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SEMINAR ON COMPUTER APPLICATIONS FOR THE CARDIOLOGIST—VII

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Computer-Aided Electrocardiography*

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The three principal forms of medical electrocardiography are the standard 12 lead electrocardiogram (ECG), the exercise ECG and the long-term ambulatory ECG. The volume of use of the 12 lead ECG is 10 to 20 times greater than that of the exercise test or the ambulatory test, and it has received correspondingly more developmental and marketing attention. A great increase in the rate of adoption of computerized electrocardiography was brought about when large scale integration of computer hardware made it possible to place the entire computational package within a standard-sized ECG cart.

Exercise ECG testing involves processing a data sample minutes in duration. Only a very few diagnostic possibilities are examined; emphasis is on measurements of the ST segment and on non-ECG observations.

Ambulatory electrocardiography currently involves only one or two ECG leads and these are tested for only a few diagnostic possibilities; however, duration of the data sample is relatively long, usually 24 hours. Computer processing involves examination of about 100,000 cardiac cycles for RR interval, QRS shape and ST segment deviation.

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Computer Analysis of the Standard 12 Lead Electrocardiogram

When it was realized that computerized measurement of the electrocardiogram (ECG) could be performed with much more accuracy and precision than was possible by the unaided hand and eye, it was hoped that it would be possible to achieve significantly more accurate interpretation of ECGs by computer than by human interpreter (1). Although this hope has not been realized in the 2 decades since computer interpretation became available, this process has made a large impact on medicine in North America. It is estimated (Drazen E, Arthur D. Little, Inc. personal communication, 1985) that of approximately 60 million ECGs performed annually in the United States, between 22 and 28 million are interpreted by computer. This represents a growth rate of 12%/year in the last 5 years.

Two advantages of the ECG computer system accounted for its widespread adoption. First, it substituted for a human electrocardiographer—a cardiologist or an internist with an interest in cardiology—in a health care setting devoid of such a specialist, such as a family practitioner's office or clinic or a small rural hospital. Second, it conserved the time of the expert cardiologist, who found it possible to overread computer interpretations in half the time required to interpret conventional ECGs. Before 1981, computerized ECG interpretation service was typically provided by large regional or national organizations by means of telephone linkage to a mainframe computer center. These services were busy enough to justify 24 hour overread service by a cardiologist at the center. This was essential because all these programs had an appreciable error rate, and also because there were and continue to be sources of ECG data error readily identified by expert electrocardiographers, such as exchange of right and left arm electrodes or of V_1 and V_3 electrodes, which computer programs do not recognize dependably (Fig. 1).

Approaches to analysis. The effort to provide computer interpretation of ECGs involved multiple approaches. The simplest was to imitate human interpretative stratagems in dealing with ECG data. Implementing this approach required collecting a sizable data base of ECGs with their interpretations and finding the measurement patterns that

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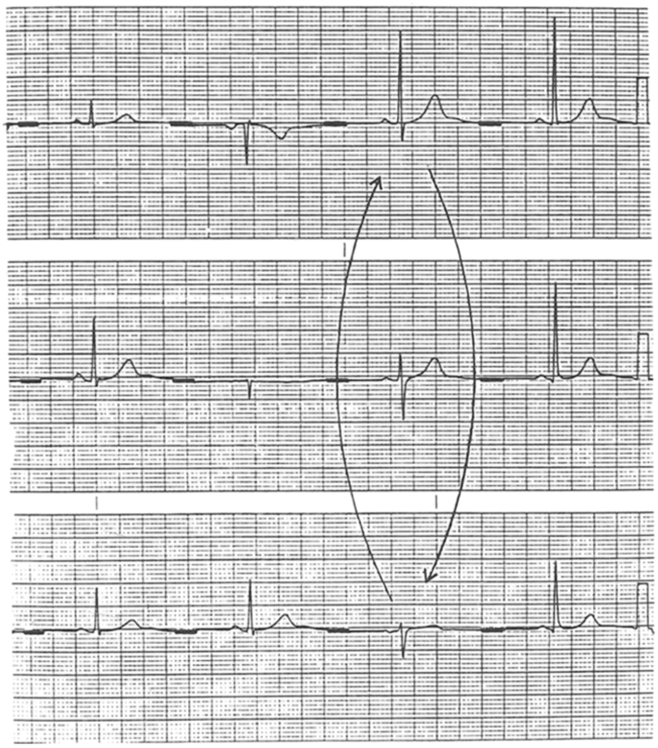

Figure 1. This computer-averaged 12 lead ECG from a normal 60 year old man had the V_1 and V_3 electrodes exchanged. Such errors are not suspected by the interpretative program, which diagnoses "right ventricular hypertrophy" or "possible anterolateral infarction."

corresponded best with each interpretative classification. This approach was used successfully by several ECG services to remote health care units without specialist availability.

At the same time, academic health scientists such as Pipberger and his colleagues (2) realized the potential that computer power gave to making a new and scientific approach to ECG interpretation. They organized the collection of a data base that would correlate clinical and cardiac catheterization data with ECGs to yield interpretative results based on probability-density algorithms and not on arbitrary clinical impressions. This was a landmark effort and its full value and impact will not be realized for years to come. It was not an immediate success with its clinical users because of its unfamiliar diagnostic probability statements and because it forces the user to employ clinical acumen in weighing likelihood of competing diagnostic statements presented by the computer. This program made its appearance before its time. Future physicians will be more familiar with such statements and will be better equipped to make the best use of the approach pioneered by this effort. This program and indeed all ECG programs are weakest in detecting right ventricular hypertrophy and healed myocardial infarction of the inferior wall. Programs do better with left ventricular hypertrophy and are at their best when recognizing bundle branch block and acute Q wave infarction. The same variations in accuracy are found in human electrocardiographers and are related to the relative subtlety of the ECG changes associated with these conditions.

A heuristic approach to ECG interpretative program creation involves taking the criteria for various interpretations and implementing them directly in computer instructions (software). This was not at all straightforward, for human measurements of wave durations and amplitudes, angles and ratios were nearly always different from those performed by machine. But Mortara and others relied on close physician collaboration and intuition in developing a program that has become the cardiologist's favorite (the 12-SL program of Marquette Electronics, Inc., Milwaukee, Wisconsin; unfortunately the details of this program's development have never been published). This program is oversensitive to an almost painful degree (3). It overlooks nothing (except an occasional pacemaker spike or egregious baseline instability), makes the interpretation "NORMAL" dependable without physician overread and gives the cardiologist overreader the opportunity to correct its many flights into diagnostic fancy (such as "second degree sinoatrial block, Wenckebach type," "atrial flutter with competing junctional pacemaker" or "cannot rule out inferior infarct [? masked by left anterior fascicular block?"]) while protecting him or her from overlooking an abnormal QT prolongation, QRS axis shift or other abnormality.

Necessity of physician overreading. Computerized interpretion as an acceptable stand-alone substitute for human reading has never been a viable option and at present the prevailing practice is for computer interpretations to be placed on the patient's chart immediately, flagged with the warning that it is an unconfirmed result to be followed by a (corrected and) confirmed result certified by a physician electrocardiographer. The time lapse between the ECG acquisition and its physician interpretation is a matter of importance. It has been worked out pragmatically by having certain diagnostic categories flagged for urgent overread. This has resulted in hospitals with their own ECG computer system having their urgent ECGs overread immediately and the others within 24 hours. Facilities employing computerized ECG carts or telephonic services have immediate overread of urgent ECGs; the others are overread within 5 days. This interval is not usually brief enough to have significant impact on the hospitalized patient's care, but does serve to satisfy hospital record-keeping needs.

Technologic variables. ECG acquisition for computer processing began with the transmission of a single ECG lead by a frequency-modulated tone over the telephone line to a mainframe computer system. With the advent of automatic three channel ECG recorders, three channel ECG data acquisition also became standard. Later, bidirectional transmission technology made it possible to include voice feedback or automatic notification to the ECG technician of poor data quality or other transmission problems. Most recently one firm has introduced digital transmission of all conventional ECG lead data simultaneously (the Marquette 12-SL system), avoiding any distortion and permitting use of all leads simultaneously in applying diagnostic algorithms.

An important characteristic of an ECG interpretative system is whether the diagnostic criteria are fixed or modifiable. If the principal user of a system is a serious and enthusiastic electrocardiographer, it is likely that he or she will wish to try to improve some of the ECG interpretations by changing some of the diagnostic criteria. This may permit individualization of the program to match a particular patient population. There is no assurance that any user-initiated changes will be improvements, however, and it is possible that such changes will actually degrade the system's diagnostic accuracy. This could lead to frustration in the user and dissatisfaction among physician clients. The Hewlett-Packard system is user modifiable for diagnostic criteria. On the other hand, a manufacturer may prefer to build the reputation that their systems perform alike, wherever they may be found. Most systems fall into this category. Finally, the manufacturer may wish to provide the user with some flexibility in report format while retaining standard criteria. The Marquette system permits the diagnostic statements to be worded in the user's choice of language, but the selection of each term is based on standard criteria installed by the manufacturer.

Most contemporary systems offer some form of serial comparison of the current ECG with previous ones but this has generally not been satisfactory. Comparisons typically involve many more statements than would be used by a clinician, because the programs are unaware of which items are relevant for the management of the patient. Programs are hampered by being based on specific numerical criteria so that patients whose ECGs are on the borderline of some criterion will be reported to have the condition, to lose it and to have it again on the basis of trivial ECG changes. This problem has been recognized and efforts to alleviate it have been made. But it is one of such difficulty that it has not been solved since its recognition nearly 10 years ago, and may remain the task of the human electrocardiographer-clinician for some time to come.

Computerized electrocardiographic service management. Another advantage of computer processing of ECGs not envisioned in early plans for interpretation of the biologic signal from the heart is that of enhancing the work patterns in the facility that provides the ECG service. One has only to recall the classical work flow to appreciate the possibilities for improvement. Transformation of the Heart Station involves automatic transmission of the bedside ECG to the facility by dial-up services in each ECG cart. ECGs are stored on hard disks and also reproduced on paper as they come in to the facility. Perhaps twice a shift, electrocardiographers examine and overread all the accumulated ECGs and write their corrections and serial comparisons on a simple worksheet, and these are taken by an editor and superimposed on the original computer interpretations. This happens rapidly because all common interpretative terms have three or four letter acronyms and operational instructions are similarly abbreviated. Corrected or confirmed interpretations are reproduced at the top of a page that presents the full 12 lead ECG on one sheet of paper. It is then visually verified, signed and delivered to the patient's chart with a request to remove and discard the original unverified copy. Ordinarily, computer processing permits a 50% reduction in office ECG processing staff, freeing office personnel for assistance with the increased demands for exercise tests, Holter ECG studies and other needs.

Convenient remote interpretation. Another aspect of computerized ECG processing is the development of the remote ECG interpretative workstation. A serious handicap of ECG overreading has been the necessity to be physically present in the facility in order to see, handle and write the result of overreading the tracings on paper worksheets. The proper set of computer instructions would permit recreation of the ECGs to be overread on a screen or on paper wherever the overreader happened to be with a proper terminal. Terminals have been developed with high resolution screens that have images as sharp as high quality original paper ECG tracings. These can be used to perform ECG overreadings in the convenience of one's office or even to record emergency ECGs after hours. The appropriate corrections or confirmations are entered by keyboard and superimposed on the original computer interpretation just as the editor would have done in the Heart Station. Previous ECGs may be called up from the computer for comparison in the same way. This remote workstation concept, originally available from Marquette Electronics and later from Burdick, provides advantages for efficient use of the cardiologist's time, rivaling the original concept of computerized interpretation.

Pediatric electrocardiograms. Interpretation of pediatric ECGs is much different from that of adult ECGs. Babies and children are unlikely to have the degenerative heart diseases that affect adults, and if they are suspected of having any heart disease at all, it is more likely to be a congenital malformation than an acquired disorder. Besides having a different repertory of interpretations, pediatric ECGs have a different set of normal standards of axis, wave amplitude and duration. For these reasons, a different program is required for interpretation of ECGs from infants and children. Of the major U.S. interpretative systems, only the Hewlett-Packard has a pediatric program, thanks largely to Ginzton and Laks (4). In Europe, the Glasgow program of Macfarlane et al. (5) and the Louvain program of Brohet et al. (6) have pediatric programs. Creators of pediatric programs conservatively limit themselves to morphologic classifications such as chamber hypertrophy and waveform axis, avoiding attempts at identification of congenital syndromes

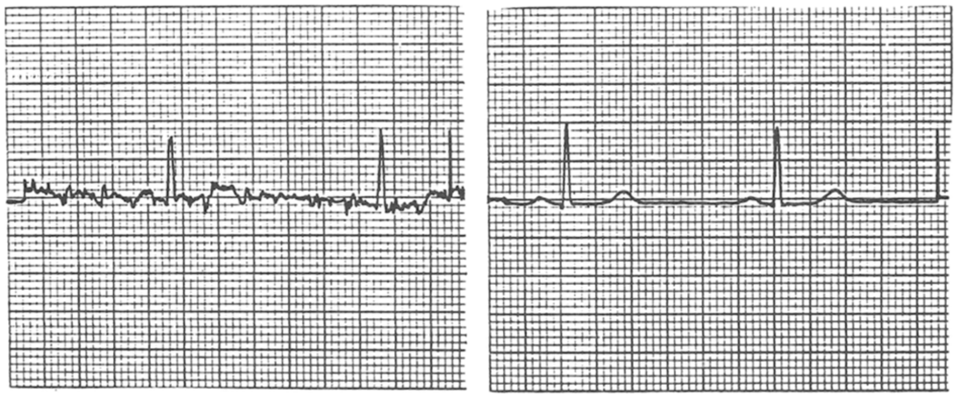

Figure 2. Lead I of ECGs taken 1 day apart from a healthy 73 year old man. The tracing on the **left** was not labeled "poor data quality" (it should have been).

such as tetralogy of Fallot or atrioventricular (AV) canal. Within these limits the available programs function very well indeed. One would think that manufacturers not providing pediatric programs would at least suppress adult interpretative statements when pediatric ECGs are being run.

Quality control algorithms. It is typical of automated ECG systems to have data quality control mechanisms that warn the operator of the presence of power line artifact, excessive skeletal muscle artifact, disconnected electrodes or other types of degradation of the ECG signal. The systems permit the technician to override the warning, however, and to acquire the ECG despite signal problems. The system should then print a statement announcing the presence and nature of the signal problem and the danger that such a problem may adversely affect interpretation. Systems vary widely in the effectiveness with which they accomplish this task, and all of them have a great deal of room for improvement. The need for quality control mechanisms varies with the skill of the operators and the environment in which ECGs are recorded. Under ideal circumstances, automatic quality control mechanisms would never be needed. In actual practice, unfortunately, poor data quality occurs occasionally. Part of the cardiologist's task is an overall inspection of the ECG and a decision as to whether any aspect of the interpretation should be qualified because of poor ECG data (Fig. 2).

Arrhythmia interpretation. It is popular to criticize the ability of ECG interpretative programs to accurately analyze disturbances of rhythm. Yet for the most commonly used systems this is probably an unfair evaluation. Inasmuch as all, or virtually all, computerized ECGs are overread by physicians expert in the interpretation of arrhythmias, the primary obligation of an automatic system is to call attention to the presence of an abnormal rhythm or heart rate that might constitute a danger to the patient between the time the ECG is recorded and the time the physician overread takes place. The major systems are quite accurate in identifying bradycardias that might be found in advanced atrioventricular (AV) block or sick sinus syndrome, and equally accurate in detecting rapid ventricular rate caused by atrial, junctional or ventricular tachycardias. This knowledge is sufficient to prompt the user to request immediate overread.

The principal impediment to highly accurate and sophisticated arrhythmia interpretation by computer is difficulty in recognizing P waves when they occur "out of place" instead of just before QRS complexes. P waves, and especially ectopic P waves, are low in amplitude and low in frequency content. Both of these features contribute to difficulty of recognition. The difficulty is compounded in complex arrhythmias in which P waves are frequently superimposed on QRS complexes and T waves. This problem has been addressed in novel fashion by investigators at Northwestern University (7). They found that by developing an averaged QRST complex from an ECG sample suspected of containing an arrhythmia, they could subtract this representative complex from the ongoing sample, leaving only P waves, which could then be detected and related to the accompanying QRS timing to recognize the presence of AV dissociation. Future work in this direction is expected to contribute significantly to accurate computer interpretation of arrhythmias.

Exercise Electrocardiography

Computer processing has been applied to the exercise ECG to improve the accuracy of diagnostic measurements of the ST segment (8). The first few years of experience with various analytic programs did not confirm this, but a recent report by Hollenberg et al. (9) suggests that it may yet be possible to achieve significant superiority of disease diagnosis by computerized analysis of the exercise ECG in combination with other data. Exercise electrocardiography is a technology that did not emerge until fluid coupled electrodes were developed that made it possible to acquire the ECG from an exercising person with a manageable amount of motion artifact (10). Even with fluid coupled electrodes the ST segments were often difficult to interpret, and thus computerized measurement was a welcome service for many cardiologists.

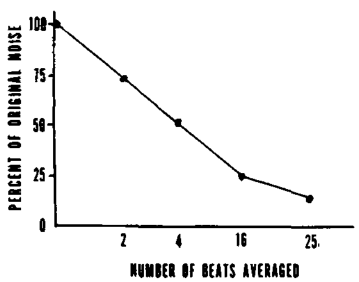

Figure 3. Effect of sample size on degree of noise reduction possible by averaging of successive cycles.

Functions of computer processing. Computer processing of the exercise ECG involves four main processes: noise reduction of the ECG signals, identification of fiducial points demarcating each waveform, measurement of specific waveform features and evaluation of these measurements to develop a diagnostic score or estimate of disease likelihood. The first three of these processes were inherent in the methodology from its beginning (11), but the latter is only now coming into its own (9). Manufacturers were at first hesitant to market hardware that might be seen as a substitute for skilled interpretation by a physician, but this hesitancy has been dissipated considerably by the success with which self-interpreting bedside ECG carts have been marketed.

Reducing noise in the exercise ECG is accomplished by bandpass filtering, in which frequencies above and below the ECG signal are sharply attenuated, typically those >100 Hz and <0.05 Hz and by averaging the cardiac complexes. When successive P-QRS-TU cycles are averaged, all other signals not synchronized with the heartbeat are progressively reduced in amplitude by simple dilution (12) (Fig. 3). Ordinarily, the amount of noise reduction achieved by averaging is in proportion to the square root of the number of cycles averaged. A limitation to the number of cardiac cycles averaged for a single measurement set stems from the realization that significant changes in the ST segment may take place in as little as 15 seconds, and to resolve this, the sample of ECG that is to be distilled into a single temporal period of measurement should be no longer than this. Fortunately, the most advantageous sample size with respect to noise reduction is between 9 and 25 beats (for noise reduction factors of 3 to 5) and with the exercise heart rates commonly encountered during testing in the 100 to 170/min range, an adequate sample can be acquired in well under 15 seconds.

Aberrant beat exclusion. A particular requirement of signal averaging is that all the beats averaged should be similar. If aberrant beats occur during the sampling period, and this is of course common in a diseased population, these aberrations must be removed from the data sample before averaging. Failure to do so will cause from slight to severe distortion of the averaged waveform. Available systems accomplish this with remarkable success, but some aberrant beats may gain inclusion nonetheless.

After noise reduction, essential features of the ECG are recognized, the most important of which, for ST segment measurements, is the end of the QRS complex, or J point. From that instant, and for the next 80 ms or so, the ST segment is measured for amplitude, slope and perhaps area (time-voltage integral). Measurements are displayed graphically and numerically on a cathode ray tube and stored for later report generation.

ST segment measurement. Measurements of the ST segment are made to detect myocardial ischemia induced by exercise stress, and it has not been determined which measurement or measurements are most accurate for this purpose. The simplest is measurement of the amplitude of the ST segment at a certain distance from a fiducial point in the ventricular complex. The best fiducial point for locating the place for measurement is the end of the QRS complex (J point). The interval from this point to the place for measuring ST amplitude is generally agreed to be 60 to 80 ms, and some investigators prefer a variable interval that represents a defined fraction of the entire ventricular complex (QT interval) to compensate for the appreciable change that takes place in this interval as the heart rate increases from rest to strenuous exercise and back again. Another stratagem of measurement is to take the amplitude of the J point and combine it with the slope of the ST segment adjacent to the J point. In an attempt to combine ST segment amplitude and slope into a single measurement, our group (11) introduced the ST integral measurement, which in effect represents the area of ST segment shift. As is usually the case when a multiplicity of choices is available, there is no clear winner among them. When definite and incontrovertible ischemia is present, all of the ST segment measurements are abnormal, but the side by side comparisons of exercise ECGs with minimal ST segment changes in patients with known degrees of coronary artery obstruction have not been published. Simoons (13) and his coworkers compared a limited number of measurements, however, and their work suggests that proportional spacing of the ST segment amplitude measurement is superior to fixed spacing. Hollenberg et al. (9) incorporated the time integral of ST segment shift throughout the exercise test, achieving test sensitivity and specificity levels that are much improved over those of simpler measurements.

Necessity for overreading. There is general agreement that ST segment measurements by computer should be reviewed carefully by a competent electrocardiographer to make sure they are consistent with visual inspection of the waveforms, and the ECG should be monitored visually by technician or physician, or both, continuously throughout the test to be sure that any aberrant beats are detected by the system (or that an appropriate notation to the contrary is made).

Computerized exercise ECG systems are now found in all small and large U.S. hospitals and in clinics where stress tests are performed frequently. In the testing of symptomatic patients these systems are no substitute for a physician-electrocardiographer and a staff capable of handling any complications that may be precipitated by stress testing. However, for screening asymptomatic subjects these systems are sometimes used by stress test teams headed by exercise physiologists with a physician in the vicinity but not necessarily in the exercise laboratory. With progressively decreasing costs of semiconductor computer components it has become possible to reduce the cost of systems from the $20,000 to $40,000 range to around $10,000 for a modest system targeted for physicians' offices and small clinics. Because these systems can record conventional 12 lead ECGs as well as exercise ECGs, they can substitute for a conventional bedside ECG between stress tests and thus provide an additional financial incentive for their purchase.

Ambulatory ECG

The original use of this method was for documentation of disturbances of heart rate or rhythm that were suspected of causing various symptoms in outpatients during the course of everyday life. Such symptoms occurred too infrequently to expect them to happen in a physician's office or clinic, so an entirely new approach to ECG recording was called for. Different terms have been applied to this methodology, including "ambulatory electrocardiography" and "long-term electrocardiography." Perhaps the most commonly used term is "Holter monitoring," named after its developer, Norman Holter (14). Working alone, he developed a miniature battery-operated tape recorder capable of storing several hours of a continuous single lead ECG. He realized the necessity for new technology to permit analysis samples of ECGs of long duration in a short time and invented a high speed scanner for this purpose. With improving hardware, the recording interval was extended from 4 to 24 hours; this length of recording has become standard (15).

Computer-aided analysis. Scanning speed was originally 60 times faster than recording speed, so that an hour of ECG could be scanned in 1 minute. Thus, a 24 hour record could be scanned in 24 minutes if no abnormality was present and the tape was not stopped periodically to run specimen rhythm strips at "real-time" speed. When numerous premature beats or other disturbances were present, however, it was necessary to stop scanning frequently and to run a paper copy of each different kind of abnormality. To analyze such a record might require well over an hour. The task of analysis was very demanding, because the analyst's undivided attention was required to avoid missing premature beats, pauses or other abnormalities that might last only 1/100 second at normal scanning speed. The need for computer-aided analysis was thus present from the outset. The technology was introduced gradually; QRS detectors and timers served to detect prematurity and postmaturity, and integrators or other simple algorithms detected gross changes in QRS shape, thereby enabling the flagging of items likely to be ventricular or supraventricular premature complexes and dropped beats. The analyst then inspected the flagged events and confirmed them or corrected them and then continued the scan.

Although many workers have contributed to the evolution of arrhythmia monitors and analyzers, the long-continuing work of Cox, Fozzard, Nolle and their coworkers (16,17) in this field deserves special mention. Their development of the AZTEC preprocessing program for real-time ECG rhythm analysis and their development of the Argus/H system for rapid analysis of ventricular arrhythmias are milestones in the development of cardiac rhythm analyzers.

QRS detection. Automatic QRS detectors and shape comparators made 24 hour trend graphs practical, in which heart rate, premature beat occurrence rate, RR interval and other selected measurements are plotted continuously for the entire study period. To facilitate the appreciation of such trends by brief inspection, plotting intervals usually represent 10 minute periods. For each period the mean, maximal and minimal values are plotted in six plots an hour, across the stationery-sized report page in one line of graphic display for each 24 hours.

Increasing availability of minicomputer power and the use of array processors and fast Fourier transform calculators made it possible to detect QRS complexes with better than 99% accuracy in good quality records and to classify them as narrow complex ("normal") or wide complex ("PVC") in better than 98% of satisfactory records. With this degree of accuracy it was feasible to require only minimal human analyst supervision of the system. It is still desirable to see and confirm at least one example of each kind of abnormality, but if one example of each is classified satisfactorily, it is considered safe to assume that the remaining instances of each abnormality are classified similarly.

This contemporary technology of ambulatory ECG analysis that is largely or almost entirely automatic brought on a major change in the way the ECG record was handled. Instead of being scanned in a linear fashion from the beginning of the magnetic tape to the end, ECG data are now transferred to a large capacity storage device ("hard disk") in the computer before any analysis is performed. Subsequent analysis can proceed using algorithms independent of real-time velocity or direction. Analyses still require a significant fraction of an hour if the record is abnormal or noisy, but the amount of data produced from the study is greatly increased. Use of more powerful (and expensive) computers could shorten analysis time with no compromise in accuracy if the market demanded.

"Real-time" analyzers. In addition to analog magnetic tape-based ambulatory ECG systems, miniaturization of computer hardware has enabled the development of portable ambulatory ECG computers that analyze the ECG as it occurs ("in real time"), store the results and also store examples of each abnormality found (18). On the patient's return to the ambulatory ECG, no further analysis of the study is required, only the generation of the report by a printer. Results of the study could thus be applied to patient management at the same visit. However, success and market penetration of these units were retarded by two factors: 1) human analyst overview and correction of the analysis results was not possible, and 2) only a limited number of rhythm strips could be stored in memory. Both of these characteristics made it necessary to place implicit faith in the accuracy of the system and many clinicians were disinclined to do so.

The use of ambulatory electrocardiography has increased since its introduction 15 years ago. With the advent of numerous potent antiarrhythmic drugs, and proof that ventricular arrhythmias increase risk of sudden death in patients with coronary heart disease, ambulatory electrocardiography is frequently used to detect ventricular arrhythmias in these patients (19). In patients found to have ventricular arrhythmias, ambulatory ECGs may then be used to evaluate the efficacy of antiarrhythmic therapy.

Detection of "silent ischemia." Because the combination of ischemia and ventricular arrhythmia is a mortality risk, and it has been found that many patients develop episodes of painless ST segment depression in addition to (or instead of) symptomatic ST depression, ambulatory electrocardiography has been used with increasing frequency to detect asymptomatic ischemia in patients with known coronary artery disease (20). Although it has not yet been definitely established, a current hypothesis is that prevention of episodes of asymptomatic ischemia will reduce complications of coronary artery disease and prolong life. There has also been some use of ambulatory electrocardiography to diagnose coronary artery disease in patients with episodes of atypical chest discomfort instead of the use of treadmill exercise testing. Although exercise testing is more sensitive than ambulatory electrocardiography in detecting coronary artery disease (21), the latter is capable of use in patients unable to undergo exercise testing.

A matter of serious concern among physicians interested in detection of ischemia by ambulatory electrocardiography is that the frequency response of most ambulatory ECG recorders is not adequate for faithful registration of the ECG ST segment, depression of which is the hallmark of myocardial ischemia. Ambulatory ECG records can and do show ST segment depression on occasion; the problem is uncertainty about the amplitude and shape of the ST segment, compared with what its appearance would be when recorded at the same time using an instrument conforming with American Heart Association standards for clinical ECG recorders. This is a technical problem in recording methodology that has been corrected by at least one ambulatory ECG system manufacturer (Cambridge Instrument Co., London) by the use of frequency modulation recording. The problem will likely be corrected by others as the demand for American Heart Association standard performance becomes widespread (22).

The use of ambulatory electrocardiography in clinical practice is accelerating because of the increasing number of indications for it. Computerized ambulatory ECG service is now almost as widely available as computerized exercise ECG testing. Cost of the most accurate ambulatory ECG analyzers, recently in the $60,000 to $80,000 range, is dropping and some of the least expensive systems may now be found in the $10,000 to $20,000 range.

Future Directions of Computerized Electrocardiography

Penetration of computerized instruments into the market for ECG instrumentation will continue for several reasons. Interpretative programs will improve. The electronic raw material of computers, microprocessors and memory chips becomes less and less expensive. The actual methodology of creating the ECG tracing has become computerized, and in some instruments has supplanted the classical galvanometer as a means of inscribing the "tracing." Computerized ECG instruments will likely cost no more, and in some cases less, than traditional instruments without computers.

It is interesting to contemplate what the effect will be on the learning of electrocardiography by medical students and house officers. At our institution, after medical students have completed the study of electrocardiography in the classical fashion, they are ready to begin overreading computer interpretations. By challenging these repeatedly (both successfully and unsuccessfully) they learn just how the program behaves, what its strengths and weaknesses are, which terms can usually be relied on and which terms should be viewed suspiciously. They learn to become clinical electrocardiographers just as rapidly and just as skillfully as before, and they are able to make optimal use of the initial, unconfirmed ECGs that are placed on the patients' chart at the time the ECG is recorded.

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