective beating that is insufficient to sustain life for more than a few minutes. In the late 1950's

with the demonstration that many patients could successfully be defibrillated with new DC defibrillation techniques, several Coronary Care Units (CCU) were formed. The intent of these units - one of which is shown in Figure 4 - is to group all patients prone to sudden death in a common area, monitor their electrocardiogram continuously on an oscilloscope, and utilize a trained team of nurses and technicians to recognize ventricular fibrillation and defibrillate very rapidly.

The most important result of these early years of coronary care experience was the observation by Lown[7] and others that ventricular fibrillation was almost invariably preceded by abnormal beats of ventricular origin known as premature ventricular contractions (PVC). Such an example is shown in Figure 5 in which a single PVC is followed by a second one which triggers ventricular fibrillation. Of equal importance to the discovery that PVC's generally precede ventricular fibrillation was the discovery that the use of pharmacologic agents to suppress PVC's not only eliminated the PVC's but eliminated ventricular fibrillation as well. In consequence, the CCU has become an area for preventative rather than crisis medicine. The major emphasis is on the recognition of premonitory arrhythmias such as PVC's and their elimination through judicial administration of drugs.

In the mid-sixties, two groups independently came to the conclusion that major decreases in the efforts of time spent by CCU nurses watching oscilloscopes and important increases in the accuracy of monitoring were theoretically obtainable by using a minicomputer to monitor PVC's. From Figure 5 it is apparent that PVC's are generally obvious. They are early

in the cycle, of abnormal morphology, and usually followed by a beat that occurs at such time as to compensate for the prematurity of the PVC. One group lead by Cox and Oliver in St. Louis,[8] felt that the primary problem in economically monitoring patients would be handling the high data rates. Consequently, they developed a series of minicomputer programs for ECG monitoring which included a preprocessor (AZTEC) which reduced each ECG to a series of lines and slopes which could then be handled by a computer. The other group, led by Lown and Feldman[9] in Worcester, felt that the primary problem would be separating the electrocardiogram from artifact - electrical noise produced by non-cardiac sources. This noise results either from electrical activity of muscle underneath electrodes or rapid shifts in the baseline resulting from changes in the coupling between the electrode and the patient (Figure 6). In consequence, their techniques emphasized digital filtering and the use of measures which were relatively noise insensitive, such as correlation techniques. Over the years, both groups, along with several others, produced programs which were reasonably effective clinically and could be incorporated into commercially viable systems built around minicomputers.

The block diagram of a typical system is shown in Figure 7.[10] A small computer monitors six to eight patients simultaneously. It recognizes PVC's and displays them to the nurses on a CRT or through automatic triggering of an ECG writer. It tabulates clinically relevant data, and shows trends of heart rate, PVC rate, and (in some of the systems) other parameters such as blood pressure.

All the current systems recognize PVC's by the characteristics described above and generally allow nurses to vary the parameters for PVC selection in such a way as to adapt to the physiologic variability that one sees from patient to patient. Approximately 25 of these systems, most of them similar in appearance to Figure 8 , are now in commercial operation, at a cost of three to ten thousand dollars per bed.

In general, the systems perform in a technically satisfactory manner. Because of the problems of artifact caused by patient movement, they tend to average approximately one false positive per patient per hour but generally pick up in excess of 90% of all PVC's. Errors of omission are caused by the occurrence of PVC's in periods of artifact or because the PVC's are late in the cycle or have morphologies close to that of the normal. On the other hand, nurse acceptance can often be a problem since the computer system demands more meticulous attention to the application of electrodes and produces a volume of information considerably greater than the nurses were prepared for. Another complicating factor is that physicians do not yet know how to use the quantitative information produced by the computer in a thoroughly rational, scientific manner.

It would appear that the state of the art of computer monitoring the ECG is not too different from computer reading of ECG's. Existing technology is capable of providing some clinical utility but substantial improvements are required before full advantage can be taken of the computer. In the cases of monitoring ECG's, major advances will come through better separation of ECG from artifact, the ability to monitor multiple leads simultaneously, and the ability to handle complex arrhythmias.

In both situations, it appears that minicomputer technology will probably dominate although large computers do have a utility in ECG diagnosis. At the other end of the scale, it appears that microprocessors may well produce major benefits, primarily through preprocessing of individual patient ECG's. As far as the software goes, most ECG diagnostic systems are written in higher level languages - either FORTRAN or PL/1 and run under conventional operating systems. On the other hand, monitoring programs are generally rather compact with extreme requirements for high speed operation. These are normally written in assembly language and frequently run without benefit of a conventional operating system.

In summary, it would appear that computer processing of electrocardiograms - for diagnostic or monitoring purposes - can, in many ways, be described as a dream postponed. The rosy predictions of the mid-sixties which foresaw near total replacement of human reading or monitoring of ECG's by computers within ten years (that's now) have not been fulfilled. Further, it is now recognized that the fulfillment of these predictions will take major advances in the state of the art - advances which will not be easy to make. On the other hand, it has been demonstrated that computers, even with their current limitations, do lead to improvements in accuracy of ECG reading or monitoring and may well decrease the cost of these services.

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FIGURE 1: ECG Lead Placement

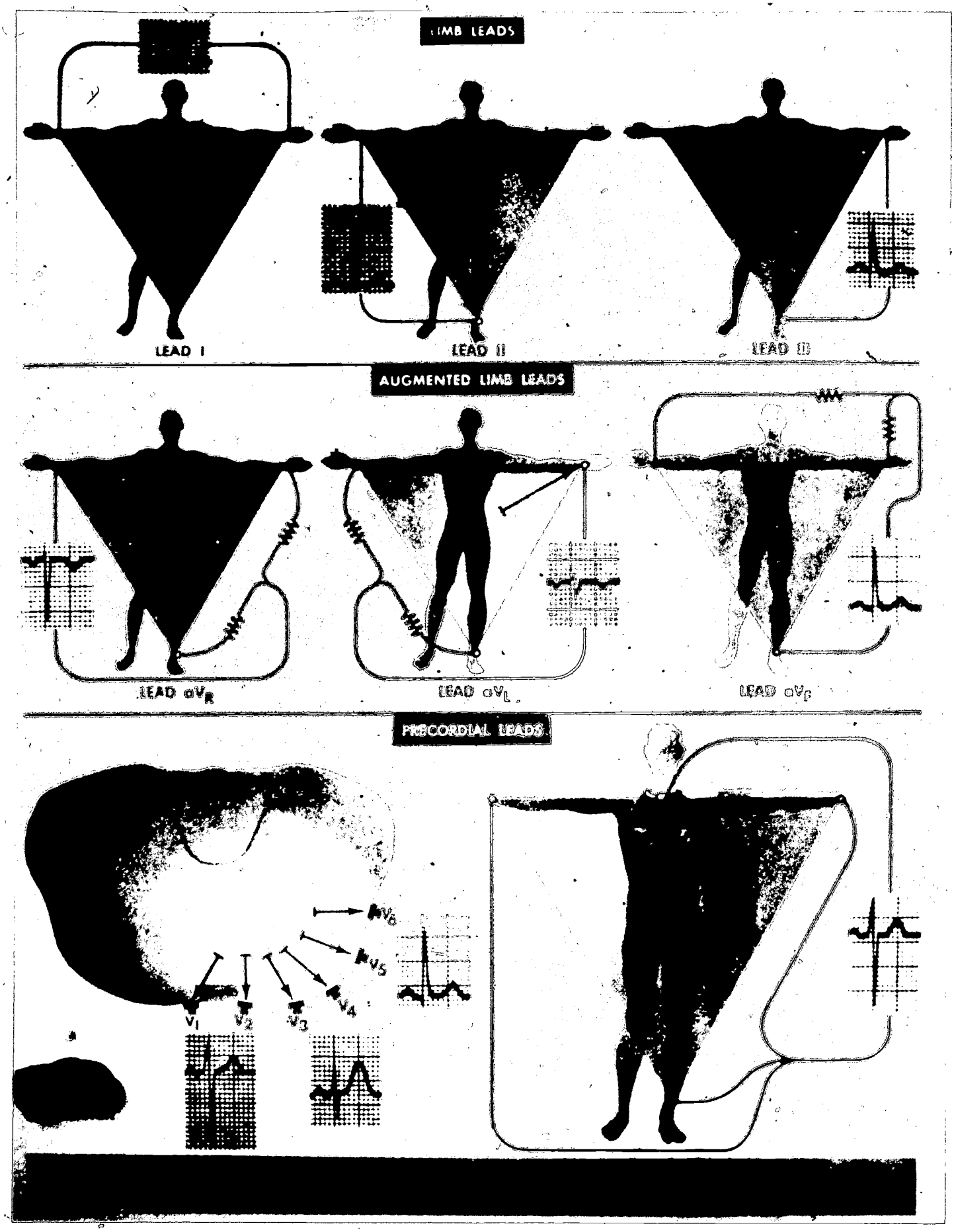


FIGURE 2: Typical Electrocardiogram

FIGURE 3: Typical Vectorcardiogram

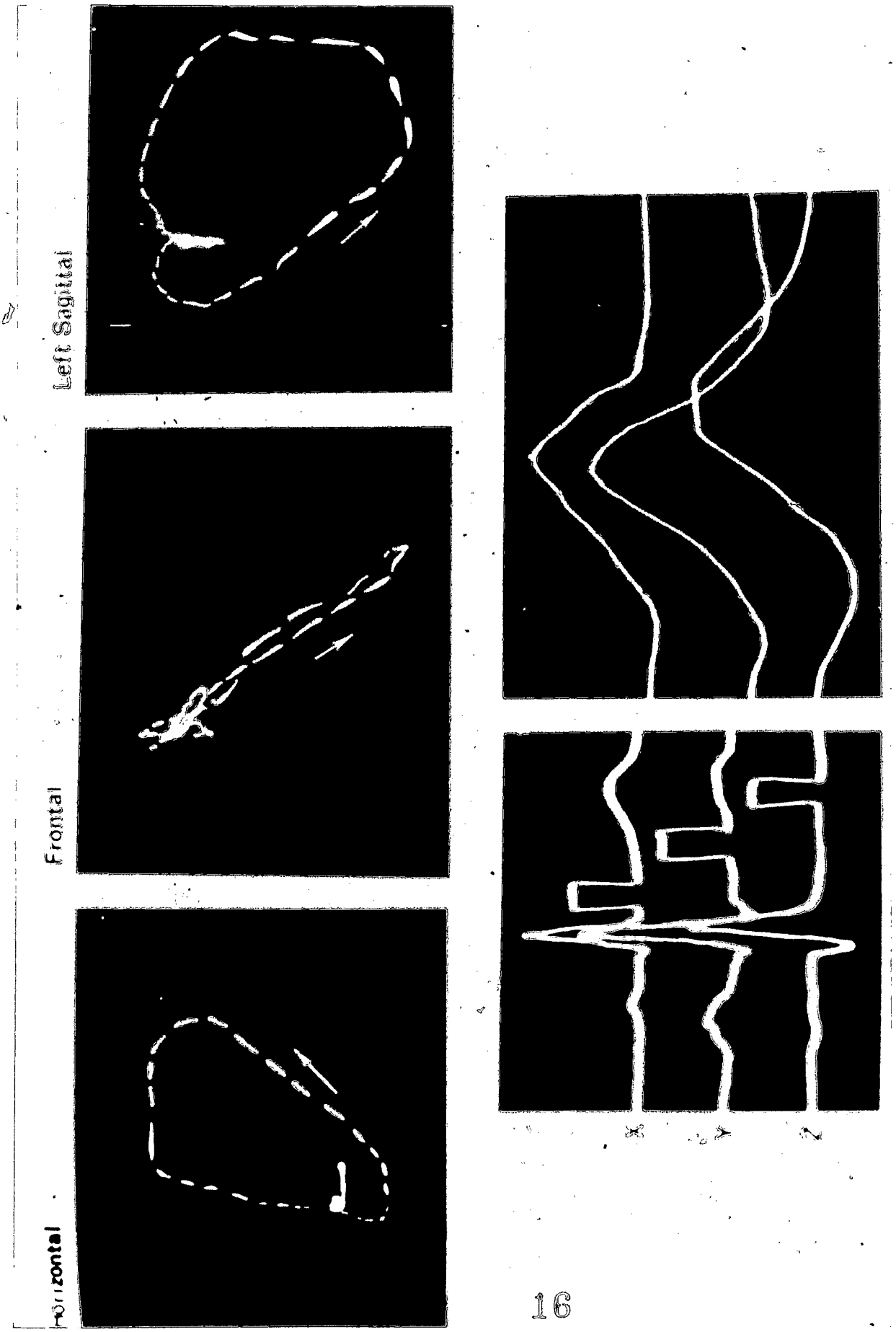
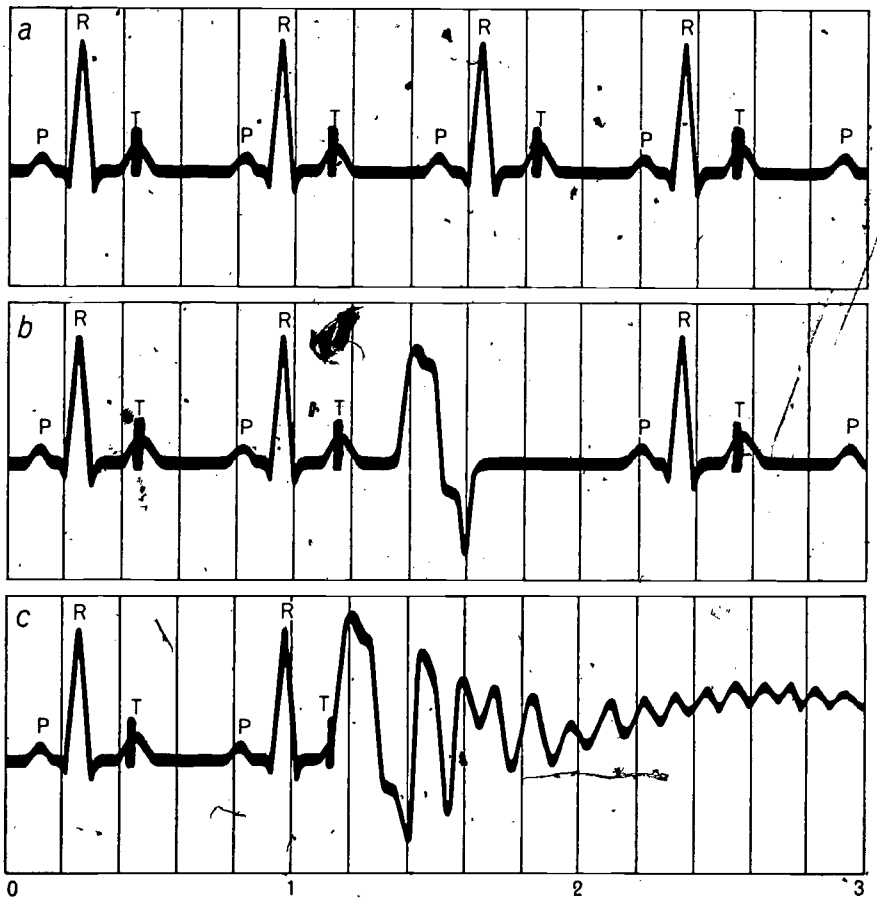


FIGURE 4 Typical CCU

FIGURE 5 ECG with PVC and Ventricular Fibrillation




TIME (SECONDS)

FIGURE 6 Example of ECG Artifacts

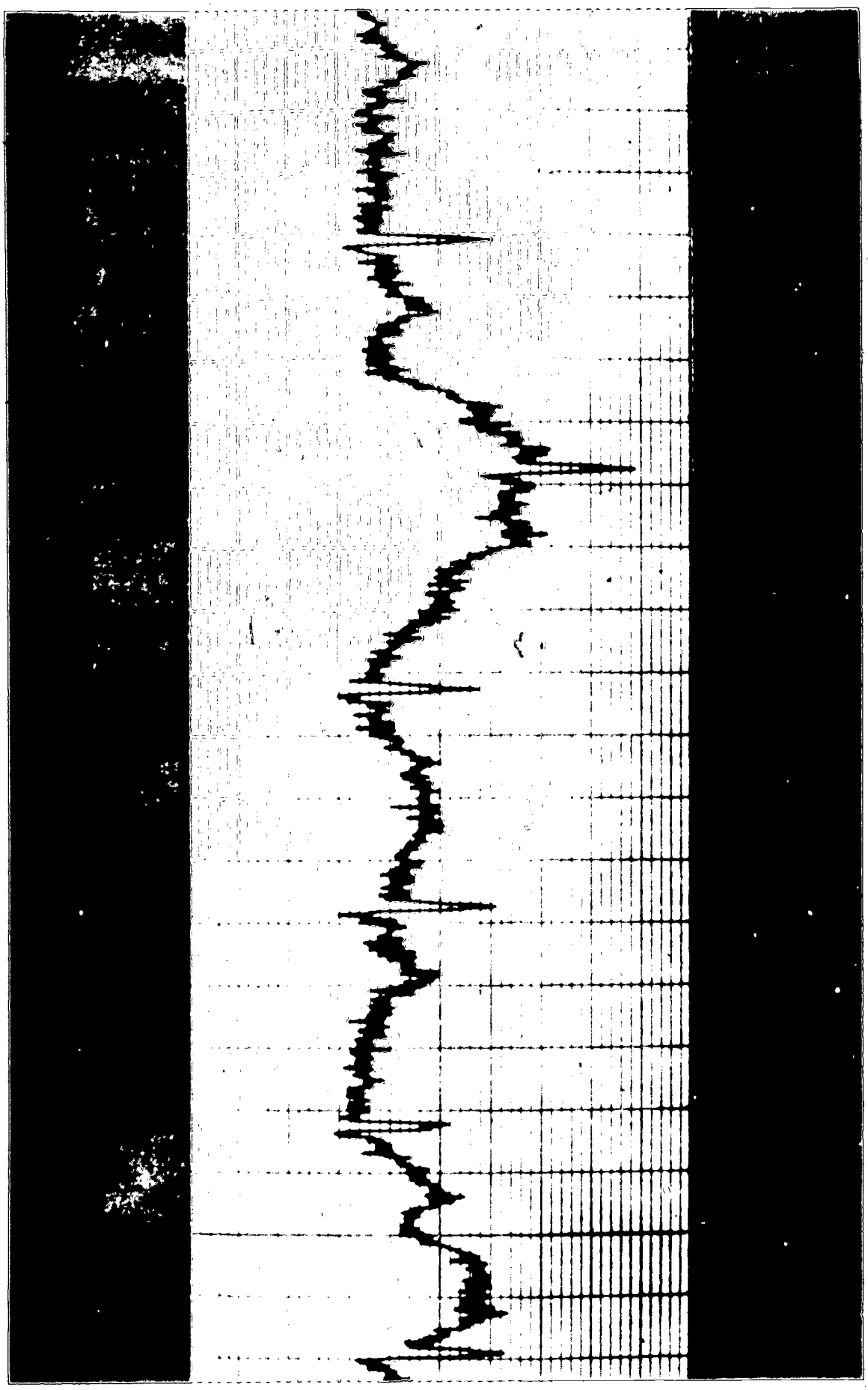


FIGURE 7 BLOCK DIAGRAM OF AN ARRHYTHMIA MONITORING SYSTEM

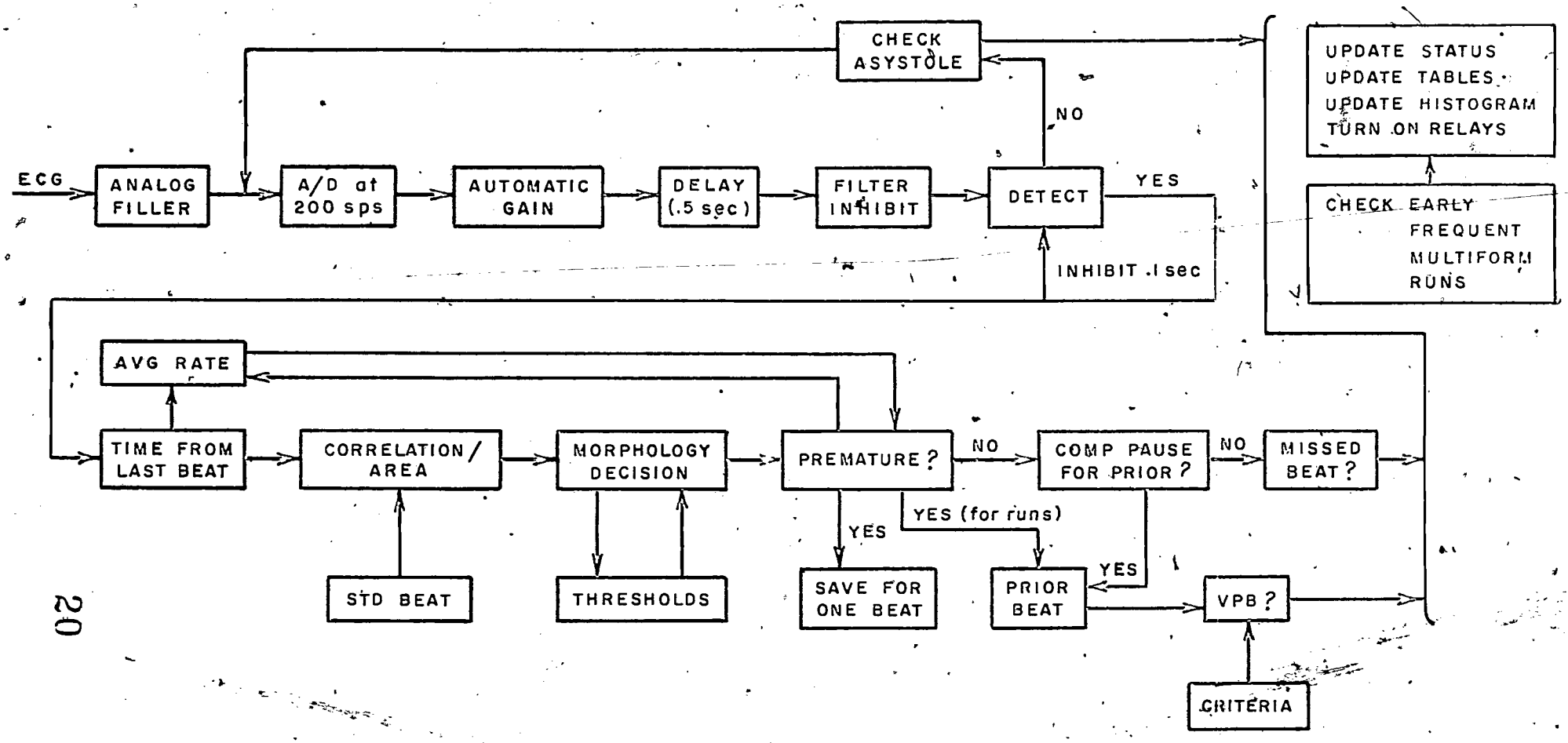


FIGURE 3: Typical Computer-Aided Central Station