SIEMENS

The SICARD 440/740 ECG analysis program

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Reprint from
electromedica (1989) 57, No. 3, pages 106-120

The Sicard 440/Sicard 740 ECG analysis program

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The development of the Siemens ECG analysis program effectively began in Glasgow in 1964. At that time, an investigation commenced into the use of computers for ECG interpretation and the first tentative methods were outlined in a preliminary publication [1]. A few years earlier, *Pipberger* [2] using the orthogonal XYZ lead system and *Caceres* [3] using the conventional 12-lead system had outlined their initial strategies for interpretation of electrocardiograms by automated methods. At that time, the XYZ leads of the orthogonal lead ECG were recorded simultaneously although initial work with the 12-lead ECG involved recording the leads individually. *Bonner* in his early work [4] with IBM also utilized leads recorded singly.

Part of the problem initially faced by the Glasgow team was to determine whether or not the use of 3 orthogonal XYZ leads was as clinically useful as the 12-lead ECG and in order to answer this question, both types of ECG were recorded from over 1,000 patients [5]. In order to simplify the analysis, the 12-lead ECG was also recorded in groups of 3 leads but in this case, they were selected as being quasi-orthogonal. For example, they consisted of leads I, aVF, V1; aVL, II, V4; V3, III, V6; V2, aVR, V5 [1, 5, 6]. From a study of 1,093 patients where the XYZ leads were compared with the 12-lead ECG, it was shown that from the clinical point of view there was no significant difference between the lead systems. The same wave recognition methods had been used for analyzing the XYZ leads and the 12-lead ECG recorded in groups of 3 leads [6]. Different diagnostic logic had been developed for the two types of electrocardiograms [5].

In view of the fact that at that time, processing of a group of three leads took the order of one minute on a PDP8 minicomputer, it was decided that for routine purposes, XYZ leads would be used to provide a routine service in Glasgow Royal Infirmary because of the significant saving in processing time compared to the use of 12 leads, which would have required 4 minutes. For most of the 1970s, a routine ECG interpretation system based on a PDP8 minicomputer, analyzing the corrected orthogonal leads derived from the modified axial lead system [7], was used in Glasgow Royal Infirmary [8]. Analysis of cardiac rhythm and comparison of serial ECGs were incorporated [9].

Towards the end of the 1970s, microprocessors became more widely available and the possibility of recording multiple leads simultaneously, i.e. up to ten or eleven leads in digital form, arose. A new project therefore commenced in Glasgow Royal Infirmary to develop a digital electrocardiograph for recording all ten independent leads of the hybrid system simultaneously [10] and at the same time, to develop a new 12-lead ECG interpretation program. Full details of the electrocardiograph were subsequently published several years later [11].

In 1981, Siemens-Elema in Stockholm expressed an interest in the 12-lead ECG program being developed in Glasgow and this ultimately formed the basis of the Mingocare® I system (CARE = Computer Assisted Reporting of Electrocardiograms) which was marketed in the mid-1980s. Details of this system and the interpretation program can be found elsewhere [12]. In essence, ECGs were recorded in digital form off-line on to cassette tape which was subsequently returned to a central PDP11-based computer system for analysis.

With recent developments in technology such as the increasing power of microprocessors and the lower cost of random access memory, it became feasible to consider incorporating a complete ECG data acquisition and analysis program into a small electrocardiograph. Out of this has arisen the Sicard® 440 and sicard 740 series of electrocardiographs (Fig. 1) which together with a Microvax based central ECG management system form the Mingocare® II System (Fig. 2). Much of the ECG analysis program which has been developed in Glasgow over the past twenty years is incorporated into these electrocardiographs and the remainder of this paper is concerned with discussion of the methods involved in interpreting the ECG. Developments in electronic technology are such that some aspects of the ECG acquisition and analysis are best dealt with by firmware, i.e. a combination of hardware and software merged into a

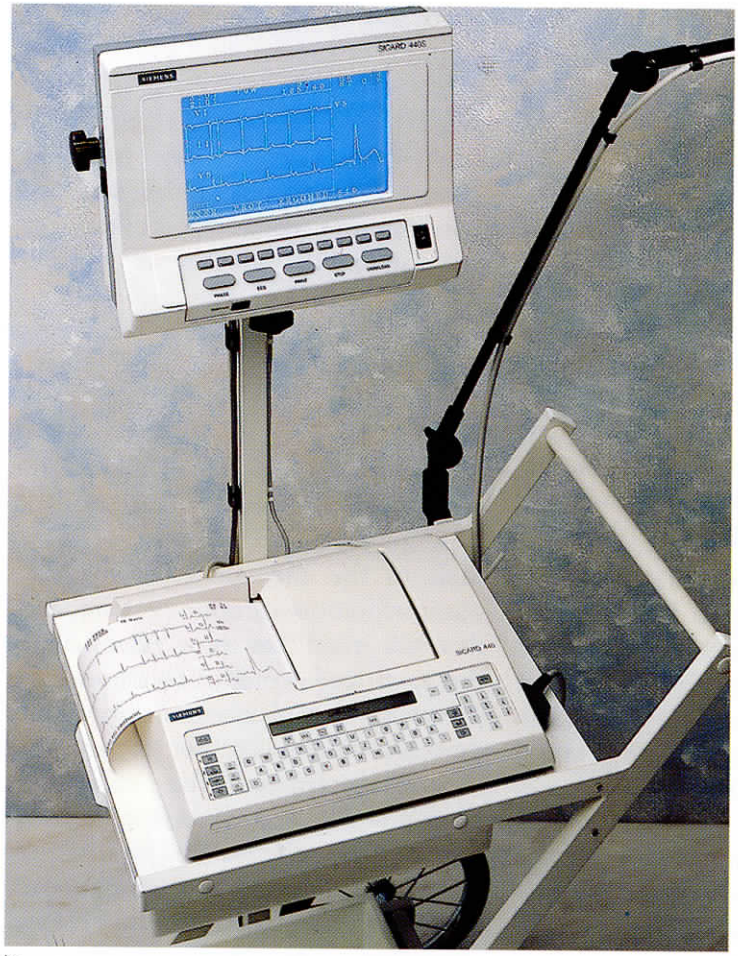

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Fig. 1

a The Sicard 440 electrocardiograph in combination with the Sicard 440S exercise ECG module

b The Sicard 740 electrocardiograph

"chip" and such aspects have been dealt with by Siemens and collaborating companies.

Data acquisition

Part of the uniqueness of the Siemens ECG analysis program is the ability to utilize data regarding the patient's age, sex, clinical classification and drug therapy. Thus, all Sicard 440 and Sicard 740 series electrocardiographs embody facilities including a complete alphanumeric keyboard to allow the input of such data in a simple manner. An extensive menu of set-up procedures can be used so that certain questions can be selected or omitted as required. For example, the user may opt to input patient's height, weight and blood pressure, if desired. These do not influence the interpretation but other factors such as race, which can be entered optionally, do indeed affect certain criteria.

It is well known that there are only eight independent leads in the 12-lead ECG. For example, if leads I and II are recorded then leads III, aVR, aVL, aVF can be calculated from I and II, e.g.

$$III = II - I$$

Thus, eight independent leads are sampled by the front-end processor and converted into digital form initially at 4,000 samples per second. This high initial rate is used basically for checking for the presence of implanted artificial cardiac pacemaker stimuli. Because of the high sampling rate it is not necessary to utilize sample and hold circuitry since the skew between channels is negligible. Ultimately, by averaging 16 consecutive samples, it is possible to reduce the effective sampling rate to 250 per second.

Digital filtering techniques are used to provide baseline stability and to remove AC interference etc. [13]. For display purposes and for rhythm analysis of 10 seconds of continuous recording etc., it is only necessary to use a form of high-pass filtering above 0.16 Hz.

QRS wave detection and typing has to be undertaken prior to averaging of similar complexes to produce the cycle used for interpretation. The following description is provided by Mortara Instruments, Inc.

The QRS detection is undertaken by a peak power detector which uses the combined absolute power from leads II, V1 and V5. The combined power is calculated as:

$$\text{Power} = \sum_i |\text{pwr}_i| = \sum_i \sum_{j=-16}^{16} |a_j|$$

where Power is the combined absolute power, pwr_i is the power in lead i, and a_j is the amplitude at 4 ms intervals of a band pass filtered lead i (i = II, V1, V5). A detection occurs when a local

maximum power is found which exceeds the current detection threshold. An adaptive detection threshold is used. Its value, which is updated on the basis of the power of previously detected beats, is calculated as:

$$D_{THR} = (D_{THR} + PK_{PWR})/2$$

where D_{THR} is the current detection threshold and PK_{PWR} is the power of the previous QRS detection point. The detection threshold is also updated every 64 ms as the interval from the last detection increases, by a decrement of

$$(D_{THR} - MIN_{THR})/16$$

where MIN_{THR} is the minimum detection threshold (a constant).

The QRS classifier is a template matching algorithm using leads II, V1, V3 and V5. The classification template consists of a special width/area parameter and amplitudes for each lead. Each new QRS is checked with all active classes (types) using:

$$A_{SUM} = \Sigma|a_i + b_i|$$
$$A_{DIF} = \Sigma|a_i - b_i|$$
$$W_{DIF} = \Sigma|w_i - v_i|$$
$$W_{DIF2} = W_{DIF}/2$$
$$W_{THR} = 1/8\ \Sigma|w_i| + C$$

where a_i and b_i are amplitudes and w_i and v_i are width/areas for lead i of the QRS and class templates respectively and C is a constant. A match requires that:

$$A_{DIF} < 1/8\ A_{SUM} \text{ and } W_{DIF2} < W_{THR}$$

or

$$A_{DIF} < 3/8\ A_{SUM} \text{ and } W_{DIF} < W_{THR}$$

The QRS is typed according to its best match. If no match is found, a new class is defined. Up to five active classes are kept by the classifier. If a new class is needed and five classes exist, the class which has been inactive (not matched) the longest is redefined as the new class. Once the QRS class has been determined, a secondary template match is done to find the best time alignment to previously detected beats of the matched class. The time alignment template match is based on amplitudes 24 ms apart using:

$$A_{DIF} = \Sigma|a_i - b_i|$$

where a_i and b_i are amplitudes for lead i of the QRS and class templates respectively. The best match is found when A_{DIF} is a minimum value during a scan ± 80 ms about the detection point.

In certain types of rhythm abnormality such as atrial bigeminy, it is possible to subdivide the dominant QRS into two on the basis of the preceding RR interval. This would be of particular importance in respect of incorporating the P wave into the averaging procedure.

Averaging of the beats which are all regarded as belonging to the cycle required for interpretation then takes place. It should be noted that it is not always the dominant cycle that has to be averaged. An example of this would be where there might be demand pacemaker activity but only one or two cyles of normally conducted beats. The latter would be averaged for the Siemens Sicard 440/740 program.

Averaging is accomplished in a multistage process [14]. First of all, the required beats are split into three separate categories. The arithmetic mean for each of the categories and for the eight independent leads is then calculated. Thereafter, the zone immediately preceding the QRS onset is taken as an estimate of the baseline which is then removed from each group. The next stage is to divide each mean beat into a high frequency and low frequency component. This is achieved by low pass filtering where the arbitrary corner frequency selected is approximately 15 Hz. The aim here is to enhance removal of high frequency noise by separating low and high frequency components prior to further "averaging". Thereafter, the final procedure is to form the median of each of the three groups of beats which are available for each lead. In this case, selection of the median value for each sample point is a simple exercise since it is the middle of three values. Thus, for each lead a median high and low frequency complex is available and the two are added together to give the desired average beat. The procedure is shown in Figure 3. Thus, the formulation of the beat to be used for interpretation has involved a combination of finding a mean and a median. This was described by its authors as a process of hybrid averaging.

The next part of the analysis is to determine the onset and offset of the various PQRST waves and thereafter measure amplitudes and durations. This is achieved by forming a compo-

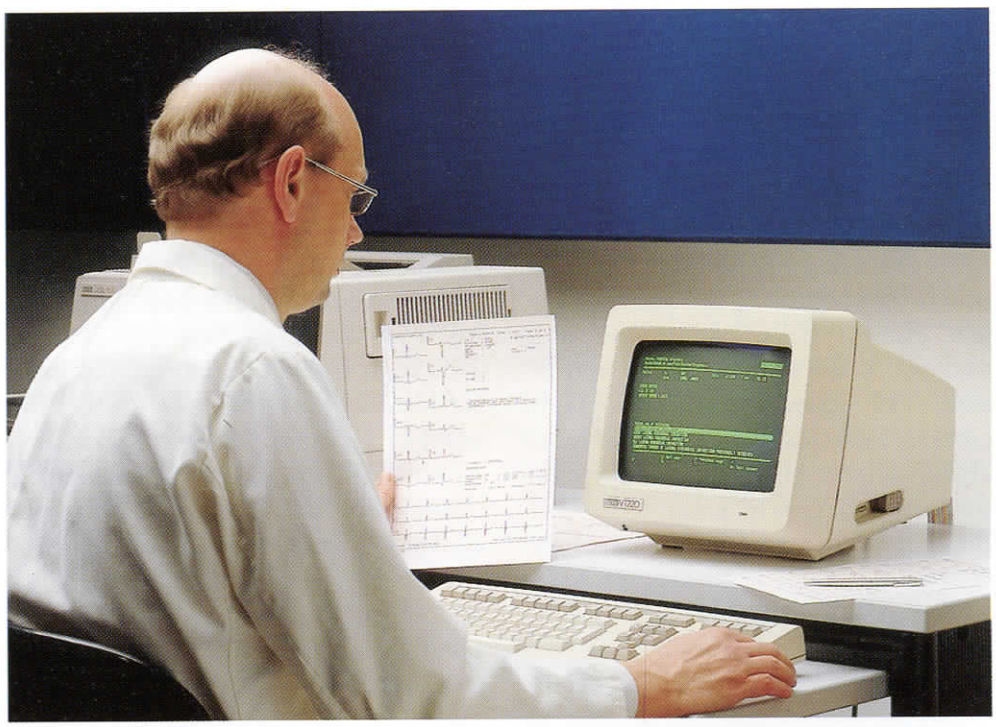

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Fig. 2 The Mingocare II central system consisting of a MicroVax series computer, editing terminal and laser printer

site beat derived by summing the modulus of first differences for the eight independent leads of the 12-lead ECG as indicated for one sampling interval by

$$\sum_{n=1}^{8} |x_n(t+1) - x_n(t)|$$

Critical values for onset and offset for this composite beat are then invoked in finding the approximate onsets and terminations of the major P, QRS and T waves. These reference points are then transferred to the individual leads and the process of finding more specific onsets and terminations for P, QRS and T waves is then carried out.

It follows that the onsets in the individual leads may well have different values and a further procedure of calculating the overall onset based on a comparison of individual onsets is then adopted. Within each lead, a small segment of baseline immediately preceding QRS onset is used to find the reference level with respect to which all QRS and T amplitudes are measured. P wave amplitudes are measured by fitting a straight line between P onset and termination in each lead.

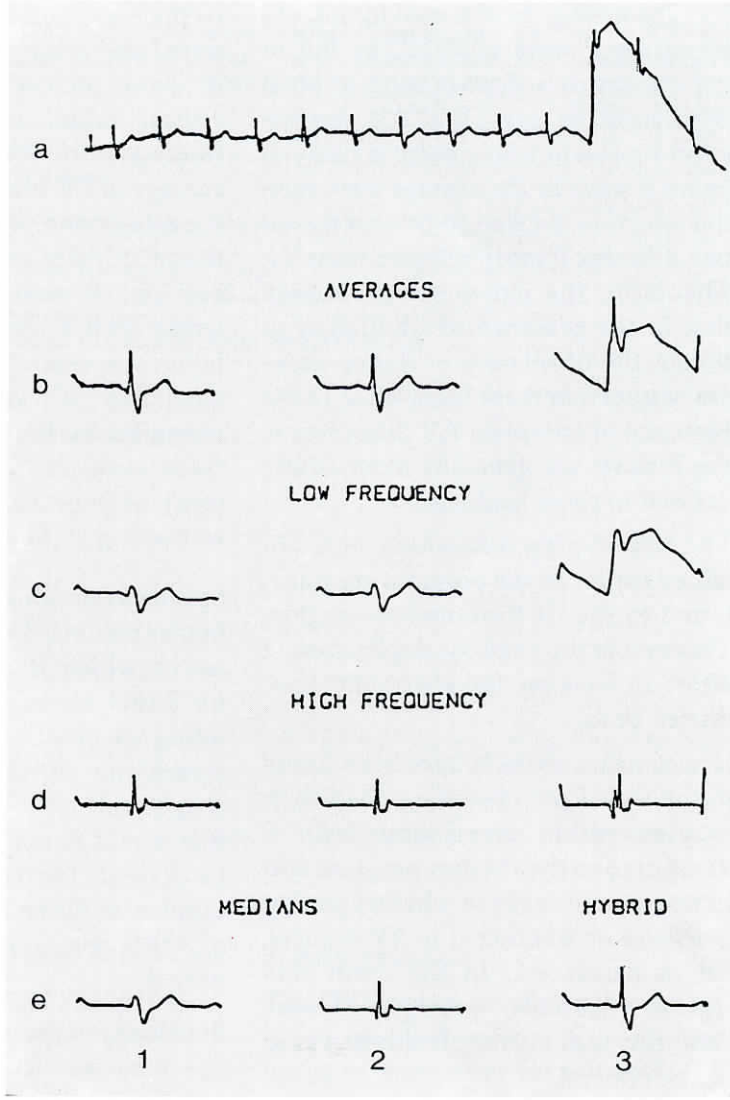


Fig. 3
A schematic illustration of the averaging procedure used in the Sicard 440/740 program. The recording (a) is first divided into 3 sections from which group means are obtained (b). Each mean is then divided into low (c) and high (d) frequency components. The median of each low (e1) and high (e2) frequency component is then obtained and added to produce the hybrid average (e3). Modified from (14) with permission

It should be clear to those who record ECGs that one of the main technical aims is to obtain an ECG which is as free from artifact as possible. This is a requirement whether or not computer assisted ECG reporting is involved. However, if there is excessive artifact on a recording, then there is every likelihood that the accuracy of computer measurement of various wave reference points will decrease. In the presence of noise it is likely that QRS duration will be measured more widely than is actually the case and the determination of a reference level with respect to which amplitudes are measured will also be less accurate. Thus, every effort should be made to ensure that technically satisfactory recordings are obtained. While the technique of signal averaging does, of course, reduce the amount of noise present, in a brief recording of ten seconds the noise reduction by signal processing methods cannot be too dramatic if it is excessive in the first instance. Furthermore, analysis of rhythm will be made more difficult. The higher is the quality of input, the more accurate will be the wave measurements and hence the interpretation.

Certain vector parameters are calculated by using a quasi-vectorial approach combining leads I, aVF and V2. In addition, some time normalized measurements of the STT segment are utilized namely, one-eighths, two-eighths and three-eighths STT amplitudes. All axes are measured using the following formula

$$\mathrm{Tan}^{-1}\ \frac{\sqrt{3}\,[f(II) + f(III)]}{2\,f(I) + f(II) - f(III)}$$

where f(x) is a function such as the sum of Q,R,S amplitudes in lead X, or QRS area in lead X, details of which can be found elsewhere [15]. Finally, various QRS and STT area measurements are calculated by simple summation of the sample values multiplied by the sampling interval.

Rhythm analysis

Three of the twelve leads are selected for rhythm analysis. When P waves are present, leads II and V1 are chosen and a third lead, generally that with the largest amplitude is selected from I, III, aVF and aVR. If flutter has been detected in lead II, then III and V1 are the other two leads selected automatically. It is well known that P waves have different morphology in different leads and therefore a search for their presence in the varying leads requires that different criteria be used. Thus, for each lead selected, a P wave type is associated. For example, this could be upright or bifid as is often the case in

V1. The average beat is used in order to select the P wave morphology but in the event that a rhythm such as atrial fibrillation or complete AV dissociation is present where there is likely to be no P wave in the average beat, then the selection is taken to be lead II, and two different P morphologies from V1. This is for the rather obvious reason that in the presence of fibrillation or flutter, the fibrillatory or flutter waves are best seen in these leads while in the presence of complete AV dissociation, the P waves are generally most clearly defined in these leads also.

The wave typing data which were obtained earlier in the program are transferred to the rhythm analysis section. This avoids the need for duplication of effort in looking for aberrantly conducted beats.

If pacemaker artifacts have been found in the signal preprocessing, then their location within the rhythm strip is transferred to the rhythm program and an assessment made of whether pacing is regular or whether it is AV sequential in nature etc. In the event that regular ventricular pacing is found, then the main interpretation would not be entered.

The search for P waves forms the basis of the rhythm analysis as might be expected and essentially this is done using the first difference of the selected leads. When the first difference is formed the data are also filtered at the same time with a low pass filter having zero response at 50 or 60 Hertz depending on the line interference frequency. The recursive filter used has remained the same over a number of years and has the following equation:

$$y(t) = y(t-1) + \frac{1}{10}\{x(t+5) + x(t-5)\}$$

where x (t) and y (t) represent the input and output values respectively. Further details can be found elsewhere [16].

Several attempts may be made to find P waves if on a first pass there is not found to be one P wave per RR interval. Criteria for P wave recognition can be adjusted and a second pass of the data made.

In the event that criteria have been lowered and multiple P waves are found in some intervals, then the original critical values are restored and the finding of one P wave in a certain percentage of RR intervals is accepted. On the other hand, if multiple P waves are found initially and criteria are raised and one P wave per RR interval is found with a regular PR interval, the latter is accepted. It is quite conceivable that in atrial fibrillation for example, the P wave recognition logic finds multiple "P waves" in the majority of intervals. This would be used in making an interpretation.

Special subroutines are utilized for particular reasons. An example would be a search which is made on every ECG for flutter waves. In this case, the differing gradients of the upslope and downslope of the flutter wave are sought and only if such a criterion is met would flutter waves be deemed to be present. Thereafter, the ratio of the number of flutter waves to the number of QRS complexes would be determined.

A different type of subroutine would check for ventricular bigeminy assuming that ventricular extrasystoles had been detected in the presence of sinus rhythm. The same subroutine would be used to look for atrial bigeminy if the RR interval were found to be irregular.

Where a single P wave may be found in a small number of RR intervals and where the PR interval is found to vary, the regularity of the PP intervals would be assessed in order to consider the possibility of the presence of AV dissociation. Allowance would be made for the fact that a P wave may have been missed by interpolating the presence of a P wave in an interval which might be twice as long as the shortest PP interval that had been measured.

The overall strategy of rhythm interpretion is to determine the dominant rhythm such as sinus rhythm or atrial fibrillation and thereafter to find any supplementary abnormalities such as atrial extrasystoles that might be present. A typical arrhythmia and the corresponding interpretation are shown in Fig. 4. Other arrhythmias are illustrated later in Figs. 5, 6, 7 and 8.

The rhythm program was assessed for sensitivity and specificity [17] and was found to be over 98 % sensitive in the detection of sinus rhythm with a specificity of 97 % (predictive value 99.6 %). The other major abnormality, atrial fibrillation, was detected with a sensitivity of 99 % and a specificity of 99 % (predictive value 95.8 %). No other rhythm abnormality occurred in the study with sufficient frequency to permit a meaningful assessment of accuracy.

Diagnostic logic

The wave measurements determined earlier in the program are transferred to the diagnostic section together with the various patient details that have been discussed above, namely, age, sex, race etc. The rhythm interpretation is also transferred to the diagnostic section of the program since, for example, there would be no need to assess P wave abnormalities if atrial fibrillation had been diagnosed.

The diagnostic section of the program has been split into fourteen sections as follows:

1. Removable Preliminary Comments
2. Preliminary Comments
3. Intervals
4. Atrial Abnormalities
5. Axis Deviation
6. Conduction Defects
7. Ventricular Hypertrophy
8. Myocardial Infarction
9. ST Abnormalities
10. STT Changes
11. Miscellaneous Abnormalities
12. Normal Statements
13. Final Reviewers Comments
14. Summary Codes.

Within most sections of the program, the diagnostic criteria have been formulated essentially as a set of rules. This leads to a speedy implementation and the total time for this section of the program, when run on a microprocessor, is less than one second. Some brief comments are made on each section in turn.

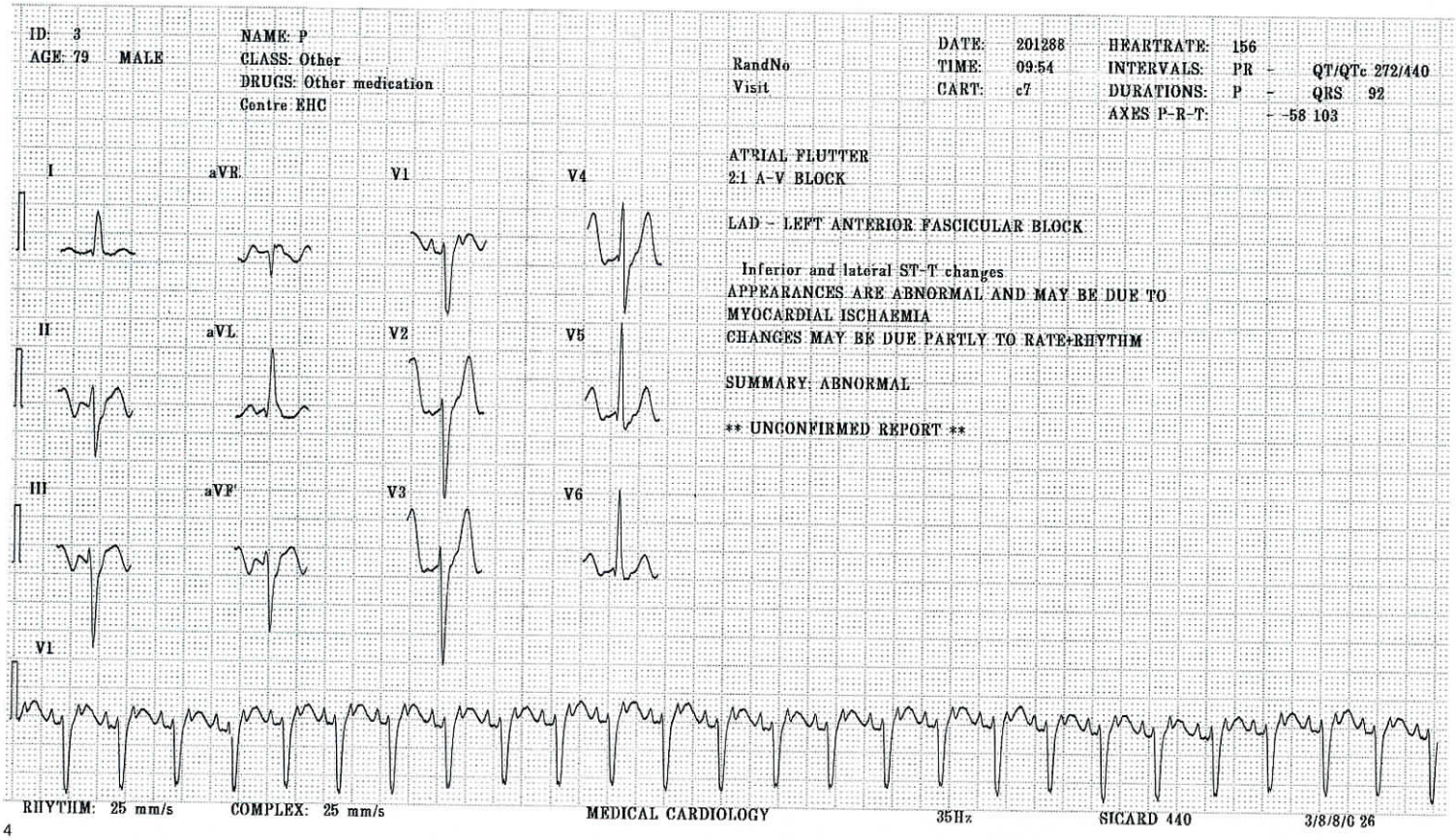


Fig. 4 An example of atrial flutter with 2:1 A-V block as reported by the Sicard 440. Note how the flutter waves affect ST segments as commented on in the final statements

1 Removable preliminary comments

This section contains some statements such as "Possible Measurement Error" which the reviewer can remove if desired. In practice such a statement is rarely seen.

2 Preliminary comments

This section deals with problems such as limb lead reversal which has to be differentiated from dextrocardia. Other problems assessed in this section would be interchange of chest leads or perhaps a technically unsatisfactory lead where clearly the amplitude of the QRS complex for example is significantly different from that on either side in the chest leads.

3 Intervals

The QT interval is assessed at this stage. The equation used to calculate the corrected QT interval QT_c is as follows:

$$QT_c = QT + 1.75\,(\text{Heart Rate} - 60)$$

It is based on studies of *Hodges* et al. [18]. If the QT interval is shortened and it is known that the patient is receiving digitalis, then the diagnostic statement would suggest that this drug was the cause of the short corrected QT interval.

The PR interval is assessed in the rhythm program because, particularly in first degree AV block with a PR interval of 0.30 to 0.40 seconds, the P wave may not appear in the average beat.

4 Atrial abnormalities

Standard criteria are used to assess the presence of atrial abnormalities. However, a somewhat widened P wave duration is used because in practice it has been found that a value of 0.14 seconds gives a much more acceptable level of specificity in determining atrial abnormalities than does the conventional 0.12 seconds. It has to be remembered that all leads are measured simultaneously and indeed, the upper limit of P wave duration determined in this way from our own research exceeds 0.13 s in males [19].

5 Axis deviation

The QRS axis is calculated using a formula specified earlier. Conventional limits of normality for left and right axis deviation are used while this section also deals with the presence of left anterior fascicular block. In this connection, the criteria defined by the WHO Ad Hoc Committee have been used [20]. Care has to be taken when setting out the logic of the program that a statement on left anterior fascicular block is not prematurely produced prior to assessing the presence of other conduction defects such as right bundle branch block.

6 Conduction defects

The recommendations of the WHO Ad Hoc Task Force [20] mentioned above are also used as far as possible in detecting conduction defects. Use is made of quasi vector criteria including spatial velocity which is reduced towards the end of the QRS in right bundle branch block and in the middle of the QRS in left bundle branch block. If the appropriate axis deviation criteria are present, then fascicular block can be added to the diag-

nosis of right bundle branch block. This would inhibit a separate statement on axis deviation resulting in a single statement such as "Right Bundle Branch Block With Left Anterior Fascicular Block".

7 Ventricular hypertrophy

In this section, the age and sex of the patient are used to a much more significant extent than in other programs. Indeed, a number of programs do not actually differentiate between male and female in the diagnosis of ventricular hypertrophy even although it is well known that upper limits of normal are both age and sex dependent. Essentially, the criteria of *Romhilt and Estes* [21] have been extended for the diagnosis of left ventricular hypertrophy. Instead of using a single value for the upper limit of normal voltage in the precordial leads, multiple values which are age and sex dependent, are substituted. An assessment of any STT changes, if present, is also included. Based on recent work from our Department which has shown that over 40 % of asymptomatic patients with LVH and secondary STT changes also have coronary artery disease, a statement suggesting that marked STT changes associated with the LVH may also be due to myocardial ischemia can be output [22]. Any report of LVH can be assigned a likelihood, e.g. "possible", "probable" (Fig. 5).

Criteria for hypertrophy are race dependent. It is known that blacks have higher voltages than whites [23] and our recent work has shown that Chinese individuals have lower voltages than whites [24, 25]. The latter data have been incorporated into the program both for males and females.

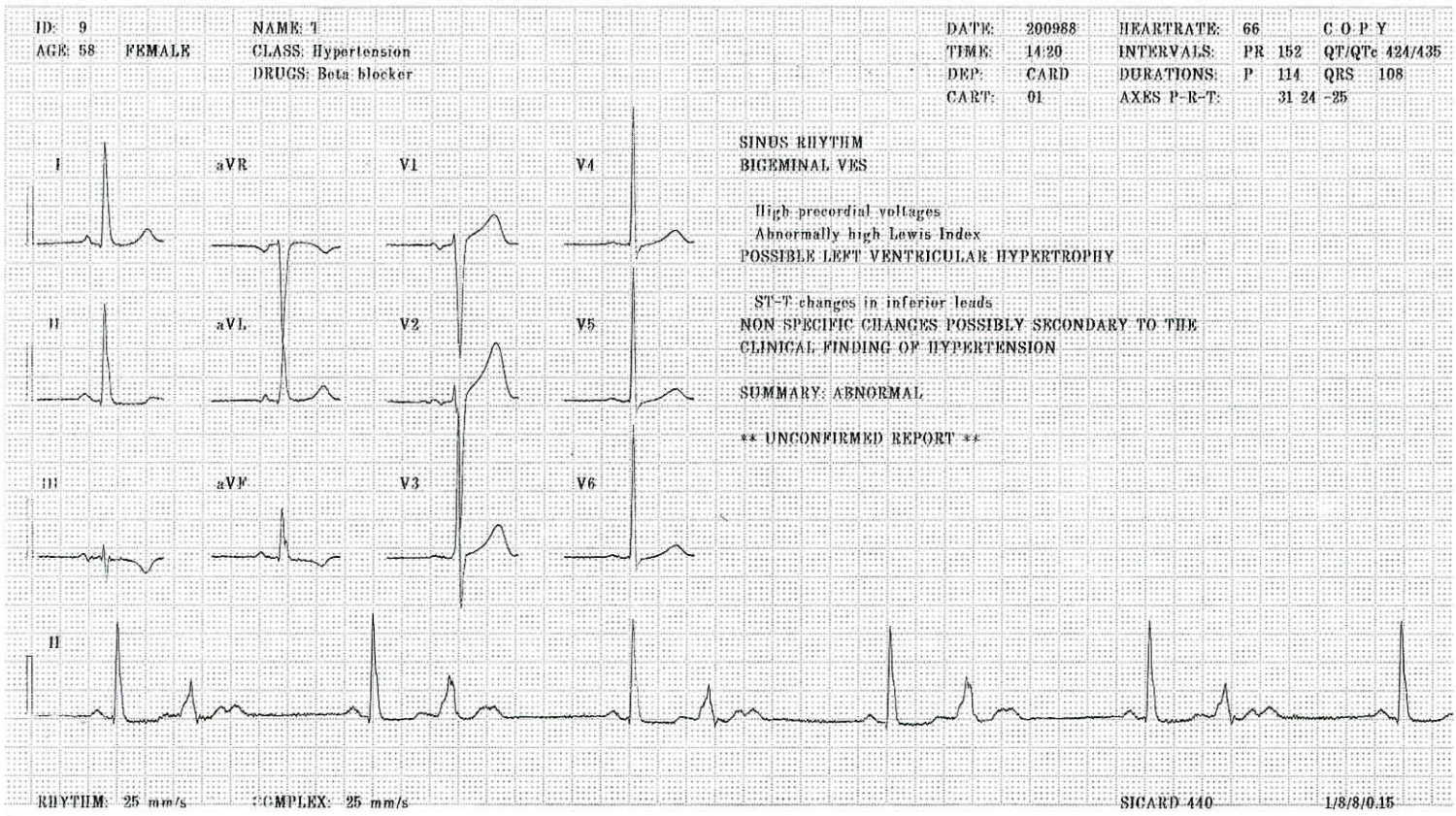
Right ventricular hypertrophy is also diagnosed on the basis of a scoring system. The usual criteria involving increased R/S ratio in V1, axis deviation, STT changes in the right precordial leads and a deep S wave in the lateral leads, are all considered. Again, some of these criteria are age and sex dependent.

Biventricular hypertrophy can be reported as a combination of LVH and RVH or if the voltage is extremely high, biventricular hypertrophy will be reported in keeping with the findings of *Gottdiener* et al. who showed that in the presence of marked LVH there was almost always a complementary RVH [26].

8 Myocardial infarction

Classical criteria for myocardial infarction have been used but in addition, data from our own study of normal individuals has been introduced when setting limits on normal Q wave duration in the inferior leads for example. While there is a tendency to think in terms of 0.03 seconds as being the upper limit of normal, our own data [15, 19] show that 0.26 seconds is a more sensitive, yet specific limit. The amount of ST elevation and the presence or absence of T wave inversion are all utilized in determining the age of an infarction if present.

Fig. 5 Several points are highlighted in this illustration. Firstly, there is bigeminal rhythm. Secondly, in this hypertensive patient, the computer report suggests possible LVH because the Lewis Index ($\{R_I + S_{III}\} - \{R_{III} + S_I\}$) exceeds the upper limit of normal of 1.8 mV for females over 50 years old. Thirdly, the clinical classification of hypertension is used in the interpretation of ST-T wave changes in the inferior leads



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Infarction can be diagnosed in the following locations:

Inferior
Lateral
Anterior
Anteroseptal
Septal
Anterolateral
Widespread.

There is also logic involved for combining Q waves in different leads so that, for example, it is possible to make a report of widespread myocardial infarction. As with the hypertrophy section, the report of myocardial infarction can be given a degree of probability by using "possible" or "probable", to indicate the degree of likelihood of the diagnosis. If these are omitted, the diagnosis is more certain (Fig. 6).

An important aspect of this particular section is serial comparison, which will be discussed below.

9 ST abnormalities

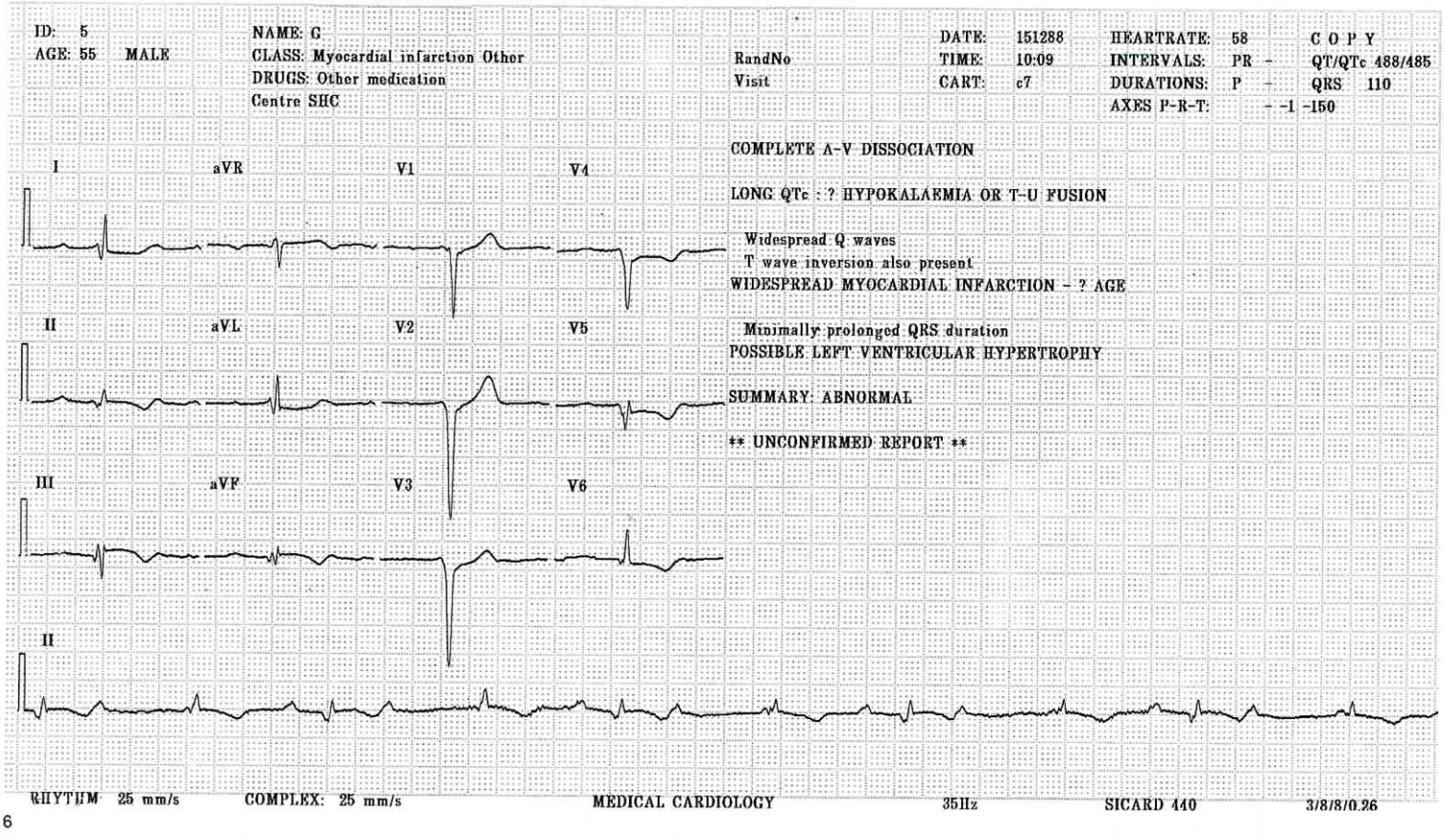
In general, this section deals with ST elevation such as might be found in the acute stages of myocardial infarction or in pericarditis and so on. The clinical classification of the patient can be used, if available, to make a more reasoned interpretation of the statement. For example, if it is known that the patient has recently undergone cardiac surgery and some ST elevation is detected, the interpretation would state "postoperative pericarditis".

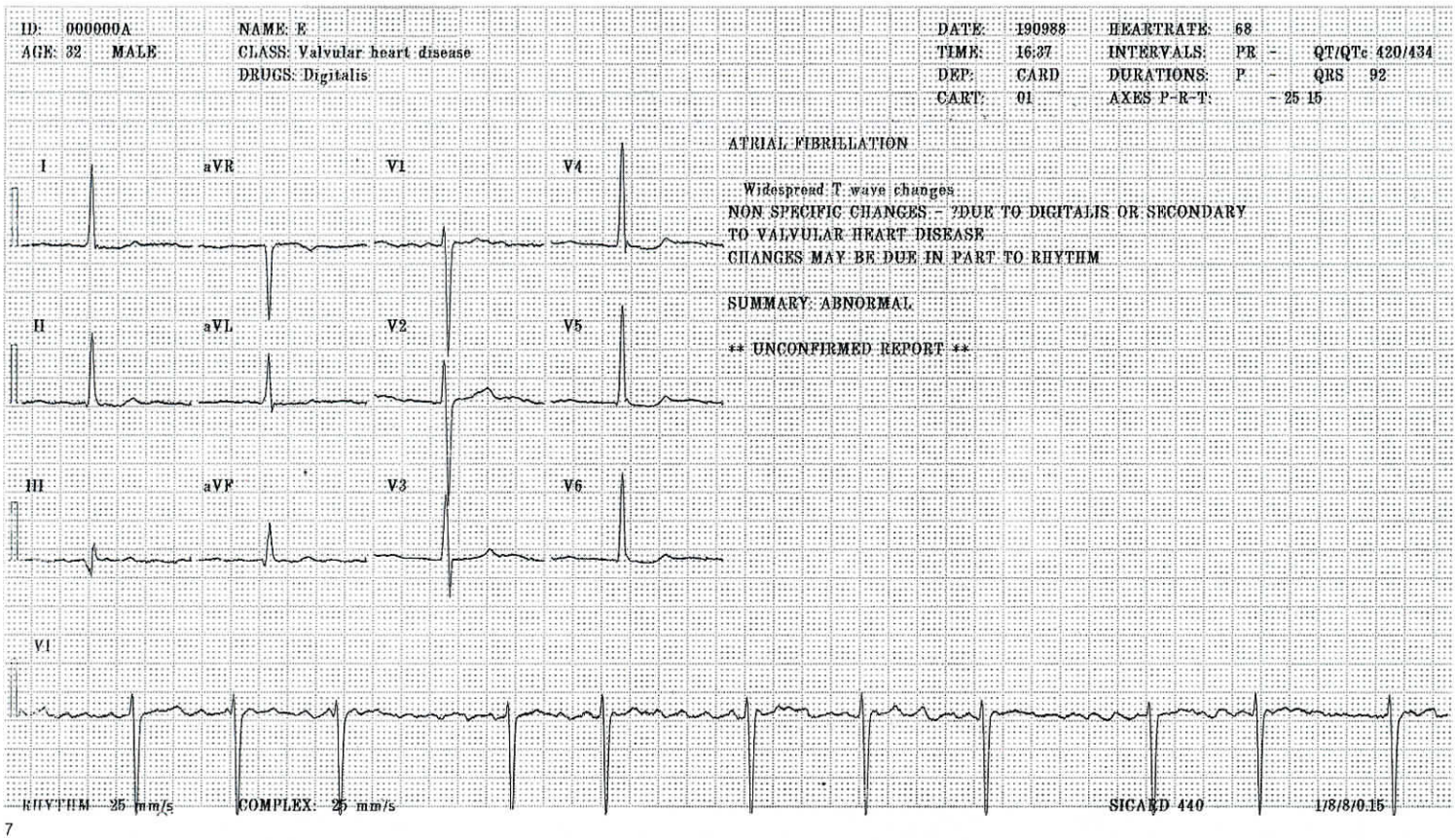
10 STT changes

Perhaps the most involved section of the program is related to the interpretation of STT changes which in many ways is one of the most difficult aspects of electrocardiography. At an early stage in the program, the amount of ST depression or T wave inversion is assessed for each lead and graded from 1 to 3 separately. Thereafter, the two classifications can be combined within a group of leads such as II, III and aVF for the inferior leads. Logical values are therefore established indicating the presence of STT changes and the particular combination of leads where they are found.

Notwithstanding this, it is also necessary to invoke additional logic when deciding whether or not to output primary STT changes. For example, given that there is left ventricular hypertrophy with STT changes, the logical associated with primary T wave abnormalities in the lateral leads would not be set given that left ventricular hypertrophy with secondary STT changes was present. This is one straightforward illustration of the concept which a physician utilizes almost subconsciously but which yet requires to be carefully defined for computer analysis.

Fig. 6 This ECG was recorded from a 55 year old male with a history of a previous myocardial infarction two years prior to the recording, a current BP of 170/100 and x-ray evidence of cardiomegaly. Note how the diagnostic logic is integrated to produce a report of widespread infarction. The rhythm interpretation is also of interest. The PP interval is regular although the RR is less so. Nevertheless, within the tolerance of the program limits, the combination has led to the report of complete A-V dissociation. It could be argued that A-V dissociation would be more appropriate. Such arrhythmias can be difficult for a computer program to interpret perfectly correctly





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Thereafter, the age, sex and clinical classification of the patient if available are utilized to interpret the STT abnormalities. For example, given that a patient had valvular heart disease and there were T wave changes present although criteria for ventricular hypertrophy were not met, the report would state that such changes were possibly due to valvular heart disease (Fig. 7).

Serial changes can also be assessed in this section and the method is discussed below.

11 Miscellaneous

A few miscellaneous abnormalities such as tall T waves and low QRS voltages are considered in this section. Some of the criteria are age and sex dependent.

12 Normal statements

It goes without saying that an ECG interpretation, of course, must contain a statement such as "within normal limits" and that in order to produce such a statement all critera will have had to be checked. In the event that no QRST abnormalities are present but there is an arrhythmia, the statement "nil else of note" is added to the interpretation.

13 Reviewer's final comments

Some statements are available in the central Mingocare II system for the reviewer to add to the final report if he wishes, e.g. "please repeat . . ." indicates that a tracing should be repeated to confirm an abnormality or to look for sequential changes.

14 Summary

Associated with each diagnostic statement in the program is a summary code. This includes normal, borderline normal, borderline abnormal, abnormal and so on including "technically unsatisfactory tracing".

At the end of the interpretation, the summary codes associated with each of the diagnostic statements which have been printed are checked and that with the highest grading is selected.

Output format

The format of each diagnostic statement consists of one or two reasons

Fig. 7 ECG recorded from a 32 year old male student from West Africa with valvular heart disease. The diagnostic logic utilizes information on drug therapy and clinical classification in order to select the appropriate output statement. When atrial fibrillation or flutter is present, the additional statement suggesting that ST and/or T wave changes may be related to rhythm is output

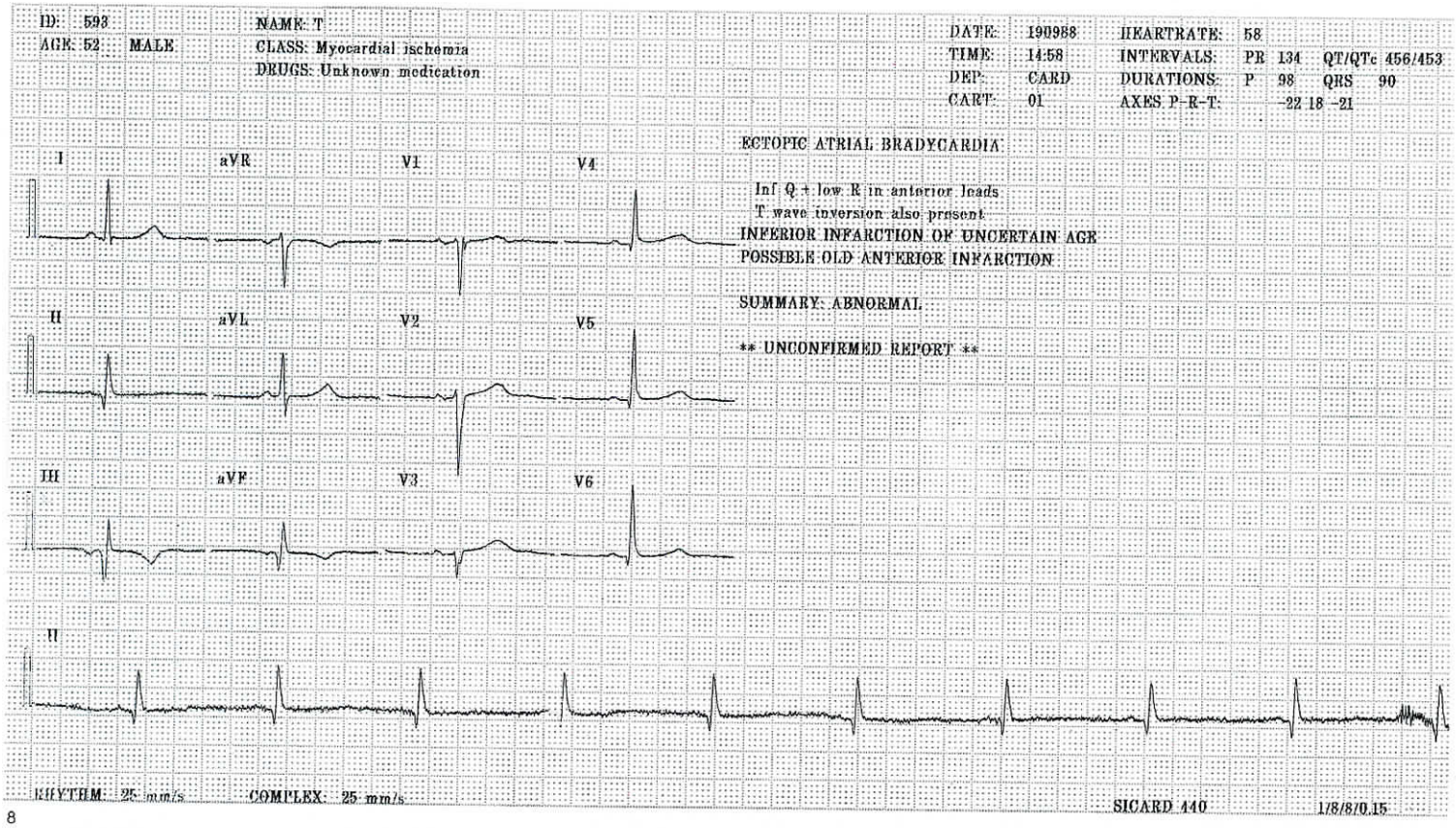


Fig. 8 An example of how the diagnostic logic is integrated to deal with infarction as a single group of statements, within which different ages and locations of infarcts are described. The ectopic atrial bradycardia is based on a P wave axis of −22° and a predominantly inverted P in aVF

together with the diagnostic statement itself. For example, in a case of a myocardial infarction the reasons normally indicate the presence of Q waves and ST elevation and/or T wave inversion while the diagnostic statement would provide the age and location of the infarction. An example is shown in Figure 8. The establishment of reasons and their selection for printout is also a complex part of the diagnostic logic. It is, however, felt that a significant advantage of the output is that the physician is made aware of why a particular diagnosis was made.

Serial changes

As mentioned above, the diagnostic program contains a facility for assessing serial changes. This is achieved by comparing the current ECG with up to three previously recorded ECGs from the same patient, namely, the first and the two most recent prior to the current ECG. Serial comparison can be undertaken on the central system or in the Sicard 440 or Sicard 740 ECG machine at the bedside assuming that the appropriate online link to the central computer is available. This is because the serial comparison logic is an integral part of the main diagnostic program which resides in the Sicard 440 and Sicard 740 and in the central system. Serial comparison is not undertaken by a separate program.

For each patient record, up to 140 bytes of information can be stored. This contains all the necessary data including rhythm statements, PQRST amplitudes of relevance, logical values indicating the presence or absence of Q waves, conduction defects etc. Individual bits of the computer word are used to compress the information in an optimum fashion. The overall structure of the serial change record is shown in Fig. 9.

Some sections of the program deal with comparison in a rather straightforward but obvious fashion. For example, if the rhythm has changed from atrial fibrillation to sinus rhythm, then the output statement would simply say that "sinus rhythm is now present".

Similar logic applies to conduction defects. On the other hand, in assessing STT changes, such as occur in myocar-

dial infarction, T wave amplitude is considered as is the more obvious change from upright to inverted T waves. Thus, if the first recording in a series shows acute myocardial infarction with ST elevation and upright T waves and the second recording shows T wave inversion in the same group of leads, the latter would be reported as "serial changes of myocardial infarction". On the other hand, if there were no changes between consecutive recordings the report would state "myocardial infarction as before". Conversely, if T wave changes are present in the first tracing but are absent in a subsequent tracing, the interpretation would indicate that there was regression of the abnormality.

The serial comparison logic has recently been extended so that on every occasion when one ECG is compared with an earlier ECG, the report gives some indication of whether or not there has been a significant change.

Discussion

The methods outlined above constitute a relatively unique approach for computer assisted reporting of electrocardiograms. The use of age, sex, race and clinical classification is extensive, much more so than in any other comparable program. It is well known that the cardiologist uses all these variables when interpreting an ECG and therefore, it is only correct that the computer approach should do likewise. Notwithstanding this, use of the clinical history and drug therapy is optional, because it appears to be desired in some hospitals that the computer interpretation should be made without a knowledge of clinical data. It is possible that the cardiologist reviewing the tracing then uses his own experience and knowledge of the patient to review the report and add an interpretation which the program might have made in the first place had the clinical data been utilized!

The use of reasons as illustrated in Figure 5 is also unique in some ways. While detailed criteria can be presented as an option, these so-called short reasons provide adequate guidance as to why an interpretation has been made. If for example, there were to be a rather bald statement of "consider the possibility of LVH" without any additional reason being specified, the less experienced physician might be in some doubt as to why such a report had been produced. It is therefore felt advisable that some guidelines are output and if a physician feels that the reasons are not substantial enough to justify the diagnosis then he can ignore the report, if he so chooses.

At the present time, the program is essentially an adult program. The author contends that unless an electrocardiograph operates at 500 samples per second there will be distortion of the pediatric and particularly neonatal waveforms to the extent that an interpretation could be erroneous. Already there have been reports in the literature of 30 % errors in amplitude measurements with electrocardiographs that use only 250 samples per second [27, 28]. For this reason, our Department has recorded ECGs on 1750 healthy neonates, infants and children in order to assess the normal limits as derived with appropriate equipment recording at 500 samples per second, where all leads have been recorded simultaneously. The six chest leads used have been V4R, V1, V2, V4, V5, V6 as is customary in subjects of this age range. The results from this study are now being incorporated into the program so that a pediatric capability will shortly be available.

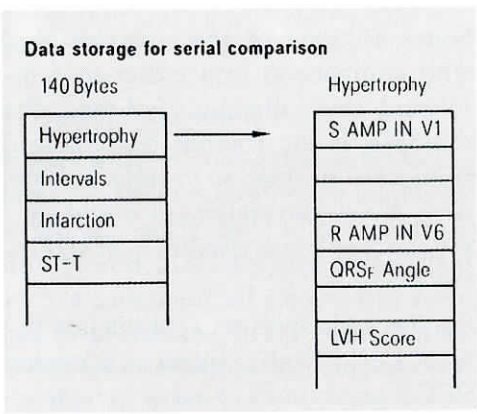
Facilities are also available to produce a Minnesota Code type output and these have already been tested on over 10,000 ECGs recorded in the "new" Whitehall Study of London Civil Servants.

Some of the features of the Sicard 440 and Sicard 740 electrocardiographs merit mention. For example, the Sicard 440 can have storage sufficient to allow sixty ECGs to be recorded and retained prior to onward transmission to a central computer system, if desired. This has considerable implications in drug studies for example where ECGs can be recorded in outlying Health Centers and then transmitted in one batch to a central system. Not only that, they can be retrieved for scrutiny at any time while they are still within the Sicard 440 memory. Likewise, the Sicard 740, for example, can also function as a computer terminal so that ECGs can be retrieved from the central system and displayed on the Sicard 740, if desired.

The output format of the ECG waveforms can be varied. On both the Sicard 440 and 740 it is possible to display the average beats at 25 or 50 mm/sec. with or without tick marks which indicate the various reference points, e.g. QRS onset, identified by the computer program. The sequence of leads can be the standard I, II, III, aVR, aVL, aVF, V1—V6 (Fig. 10) or the Cabrera format, viz. aVL, I, -aVR, II, aVF, III, V1—V6 (Fig. 11). On the Sicard 740 there is a further option that allows the so-called American format of display to be selected (Fig. 12). In this case, the average beats are replaced by 2.4 second strips of continuous recording. It may also be appropriate to note at this point that the English version of the diagnostic text is available in two versions — European and American! For example, American cardiologists prefer the term "Extensive Infarction" as opposed to the European "Widespread Infarction".

The Sicard 440 can also be combined with a separate exercise ECG analysis module with display screen but a discussion of the Sicard 440S (Fig. 1a) is beyond the scope of the present article.

Fig. 9 Part of the structure of the serial changes record which occupies 140 bytes per interpretation



9

This paper has made little of the features of the central Mingocare II system since essentially it has been a discussion of the analysis program. It should, however, be mentioned that the MicroVax based system provides the management facilities for the storage and retrieval of ECGs which are essential for serial comparison. In addition, there are over-reading facilities available on the central system which allow a cardiologist to adjust an interpretation if he so wishes and to add his own comments, if desired. The data base has facilities for searching for patients with a particular abnormality or to produce statistics on the number of times a particular statement has been printed or deleted by a reviewer. The whole program runs on the central system under the Ultrix (Unix) operating system which is becoming one of the most widely accepted operating systems in computing. Many other points could be added concerning the facilities on Mingocare II but these can be found elsewhere in the appropriate literature.

It is pleasing to record that a second Mingocare II system has recently been installed in the author's laboratory solely to cope with the needs of a large primary prevention trial involving a new cholesterol lowering agent. Up to thirty Sicard 440's will be used to record ECGs annually on over 6000 volunteers scattered throughout towns in the West of Scotland, around Glasgow. ECGs will be stored in the Sicard 440 and periodically (at least once a week) transmitted by telephone to Glasgow for storage and review. In addition, the

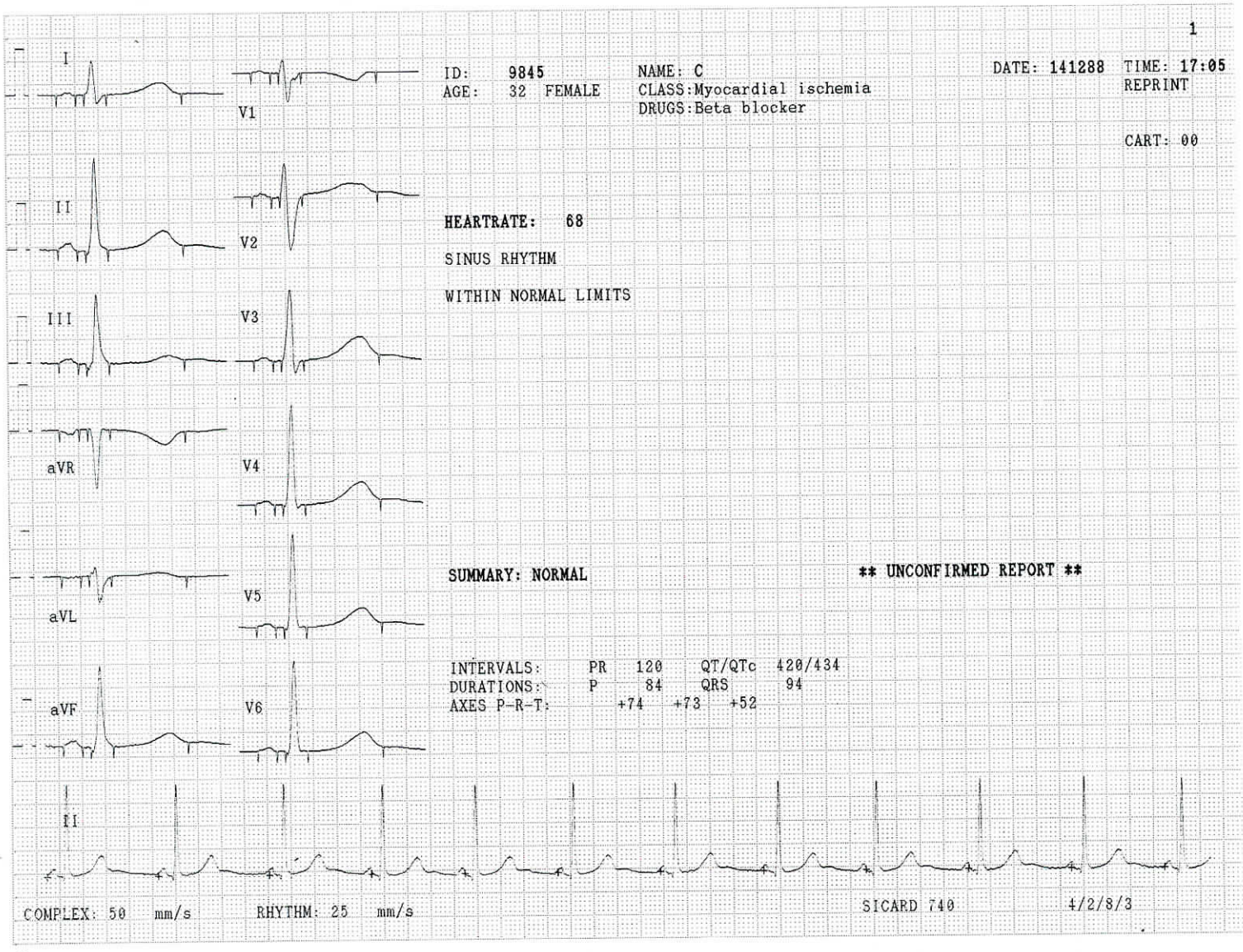
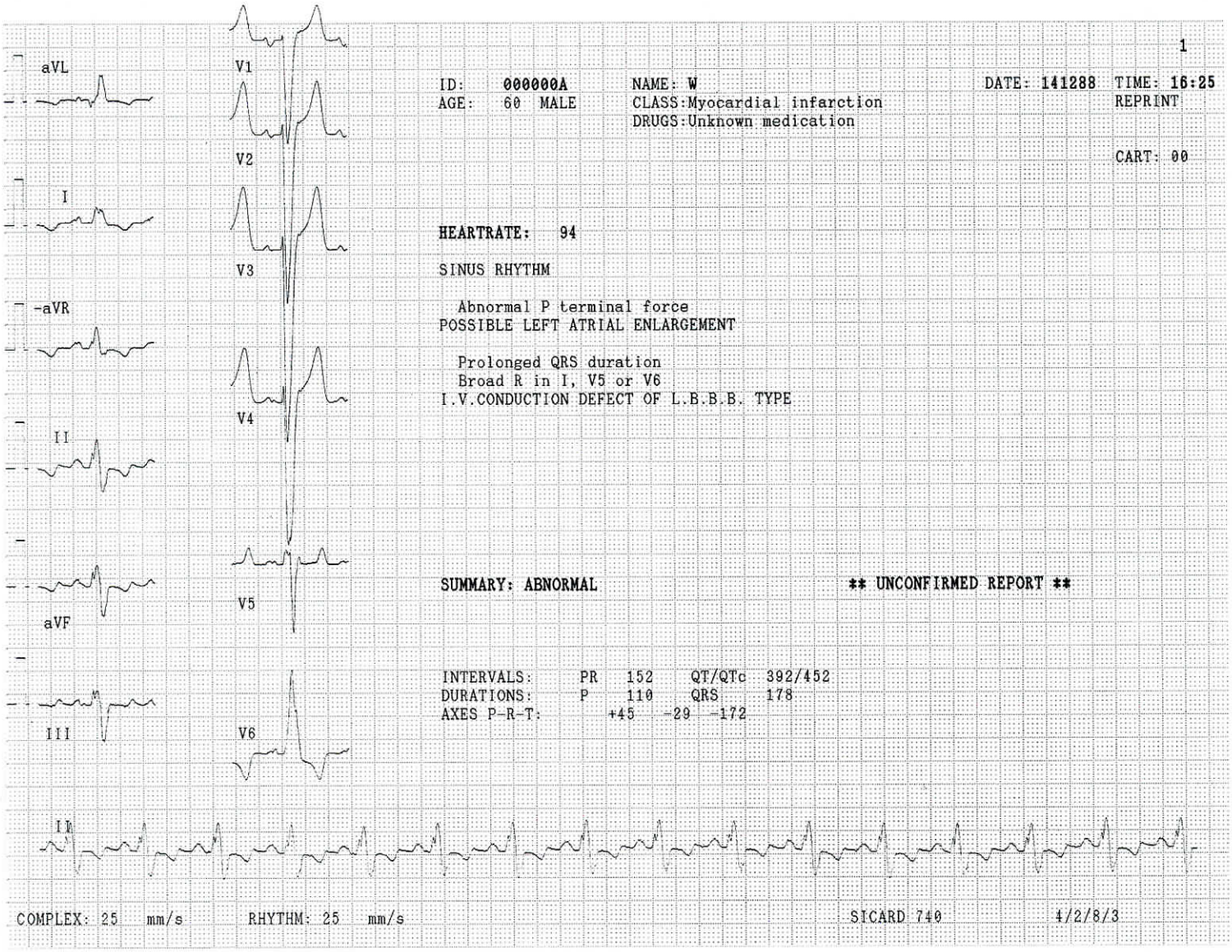


Fig. 10 An illustration of the "European" output format with 50 mm/sec average beats and tick marks indicating various computer derived reference points. The + signs (optional) in the rhythm strip indicate the beats selected for averaging

10



11

Minnesota Coding which is normally demanded in such large scale epidemiological trials will be undertaken centrally on the Mingocare system. Trial volunteers will be followed for five years after inclusion in the study and hence routines for serial comparison according to Minnesota Code rules are currently being developed. Data can be extracted from Mingocare files for transfer to other computers involved in collating all the clinical data from the trial.

The Glasgow Program on which the Siemens analysis has been based has been assessed in the European Project on Common Standards for Electrocardiography [29]. In a pilot study of 250 cases where various computer programs were assessed against the clinical diagnosis [30], the Glasgow Program had the highest total accuracy of all programs in the study [31]. Notwithstanding this, the program is under continuous development and many improvements and alterations have been incorporated since the time of that particular pilot study. One of the major advantages of a program which is developed in a clinical environment is the daily check on performance and the ability to expand the features continuously as further experience is gained. In addition, the capability of responding to comments from users in different countries has been amply demonstrated over previous years. While it is not the policy of Siemens to have different versions of the program for different countries,

Fig. 11 An example of the Cabrera format where leads in the frontal plane are displayed in the sequence aVL, I, -aVR, II, aVF, III. The average beats are written at 25 mm/sec but can be 50 mm/sec if desired

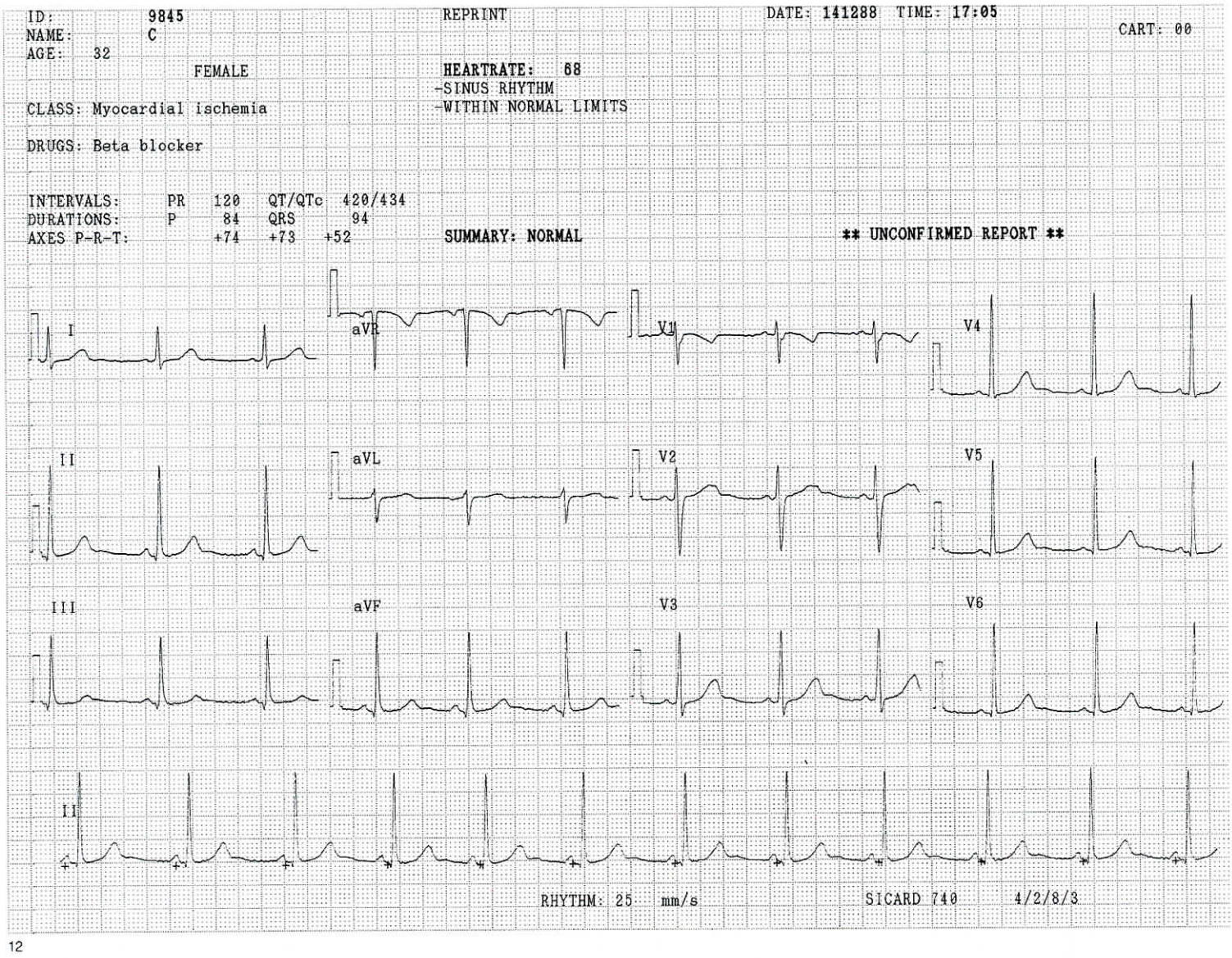


Fig. 12 This illustration shows the so-called American format where 2.4 seconds of each lead are favored instead of the average beats. This display can be contrasted with that of the same ECG in Fig. 10

although of course, the output of the program has already been translated into six different languages (while others are currently under consideration), it must be the case that the ECG program benefits from the experience of cardiologists in different schools. To this end, the program will undoubtedly continue to be expanded and enhanced in the coming years despite its high degree of accuracy at the present time.

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The author wishes to acknowledge the assistance of Mr. *J. Mertens* of Mortara Instruments, Inc. in the preparation of the section on QRS detection and typing.

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Order-No. A19100-M3112-E31-01-7600
Printed in the Federal Republic of Germany
55026 SD 11893.