DIGITAL PROCESSING OF PHONOCARDIOGRAMS: FIRST RESULTS

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SUMMARY

Phonocardiography is the recording of the heart sounds. In this paper, the authors propose a method for phonocardiograms automatic parameterisation. The results of an automatic typological study made on parameterised records are presented. The parameterisation method is based on the segmentation of the signals into intervals of several hundredths of a second and on the analysis of their frequency spectrum by Fast Fourier Transform. For the typological study, a method of factorial analysis is applied to two sets of patients afflicted with two heart diseases, different but similar with respect to their symptoms: aortic valvular stenosis and subaortic idiopathic stenosis. The typological analysis allows one to clearly distinguish between these two groups of diseases.

SOMMAIRE

La phonocardiographie est l'enregistrement des bruits et des souffles émis par le coeur. Dans cet article, les auteurs proposent une méthode automatique de paramétrisation du phonocardiogramme et présentent les résultats d'une étude typologique faite à partir d'enregistrements paramétrisés. Le principe de la méthode de paramétrisation des signaux repose sur leur segmentation en intervalles de temps de quelques centièmes de seconde et sur l'analyse de leur spectre de fréquence obtenue par transformation rapide de Fourier. Pour la typologie, une méthode d'analyse factorielle est appliquée; elle porte sur des malades atteints de deux cardiopathies différentes mais très voisines par leur symptomalogie: le retrécissement aortique et la cardiomyopathie obstructive. L'étude typologique permet de séparer nettement et de retrouver les deux catégories de maladies testées.

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INTRODUCTION

Phonocardiography is the recording of the heart sounds. These sounds are recorded on the thorax surface and are either normal or pathological (Py *et al.* (1972)).

In addition to clinical examination data, heart exploration currently uses the results of different external records. These analogical records are the electrocardiogram (ECG), the phonocardiogram (PCG) and two types of mecanograms: the

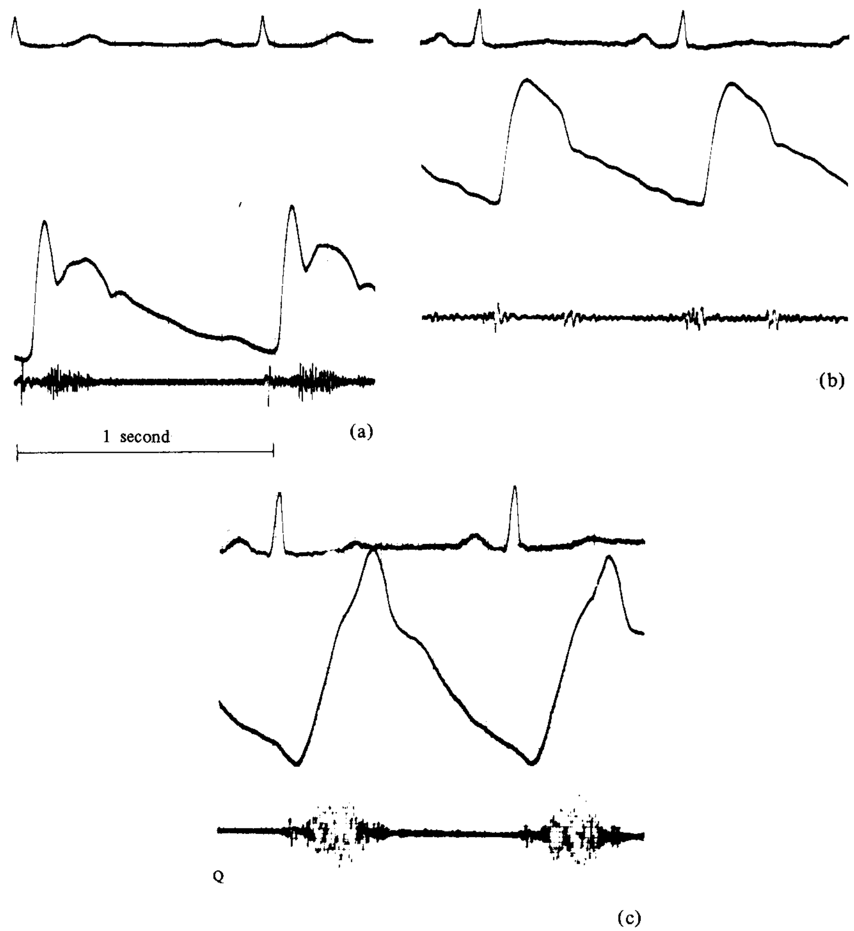

Fig. 1. Simultaneous records of the electrocardiogram, carotidogram and phonocardiogram: (a) patient affected with subaortic idiopathic stenosis (SAIS); (b) normal subject; (c) patient carrier of aortic valvular stenosis (AVS). During the AVS and SAIS the phonocardiogram shows a systolic murmur between the first and second heart sound.

apexogram and the carotidogram. These signals give varied information on electrical activity, noises and strokes of the apex of the heart, as well as on volumetric and pressure variations at the carotid level (Py *et al.*, 1972) (Fig. 1). These data help physicians in their daily diagnoses and therapeutic decisions, especially in surgery.

While the automatic interpretation of the ECG is now classical, an in-depth research on the PCG still remains to be carried out. Medical interest in this signal is, however, sure: it informs on heart hemodynamics and the functioning of the heart's vascular system; but the complexity of the signal makes its study quite intricate.

In the following, we describe one method of PCG parameterisation and the results of a typological study based on parameterised records of subjects afflicted with two different heart diseases causing similar symptoms: aortic valvular stenosis (AVS) and subaortic idiopathic stenosis (SAIS).

RECORDING AND ANALOGICAL/DIGITAL CONVERSION OF SIGNALS

Records are collected in the Cardiological Clinic* of Broussais Hospital in Paris. ECG, PCG and mecanograms are recorded simultaneously on a magnetic tape, in frequency modulation. The A/D conversion speed is 750 points/sec for the ECG and mecanograms and 3000 points/sec for the PCG. The recording lasts 2 to 3 min per patient and includes 4 signals: one ECG derivation (D2), one mecanogram (apexo or carotidogram) and the PCG recorded on two different places on the anterior face of the thorax. After the digital conversion, 1 sec of recording includes 7500 values, amounting to approximately 1,500,000 values for the total recording of a given patient. These numerical data, recorded on digital tape, constitute an extensive patient file.

DESCRIPTION OF THE SIGNALS PROCESSING SYSTEM

To process the numerical data, a system of programs, exploitable in conversational mode, was realised on a CII-90.80† computer at IRIA (Litwin, 1971; Litwin, 1973). This system consists of a set of modules which assure the following basic functions: (i) file management, (ii) spectral treatment, (iii) parameterisation and typology. The file management modules make it possible to locate relevant portions of recordings, to visualise their contents and label them, and, generally, to perform the usual file management operations.

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For signal spectral treatment one disposes of several modules which, according to their sequence, permit various calculations, such as frequency spectrum, inter-signal correlations, transfer functions, digital filtering, impulse responses, etc. All these calculations use the algorithms of Simple and Inverted Fast Fourier Transforms (Brigham and Morrow, 1967; Cooley and Tukey, 1965).

The functioning of some parameterisation and typology modules is illustrated in this paper by examples.

All these modules are independent but follow certain rules in common use of data. Each user can add his own modules to the system. Thanks to the conversational mode, he can vary the sequence of modules in many different ways, according to the problems met during the analysis of his signals.

PHONOCARDIOGRAM PARAMETERISATION

In the case of phonocardiogram parameterisation, one could have chosen criteria usually used by phonocardiographists. However, these criteria, based on the form and the localisation of sounds and murmurs in the heart cycle, are difficult to define precisely: they are more qualitative than quantitative and change with various laboratories. They therefore appear unsuitable for digital processing.

The method of parameterisation finally adopted is perfectly objective and quantitative: the parameters obtained are precisely defined and their number limited to a few dozen, which makes processing possible on a middle-sized computer. The principle of this method is based on the segmentation of signals and the analysis of their frequency spectrum by Fast Fourier Transform (Brigham and Morrow, 1967; Cooley and Tukey, 1965). While this methodology differs completely from the usual clinical procedures, it nevertheless takes the physiopathological features of phonocardiograms into account. One notes, in fact, that this signal, with a one-second periodicity, corresponds to a relatively slow sequence of heart phenomena: the opening and closing of heart valves, the injection or expulsion of blood through them, the muscular contractions which are the origin of sounds and murmurs and follow one another at some hundredths or tenths of a second during a cardiac revolution. It therefore seems sufficient to divide the signal into regular segments of some hundredths of a second and to simply parameterise each segment. We refer to this as 'the method of parameterisation by segmentation'.

Although the PCG is a periodical signal, one may observe, for a given patient, weak variations from one cardiac revolution to another. That is why each patient is characterised on an average by four portions of digitised records, called articles, each lasting 1·2 sec. One article approximately corresponds to one cardiac revolution.

With the PCG synchronised on cardiac electrical activity, the origin of segmentation corresponding in time to the beginning of QRS complex of the ECG (Fig. 1(c))

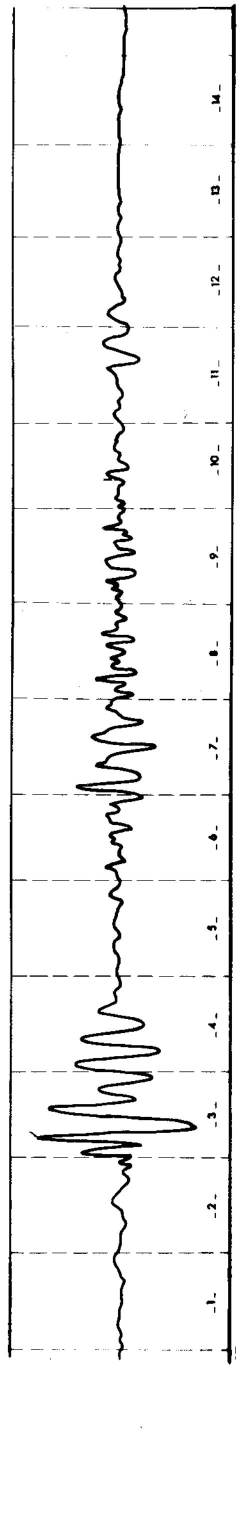

Fig. 2. Subaortic idiopathic stenosis phonocardiogram redrawn from the sample points. This record portion (14 segments of 47 m/sec) shows the first heart sound and the systolic murmur.

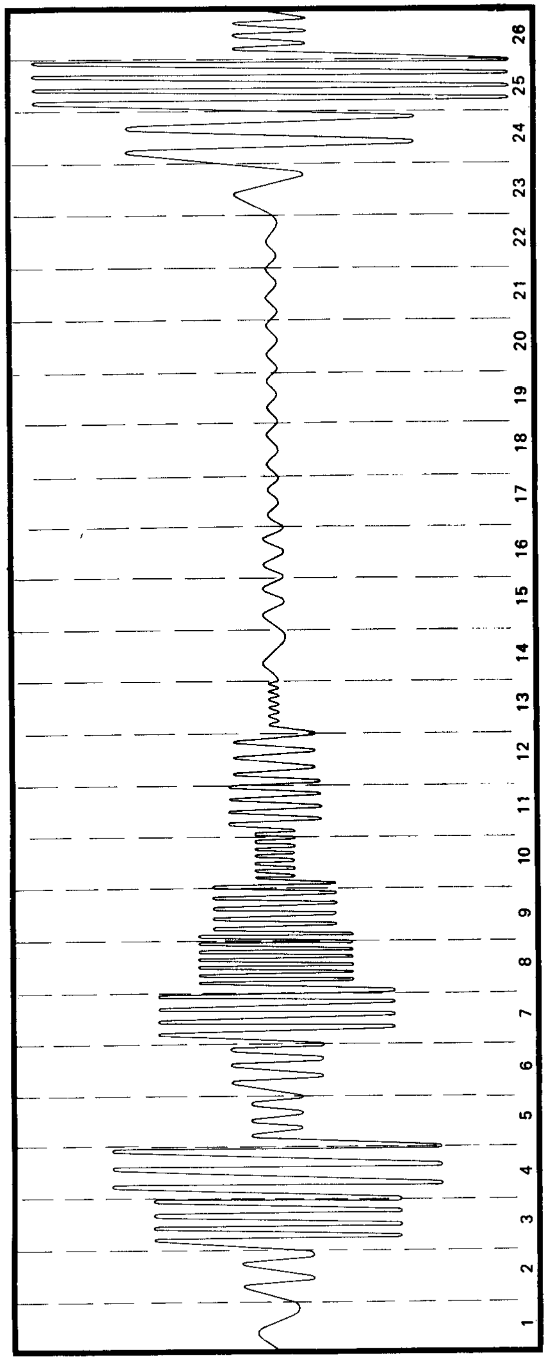

Fig. 3. Reconstruction of the phonocardiogram shown in Fig. 2, from parameters of Table 1.

TABLE 1

PHONOCARDIOGRAM PARAMETERISATION TABLE OF THE SAIS SHOWN IN FIG. 2. EACH SEGMENT IS CHARACTERISED BY TWO PARAMETERS: ONE AMPLITUDE AND ONE FREQUENCY (*v.g.* text)

Segment No.	*Amplitude*	*Frequency*
1	36·4	23·4
2	71·3	46·9
3	239·0	93·7
4	324·0	70·3
5	46·8	70·3
6	90·7	70·3
7	223·0	93·7
8	138·0	187·0
9	119·0	117·0
10	38·0	164·0
11	91·9	93·7
12	92·7	70·3
13	7·19	117·0
14	19·2	23·4
15	16·4	46·9
16	15·8	46·9
17	14·0	46·9
18	11·0	46·9
19	11·4	46·9
20	14·3	46·9
21	11·0	46·9
22	14·9	46·9
23	55·3	23·4
24	282·0	46·9
25	463·0	93·7
26	80·4	70·3

is chosen for each article. Thus, each article is divided into 26 successive segments of 0·047 sec, each one representing 128 sample points. A segment is characterised by two parameters: the highest amplitude of its frequency spectrum, obtained by the FFT, and the corresponding frequency (Fig. 2 and Table 1). From these 52 parameters, it is possible to reconstruct the corresponding signal (Figs. 2 and 3).

TYPOLOGICAL STUDY

A typological study has been made on the parameterised phonocardiograms of 17 patients. Ten patients were afflicted with aortic valvular stenosis (AVS) and the seven others with subaortic idiopathic stenosis (SAIS). Both diseases have a very similar acoustic symptomatology, consisting of a systolic ejection murmur, which makes their differential diagnosis difficult. During systole, *i.e.* during the blood expulsion from the left ventricle to the aorta across the aortic valve, in both diseases, a murmur is audible between the first and second heart sounds.

The systolic murmur is the sonic expression of a blockage of blood ejection from the ventricle towards the aorta. In AVS the blockage is permanent and due to

TABLE 2

TABLE OF CORRESPONDENCE BETWEEN PATIENTS AND PARAMETERS. EACH PATIENT IS CHARACTERISED BY AN AVERAGE OF FOUR ARTICLES. AN ARTICLE IS CHARACTERISED BY 26 SEGMENTS, GIVING 52 AMPLITUDES AND FREQUENCIES

			Segment (1)------		-Segment (l)-------		-Segment (26)	
			Ampl.	Freq.	Ampl.	Freq.	Ampl.	Freq.
Patients	Patient (1)	article (1)	$K_{1,1}$	$K_{1,2}$	$K_{1,2l-1}$	$K_{1,2l}$	$K_{1,51}$	$K_{1,52}$
		article (2)	$K_{2,1}$	$K_{2,2}$	$K_{2,2l-1}$	$K_{2,2l}$	$K_{2,51}$	$K_{2,52}$
		article (3)	$K_{3,1}$	$K_{3,2}$	$K_{3,2l-1}$	$K_{3,2l}$	$K_{3,51}$	$K_{3,52}$
		article (4)	$K_{4,1}$	$K_{4,2}$	$K_{4,2l-1}$	$K_{4,2l}$	$K_{4,51}$	$K_{4,52}$
		article (i)	$K_{i,1}$	$K_{i,2}$	$K_{i,2l-1}$	$K_{i,2l}$	$K_{i,51}$	$K_{i,52}$
		article (i′)	$K_{i',1}$	$K_{i',2}$	$K_{i',2l-1}$	$K_{i',2l}$	$K_{i',51}$	$K_{i',52}$
		article (65)	$K_{65,1}$	$K_{65,2}$	$K_{65,2l-1}$	$K_{65,2l}$	$K_{65,51}$	$K_{65,52}$
	Patient (17)	article (66)	$K_{66,1}$	$K_{66,2}$	$K_{66,2l-1}$	$K_{66,2l}$	$K_{66,51}$	$K_{66,52}$
		article (67)	$K_{67,1}$	$K_{67,2}$- -	-$K_{67,2l-1}$	$K_{67,2l}$- - -	-$K_{67,51}$	$K_{67,52}$

the joining together of the three cusps of the aortic valve; the systolic murmur remains throughout systole (Fig. 1). SAIS causes a non-permanent blockage: this is a muscular stenosis which takes place progressively during the left ventricular contraction. The start of blood ejection is normal and the blockage occurs only at a later stage of systole. The murmur is delayed during systole: a latent interval of varying length separates it from the end of the first sound (Fig. 1).

Each PCG being characterised by an average of 4 articles, the typological study bears on 67 articles, in a 52 dimensional parameter space (Table 2). The method followed J. P. Benzecri's correspondence factorial analysis (Benzecri, 1969). The purpose of this analysis is to research the principal inertia axes of articles set in parameter space, and to obtain a graphic representation of planes defined by these axes. By this representation, one may appreciate the proximities between individuals and recognise eventual groupings. Proximities are computed from χ^2 distance.

The table used for these calculations (Table 3) is obtained from the initial data table (Table 2), by substituting the observed values K_{ij} of the parameters P_j by the weights W_{ij} such as:

$$W_{ij} = \frac{K_{ij}}{K} \quad \text{with} \quad K = \sum_{j=1}^{52} \sum_{i=1}^{67} K_{ij}$$

The distance $d(A_i, A'_i)$ between two articles, A_i and A'_i, is given by:

$$d(A_i, A'_i) = \sum_{j=1}^{52} \frac{1}{W_{.j}} \left(\frac{W_{ij}}{W_{i.}} - \frac{W_{i'j}}{W_{i'.}} \right)^2$$

with:

$$A_i = (W_{i.1}, W_{i.2}, \ldots, W_{i.52})$$

$$A'_i = (W_{i'1}, W_{i'2}, \ldots, W_{i'52})$$

TABLE 3

TABLE OF THE W_{ij} WEIGHTS SERVING BASIS FOR PROXIMITY CALCULATIONS BETWEEN ARTICLES IN TERMS OF χ^2 DISTANCE

		Parameters				
		P_1	P_2	P_j	P_{52}	
Articles	A_1	$W_{1,1}$	$W_{1,2}$	$W_{1,j}$	$W_{1,52}$	$W_{1.}$
	A_2	$W_{2,1}$	$W_{2,2}$	$W_{2,j}$	$W_{2,52}$	$W_{2.}$
	A_i	$W_{i,1}$	$W_{i,2}$	$W_{i,j}$	$W_{i,52}$	$W_{i.}$
	$A_{i'}$	$W_{i'1}$	$W_{i',2}$	$W_{i'j}$	$W_{i',52}$	$W_{i'.}$
	A_{67}	$W_{67,1}$	$W_{67,2}$	$W_{67,j}$	$W_{67,52}$	$W_{67.}$
		$W_{.1}$	$W_{.2}$	$W_{.j}$	$W_{.52}$	

$$W_{i.} = \frac{1}{K} \sum_{j=1}^{52} K_{ij} = \sum_{j=1}^{52} W_{ij}$$

$$W_{.j} = \frac{1}{K} \sum_{i=1}^{67} K_{ij} = \sum_{i=1}^{67} W_{ij}$$

$W_{i.}$ and $W_{.j}$ are the marginal weights of lines and columns.

In our example, one may justify the use of the χ^2 distance, and show how the weightings by the $W_{i.}$ and the $W_{.j}$ in the calculation of $d(A_i, A_{i'})$ indicate that:

(i) If some parameters have very high observed values in relation to other parameters (amplitude of the first sound compared with murmur amplitude), the weightings by marginal weights $W_{.j}$ prevent these parameters from playing an excessive role in proximity evaluation;

(ii) if the parameter observation conditions vary according to individuals (sound deadening in the case of obese patients) weighting by marginal weights $W_{i.}$ attenuates the differences dissociated from the nature of diseases.

In our application, the 67 observations are distributed into two very distinct classes (Fig. 4). The AVS constitutes a relatively compact group, while the SAIS offers a much broader class. The five main axes extracted by factorial analysis account for 58 per cent of the total inertia.

DISCUSSION

In this paper, we present an original method of phonocardiogram parameterisation which, as far as we know, has allowed us to realise the first attempt of typological analysis of this signal. With only a few seconds of each patient's recordings, we have been able to divide patients into two distinct disease categories: AVS and

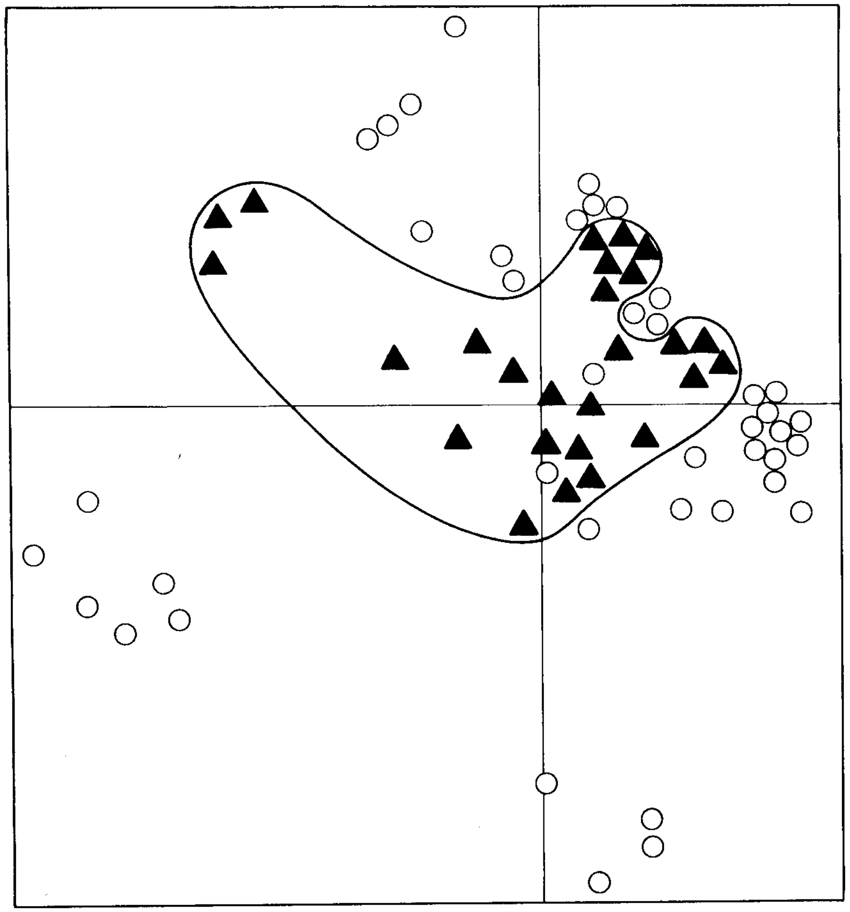

Fig. 4. Graphic representation given by the correspondence factorial analysis. The 67 observation of aortic valvular stenosis (AVS, ▲) and of subaortic idiopathic stenosis (SAIS, ○) are distributed into two distinct classes. The AVS constitute a compact group, while the SIAS are disposed in a much broader group. These findings agree with the anatomical and physiopathological characteristics of both diseases. The inertia percentage extracted by the two principal axes is of 34 per cent.

SAIS. A study of automatic classification will allow us to deepen this first work. At the present time, however, actual results show that the segmentation method is well adapted to PCG parameterisation, making it possible to extract useful and relevant data for numerical analysis.

The graphic representation of correspondence factorial analysis concurs perfectly with the anatomical, physiopathological and clinical characteristics of the two disorders under study. In SAIS, the PCG profile varies with individuals; this

undoubtedly explains why the class of patients suffering from that illness appears extensive.

On the contrary, patients with AVS constitute a compact group. The AVS is, indeed, a valvular disorder in which anatomical lesions are precise and relatively constant from one individual to another.

The division of patients into two distinct classes indicates the possibility of their computer discrimination. Furthermore, the initial results of discriminant analysis of these data, according to the Sebestyen method (Sebestyen, 1962), confirm this opinion (non-published results).

By associating PCG analysis with ECG, apexogram and carotidogram results, diagnosis of a great number of cardiac diseases becomes feasible, using only external records; in some cases, onecould thus avoidexplorations likecatheterisation which are costly and painful for patients.

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