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Full Length Research paper

An attempt to develop a novel systemic technique for the evaluation of cardiovascular system

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A limited number of noninvasive techniques are available for the study of the state of the circulatory system. In this paper, we introduce, for the first time, a systemic method that can be used to assess the function of the cardiovascular system as a whole by building templates (patterns) that characterize its different states. This novel method makes use of the information embedded in both, the ECG, which characterizes mainly the function of the heart, and the pulse waveform, which reflects the function of the blood vessels. The main idea here is to combine the two signals simultaneously in a way to get a two-dimensional plot or a vectorgram, which is called a vectorcardiovasculargram (VCVG), while the technique for obtaining it is the vectorcardiovasculargraphy. Since there is a lack in factual data in clinical situation, we have used Matlab techniques to simulate the ECG and pulse wave signals of normal and some pathologic cases and then to construct the vectorgram for them. In order to test this method, we have created additional vectorgrams by using some ECG signals and pulse waveforms taken from the directory of the BioBench software. The shapes of the vectorcardiovasculargrams obtained varied according to the structural and functional performance of the circulation system. This is why they can be used clinically for diagnosis of the pathological states and diseases of the cardiovascular system.

Key words: Cardiovascular system, cardiovascular diseases, diagnostic methods, vectorgram, vectorcardiovasculargraphy.

INTRODUCTION

Cardiovascular system is one of the most important systems of the living organism. The cardiovascular state has special impact on the life style (day-to-day activity) of the people. This physiological system may be affected by several pathological reasons/conditions, which deteriorate the efficiency of the system and cause many cardiovascular diseases. It is important to have reliable tools to recognize or diagnose these diseases so that cardiologists can provide the proper and quick treatment to the patients. Many methods are used for the assessment of the functional and morphological states of the cardiovascular system. Most of these methods elicit needed information from either the heart or blood vessels, mainly the arteries. Some of these methods are invasive, whereas others are considered noninvasive.

ECG, echocardiography, phonocardiography, and medical imaging techniques are used for the study of the heart. A fewer methods are used for the study of the vascular tree; amongst those methods, we consider the measurement of blood pressure, blood flow, sphygmography, and catheterization (Richard, 2004). The most common method depends on recording the ECG. The analysis of this signal can indicate any changes that occur in the function and structure of the heart. Such changes indicate the development of some diseases like cardiac infarction, left/right bundle branch block, different types of cardiac arrhythmias, degrees of heart block, myocardial ischemia, different types of PVCs, and so on (Bollmann et al., 2006; http://www.rmpd.org.uk/abstracts/cardiovascular_physics.htm; Hampton, 2008; Goldberger, 2006; Mary Boudreau Conover, 2004; Galen, 2001; Dubin, 2000).

Pulse-wave recording (sphygmography) provides a simple, repeatable, noninvasive mean of assessing the

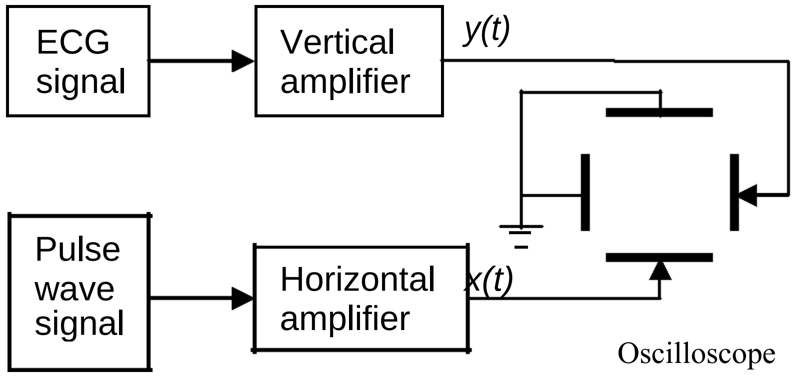

Figure 1. Vectorcardiovasculargraphy method.

vascular system (Jay et al., 1995). The information, which the pulse affords, is of great importance, although pulse wave analyses had limited uses in the past. Recently pulse-wave recording has been recognized as a technique that complements the conventional blood pressure measurements in studying the blood pressure in the main arteries that is used to calculate the strain on the heart and provide additional information on arterial stiffness and vascular tonality (Protogerou, et al., 2006). Many published scientific papers and clinical researches in these lines (Michael et al., 2001; Shunji et al., 1998; Millasseau et al., 2002) demonstrate clearly how the pathology of the blood vessels affects the condition of the heart. For example, the arterial stiffness or compliance, which associates with increased cardiovascular risk, has direct relation with the strain on the heart. This shows the profound need to have a systemic technique that can examine both the cardiac and vascular state simultaneously.

Existing methods such as imaging systems or catheterization are expensive and often require special arrangements, which underline the importance of developing a systemic device that is inexpensive, cost-effective, precise, simple, and does not require any special arrangements. To comply with these requirements and facilitate the clinical practice with a new diagnostic, early detection, and monitoring tool in the cardiovascular medicine, a method of vectorcardiovasculargraphy has been proposed. Practically, it can be implemented in any patient- or cardiac monitoring system and even in a stand-alone device.

VECTORCARDIOVASCULARGRAPHY METHOD

Vectorcardiovasculargraphy is a new method by which we intend to examine the operation and structure of the circulatory system in human body in order to determine the presence of a disease and predict its development. The main objective here was to construct a two-dimensional graph by simultaneously recording both the ECG and pulse wave signals in such a way that the first signal could be applied on the y-axis, while the other signal has been presented on the x-axis of an oscilloscope or a monitor as illustrated in Figure 1. The vectorgram obtained consists of many closed contours. It was found that the shape and number of these contours were specific for different states of the cardiovascular system, normal or pathologic. The main feature of this vectorgram was that it showed the variations of the ECG and pulse wave at once.

This observation allowed us to consider this figure as a systemic indicator of the cardiovascular system as a whole. In the present study, we have emphasized the changes in the ECG and pulse waveforms and showed how they are related to the physiological or pathological changes in the cardiovascular system. This would be accomplished based on simulated ECG and pulse waveforms built up using Matlab technique. We faced difficulties in performing actual recordings in a clinical setting which compelled us to restrict our work in this investigation to the simulation results and the standard signals stored in the BioBench software.

Mathematical modeling of the ECG and pulse wave signals

To generate the ECG, y(t), we have divided it into different successive parts, then each part was represented mathematically by a piecewise continuous function as follows:

$$y(t) = \begin{cases} 0, \ldots\ldots \text{for } 0.00 < t \le t_1 \\ A_1 \sin 2\pi f_1 (t - t_1), \ldots\ldots \text{for } t_1 < t \le t_2 \\ 0, \ldots\ldots \text{for } t_2 < t \le t_3 \\ S_1 (t - t_3), \ldots\ldots \text{for } t_3 < t \le t_4 \\ -0.06 + S_2 (t - t_4), \ldots\ldots \text{for } t_4 < t \le t_5 \\ 1 + S_3 (t - t_5), \ldots\ldots \text{for } t_5 < t \le t_6 \\ -0.3 + S_4 (t - t_6), \ldots\ldots \text{for } t_6 < t \le t_7 \\ 0, \ldots\ldots \text{for } t_7 < t \le t_8 \\ A_2 \sin 2\pi f_2 (t - t_8), \ldots\ldots \text{for } t_8 < t \le t_9 \\ A_3 \sin 2\pi f_3 (t - t_9), \ldots\ldots \text{for } t_9 < t \le t_{10} \\ 0, \ldots\ldots \text{for } t_{10} < t \le T \end{cases} \quad (1)$$

The value of the amplitudes A_i (mV), frequency f_i (Hz), slope S_j (mV/s), and time intervals t_k (s), stated in Expression (1), were

Table 1. The estimated values of the parameters of different parts of the simulated ECG signal.

A_1	0.1	t_1	0.08
A_2	0.2	t_2	0.175
A_3	0.2	t_3	0.25
f_1	5.25	t_4	0.27
f_2	3.0	t_5	0.30
f_3	2.8	t_6	0.32
S_1	-3	t_7	0.34
S_2	35.33	t_8	0.48
S_3	-65	t_9	0.56
S_4	15	t_{10}	0.66
		T	0.85

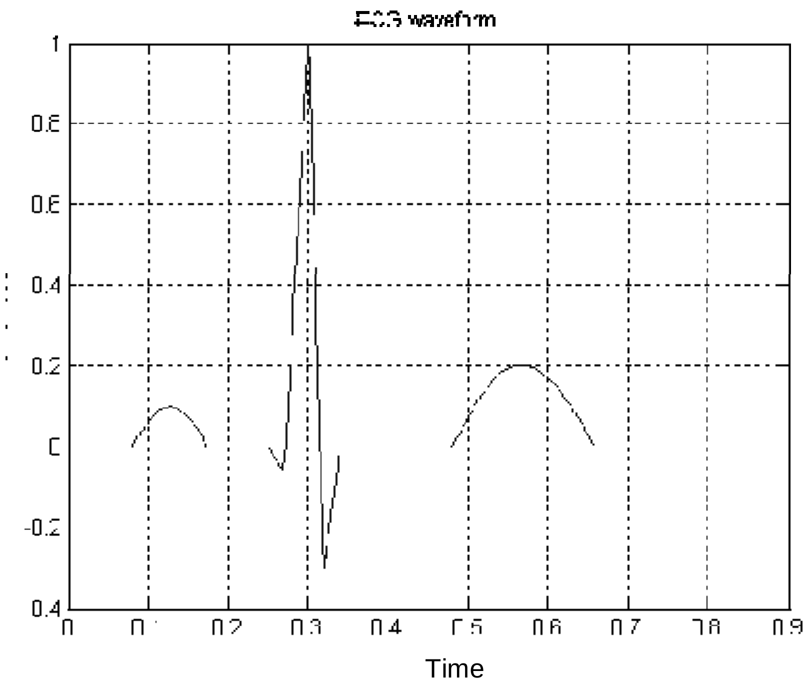

Figure 2. ECG plot by MATLAB for the data of Table 1.

measured from real ECG recordings for normal and some cardiovascular diseases. In this expression, the second, fourth, fifth, sixth, seventh, ninth, and tenth rows represent the P, Q, increasing R, decreasing R, S, increasing T, and decreasing T waves respectively. Table 1 includes those values for a person, who does not suffer from any cardiovascular disease. Figure 2 illustrates the normal ECG simulated for these values. Pulse wave was generated by presenting it by a number of piecewise continuous functions over the cardiac cycle period T. This would look like:

$$x(t) = \begin{cases} B_1 \exp[-h(t-0.00)], \ldots\ldots\ldots\ldots for\ 0.00 < t \le t_{11} \\ A_4 \sin 2\pi f_4 (t - t_{11}), \ldots\ldots\ldots\ldots for\ t_{11} < t \le t_{12} \\ S_5 (t - t_{12}) + B_2, \ldots\ldots\ldots\ldots for\ t_{12} < t \le t_{13} \\ B_3 \exp[-h(t - t_{13})], \ldots\ldots\ldots\ldots for\ t_{13} < t \le T \end{cases} \quad (2)$$

The values of the pulse's scaled maximal amplitude A_4 (mmHg), the pressure pulse scaled values at the start of the cardiac cycle B_1 (mmHg), at the beginning of the dicrotic notch B_2 (mmHg), at the end of it B_3 (mmHg), the time constant h (s^{-1}), the slope S_5 (mmHg/s), f_4 (Hz), and the time intervals t_i (s) are calculated empirically for normal and some pathological cases. The values and graph corresponding to the normal state are shown in Table 2 and Figure 3 respectively.

SIMULATION AND RESULTS

After generating the ECG and pulse wave signals, their vector curve has been constructed. For that purpose, we have used the code that have been built by Matlab and

Table 2. The estimated values of the parameters of different parts of the simulated pulse wave signal.

A_4	B_1	B_2	B_3	h	S_5	f_4
1	0.2	0.57	0.66	6.1	2.0	1.5
t_{11}	t_{12}	t_{13}	T			
0.34	0.605	0.65	0.85			

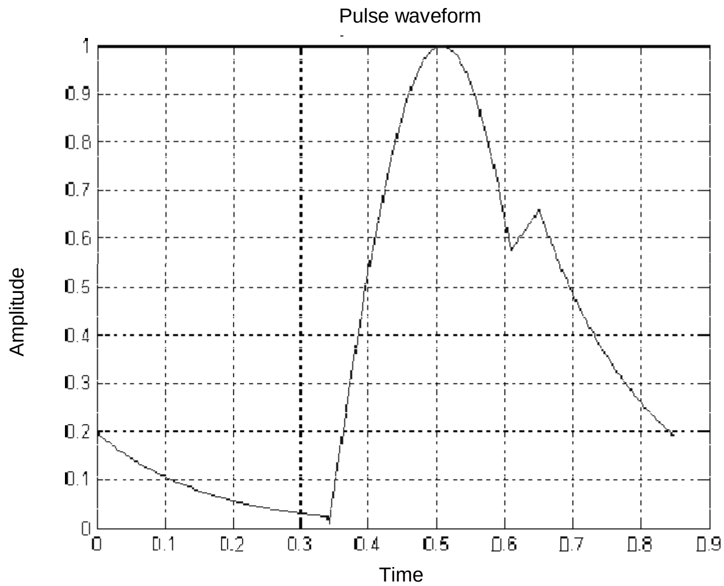

Figure 3. Pulse wave plot by MATLAB for the data of Table 2.

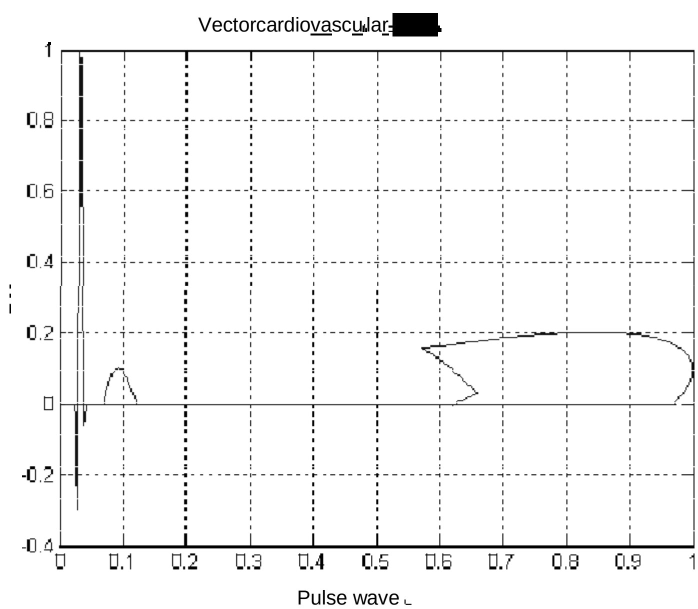

Figure 4. VCVG pattern for a normal person.

then executed it as an x-y plot, which helped in obtaining a vectorcardiovasculargram shown in Figure 4.

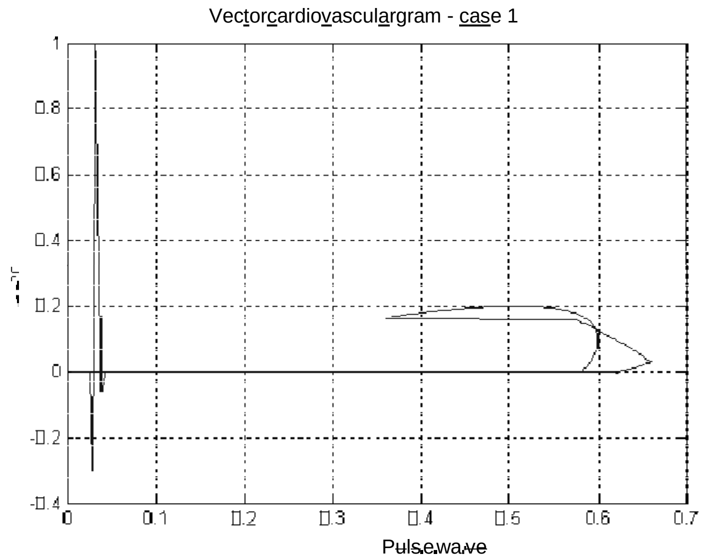

Figure 5. VCVG pattern for a patient with mitral stenosis and low pressure.

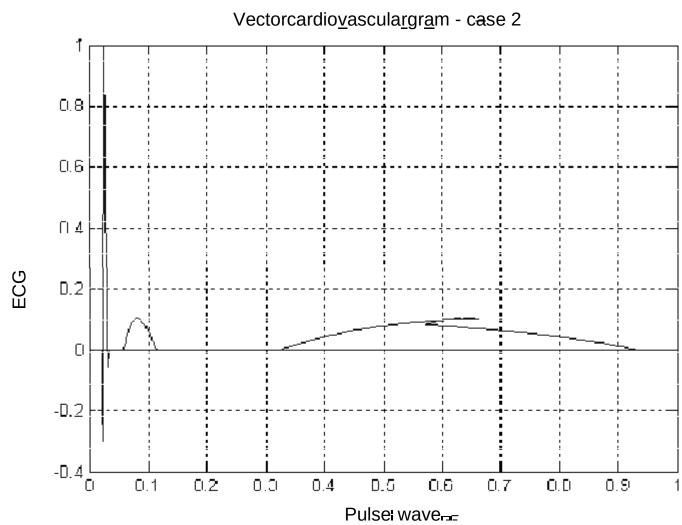

Figure 6. VCVG pattern for a patient with inferior infarction and delayed pulse.

Diagnostic merit of the method

It is essential to develop simple, affordable, cheap, and sensitive methods to test the cardiovascular system and diagnose its condition. Our proposed method is capable of satisfying these requirements. The method is simple and all what it needs is to record the ECG and the arterial pulse wave from the patient and to apply them to any two-dimensional graphical display, the role of which can be played by any patient monitor traditionally available in all hospitals. The equipment needed to perform recording of the VCVG have minimal cost.

The sensitivity of the method is manifested by the significant change in the shape of the VCVG, which would be seen clearly when we make any subtle change in either the ECG or the pulse wave signal. This gives the diagnostic power of the method. In order to confirm this fact, we have changed the parameters in Table 1 and 2 and plotted the vectorgrams for the following pathological cases of the cardiovascular system:

Case 1: Mitral stenosis low pressure VCVG (Figure 5), which is medically characterized by the absence of P wave in the ECG and low amplitude in pulse wave.

Case 2: Inferior infarction delayed VCVG (Figure 6), which is characterized by prolonged ST segment and low

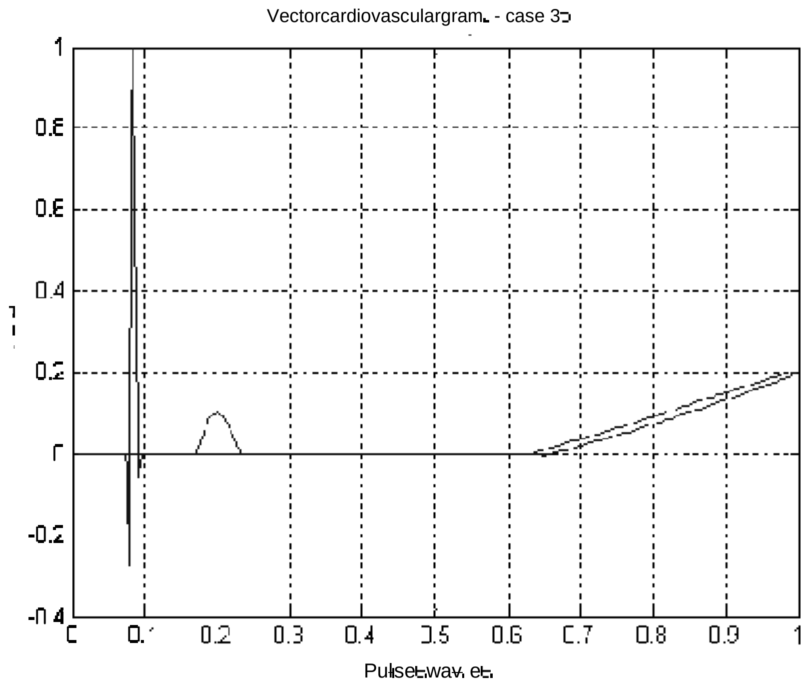

Figure 7. VCVG pattern for a patient with atrioventricular block.

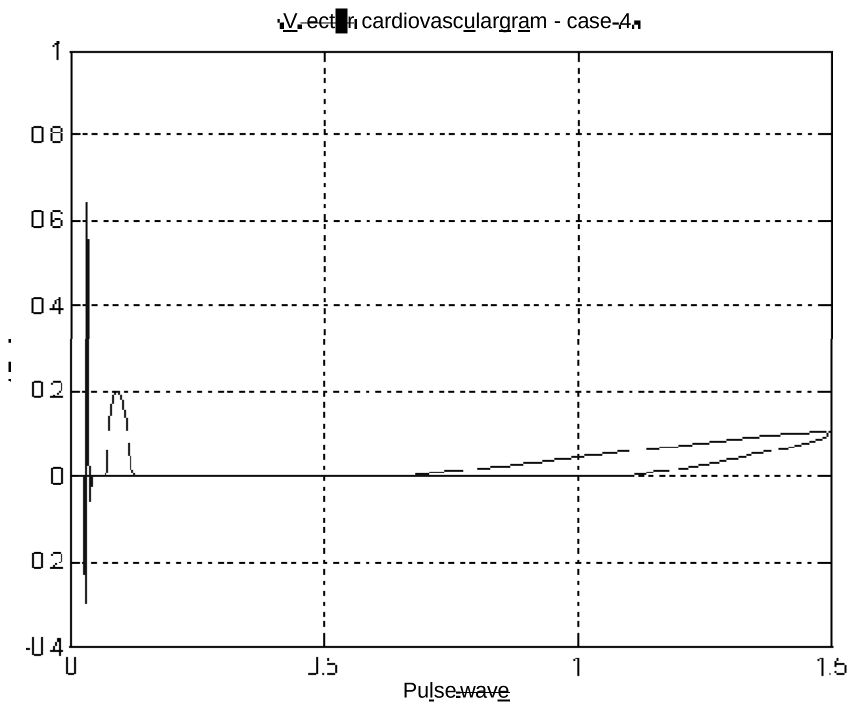

Figure 8. VCVG pattern for a patient with atrial hypertrophy and high pressure.

T wave in the ECG and delayed start of the pulse wave.
Case 3: Atrioventricular block VCVG (Figure 7), which reflects an ECG with prolonged PR interval and slow decaying catacrotic part of the pulse wave.
Case 4: Atrial hypertrophy-high pressure VCVG (Figure 8), in which the ECG has high P and low T waves and the

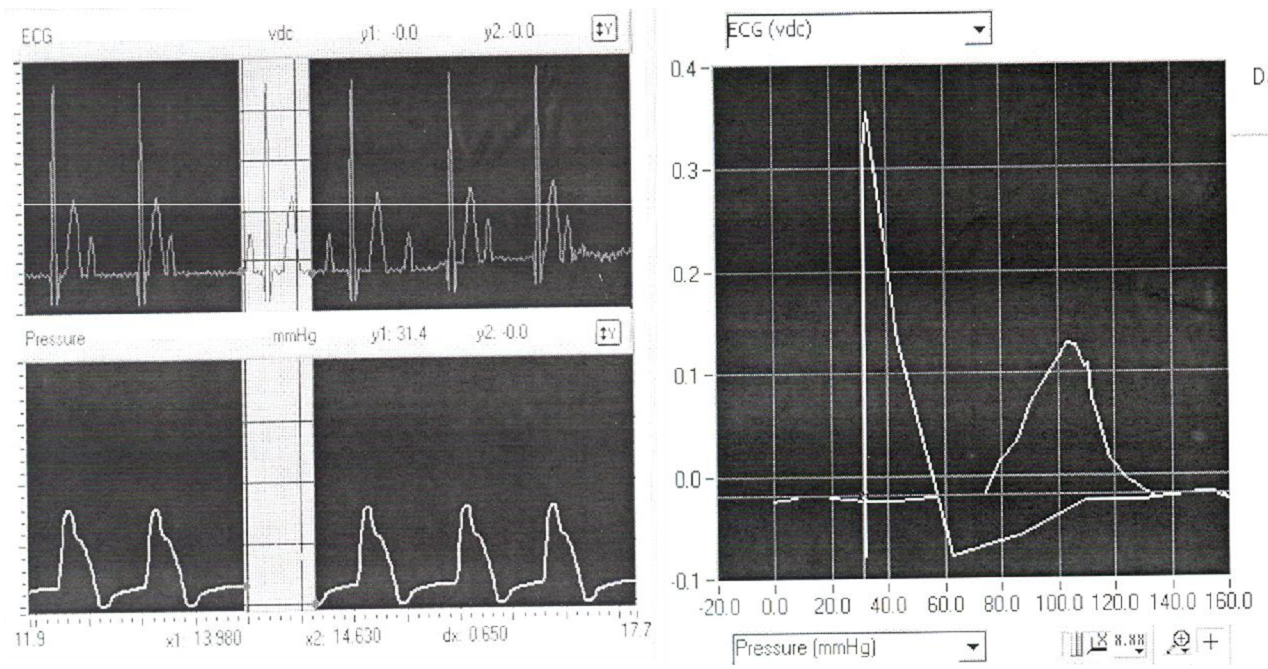

Figure 9. a) ECG signal, b) pulse wave signal taken from the BioBench directory for the 2nd degree AV block, and c) obtained VCVG.

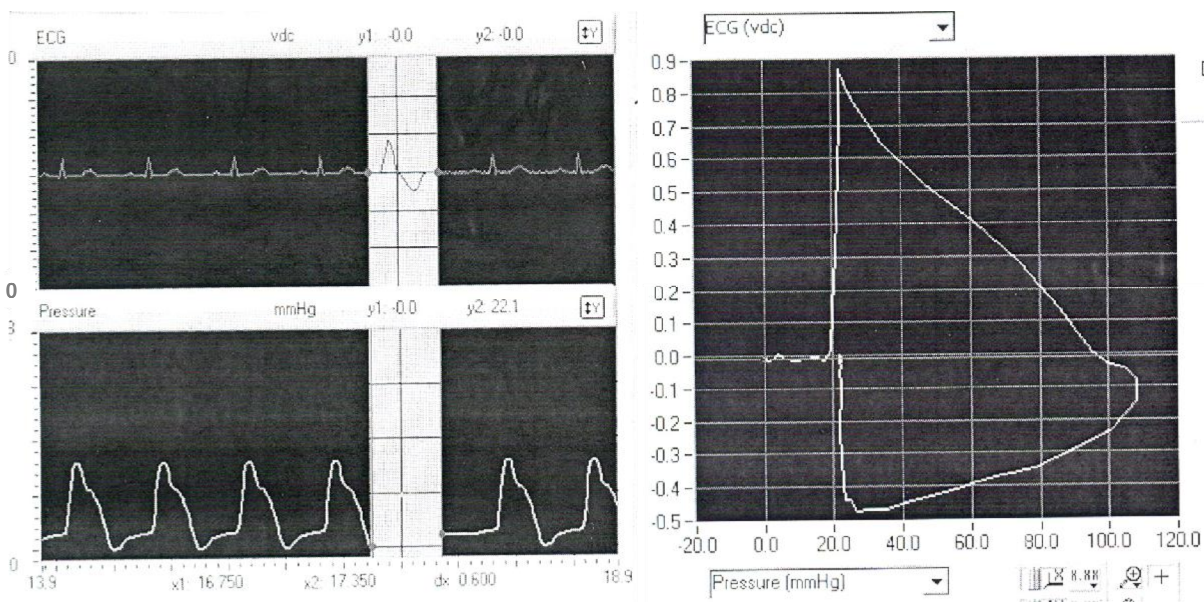

Figure 10. a) ECG signal, b) pulse wave signal taken from the BioBench directory for the Multiform PVC, and c) obtained VCVG.

pulse wave of high-amplitude.

Testing the method by BioBench software

BioBench software includes a directory in which many of biosignals are stored as examples. We have used examples of the ECG and artery pulse wave signals that characterize some other cardiovascular diseases such as the 2nd degree AV block, multiform PVC, and frequent PVC (Bigeminy). Figures 9 to 11 shows the ECG signals (a), the pulse wave signals (b), and the VCVG (c) of these cases. These figures clearly illustrate how the

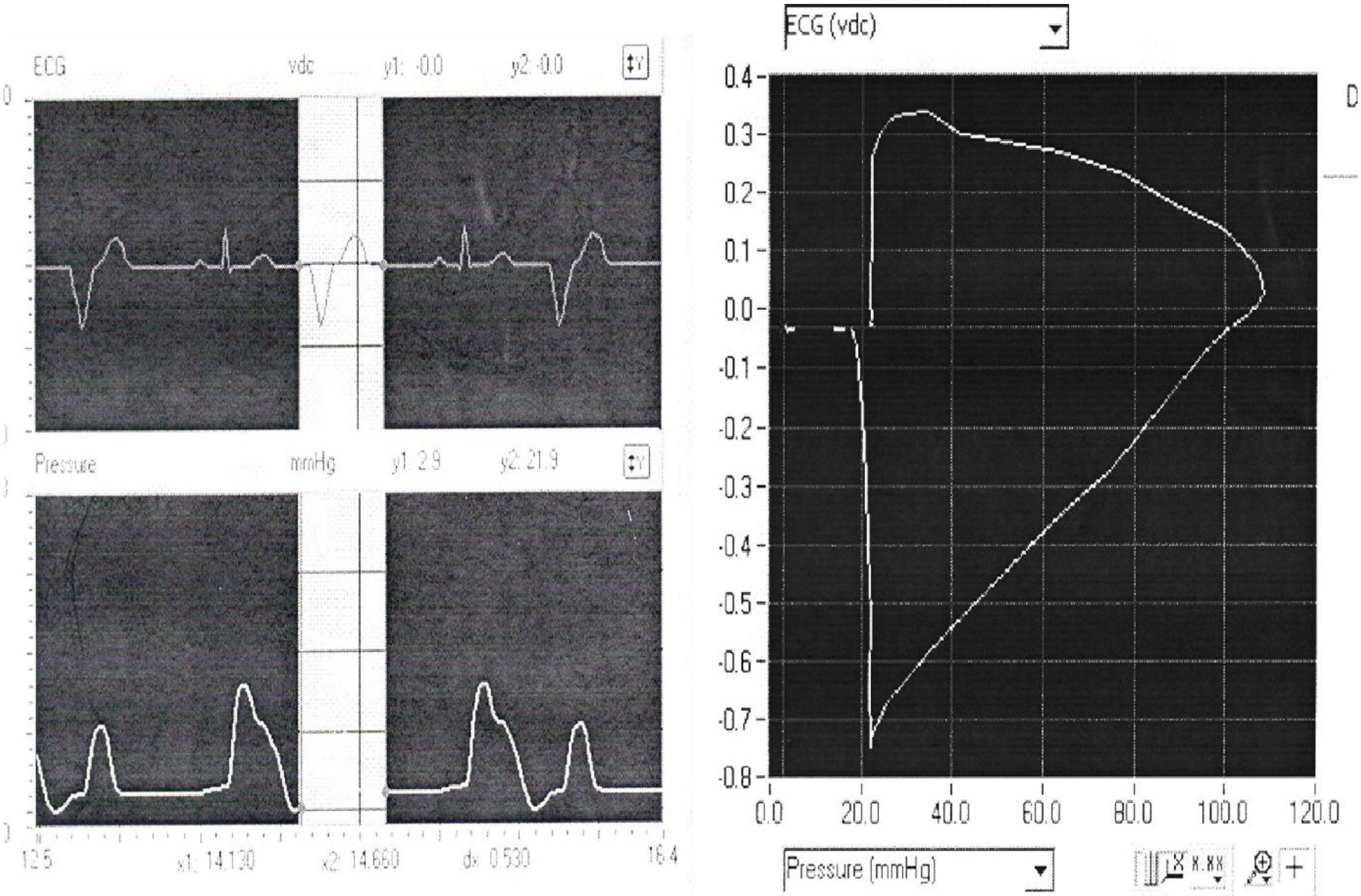

Figure 11. a) ECG signal, b) pulse wave signal taken from the BioBench directory for the Frequent PVC, and c) obtained VCVG.

VCVG differs for different cases of cardiovascular diseases. Figure 12 illustrates the VCVGs for additional cases such as multifocal PVC, PVC early, Atrial fibrillation, ECG paced, Normal rhythm (60 bpm), and PACs.

Conclusion and future work

The corner stone of this investigation was to introduce a technique that could contribute to the clinical practice in cardiology in an easy and affordable way for any hospital or medical center. Examples and figures stated have led to the following features and merits of this new method:

a) VCVG can be useful for both, physiologists and clinicians, since ECG is recognized well by clinicians, while the pulse wave is more comprehended by physiologists.

b) VCVG contains more information either than the ECG or pulse wave signals so that it can be used in those cases where the information given by any of them is not sufficient to have a final diagnosis.

c) VCVG is simple, sensitive and cost effective, as compared to other test methods like CT and MRI.

d) VCVG varies with any deviation in the original ECG or pulse wave signals, so it may be used to examine the effect of medicines, special drugs or hormones on a patient.

e) VCVG can create different patterns for different diseases. Hence, it can be used for the on-line computerized monitoring and dynamic analysis of patients with cardiovascular diseases.

f) In order to extend the diagnostic capabilities of the VCVG, we can introduce numerical values, such as the area (S), perimeter (L), and other additional quantitative informative variables that can be computed from the graphical presentations.

g) The future work will be the implementation of this method by designing a device, in the form of a VCVG monitor or a module added to any cardiac monitoring system, and then performing a real recording on patients in a hospital setting to show the efficacy of the vectorcardiovasculargraphy method.

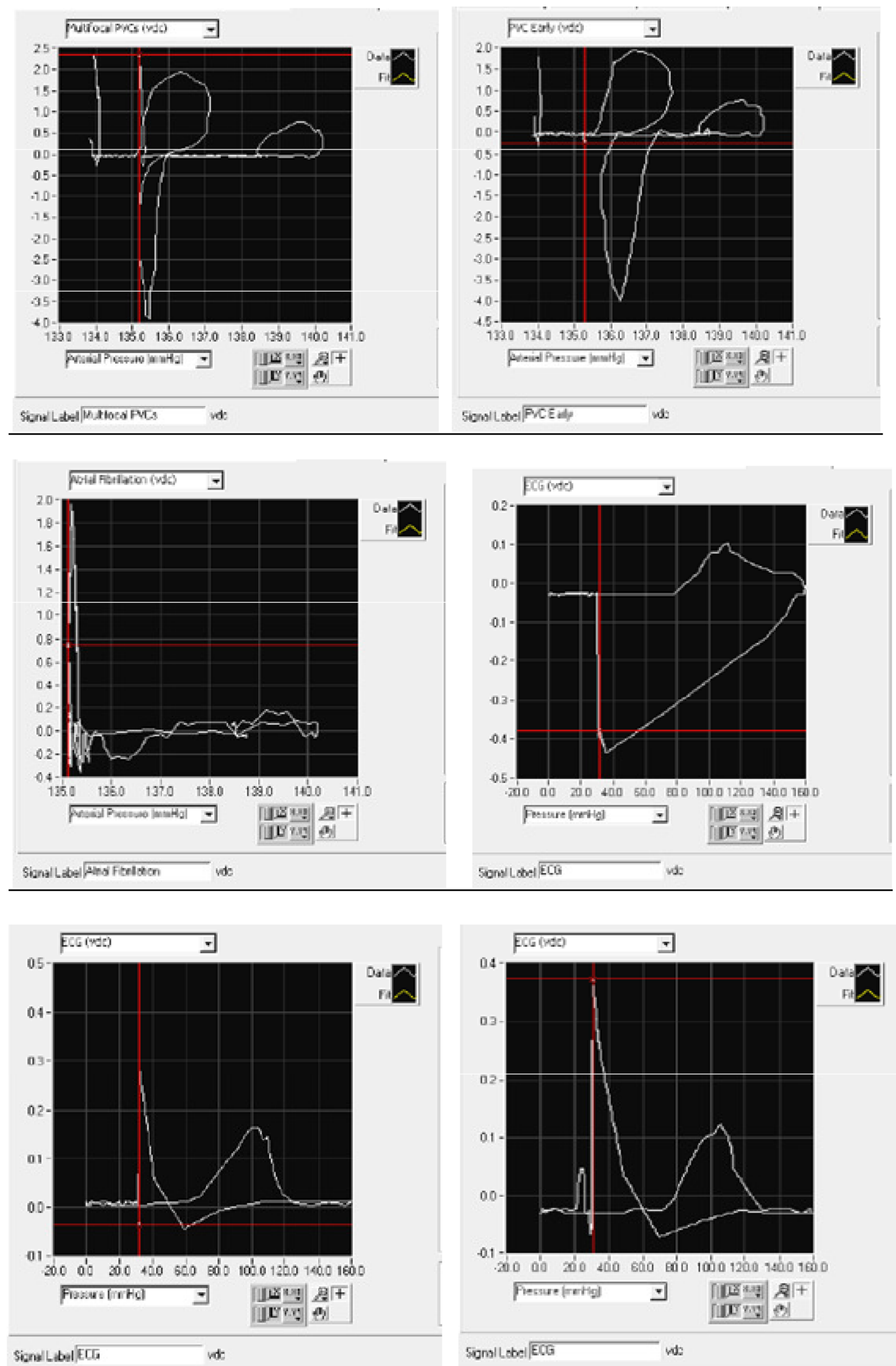

Figure 12. VCVGs for cases of a) Multifocal PVC, b) PVC Early, c) Atrial Fibrillation, d) ECG Paced, e) Normal Rhythm (60 bpm), and f) PACs.

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