Computerised Analysis, Interpretation, Storage and Retrieval of Electrocardiograms

A STUDY AND REVIEW OF AVAILABLE SYSTEMS

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SUMMARY

A study was undertaken to determine the feasibility of introducing a computerised electrocardiographic analysis and interpretive system as a service to a teaching and referral hospital.

Available computer equipment and programmes are considered. The accuracy and quality of the analysis and interpretation of the electrocardiographic contours are basically dependent on such factors as pattern recognition, the criteria adopted for determining abnormalities, the relative values placed on scalar and orthogonal leads and the role of review by the physician.

It is concluded that such systems are at a stage where they can feasibly be introduced and should be of advantage in freeing the physician from routine measuring and screening of electrocardiograms, thus saving many hours of professional and academic time.

Furthermore, such systems can contribute greatly as an educational tool and increase the general knowledge of electrocardiography.

Systems for storage and retrieval are also being developed and becoming available. The whole field is a developing one and continuous updating of programmes by the addition of more data, particularly for children, and the introduction of electrocardiographic comparison programmes need to be expedited.

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Electrocardiography can be considered as the nucleus of a cardiological service in any clinical diagnostic situation, whether it be within a large teaching hospital centre, within smaller peripheral and distant rural hospitals, or within everyday private practice. There is an increasing awareness of the value of the electrocardiogram in the evaluation of known heart disease and in the diagnosis of cardiac conditions, and as a baseline study for any patient who is to undergo any major or even minor surgical procedure. The rapid increase in the number of coronary care units has resulted in a further demand for electrocardiography. During the course of the acute myocardial infarction delayed electrocardiographic evidence of infarction and the development of conduction and arrhythmic disturbances warrant repeated electrocardiographic examinations daily or several times daily, also for purposes of comparison. Furthermore, general practitioners and life insurance companies are increasingly insisting on electrocardiographic examinations. If electrocardiograms could be readily taken and fully analysed without consuming the valuable time of a physician, population surveys would be of great value in the early detection of a wide variety of cardiac disorders.

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An increasing and overburdening load is being placed on the electrocardiographic services of institutions, involving not only technician time, but valuable physician or cardiologist time spent in the analysis, interpretation and comparison of electrocardiograms. Mass population surveys are not feasible with the present-day manual approach.

The steps taken in the conventional processing of an electrocardiogram include the following: data acquisition by a technician with a conventional electrocardiographic recorder; cutting and mounting the graph; reading, analysis and diagnosis of the electrocardiogram (done by an electrocardiographer); a report on the interpretation, compiled by the cardiologist; the production of a hard copy of the electrocardiogram, with a typewritten report distributed to the source of request; and a system of filing and record-keeping so that electrocardiograms may later be retrieved for purposes of comparison, review and research.

This whole process is time-consuming for both technicians and administrative personnel, and also for the physician/electrocardiographer; and of necessity an electrocardiogram and report often cannot reach the bedside of the patient within 24 hours. Systems are now being developed which can free the physician from routine tasks, providing more time for patient care and also guaranteeing a certain level of quality.[1-5] These semi-automated systems, dependent on a digital computer, facilitate the recording of higher quality electrocardiograms, assist diagnosis and aid follow-up management of the patient. Specialist experience can be brought within seconds to every patient's bedside since the electrocardiographic data are directly transmitted to the processing system by telephone and the signals are analysed instantaneously.

The electrocardiogram was chosen as the first signal for automated recognition and interpretation of patterns in medicine, because physicians are most familiar with it and they have had 50 years of experience in relating the patterns to specific and clinical purposes.

A study and investigation was undertaken (*i*) to determine the feasibility of a computerised electrocardiographic system, in relation to both the hardware required and the programmes (software) available; and (*ii*) to recommend a method for filing, storage and retrieval of electrocardiographic information.

FEASIBILITY

Hardware

The feasibility of such an automated service is dependent upon the availability of suitable processing equipment and peripheral input and output systems. A variety of sophisticated hardware is available (International Business Machines Corporation (IBM); Control Data Corporation; Hewlett-Packard (HP); Siemens; Cro-Med Bionics Corporation; Marquette Electronics Inc).

Electrocardiograms (ECGs) can be run in batch mode in an off-line system, but restriction to this system will significantly annul the advantage of fast computer analysis, which could be very valuable in emergencies. In addition, immediate feedback from the computer to the technician recording the ECG is most helpful in avoidance of operator error. It is accepted in all computer applications where raw data are fed into a computer that some form of monitoring is essential. This indicates that at least some of the ECG information should be processed in real time with feedback to the operator.

Experience has shown that although in theory it is possible to mix real-time applications with a large-batch computation load in a general-purpose, time-sharing system, this raises many problems in practice. Minicomputer systems, however, having been designed for real-time processing, lend themselves ideally to this purpose. It is possible to run more than one programme simultaneously on such a system as well, but the difference is that the complete mix is known beforehand and can be catered for in the executive programme. Furthermore, there are seldom more than a few programmes operative in the system at any one time, and when the load reaches such a magnitude that response time becomes too long, it is customary and normally quite economical to then duplicate the system partially or entirely.

A minimum system for ECGs requires about 24 K words of core plus 1,25 million words of disc storage. If, however, a certain amount of patient file handling is to be included, this should be at least 32 K words of core storage and 2,5 million words of disc storage.

Mobile ECG data acquisition cars can accept the ECG directly from the patient, make an automatic graphic recording on three simultaneous channels and transmit the ECG with a patient identification number on standard voice-grade telephone lines to the computer system at a remote location; or the patient's ECG and identification can be recorded on site on magnetic tape, either in analogue or digital form, which is then delivered to a computer for playback and processing. These systems are available from several manufacturers (Hewlett-Packard (HP); Marquette Electronics Inc.; Cambridge; Computer Instruments Corporation; Beckman Instruments Inc.; Dex System).

A printed interpretive statement, either at the computer site or at the patient site, can be given in less than one minute with a print-out in either a long form, which includes all the measurements and the logic for the interpretation, or in a short form which makes only an interpretive statement. The displays can include the vector loops of the XYZ orthogonal system, such as that of Frank.

The Programme (Software)

Various programmes have been developed over the past 10 years to meet the demands for accurate electrocardiographic analysis and interpretation.*

The accuracy and quality of the analysis and interpretation of the electrocardiographic contours are basically dependent on several factors:

(i) the pattern recognition and measurements which are made;
(ii) the criteria which are adopted for determining abnormalities;
(iii) the relative value placed on the 12 scalar leads (leads 1, 2, 3, aVR, aVL, aVF, V1 - V6) or on an orthogonal XYZ lead system such as that of Frank;
(iv) physician review;
(v) criteria for children;
(vi) comparative electrocardiography;
(vii) the print-out form.

Pattern recognition and measurements: The amplitudes, slopes and durations of the various waves and segments of the ECG are calculated, tabulated and interpreted. The primary function is the selection of points to describe the ECG wave form. Sampling is done at rates of at least 250 per second, but it may be preferred to sample at higher rates such as 500 per second. In the scalar lead programme, each simultaneous lead set (1, 2, 3; aVR, aVL, aVF; V1, V2, V3; V4, V5, V6) is recorded for up to 5 seconds, allowing a typical recording time of 20 seconds. The combined scalar and orthogonal lead system also records for approximately 20 seconds.

Pattern recognition may depend on singling out the most representative cardiac cycle wave for analysis,[6-11] labelling the onset of each of the components of the P, Q, R, S and T waves, measuring the amplitudes in millivolts and constructing core-resident tables from which an interpretation can be made. In the Pipberger[12-14] programme the pattern recognition depends on the average

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of measurements made on all recorded cycles of the ECG and not on the most representative cycle.

A noise factor is calculated, and if in any lead this exceeds a present value, the ECG is considered too noisy for further analysis and is rejected.

Rhythm analysis is obtained from the logic devoted to basic pattern recognition in addition to logic devoted to the recognition of arrhythmias.

Adjacent pairs of QRS complexes are organised into 'units', a concept which permits separation of basic from ectopic rhythm. For each set of three R-wave peaks, there are two RR intervals. If the smaller one is less than three-quarters of the larger, an arrhythmia is flagged. Further detailed analysis of arrhythmias is dependent on searching, identifying and typing the P waves, determining the presence or absence of a regularly spaced train of P waves, and the application of special tests for arrhythmias such as atrial fibrillation. This complex computer activity of measurement, pattern recognition and arrhythmia determination is described in different publications.[1-4]

The criteria: The parameters (amplitudes, duration, axes, etc.) are compared against limits or other parameters for each lead. The final interpretation will therefore be the product of the comparison of the established values obtained for the particular ECG and criteria for diagnosis incorporated into the programme. Different sets of criteria have been programmed, based on available knowledge from the electrocardiographic literature, the combined views of panels of cardiologists and, in the case of the Pipberger programme, on observations on a bank of patients with heart disease with diagnoses proved by autopsy or special investigation.

Scalar and orthogonal leads: At the Mount Sinai Hospital in New York, Pordy has developed an operational on-line electrocardiographic analysis and interpretive system based on the 12 scalar leads. He is convinced, and presents supporting evidence, that the scalar leads are superior to the vectorcardiographic leads, and he believes that the vectorcardiogram misreads about 25% of contour diagnosis.[7]

The IBM Health Care Support/Electrocardiogram (ECG) programme, the new programme of Bonner, based on the 12 scalar leads plus 3 orthogonal leads not used for interpretation but for rhythm diagnosis, is in use at several centres in the USA and in Europe. The programme is claimed to be highly accurate. Since no dedicated computer is known to us to be available for this programme, one is limited to a batch mode interpretive system. Moreover, some evidence from a comparison of interpretations made with the Pordy programme suggests that it is capable of erroneous diagnosis.[7] It was also stated that the Bonner programme tends to read a negative P wave lying close to QRS in standard lead I as a Q wave, and that in the presence of left ventricular hypertrophy anteroseptal infarction can be missed.[15]

The 12-lead scalar electrocardiogram is used by Caceres, who has an ongoing programme improvement project and will release a new programme by 1974.[9] The quality is claimed to be such that it would make it quite unnecessary for a physician to review the product. This new programme, like the Pordy programme, includes the capability of comparative electrocardiography. Contour analysis is now possible in the presence of arrhythmias. The new programme has a capability of diagnosing the 15 most common arrhythmias with considerable accuracy.

Pipberger has developed a programme which up to this stage has been of a developmental and research nature, with the emphasis on the orthogonal lead system of Frank. The ECG is produced and displayed as vector loops, together with an interpretive statement derived from the 3 XYZ leads. The measurements are calculated on the mean values of all the complexes registered, and not based on the most representative complex such as is the case in the Bonner, Caceres and Pordy programmes. The measurements made are analysed by multivariant analysis, and the interpretive statement is expressed in a form of probabilities in such a way that a diagnosis would be given, for instance, as left ventricular hypertrophy 64% probability, myocardial infarction 40% probability. The multivariant analysis of the measurements is a procedure which is followed by only one other group, in Japan.[14] The criteria in the Pipberger programme have been painstakingly developed on the basis of electrocardiographic findings in cases of proven diagnosis, proved either by autopsy or by special cardiological investigations such as cardiac catheterisation and angiocardiography. The data bank for this purpose is now based on records of about 28 000 patients.[14]

In a comparison of the computer diagnosis of the ECG with the individual diagnosis of cardiologists in cases of proven diagnosis, the cardiologist's performance was 54% accurate, against the 80% accuracy of the computer. This programme has been adopted by Hugenholtz in Rotterdam, Holland.[14] The programme is to be made operational as a service for the Veterans Administration Hospital in Washington, and will also be coupled to a children's hospital and an additional hospital during 1973.[14]

The Smith programme, which has been developed at the Mayo Clinic, is based on the analysis of the 12 scalar leads and the 3 orthogonal XYZ leads of Frank.[10,11] Measurements from the 12 scalar leads are presented in the print-out report of the analysis, but the interpretation is made from the orthogonal leads.

Smith is confident that there is no significant difference between the use of the scalar leads compared with the vectorcardiogram with regard to accuracy. The vectorcardiogram may be better than the scalar leads in perhaps 1:20 000 instances. The two systems give the same information; there is only a difference in presentation. Smith also believes that the multivariant analysis used by Pipberger tends to diffuse the diagnostic criteria and to make diagnosis less definite.[11] Expressing these diagnoses in the form of probabilities is in fact confusing for the consumer, who would prefer to have a definite electrocardiographic interpretation to fit into the general clinical picture with other laboratory findings for diagnosis. Comparative electrocardiography is also possible and the new programme will be released in 1973. Pipberger[16] stresses the point that the ultimate test for a particular programme is diagnostic accuracy.

Physician review: Whether or not the interpreted ECG should undergo physician review, or to what extent it should be reviewed, is a matter of great difference of opinion. Pordy[7] is categorical about the fact that every ECG should be reviewed before it is finally released. His on-line system makes provision for review after processing by a panel of physicians/cardiologists. Any corrections are then introduced into the further processing, so that the final hard copy and print-out is an amended version. He is of the opinion that normal and abnormal ECGs must be reviewed in this fashion. The fact that Pipberger has demonstrated to his own satisfaction that computer diagnosis is superior to that of a cardiologist/physician,[16] leads him to the conclusion that there is no need for a review, since the accuracy of human interpretation is so much less than that of the automated machine.

It is Caceres's view,[9] too, that the new programme which will shortly be released by him will make a 'central review' of the ECG unnecessary. The question of 'central review' is emphasised, because the review may be done at the consumer end and there should be no need for a central point where all or any ECGs are first reviewed and corrected. This will allow the individual physician/cardiologist to make his own assessment, and where other hospitals are linked to the central system, such hospitals can organise their own reviewing system if they so wish.

A general system of surveillance of the quality of the electrocardiographic interpretation is the requirement of Smith.[11] In his view it is unnecessary to review normal ECGs and in his experience perhaps one out of every thousand interpretations subjected to review by a cardiologist is altered. This alteration does not necessarily mean an improvement. Consequently Smith states that (*a*) normal ECGs need not be reviewed; (*b*) abnormal ECGs in which the type of abnormality is of a kind where there is a 100% agreement as to the nature of the abnormality, for instance the diagnosis of a pure posterior myocardial infarction, need not be reviewed; (*c*) where the diagnoses have a wider variety of interpretive possibilities the ECGs should be reviewed. The programme should therefore include a certain quality control for the different diagnoses; and the greater the degree of agreement with regard to criteria for a diagnosis, the less the need for review exists, so that an increasingly large number of abnormal ECGs can be included in the mainstream of records which need not be reviewed. The higher the possible diagnostic error, the more a physician's review becomes necessary.

Criteria for children: The various programmes have thus far not included sufficient criteria to meet the demands for the various ages from 0 to 20 years. However, the newer programmes of Caceres[9] will have sufficient criteria for interpretation from the age of 5 years. Pipberger will include criteria for children, once they are linked up with a children's hospital.[14] The Smith programme is now making provision for the addition of criteria in relation to children, and normal values are being fed into the programme to include the ages 0 - 20 years in different categories.[11]

Comparative electrocardiography: The comparison of ECGs taken in the immediate follow-up period, particularly in the intensive care units, and baseline ECGs done pre-operatively, is becoming an increasingly important facet of clinical electrocardiography. The programmes of Pordy, Caceres and Smith allow for the possibility of comparison, but this requires an increase in active storage space in the computer system. This type of storage is most efficiently supplied by means of disc storage.

The print-out form: All available programmes permit the option of having a print-out in a long or a short form. The long form includes the actual measurements to any degree of detail required. This is then followed by an interpretive statement with reasons for arriving at the particular diagnosis. The form in which the interpretation is required will depend on the type of consumer.

Firstly, the cardiologist requiring the ECG will wish to have the complete information, including the graph and all the measurements, as well as the analysis and the reasons for the interpretive statement. He would then probably assess the ECG for himself and compare this with the computer diagnosis, and if there is a difference of interpretation he would most likely prefer his own interpretation.

Secondly, the general physician or postgraduate student and the undergraduate student will perhaps also require the long form, but would have more interest in the interpretive statement and the logic for the conclusions arrived at. They would tend to accept the computer diagnosis.

Thirdly, the general practitioner and non-internist specialist in hospital service would have most interest in computer diagnosis and none in details.

Storage

The storage of electrocardiographic information must be viewed on a functional rather than an encyclopaedic basis:

Short-term: Short-term storage is required for the period in which the ECG will be active and may have to be retrieved rapidly for comparative purposes, or for inclusion in the patient file, or when taken on an out-patient awaiting admission to hospital. This type of storage is best done on magnetic disc, which is expensive and can be used to only a limited extent. It is therefore necessary to decide how long the ECG should stay in this form. An arbitrary time of, say, the average hospital stay or the average time of awaiting admission from a clinic, may be set—a period of 3 weeks may be reasonable.

Intermediate term: An intermediate period of storage is required in which the ECG may be called for because of the possible readmission of a patient. This is a difficult length of time to determine. It is fairly certain, however, that only a small percentage of ECGs need be stored in this form for more than a year. Magnetic tape storage could be considered for this purpose. Digital tape would make an ECG more rapidly retrievable and has fewer problems than analogue tape. A magnetic data card system has been developed and appears to be close to ideal for intermediate and long-term storage (Marquette Electronics Inc.). The card has magnetic tape strips which can record in both a digital and an analogue form. The system automatically receives ECGs, along with patient identification data, by telephone or from tape cassettes. As each record is received, it is transcribed onto a magnetic data card. Later diagnostic codes and computer commentary can be recorded or corrected on the same card. Automatic reproduction of recorded data is quickly accomplished. Recorded data cards can be stored, 2 000 cards per drawer. This file can be extended.

Raw digitised ECGs contain from 15 000 to 60 000 'bytes' (8-bit characters). An accumulation of 100 000 ECGs would represent some 1,5 - 6 billion bytes. A disc pack of 731-metre reel of digital tape can store 5 - 20 million bytes. As a result it would require several hundred disc packs or tape reels to store these records.

Five minutes are required to load and search digital tape, somewhat less for a disc pack. If 100 old tracings per day have to be located, 2 full-time computer technicians are required. It is claimed that 100 magnetic data cards can be retrieved from the files in less than one hour and can be converted into hard copy in 15 minutes. A computer is not required for such a procedure. This new central magnetic data card system appears to be a very valuable adjunct for storage and retrieval purposes, which could serve both intermediate and the long-term needs.

Long-term: A less costly but also less useful form of storage is the microfilm card storage (3M Brand Filmsort Cards, 3M Co., St Paul, Minn., USA). The ECG is in a form in which it cannot be reanalysed or compared by means of the computer.

Benefits of an Automated ECG System

Experience has taught that once an analytical and interpretive electrocardiographic system becomes operational, it greatly contributes to the elevation of the general knowledge of electrocardiographic interpretation.[9,14,15] It has turned out to be a powerful educational instrument. Wright[15] of the Baylor College of Medicine, Houston, Texas, states that their senior medical students become as well versed in the interpretation of ECGs within 5½ weeks of exposure to this system as their senior resident staff. The fact that the interpretive statement is presented together with the reasoning for the diagnosis, means that the reviewing physician can look at the tracing critically and study the unknown facets in depth.

Great advantage is derived from freeing the physician and the cardiologist from routine measuring and screening of ECGs, and thus many hours of professional and academic time are saved.

The service aspect of an automated system is not limited to large teaching institutions, but applies particularly to institutions, whether they be large or small, where there may be few if any cardiologists or internists available to read and interpret ECGs. Ideally, such a centralised system can be linked with peripheral and rural hospitals and even mission stations and general practitioner groups in outlying areas.

The storage of the vast amount of accumulated electrocardiographic data in a form in which it is retrievable and comparable, can also be best accomplished by this means.

There can then be little doubt that provided the criteria of accuracy are ensured, the installation of such a computerised system for electrocardiographic analysis and interpretation can be justified. The direct and indirect benefits, consisting of the educational value, service value and the storage facility, would outweigh the fiscal considerations.

DISCUSSION

The general conclusion is that a cardiographic analysis and interpretive system can be installed and made operational to the benefit of any teaching hospital and its environment. The 12-lead scalar electrocardiographic programme appears at present to be most suitable to our local requirements and will provide an acceptable form of electrocardiographic presentation. With the increasing trend towards the use of an orthogonal lead system, a programme which includes both the 12 leads and the orthogonal leads may be preferable. An on-line system is functionally preferable and can be readily installed in a central complex and linked with peripheral hospitals, by means of the telephone network. However, it does seem necessary to make provision for an off-line possibility as a back-up facility and for the purpose of surveys in outlying areas. Storage facilities must be provided on a short-term basis, during which ECGs are actively required, particularly for comparative purposes, and also on intermediate and long-term bases. Disc capacity is therefore necessary for short-term purposes, and the most suitable long-term system is one in which a single manual step is required, but which is both economical and efficient, such as the magnetic data card system.

The form which the print-out takes is optional and can be varied according to consumer requirement.

All the available programmes are still being improved upon, but have reached a general state of maturity which makes them acceptable for routine service. It can be reasoned that the electrocardiographic interpretation is better done by a computer than by an individual cardiologist. Programmes will soon include criteria for children, and provision is made for comparative electrocardiography. No programme can thus far be regarded as infallible, but recognition of the normal ECG has a degree of accuracy of more than 99%. The accuracy with abnormalities varies, depending upon the degree of consensus regarding the criteria for a particular diagnosis and on the measurements decided upon to indicate abnormality. The scalar leads are perhaps inferior to vectorcardiogram leads as regards accuracy, but opinions differ. Since the scalar leads are more widely acceptable in this country, as is the case in most other parts of the world, and the vector leads are not so familiar to most cardiologists and practising physicians, a programme at this stage would include the 12 scalar leads. If the vector leads were more familiar, they would certainly be more economical, because measurements in only 3 leads are required for interpretative purposes. Rhythm analysis has been brought to a stage where the bulk of arrhythmias are diagnosed accurately, and prevailing opinion is that great progress in accuracy has been made with regard to arrhythmias.

The available programmes are of such quality at present that a complete review of all ECGs is not necessary. An increasingly larger number of abnormal ECGs may in future be included in the mainstream of normal ECGs which are not reviewed. The diametrically opposed views of Pordy and Pipberger, the former being in favour of review on every ECG, and the latter advocating no interference from the physician/cardiologist because of superior performance by the computer, cannot be completely accepted. There need be no objection to having an organisation run on the lines suggested by Caceres,[9] where review is done at the receiving end of the interpretative statement.

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Variant (Prinzmetal's) Form of Angina Pectoris Manifesting in Complicating Ventricular Extrasystoles

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SUMMARY

A case of the variant (Prinzmetal's) atypical form of angina pectoris is presented. Secondary and primary changes affecting the S-T segment and T wave are discussed.

The features were also present, and indeed more marked, in complicating ventricular extrasystoles, one of which reflected the infarction pattern.

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In 1959 Prinzmetal *et al.*[1,2] focused attention on an unusual form of angina pectoris, which has been termed the variant or atypical form of angina pectoris.

The distribution of the pain is identical with the classic form of angina pectoris, being substernal with radiation to the jaw and down the ulnar surfaces of the arms and being oppressive in character. Unlike the classic form of angina pectoris, however, the pain frequently occurs spontaneously and is not necessarily related to effort or emotion. The pain is usually severe and of longer duration. It usually presents with a series of attacks which tend to be cyclical, recurring every few minutes with peaks of remarkable constancy, and frequently at the same time or times of each day. The waxing and waning periods of chest pain are often of equal duration, unlike the typical form of angina pectoris where the waning period is shorter and more abrupt than the waxing period. The attacks frequently progress to myocardial infarction, and it is noteworthy that the severe angina pectoris frequently disappears dramatically after such an infarction. The condition is usually associated with a grave prognosis. Recent reports have indicated that the variant angina pectoris with the typical electrocardiographic changes may also be precipitated by effort.[3]

Electrocardiographically, the variant form of angina pectoris has the following characteristics. There is transient elevation of the S-T segment in leads orientated to the apex and the adjacent anteroseptal region, viz. leads V2 to V6, particularly leads V4 and V5. Occasionally, and especially with vertical hearts, the manifestation appears particularly in standard leads II, III and lead AVF. The associated T waves are usually upright, but may be inverted. When the T wave is upright, the elevated S-T segment will have a concave-upward or upward sloping appearance. This manifestation is similar to the hyperacute early injury phase of acute myocardial infarction. When the associated T wave is inverted, the elevated S-T

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