ACTA MED PORT 3: 133, 1981

POLARCARDIOGRAPHIC ANALYSIS BY AUTOMATED DIGITAL MINICOMPUTER

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SUMMARY

Polarcardiographic criteria for myocardial infarction were established using an analogic computer and human readers. The sensitivity for revealing old myocardial infartion was found to be 37% greater than for ECG, with a false positive rate of less than 5%. The introduction of digital minicomputers, performing electronic measurements and vector analysis, allowed to process a daily large number of electrocardiologic tests as a routine clinical service (Woodward ECG Computer System). In the present study, the performance of the computer program in applying the polarcardiographic criteria for myocardial infarction was matched with that previously applied by human readers. Using the coronary-ventriculography as a golden standard, there were no significant differences in the specificity and the sensitivity was 51% for human readers versus 53% for the computer; when combined, both the computer and the cardiologist's overread, the sensitivity was increased to 61%. Using the new computer expanded diagnostic criteria, the sensitivity was 61%, and was raised to 67% with combined overreading. The sensitivities and the specificities obtained when the computer diagnosis and visual interpretations are combined, are those that apply to the Woodward ECG Computer System in daily use.

The use of polar coordinates to describe the heart vector goes back to Einthoven, whose electrical axis was the first of these coordinates to receive clinical application. More extensive application of polar coordinates had to await the development of computers, analog and digital. At first analog computers were used and many such special-purpose devices have been built in various parts of the world. The first was built in Germany and referred to in the literature in 1937, [1] although details were not given. The first clinically practical instrument, built in Vancouver, began its clinical trial in 1961. [2] The *polarcardiograms* it produced were continuous graphs of the polar coordinates of the heart vectors throughout the cardiac cycle for as many beats as desired. These polarcardiograms (PCGs) were so different from electrocardiograms (ECGs) and vectorcardiograms (VCGs) that entirely new diagnostic criteria had to be developed. Until these criteria were tested on an extensive series of patients the potential value of PCGs was unknown.

Tests on nearly 500 elderly men showed that five simple polarcardiographic (polar) criteria, applying to the QRS complex, indicate infarction that is often obscure in the ECG. [3] The sensitivity of the PCG for revealing old infartion was found to be 37 percent greater than that for the ECG, with a false positive rate, among nearly 200 normal young adults, of less than five percent. [4] Subsequent studies confirmed the value of these criteria and added others to them that broadened polar interpretation to include the various conditions recognized in the interpretation of the ECG. [5, 6] These studies included one of 254 hospital staff, among whom a correlation between age, smoking habits, and positive rate of polar criteria was demonstrated. [7] In another study of 1000 patients, [8] angiocardiography was used as a standard for forming two

Received: 2 January 1981

groups of patients — one assumed to have infarctions, the other not — as an independent basis for evaluating polar criteria for infartion. The sensitivity was 36 percent greater for the PCG than for the ECG, but the apparent specificity was eight percent lower.

The introduction of digital computer techniques to obtain PCGs was described by Yano and Pipberger in 1964. [9] In Vancouver, work with digital computation of PCGs began in 1970. A routine clinical service has been running since 1977, provided by the Woodward ECG Computer System. [10] The program which includes waveform detection, measurement, and analysis sections is based largely, upon polar coordinates of the heart vector. Until now, no report has been given of the performance of the program in applying the infarction criteria which had previously been applied by human readers.

METHODS

The test data for the present study were derived from the original analog tape recordings made for previously reported studies using visually interpreted analog data. [7, 8]

The xyz signals obtained from the Frank lead system were recorded on magnetic tape in analog form. The subjects were supine, the level of the chest electrodes was at the 4th interspace of the sternal border, and a chest protactor was used to locate the C electrode in the region of the left nipple. The recordings were transcribed, digitized, compressed, and prepared for transmission to the digital computers by a Totemite preprocessing station. [11] The number of beats transmitted varied from three to nine and was usually five or six. It depended upon the number contained in the buffer memory of the preprocessor, and this was dependent upon the heart rate and the amount of data compression — a function of the amount of baseline noise. Each of the beats received was analyzed and identified in the tables of measurement and diagnostic statements. Although the diagnostic statements tend to be similar for each of the beats, thereby providing an index of reproducibility, they are not always identical. An infarction may be detected in some beats but not in others. The greater the number of beats manifesting positive criteria for infarction, the stronger the diagnosis. For the purpose of this study, the computer diagnosis was considered to be positive for infarction when infartion was reported for two or more beats.

Three population samples were studied. The first sample comprised 254 subjects, believed to be healthy, who volunteered from a hospital staff. [7] The second and third samples were selected from a series of 1000 patients studied by angiocardiography, the second sample was composed of 255 patients who had 100% occlusion of at least one major coronary artery, and the fourth sample contained 79 subjects showing less than 50% occlusion, no dyskinesia or akinesia, normal hemodynamics, and with a ngative history of infarction. The 334 cases in samples three and four formed a subset of 436 cases previously studied; [7, 8] not all the original tape recordings were available.

THE CRITERIA

It would be beyond the scope of this paper to describe these in detail, but a few remarks will illustrate some of the considerations involved. The original criteria although explicit enough for visual interpretation of PCGs had to be more accurately defined before they could be incorporated in a program for analysis by digital computer. For example, the beta-downslope criterion, which for visual reading was stated as: β_{QRS} *has a downslope before* tm_{QRS} *reaches its maximum — initial downslopes terminating with*

β_{QRS} *greater than* $+ 75^o$ *are ignored,*[6] where β_{QRS} means the QRS complex in the beta tracing, i. e., the graph against time of the beta angle, which is the angle of the heart vector in the transverse, or horizontal, plane, and tm_{QRS} is the component of the tracing of the magnitude of the heart vectors in the transverse plane. Normally, the transverse VCG loop is inscribed in a counterclockwise direction; the choice of angular polarity is such that this results in an upsweeping beta tracing. Reversals in the direction of rotation are reflected as downslopes in β_{QRS}. Even quite small downslopes, corresponding to kinks or notches in the loop, may indicate infarction.

The perception of a downslope is visual; to translate this into computer language involves instructions that redefine what is meant by a downslope. To qualify as manifesting a downslope such that would satisfy a visual interpretation, β_{QRS} must show the equivalent of at least a five-degree change in the downward direction within a period of 5 ms. Flat segments of β_{QRS} occurring within a segment otherwise qualifying as a downslope are considered to be neutral. Very small upslopes may occur within a region considered to constitute a downslope; these are taken into account by a downslope counter that ensures that their effect is neutralized by other changes in β, before a downslope is defined.

In addition to the original polar criteria, a criterion has been added to improve the sensitivity of the program in the detection of cases showing significant Q waves in inferior leads of the ECG. This criterion is $\frac{QY}{MR} > .22$, where QY is the amplitude of the Q wave in the Y lead, of the Frank lead system, and MR is the spatial magnitude of the maximum QRS vector. The effect of MR in the denominator is to compensate for large Q waves occurring as a result of left ventricular hypertrophy. The cut point of .22 was determined from clinical cases and from 195 normal young adults from a university campus.

In applying the infarction criteria, it is obviously essential that conditions such as left bundle branch block, that can also give β_{QRS} downsolpes, etc., should be allowed for. The computer program, therefore, has to be virtually complete before its performance in detecting infarction can be assessed. During its three years of full clinical operation, approximately 50 000 cases have been processed and the outputs overread by cardiologists. A logic-trace device has been used to show the exact pathway leading to a given diagnostic statement, thereby permitting errors to be corrected. This debugging process has produced a program which is stable and suitable for the tests to be described.

Because the series of 195 normals was used in developing some of the cut points it is not valid to use them in the evaluation of the performance of the program. The data from the 254 hospital staff and the 334 patients studied by angiocardiography are acceptable, however, because they were not used in developing the program.

RESULTS

The age, sex, and smoking habits of the 254 hospital staff are given in Table 1 (the smoking habits of two of the subjects were not recorded).

The diagnosis of infarction by polar criteria applied visually to original analog recordings and applied by computer are shown in Tables 2 and 4. Table 2 shows the relationship with age, in which the subjects are separated into those under 40 years and those aged 40 and over. Visually, the criteria were found in 2 (2%) of the under-40 group, and compared with 22 (11.8%) of the 40-and-over group. The difference was significant. The computer criteria are less sensitive, they detected only seven cases

(3.7%), all in the older age group. Here age factor was not significant. Table 2 also shows the relationship of positive criteria with smoking habits. The visually-applied criteria were present in 18 (14.4%) of the smokers but only 6 (4.7%) of the nonsmokers. This was highly significant. Six of the seven cases found by the computer were smokers; this was significant. It is of interest to note the following details concerning the seven positive cases according to the computer-detected polar criteria for infarction. The computer found beta downslopes, i. e., evidence of anterior infarction, in four of the seven cases. Two of these were men, both over 60, whose ECGDs showed previous anterior or anteroseptal infarction, which was also visible in their VCGs. The two women were aged 44 and 53. In one, the ECGD showed a poor growth of r_{V2}. The VCGs of both showed anterior infarctions. In the three remaining cases, the computer found evidence of inferior infarction (sagittal magnitude returning to zero after an initial deflection, or a gamma downslope — where gamma is the angle in the sagittal plane). These were women aged 43, 47, and 57, all smokers. The ECGD of one showed atrial hypertrophy, the others were normal. However, the VCGs of two showed evidence of inferior infarction. This means that there was only one case in which the computer's findings were uncorroborated. If this is regarded as a false positive, the overall false positive rate is 0.4 percent.

Table 1

Hospital staff: age, sex, smoking

	Age group				
	20-29	30-39	40-49	50-59	≥60
males	6	12	35	50	14
females	30	19	32	43	13
	20-34	35-49	>49		
smokers	27	45	53		
nonsmokers	28	33	66		

Table 2

Hospital staff: polar criteria vs age and smoking

		cases with positive criteria	
age:	n	visually	by computer
under 40	67	2 (3%)	0
40 and over	187	22 (11.8%)	7 (3.7%)
		p = .02	p = .11
smokers	125	18 (14.4%)	6 (4.8%)
nonsmokers	172	6 (4.7%)	1 (0.8%)
		p = .01	p = .05

The age and sex distribution of the 255 patients studied by coronary angiography and found to have 100 percent occlusion of at least one major vessel, and for the 79 patients with less than 50 percent occlusion, normal hemodynamics, and negative history of infarction are given in Table 3.

Using the coronary angiograms as evidence of infarction, the cases have been placed in two-by-two contingency tables according to whether or not the computer criteria for infarction were present (Table 4). From this, sensitivity and specificity of the computer were determined as 53% and 99%, respectively. The table shows a corresponding contingency table for visual reading of the derived 12-lead electrocardiograms (ECGD), giving a sensitivity of 51% and specificity of 100%.

The computer and ECGD readings give similar sensitivities but their cases do not fully overlap. In fact, of the cases missed by the ECGD, the computer detected 20 percent. Consequently, combining, both (Table 4), a rise in sensitivity to 61 percent is obtained. This number applies to the system as it is now used in which visual and computer readings are combined.

Although they have not yet been implemented in the standard program, some new criteria have been developed. These give a sensitivity of 61 percent with a specificity of 99 percent (Table 4). When these are combined with a visual reading of the ECGD (Table 4), the sensitivity rises to 68 percent. of the 125 cases missed by the ECGD, the expanded criteria found 41, i. e., 33 percent more.

It is of interest to note that the single false positive case, according to the computer, was a 30-year old man whose angiograms were normal but whose ECGD shows very small Q waves in V2 and V3, although it was read as normal. Thus a focal infarction is a possibility. This is not entirely ruled out by the coronary findings, since some infarctions occur with apparently normal coronaries.

Table 3

Patients studied by coronary angiography: age and sex

	20-29	30-39	40-49	50-59	≥60
Less than 50% occlusion, normal hemodynamics, negative history:					
males	2	10	12	10	4
females	1	3	16	19	2
100% occlusion of at least one major vessel:					
males	2	12	86	79	41
females	—	—	9	23	5

Table 4

Angiography vs computer and visual ECGD

		Angiography		Sensitivity	Specificity
		MI	$\overline{MI}$	(%)	(%)
Computer	MI	135	1		
	$\overline{MI}$	120	78	53	99
visual ECGD	MI	130	0		
	$\overline{MI}$	125	79	51	100
Computer + ECGD	MI	155	1		
	$\overline{MI}$	100	78	61	99
Computer, expanded criteria	MI	156	1		
	$\overline{MI}$	99	78	61	99
Computer, expanded, + ECGD	MI	171	1		
	$\overline{MI}$	84	78	67	99

Totals 255 + 79 = 334

DISCUSSION

It is clear that the polar criteria as implemented in the computer program are somewhat more difficult to satisfy than the visual polar criteria developed from study of analog PCGs. This is a consequence of an effort, during program development, to make the criteria more stringent and, it was hoped, more specific. High specificity is important because of the way in which the computer is used. In the Woodward system, the computer is intended to function as a tool to aid the interpreter to reach a more accurate diagnosis than he otherwise might, but not to replace him. Normally, the interpreter reads the ECGD and looks at the computer's comments, to form a final interpretation. Not infrequently, the ECGD may fail to show the abnormality causing the computer to diagnose infarction. Usually on these occasions, the VCG will show it. Therefore, when it finds an infarction, the computer generates a VCG. Occasionally, however, even the VCG will not clearly show the tell-tale signs of infarction detected by the computer on the basis of polar criteria. In these cases, the interpreter can weight his interpretation accordingly and even call attention to the computer's statements. But he must feel reasonably confident that the computer is correct — hence the need for high specificity. The high specificity achieved has done much to enhance the acceptability of the computer. In the clinical application of the analog polarcardiograph, it was decided that a false-positive rate of up to five percent was acceptable because of the substancial increase in sensitivity that was obtained. This may be a good rate for a screen test but the impact of the computer's reporting an infarct in a normal young woman, for example, would have been so negative to the interpreters that a much lower false positive rate — or higher specificity — was sought. This has been achieved.

That a low false-positive rate has been achieved is apparent from the study of the 225 hospital staff, and the 79 patients considered to be infarction-negative on the basis of coronary angiography. Of course, angiography, like any other test, is not infallible. It is well known that previous infarction may sometimes be associated with normal-appearing coronaries. To illustrate the problem this may cause, let us assume that a perfect computer program has been devised that has a sensitivity and specificity of 100 percent. Being more sensitive than any other test, it would detect silent infartions not revealed by other means. In any evaluation based on other evidence these would appear as false positives. For this rason, a specificity somewhat less than 100 percent could be a consequence of good, rather than erroneous, performance. This was appreciated in earlier evaluation studies of polarcardiography. If the apparent-false-positive rate increased with risk factors for infarction, then the thesis that the cases detected were really true positives was, at least, tenable. This seems to apply to the independent risk factors of age and smoking habits of the hospital staff and the rate of positive cases according to the visually-applied infarction criteria. Thus it might well be that the visual polar criteria are more accurate than those applied by the computer. The computer results, unlike those obtained with visual readings, did not reveal a significant correlation with age, but this seems to be due to the small numbers involved. In fact, all seven positives were over the age of 40, but the under-40 group was not quite large enough to make this significant. The nonsmokers, however, were equal in number to the smokers, so that the finding of six positives among the latter, compared with only one among the former, was significant. Small adjustments could probably raise the sensitivity of the program if a lower specificity would be acceptable but, in the environment in which it is used, the specificity of the computer-found criteria seems to be about right.

It is of interest to note that the computer, using its programmed criteria, detects 20 percent of the cases of infarction missed from reading the ECDG. This is a valuable improvement. Apparently, though, it can be considerably improved — as the addition of three new criteria, in the expanded version of the program, shows. The computer can then detect 33 percent of cases missed from reading the ECGD.

Some comments regarding the visual reading of the ECGD are necessary for completeness. The validity of substituting the ECGD are necessary for completeness. The validity of substituting the ECGD for the ECG in this evaluation study rests upon the reported finding that a computer program — in the Telemed system —, designed to interpret the ECG actually performed better when interpreting the ECGD. [12] This finding was independently corroborated by Bruce et al in a similar study. [13] It has also been supported by experience in visually interpreting ECGs and ECGDs. When the ECG readings are substituted for the ECGD readings in the study, the computers performance is relatively even better. The ECGDs generated by the computer are of better quality than conventionally-obtained ECGs because of the use of certain enhancement techniques applied by the computer, viz., baseline straightening, selective filtering, [14] and because the effective response of our 300 Hz is much better than that of a direct hot-stylus electrocardiograph. Although using the ECGD interpretation rather than the interpretation of the ECG, may seem slightly unfair to the computer, it is of greater interest because it is the ECGD, not the ECG, that is seen when the computer statements are assessed or over-read. The sensitivities and specificities obtained when the computer diagnoses and visual interpretations are combined are, indeed, those that apply to the system in daily use.

RESUMO

O emprego de coordenadas esféricas ou polares para definir os vectores cardíacos vem desde Einthoven. Contudo, por razões técnicas, o desenvolvimento da Vectocardiografia foi baseado no emprego de coordenadas rectangulares ou cartesianas. O advento da utilização de computadores em electrocardiologia permitiu o desenvolvimento de uma metodologia de análise dos vectores cardíacos baseada em coordenadas polares (Polarcardiografia). Foram estabelecidos critérios diagnósticos de infarto do miocárdio segundo esta metodologia, usando um computador analógico e sendo os traçados interpretados por cardiologistas. A sensibilidade em relação a infartos do miocárdio cicatrizados foi 37% superior à do ECG clássico, com menos de 5% de falsos positivos. A introdução de minicomputadores digitais em substituição dos analógicos, com medições e análise de vectores feitos electronicamente, permitiu o processamento de grande número diariamente de exames electrocardiológicos (VCG, ECG Derivado dos sinais vectocardiográficos — ECGD, electrocardiograma ortogonal corrigido de Frank e gráficos de vectocardiografia tridimensional — polarcardiograma e esferocardiograma), como um serviço clínico de rotina, embora o habitualmente requesitado seja apenas o ECG. No presente estudo, é comparada a *performance* do programa diagnóstico do computador, baseado essencialmente nos critérios de diagnóstico polarcardiográfico de infarto do miocárdio, cam a dos cardiologistas que fizeram a leitura dos mesmos traçados. Usando a coronário-ventriculografia como teste por comparação, não foi encontrada diferença significativa nas especificidades, enquanto a sensibilidade foi de 51% para a leitura humana, contra 53% na leitura pelo computador; quando combinadas as duas leituras, a sensibilidade aumentou para 61%. Testando novos critérios diagnósticos para o computador, a sensibilidade melhorou para 61%, sem diminuição da especificidade; empregando estes novos critérios junto com a interpretação do cardiologista, a sensibilidade aumentou para 67%. As sensibilidades e especificidades obtidas com a combinação das interpretações dos traçados feitas pelo computador e pelo cardiologista, são as aplicadas na rotina diária do Woodward Computer System, de Vancouver.

REFERENCES

1. HOLLMANN W, HOLLMANN. HE: Neue elektrokardiographische Untersuchungsmethoden. *Z. Kreislaufforsch* 1937; 29: 465.
2. MOORE AD, HARDING P, and DOWER, GE: The Polarcardiograph. An analogue computer that provides spherical polar coordinates of the heart vector. *Am Heart J* 1962; 64: 382-391.
3. DOWER GE, HORN HE, and ZIEGLER WG: The Polarcardiograph: terminology and normal findings. *Am Heart J* 1965;.69: 369-381.
4. DOWER GE, and HORN HE: The Polarcardiogrph: further studies of normal subjects, refinement of criteria for infarction, and a report on autopsied cases. *Am Heart J* 1966; 72: 451-462.
5. DOWER GE: Polarcardiography. In: *Electrical Activity of the Heart,* edited by GW Manning and SP Ahuja, Charles C. Thomas, Springfield, Illinois, 1969, pp 215-253.
6. DOWER GE: *Polarcardiography.* Charles C. Thomas, Springfield, Illinois, 1971.
7. DOWER GE and OSBORNE JA: Polarcardiographic study of hospital staff — abnormalities found in smokers. *J Electrocardiol* 1972; 5: 273-280.
8. OSBORNE JA, and DOWER GE: Polarcardiographic criteria for infarction evaluated by angiocardiography. *J Electrocardiol* 1977; 10: 237-44.
9. YANO K, PIPBERGER HV: Spatial magnitude, orientation and velocity of the normal and abnormal QRS complex. *Circulation* 1964; 29: 107.
10. DOWER GE, OSBORNE JA, STEWART D, and SCHORTINGHUIS AC: A new system for ECG analysis oriented toward polarcardiography. In: *Computers in Cardiology,* Rotterdam, 1977.

11. STEWART D, SCHORTINGHUIS AC, and DOWER R. High-quality heart signals on standard telephone lines. In: *Proceedings of the Third International Conference on Computer Communication*, Toronto, August 1976, pp 189-190.
12. DOWER GE, and MACHADO BASTOS H: XYZ data interpreted by a 12-lead computer program using the derived electrocardiogram. *J Electrocardiol* 1979; 12: 249-261.
13. BRUCE RA, BELANGER L, and TRIMBLE S: Increased sensivity for Telemed diagnosis of myocardial infarction by use of 12-lead electrocardiogram derived from Frank XYZ leads. *Proceedings of the 1980 Engineering Foundation Conference: Computerized Interpretation of the ECG V*, Editors: Prior TA, Bailey JJ, May, 1980.
14. DOWER RG, and DOWER GE. Time-selective filtering for computerized electrocardiography. In: Computers in Cardiology, Geneva, Switzerland, 1979, pp 267-270.

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