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CARDIAC OUTPUT MONITORING WITH AN IMPEDANCE CARDIOGRAPH

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ABSTRACT

Information about the pulse rate and stroke volume can be obtained by monitoring the changes in the impedance of the thoracic region due to the flow of blood. Here an instrument which monitors the thoracic impedance using ECG chest electrodes has been used. In this instrument, a high frequency (100 KHZ), low intensity sinusoidal current is injected into the thoracic region and the voltage waveform obtained by modulation of the current waveform because of thoracic impedance is sensed. The waveform is then amplified and demodulated to get the impedance waveform Z(t). Waveform Z(t), its derivative dZ/dt, and derivative of the ECG waveform de/dt are fed through signal isolators(opto couplers) to an ADC card installed in a PC. The impedance derivative(dZ/dt) is averaged using de/dt waveform as a trigger, and then is used for calculating the stroke volume. Heart rate is found from the de/dt waveform. The product of stroke volume and the heart rate gives the cardiac output.

Experiments were carried out using this instrumment for monitoring Cardiac output. Readings were taken with several subjects in resting position as well as while doing exercise using exercise bicycle. The results showed relationship of the heart rate and cardiac output.

INTRODUCTION

The conventional methods used to measure the cardiac output used clinically are the Fick's oxygen method and the Indicator dilution method[1]. These methods are either invasive or require expensive equipment. Impedance cardiograph uses an easy, inexpensive and non-invasive impedance (plethysmography) technique for the measurement of cardiac output. The measured cardiac output values with this technique are generally in good agreement with the values obtained by the standard technique measurements on healthy human beings. However the agreement is not very good for people suffering from cardiac disorders like valvular defects or ventricular defects. Here we briefly describe the operation of the impedance cardiograph instrument[2][3] and the experiments carried out on various subjects in resting position and while exercising. This is followed by a discussion on the results obtained.

IMPEDANCE CARDIOGRAPHY.

Cardiac output is the volume of blood pumped into the aorta by the heart in one minute. Its measure is highly dependent on the body and its level of activity. Some of the factors that influence cardiac output are age, size of body, exercising level. It averages around 5 to 6 liters/minute for a healthy young adult male.

To measure the cardiac output, impedance plethysmography is used, which measures the electrical impedance of a body segment between two electrodes. Since the volumes of skeletal and cardiac muscles remain more or less the same, the change in the impedance of the thorax region is mainly due to change in the blood volume. During systole, the impedance decreases, hence the thorax has increased blood volume. It was assumed earlier that the lungs, which receive the output of the right ventricle during systole, were responsible for the impedance change. Since the volume of blood pumped out by the heart to the body is the same as the volume of blood pumped by right ventricle to the lungs, the impedance waveform is an indicator of the functioning of the heart.

Electrodes are used to inject current and to measure the voltage modulated by the thoracic impedance. They can be used in either bipolar or tetrapolar configuration[4].In the bipolar configuration, two electrodes inject the current and sense the voltage. In the tetrapolar configuration, two electrodes inject current in the body segment. However, two different electrodes sense modulated wave. In the bipolar case, the impedance detected includes the skin-electrode interface impedance which can cause errors. In the tetrapolar configuration, the voltage sensed will be due to thoracic impedance only, if the current drawn by the receiving circuit is negligible and hence preferred.

The electrodes can be either band electrodes or spot electrodes. Band electrodes can be made up of aluminized ribbon or adhesive tapes with a number of small electrodes. Spot electrodes are of suction type or adhesive type. The signal-to-noise ratio from spot electrodes is greater than that from band electrodes[4]. Also, for long term monitoring, band electrodes are inconvenient as they may produce irritation and choking sensation in some patients.

The spot type ECG electrode consists of a nickel plated steel rim attached to a rubber bulb. These electrodes are based on the suction principle. But they require a conduction gel to make a good contact with the body. The placement of the electrodes in tetrapolar configuration is shown in Fig.1

Electrodes I1 and I2 form the current injecting pair while the inner electrode pair V1 and V2 sense the voltage.

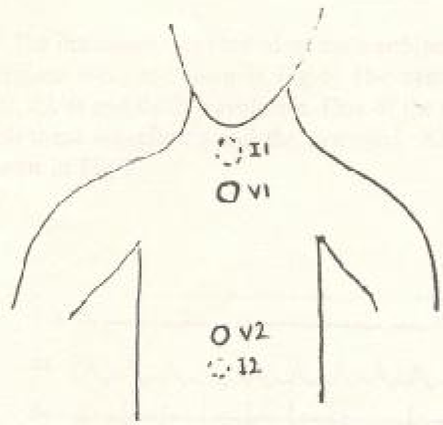

Fig.1 Placement of electrodes in Tetrapolar configuration.

IMPEDANCE CARDIOGRAPH INSTRUMENT.

The overall system [5] consists of:

a : excitation circuit and current electrodes.

b : sensing circuit : voltage electrodes, instrumentation amplifier with high pass filter for impedance Z(t), demodulator, dc cancellation circuit, differentiator circuit. Instrumentation amplifier with low pass filter for ECG e(t), differentiater, and signal isolators for Z(t), dZ/dt and de/dt.

c : analysis setup : A/D converter and PC.

The excitation circuit produces a high frequency low intensity sinusoidal current. The current is injected in the patient's thoracic region using current electrodes(I1,I2). The voltage electrodes(V1,V2) sense the voltage produced which is directly proportional to the product of the current and the thoracic impedance. This modulated wave is amplified by instrumentation amplifier. The demodulator recovers the modulating impedance waveform Z(t).

The base impedance part in the impedance waveform is removed by the DC cancellation circuit. The variable impedance waveform thus obtained is differentiated to get the dZ/dt waveform. The ECG waveform e(t)is obtained by an instrumentation amplifier with LPF from the same voltage electrode pair, as the ones used for Z(t) sensing. This waveform is differentiated to obtain its derivative. It is used as a trigger for averaging the dZ/dt waveform over a number of cycles to obtain a better estimation of the stroke volume. This part of the circuit is battery operated. The Z(t), dZ/dt and de/dt waveforms are fed to three optical isolator circuits.They offer galvanic isolation of the battery operated circuit and the patient from the mains operated equipments like a PC.

The opto-isolated analog outputs of the sensing circuit are connected to the A/D channels of the PCL-208 card(Dynalog microsystems, Bombay). The analysis program uses the A/D driver routines for acquisition of the waveform. The data are sampled with specified sampling rate (typically 200 samples per second per channel) and for the specified number of samples (limited by the available memory size). They are transfered to an array by program control data transfer.

The outputs from the impedance cardiograph circuit are the Z(t), dZ/dt and de/dt waveforms. The base impedance Zo, (dZ/dt)min and the left ventricular ejection time (LVET) are calculated using these waveforms.

The stoke volume is defined as the volume of the blood pumped out of the left ventricle with every heart beat. Using impedance cardiography technique it can be estimated as the product of the initial rate of change of impedance and the time the aortic and pulmonic valves open.The impedance waveform consists of a slow changing base impedance Z°. If L is the distance between the electrodes then stoke volume is calculated as

$$STOKE\ VOLUME\ \Delta V = \rho \frac{L^2}{Z_o^2}\ (dz/dt)_{min}\quad (1$$

This is the kubicek's formula. Heart rate is estimated from the derivative of the ECG waveform.

$$CARDIAC\ OUTPUT = \Delta V \times HEART\ RATE$$

The typical dz/dt has the features explained in fig 2[6].

A-wave : It is the downward deflection due to atrial systole.

B-wave : It is associated with the first heart sound.

C-wave : is a major upward deflection occurring during the systole. Its value is the (dz/dt)min required in kubicek's formula.

X-Y wave: indicates the closing of the Aortic valve and the pulmonary valve.

O-wave: This occurs during the early diastole and is reported to be associated with the diastole and with the mitral valve opening. This has been shown to increase significantly with heart failure and in a few cases of coronary artery diseases.

For these calculations, the output waveforms are fed to a PC The data is digitized by a data acquisition card and processed by using the real time data collection program "ICGREAL" andan analysis program"ICGOFFL".

EXPERIMENTAL METHOD

The instrument was tested on male subjects. The electrode positions were as shown in Fig 1. The system detected the Z(t), dZ/dt and de/dt waveforms. One of the sample recording with these waveforms and the averaged dZ/dt waveform is shown in Fig 2.

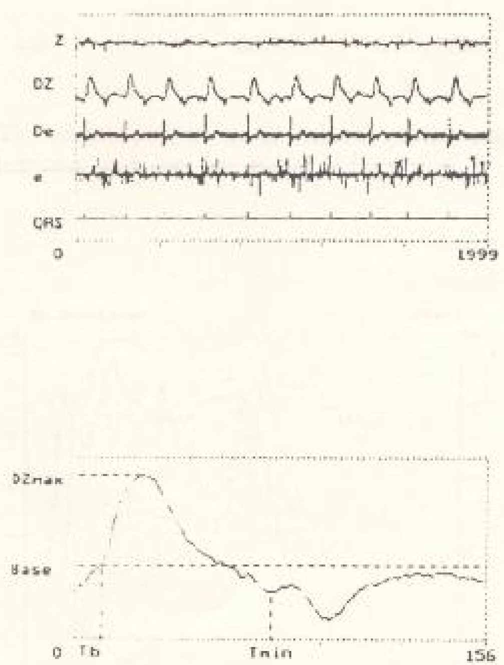

Fig.2 Sample recording of Z(t), dZ/dt, de/dt waveform and the averaged dZ/dt waveform.

Two types of measurements have been made with the impedance cardiograph. The measurements were made on subjects in standing and exercising conditions. Two types of electrodes can be used : small bulb type reusable metal electrodes with ECG jelly, and the disposable Ag-AgCl spot electrodes.But here only small bulb type metal electrode was used.

For experiment with subject under rest, the subject was asked to stand without making unnecessary movement and reusable bulb electrodes were placed in the configuration described above in Fig 1. Each observation was made for a duration of 10 seconds.

For experiment under exercise condition, the subject was made to exercise on an exercise bicycle vigorously for a duration of around five minutes, till the heart rate roughly doubled. The subject was then asked to stop and asked to relax without making unnecessary movements. During exercise as well as recovery phases, the readings were taken at intervals of 10 seconds. There was a facility of interrupting the experiment at any time.

RESULTS

The results for subjects under rest were obtained and are given in Table 1. It can be observed that under resting condition the cardiac output is almost stable. The mean and standard deviation were obtained for various subjects as shown in Table 2.

Table 1: Test results obtained from subjects at rest.The test results obtained indicate mean readings taken at an interval of 10 seconds.

Rho= 142.5 Ohm/cm
L = 15 cm
Subject:man

Test no.	Z_0 (ohms)	HR (beats/min)	SV (ml)	CO (l/min)
1.	7.9	63.5	65.2	4.1
2.	7.9	64.6	59.0	3.8
3.	7.9	62.1	77.0	4.7
4.	7.9	61.2	73.7	4.5
5.	7.9	64.0	78.1	5.0
6.	7.9	63.7	72.2	4.5
7.	7.8	61.4	73.2	4.4
8.	7.9	64.3	74.2	4.7

Deviation was observed from the mean values in most subjects. In subject "sun" the deviation was high. The heart rate of this subject was not steady although he was at rest.Recordings for subjects were taken with different values of gain which is one of the input parameters in software ICGREAL. Changing the values of gain changes the values of stoke volume and the cardiac output. In subjects "krs" and "tmp" the gain has been reduced while in case of subject "sun" the value of the gain has been increased.The values shown here have been scaled accordingly taking in to consideration the averaged cardiac output.

The results for different breathing conditions were obtained and the observations were taken every 10 seconds till the heart rate came close to normal.

Table 2: Mean and Standard Deviation of test results with subjects under resting condition.

Subject code.	Z_0 (ohms) mean(s.d.)	HR (beats/min) mean(s.d.)	SV (ml) mean(s.d.)	CO (l/min) mean(s.d.)
man	7.9(0.3)	63.1(0.3)	71.5(5.9)	4.5(1.0)
slu	13.4(0.3)	70.1(2.8)	60.4(3.3)	4.2(0.8)
krs	15.6	90.0(3.4)	53.2(30.6)	4.7(1.0)
tmp	19.8	74.9(2.7)	58.9(55.4)	4.3
sun	10.0	66.5(27.0)	67.3(106.2)	4.4(0.1)

The variation of the stroke volume, cardiac output, and the heart rate with time are shown in Fig 3.

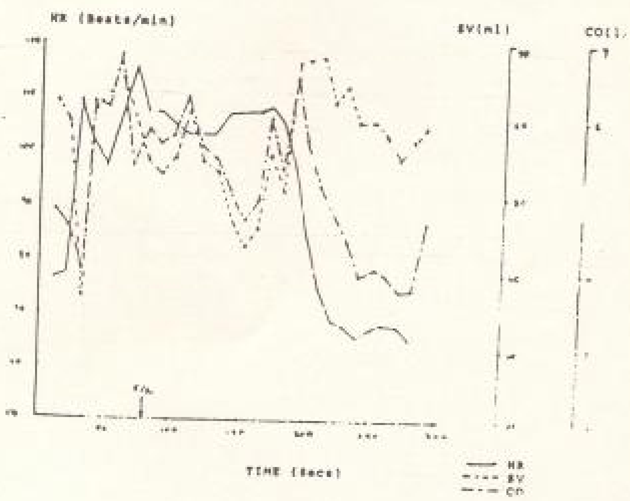

Fig.3. Variation of heart rate, stoke volume and cardiac output for subject undergoing exercise and then relaxing.

Results showed that initially when heart rate increases stoke volume and cardiac output reduces. As the heart rate goes on decreasing results showed an increase in the stoke volume but reduction in the cardiac output. This trend is observed till the stoke volume is stabilised. When the subject was told to relax as marked on the graph the heart rate decreases. Results obtained showed a further reduction in the stoke volume and cardiac output till the heart rate stabilises.

DISCUSSION

Consider the subject undergoing exercise. As the heart rate is increased the stoke volume is not large because the time available for pumping per stroke is less hence the cardiac output is also less. As we see from the graph that as consumption of oxygen is reduced the heart rate goes down and the time available during the systole is increased this is reflected by an increase in the stroke volume but the net cardiac output is reduced. This trend continues till a certain maximum stroke volume has stabilized. The body oxygen requirement is now much lower as most of the oxygen requirement has been met. Now the heart rate is very high and the subject stops exercising. Further reduction in the stroke volume is observed as the heart rate stabilizes. This probably is because the stoke volume is close to the possible optimum value without giving unnecessary strain on the cardiac muscles. The body now recovers more slowly and the cardiac output reduces slowly.

These experiments have been carried out on various subjects. It is to be noted that the Impedance Cardiograph does not give accurate absolute value of the cardiac output but the relative values obtained seem to be acceptable. Here the purpose carrying out experiments was to show how the heart rate, stike volume and cardiac output value changes for various subjects under rest and during exercise. Incase of subject **sun** the heart rate varied though the subject was at rest. Large deviation from the mean was observed in the values of stoke volume and cardiac output. To overcome this problem a new model has to be designed for calculating the stoke volume and modifying the kubicek's formula used here. The calculation of Left ventricular ejection time(LVET) is very important parameter for stoke's volume. In the present model it has been assumed that in early systole blood flows into the lungs without flowing out and that the rate of flow of blood into the lungs is constant for the complete LVET(time for which blood flows out of the left ventricle).Hence any changes in the impedance during the LVET is not taken into consideration which may cause error in the calculation of stoke volume as observed clearly in the values of subject sun. In short, there is a need to redesign the model which would consider the change in the impedance at every instant rather than assuming it to be constant in left ventricular ejection time.

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