CLASSIFICATION OF IMPEDANCE CARDIOGRAM FOR HEMODYNAMIC STUDIES

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree of

MASTER OF TECHNOLOGY

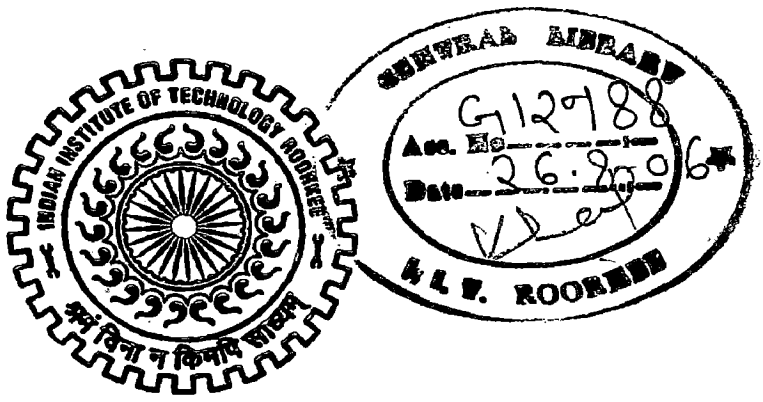
in

ELECTRICAL ENGINEERING

(With Specialization in Measurement & Instrumentation)

By

VENKATA RAMAKRISHNA KAVIRAYANI



DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE-247 667 (INDIA)

JUNE, 2006

CANDIDATE'S DECLARATION

I hereby declare that the work presented in this dissertation entitled **"Classification of Impedance Cardiogram for hemodynamic studies"** submitted in partial fulfillment of the requirement for the award of the degree of **Master of Technology** with specialization in **Measurement and Instrumentation** in the Department of Electrical Engineering, **Indian Institute of Technology Roorkee,** Roorkee is an authentic record of my own work carried out from July 2005 to June 2006 under the guidance of **Dr. Vinod Kumar**, Professor, Department of Electrical Engineering, Indian Institute of Technology Roorkee, Roorkee.

I have not submitted the matter embodied in this report for the award of any other degree or diploma.

Date: June, 2006
Place: Roorkee

K. V. Rama Krishna
(VENKATA RAMAKRISHNA KAVIRAYANI)

CERTIFICATE

This is to certify that the above statement made by the candidate is true to the best of my knowledge and belief.

(Dr. Vinod Kumar)
Professor,
Department of Electrical Engineering,
Indian Institute of Technology Roorkee,
Roorkee – 247667, India.

Date:
Place: Roorkee

ACKNOWLEDGEMENTS

I express my foremost and deepest gratitude to **Dr. VINOD KUMAR**, Professor, Department of Electrical Engineering, Indian Institute of Technology Roorkee, Roorkee for his valuable guidance, support and motivation throughout this work. I have deep sense of admiration for his innate goodness and inexhaustible enthusiasm. The valuable hours of discussion and suggestions that I had with him have undoubtedly helped in supplementing my thoughts in the right direction for attaining the desired objective. I consider myself extremely fortunate for having got the opportunity to learn and work under his able supervision over the entire period of my association with him.

I also thank **Dr. G.D.JINDAL,** Head, Bio-Medical Section, Electronics Division, Mod. Labs, BARC, Mumbai for his valuable suggestions and help in understanding the basics of this work.

My sincere thanks to all faculty members of Measurement & Instrumentation for their constant encouragement, caring words, constructive criticism and suggestions towards the successful completion of this work.

I do acknowledge with immense gratitude the timely help and support, which I received from my classmates and the Research Scholars in the "Instrumentation and Signal Processing Laboratory". I am also thankful to the staff of this Lab for their kind cooperation.

Last but not least, I'm highly indebted to my parents, whose sincere prayers, best wishes, moral support and encouragement have a constant source of assurance, guidance, strength, and inspiration to me.

K. V. Rama Krishna

(VENKATA RAMAKRISHNA KAVIRAYANI)

ABSTRACT

Impedance Cardiography is a technique which is used for the diagnosis of the heart. When a sinusoidal current of 10 μA to mA amplitude and 20 to 100 kHz frequency is applied to the transthoracic region some voltage is developed between the voltage electrodes as the blood acts like impedance. The signal obtained is called the impedance cardiogram or ICG.

Using Artificial Neural Networks the most important complex of ICG called BCX complex is detected. Hemodynamic parameters like stroke volume, cardiac output, heart rate, cardiac work are calculated from this complex. With one data file of a normal subject the neural network is trained and test on the remaining data files by calculating the parameters from the predicted signal and verifying them with the normal values.

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

BSA – Body Surface Area

CI – Cardiac Index

CO – Cardiac output

DBP – Diastolic Blood Pressure

ECG – Electrocardiography

HR – Heart Rate

ICG – Impedance Cardiography

ICVG – Impedance Cardio-Vasography

IPG – Impedance Plethysmography

LCW – Left Cardiac Work

LCWI – Left Cardiac Work Index

LVET – Left Ventricular Ejection Time

MAP – Mean Arterial Pressure

PAWP – Pulmonary Artery Wedge Pressure

PCG – Phonocardiography

PEP – Pre-Ejection Period

SBP – Systolic Blood Pressure

SI – Stroke Index

SV – Stroke Volume

SVR – Systemic Vascular Resistance

SVRI – Systemic Vascular Resistance Index

TFC – Thoracic Fluid Content

TFI – Thoracic Fluid Index

VI – Velocity Index

CONTENTS

CHAPTER 1

IMPEDANCE CARDIOGRAPHY

1.1 INTRODUCTION

Impedance cardiography (ICG) is a technique in which stroke volume or cardiac output is estimated by the waveforms of transthoracic electrical impedance. ICG signal is one of the Impedance Plethysmographic technique which is applied at the transthoracic region. So before knowing about Impedance cardiography, it is necessary to know about Impedance Plethysmography and its techniques. The basic principles of impedance plethysmography are also applicable to impedance cardiography.

1.2Impedance Plethysmography

Impedance Plethysmography (IPG) is a technique in which volume change in the tissue is measured by the change of electrical impedance. Blood is a good conductor of electricity. The amount of blood in any part of the body is inversely proportional to the electrical impedance and its first time-derivative gives relevant information about the circulation.

Jan Nyboer et al first introduced this technique in 1940 by correlating the change in the impedance with the flow of blood. Then Kubicek et al introduced the first time derivative of the impedance (dZ/dt) for computing stroke volume, cardiac output, systolic time intervals, etc.

The following figure shows the block diagram of an impedance plethysmograph system.

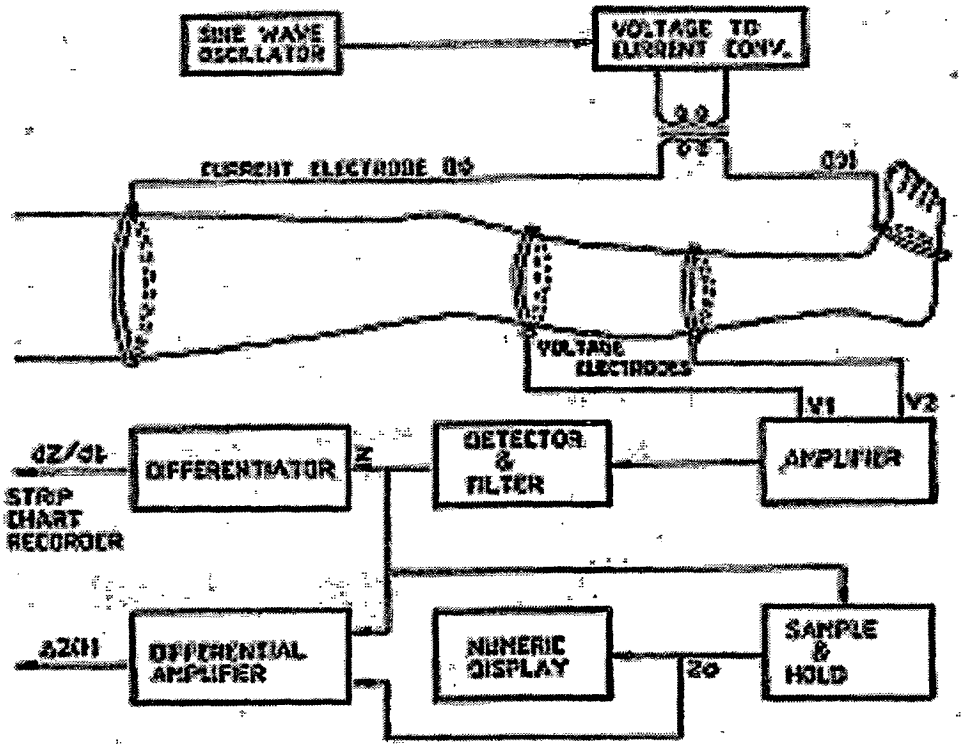


Figure 1.1: Block diagram of impedance plethysmography.(courtesy : Electrical impedance & photo Plethysmography for medical applications – G.D.Jindal, T.S.Ananthakrishna, S.K.Kataria, Vineet Sinha, Rajesh Kumar Jain, Sadhana A.Mandlik, A.R.Kni, Mousami A.Nail, S.K.Singh, BARC 2005)

This system comprises of a sine-wave oscillator followed by voltage to current converter. The output of this converter is a sinusoidal current of constant amplitude (say 1-10 mA). This current can be passed through the body segment with help of two band electrodes called the current electrodes I_1 and I_2. Voltage

signal developed along the current path is sensed with the help of another pair of electrodes called sensing or voltage electrodes V_1 and V_2. The amplitude of the signal acquired is directly proportional to the electrical impedance of the body segment between the electrodes V_1 and V_2. This output signal is proportional to instantaneous impedance (Z) of the body segment. Initial values of the impedance known as basal impedance (Zo) is obtained from a sample and hold circuit and numerically displayed on the panel.

Small changes in the impedance of the body segment caused by physiological processes like blood circulation, respiration etc, are obtained by subtracting the initial value of the impedance from the instantaneous impedance and is called the $\Delta Z(t)$ waveform. The Z is also differentiated with respect to time to get the rate of change of impedance called the dZ/dt waveform. These waveforms are recorded on the strip chart recorder to relate them with blood volume changes directly.

1.3 Impedance Plethysmography Principles

Electrical Conduction in Biological Matter

Biological tissues such as muscle, bone, etc, and biological fluids such as blood, urine, cerebrospinal fluid, etc, are neither good conductors of electricity as metals nor bad conductors as wood. This intermediate property of the biological matter makes its measurement feasible by simple instruments. The conductivity of biological fluids is more than that of tissues due to abundant charge carriers in the former. Conductivity is the measure of the ability of electric charges to move in

the material under the influence of as electric field. The conductivity (σ) is either expressed directly or by its reciprocal known as resistivity (ρ).

For the materials, obeying Ohms law, resistivity is defined as the resistance offered by 1 cm cube of the material to the flow of electric current. The resistivity is independent of the geometrical configuration of the material and can be calculated from the inherent properties of the material as described below:

If N is the number of charge carriers available in the material per unit volume, Q is the charge (in coulombs) per charge carrier and μ is the mobility of the charge carrier or the net velocity imparted to the charge carrier by as electric field of unit strength, the conductivity of the material is given as:

$$\sigma = NQ\mu$$

$$or$$

$$\rho = \frac{1}{NQ\mu}$$

Where N and Q are constants for a material. But μ is temperature dependent. Hence σ or ρ is need to be specified at a particular temperature.

From the value of ρ it is possible to calculate the electrical resistance offered by the material of known geometry. If L (cm) is the length and A (cm^2) is the area of the cross section of a homogeneous cylindrical conductor, resistance (R) is given as:

$$R = \rho \frac{L}{A}$$

R can be accurately measured for any object using Ohms Law. In this case constant current is passed through the object and the voltage developed across is measured. The ratio of voltage and current gives the value of R. As L and A can be physically measured, the above equation can be used for determination of ρ. The following table gives the resistivity of various biological materials.

Table 1.1Resistivities of the biological materials

Sl.No	Biological Material	Resistivity (Ω-cm)
1	Urine	30
2	Plasma	63
3	Cerebrospinal Fluid	65
4	Blood	150
5	Skeletal Muscle	300
6	Cardiac Muscle	750
7	Lung	1275
8	Fat	2500
9	Bone	16600

courtesy : Electrical impedance & photo Plethysmography for medical applications – G.D.Jindal, T.S.Ananthakrishna, S.K.Kataria, Vineet Sinha, Rajesh Kumar Jain, Sadhana A.Mandlik, A.R.Kni, Mousami A.Nail, S.K.Singh, BARC 2005

From the above discussion the electrical conductivity of blood is known. For impedance plethysmography various theories are applied. Some of them are discussed below.

Parallel Conductor Theory

According to this theory, the action of the systole is to place additional impedance Z_b in parallel with basal impedance of the body segment (Z_o) at the end of diastole. The instantaneous impedance of the body segment (Z) is given by the parallel combination of Z_0 and Z_b as:

$$Z = \frac{Z_o . Z_b}{Z_o + Z_b}$$

from this equation Z_b is calculated as:

$$Z_b = \frac{Z_o . Z}{dZ}$$

where dZ is the change in impedance ($Z - Z_o$). Since Z_o and Z differ by a very small amount, Z in the numerator can be replaced by Z_o to obtain

$$Z_b = \frac{Z_o^2}{dZ}$$

Assuming the volume of blood, which corresponds to Z_b, can be represented as a uniform conductor having a length "L" and area of cross-section "a", Z_b can be replaced by $\rho_b \frac{L}{a}$ *or* $\rho_b \frac{L^2}{dV}$, where ρ_b is the resistivity of the blood and dV is the volume of blood entering into the segment. Hence the above equation is written as:

$$\rho_b \frac{L^2}{dV} = \frac{Z_o^2}{dZ}$$

or

$$dV = \rho_b L^2 \frac{dZ}{Z_o^2}$$

Hence from the above equation the change in volume of blood is obtained.

Two Compartment Model

In this model body segment is considered as a uniform cylinder with a column of blood along its axis and body tissue surrounding the blood column (see the below figure).

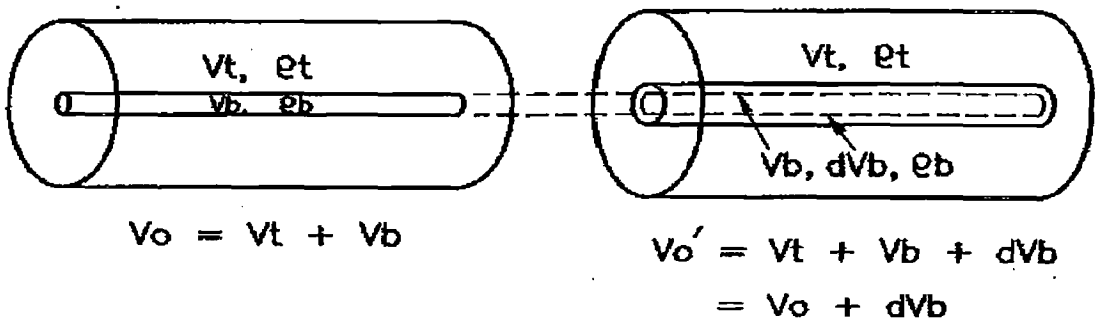


Figure 1.2 Two compartment method [2]

If L be the distance between the sensing electrodes, the impedance Z of the body segment is given as:

$$\frac{1}{Z} = \frac{1}{Z_t} + \frac{1}{Z_b}$$

where Zt is the impedance of the surrounding tissue and Z_b is the impedance of the blood column. If A_t and A_b are the cross-sectional areas and ρ_t and ρ_b are the

resistivities of the surrounding tissue and the blood column respectively, then by Ohm's law Z_t and Z_b are given as:

$$Z_t = \rho_t \frac{L}{A_t} \quad and \quad Z_b = \rho_b \frac{L}{A_b}$$

Hence

$$Z = \frac{\rho_t \rho_b L}{\rho_b A_t + \rho_t A_b} = \frac{\rho_t \rho_b L}{\rho_b V_t + \rho_t V_b} \qquad \text{.....I}$$

where,

V_t is the total volume of surrounding tissue

V_b is the total volume of the blood conductor

Assuming that a volume of blood dV_b enters the region between sensing electrodes, there is a small increase in the area of the blood conductor and the volume of the surrounding tissue remains unaltered. The expression for the change in impedance (dZ) of the body segment can be written as:

$$dZ = -\frac{\rho_b \rho_t^2 L^2}{(\rho_t V_b + \rho_b V_t)^2} dV_b$$

From equation I

$$dV_b = -\rho_b L^2 \frac{dZ}{Z^2}$$

The above equation can be used for estimation of blood volume dV_b entering into the body segment by making the following assumptions:

(a) Cross-sectional area of the tissue mass is constant.

(b) The area of the blood conductor increases with entry of blood in the region between sensing electrodes.

(c) The length L is constant.

The negative sign signifies that the entry of the blood produces a decrease in the electrical impedance. This decrease in impedance is recorded as positive deflection in an Impedance Plethysmography system. For calculating total volume of blood (ΔV) entering a body segment during entire systole, the dZ in the above equation is replaced by the total change in impedance (ΔZ) occurring during the period as:

$$\Delta V = \rho_b \, L^2 \frac{\Delta Z}{Z_o^2}$$

Venous Occlusion Method

The venous occlusion method is a fundamental technique of quantitative determination of the limb blood flow from the plethysmographic measurement. The principle of the venous occlusion method applied to a segment of the lower leg is illustrated in figure 1.3. Two cuffs are attached to the proximal and distal sites of the segment, and a pressure higher than the maximum arterial pressure is applied to the distal cuff so that all arteries and veins under the cuff are occluded. Then a pressure slightly lower than the minimal arterial pressure is applied instantaneously to the proximal cuff so that only the veins are occluded at this level, but arterial blood flow is not obstructed.

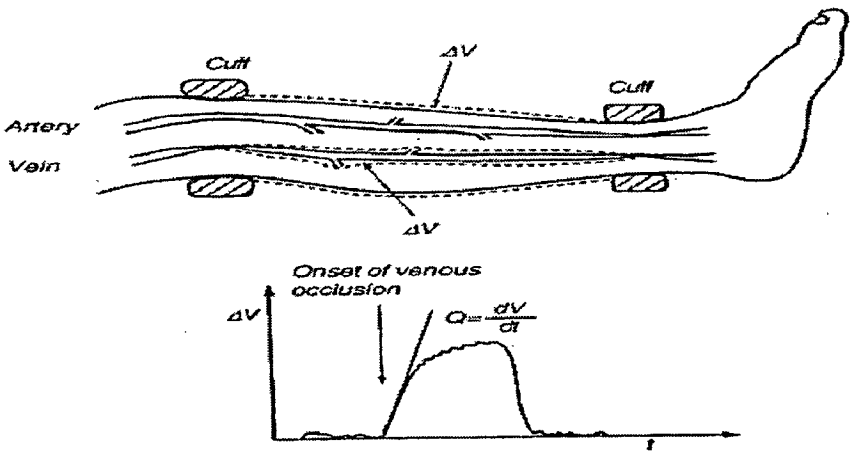


Figure 1.3: Venous occlusion method [1]

Then the volume change of the segment is recorded. Hence the blood flow, Q, is determined by the rate of increase of the volume, $\frac{dV}{dt}$ This technique can also be applied to the whole limb or the extremity of the limb and has been widely used in physiological studies.

For normal subjects, the proximal cuff pressure for venous occlusion is chosen to be around 6.7 kPa (50 mm Hg), and the distal pressure is around 20 kPa (150 mm Hg). To perform venous occlusion quickly, the cuff pressure for venous occlusion should be applied in a short time.

Many researchers have examined the validity of the venous occlusion method, and it was shown that as long as an appropriate cuff pressure is applied, the venous flow can be completely obstructed while the arterial pressure distal from the venous occlusion cuff remains unchanged. But, it was pointed that there are still many causes of error due to local tissue deformation at the cuff inflation and to the technique of volume recording [1].

1.4 IPG Signals

There are a number of waveforms of Impedance Plethysmograph [2] that are used for the diagnosis of the patient health condition. They are described in brief below.

ΔZ Waveform

Figure 1.4 shows a typical ΔZ (t) waveform, recorded from thoracic region in relation with electrocardiogram (ECG) and phonocardiogram (PCG).

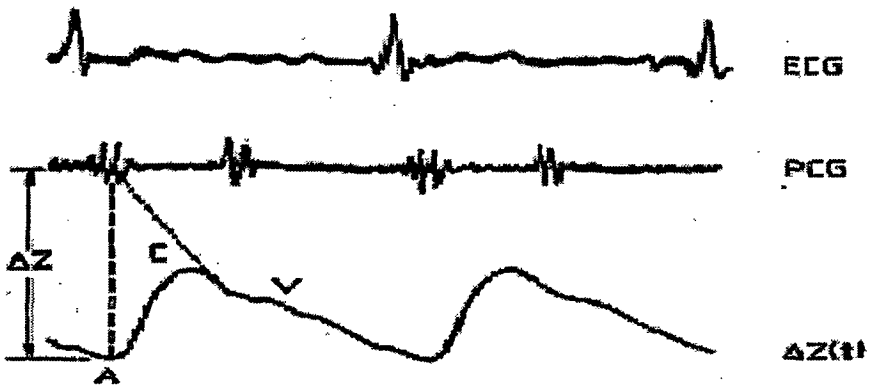


Figure 1.4: ΔZ (t) waveform in relation to ECG and PCG [2]

The waveform is comprised of three waves namely A, C and V waves. A-wave is synchronous with first heart sound representing the onset of ventricular systole. Hence upstroke AC represents the increase in the blood volume in the region. During this time the rate of incoming is more than that of distal runoff. Hence AC represents the net incoming of blood into the segment. At point C the incoming rate equals that of the distal runoff and there after the rate of distal

runoff supercedes that of inflow causing a downward deflection. The total change in the impedance in one cycle is obtained by integrating the rate of distal runoff over the systolic period. Substituting this value as ΔZ in the equation

$$\Delta V = \rho_b L^2 \frac{\Delta Z}{Z_o^2}$$

the incoming blood volume during one cardiac cycle is obtained.

dZ/dt Waveform

This waveform is obtained by electronically differentiating either the instantaneous impedance (Z) or ΔZ (t) signal, which directly give the rate of change of impedance [2]. A typical dZ/dt waveform in relation with ECG and PCG is illustrated in the figure 1.5.

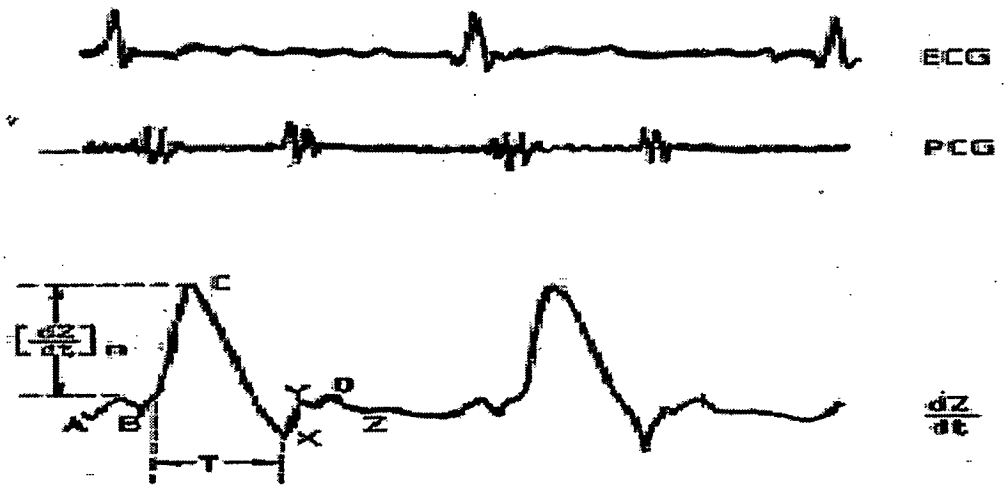


Figure 1.5: dZ/dt waveform in relation with ECG and PCG [2]

Various phase reversal points in this waveform are labeled as A, B, C, X, Y, O and Z. The complex BCX corresponds to ventricular systole and complex XYOZ

corresponds to ventricular diastole in time domain. This waveform is preferred over ΔZ (t) waveform for the following reasons:

1. The phase reversal points are clearly detectable from the waveform and represent important events of the cardiac cycle.

2. The blood flow related signals are enhanced and respiratory component is suppressed due to differentiation.

3. The maximum rate of change of impedance $(dZ/dt)_m$ can be directly measured as the amplitude of C-wave.

Multiplication of $(dZ/dt)_m$ with the left ventricular ejection time (T) gives the total change in impedance for the entire systolic period. Hence using this value the stroke volume (SV) is calculated as:

$$SV = -\frac{\rho_b L^2}{Z_o^2}\left(\frac{dZ}{dt}\right)_m T$$

Impedance Cardio-vasographic waveform

Impedance Cardio-vasograph (ICVG) is a $\frac{dZ}{dt}$ waveform recorded from thorax and knee. Figure 1.6 shows the impedance cardio-vasographic waveforms recorded from thoracic region (b) and from knee (c) in relation with ECG signal.

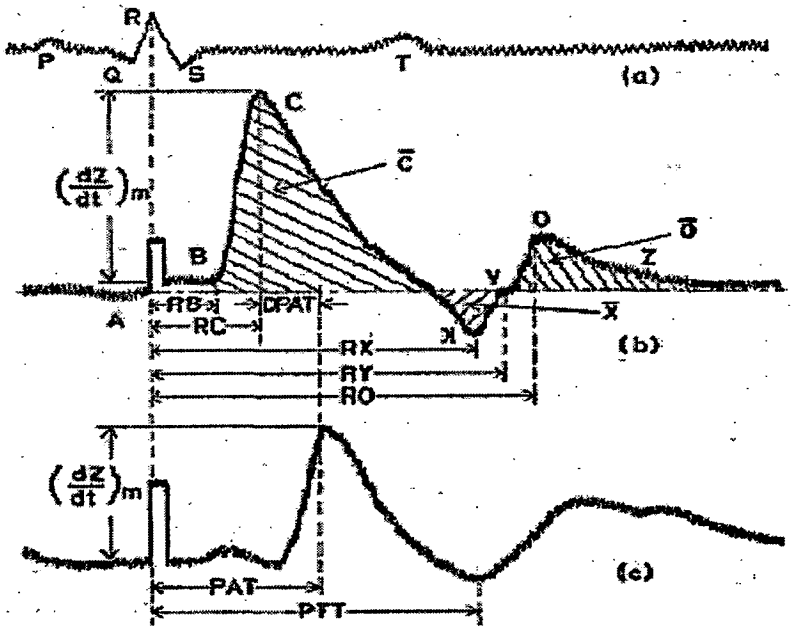


Figure 1.6: ICVG waveforms (b) recorded from thoracic region and (c) from knee region in a normal subject in relation with (a) the ECG [2].

In general the shape of ICVG waveform [2] changes very little from location to location. The thoracic waveform consists of two major positive deflections. Following the R-wave of ECG, the first major deflection starts from point B, reaches the peak at point C and then descends till point X, which is below the base line. This BCX complex is called the systolic wave or the C-wave as it occurs during ventricular systole. The second major deflection starts from point X, reaches the peak at point O and then gradually descends till the onset of the next cardiac cycle. This wave is called the diastolic wave or the O-wave. The AB-wave is termed as the pre-ejection wave. At any instant of time the rate of change of impedance is directly measurable from this waveform.

The maximum rate of impedance $(dZ/dt)_m$ required for the computation of the hemodynamic parameters is measured as height of C from B. In the absence of discernible B point, the height of C above the base line is measured. But, in case of ambiguity in the base line and absence of a clear B point, 85% of the height of

C from A point is taken as $(dZ/dt)_m$ as an approximation. Product of $(dZ/dt)_m$ and the duration of C-wave (RX-RB) gives the total charge in impedance ΔZ occurring during a cardiac cycle. The basic quantities measured from ICVG waveform are:

(a) The value of basal impedance Z_0

(b) Change in impedance during a defined interval of time

(c) Rate of change of impedance at any instant of time

(d) Time elapsed between R-wave of ECG and various phase reversal points in the ICVG waveform

(e) The area under systolic wave and diastolic wave of the ICVG waveform.

These values are used for the computation of various Hemodynamic parameters for the assessment of cardiac diseases.

Impedance Cardiographic waveform

IPG waveform recorded from the thoracic region is commonly known as impedance cardiogram (ICG). Figure 1.7 shows an ICG waveform recorded from a normal subject

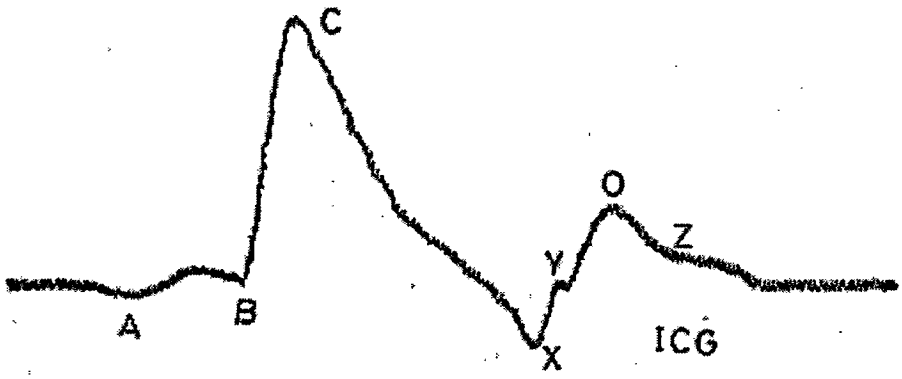


Figure 1.7: ICG waveform of a normal subject[2]

1.5 Impedance Cardiography

Impedance cardiography (ICG) is a technique in which stroke volume or cardiac output is estimated by the waveforms of transthoracic electrical impedance. To record transthoracic electrical impedance, the electrodes are placed as shown in the figure 1.8.

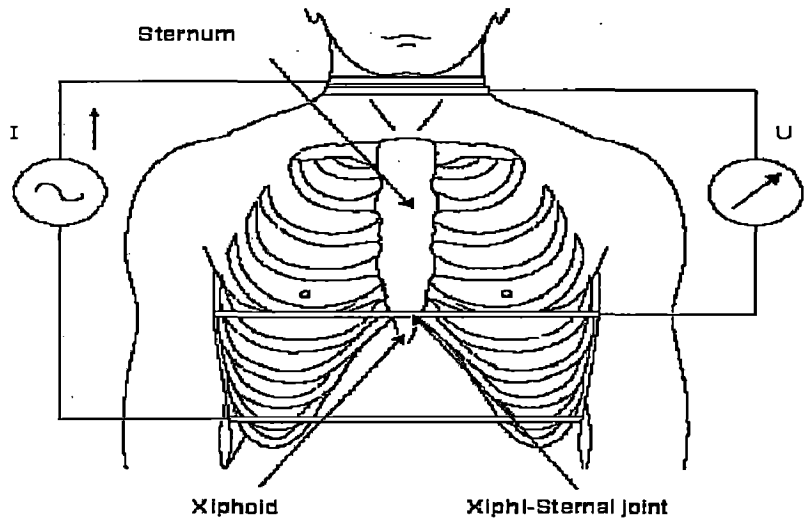


Figure 1.8: Placement of electrodes to patient for the measurement of ICG [4]

As shown from the figure 1.8 for the outer electrode pair, one electrode is placed around the abdomen and the other around the upper part of the neck. For the inner electrode pair, one electrode is placed around the thorax at the level of the joint between the xiphoid and the sternum, known as xiphi-sternal joint, and the other electrode is placed around the lower part of the neck [4]. An a.c. current within the range of 20 to 100 kHz at a current level within the range of 10 μA to 10 mA is supplied through the current electrodes and the voltage induced between the voltage electrodes is measured. The thoracic impedance, Z, is defined by the obtained voltage, V, divided by the supplied current, I.

Figure 1.9 [2] shows a typical ICG waveform in relation with ECG and PCG. The waveform mainly consists of three components namely, 'ab' wave, 'C' wave and 'O' wave. The 'C' wave is the largest peak in the waveform and occurs during ventricular systole. The 'O' wave and 'ab' wave are recorded during diastole and Pre-ejection period (PEP) respectively.

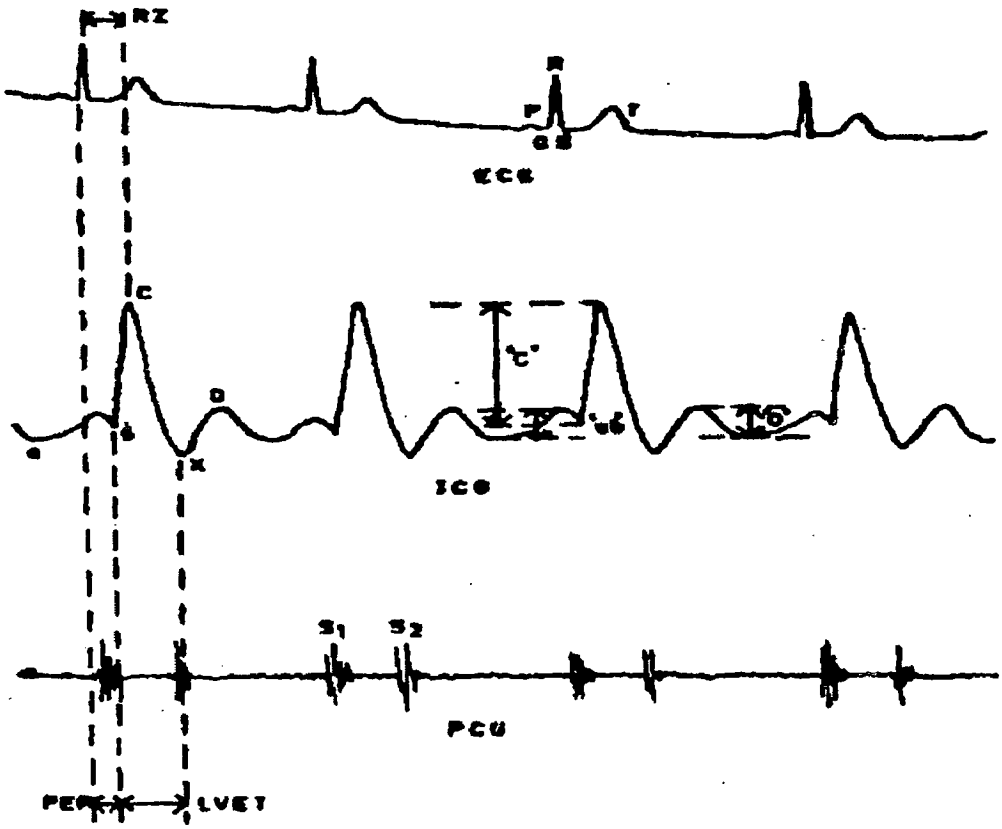


Figure 1.9 ICG waveform of a normal subject in relation with ECG and PCG

Systolic time intervals such as left ventricular ejection time (LVET) and PEP and amplitudes of the three components are derived from ECG and ICG as shown in the figure 1.9. Table 1.2 gives the normal values for various parameters in normal subjects.

Table 1.2 Normal values of ICG parameters [2]

ICG PARAMETERS	**NORMALVALUES**
Basal Impedance	Men 20 - 30 ohms, Women 25 - 35 ohms
Stroke volume	60 – 20 ml/beat
Cardiac Output	4 – 8 l/min.
Pre-ejection period (PEP)	0.05 – 0.12 sec
$(DZ/dt)_{max}$	0.8 – 2.5 ohm/sec
Left ventricular ejection time (LVET)	0.25 – 0.35 seconds

CHAPTER 2
HEMODYNAMIC PARAMETERS

2.1 Introduction:

The parameters which help a doctor in the diagnosis of a patient are the hemodynamic parameters [4,10]. There different types of parameters which are used in diagnosis. In this chapters those parameters are discussed which are derived or obtained from the ICG signal. These parameters tell the functionality and the condition of the heart.

The parameters are mainly divided into six categories:

1) Blood Flow
2) Blood Pressure
3) Cardiac work
4) Resistance
5) Contractility
6) Fluid status

2.2 Blood Flow

The blood flow [3,10] at any point in the circulatory system is the volume of blood that passes that point during a unit of time. Blood flow is highest in the pulmonary artery and the aorta, where these blood vessels leave the heart. In the capillaries the blood flow is slow. In the arteries, the blood flow is pulsatile. In some blood vessels a reversal of the flow can occur during certain parts of the heart beat cycle. From blood flow in a given vessel, a number of other characteristic variables or parameters are obtained. They are:

1) Stroke Volume
2) Stroke Index
3) Heart Rate
4) Cardiac Output
5) Cardiac Index

2.2.1 Stroke volume

Stroke Volume is defined as the amount of blood ejected by the heart in one beat. Generally the blood ejected by the left ventricle during one left ventricle contraction is called left ventricular stroke volume and that by the right ventricular in one right ventricular contraction is called right ventricular stroke volume. The stroke volume varies as a function of time giving rise to stroke volume variability. Stroke volume is measured in terms of cc/beat.

2.2.2 Stroke Index

Stroke index is defined as the stroke volume normalized for body surface area. It is an adjustment of the stroke volume based of the size of the person's body i.e., based on body surface area (BSA). Stroke index is measured in terms of cc/beat/cm^2.

2.2.3 Heart Rate

Heart Rate (HR) is defined as the number of heart beats per minute. The heart rate is obtained from ECG waveform or it can be obtained from the ICG signal itself. In the first approach both ECG and ICG of the patient have to be recorded simultaneously, this necessitates applying large number of electrodes to the patient and acquiring both the signals. So it is advisable to derive the heart rate from the ICG signal itself. From ICG signal the difference between two

consecutive C peaks is considered as the heart rate. Heart rate is measured is terms of beats/min.

2.2.4 Cardiac Output

Cardiac output is one of the most important parameter of the circulatory system. It is defined as the amount of blood ejected by the heart in one minute and is usually expressed in liter/min. It is also the measure of the available blood flow for all tissues of the body. Cardiac output is measured in terms of litres/min

2.2.5 Cardiac Index

Cardiac Index, like stroke index, is an adjustment of the cardiac output based on the size of the person's body. It is the most and individualized cardiac parameter. It is based on body surface area (BSA). Cardiac index is measured in terms of litres/min/cm^2.

2.3 Blood Pressure

Blood pressure [3,4,9] is the pressure of the blood in arteries which take the blood away from the heart to the rest of the body. The heart is a pump that beats by contracting and then relaxing. The pressure of blood flowing through the arteries varies at different times in the heartbeat cycle.

- The highest pressure, known as systolic pressure, is the pressure when the beat or contraction of the heart forces blood round the body.

- The lowest pressure, diastolic pressure, is the pressure between heartbeats when the heart is resting.

The following are the parameters that come under this category

1) Mean Arterial Pressure
2) Central Venous Pressure
3) Pulmonary Artery Wedge Pressure

2.3.1 Mean Arterial Pressure

Mean arterial pressure is defined as the average pressure exerted by the blood on the arterial walls. It is also a weighted average of systolic and diastolic blood pressure. Generally, MAP falls about one-third of the way between the diastolic low and the systolic peak. Mean arterial pressure is measured in terms of mm Hg.

2.3.2 Central Venous Pressure

The central venous pressure is a measurement of the pressure in the right atrium. This reflects the right ventricular diastolic pressure, or the ability of the right side of the heart to pump blood. This is a valuable tool for assessing the relationship between cardiac action and blood volume. Its default value is 6 mm of Hg. Central venous pressure is measured in terms of mm Hg.

2.3.3 Pulmonary Artery Wedge Pressure

The pulmonary artery catheter is inflated. As the pulmonary artery catheter makes its way into small capillary vessels and becomes wedged. The pulmonary

artery wage pressures (PAWP) may be measured. Generally, this measurement is more important than the central venous pressure. If there is left ventricular dysfunctions, such as with a myocardial infarct or cardiomyopathy, a threat to tissue oxygenation and low cardiac output may exist. Using PAWP cardiac work parameters are calculated. Its default value is 10 mm of Hg. Pulmonary artery wedge pressure is measured in terms of mm Hg.

2.4 Cardiac Work

Cardiac work [11] is the total work done by the heart in one beat cycle. Total work means work done by both the chambers of the heart i.e., from right artrium to left ventricle. Mainly two parameters are considered in the cardiac work. They are:

1) Left Cardiac Work
2) Left Cardiac Work Index

2.4.1 Left Cardiac Work

Left cardiac work is defined as an indicator of the amount of work the left ventricle must perform to pump blood each minute. It is derived from three parameters MAP, PAWP and CO mentioned above. Left cardiac work is measured in terms of kg cm.

2.4.2 Left Cardiac Work Index

Left cardiac work index, like SVI and CI, is an adjustment of the left cardiac work based on the size of the person's body. In other words it is LCW normalized for body surface area (BSA). Left cardiac work index is measured in terms of kg/cm.

2.5 Resistance

Here resistance [4,10,11] is that amount which must be overcome by the heart during the cardiac work. Mainly two parameters are calculated. They are

1) Systematic Vascular Resistance
2) Systematic Vascular Resistance Index

2.5.1 Systematic Vascular Resistance

Systematic vascular resistance is defined as the resistance to the flow of blood in the arterial system, often referred to as "Afterload". It is also defined as the resistance that must be overcome by the ventricles to pump blood into the systemic circulation. Systematic vascular resistance is measured in terms of dynes sec/cm^5.

2.5.2 Systematic Vascular Resistance Index

Systematic vascular resistance index, like all other indexes, is an adjustment of the systematic vascular resistance based on the size of the person's body. In other words it is SVR normalized for body surface area (BSA). Systematic vascular resistance index is measured in terms of dynes sec m^2/cm^5.

2.6 Contractility

Contractility [4,10,12] is considered as the indicator of the left ventricular function. It mainly gives the information about the ventricular functionality of the heart. The main parameters are:

1) Left Ventricular Ejection Time
2) Pre-Ejection Period
3) Systolic Time Ratio
4) Velocity Index

2.6.1 Left Ventricular Ejection Time

Left ventricular ejection time is the time interval between the B-point and the X-point of the ICG signal. As discussed in the previous chapters, the B-point marks the opening and the X-point the closing of the aortic valve. The LVET is the duration of the mechanical systole. Left ventricular ejection time is measured in terms of sec.

2.6.2 Pre-Ejection Period

Pre-ejection period is the time interval from the beginning of electrical stimulation of the ventricles to the opening of the aortic valve (electrical systole). It the time interval from the beginning of the Q wave on the ECG to B point on the ICG signal. Pre-ejection period is measured in terms of secs.

2.6.3 Systolic Time Ratio

Systolic time ratio is the ratio of the electrical and mechanical systole. In other words it is the ratio of PEP and LVET. Systolic time ratio is a ratio hence it does not have units.

2.6.4 Velocity Index

Velocity index is defined as the peak velocity of blood flow in the aorta. It is equivalent to the normalized amplitude of the systolic wave in the ICG signal. Velocity index is measured in terms of per 1000 secs.

2.7 Fluid Status

The status of all fluids [11] like blood is considered. Status can be the flow, impedance (in case of ICG) etc. The main parameters are:

1) Basal impedance, Z_o
2) Thoracic Fluid Index
3) Thoracic Fluid Content

2.7.1 Basal Impedance, Z_o

Basal impedance, Z_o, is the total impedance offered by the body segment between the voltage electrodes. It depends on the type of measurement segment (muscle-bone ratio, diameter) and on the measurement electrode distance. Since exact standard electrode positions don't exist, the absolute value is less important

than changes. Changes in Z_o can be caused by changes in venous blood volume or by edema. Basal impedance is measured in terms of ohms.

2.7.2 Thoracic Fluid Index

Thoracic fluid index is the baseline thoracic impedance, Z_0. It is measured in terms of ohms.

2.7.3 Thoracic Fluid Content

Thoracic Fluid Content is defined as the electrical conductivity of the chest cavity, which is primarily determined by the intravascular and interstitial fluids in the thorax. Thoracic fluid content is measured in terms of per kohm.

The formulae used for calculating all these parameters are given in Appendix A.

CHAPTER 3

DETECTION OF BCX COMPLEX

3.1 INTRODUCTION

BCX complex is known as the systolic wave in ICG signal. So it is very important to detect this complex. In this work the complex is detected using Artificial Neural Networks. But why ANN? Of course in the previous years techniques such as power spectra analysis [5,6] of ICG were carried out.

J.Fortin, W.Habenbacher in their work designed a system [5] for the online analysis of all relevant hemodynamic parameters. In their work for online monitoring of the frequency content of a biological signal they used "Recursive Least Square Algorithm". For the analysis of parameters the system consists of patient Biosignal electronic system (PBES), ECG, ICG, continuous blood pressure and pulse oximetry. Using all these signals, hemodynamic parameters were calculated. For the analysis of each signal a different technique is used. But the parameters that were calculated by them can be calculated using ICG signal itself.

An Advanced Signal Processing Technique for ICG was developed using Wigner Distribution (WD) and Pseudo-Wigner Distribution [6]. This technique has been developed for the enhancement of the ICG signal. The time-frequency distribution is used to identify the "B", "C" and "X" points from the ICG signal for the computation of LVET and $\frac{dZ}{dt}_{\max}$. With this technique, many of event points were clearly identifiable. However this technique had some limitations. When actually using the PWD, a larger amount of computational power is needed. This will increase the measuring time; where as the computation for the spectrogram may be much less.

Research work has been done using ANN for ICG signal. Using ANN motion artifacts in IPG were detected [8]. For this detection a 3 – layered neural network was used. The input for this network is the raw IPG signal and the output gives whether motion artifact is present or absent.

One of the hemodynamic parameter Stroke Volume is computed from ICG signal using ANN [7]. For this computation also a 3 – layered neural network was used. The input for this neural network are the parameters used for the calculation of stroke volume. So before giving the inputs to the network they must be calculated manually. The output of the network is the stroke volume.

In the present work, the neural network depicts "B", "C" and "X" points. Using these points hemodynamic parameters are calculated.

3.2 Block diagram for the detection of BCX complex:

The following block diagram shows how this complex is detected.

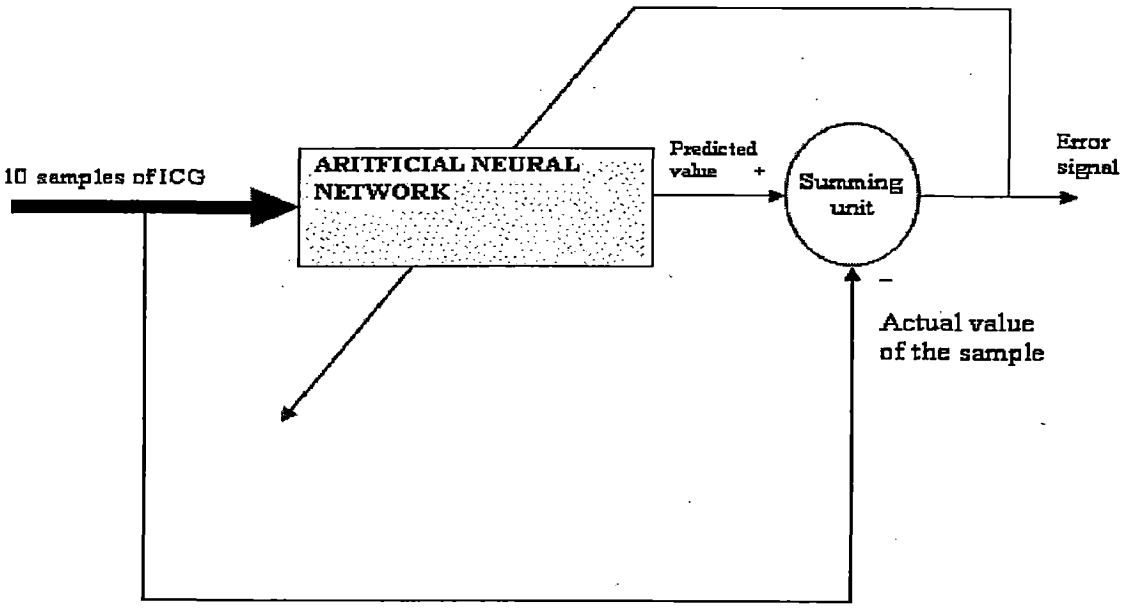


Figure #.1 Block Diagram for the detection of BCX complex

In this detection, the input is digitized ICG signal. The neural network receives the input i.e., a set of last ten ICG signal samples. The output of the neural network is the predicted next sample. In the prediction of next sample the neural network predicts the non-BCX samples. The summing unit in the block diagram computes the error in the prediction as the difference between the actual value of current input and its predicted value from the neural network.

3.3 Neural Network Architecture:

The neural network used is a multilayered perception. In this work it is 3-layered, as shown in the below figure.

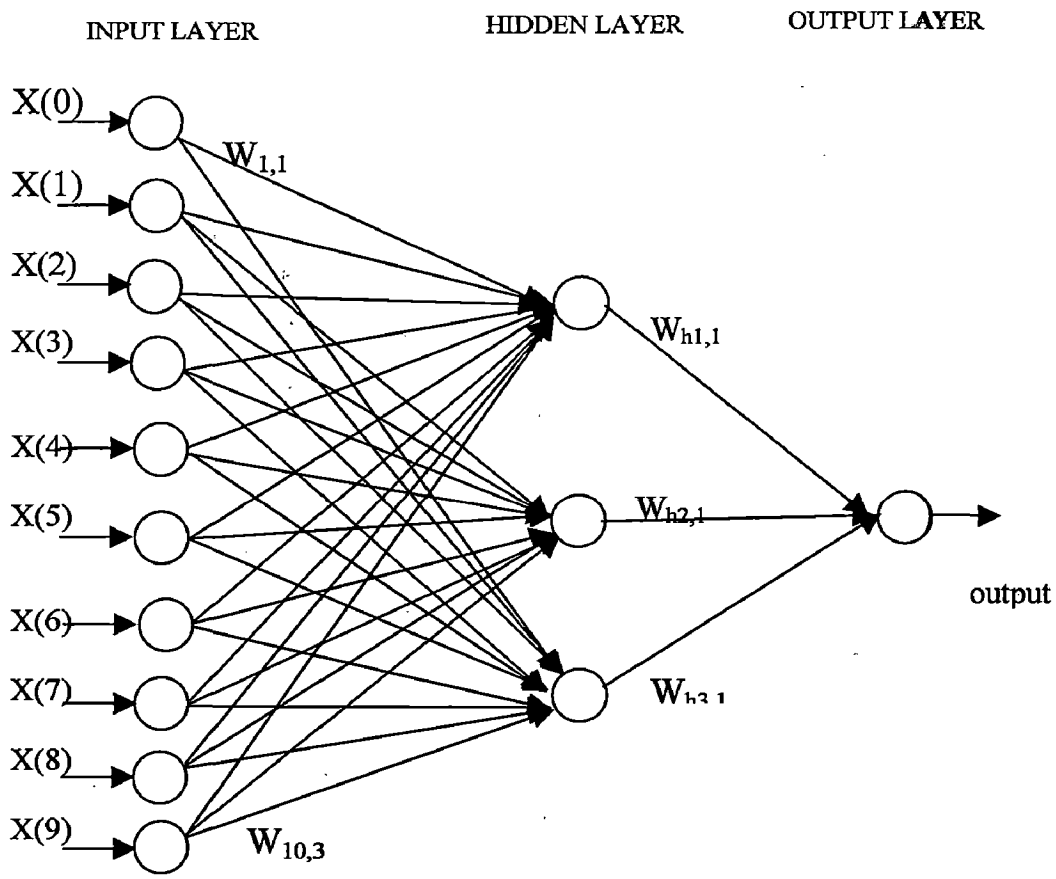


Figure 3.2 Architecture of ANN

The network used is a feed forward back-propagation neural network, having a sigmoid transfer function.

During the training phase the network not only receives the ten samples of ICG but also the error computed by the summing unit in order to adjust the interconnection strengths of the neural network. As said earlier this network takes the 10 samples of ICG signal as input and predicts the next sample of the ICG signal. The output is a non-BCX sample. For BCX complex samples the output of the network is low (almost zero). This is because at the output of summing unit maximum error is obtained at C point position.

3.4 Training Phase of Neural Network:

The flow chart in figure 3.3 depicts the training phase. In the training phase a normal ICG signal is taken which has 255 BCX complexes. As said earlier that the network depicts the non-BCX complex samples, first the network takes the last ten samples of ICG signal and checks whether the samples contain non-BCX segment or not. If the samples contain BCX samples, the output is low and the network takes next set of input without adjusting the interconnection strengths. If the samples contain non-BCX samples, the network will adjust the interconnection strengths and error is computed at the output. The error is computed by adjusting the interconnection strengths till the error is minimum. If the error is minimum then next set of input is taken and the above process is continued till all the training sets are exhausted.

In this way the neural network is trained for all the non-BCX complex samples. After the training of the network all the interconnection strengths i.e., weights and biases are stored so that the neural network is used for other data sets of ICG signal.

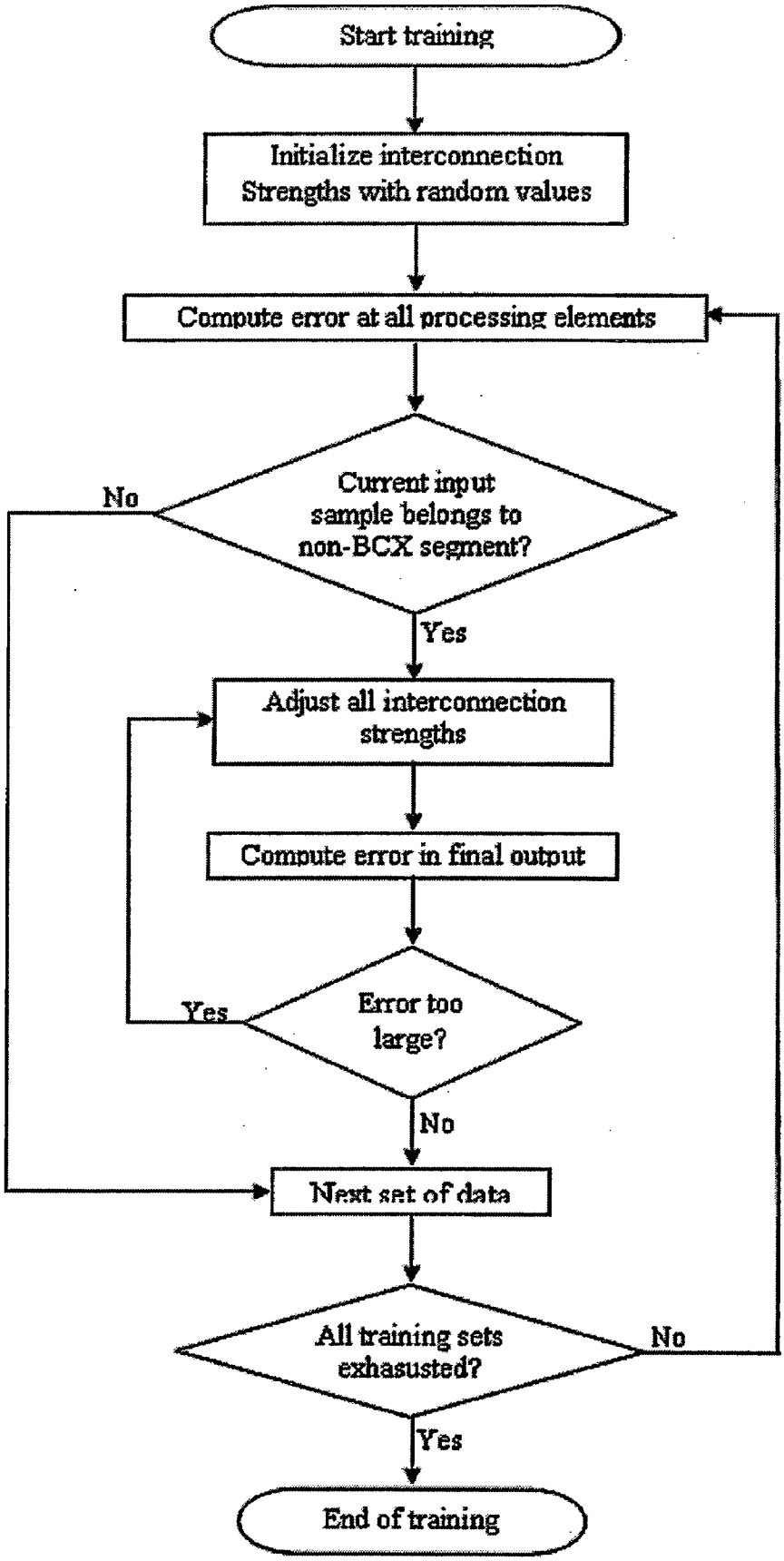


Figure 3.3: flowchart depicting the training phase

3.5 BCX-complex Analysis:

The neural network is now ready for the prediction of ICG signal as mentioned in the previous section. The error computed by the summing unit (figure 3.1) highlights the BCX-complex as the network depicts the non-BCX points. For this purpose two points were considered. One, the window width and two, the threshold value. With this consideration first C point is detected. After detecting C peak B and X peaks are detected using the back sloped algorithm. This way the position of B, C or X peaks is located as illustrated in the below figure.

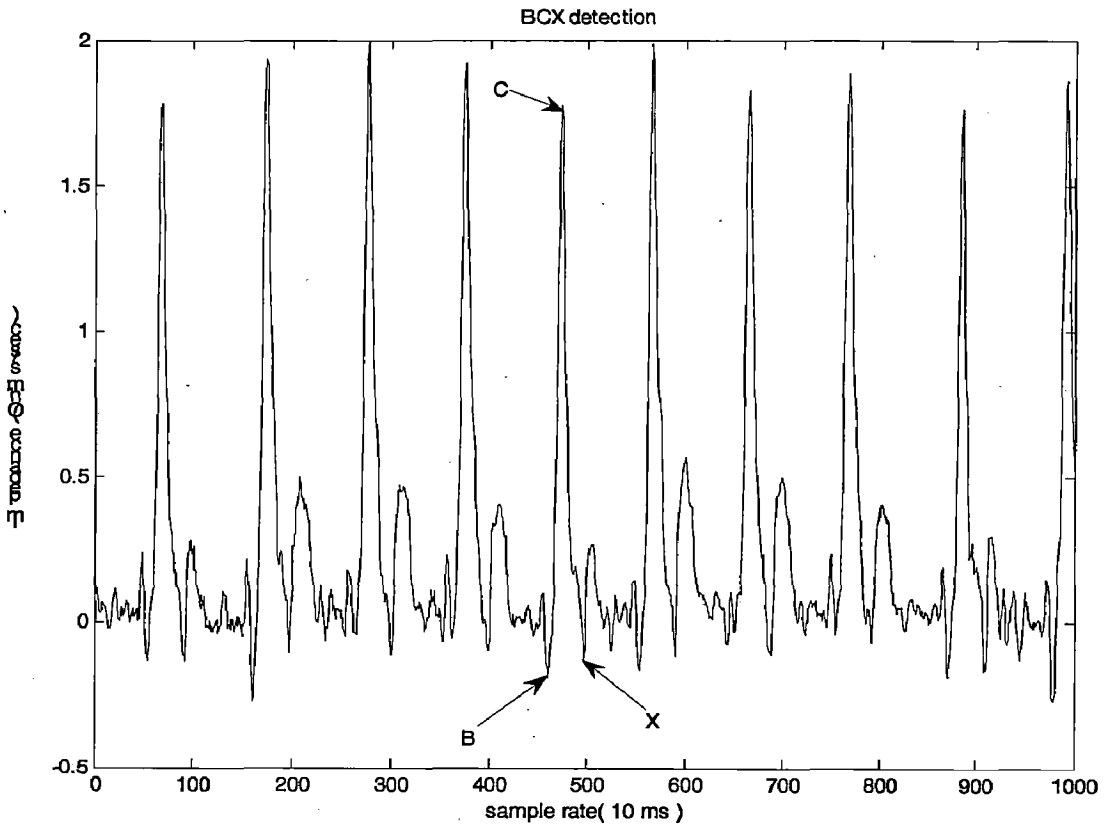


Figure 3.4 ICG signal (output of summing unit)

The positions of B, C and X points obtained from the above graph are shown in table 3.1(b). In table 3.1(a) the actual positions of B, C and X points are shown.

Table 3.1(a): actual location of BCX points

Sample number of			
Sl.no	B point	C point	X point
1	64	79	100
2	171	184	198
3	274	286	300
4	372	385	404
5	470	483	496
6	563	576	592
7	666	674	688
8	764	778	796
9	887	896	904

Table 3.1(b) : ANN based BCX detection:

Sample number of			
Sl.no	B point	C point	X point
1	54	69	90
2	161	174	189
3	264	276	290
4	362	375	394
5	460	473	486
6	553	566	582
7	656	664	678
8	754	768	786
9	877	886	894

The values in table 3.1(a) are the actual sample numbers of B, C and X points and those in table 3.1(b) are the sample numbers depicted using the neural network. In the above tables only nine BCX sample numbers were shown. But in the prediction all the 255 BCX complex samples detected. On observing the tables the predicted values are 10 less than that of the original. This is because the prediction of samples starts from the 11^{th} sample. The first 10 samples are the first input set to the neural network. Hence there is always a delay of 10 samples in every detection.

Using these position values the amplitudes of B, C and X points are obtained and are used for the calculation of Hemodynamic Parameters.

CHAPTER 4
RESULTS AND DISCUSSIONS

The neural network after training is stored for the simulation of the desired ICG signal so that the hemodynamic parameters are calculated. About training of neural network and hemodynamic parameters were discussed in the previous chapters. In this chapters the results obtained are discussed and also about the future scope.

4.1 GUI

The following figure is the Graphical User Interface (GUI) used for loading the desired file and obtaining the values of the hemodynamic parameters.

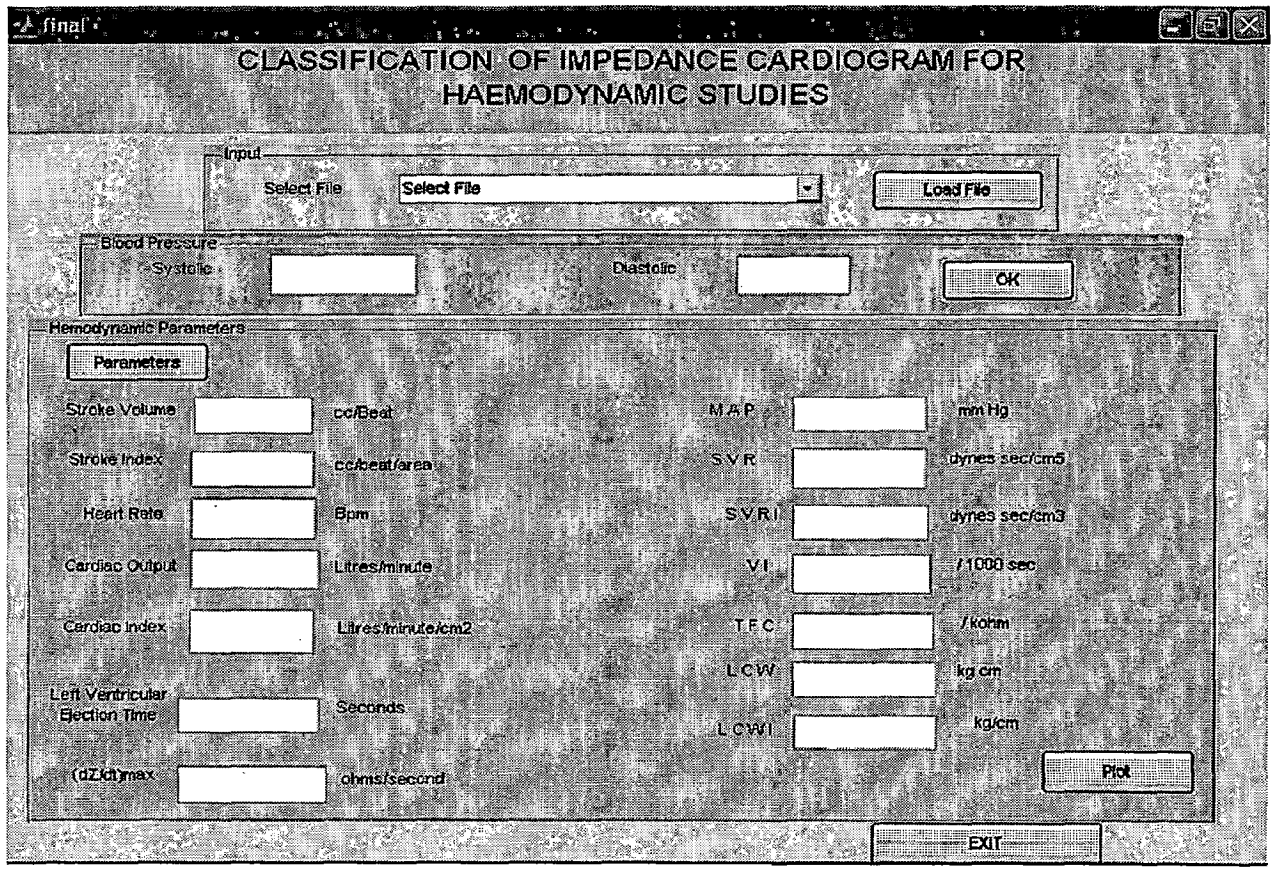


Figure 4.1: GUI of the work

First the desired file is selected from the select file option and the same is loaded. Then the systolic and diastolic blood pressures are to be given in the blood pressure panel. Then by clicking the parameter button value of various parameters are obtained in the boxes shown. For plotting the result signal, press the button PLOT. In this work 5 data files each having 255 BCX complexes are taken for the calculation of hemodynamic parameters. All the data files are of normal subjects only. The graphs of these files and the parameter values obtained are shown in the following figures.

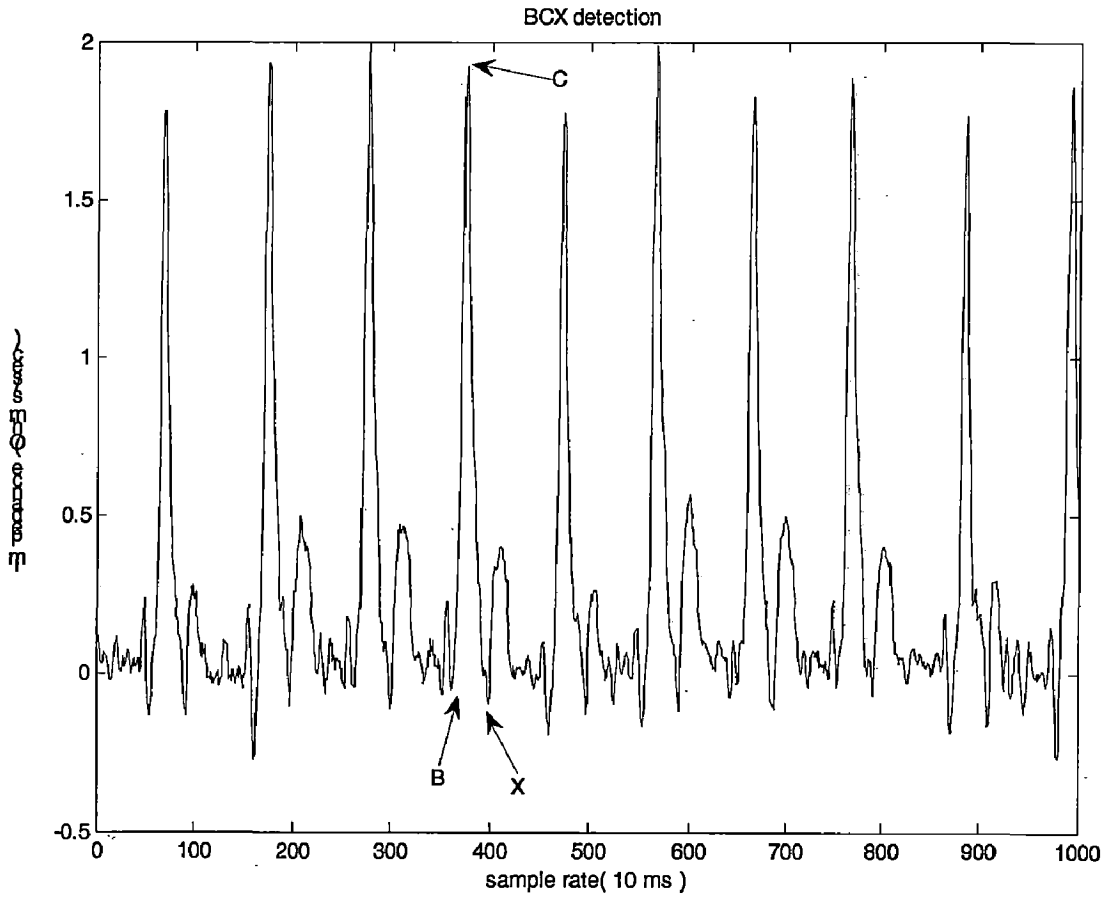


Figure 4.2: result signal of data file 1

Table 4.1 Hemodynamic parameter values for the data file1

Sl.no	Hemodynamic parameter	Data file 1	
		Actual values	Calculated values
1	Stroke Volume	84.66	83.95
2	Stroke Index	0.135	0.134
3	Heart Rate	70	71
4	Cardiac Output	5.92	5.96
5	Cardiac Index	0.0095	0.0095
6	Left Ventricular Ejection Time	0.37	0.38
7	$(dZ/dt)_{max}$	1.379	1.389
8	Mean Arterial Pressure	93	93
9	Systematic Vascular Resistance	1175.68	1167.76
10	Systematic Vascular Resistance Index	732.63	729.85
11	Velocity Index	58.01	58.44
12	Thoracic Fluid Content	42.07	42.07
13	Left Cardiac Work	7.076	7.123
14	Left Cardiac Work Index	0.0113	0.0114

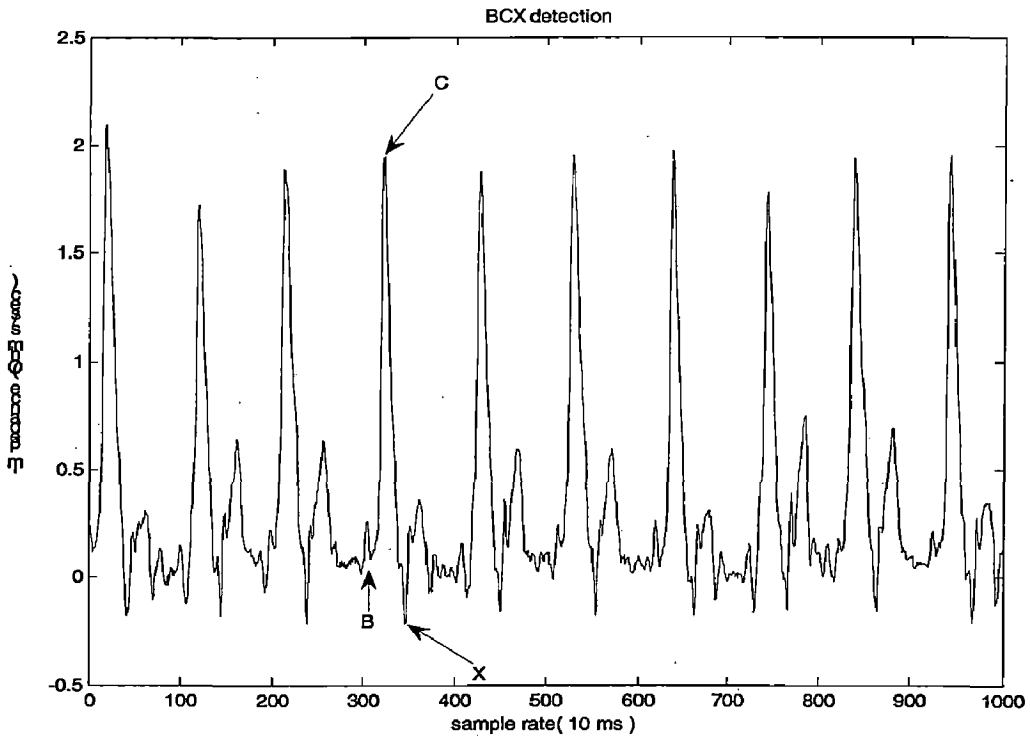


Figure 4.3: result signal of data file 2

Table 4.2 Hemodynamic parameter values for the data file2

Sl.no	Hemodynamic parameter	Data file 2	
		Actual values	Calculated values
1	Stroke Volume	72.59	87.31
2	Stroke Index	0.116	0.140
3	Heart Rate	68	68
4	Cardiac Output	4.93	5.64
5	Cardiac Index	0.0079	0.0095
6	Left Ventricular Ejection Time	0.38	0.46
7	$(dZ/dt)_{max}$	1.228	1.340
8	Mean Arterial Pressure	93	93
9	Systematic Vascular Resistance	1410.10	1172.76
10	Systematic Vascular Resistance Index	881.31	732.71
11	Velocity Index	50.02	54.56
12	Thoracic Fluid Content	40.73	40.73

13	Left Cardiac Work	5.899	7.096
14	Left Cardiac Work Index	0.0094	0.0113

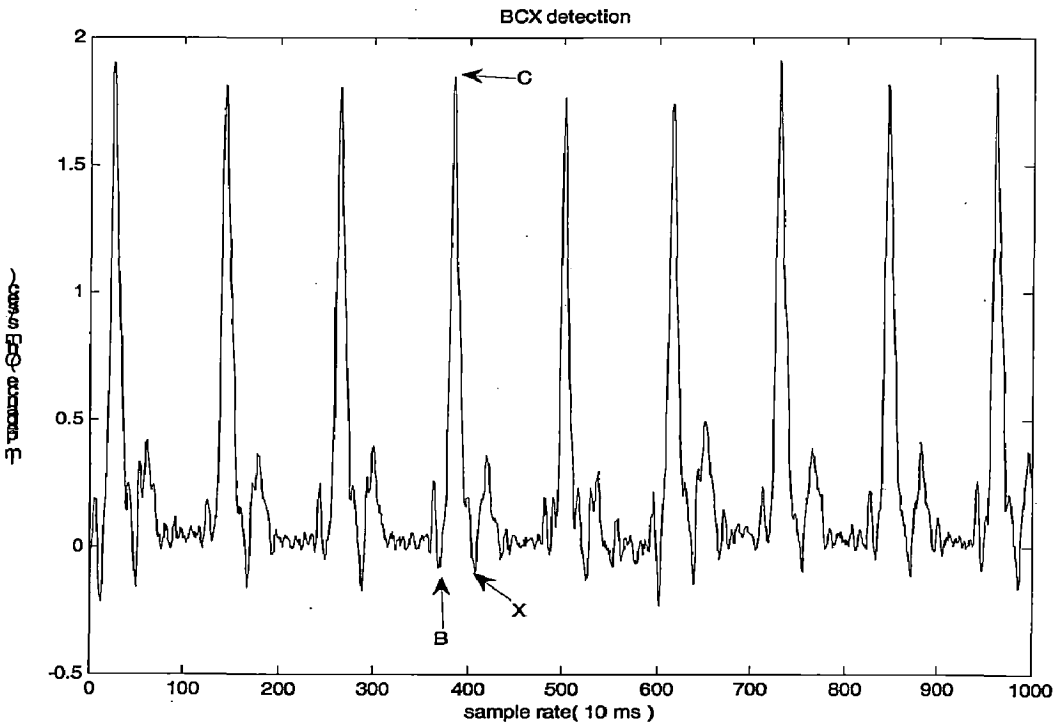


Figure 4.4: result signal of data file 3

Table 4.3 Hemodynamic parameter values for the data file3

Sl.no	Hemodynamic parameter	Data file 3	
		Actual values	Calculated values
1	Stroke Volume	85.47	91.19
2	Stroke Index	0.137	0.146
3	Heart Rate	74	75
4	Cardiac Output	6.32	6.84
5	Cardiac Index	0.0101	0.0110
6	Left Ventricular Ejection Time	0.37	0.38
7	$(dZ/dt)_{max}$	1.347	1.465
8	Mean Arterial Pressure	93	93
9	Systematic Vascular Resistance	1100.33	1017.7

10	Systematic Vascular Resistance Index	687.71	636.05
11	Velocity Index	57.61	62.67
12	Thoracic Fluid Content	42.77	42.77
13	Left Cardiac Work	7.56	8.174
14	Left Cardiac Work Index	0.0120	0.0131

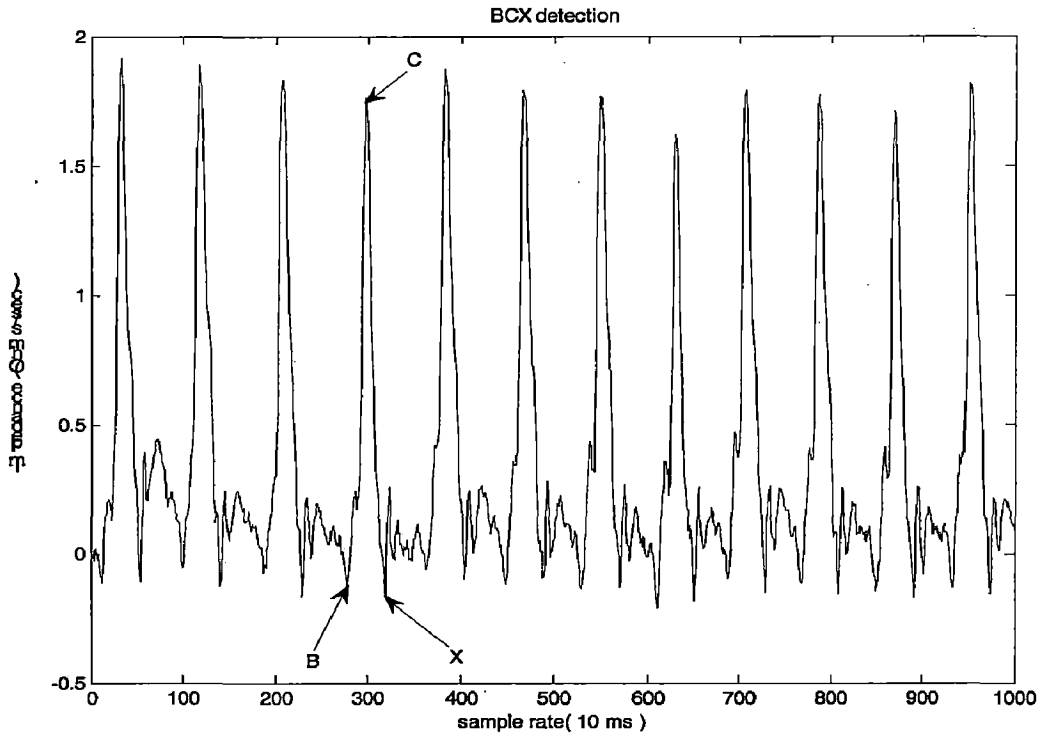


Figure 4.5: result signal of data file 4

Table 4.4 Hemodynamic parameter values for the data file 4

Sl.no	Hemodynamic parameter	Data file 4	
		Actual values	Calculated values
1	Stroke Volume	55.93	57.14
2	Stroke Index	0.0093	0.091
3	Heart Rate	84	85
4	Cardiac Output	4.76	4.86
5	Cardiac Index	0.0072	0.0078
6	Left Ventricular Ejection Time	0.42	0.42
7	$(dZ/dt)_{max}$	1.433	1.354

8	Mean Arterial Pressure	93	93
9	Systematic Vascular Resistance	1502.7	1432.1
10	Systematic Vascular Resistance Index	1026.7	892.31
11	Velocity Index	54.88	51.85
12	Thoracic Fluid Content	38.30	38.30
13	Left Cardiac Work	5.614	5.809
14	Left Cardiac Work Index	0.0092	0.0093

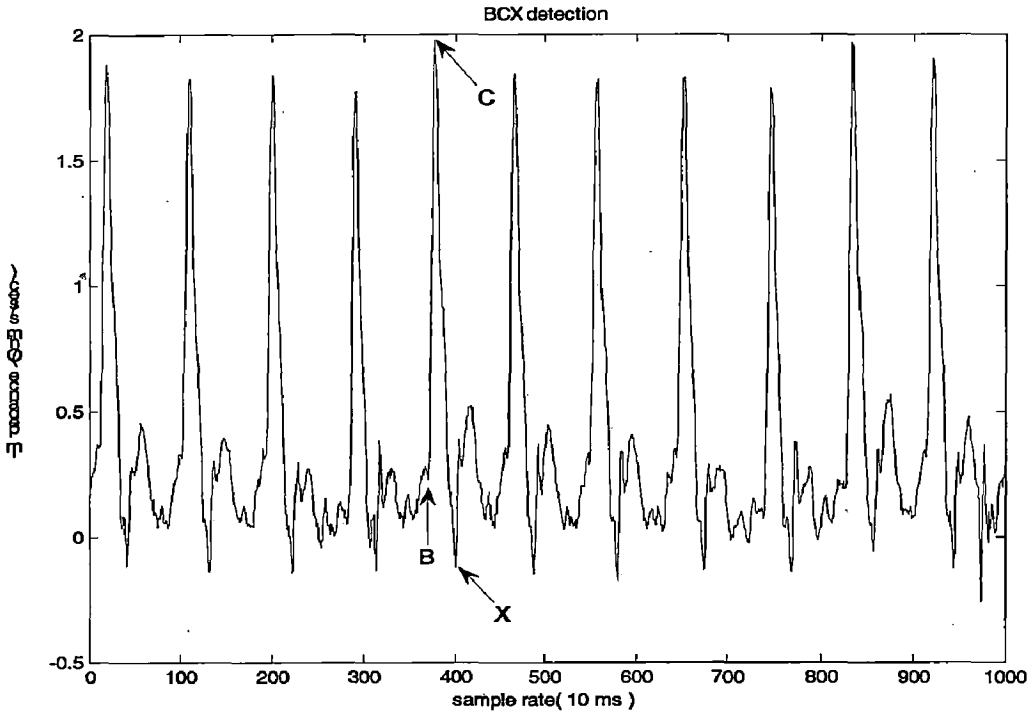


Figure 4.6: result signal of data file 5

Table 4.5 Hemodynamic parameter values for the data file 5

Sl.no	Hemodynamic parameter	Data file 5	
		Actual values	Calculated values
1	Stroke Volume	59.49	49.24
2	Stroke Index	0.095	0.079
3	Heart Rate	63	63
4	Cardiac Output	3.75	3.10
5	Cardiac Index	0.0060	0.0050

6	Left Ventricular Ejection Time	0.29	0.3
7	$(dZ/dt)_{max}$	1.196	1.278
8	Mean Arterial Pressure	93	93
9	Systematic Vascular Resistance	1857.19	2243.68
10	Systematic Vascular Resistance Index	1160.75	1402.3
11	Velocity Index	51.15	54.68
12	Thoracic Fluid Content	42.77	42.77
13	Left Cardiac Work	4.477	3.707
14	Left Cardiac Work Index	0.0072	0.0059

4.2 Discussion

The parameters shown in the table are calculated using the formulae given in appendix A. In the present work five data files of normal subjects are used. Each data file consists of 255 BCX complexes are. The values obtained are within the normal range [4,11] indicating that the subjects are normal. For abnormal conditions the parameter values will be out of range .

As discussed earlier these parameters are useful in determining the functionality and condition of the circulatory system. In the GUI figure (shown in figure 4.1) some parameters like systolic blood pressure (SBP) and diastolic blood pressure (DBP) are to be given manually for the calculation of the parameters like MAP, SVR, SVRI.

4.3 Conclusion

In the present work Artificial Neural Network is used for the detection of BCX complex. The following are the conclusions

1) Due to the limitations of the previous methods for calculating the hemodynamic parameters using ICG signal ANN prediction is used. ANN is useful in predicting the BCX complex. The reason for taking the 3 – layered neural network is: if the network is having more number of neurons in the hidden layer then the training time of the network is increased.
2) Care has been taking for the detection of B and X points. Because in the case of Aortic Incompetence [] disease a slur is present in the down stroke of the 'C' – wave.
3) In this work five data files of normal subjects are used for calculating the hemodynamic parameters. Each data file consists of 255 BCX complexes. The parameters calculated are within the normal range. For abnormal data files the values of parameters will be out of range. For example, in case of hypertension the value of stroke volume is more and there by increasing the value of cardiac output and that of LCW.

4.4 Future Scope

The data files used in this work are of normal subjects. By taking some abnormal cases diseases like hypertension can be detected. This work can be extended for detecting the remaining points like Y, O, and Z. When these points are detected using the morphology of the signal many diseases like mitral stenosis and mitral incompetence can be diagnosed.

APPENDIX A
FORMULAE USED

Stroke Volume:

$$SV\,(in\,cc/beat) = \rho \frac{L^2}{Z_o^2} T_{LVET} \left(\frac{dZ}{dt}\right)_{\max}$$

Where,

ρ = Blood resistivity; ohm-cm

L = Length between the voltage electrodes; cms

Z_o = Basal impedance; ohms

T_{LVET} = Left ventricular ejection time; seconds

$\left(\frac{dZ}{dt}\right)_{\max}$ = Maximum height of $\frac{dZ}{dt}$ waveform; ohm/sec

Cardiac output:

$$CO = \frac{SV\,x\,HR}{1000} \quad \text{Liters/min}$$

Where,

SV = Stroke Volume; cc/beat

HR = Heart Rate; beats/min

Stroke Index:

$$SI = \frac{SV}{BSA} \quad \text{cc/beat/m}^2$$

Where,

BSA = Body Surface Area; cm^2

Cardiac Index:

$$CI = \frac{CO}{BSA} \text{ l/min/m}^2$$

Mean Arterial Pressure:

$$MAP = \frac{SBP - DBP}{3} + DBP \text{ mm Hg}$$

Where,

SBP = Systolic Blood Pressure; mm Hg

DBP = Diastolic Blood Pressure; mm Hg

Systemic Vascular Resistance:

$$SVR = 80. \frac{MAP - CVP}{CO} \text{ dynes sec/cm}^5$$

Where,

CVP = Central Venous Pressure; mm Hg

Systemic Vascular Resistance Index:

$$SVRI = 80. \frac{MAP - CVP}{CI} \text{ dynes sec m}^2 / \text{cm}^5$$

Velocity Index:

$$VI = \frac{\left(\frac{dZ}{dt}\right)_{\max}}{TFI} / 1000 \text{ sec}$$

Thoracic Fluid Content:

$$TFC = \frac{1}{TFI} \text{ /k ohm}$$

Left Cardiac Work:

$$LCW = (MAP - PAWP)x.COx0.0144 \text{ kg m}$$

Left Cardiac Work Index:

$$LCWI = (MAP - PAWP)xCIx0.0144 \text{ kg m/m}^2$$

REFERENCES

1. Biomedical Transducers & Instruments – Tatsuo Togawa, Toshiyo Tamura, P.Ake Oberg

2. Electrical Impedance & Photo Plethysmography for medical applications – G.D.Jindal, T.S. Ananthakrishan, S.K. Kataria, Vineet Sinha, Rajesh Kumar Jian, Sadhana A.Mandlik, A.R.Kini, Mousami A. Nail, S.K. Singh, BARC

3. Biomedical Instrumentation and Measurements – Leslie Cromwell, Fred J. Weibell, Erich A. Pfeiffer

4. chapter 25 : impedance cardiography from the ebook http://butler.cc.tut.fi/~malmivuo/bem/bembook/25/25.htm

5. Real – Time Monitor For Hemodynamic Beat – To – Beat Parameters And Power Spectral Analysis of the Biosignals : J.Fortin, W. Habenbacher, P.Wach, F.Skrabal: Proceedings of the 20th Annual conference of the IEEE Engineering and Biology Society, Vol. 20, No 1, 1998.

6. An Advanced Signal Processing Technique for Impedance Cardiography – Xiang Wang, Hun H.Sun and Joseph M. Van De Water: IEEE Transactions on Biomedical Engineering, vol. 43, No 2, February 1995.

7. Electrical Impedance Cardiography Using Artificial Neural Networks – Ajitkumar P.Mulavara, William D. Timmons, Meera S. Nair, Vineet Gupta,

Amaresh A. R. Kumar, and Bruce C. Taylor: Annals of Biomedical Engineering Vol. 26, pp. 577 – 583, 1998.

8. Detection of Motion Artifacts in Electrical Impedance Plethysmography Signals using Neural Networks – Dinesh G. Haryadi, Sastry K.L.A., Ramnath Boreda, William D. Timmons, Bruce C.Taylor: 0-7803-1377-1/93 IEEE

9. Heart Information Series. Number 4 March 2005 British Heart Foundation 14 Fitzhardinge Street, London W1H 6DH

10. Biopac systems Manual Version 3.8.3 2/10/05 AcqKnowledge 3.8.1 Windows PC nad 3.9 Mac OS

11. Impedance Cardiography: Summary of Recent Literature – Wantagh Incorporated, Noninvasive Hemodynamic Technologies.

12. Left Ventricular Function in Chronic Fatigue Syndrome: Data from Nuclear Ventriculography Studies of Response to Exercise and Postural Stress Arnold Peckerman Benjamin Natelson et al Experimental Biology: American Physiological Society Conference, 11-15th April 2003, San Diego, CA