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Commentary

The Birth of Automatic ECG Screening by Digital Electronic Computer

Reflections on H.V. Pipberger et al.'s paper:
Automatic Screening of Normal and Abnormal Electrocardiograms by Means of a Digital Electronic Computer

Background

This commentary on the 1961 paper by Pipberger, Arms and Stallmann [1] is a reflection on a rather special period in the evolution of electrocardiography in relation to medical informatics. There was a tangible feeling of excitement on the arena staging these events in Washington, DC, 15 years after the end of the Second World War. Medical electronics had started to boom. There was the expectation of a new era - digital computers were going to revolutionize medical practice, electrocardiography in particular. There was excitement generated by the rivalry among the pioneers - who was going to be the first to process ECGs automatically by a digital computer? There were optimists, outnumbered by the skeptics - medical professionals in general resented the claims that the computer could take over any functions requiring their skills as diagnostic wizards.

Hubert Pipberger, the principal author of the paper we are examining, was one of the enthusiastic optimistic pioneers. Pipberger worked in a rather special environment in Washington. The Veterans Administration (VA) had chosen electrocardiography for a pilot study in automatic data processing. Pipberger held an appointment as a Contract Physician for Electrocardiographic Research at the VA Hospital. The circumstances at the VA were favorable for multicenter collaboration in the project within the extensive VA hospital network. Analog FM technology suitable for ECG recording was well developed since the war years. By the end of 1959, Pipberger's collaborating team had already collected ECGs of nearly 1,000 patients on FM tapes. The missing link necessary for digital computer processing was the analog-to-digital converter. The VA had contracted the National Bureau of Standards to construct an analog-to-digital conversion system for the pilot project. The Bureau also provided access to a digital magnetic tape recorder and an IBM 704 digital computer.

The Automatic Procedure

The 1950s were the "golden era" of vectorcardiography, and numerous so-called corrected orthogonal lead systems had been developed by researchers in electrocardiography. Pipberger had chosen Otto Schmitt's SVEC III for the pilot study, although he later switched to the Frank lead system for his ECG projects. The analog-to-digital conversion system at the National Bureau of Standards was capable of sampling three channel signals, with adequate time coherence which was a requirement for vectorcardiographic analysis of the orthogonal leads.

The primary objective of Pipberger's pilot study was to demonstrate the feasibility of screening of normal and abnormal ECGs, and he chose computation of the spatial ventricular gradient as the means for separating abnormal ECGs from normals. Determination of the spatial ventricular gradient was a rather simple procedure, requiring just an algorithm for numerical integration of the ECG amplitudes over one cardiac cycle. As the output, three numbers were printed, consisting of the polar coordinates of the ventricular gradient vector. Classification was performed by checking whether the values of these three variables were outside the 95% range of the values in the normal group, in which case the ECG was labeled as abnormal.

The hardware arrangement was

massive in size. The cabinets housing the electronics for the control unit and the analog and the digital recorders were each taller than a man standing, not to mention the size of the IBM 704 computer. This was still largely the era of the vacuum tube. Semiconductor circuits were emerging and the boom in medical electronics had produced transistorized preamplifiers, but their practical utility in electrocardiography had not yet been demonstrated. The frequency response of the analog recording system was flat from 0.1 Hz to 1,250 Hz and the sampling rate was 1,000 samples per second per channel (amplitude resolution is not mentioned). The overall arrangement can be considered as a high-fidelity system, even by the present-day standards, although the low frequency response of the preamplifiers (0.1 Hz) was too low for the precision integration required for computation of the ventricular gradient.

Results and Conclusions of the Authors

The study group consisted of 122 normals and 144 randomly chosen abnormals. In present-day's epidemiological terminology, the overall sensitivity in terms of correctly recognizing abnormal ECGs was 91% at 95% specificity, and the sensitivity in various abnormal subgroups ranged from 71% to 100%. The authors concluded that their automatic procedure separates normal and abnormal with a high degree of precision, and that the diagnostic accuracy of the automatic screening procedure is "at least as high as or higher than that of the conventional 12-lead ECG alone." In the Discussion, the authors emphasize that the procedure lends itself to large-scale epidemiological studies so that ECG processing can be trusted completely to technicians and automatic processing. The authors also suggest that the physician needs to read and interpret only those records which are classified as abnormal by the computer.

Pipberger's paper had flaws if judged in the light of present-day standards and knowledge. It reflects the enthusiasm of the authors, with overly optimistic interpretation of the study results. It is hard to see how the accuracy of the computer procedure could be considered "at least as high as or higher than that of the standard 12-lead ECG alone" because visual 12-lead criteria were used as the standard for selecting abnormalities. The proposition that the physician needs to validate only those ECGs classified as abnormal by the automatic procedure is hardly justifiable when nearly 30% of records with right-ventricular hypertrophy and nearly 20% with left-ventricular hypertrophy would be missed as false negatives.

The procedure itself required several steps with human intervention and it was not really automatic in comparison with present-day computerized electrocardiographs. The ECGs had to be recorded on analog tapes and the tapes transported for analog-to-digital conversion. The operator had to monitor and view several cardiac cycles on the oscilloscope screen to rule out ectopic complexes and artifacts and to trigger the analog-to-digital conversion and digital recording system into operation, in anticipation of the appearance of a stationary P-QRS-T complex. Finally, the digital tape had to be taken for processing by the digital computer, the output printed and used for classification. However, these are all minor details in comparison with the main aspects of the report, that automatic screening of ECGs by a digital computer was feasible.

The Impact of the Report

The report on the feasibility of automatic ECG screening by a digital computer was big news at the time of its publication in 1961. The system was also reported by Alan Berson from Pipberger's group at the 1961 International Conference on Medical Electronics in New York. At that same conference there was also a presentation from the group working under the direction of Cesar Caceres in Washington on an ECG wave measurement program written for an LGP-30 digital computer. Very few electrocardiographers those days had access to digital computers or would have even known what to do with them, had they had digital ECG records in their custody. Every step of progress in ECG processing reported was a novelty. Electrocardiographers even considered an earlier communication from Pipberger's group exciting, describing the analog-to-digital system which was presented at the Fall 1959 Scientific Sessions of the American Heart Association. An expanded version of that paper was readily accepted for publication by Circulation in 1960 [2]. Just the feasibility of numerical integration of ECGs to determine the components of the spatial ventricular gradient vector was considered an achievement. It was certainly appreciated by those investigators who had previously needed to resort to time-consuming cumbersome planimetric methods using hard-copy ECGs for this purpose.

The entry of digital computers into electrocardiography had a major impact on the evolution of electrocardiography in general. It signaled the end of the analog computing era in electrocardiographic research. In skilled hands, analog computers had performed remarkably well in producing all kinds of coordinate transformations, rotations, integrations, differentiations and fancy displays. Their main weakness was the relative complexity of operations, the lack of a convenient storage medium and unsuitability for mass processing. Pipberger's 1961 paper opened the door to the prospects of introducing more advanced concepts of medical informatics into electrocardiography. In short succession, advanced statistical concepts using likelihood ratio tests, non-linear probability density distributions and Bayesian-type multigroup classification algorithms developed in large well-documented groups of abnormalities emerged from the work of the VA group through the collaboration of Pipberger with Jerry Cornfield, a noted statistician. Regrettably, these more advanced concepts were largely ignored by other electrocardiographers.

The Concepts - Are They Still Valid?

Wilson's concept of the ventricular gradient from 1934 is an expression for the relative degree of concordance (polarity) of QRS and T waves, a notion almost as old as electrocardiography itself. Burger, a noted Dutch biophysicist, demonstrated by his elegant formulation of a mathematical model that the ventricular gradient was an expression of the spatial gradient of the action potential durations [3]. Hypothetically, the ventricular gradient vector would be zero if action potential durations were equal in all myocytes, and if all intracardiac and extracardiac factors modifying current flow and potential field in the torso remained stationary throughout the cardiac excitation - repolarization cycle (which is not the case). The ventricular gradient was traditionally expected to be independent of the spatial sequence of excitation. This would permit, in principle, separation of the primary from the secondary (those due to changes in excitation sequence) repolarization abnormalities. Pipberger's results imply two things: (1) That repolarization was abnormal in a large fraction of patients with old myocardial infarction and ventricular hypertrophies (i.e., there are primary repolarization abnormalities in these conditions), and (2) that the ventricular gradient deviates from normal in complete bundle branch blocks because the time course of excitation differs from the normal sequence, this means that the ventricular gradient is not independent of the spatial/temporal sequence of excitation.

Pipberger wisely refrained in his paper from using too many variables in relation to the sample size of the study population in his evaluation of classification accuracy, in the separation of abnormal ECGs from the normals. However, the sample size in Pipberger's initial study was definitely too small for stratification into abnormal categories for differential diagnosis. Also, there remained the need to demonstrate the stability of the results in an independent test group. Pipberger was well aware of this fact, and he was one of the first to emphasize the need to use ECG-independent data in the selection of study groups, except for conditions defined by the ECG itself (arrhythmias and conduction defects).

Pipberger was convinced that, in terms of their information content and reduction of redundant information, the orthogonal ECG leads were superior and in many aspects more suitable for computer analysis than the standard 12-lead ECGs. Caceres, the other early pioneer, had chosen an entirely different approach. His group had contracted Airborne Instruments Laboratory to construct a single-channel analog-to-digital converter for digitizing standard 12-lead ECGs. ECG wave recognition from single-channel signals turned out to be an exceedingly difficult task, which required an eight year effort by a large team and which at the end was not entirely successful. The use of three simultaneous orthogonal leads greatly facilitated the development of effective algorithms for ECG wave detection by the VA group and others. However, ECG programs using orthogonal leads did not gain widespread acceptance and in the years to come, the use of vectorcardiographic leads nearly disappeared from clinical electrocardiography. With the advent and more common use of multichannel recording and analog-to-digital conversion systems, the advantage of the orthogonal leads gradually vanished and the newer ECG programs with traditional deterministic logic for classification of the standard 12-lead ECG started to dominate electrocardiography.

References

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