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A CARDIAC OUTPUT MONITOR USING IMPEDANCE PLETHYSMOGRAPHY

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Abstract

The cardiac stroke volume can be measured non-invasively by monitoring the changes in the thoracic impedance due to the flow of blood. This paper describes a system which monitors the thoracic impedance using spot electrodes. A high frequency current is injected in the patient's thoracic region and the resulting voltage waveform is sensed. This is used for obtaining the impedance waveform and its derivative, which is ensemble averaged. The stroke volume is calculated using the Kubicek's formula, and then the cardiac output is computed. Excitation and sensing circuits are battery operated and the patient is totally isolated from mains power supply.

1 Introduction

Impedance cardiography is a non-invasive technique for measurement of cardiac stroke volume (SV). The SV is calculated from the changes in the thoracic impedance Z caused by the varying amount of blood in the lungs during a cardiac cycle [1-4]. The resistivity of blood (ρ) is far less than other body tissues, therefore it was postulated that the changes in Z are mainly due to the changing volume of blood in the thorax [1]. Two models, namely "two compartment model" and "parallel conductor model" have been proposed [2, 5] and both lead to the Kubicek's equation -

$$SV = \rho . \left(\frac{L^2}{Z_0^2}\right) . \Delta Z \qquad (1)$$

where Z_0 is the base impedance and L is the length of the conductor column in the model. The change in impedance, ΔZ, is calculated using 'forward slope extrapolation' procedure suggested by Patterson [2],

$$\Delta Z = \left(\frac{dZ}{dt}\right)_m . LVET \qquad (2)$$

where $\left(\frac{dZ}{dt}\right)_m$ is the maximum value of $-\left(\frac{dZ}{dt}\right)$, and $LVET$ is the left ventricular ejection time.

Here we describe a cardiac output monitor based on the above technique. The instrument has been designed with complete isolation of the human subject from the mains and a PC is used for processing of the waveform and display of the results.

2 Instrument Setup

The instrument setup is a modification of the circuit earlier reported by Zhang *et al.* [6]. The block diagram of the setup is shown in Fig. 1. The thoracic impedance is measured by injecting a high frequency current at the extremities of the thoracic region and sensing the voltage developed between them. The electrodes used are spot type electrodes in tetrapolar configuration [4].

The excitation circuit is a Wien bridge oscillator and a voltage to current converter generating a 100 KHz, low intensity (<5 mA) sinusoidal current. The current electrodes are placed in the front. The voltage electrodes, placed at the back, sense the voltage which is product of the current and Z. This modulated waveform is amplified by an instrumentation amplifier ($I.A.$) built using opamps $U3, U4$, and $U5$ shown in Fig 2-a. A demodulator, which is a rectifier detector (lowpass cutoff 30 Hz) using $U6$ and $U7$ recovers the modulating impedance waveform, $Z(t)$. The base impedance part and motion artifacts in the impedance waveform are removed by an automatic DC cancellation circuit, realized by $U8, U9, U10, U11$, and $U12$ (Fig. 2-b). The waveform is then amplified and differentiated by $U13$ and $U14$ to get the $(\frac{dZ}{dt})$ waveform.

The ECG waveform, $e(t)$ is obtained by an $I.A.$ with lowpass filter (cutoff 40 Hz) from the same voltage electrode pair. This circuit, shown in Fig. 2-c, is realized using low drift opamps $U15, U16$, and $U17$. The waveform is bandpass filtered and differentiated by $U18$ and $U19$ respectively to get the $(\frac{de}{dt})$ waveform. The sharp peak of $(\frac{de}{dt})$ waveform corresponding to the QRS complex is used as a trigger for ensemble averaging the $(\frac{dZ}{dt})$ waveform over a number of cycles to reduce the effect of breathing artifacts.

All the circuit blocks having connection to excitation and sensing electrodes are battery powered, and use only low power IC's and no inductors. Linearized optical isolator circuits [7, 8] are used for a galvanic isolation between the battery operated sensing circuit and the mains powered analysis setup.

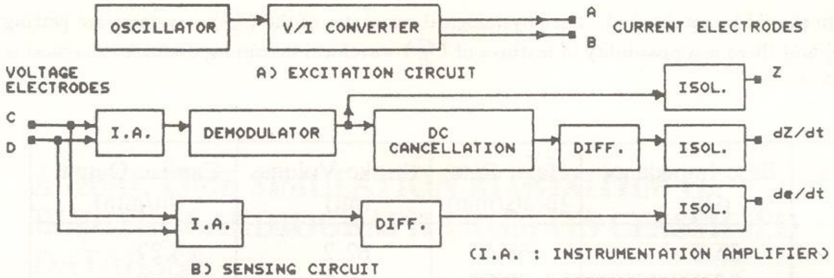
3 Analysis Setup

A PC is used for waveform storage, retrieval, processing, and displaying, in order to achieve flexibility in the development stage. The waveforms are sampled by a PC add on data acquisition card, PCL718 (Dynalog Micro-Systems, Bombay). The peaks in the $(\frac{de}{dt})$ waveform are detected using down crossings of threshold. Using these, the $(\frac{dZ}{dt})$ waveform is averaged for $\frac{3}{4}^{th}$ of a cycle, as all the features of interest occur in this interval [6]. Since the baseline is often noisy, the average value of averaged $(\frac{dZ}{dt})$ is taken as the baseline and $(\frac{dZ}{dt})_m$ is calculated as the peak above this baseline. The difference in the baseline crossing time and the time when the valley occurs is taken as $LVET$. SV is calculated using Kubicek's formula and this alongwith heart beat rate is used for calculating cardiac output.

4 Test Results

The system was tested on a number of subjects with normal health. Data were obtained with normal breathing, inhaled breath and exhaled breath. Impedance waveform, its derivative and derivative of the ECG signal for one of the subjects are shown in Fig. 3, and the averaged $(\frac{dZ}{dt})$ waveform is shown in Fig. 4. The analysis results for this subject are given in Table 1. It can be seen that Z increased with inhaling and decreased with exhaling. Both the heart rate and stroke volume changed in different breathing conditions. These results are uncalibrated, hence give only relative changes.

The effect of exercise on the heart rate and stroke volume has to be studied using this system, and test results need to be calibrated against standard clinical techniques. Further, an empirical formula relating $LVET$ with the time difference in the occurrence of the peak and valley of the

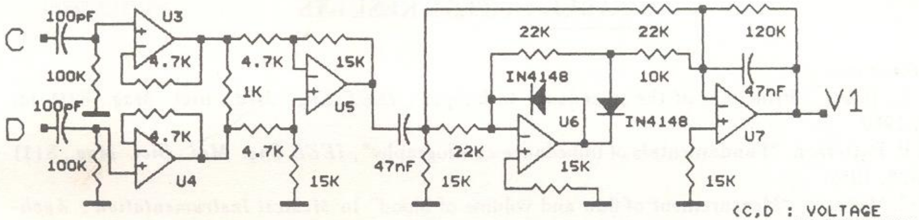


(I.A. : INSTRUMENTATION AMPLIFIER)

(DIFF. : DIFFERENTIATOR)

(ISOL. : SIGNAL ISOLATOR)

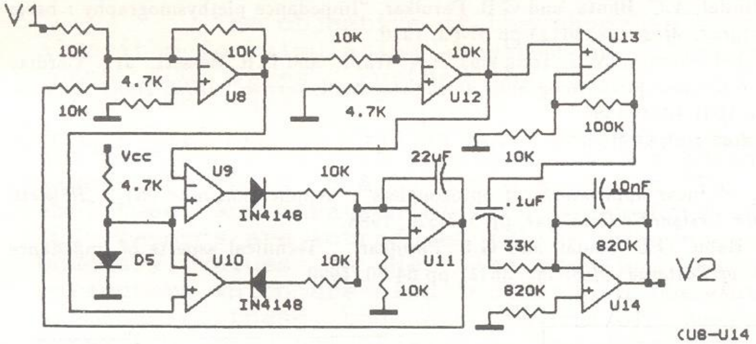
FIG.1 : OVERALL SETUP



(C,D : VOLTAGE ELECTRODES)

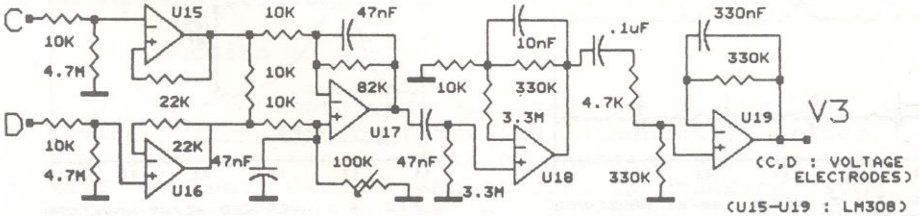
FIG. 2-a : CIRCUIT FOR VOLTAGE SENSING AND EXTRACTION OF Z(t) WAVEFORM

(U1-U7 : CA3100)



(U8-U14 : LF347)

FIG. 2-b : CIRCUIT FOR DC CANCELLATION AND DIFFERENTIATION OF Z(t)



(C,D : VOLTAGE ELECTRODES)

(U15-U19 : LM308)

FIG. 2-c : CIRCUIT FOR SENSING ECG WAVEFORM AND OBTAINING ITS DERIVATIVE

($\frac{dZ}{dt}$) waveform should be established. The physiological correlates of the ($\frac{dZ}{dt}$) waveform are getting established [9] and there is a possibility of features of ($\frac{dZ}{dt}$) waveform becoming useful for diagnosing cardiac disorders.

Breathing	Base Impedance (Ω)	Heart Rate (beats/min)	Stroke Volume (ml)	Cardiac Output (lit/min)
Normal	25.0	68.6	62.2	4.27
Inhale	25.1	74.9	46.2	3.50
Exhale	24.2	68.4	38.3	2.62

TABLE 1 : TEST RESULTS

5 References

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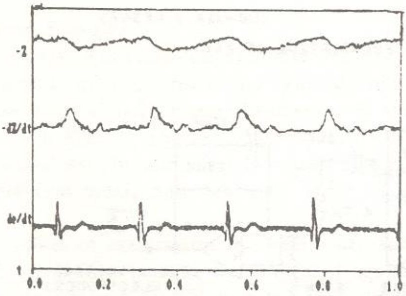

FIG. 3 : Z, dZ/dt, de/dt WAVEFORMS

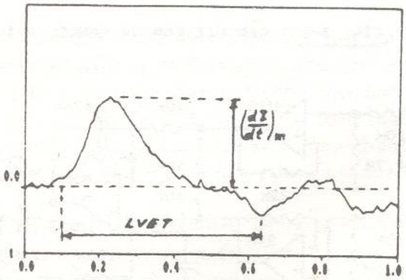

FIG. 4 : AVERAGED dZ/dt WAVEFORM