A Method for Evaluating Computer Programs for Electrocardiographic Interpretation

II. Application to Version D of the PHS Program and the Mayo Clinic Program of 1968

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SUMMARY

A previously described method for evaluating computer programs for electrocardiographic (ECG) interpretation was applied to Version D of the Public Health Service (PHS) program and to the Mayo Clinic program of 1968. Staff cardiologists found agreement with the results of the PHS program in 45.5% of 1150 unselected tracings. Clinically significant disagreements based strictly on application of different criteria occurred in 29%, while disagreements based on program errors were found in 25.5%. The corresponding results for the Mayo Clinic program are: agreement in 47%, disagreements due to criteria differences in 30.9%, and disagreements due to program errors in 22.1%.

Both programs had serious deficiencies, particularly in the diagnostic categories of myocardial infarction and cardiac arrhythmias. PHS program errors resulted primarily from mismeasurements and deficient program logic, while Mayo Clinic program errors more frequently resulted from pattern recognition failures. Neither program appears suitable for routine clinical use at the present time.

Additional Indexing Words:

Computer Analysis

Clinical Applications

Research and Technology (cf. IBM program). As in that study, disagreement between readers and program were separated into criteria differences, program errors, and reader errors. A complete set of diagnostic criteria used by the PHS program was available. The available information on the Mayo Clinic program’s diagnostic criteria was incomplete. Hence when a disagreement between readers and the Mayo program was not clearly due to program error, the disagreement was catalogued in the results as a criteria difference. Therefore the true error rate for this program may exceed that which we were able to document.

Results

The results are expressed in bar graphs (fig. 1). The first pair of bars in each graph reflects the sensitivity of the programs relative to the readers and the last pair of bars is an indicator of the specificity of the programs relative to the readers. From these values for sensitivity and specificity two-by-two tables for our results can be constructed. The total number of cases for each table would be 1150, except in the instance of infarction where the total is 1180 due to the fact that more than one infarct statement can be made on a given tracing.

Left Ventricular Hypertrophy

The readers used the point score system of Romhilt and Estes for diagnosing LVH. The PHS criteria are
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based solely on the QRS voltages while the Mayo algorithm incorporates measurements from segments of the QRS and the ST-T waves in a complex fashion. All three systems have a weak and strong diagnostic category, but for purposes of constructing figure 1, the statements were merged into a single LVH positive category. In both programs, errors produced relatively few disagreements. Sensitivity with respect to the Romhilt-Estes criteria was: PHS, 77.5% (124/160) and Mayo, 64.4% (103/160) (see first pair of bars, figure 1). Specificity was: PHS, 80.2% (794/990) and Mayo, 92.8% (919/990) (see last pair of bars, figure 1).

Myocardial Infarction

The criteria used by the readers and by the programs are outlined in the Appendix at the end of this paper. Each system utilized three degrees of severity in its diagnostic language. With these criteria the readers made a total of 178 distinct infarct statements in 148 of the 1150 tracings. In constructing figure 2, these three degrees of severity were merged into a single, positive category. As one would expect in this difficult area, criteria differences were common. But more importantly, both programs made frequent errors especially in overcalling infarcts (third and fourth bars). The PHS program made 86 (34.8%) distinct infarct statements and the Mayo program made 90 (32.4%) statements which resulted from program errors. About half of the 86 PHS errors resulted from a mismeasurement of Q width, especially in leads II, III, and aVF. Others resulted from missing a small but definite R wave with the following S wave misread as a Q wave. This occurred in leads V1 and V2 as well as II, III, and aVF.

Most of the 90 Mayo program errors were attributable to premature marking of the QRS onset.

Sensitivity with respect to the readers was: PHS, 65.8% (117/178) and Mayo 56.2% (100/178) (fig. 2, see first pair of bars). Specificity was: PHS, 88.5% (885/1002) and Mayo, 83.8% (888/1002) (fig. 2, see last pair of bars).

Arrhythmias

The cardiac rhythm was readily apparent in all of the tracings studied except one which was excluded (fig. 3, 4). Differences between the readers and the programs with regard to distinguishing ventricular premature complexes from aberrant supraventricular complexes occurred very rarely and were catalogued as agreements. Thus criteria differences did not occur in this part of the data analysis. Therefore the bar graphs in figures 3 and 4 do not contain a segment for criteria differences, i.e., only the categories of agreement (bottom segment) and program error (top segment) are necessary.

The readers identified 242 tracings with rhythm disturbances. Atrial fibrillation and ventricular arrhythmias (mainly premature ventricular contrac-

![Figure 1](http://circ.ahajournals.org/)

Left Ventricular Hypertrophy. The number (N = ) written above the first pair of bars represents the total number of times the readers made the diagnostic statement listed. The numbers (N = ) over the middle pair of bars represent the total number of times the programs made the diagnostic statement in question. The number (N = ) over the third pair of bars represents the total number of tracings in which the readers did not make the diagnostic statement under consideration. Each bar is subdivided into three segments. The bottom segment indicates the percent of cases in which the readers were in agreement with the computer program. The middle segment indicates the percent of cases in which the readers and the computer program disagree due solely to the utilization of different diagnostic criteria. The top segment indicates the percentage of cases in which disagreements between the readers and computer program resulted from program errors, viz., pattern recognition failures, mismeasurements, and/or deficient program logic. Few program errors occurred in the diagnosis of LVH. The Romhilt-Estes criteria used by the readers are reportedly more specific than criteria based only on QRS voltage which have the same sensitivity. This may explain the percentage of criteria differences, in part.

![Figure 2](http://circ.ahajournals.org/)

Infarct. Many false positives resulted from a poor algorithm for detecting QRS onset.
Atrial Fibrillation. Accuracy shown above in detecting atrial fibrillation illustrates the difficulty in analyzing ECG rhythms by computer programs.

PVCs (PVC) accounted for 85% of these abnormalities and therefore these two categories were analyzed individually.

Atrial Fibrillation

Sensitivity to atrial fibrillation was: PHS 52.2% (88/159) and Mayo 76.6% (122/159) (fig. 3, see first part of bars). Specificity was: PHS 99.5% (986/991) and Mayo, 98.7% (978/991) (fig. 3, see last pair of bars).

Ventricular Arrhythmias

When the entire tracing including both the 12 leads and the Frank XYZ leads was reviewed, the readers identified 81 tracings with ventricular arrhythmias: 74 with PVCs, five with electronic pacemakers, and two with ventricular bigeminy (fig. 4). However, because the PHS program processes only the 12 standard leads and the Mayo program processes only the Frank XYZ leads, each program had a different number of opportunities to detect ventricular extrasystoles. Hence, 66 ventricular arrhythmias were found in the 12 leads and hence potentially identifiable by the PHS program whereas 50 ventricular arrhythmias were found in the XYZ leads and hence potentially identifiable by the Mayo program. Both programs correctly identified only one of the five electronic pacemaker rhythms. Furthermore the PHS program falsely labeled one tracing as having pacemaker rhythm. Fifty-nine tracings had one or more PVCs occurring in leads processed by the PHS program. Only 35 of these 59 were correctly identified. Thus the PHS program failed to recognize 45.4% of the ventricular arrhythmias. Furthermore, the PHS program made the diagnostic statement of ventricular arrhythmia in 66 (6.1%) tracings in which none were present (fig. 4, third bar).

The Mayo program also has serious deficiencies in recognizing ventricular arrhythmias. Of the 50 tracings which had ventricular arrhythmias in the XYZ leads, only 35 (70%) were properly identified. Conversely the program made the diagnosis of ventricular arrhythmia in 61 tracings. In 26 (42.6%) of these, no such abnormality was manifested (fig. 4, fourth bar).

First Degree Atrioventricular (A-V) Block

The PHS program selects only one beat in each lead for measuring the P-R interval, which renders it sensitive to mild baseline sway and low amplitude noise. It processes each of the 12 leads separately and prints out 12 values for the P-R interval which often vary widely. Except for the P wave amplitude, the program has no logic to tell which of the twelve values are more reliable. Therefore, to avoid overcalling first degree A-V block, the PHS program requires that the P-R interval must exceed 0.22 seconds in at least two leads. This threshold is not adjusted for cardiac rate. In a few cases with a long P-R interval (greater than 0.30 second) but with a P wave which was clearly distinct from the T wave due to bradycardia, the program apparently failed to search far enough back from the QRS complex to identify the P wave. As a consequence of these various problems, the PHS program failed to identify 29 (47.5%) of the 61 tracings with first degree A-V block (figure 5, first bar). Conversely, of the 50 in which the program made the diagnosis of first degree A-V block, 18 (36%) were in error (figure 5, third bar). As noted before, the Mayo program has serious difficulty in finding the onset of the QRS complex, often marking it prematurely. Thus its sensitivity relative to the readers in identifying first degree A-V block was only 39.4% (24/61).

Circulation, Volume 50, July 1974
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Specificity in first degree A-V block was: PHS, 98.3% (1071/1089) and Mayo, 99.5% (1082/1089) (see last pair of bars).

Second Degree Atrioventricular Block

There were eight cases of second degree A-V block. The PHS program has no algorithm for this abnormality and therefore identified none. Although the Mayo program has such an algorithm, it was never triggered by any tracing whatsoever.

Intraventricular Conduction Delay

Although criteria differences were common, program errors were relatively rare. Sensitivity with respect to the readers was: PHS, 67% (79/118) and Mayo, 73.8% (87/118) (see first pair of bars). Specificity was: PHS, 98.9% (1021/1032) and Mayo, 96.8% (999/1032) (see last pair of bars, fig. 6).

Axis Deviation

The PHS program uses only two of the six limb leads in determining the frontal plane axis. The QRS complex amplitudes are obtained from a single beat in each of the two leads, each of which is subject to independent noise effects and respiratory variation. The program errors due to this rather crude algorithm produced 13 false negatives (5.9%, first bar, fig. 7) and 17 false positives (7.7%, third bar).

The Mayo program determines axis from a single beat using simultaneous data recorded in the XYZ leads. As in several other diagnostic categories, early marking of the QRS onset resulted in 15 false calls of "left axis deviation from later forces" (9%, fourth bar).

Sensitivity with respect to the readers was: PHS, 84.1% (186/221) and Mayo, 57% (126/221). Specificity was: PHS, 96.3% (894/929) and Mayo, 95.6% (888/929).

Primary ST and T Wave Changes

Most disagreements in this area were based upon criteria differences only (fig. 8). Sensitivity with respect to the readers was: PHS, 62.2% (143/230) and Mayo, 72.6% (167/230). Specificity was: PHS, 95.8% (881/920) and Mayo, 93.1% (855/920).

Over-all Performance

In 524 tracings (45.5%), the readers and the PHS program were essentially in agreement, while diagnostic disagreements were registered in the remaining 626 (fig. 9, first bar). Detailed analysis

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Figure 5

First Degree Atrioventricular Block. Program errors in determining first degree A-V block result from inefficient algorithms to find P wave and QRS onset.

Figure 6

Intraventricular Conduction Delay. PHS program shows about three times as many errors as the Mayo program in the determination of intraventricular conduction delays.

Figure 7

Axis Deviation. The determination of axis is affected by the program's checks for consistency as well as its algorithm for detecting QRS onset.
Primary ST and T Wave Change. Most disagreements on primary ST and T wave changes are matters of criteria differences.

revealed that 333 of these disagreements were based upon the application of different diagnostic criteria (29%). In the remaining 293 tracings (25.5%), major diagnostic disagreements resulted from program errors, the nature of which has been described.

The corresponding results for the Mayo program are: agreement in 540 (47%), disagreement due to criteria differences in 355 (30.9%), and significant disagreements due to program errors in 255 (22.1%).

Discussion

PHS Program — Version D

It is evident from the data presented that Version D of the PHS program has a number of serious deficiencies which severely limit its usefulness.

Mismeasurements of Q wave width and failure to recognize small initial R waves commonly occur, resulting in erroneous infarct diagnoses (fig. 2). Arrhythmia diagnoses are very poor due primarily to deficient program logic and difficulty with P wave recognition. The program has no logic for distinguishing supraventricular from ventricular extrasystoles nor does it seek ventricular extrasystoles in the context of atrial fibrillation. It has no algorithm for more complex diagnoses such as second degree A-V block, atrioventricular dissociation, or accelerated atrioventricular conduction. A poor algorithm for P wave recognition resulted in false statements of "nodal rhythm" and "abnormal atrial focus" and was also responsible for failure to identify several cases of atrial fibrillation. Weaknesses in the algorithms for the diagnosis of first degree A-V block and axis deviation were also reflected by the number of errors in these categories. Additional mistakes are created by the algorithm for noise rejection; it frequently mistakes the F waves of coarse atrial fibrillation for noise and discards these leads along with all the pattern diagnoses contained in them (e.g., infarct, etc.).

Our results, showing agreement between the program and readers in 45.5% of the tracings, are quite similar to other previous reports. Even more favorable reports have noted diagnostic errors in 10-15% of the tracings reviewed. In summary, Version D of the PHS program appears to have little, if any, value as a routine clinical tool. More recently Version E of the PHS program has been released. Whether the deficiencies have been corrected in this newer version requires further study.

Mayo Clinic Program of 1968

The Mayo Clinic Program of 1968 also has severe limitations. Diagnostic disagreements due to program errors occurred in a minimum of 22.1% of the tracings in our series. A large majority of these errors arose from two poorly operating algorithms, namely, the algorithm for determining the onset and offset of the QRS complex, and the algorithm for locating the P wave.

The QRS algorithm was variable in its performance, even on different beats of the same tracing. As a result, the program printed out the statement "intermittent aberrant conduction" in 33 tracings in which no rhythm disturbance was apparent. By marking the QRS onset prematurely, numerous errors occurred in the diagnostic categories of myocardial infarction, first degree A-V block, accelerated A-V conduction (WPW), and axis deviation. In addition to these problems, difficulty in locating the P wave resulted in many false diagnoses of nodal rhythm, despite clearly apparent P waves in the XYZ leads.
Comparison of our results with those of previous reports on the Mayo Clinic program is difficult because none of these studies distinguished over-all agreement from agreement within specific categories and/or did not separate program errors from criteria differences.10-13

Aside from processing a different lead system, the Mayo Clinic program differs from the PHS and IBM in another, very important aspect. The measurements of the PHS and IBM programs are easy to check with the original tracing and the criteria for each diagnostic statement are printed out with that statement. Hence, it is possible for the human reader to perform quality checking and overview. In contrast, the measurements of the Mayo Clinic program — e.g., the direction of the first 30 millisecond QRS vector in three dimensional (XYZ) space — is not easily checked with the original tracing, even if plots of the QRS loop in frontal, sagittal, and horizontal planes are added. Furthermore, the diagnostic statements are not accompanied by the criteria that were used to make them. Therefore, the important function of human quality checking and overview is not practically feasible using the Mayo Clinic program.

In summary, because of the frequency of program errors and the difficulty of human overview, the Mayo Clinic program of 1968 cannot be recommended as a routine clinical tool.

References


Appendix

Semantic Equivalents:

1. Readers — Consistent with infarct
   IBM — Consistent with infarct
   PHS — Consistent with infarct
   Mayo — Abnormal depolarization probably from infarct
2. Readers — Possible infarct
   IBM — Possible infarct
   PHS — Possible infarct
   Mayo — Unusual early depolarization possibly from infarct
   — Unusual early depolarization suggest loss of ... forces
   — Depolarization abnormality with T abnormality suggests infarct
3. Readers — Remotely consider infarct
   IBM — Consider infarct
   PHS — Poor R progression
   — Decreasing R amplitude (precordial)
   — Consider infarct
   Mayo — Low anterior voltage
   — Prominent anterior voltage
   — Unusual early depolarization

Readers Criteria:

1. Consistent with infarct
   Presence of initial R in V1 with: abnormal Q (at least 0.03 sec duration) in V3 or V4 or V5 or progressive decrease in R in V4 or V5 with no abnormal Q in V3, V4, aVL, I, II, or III.
   Q5 (at least 0.03 sec) in V1 and absent Q in V5 and V6.
   Abnormal Q’s (at least 0.03 sec) in V6, V5, I, or aVL.
   Normal Q (0.03 sec or more) in I and aVL.
   Abnormal Q (0.04 sec or more) in aVF with Q/R amplitude ratio ≥1/4 or more.
   Slurred R greater than 0.04 sec with R/S ratio greater than 1 in V1 and no other reasons for right ventricular hypertrophy.
   Any type 2 QRS changes (see below) accompanied by compatible T wave change or elevated ST segment.

2. Possible infarct
   Poor R progression (less than 0.1 mV per lead) in V1 through V6.
   Any Q greater than 0.02 sec in V2 or V3 or V4.
   Type 3 QRS changes (see below) in precordial leads with compatible T wave change or elevated ST segment.
   Q duration greater than 0.025 sec with Q/R ratio greater than 1/3 in three of the following four leads: V5, V4, I, or aVL.
   Q duration greater than 0.03 sec in all leads: II, III, and aVF.
   Type 3 QRS changes (see below) in leads II, III, and aVF, accompanied by compatible T wave change or elevated ST segment.
3. Remotely consider infarct

Poor R progression (less than 0.1 mV per lead) across leads V₁ through V₄
Initial R in V₁, with any Q in V₂ or V₃, or V₄ when the R/S ratio is less than 1 in V₄
Q duration greater than 0.02 sec in all three leads (II, III, aVF) with Q/R ratio greater than ¾ in two of these leads.
Q duration greater than 0.03 sec with Q/R greater than ¾ in aVF.

IBM Criteria

Any lead I infarction requires a Q in aVF, at least as wide in I as well as following the criteria. Any lead aVF infarction needs a Q in I wider than 0.1 mV in lead I. Any lead II infarction requires Q at least as wide in lead III or aVF as in II. The only exceptions to these rules occur when there are compatible ST and T changes in inferior or lateral leads.

Type I. Consistent With . . . Infarction
Q/R amplitude ratio >⅓ or more plus Q duration 0.035 sec or more in any of the leads I, II, V₁⁺
QRS angle (frontal plane) less than 35 degrees plus Q duration 0.035 sec or more in lead II.
QRS angle more than 70 degrees plus Q duration 0.035 sec or more in lead I.
Q duration 0.04 sec or more in leads I, II, V₂⁺
QRS duration 0.05 sec or more in lead aVF plus Q duration more than 0.02 in lead II.
QS pattern when R wave is present in adjacent lead to the right on the chest leads V₄⁺ (if V₃ then R in V₃ must be than 0.07 mV).
QS pattern in all leads V₁⁺ or V₁⁻ or V₃⁺.
Any R in V₁ or V₂ plus QS in V₃, V₄, or V₅.

Type II. Possible . . . Infarction
Q/R amplitude ratio >⅓ or more plus Q duration between 0.025 and 0.035 sec in any of the leads I, II, V₁⁺
QRS angle less than 35 degrees plus Q duration between 0.025 and 0.035 sec in lead II.
QRS angle more than 70 degrees plus Q duration between 0.025 and 0.035 sec in lead I.
Q duration 0.05 sec or more plus R amplitude of 0.3 mV or more in lead aVF.
Q duration between 0.03 and 0.04 sec in any of leads II, V₂⁺
QRS duration at least 0.05 sec in lead III plus any Q in II if R less than 0.15 mV in lead III plus any Q having at least 0.1 mV amplitude and 0.02 sec duration in aVF plus (QRS angle less than 35 degrees or Q in lead III greater than 0.5 mV amplitude).
Q duration between 0.04 and 0.05 sec in lead aVF plus Q more than 0.02 sec in lead II.
QS pattern in all of leads V₁⁻.
R amplitude in precordial lead less than 0.15 mV and at least 0.15 mV smaller than either of the two rightward adjacent precordial leads (not valid if RVH or RBBB indicated).
Q duration 0.03 sec or more in V₂ with R amplitude than 0.2 mV.

Type III. Consistent With . . . Infarction
Q/R amplitude ratio between ¾ and ¾ plus Q duration between 0.025 and 0.035 sec in any of leads I, V₂⁺
QRS duration between 0.025 and 0.04 sec in lead I.
QS pattern in leads V₁ and V₂ (not valid if LVH or RVH indicated).
Q duration between 0.04 and 0.05 sec plus R amplitude of 0.3 mV or more in aVF.
Q duration between 0.04 and 0.05 sec in lead III plus any Q wave in lead II if R less than 0.15 in lead III plus any Q wave having at least 0.1 mV amplitude and 0.02 sec duration is lead aVF plus (QRS angle less than 35 degrees or Q in lead III greater than 0.5 mV).
If QS lead V₃ and initial R in V₄ less than 0.07 mV, say "CONSIDER ANTEROSEPTAL INFARCTION, CHECK TO BE SURE A QS DEFLECTION IS PRESENT IN V₃ (NO INITIAL R WAVE)."
If QRS in lead V₃ with S predominating with RS or QS in lead V₁, say, "CONSIDER ANTEROSEPTAL INFARCTION."

If any type Q abnormality is coupled with a T wave abnormality consistent with that location of infarction, the type is changed to one lower (i.e., Type II becomes Type I).
If right ventricular hypertrophy exists and the QRS axis is more than 110 degrees or more negative than −140 degrees, suppress Type II or Type III inferior infarction.
If inferior infarction exists and low QRS amplitude is in any frontal plane lead, say, "WARNING, INFARCTION STATEMENT BE INCORRECT BECAUSE OF MEASUREMENT ERROR. CHECK FOR SMALL R WAVES WHICH MAY HAVE BEEN MISSED BECAUSE OF LOW QRS AMPLITUDE IN FRONTAL PLANE LEAD."

If the infarction is present with T abnormality but no J elevation, add "AGE INDETERMINATE." In anterior infarction, if J is elevated more than 0.1 mV in two leads of V₅, add, "AGE INDETERMINANT, PROBABLY RECENT."
If the J point is elevated according to the criteria listed below, the statement, "INFARCTION PROBABLY ACUTE," is added to the statement representing the location of the elevation and the Type becomes one lower.

Criteria for J point elevation
Greater than 0.06 mV in two of three leads, II, III, and aVF with inferior infarction.
Greater than 0.15 mV in leads I and aVF.
Greater than 0.2 mV with T amplitude less than 1 mV in leads V₁⁺ or V₂⁺.
Greater than 0.5 mV with T amplitude more than 1 mV in leads V₁⁺ or V₂⁺.
Greater than 0.3 mV (with QRS change in same leads) in any of leads V₁⁻.

PHS Criteria

1. Consistent With . . . Infarction

1025 R absent in two leads, V₂⁻, V₃⁻.
1020 R amplitude 0.1 mV or less with T amplitude negative 0.1 mV or more in two leads V₅⁻.
1030 changes of 1010 (see below) accompanied in the same leads by STE (end) elevation of 0.08 mV or more and T amplitude is no higher than 0.05 mV above STE (end).
1013 Q/R greater than ¾ and Q duration at least 0.04 sec in one lead; plus Q/R greater than ¾ and Q duration at least 0.08 sec in another lead; plus peak-to-peak QRS voltage of at least 0.2 mV in both of these leads; in any two leads of V₅, V₆, I, and aVF.
1022 Changes of 1012 (see below) accompanied by T amplitude negative 0.1 mV or more in the same leads.
1014 Q/R greater than ¾ and Q duration 0.04 sec or more with peak-to-peak QRS voltage at least 0.2 mV in two leads of II, III, and aVF.
1021 Changes of 1011 (see below) accompanied by T amplitude negative 0.1 mV or more in two leads of II, III, and aVF.

2. Possible infarct

1010 R amplitude 0.1 mV or less in two leads V₂⁻.
1012 Q/R ratio greater than ¾ and Q duration at least 0.04 sec in
one lead; Q/R ratio greater than 1/4 or Q duration at least 0.03 sec in another lead; peak-to-peak QRS voltage at least 0.2 mV in both leads; from leads V2, V4, I, and aVL.

1011 Q/R ratio greater than 1/4 and Q duration at least 0.03 sec in one lead; Q/R ratio greater than 1/4 or Q duration at least 0.03 sec in another lead; peak-to-peak QRS voltage at least 0.2 mV in both leads; from leads II, III, and aVF.

Q duration 0.03 sec or more in all three leads, II, III, and aVF.

0301 R amplitude is 0.3 mV or more and exceeds both S and Q amplitudes and R duration is 0.04 sec or more in lead V1 with QRS axis between 76 and 269 degrees.

Decreasing R amplitude V1,2

1101 QS present in V2 or V3 with R present in V1 or V2.

Poor R progression in V leads

224 R amplitude 0.15 mV or less with peak-to-peak QRS voltage 0.2 mV or less (sic) in leads V2 and V3 or V4 or V6.

All diagnoses above are suppressed by left bundle branch block and dextrocardia. In addition, posterior infarct (0300 and 0301) is suppressed by complete right bundle branch block and intraventricular conduction defect of the left bundle type.

3. Consider infarct or fibrosis

1015 Q amplitude 0.07 mV or more with R present in lead V2 or V3 and Q absent in leads V4 or V6.
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Circulation. 1974;50:80-87
doi: 10.1161/01.CIR.50.1.80

Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

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