Cardiac Function Evaluation of Healthy Young Adults by Consuming Energy Drinks

By

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Biomedical Engineering

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Declaration

This is to certify that the thesis work entitled "**Cardiac Function Evaluation of Healthy Young Adults by Consuming Energy Drinks**" has been carried out by **Md. Bashir Uddin** in the Department of Biomedical Engineering, Khulna University of Engineering & Technology, Khulna, Bangladesh. The above thesis work or any part of this work has not been submitted anywhere for the award of any degree or diploma.

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Abstract

Energy drink (ED) is a beverage that mainly contains some form of legal stimulants which are supposed to give consumers a short term boost in energy. It is a type of beverage containing caffeine as main stimulant, which is marketed as providing both mental and physical stimulation. With ED becoming a worldwide phenomenon, the short- and long-term effects of these beverages must be evaluated more closely in order to fully comprehend the psychological impact of these products. The market and degree of consumption of ED is increasing every year, but only few have global knowledge of their ingredients and actual physiological and psychological effects. Although ED have been sold worldwide for more than a decade, only a few published studies have examined their effects on health and well-being. The effects of ED consumption on physiological and psychological are more or less investigated but the effects of ED consumption on heart activity or cardiac function aren't well studied. The main aim of this study is to evaluate cardiac function of healthy young adults by consuming ED analyzing different cardiac signals. The modeling of cardiac signals with consuming ED is the partial objective of this study.

The electrical activity of the heart over a period of time can be represented by the properties of Electrocardiogram (ECG) wave. Photo Plethysmogram (PPG) is the tactile arterial palpation of the heartbeat which is also known as pulse. ECG and PPG signals are used in this study as cardiac signals which are recorded by biopac accessories from healthy human subjects. ECG is recorded using electrode lead set connected to MP36 data acquisition unit. PPG (pulse) is also recorded using pulse transducer connected to the same MP36 data acquisition unit. ECG and PPG are recorded at both before and after the consumption of ED. The Laser Doppler Flowmetry (LDF) recording is also done for results verification for certain subjects. The consumption of ED affects heart activity that is determined in this study using electrocardiographic and photo plethysmographic parameters. The ECG parameters analysis show significant reduction in their corresponding amplitude as well as heart rate due to having ED. The amplitude of R wave of ECG increases little bit that may give short-term boost of energy. A notable decrement in peak to peak amplitude of PPG as well as pulse rate is observed due to having ED. The

spectrum or frequency components for ECG as well as PPG signal decreases with a significant rate from the instant of having ED. That is, the spectrum parameters of cardiac activity decrease due to the consumption of energy drinks. The spectrum analysis of LDF signal also results similar type of decrement in their spectrum parameters for same type of energy drinks consumption. This LDF signal analysis validates our main experimental results. These results reflect adverse impacts of energy drinks consumption on cardiac activity.

ECG is the main cardiac signal which represents complete cardiac function which is the measurement of bio-electric potential produced by rhythmical cardiac activities (contraction and relaxation) of the cardiac muscle. Different cardiac functions can be easily identified by ECG that's why ECG modeling is the most important with the consumption of energy drinks. Different techniques have been developed in the past for modeling of ECG. An ECG model is proposed in this study using peak amplitude based Gaussian function with some modifications in both before and after having ED. This model is best suited with practical ECG parameters. Using this ECG model it is possible to find out cardiac parameters which are needed for the evaluation of cardiac function with having ED. In this research, we have find out cardiac parameters using our ECG model and compared with real ECG parameters. The comparison results less error between real ECG and model ECG in the evaluation of cardiac function with consuming ED. Thus this ECG model is effective to evaluate cardiac function with the consumption of ED.

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List of Abbreviations

ECG	Electrocardiogram
EKG	Electrokardiogram
PPG	Pulse Plethysmogram
ED	Energy Drinks
SD	Standard Deviation
MRI	Magnetic Resonance Imaging
VAT	Ventricular Activation Time
BPM	Bits Per Minute
HR	Heart Rate
LED	Light Emitting Diode
DSP	Digital Signal Processing
FFT	Fast Fourier Transform
DFT	Discrete Fourier Transform
PSD	Power Spectral Density
MSE	Mean Square Error
NMSE	Normalized Mean Square Error
RMSE	Root Mean Square Error
NRMSE	Normalized Root Mean Square Error
PNRMSE	Percentage Normalized Root Mean Square Error
LDF	Laser Doppler Flowmetry
BPU	Blood Perfusion Unit

Nomenclature

$x(t)$ = A signal

$x(\omega)$ = Fourier transform of a signal $x(t)$

E = Energy of a signal $x(t)$

ω = Angular frequency

$S_{xx}(\omega)$ = Energy/power spectral density of a signal $x(t)$

P = Total power of a signal $x(t)$

$x_T(\omega)$ = Truncated Fourier transform of a signal $x(t)$

$F(t)$ = Gaussian function/Recorded ECG signal

A, B, C, D = Real constant

$F_P(t)$ = Gaussian function for P wave

$F_Q(t)$ = Gaussian function for Q wave

$F_R(t)$ = Gaussian function for R wave

$F_S(t)$ = Gaussian function for S wave

$F_T(t)$ = Gaussian function for T wave

$F_{ECG,M}(t)$ = Function to generate ECG signal with mathematical model

$F_M(t)$ = ECG signal generated by mathematical model

$F_{ECG,MM}(t)$ = Function to generate ECG signal with modified mathematical model

M = Factor of multiplication

$F_{ECG,BD}(t)$ = Function to generate ECG signal before having ED

$F_{ECG,AD}(t)$ = Function to generate ECG signal after having ED

Chapter I

Introduction

1.1 State of Art

An energy drink is a beverage that contains some form of legal stimulant and/or vitamins which are supposed to give consumers a short term boost in energy. It is a type of beverage containing stimulant drugs, chiefly caffeine, which is marketed as providing mental or physical stimulation. They may or may not be carbonated, and generally contain large amounts of caffeine and other stimulants, and many also contain sugar or other sweeteners, herbal extracts and amino acids.

Energy drinks were an active subset of the early soft drink industry, which was originally dominated by pharmacists and less scrupulous patent medicine salesmen. Coca-Cola, for instance, was originally marketed as an energy booster. In the early 1980s, it was promoted as an energy drink for 'replenishing lost energy' and developed an "energy booster" drink containing B vitamins, caffeine and cane sugar. In 1985, Jolt Cola was introduced in the United States. Its marketing strategy centered on the drink's caffeine content, billing it as a means to promote wakefulness. The initial slogan was, 'All the sugar and twice the caffeine'. In 1995, PepsiCo launched Josta, the first energy drink introduced by a major US beverage company, but Pepsi discontinued the product in 1999. Pepsi would later return to the energy drink market with the AMP brand. Red Bull is the dominant brand in the US after its introduction in 1997, with a market share of approximately 47% [1]. In New Zealand and Australia, the current leading energy drinks product in those markets V was introduced by Frucor Beverages. It is now serves over 60% of market in New Zealand and Australia [2]. By 2001, the US energy drink market had grown to nearly 8 million per year in retail sales. Over the next 5 years, it grew an average of over 50% per year, totaling over $3 billion in 2005 [3]. The market is currently estimated at over $12.5 Billion, having grown 60% between 2008-2012 [4].

A 2008 statewide Patient Poll conducted by the Pennsylvania Medical Society's Institute for Good Medicine found that: 20% of respondents ages 21–30 had used energy drinks in high school or college to stay awake longer to study or write a paper; 70% of respondents knew someone who had used an energy drink to stay awake longer to study or work [5]. Since 2002, there has been a growing trend for packaging energy drink in bigger cans. Since in many countries, including the US and Canada, there is a limitation on the maximum caffeine per serving in energy drinks, this allows manufacturers to include a greater amount of caffeine by including multiple servings per container. Popular brands such as Red Bull, Hype Energy Drinks and Monster have increased the amount of ounces per can. As of 2009, the industry has moved towards the use of natural stimulants and reduced sugar. On August 14, 2012, the word "energy drink" was listed for the first time in the mainstream Merriam-Webster's Collegiate Dictionary [6].

Energy Drinks (ED) are a group of beverages used by consumers to provide an extra boost in energy, promote wakefulness, maintain alertness, and provide cognitive and mood enhancement [7]. Energy drinks mostly contain caffeine, taurine, l-carnitine, carbohydrates, glucuronolactone, vitamins, and other herbal supplements like ginseng and guarana among others [8]. Additives such as guarana, yerba mate, cocoa, and kola nut may increase the caffeine content of energy drinks unbeknownst to consumers [9], as manufacturers of these products are not required to include the caffeine content of these herbal supplements in the nutritional information [10].

Energy drinks contain some form of legal stimulant which are meant to give consumers a short term boost in energy [11]. The “Magical” Ingredients of these drinks have one thing in common: all of them contain a lot of caffeine. These could be considered the “active ingredients” [12]. A typical energy drink can contain up to 80 milligrams of caffeine (about the same amount as a cup of coffee) [13]. Different brands of energy drinks contain caffeine ranging from 50mg to 550mg per can or bottle. Energy drinks have added caffeine and other ingredients that their manufacturers say increase stamina and "boost" performance. They're designed for students, athletes and anyone else who wants an extra energy kick. Caffeine is one of the most commonly consumed alkaloids worldwide in the form of coffee, tea, or soft drinks, and in high doses may cause abnormal stimulation of the nervous system [14], as well as adverse effects in the cardiovascular, hematologic, and gastrointestinal systems [10]. With energy drinks becoming a worldwide phenomenon, the

short- and long-term effects of these beverages must be evaluated more closely in order to fully comprehend the psychological impact of these products. The market and degree of consumption of energy drinks is increasing every year, but only few have global knowledge of their ingredients and actual physiological and psychological effects [15].

Energy drinks are caffeinated beverages designed primarily to increase the consumer's physical endurance. Companies that market these products usually target young adults. A survey of energy drink consumption by young people revealed that 51% reported consuming at least one energy drink per month [16]. It should be noted that, although energy drinks have been sold worldwide for more than a decade, only a few published studies have examined their effects on health and well-being. The effects of energy drink consumption on hemodynamic and electrocardiographic parameters were investigated in healthy young adults, and reported a significantly changed heart rate and blood pressure within 4 hours [17]-[18]. The effects of energy drinks consumption on blood perfusion in healthy young adults were studied using Laser Doppler Flowmetry to evaluate respiratory and heart function [19], as well as using Wavelet Transform to find out Metabolic, Sympathetic and Myogenic Function [20]. These groups of beverages used by consumers that have stimulant effects on the central nervous system (CNS) and their consumption is accompanied by an expectation of improving user's performance physically and mentally [21]. Three studies published in two articles by Kennedy and Scholey demonstrate the positive effects of energy drinks on cognitive performance [22]-[23].

The electrical activity of the heart over a period of time can be represented by Electrocardiogram (ECG). Pulse (PPG) is the tactile arterial palpation of the heartbeat. ECG and PPG (Photo Plethysmogram) can be used to determine the cardiac activity or function using the parameters such as peak amplitude of different waves especially R peak amplitude, their intervals as well as segments, QRS complex, R-R interval, p-p amplitude of pulse, heart rate or pulse rate etc. The spectrum or frequency components of ECG and pulse (PPG) can also be used to evaluate cardiac function. The spectrum analysis of signal from human forearm skin has revealed five characteristic frequencies [24]-[25]. In addition to the cardiac and respiratory rhythms around 1 and 0.3 Hz, respectively [25]-[26], three frequencies have been detected in the regions around 0.1, 0.04, and 0.01 Hz in human skin [24]-[26]. Among these five frequency characteristics, heart or cardiac activity is detected within the frequency range about 0.6 to 1.6 Hz.

The effects of energy drinks consumption on cardiac functions haven't well studied yet and we hypothesized that the energy drinks consumption changes control mechanisms of cardiac activities which would result in differences in the parameters related to cardiac function. Determination of the effects of energy drinks consumption on cardiac function of healthy young adults is the main aim of this study by analyzing electrocardiographic and photo plethysmographic parameters as well as their spectrum components.

1.2 Objectives

The objectives of this research work are as follows:

- To determine the changes in cardiac activities due to the consumption of energy drinks (ED).
- To evaluate the impacts of having energy drinks on electrocardiography (ECG) and photo plethysmography (PPG).
- To evaluate cardiac functions by analyzing spectrum components of cardiac signals.
- To investigate the changes in peak amplitude of different waves of ECG as well as their intervals due to the consumption of ED.
- To propose a mathematical model for generating ECG with considering the effects of having energy drinks.
- To find the accuracy between the parameters of Real ECG and Model ECG.
- Finally, to validate the cardiac function by analyzing LDF signal due to having ED.

1.3 Contributions

The contributions of this research are listed below:

- Cardiac function parameters of different cardiac signals have been investigated with consuming ED and analyzing these parameters cardiac function is evaluated.
- An ECG model is proposed which can generate ECG signal at before and after having ED with low error rates.
- Proposed ECG model for the consumption of ED can be used to check heart parameters to evaluate cardiac function.

- Cardiac function evaluation has been justified by analyzing Laser Doppler Flowmetry. Results have been validated with spectrum analysis.

1.4 Potential Applications of this Research

The scope of this research is very wide-ranging. Some of them are:

- This research can be used to find out the impacts of energy drinks consumption on cardiac activity.
- The results of this study are applicable in investigation of cardiac function or cardiac parameter variations due to having energy drinks.
- The proposed ECG model can be applicable in modeling ECG in different physiological conditions.
- The proposed ECG model can also be applicable in modeling ECG with varying the type of energy drinks and the amount of caffeine.

1.5 Organization of the Thesis

Chapter I: This chapter contains introductory information such as short history and previous works on energy drinks, its impacts as well as the objectives, contribution and applications of this thesis.

Chapter II: In this chapter different types of energy beverages, their ingredients, and effects are discussed.

Chapter III: In this chapter different types of cardiac signals, their analysis to evaluate cardiac function are discussed as well as an ECG model is proposed to generate ECG at both normal and energized condition.

Chapter IV: This chapter deals with the final results of this research with elaborate discussions by analyzing different cardiac signal and their corresponding parameters.

Chapter V: In this chapter we have justified some of our summary results by analyzing Laser Doppler Flowmetry (LDF).

Chapter VI: Finally this section deals with concluding talks and future works.

Chapter II

Energy Drinks: A Caffeinated Beverage

2.1 Energy Beverages

Energy beverages are basically one type of caffeinated beverages or drinks that contain caffeine and other ingredients which are supposed to give consumers a short term boost in energy. A caffeinated drink or caffeinated beverage is a drink which contains caffeine, a stimulant which is legal and popular in most developed countries. The most common naturally caffeinated beverages are coffee and tea, which in one form or another (usually served hot, but sometimes iced) feature in most world cultures. Other drinks are artificially caffeinated as part of their production process. These include certain soft drinks (primarily cola drinks), and also energy drinks designed as a stimulant, and to perpetuate activity at times when the user might ordinarily be asleep.

The consumption of caffeinated drinks is often intended entirely or partly for the physical and mental effects of caffeine. Examples include the consumption of tea or coffee with breakfast in many westernized societies, in order to 'wake oneself up', or the deliberate consumption of energy drinks by students wishing to study through the night, or revellers seeking to maintain an alert attitude during social recreation. Examples of energy beverage or drinks are Tiger, Speed, Monster, Rockstar, RedBull etc as shown in Figure 2.1.

Tiger Speed Monster RedBull Rockster

Figure 2.1: Different types of energy drinks or beverages.

2.1.1 Energy Drink Brands

There are so many brands of energy drinks in the world. Different brands of energy drinks use their own specification to manufacture energy beverages. Red Bull continues to dominate as the energy drink leader, but Monster has experienced huge growth in the last few years. The energy drink market continues to grow even in light of the tough economy and increased health scrutiny. Soda sales have been declining steadily over the same period, while energy drink sales have been booming. Despite recent FDA scrutiny regarding the safety of these beverages, 2013 energy drink sales are up 6.7% over last year in the USA alone as shown in Figure 2.2. Different companies of energy drink are manufacturing different brands with varying the ingredients. People are consuming energy drinks every day without thinking the adverse effects of it. Actually they aren't concern about the negative aspects of consumption of energy drinks on a regular basis.

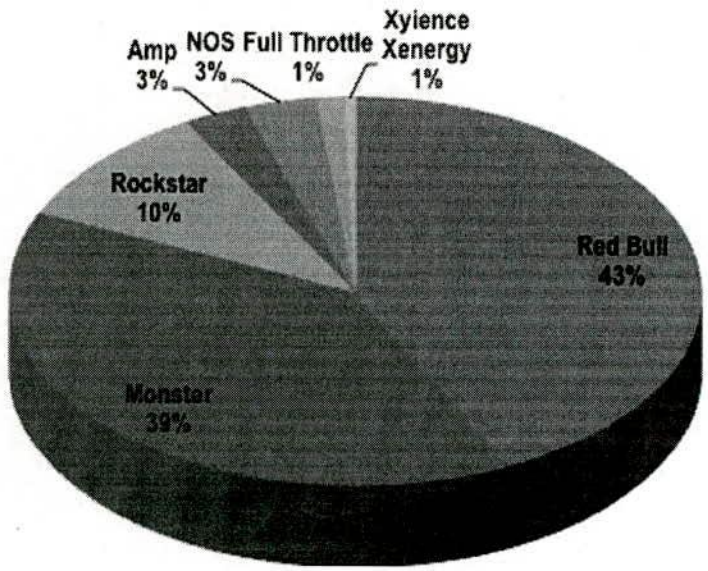

Figure 2.2: Energy drink brand market share 2013

A list of top selling energy drink brands during recent three years is given in Table 2.1. A huge part of energy drink popularity is in the sponsorship efforts, with top brands spending large sums of money to achieve brand placement. Xyience has definitely been lifting their marketing efforts and it's paying off with their recent entrance into the top 15 energy drinks ranking.

Table 2.1: Top selling energy drink brands during recent three years

Rank	Brand	2013 sales ($millions)	Brand	2012 sales ($millions)	Brand	2011 sales ($millions)
1	Red Bull	3,433	Red Bull	2,950	Red Bull	2,300
2	Monster	3,147	Monster	2,600	Monster	1,900
3	Rockstar	821	Rockstar	780	Rockstar	660
4	NOS	274	Amp	300	Amp	330
5	Amp	239	NOS	250	Doubleshot	250
6	Full Throttle	104	Full Throttle	140	NOS	220
7	Xyience Xenergy	43	Xyience Xenergy	40	Full Throttle	130
8	VPX Redline	-	VPX Redline	15	Xyience Xenergy	30

2.1.2 Ingredients

Energy drinks generally contain methylxanthines (including caffeine), B vitamins, and herbs. Other commonly used ingredients are carbonated water, guarana, yerba mate, acai, and taurine, plus various forms of ginseng, maltodextrin, inositol, carnitine, creatine, glucuronolactone, and ginkgo biloba [27]. Some contain high levels of sugar, and many brands offer artificially sweetened 'diet' versions. A common ingredient in most energy drinks is caffeine (often in the form of guarana or yerba mate). Caffeine is the stimulant that is found in coffee and tea. There is little or no evidence that any of the ingredients found in energy drinks other than caffeine or sugar have a significant physiological effect [27]. Energy drinks contain about three times the amount of caffeine as cola [28]. Twelve ounces of Coca-Cola Classic contains 35 mg of caffeine, whereas a Monster Energy Drink contains 120 mg of caffeine [29].

2.2 Effects of Caffeine

Energy drinks basically contain caffeine as main ingredient. In November 2010, the University of Texas Medical School at Houston reported that energy drinks contain more

caffeine than a strong cup of coffee [30], and that the caffeine combined with other ingredients (sometimes not reported correctly on labels) such as guarana, taurine, other herbs, vitamins and minerals may interact. Energy drinks consumed with alcohol may affect heart rates, blood pressure and even mental states. The caffeine content of energy drinks range from 80–300 mg per 16-oz serving whereas a 16-oz cup of coffee can contain 70–200 mg.

Health experts say caffeine prevents sleepiness and delays the feeling of drunkenness normally experienced when drinking alcohol, causing some people to continue drinking after they normally would have stopped [31]. Caffeine is a very mild diuretic in comparison with alcohol, but some experts believe that mixing energy drinks with alcohol can cause greater dehydration than alcohol alone [32].

2.2.1 Physiological and Psychological Effects

Energy drinks have the effects caffeine and sugar provide, but there is little or no evidence that the wide variety of other ingredients have any effect [27]. However, a variety of physiological and psychological effects have been attributed to energy drinks and their ingredients. Two studies reported significant improvements in mental and cognitive performances as well as increased subjective alertness [33]. Excess consumption of energy drinks may induce mild to moderate euphoria primarily caused by stimulant properties of caffeine and may also induce agitation, anxiety, irritability and insomnia [34]-[35]. During repeated cycling tests in young healthy adults an energy drink significantly increased upper body muscle endurance [36]. It has been suggested that reversal of caffeine withdrawal is a major component of the effects of caffeine on mood and performance [37].

Restorative properties were shown by a combination of caffeine and the sugar glucose in an energy drink [38], and some degree of synergy between the cognition-modulating effects of glucose and caffeine was also suggested [23]. In one experiment, a glucose-based energy drink (containing caffeine, taurine and glucuronolactone) was given to eleven tired participants being tested in a driving simulator. Lane drifting and reaction times were measured for two hours post-treatment and showed significant improvement [39]. Two articles concluded that the improved information processing and other effects

could not be explained in terms of the restoration of plasma caffeine levels to normal following caffeine withdrawal [40]-[41].

Consumption of a single energy drink will not lead to excessive caffeine intake, but consumption of two or more drinks in a single day can [42]. Other stimulants such as ginseng are often added to energy drinks and may enhance the effects of caffeine [43] and ingredients such as guarana themselves contain caffeine. Adverse effects associated with caffeine consumption in amounts greater than 400 mg include nervousness, irritability, sleeplessness, increased urination, abnormal heart rhythms (arrhythmia), and dyspepsia. Consumption also has been known to cause pupil dilation when taken with certain antidepressants [42]. Most mainstream energy drinks do not provide electrolytes, and have a higher likelihood of an energy "crash-and-burn" effect. Caffeine in energy drinks can cause the excretion of water from the body to dilute high concentrations of sugar entering the blood stream, leading to dehydration. If the body is dehydrated by 1%, performance is decreased by up to 10% [44]. In the US, energy drinks have been linked with reports of nausea, abnormal heart rhythms and emergency room visits [45]. The drinks may cause seizures due to the "crash" following the energy high that occurs after consumption [46]. Caffeine dosage is not required to be on the product label for food in the United States, unlike drugs, but some advocates are urging the FDA to change this practice [47].

2.2.2 Health Effects

There are many things in this world that are delicious and convenient, are horrible for our bodies. A research team at the University of Bonn in Germany has found that energy drinks take a serious toll on our heart. As part of their study, researchers gave 17 subjects an energy-style drink containing 32mg per 100ml of caffeine and 400mg per 100 ml of taurine. The scientists then looked at images of the participants' hearts just one hour after they consumed the beverage. And, what they saw is kind of frightening. The contractions were so much more forceful after just one energy drink, that children, and those with certain health conditions, ought to avoid the drink altogether. The images showed the left ventricle (responsible for pumping blood through the body) was contracting harder an hour after the energy drink was consumed than before consumption.

There are many side effects known to be associated with a high intake of caffeine, including rapid heart rate, palpitations, rise in blood pressure, and, in the most severe

cases, seizures or sudden death. While the study shows that energy drinks have a short-term impact on cardiac contractility, it remains unclear "exactly how or if this greater contractility of the heart impacts daily activities or athletic performance," or how it effects those with heart disease. The study, which observed the effects of energy drinks in 18 people, found that those who drank high levels of caffeine or taurine showed significantly increased heart contraction rates one hour later. "Until now, we haven't known exactly what effect these energy drinks have on the function of the heart", study researcher Jonas Dorner, of the cardiovascular imaging section at the University of Bonn, Germany, said in a statement. "There are concerns about the products' potential adverse side effects on heart function, especially in adolescents and young adults, but there is little or no regulation of energy drink sales".

The study, which was presented on Monday at the annual meeting of the Radiological Society of North America, used MRI scans in 18 healthy volunteers -- 15 men and three women with an average age of 27.5-- to see how the chemicals in energy drinks affected their hearts. Each participant drank a mixture containing taurine and caffeine. An hour after consuming the drinks, cardiac MRIs of the participants showed significantly increased peak strain and peak systolic strain rates in the left ventricle of their hearts. This isn't the first study to address the harmful effects energy drinks pose. A 2013 report from the Substance Abuse and Mental Health Services Administration stated that in the U.S. from 2007 to 2011, the number of emergency department visits related to energy drink consumption nearly doubled, increasing from 10,068 to 20,783. "We have shown that even small amounts of energy drinks alter heart function", Dorner told HealthDay. Because of that, further investigation needs to be done to address concerns regarding long-term effects on kids and long-term effects on people with heart disease.

The health effects of caffeine have been extensively studied. Short term side effects such as headache, nausea, and anxiety have been shown as symptoms of mild caffeine consumption [48]. The long term effects of moderate caffeine consumption can be a reduced risk of developing Parkinson's disease, type 2 diabetes, hepatic diseases, and cardiovascular disease [49]. A mild stimulant of the central nervous system, caffeine also stimulates cardiac muscle, relaxes smooth muscle, increases gastric secretions, and produces dieresis [50].

Positive effects:

- High long-term consumption is associated with a lower risk of cardiovascular disease and diabetes.
- Research is beginning to suggest that caffeine minimizes the cognitive decline associated with aging [51], including reducing risk of Alzheimer's disease [52].
- Caffeine increases levels of neurotransmitters such as norepinephrine, acetylcholine, dopamine, serotonin, epinephrine and glutamate [53].
- Acetylcholine is associated with attention, concentration, learning, and memory but there is no conclusive evidence yet that caffeine has any effect on memory and cognitive function [54].
- Low doses of caffeine show increased alertness and decreased fatigue [55].
- Caffeine has been shown to increase the metabolic rate [56].
- Caffeine may reduce the risk of developing cancer and produce a delay in the average onset of cancer.
- Caffeine is associated with a reduced risk of Parkinson's disease, and use of caffeine is studied as a treatment for the Parkinson's disease motor symptoms [57].
- Caffeine may lower the risk of developing type 2 diabetes.
- Caffeine may reduce certain kind of hepatic cancers.
- Caffeine may be a source of healthful antioxidant activity against some free radicals inside the body [58].

Negative effects:

- Caffeine can increase blood pressure in non-habitual consumers. High blood pressure is associated with an increase in strokes, and cerebral vascular disease, which in turn increase the risk of multi-infarct dementia [59].
- Caffeine may reduce control of fine motor movements (e.g. producing shaky hands) [55].
- Caffeine can increase cortisol secretion, some tolerance is developed [60].
- Caffeine can contribute to increased insomnia and sleep latency [55].
- Caffeine is addictive [55]. Caffeine withdrawal can produce headache, fatigue and decreased alertness.
- High doses of caffeine (300 mg or higher) can cause anxiety [55].

- High caffeine consumption has been linked to an increase in the likelihood of experiencing auditory hallucinations [61].
- High caffeine consumption accelerates bone loss at the spine in elderly postmenopausal women [62].

2.3 Health Effects of Sugar

Most of us have heard the good advice that we need to eat less sugar - and rightly so. However, despite the numerous warnings by health authorities of the ill effects of sugar, the majority of the population is still consuming sugar on a daily basis in some form or other. Sugar is both a broad category and a misleading one. Sugar includes glucose, fructose (as in fruit sugar), lactose (as in milk), sucrose (as in table sugar), maltose or malts (as in rice malt and honey), jam (contains concentrated juice, which is high in fruit sugar), maple syrup, corn syrup, palm sugar (traditionally used in macrobiotic cooking), and the very deceiving organic brown sugar, which is not all that different from white sugar. Even alcohol is a sugar. All of these sugars are problematic in many different ways. The sugar industry is not in decline and obesity is on the increase. Sugar is a major culprit in the case against obesity. For obese individuals, consuming even a teaspoon of sugar a day would cause metabolic imbalances that contribute to obesity. Sugar is to be avoided, not only by the obese but by healthy individuals.

Nancy Appleton, PhD, clinical nutritionist, has compiled a list of 146 reasons on 'how sugar is ruining your health' in her book Lick the Sugar Habit. Here are some of them [63]:

- Sugar can decrease growth hormone
- Sugar feeds cancer
- Sugar increases cholesterol
- Sugar can weaken eyesight
- Sugar can cause drowsiness and decreased activity in children
- Sugar can interfere with the absorption of protein
- Sugar causes food allergies
- Sugar contributes to diabetes
- Sugar can contribute to eczema in children
- Sugar can cause cardiovascular disease
- Sugar can impair the structure of DNA

- Sugar can cause hyperactivity, anxiety, difficulty concentrating, and crankiness in children
- Sugar contributes to the reduction in defense against bacterial infection (infectious diseases)
- Sugar greatly assists the uncontrolled growth of Candida Albicans (yeast infections)

The body changes sugar into 2 to 5 times more fat in the bloodstream than it does starch. With 146 proven reasons why sugar is bad for us, is there perhaps one single reason as to why we might need it? The only interesting thing about sugar is that it tastes good and makes us temporarily feel good. This is an area worth exploring.

2.4 Effects of Energy Drinks

The consumer basically takes energy drinks to produce a short-term boost of energy or to improve physical and mental performance. Energy drinks may give short-term boost of energy as well as improving physical and mental performance but it may be a subject to concern because of its negative impacts. The number of people receiving emergency treatment because they consumed energy drinks has spiked in the U.S. over the past few years. With its ever increasing popularity, and availability, the energy drink industry has seen huge growth as more and more people of all demographics are consuming their products. Excessive energy drink consumption can have some severe medical and behavioral consequences; it's proving to become a serious public health concern. It commonly causes health complications, such as insomnia, migraine, seizures and heart problems.

2.4.1 Health Effects

We all know that an energy drink can be great when you need a quick boost, but a new study is again calling their safety—more specifically, their effects on heart health—into question. A review of previous research, presented at the 2013 American Heart Association meeting in New Orleans, found that drinking one to three energy drinks could mess with your heart rhythm and increase your blood pressure. If severe enough, these changes could lead to an irregular heartbeat or even sudden cardiac death. In the seven studies reviewed which involved people between 18 and 45 years old, those who

consumed energy drinks experienced a 4 percent change in the rhythm of their heart. In addition, their systolic blood pressure jumped by 3.5 points. While the changes seem small, they can still cause problems for certain people. According to AHA spokesperson Gordon F. Tomaselli, M.D., those with an existing heart condition or a family history of heart problems, like an irregular heartbeat, should avoid drinking energy drinks. Some men could have an undiagnosed heart condition that could land them in the emergency room after one energy drink too many. Just don't overdo it by downing several cans in one day, and when you do drink one, keep an eye out for these side effects, which could signal a bad reaction [64]:

- Racing heart
- Skipping or jumping heartbeat
- Feeling jittery or anxious
- Extended dizzy spells.

2.4.2 Side Effects

Energy Drinks have become a major issue as people continue to consume more and more. Recent research in Australia has highlighted the risks with over-consumption of energy drinks. This data was gathered from 7 years of calls to the Australian Poisons Center.

Listed in order of most common to least common [65]:

1. Palpitations / tachycardia
2. Tremor / shaking
3. Agitation / restlessness
4. Gastrointestinal upset
5. Chest pain / ischaemia
6. Dizziness / syncope
7. Paraesthesia (tingling or numbing of the skin)
8. Insomnia
9. Respiratory distress
10. Headache

Chapter III

Analysis of Cardiac Signals

3.1 What are Cardiac Signals?

The signals which can be used to determine cardiac or heart function or activity easily are known as cardiac signals. Cardiac activity evaluation is easy using different parameters of these cardiac signals. Parameters associated with cardiac signals are known as cardiac parameters or heart function parameters. Some of the cardiac function parameters are ECG parameters (heart rate, peak amplitude of different waves especially R peak, different intervals etc.), PPG parameters (pulse rate, p-p amplitude etc.), cardiac output, blood flow etc. Using electrocardiogram (ECG), cardiac functions can be easily evaluated. Besides, the analysis of spectral components of ECG and PPG is helpful to find out cardiac function.

3.1.1 Electrocardiogram

An electrocardiogram (ECG) is an electrical recording of the heart and is used in the investigation of heart condition or heart disease. Thus the electrical activity of the heart over a period of time can be represented by Electrocardiogram (ECG). With each heartbeat, an electrical signal spreads from the top of the heart to the bottom. As it travels, the signal causes the heart to contract and pump blood. The process repeats with each new heartbeat. The heart's electrical signals set the rhythm of the heartbeat.

An ECG shows:

- How fast your heart is beating
- Whether the rhythm of your heartbeat is steady or irregular
- The strength and timing of electrical signals as they pass through each part of your heart

A typical ECG tracing of the cardiac cycle (heartbeat) consists of a P wave, a QRS complex, a T wave, and a U wave, which is normally invisible in 50 to 75% of ECGs

because it is hidden by the T wave and upcoming new P wave as shown in Figure 3.1. The baseline of the electrocardiogram (the flat horizontal segments) is measured as the portion of the tracing following the T wave and preceding the next P wave and the segment between the P wave and the following QRS complex (PR segment). In a normal healthy heart, the baseline is equivalent to the isoelectric line (0mV) and represents the periods in the cardiac cycle when there are no currents flowing towards either the positive or negative ends of the ECG leads. However, in a diseased heart the baseline may be elevated (e.g. cardiac ischaemia) or depressed (e.g. myocardial infarction) relative to the isoelectric line due to injury currents flowing during the TP and PR intervals when the ventricles are at rest. The ST segment typically remains close to the isoelectric line as this is the period when the ventricles are fully depolarised and thus no currents can flow in the ECG leads. Since most ECG recordings do not indicate where the 0mV line is, baseline depression often gives the appearance of an elevation of the ST segment and conversely baseline elevation gives the appearance of depression of the ST segment [66].

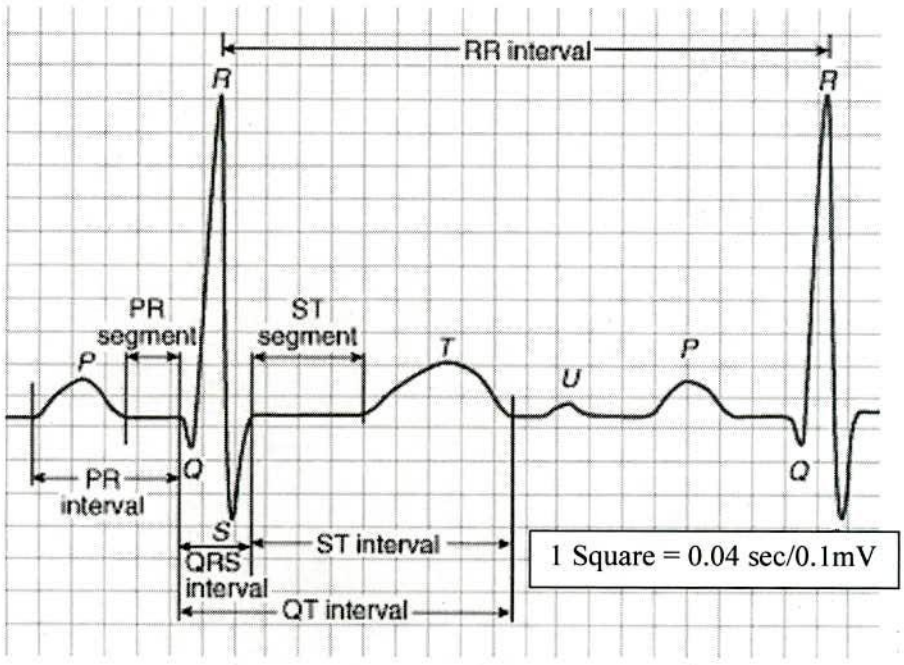

Figure 3.1: A generalized waveform of ECG

A short description of different waves, segments and intervals of ECG is listed below in Table 3.1.

Table 3.1: Specification of different waves, segments and intervals of ECG

Feature	Description	Duration
RR interval	The interval between an R wave and the next R wave; normal resting heart rate is between 60 and 100 bpm.	0.6 to 1.2s
P wave	During normal atrial depolarization, the main electrical vector is directed from the SA node towards the AV node and spreads from the right atrium to the left atrium. This turns into the P wave on the ECG.	80ms
PR interval	The PR interval is measured from the beginning of the P wave to the beginning of the QRS complex. The PR interval reflects the time the electrical impulse takes to travel from the sinus node through the AV node and entering the ventricles. The PR interval is, therefore, a good estimate of AV node function.	120 to 200ms
PR segment	The PR segment connects the P wave and the QRS complex. The impulse vector is from the AV node to the bundle of His to the bundle branches and then to the Purkinje fibers. This electrical activity does not produce a contraction directly and is merely traveling down towards the ventricles, and this shows up flat on the ECG. The PR interval is more clinically relevant.	50 to 120ms
QRS complex	The QRS complex reflects the rapid depolarization of the right and left ventricles. The ventricles have a large muscle mass compared to the atria, so the QRS complex usually has much larger amplitude than the P-wave.	80 to 120ms
ST segment	The ST segment connects the QRS complex and the T wave. The ST segment represents the period when the ventricles are depolarized. It is isoelectric.	80 to 120ms
T wave	The T wave represents the repolarization (or recovery) of the ventricles. The interval from the beginning of the QRS complex to the apex of the T wave is referred to as the absolute refractory period. The last half of the T wave is referred to as the relative refractory period (or vulnerable period).	160ms
ST	The ST interval is measured from the QRS end point to the end of	320ms

interval	the T wave.	
QT interval	The QT interval is measured from the beginning of the QRS complex to the end of the T wave. A prolonged QT interval is a risk factor for ventricular tachyarrhythmias and sudden death. It varies with heart rate and, for clinical relevance, requires a correction for this, giving the QTc.	Up to 420ms in heart rate of 60 bpm
U wave	The U wave is hypothesized to be caused by the repolarization of the interventricular septum. It normally has low amplitude, and even more often is completely absent. It always follows the T wave, and also follows the same direction in amplitude. If it is too prominent, suspect hypokalemia, hypercalcemia or hyperthyroidism [67].	

The QRS complex is a name for the combination of three of the graphical deflections seen on a typical electrocardiogram (ECG) as shown in Figure 3.2. It is usually the central and most visually obvious part of the tracing. It corresponds to the depolarization of the right and left ventricles of the human heart. In adults, it normally lasts 0.06 - 0.10 s; in children and during physical activity, it may be shorter. Typically an ECG has five deflections, arbitrarily named "P" to "T" waves. The Q, R, and S waves occur in rapid succession, do not all appear in all leads, and reflect a single event, and thus are usually considered together. A Q wave is any downward deflection after the P wave. An R wave follows as an upward deflection, and the S wave is any downward deflection after the R wave. The T wave follows the S wave, and in some cases an additional U wave follows the T wave.

In biomedical engineering, the maximum amplitude in the R wave is usually called "R peak amplitude" or just "R peak" [68]-[69]. Accurate R peak detection is essential in signal processing equipment for heart rate measurement and it is the main feature used for arrhythmia detection [70]-[71]. QRS complex is most important among all waves, segments and intervals of ECG because of the R peak. The value of R peak is very high compared to the others and can be used as a parameter to determine heart condition.

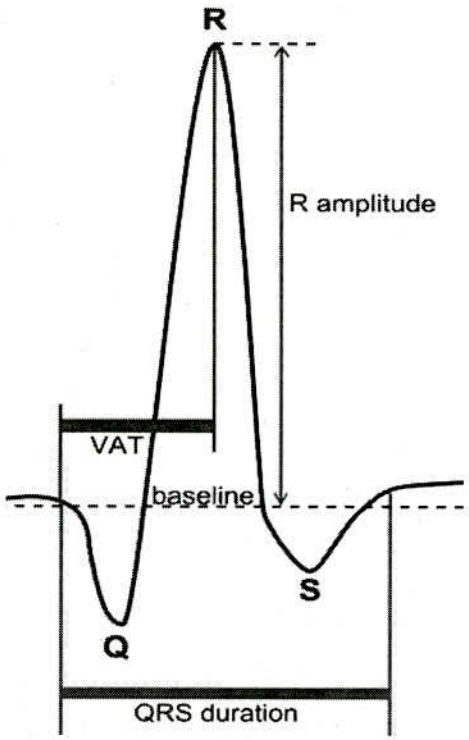

Figure 3.2: Schematic representation of the QRS complex showing VAT (Ventricular Activation Time)

3.1.2 Photo Plethysmogram

The blood volume changes within an organ by using volume displacement technique are known as plethysmography. One type of transducer used in plethysmography operates by converting light energy to electrical energy and thus is called a photoelectric transducer. The photoelectric transducer works by shining a beam of light through the skin and measuring the amount of light that is reflected. Blood absorbs light in a manner proportional to blood volume. The greater the blood volume, the greater the blood absorption and vice-versa. The photoelectric transducer converts the reflected light into electrical signals, which can then be processed and displayed by the recorder.

A photo plethysmogram (PPG) is an optically obtained plethysmogram, a volumetric measurement of an organ. A PPG is often obtained by using a pulse oximeter/transducer which illuminates the skin and measures changes in light absorption [72]. With each cardiac cycle the heart pumps blood to the periphery. Even though this pressure pulse is somewhat damped by the time it reaches the skin, it is enough to distend the arteries and

arterioles in the subcutaneous tissue. The change in volume caused by the pressure pulse is detected by illuminating the skin with the light from a light-emitting diode (LED) and then measuring the amount of light either transmitted or reflected to a photodiode. Each cardiac cycle appears as a peak, as seen in the Figure 3.3. A typical connection of pulse transducer to the subject is shown in Figure 3.4.

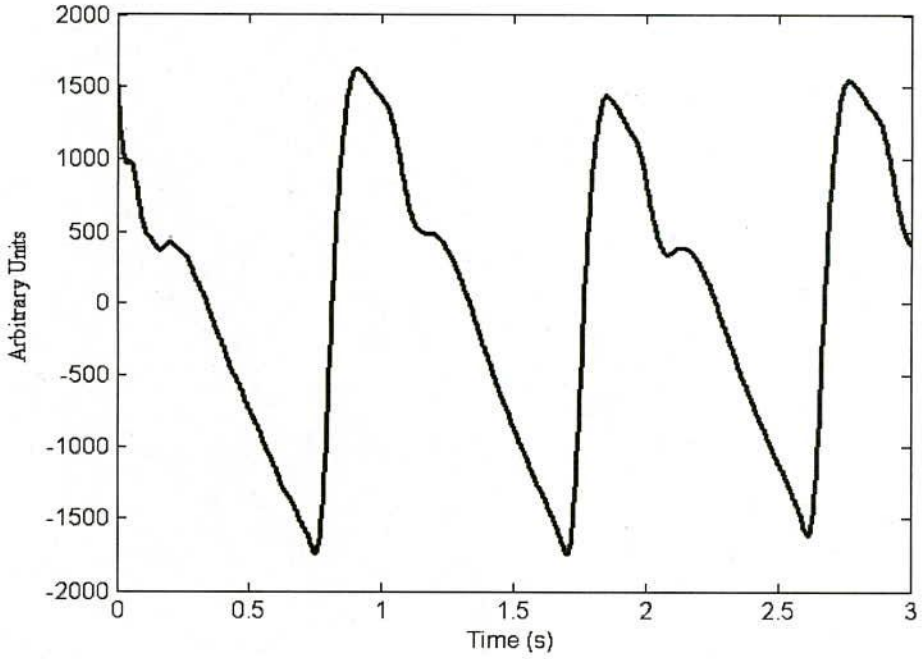

Figure 3.3: Representative PPG taken by Pulse Transducer

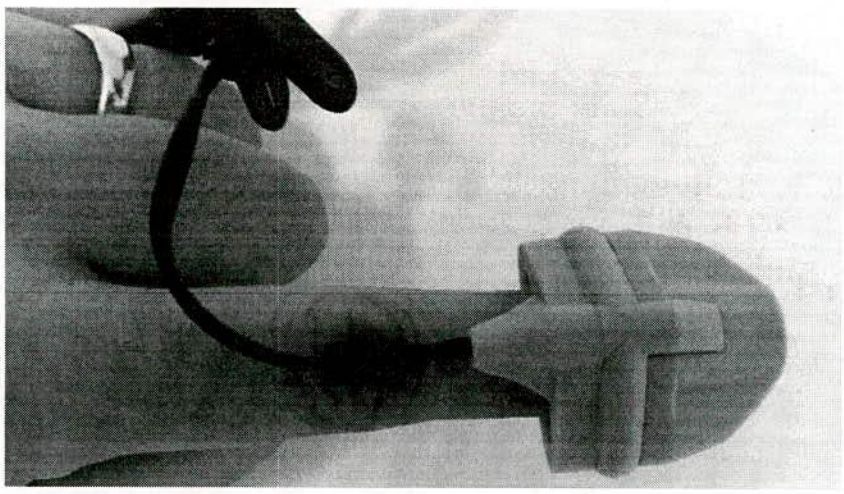

Figure 3.4: Pulse Transducer connected to index finger

3.1.3 Heart Rate or Pulse Rate

Heart rate (HR) or pulse rate (PR) refers to the speed of the heartbeat, specifically the number of heartbeats per unit of time. The heart rate is typically expressed as beats per minute (bpm). The heart rate can vary according to the body's physical needs, including the need to absorb oxygen and excrete carbon dioxide. Activities that can provoke change include physical exercise, sleep, illness, ingesting, and drugs. The normal human heart rate ranges from 60–100 bpm. Bradycardia refers to a slow heart rate, defined as below 60 bpm. Tachycardia refers to a fast heart rate, defined as above 100 bpm. When the heart is not beating in a regular pattern, this is referred to as an arrhythmia. These abnormalities of heart rate sometimes, but not always, indicate disease. Normal heart rates at rest [73], in beats per minute (BPM) are listed in Table 3.2:

Table 3.2: Normal heart rates at rest

Si. No.	Persons	Age	Heart rate (BPM)
01	Newborn baby	1 to 30 days	120 to160
02	Baby	1 to 12 months	80 to 140
03	Baby/toddler	1 to 2 years	80 to 130
04	Toddler/young child	2 to 6 years	75 to 120
05	Child	7 to 12 years	75 to 110
06	Adults	18+ years	60 to 100
07	Adults athlete	18+ years	40 to 60

Heart rate is measured by finding the pulse of the heart. This pulse rate can be found at any point on the body where the artery's pulsation is transmitted to the surface by pressuring it with the index and middle fingers; often it is compressed against an underlying structure like bone. (A good area is on the neck, under the corner of the jaw.) The thumb should not be used for measuring another person's heart rate, as its strong pulse may interfere with the correct perception of the target pulse. The radial artery is the easiest to use to check the heart rate. However, in emergency situations the most reliable arteries to measure heart rate are carotid arteries. This is important mainly in patients with atrial fibrillation, in whom heart beats are irregular and stroke volume is largely different from

one beat to another. In those beats following a shorter diastolic interval left ventricle doesn't fill properly, stroke volume is lower and pulse wave is not strong enough to be detected by palpation on a distal artery like the radial artery.

Possible points for measuring the heart rate are [74]:

1. The ventral aspect of the wrist on the side of the thumb (radial artery).
2. The ulnar artery.
3. The neck (carotid artery).
4. The inside of the elbow, or under the biceps muscle (brachial artery).
5. The groin (femoral artery).
6. Behind the medial malleolus on the feet (posterior tibial artery).
7. Middle of dorsum of the foot (dorsalis pedis).
8. Behind the knee (popliteal artery).
9. Over the abdomen (abdominal aorta).
10. The chest (apex of the heart), which can be felt with one's hand or fingers. It is also possible to auscultate the heart using a stethoscope.
11. The temple (superficial temporal artery).
12. The lateral edge of the mandible (facial artery).
13. The side of the head nears the ear (posterior auricular artery).

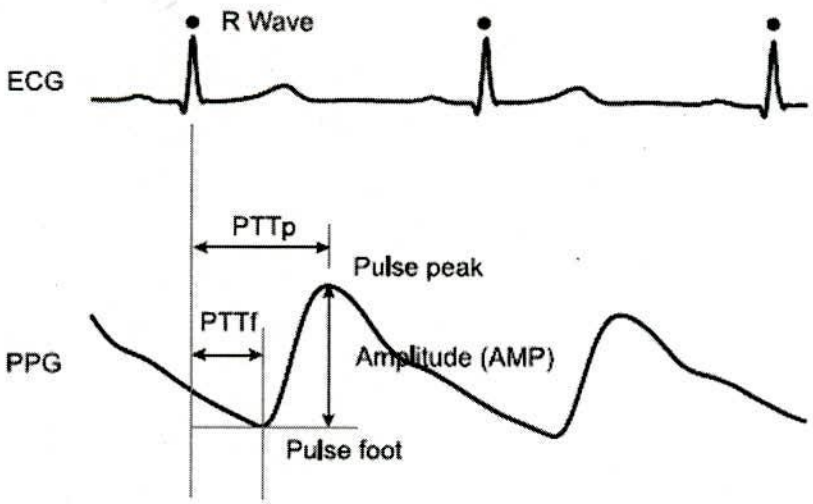

Figure 3.5: A schematic diagram of ECG and PPG

A more precise method of determining pulse involves the use of an electrocardiograph, or ECG. Continuous electrocardiograph monitoring of the heart is routinely done in many clinical settings, especially in critical care medicine. On an ECG the heart rate is measured using the R wave to R wave interval (RR interval) as shown in (3.1) using Figure 3.5.

$$HR\,(in\ BPM) = \frac{60}{R\ to\ R\ \text{interval (sec)}} \tag{3.1}$$

If R to R interval of ECG for a typical subject is 800 msec or 0.8 sec, then using above equation we calculate the heart rate of that subject. The heart rate will be 60/0.8 or 75 BPM.

3.1.4 What are Cardiac Function Parameters?

The cardiac activity or function can be evaluated using different parameters related to the heart or cardiac signals. These parameters are known as cardiac function parameters. This research is based on two types of cardiac signals: ECG & PPG. Some of the cardiac function parameters based on ECG and PPG are listed below:

(i) R peak amplitude
(ii) Peak amplitude of P, Q, S & T waves
(iii) RR interval
(iv) Peak to peak amplitude of PPG
(v) Heart rate or pulse rate
(vi) Frequency components of ECG & PPG, etc.

3.2 Spectrum Analysis of Cardiac Signals – Fourier Transform

Spectrum analysis is referred to as frequency domain analysis or spectrum density estimation, is the technical process of decomposing a complex signal into simpler parts. Many physical processes are best described as a sum of many individual frequency components. Any process that quantifies the various amounts (e.g. amplitudes, powers, intensities, or phases), versus frequency can be called spectrum analysis. Spectrum analysis can be performed on the entire signal. Alternatively, a signal can be broken into short segments (sometimes called frames), and spectrum analysis may be applied to these individual segments. Periodic functions are particularly well-suited for this sub-division.

General mathematical techniques for analyzing non-periodic functions fall into the category of Fourier analysis.

The Fourier transform of a function produces a frequency spectrum which contains all of the information about the original signal, but in a different form. This means that the original function can be completely reconstructed (synthesized) by an inverse Fourier transform. For perfect reconstruction, the spectrum analyzer must preserve both the amplitude and phase of each frequency component. These two pieces of information can be represented as a 2-dimensional vector, as a complex number, or as magnitude (amplitude) and phase in polar coordinates. A common technique in signal processing is to consider the squared amplitude, or power; in this case the resulting plot is referred to as a power spectrum.

In practice, nearly all software and electronic devices that generate frequency spectra apply a fast Fourier transform (FFT), which is a specific mathematical approximation to the full integral solution. Formally stated, the FFT is a method for computing the discrete Fourier transform of a sampled signal. Because of reversibility, the Fourier transform is called a representation of the function, in terms of frequency instead of time; thus, it is a frequency domain representation. Linear operations that could be performed in the time domain have counterparts that can often be performed more easily in the frequency domain. Frequency analysis also simplifies the understanding and interpretation of the effects of various time-domain operations, both linear and non-linear. For instance, only non-linear or time-variant operations can create new frequencies in the frequency spectrum.

3.2.1 Frequency Spectrum

The frequency spectrum of a time-domain signal is a representation of that signal in the frequency domain as shown in Figure 3.6. The frequency spectrum can be generated via a Fourier transform of the signal, and the resulting values are usually presented as amplitude and phase, both plotted versus frequency [75]. Any signal that can be represented as amplitude that varies with time has a corresponding frequency spectrum. This includes familiar concepts such as visible light (color), musical notes, radio/TV channels, and even the regular rotation of the earth. When these physical phenomena are represented in the

form of a frequency spectrum, certain physical descriptions of their internal processes become much simpler. Often, the frequency spectrum clearly shows harmonics, visible as distinct spikes or lines at particular frequencies that provide insight into the mechanisms that generate the entire signal.

A fast Fourier transform (FFT) is an algorithm to compute the discrete Fourier transform (DFT) and it's inverse. A Fourier transform converts time (or space) to frequency and vice versa; an FFT rapidly computes such transformations. As a result, fast Fourier transforms are widely used for many applications in engineering, science, and mathematics. The basic ideas were popularized in 1965, but some FFTs had been previously known as early as 1805. Fast Fourier transforms have been described as "the most important numerical algorithm of our lifetime" [76].

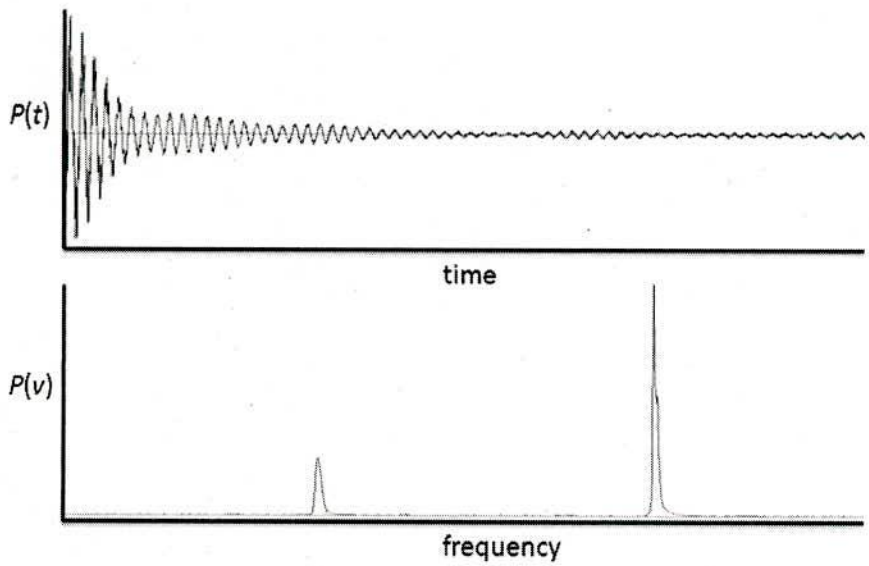

Figure 3.6: Frequency and time domain for the same signal

An FFT computes the DFT and produces exactly the same result as evaluating the DFT definition directly; the only difference is that an FFT is much faster. (In the presence of round-off error, many FFT algorithms are also much more accurate than evaluating the DFT definition directly, as discussed below.)

Let $x_0, x_1, \ldots\ldots, x_{N-1}$ be complex numbers. The DFT is defined by the formula-

$$X_k = \sum_{n=0}^{N-1} x_n e^{-j\frac{2\pi nk}{N}} \qquad k = 0,1,\cdots,N-1 \tag{3.2}$$

Evaluating this definition directly requires $O(N^2)$ operations: there are N outputs X_k, and each output requires a sum of N terms. An FFT is any method to compute the same results in $O(N \log N)$ operations. More precisely, all known FFT algorithms require $O(N \log N)$ operations. To illustrate the savings of an FFT, consider the count of complex multiplications and additions. Evaluating the DFT's sums directly involves N^2 complex multiplications and $N(N-1)$ complex additions [of which $O(N)$ operations can be saved by eliminating trivial operations such as multiplications by 1].

3.2.2 Spectral Density

In statistical signal processing, statistics, and physics, the spectrum of a time-series or signal is a positive real function of a frequency variable associated with a stationary stochastic process, or a deterministic function of time, which has dimensions of power per hertz (Hz), or energy per hertz. Intuitively, the spectrum decomposes the content of a stochastic process into different frequencies present in that process, and helps identify periodicities. More specific terms which are used are the power spectrum, spectral density, power spectral density, or energy spectral density.

3.2.3 Energy Spectral Density

Energy spectral density describes how the energy of a signal or a time series is distributed with frequency. Here, the term energy is used in the generalized sense of signal processing; that is, the energy of a signal $x(t)$ is [77]:

$$E = \int_{-\infty}^{\infty} |x(t)|^2 \, dt \tag{3.3}$$

The energy spectral density is most suitable for transients that is, pulse-like signals having a finite total energy. In this case, Parseval's theorem gives us an alternate expression for the energy of the signal in terms of its Fourier transform, $x(\omega)$ [77]:

$$E = \int_{-\infty}^{\infty} |x(t)|^2 \, dt = \frac{1}{2\pi} \int_{-\infty}^{\infty} |x(\omega)|^2 \, d\omega \tag{3.4}$$

Here ω is the angular frequency. Since the integral on the right-hand side is the energy of the signal, the integrand $|x(\omega)|^2$ can be interpreted as a density function describing the energy per unit frequency contained in the signal at frequency ω. In light of this, the energy spectral density of a signal $x(t)$ is defined as [77]:

$$S_{xx}(\omega) = |x(\omega)|^2 = \left| \int_{-\infty}^{\infty} x(t)\, e^{-j\omega t}\, dt \right|^2 \tag{3.5}$$

3.2.4 Power Spectral Density

The above definition of energy spectral density is most suitable for transients, i.e., pulse-like signals, for which the Fourier transforms of the signals exist. For continued signals that describe, for example, stationary physical processes, it makes more sense to define a power spectral density (PSD), which describes how the power of a signal or time series is distributed over the different frequencies, as in the simple example given previously. Here, power can be the actual physical power, or more often, for convenience with abstract signals, can be defined as the squared value of the signal. The total power P of a signal $x(t)$ is the following time average:

$$P = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} x(t)^2\, dt \tag{3.6}$$

The power of a signal may be finite even if the energy is infinite. For example, a 10-volt power supply connected to a 1 kΩ resistor delivers $(10\ \text{V})^2/(1\ \text{k}\Omega) = 0.1$ W of power at any given time; however, if the supply is allowed to operate for an infinite amount of time, it will deliver an infinite amount of energy (0.1 J each second for an infinite number of seconds).

In analyzing the frequency content of the signal $x(t)$, one might like to compute the ordinary Fourier transform $x(\omega)$; however, for many signals of interest this Fourier transform does not exist. Because of this, it is advantageous to work with a truncated Fourier transform $x_T(\omega)$, where the signal is integrated only over a finite interval [0, T]:

$$x_T(\omega) = \frac{1}{\sqrt{T}} \int_0^T x(t) e^{-j\omega t}\, dt \tag{3.7}$$

Then the power spectral density can be defined as [78]-[79]:

$$S_{xx}(\omega) = \lim_{T \to \infty} \mathrm{E}[\left|x_T(w)\right|^2] \tag{3.8}$$

Here E denotes the expected value; explicitly, we have [79]:

$$\mathrm{E}[\left|x_T(w)\right|^2] = \mathrm{E}[\frac{1}{T} \int_0^T x^*(t)\, e^{j\omega t}\, dt \int_0^T x(t')\, e^{-j\omega t}\, dt']$$

$$= \frac{1}{T} \int_0^T \int_0^T \mathrm{E}[x^*(t)\, x(t')]\, e^{j\omega(t-t')}\, dt\, dt'] \tag{3.9}$$

3.3 Mathematical Modeling of Cardiac Signals

Electrocardiogram (ECG) is the main cardiac signal which represents complete cardiac function. ECG is the measurement of bio-electric potential produced by rhythmical cardiac activities (contraction and relaxation) of the cardiac muscle. Different cardiac functions can be easily identified by ECG that's why ECG modeling is the most important in biomedical signal analysis.

Different techniques have been developed in the past for modeling of ECG. For feature extraction and data compression, a pole-zero model of ECG was represented by [80]. Another study reported ECG signals with pole-zero model, the poles and zeros from clusters [81] and the clusters can be related to the constituent waves of the ECG. Transform-type models like nonlinear transform using multiplication backward difference for detecting QRS. Another Orthonormal basis of Hermite functions for pattern recognition purposes in ECG was stated by [82] using only QRS complex. Polynomial approximation modeling was used to model the ECG for data compression [83]. Other researchers like [84] used parametric modeling of the discrete cosine transform of the ECG for data compression. However, these types of modeling do not provide a direct representation of the constituent waves in the ECG as medical experts are needed for making diagnosis.

Chip Away Decomposition (ChAD) algorithm which is an iterative method for Gaussian parameter determination was used for decomposing and representing the ECG model by [85]. References [86]-[87] improved the proposed model in [88] with accounting T wave asymmetry. Modeling of ECG with seven Gaussian functions has been investigated by Clifford et al. [89] by means of 3D state-space model which require numerical integration using a fourth-order Runge-Kutta method. S. Paravena et al. [90] used a large number of Gaussian functions with no base line drift factor. They used 4 to 133 Gaussian functions based on minimum bank method and zero crossing method. But fitting this method to the real ECG is not efficient. Moreover, increasing number of Gaussian function require much time to run the program. Authors in [91] proposed a model using Gaussian function but they haven't represented QRS wave individually as well as it is unable to fit with the real ECG at a significant level. They used double differentiation of the Gaussian function which is time consuming and need complex mathematical operation. The fitting techniques were inefficient because they were not capable to fit any negative values in their model which was quite common in real data. Another mathematical model was proposed using single differentiation of Gaussian function [92] but matching with peak amplitude of Q and S waves were not sufficient.

In this study, a peak amplitude based Gaussian function (Gaussian peak function) is used to model complete ECG as well as P, Q, R, S and T wave individually and is very simple as compared to earlier mentioned model. In addition, there is no need of preprocessing of the baseline like [91], the model can automatically shift the baseline as normally exist in the real ECG. The peak amplitude based parameters are evaluated after fitting model ECG with real ECG and have been compared with real ECG peak amplitudes of different waves. Performance of this model is evaluated by analyzing different error parameters.

3.3.1 Proposed Approach

ECG signal is the combination of P, Q, R, S, and T waves which are more symmetrical to the Gaussian wave (bell curve) shape that quickly falls off towards zero at both sides. Gaussian function is widely used in signal processing as well as modeling.

A Gaussian function is a function of the form:

$$F(t) = A\,e^{-\left(\frac{(t-B)^2}{2C^2}\right)} + D \tag{3.10}$$

Where A, B, C, and D are real constants.

A is the height of the curve's peak, B is the position of the center of the peak, C controls the width of the curve, and D is the constant for baseline fitting.

If i ∈ (P, Q, R, S, T) then Gaussian function for each wave of ECG signal can be written as:

$$F_P(t) = A_P\,e^{-\left(\frac{(t-B_P)^2}{2C_P^{\,2}}\right)} + D_P \tag{3.11}$$

$$F_Q(t) = A_Q\,e^{-\left(\frac{(t-B_Q)^2}{2C_Q^{\,2}}\right)} + D_Q \tag{3.12}$$

$$F_R(t) = A_R\,e^{-\left(\frac{(t-B_R)^2}{2C_R^{\,2}}\right)} + D_R \tag{3.13}$$

$$F_S(t) = A_S\,e^{-\left(\frac{(t-B_S)^2}{2C_S^{\,2}}\right)} + D_S \tag{3.14}$$

$$F_T(t) = A_T\,e^{-\left(\frac{(t-B_T)^2}{2C_T^{\,2}}\right)} + D_T \tag{3.15}$$

Simply the general equation of ECG can be written as:

$$F_{ECG,M}(t) = \sum_{i \in P,Q,R,S,T} \left(A_i e^{-\left(\frac{(t-B_i)^2}{2C_i^2} \right)} + D_i \right) \tag{3.16}$$

Where $F_{ECG,M}(t)$ is the function to generate ECG using proposed model (M for indicating model). If we perform normal sum of Eq. (3.16), the individual P, Q, R, S, T waves of ECG will be overlapped with each other. To solve this problem, waves of ECG are fitted to their right position using shifting and zero padding method. Here D_i can be used for model fitting to adjust the baseline. Noisy signal generation is an extra feature of this model.

3.3.2 Error Evaluation Parameters

If $F(t)$ is the recorded ECG signal and $F_M(t)$ is the ECG signal generated by the mathematical model, the Mean Square Error (MSE) is defined as:

$$MSE = \frac{1}{N} \sum_{t=0}^{N-1} [F(t) - F_M(t)]^2 \tag{3.17}$$

The normalized form of MSE is defined as:

$$NMSE = \frac{\sum_{t=0}^{N-1} [F(t) - F_M(t)]^2}{\sum_{t=0}^{N-1} [F(t)]^2} \tag{3.18}$$

Another measurement is Root Mean Square Error (RMSE), which is:

$$RMSE = \sqrt{\frac{1}{N} \sum_{t=0}^{N-1} [F(t) - F_M(t)]^2} \tag{3.19}$$

The normalized version of RMSE is defined as:

$$NRMSE = \sqrt{\frac{\sum_{t=0}^{N-1} [F(t) - F_M(t)]^2}{\sum_{t=0}^{N-1} [F(t)]^2}} \tag{3.20}$$

Percent Normalized Root Mean Square Error is defined as:

$$PNRMSE = \sqrt{\frac{\sum_{t=0}^{N-1} [F(t) - F_M(t)]^2}{\sum_{t=0}^{N-1} [F(t)]^2}} \times 100\% \tag{3.21}$$

The Q and S waves of ECG signal are quite different from other waves such as P, R and T. In case of P, R and T waves, the peak point lie at the centre of the wave approximately which can be modeled easily using Gaussian function. But for Q and S wave, the peak point doesn't lie at the centre of the corresponding wave. For this reason, acceptable amplitude matching between Real ECG and Model ECG is not possible in case of Q and S waves. To reduce error, we have to modify our proposed model.

3.3.3 Modified Proposed Model

For more accurate fitting of Q and S waves of ECG as well as less error between real ECG and model ECG, we have to modify the model explained above. Modified Proposed Model is explained below:

$$F_{ECG,MM}(t) = \sum_{i \in P,Q,R,S,T} \left(M_i A_i e^{-\left(\frac{(t - B_i)^2}{2C_i^2} \right)} + D_i \right) \tag{3.22}$$

Where $F_{ECG,MM}(t)$ is the function to generate ECG using modified proposed model (*MM* for indicating modified model) and M is the factor of multiplication whose values are:

$$M_i = 1 \text{ when } i \in P, R, T$$

$$M_i = 1 \text{ to } 2 \text{ when } i \in Q, S$$

We have to find a suitable value or range of values for M_i (i ∈ Q, S) for which Q and S waves will be best fitted and error between Real ECG and Model ECG will be acceptable.

3.3.4 Novelty of the Modified Proposed Model

Though generating ECG by using Gaussian function is done by [90]-[92], the novelty of our modified proposed model are as follows:

a. The modified proposed model can generate ECG and is capable of detecting various kind of practical phenomena such as brachycardia (slow heart rate), tachycardia (fast heart rate) and HRV (heart rate variability) etc.
b. It doesn't need three dimensional state spaces which are difficult for realization and simulation.
c. It doesn't need any differentiation of function also which is difficult to understand.
d. An extra baseline parameter of this model reduces the preprocessing of signal by automatically adjust the baseline.
e. This model can more accurately model Q and S waves as well as P, R and T waves with low error in peak amplitude matching.
f. Noisy ECG signal can be modeled simply by adding a noise parameter in D_i with the model.

3.3.5 Modeling ECG having Energy Drinks

It is very difficult to make different model for ECG at before and after the consumption of energy drinks because the consumption of energy drinks results very little difference in peak amplitude of different waves of ECG. In this study we have proposed an approximate model for generating ECG at both before (normal ECG) and after (energized ECG) having energy drinks.

The approximate model for generating ECG at before having energy drinks is:

$$F_{ECG,BD}(t) = \sum_{i \in P,Q,R,S,T} \left(M_i A_i e^{-\left(\frac{(t-B_i)^2}{2C_i^2} \right)} + D_i \right) \quad (3.23)$$

Where $F_{ECG,BD}(t)$ is the function to generate ECG at before having energy drinks (*BD* for indicating before drink) and

$$M_i = 1 \text{ when } i \in P,R,T$$

$$M_i = 1.20 \text{ when } i \in Q$$

$$M_i = 1.25 \text{ when } i \in S$$

The approximate model for generating ECG at after having energy drinks is:

$$F_{ECG,AD}(t) = \sum_{i \in P,Q,R,S,T} \left(M_i A_i e^{-\left(\frac{(t-B_i)^2}{2C_i^2} \right)} + D_i \right) \quad (3.24)$$

Where $F_{ECG,AD}(t)$ is the function to generate ECG at after having energy drinks (*AD* for indicating after drink) and

$$M_i = 1 \text{ when } i \in P,R,T$$

$$M_i = 1.25 \text{ when } i \in Q$$

$$M_i = 1.35 \text{ when } i \in S$$

Chapter IV

Experimental Results & Discussions

4.1 Subjects Specifications

Ten healthy young Subjects between 19 and 27 years old were enrolled for this study. The Subjects had not taken any medication during the week prior to the study. None of the Subjects were smokers and they refrained from alcohol and caffeine containing drinks and performed heavy exercise at least 6 hours prior to the study. The Subject had not any disorder, hypertension, heart surgery, stroke, or any history of cardiovascular degeneration. After being informed of the study design, they gave their written consent. The study was approved by the local Ethics Committee. Each participant had an initial visit to the experimental laboratory for a physical examination and a medical history assessment. Details about the Subjects are listed in Table 4.1.

Table 4.1: Detail information of the Subjects

Si. No.	Subject	Gender	Age (yrs)	Weight (kgs)	Height (cms)	History of cardiovascular disease
1	S1	Male	27	82	170.18	No
2	S2	Male	23	65	170.18	No
3	S3	Male	25	76	170.18	No
4	S4	Male	27	70	168.91	No
5	S5	Male	25	67	167.64	No
6	S6	Male	19	60	173.99	No
7	S7	Male	19	59	177.80	No
8	S8	Male	20	66	175.26	No
9	S9	Male	20	54	172.72	No
10	S10	Male	21	61	170.18	No

The values of Mean ± Standard Deviation (SD) for age, weight, height and Body Mass Index (BMI) of Subjects are given in Table 4.2.

Table 4.2: Demographic characteristics of study participants

Parameters	Values (Mean ± SD)
Age (yrs)	22.6 ± 3.04
Weight (kgs)	66 ± 7.92
Height (cms)	171.70 ± 2.99
BMI (kg/m^2)	22.44 ± 3.11

4.2 Necessary Tools Specifications

There are different types of tool and software required for data acquisition from subjects. Among them some important tools are listed in Table 4.3. It should be remember that we used other basic tools like personal computer, connecting cable, chair, table etc. Detail about these items is listed in Table 4.3. These tools are required for whole experimental period (during data/signal recording as well as signal analysis).

Table 4.3: Tools required for data acquisition

Si. No.	Name of the tool	Model	Description	Used for
1	Cable	SS2LA (Biopac, USA)	Fully shielded, permits high-resolution recording	Collecting ECG signal from body through electrodes
2	Pulse Transducer	SS4LA (Biopac, USA)	Permits high-resolution sensing and recording	Collecting pulse signal from skin
3	LDF Probe	TSD 140 (Biopac, USA)	Highly sensitive and calibrated	Blood flow measurement from human skin
4	Vinyl Electrode	EL503 (Biopac, USA)	Disposable	Connecting the body skin with data acquisition cable

5	Electrode Gel	GEL101 (Biopac, USA)	Formulated with 0.5% saline in a neutral base	Ensuring better conductivity between skin and the electrode
6	Data Acquisition Unit	MP36 (Biopac, USA)	Built-in universal amplifiers	Recording and conditioning electrical signals from the skin
7	Data Acquisition Unit	MP150 (Biopac, USA)	Built-in universal amplifiers	Recording and conditioning electrical signals from the skin
8	LDF Amplifier	LDF100C (Biopac, USA)	Blood perfusion amplifiers	Recording and conditioning LDF signals from skin
9	Interfacing Cable	Biopac, USA	Reliable interfacing between computer and module	Connecting MP36 unit with computer
10	Computer System	Windows XP & Windows 7	Highly configured	Data recording and analysis throughout whole exp. Period
11	Biopac Student Lab Software	BSL Lessons 3.7.3 & BSL PRO 3.7.3 (Biopac, USA)	Complete guide for designed experiments	Data recording and analysis
12	Skin Cleanser	Biopac, USA	Active chemical	Clean the skin of subjects and remove dust, etc.
13	AcqKnowledge Software	AcqKnowledge 4.0 & 4.1 (Biopac, USA)	Data recording and analyzing software	Data recording and analysis

4.3 Experimental Setup

The study was performed in a quiet room with the temperature kept constant at 25°C (24-26). Initially, we verified all connections and power supply of computer before turning it on. We also verified the connection of power supply for each module of MP36 data acquisition unit as well as their individual interfacing cable between computer and MP36 unit. We turned only the computer on after ensuring that all connections associated with hardware were ok for our experiment. Biopac student lab (BSL 3.7.3 and BSL PRO 3.7.3) software and AcqKnowledge software (AcqKnowledge 4.0 or AcqKnowledge 4.1) were installed in our computer before.

4.3.1 Hardware Setup

In this thesis, I used single modules of MP36 data acquisition unit. At first, the BIOPAC MP36 data acquisition units were turned off. Then electrode lead set (SS2LA) was plugged into channel 1 of MP36 (Biopac, USA) data acquisition unit for the purpose of ECG recordings. Also a pulse transducer (SS4LA) was plugged into channel 2 of MP36 (Biopac, USA) data acquisition unit for the purpose of pulse recordings as showed in Figure 4.1.

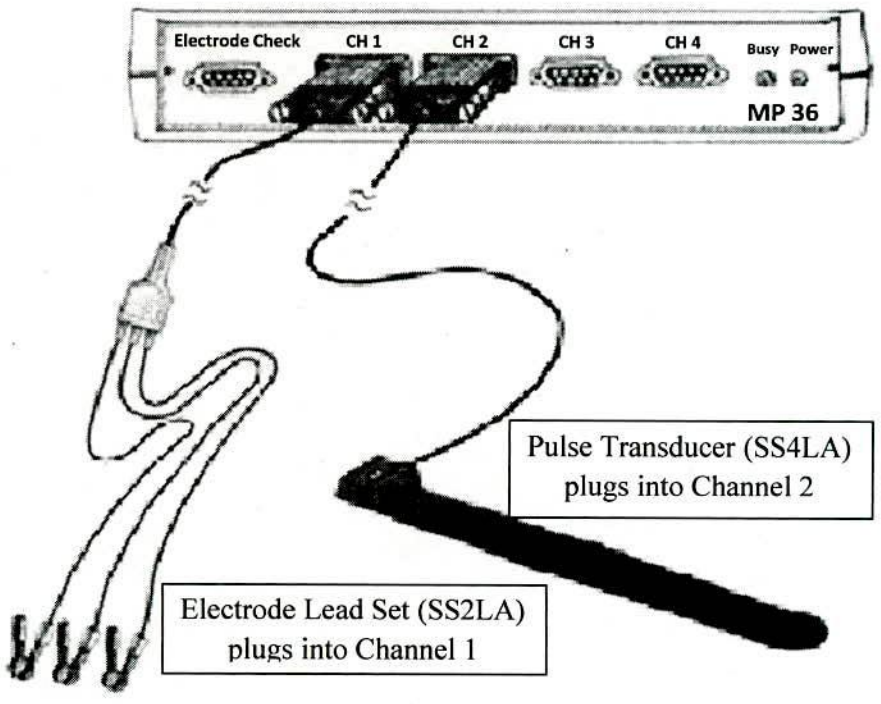

Figure 4.1: Hardware setup of MP36 module 1 for ECG and pulse recordings.

4.3.2 Database - Subject Preparation

For ECG recordings, three electrodes (EL503) were placed on the Subject body as showed in Figure 4.2. That is, one electrode on the medial surface of the right leg, just above the ankle bone; other electrode on the medial surface of the left leg, just above the ankle bone; and third electrode on the right anterior forearm just above the wrist (same side of arm as the palm of hand).

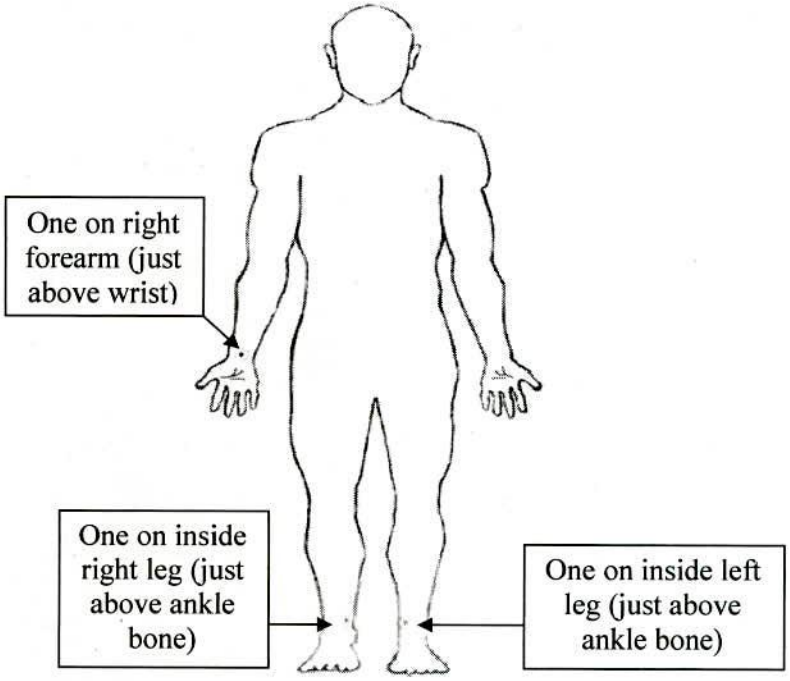

Figure 4.2: Subject setup for ECG recordings.

It is important that I followed the electrode procedure below to obtain an optimal ECG recording:

- The surface of the skin was abraded at the points of electrode placement in about a 2" diameter.
- Alcohol was not used to clean the skin because alcohol dries the skin and prevent good electrical contact with the electrode.
- An electrode was peeled off using the tab without touching the adhesive.
- A drop of GEL1 electrode gel was placed onto the small sponge of

the electrode (without allowing any gel to get on the adhesive).

- The electrodes were attached to the skin in the positions shown (over the previously abraded areas).

After placing three electrodes, the Subjects were rested in patient bed in supine position. For optimal electrode adhesion, the electrodes were placed on the Subject's skin at least 5 minutes before the start of the calibration procedure.

For evaluating our system a database of ten subjects is created. Details of Subjects are given in section 4.1 and the summary of the database is:

Number of Subjects	:	10
Electrode Position	:	Hand and legs
Transducer Position	:	Index finger tip
Average Age of Subjects	:	22.6 years
Average Weight of Subjects	:	66 kg
Average Height of Subjects	:	171.70 cm
Average BMI of Subjects	:	22.44 kg/m^2
Subjects' sex	:	Male
Time of Recording	:	About 1.7 hours
History of cardiovascular diseases	:	No

4.3.3 End-Connection Setup

The electrode lead set (SS2LA) was attached to the electrodes (EL503) placed on the Subject, following the color code as showed in Figure 4.3(a). Each of the pinch connectors on the end of the electrode cable were attached to a specific electrode. The electrode cables connected each cable to the proper electrode. The pinch connectors work like a small clothespin, but will only latch into the nipple of the electrode from the one side of the connector. Window of the pulse sensor (SS2LA) was cleaned and wrapped the transducer snugly around the tip of subject's index finger on the left hand. Pulse transducer was positioned so that the sensor is on the bottom of subject's fingertip (the part without the fingernail) as showed in Figure 4.3(b). Electrode cables were positioned such that they were not pulling on the electrodes or the transducer. The electrode cable clip (where the

cable meets the three individual colored wires) was attached to a convenient location (cab be on the subject's clothes). This had relieved cable strain. The subject was not in contact with nearby metal objects (faucets, pipes, etc.), and any wrist or ankle bracelets were removed. The subject was relaxed in supine position.

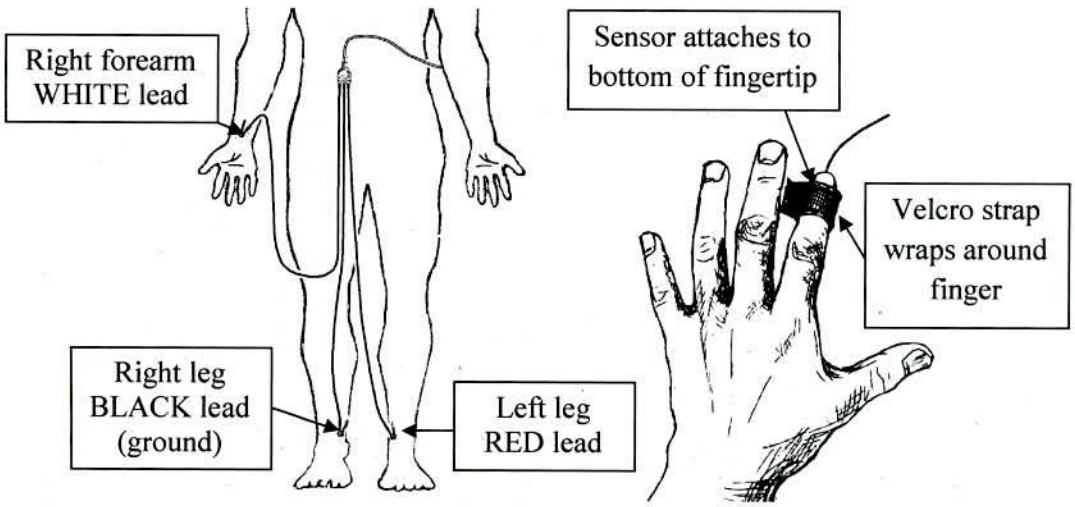

Figure 4.3: Setup of (a) electrode lead set with electrodes, (b) Pulse sensor position in hand.

4.3.4 Software and Calibration Setup

Biopac Student Lab software was started in one computer (PC 1) with which MP36 module 1 was connected and specific lesson for ECG and pulse recordings were chosen. From another computer (PC 2) with which MP36 module 2 was connected, Biopac Student Lab software was started and specific lesson for blood pressure measurements were chosen. Experimental setup was finished with typing a filename where recorded data will be saved. The calibration procedure establishes the hardware's internal parameters (such as gain, offset, and scaling) and is critical for optimum performance. Close attention was being used to the calibration process. To calibrate MP36 module 1, electrode connections were checked again and the subject was relaxed. After starting calibration, we waited for calibration procedure to stop. The Subject was remained relaxed throughout calibration and the calibration procedure was stopped automatically after 8 seconds. At the end of the 8-sec calibration recording, the screen resembled Figure 4.4. This was the end of calibration for MP36 module 1.

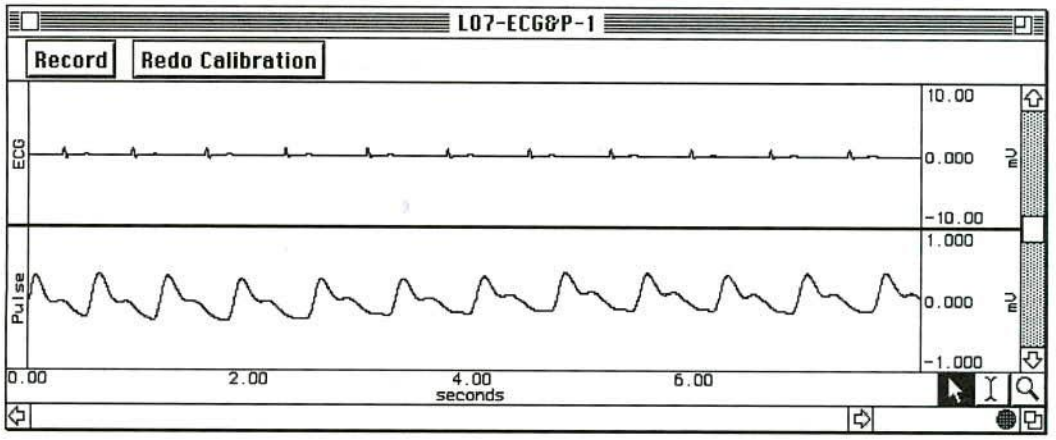

Figure 4.4: Calibration procedure for ECG and pulse recordings.

4.4 Cardiac Signals Recording

Food intake was restricted to a light meal 2 hour prior to the test. The Subjects were resting in the supine position throughout the whole experimental period. The whole data recording procedure is showed in Figure 4.5.

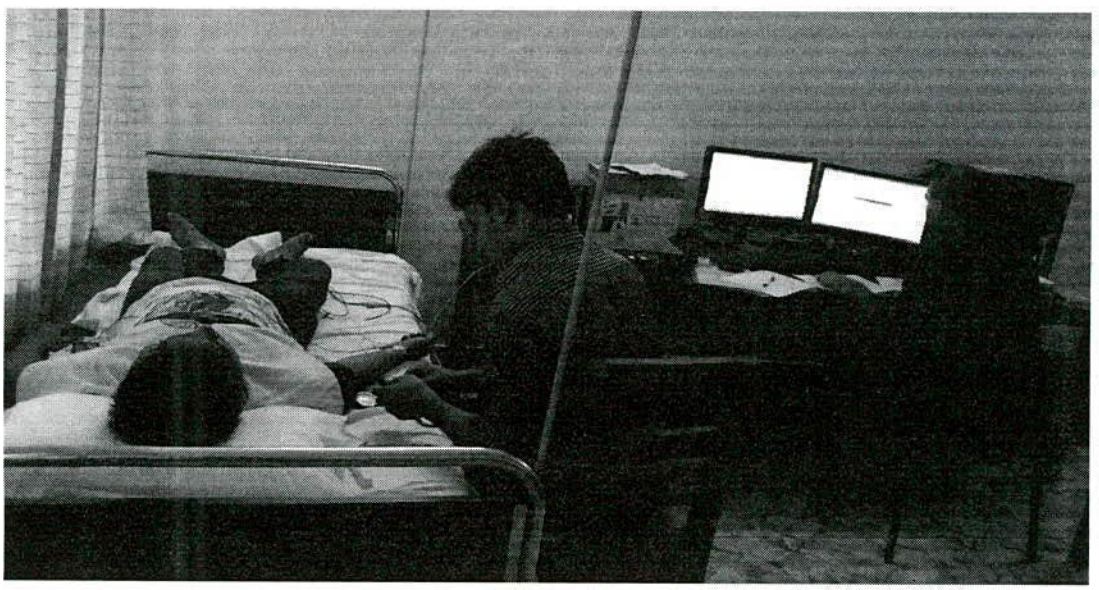

Figure 4.5: Cardiac signals recording with Subject at supine position and relaxed.

To minimize muscle (EMG) corruption of the ECG signal and baseline drift:

- The Subject was kept still during all of the recording segments because the recording from the pulse transducer is sensitive to motion and the ECG recording is sensitive to EMG artifact.

- The Subject was relaxed state for each recording segment.
- We checked to make sure that the cable is not pulling on the pulse transducer.
- The recording was suspended before the Subject prepares for the next recording segment.
- It was also made sure that the electrodes do not "peel up".

4.4.1 Cardiac Signals at Normal Condition

At least 5 minutes were allowed for acclimatization before the measurements were performed on the subject's body. Before having energy drinks (normal condition), ECG and pulse measurements were performed with a time period about 10 minutes. The recordings of ECG and pulse for a Subject at normal condition with a short duration are showed in Figure 4.6 and Figure 4.7 respectively.

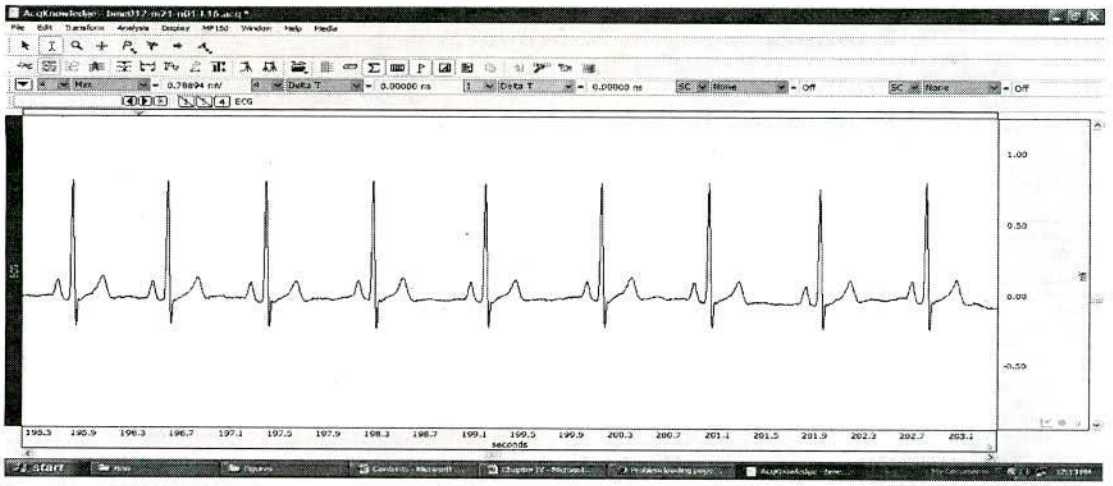

Figure 4.6: ECG recording before having ED.

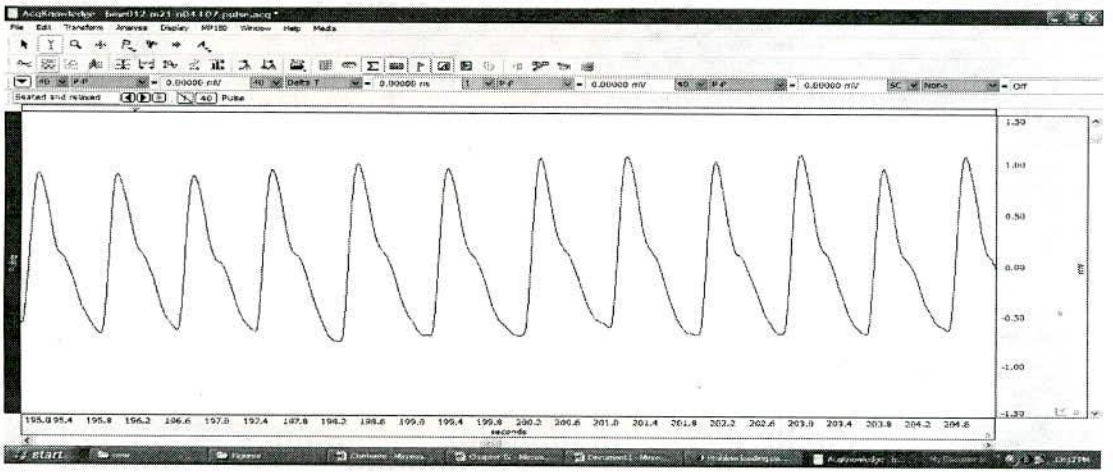

Figure 4.7: Pulse recording before having ED.

4.4.2 Cardiac Signals at Energized Condition

Royal Tiger Energy drinks (ED) of serving size of 270 ml/bottle which contains caffeine 54 mg/270 ml, sugar 41.5 gm/270 ml and other ingredients e.g. carbonated water, acidity regulators (E330, E331), vitamins, flavor (natural, nature identical & artificial), preservatives (E211) & colors (E102) were used in this experiment. After having energy drinks, ECG and pulse recordings were performed with a time period about 95 minutes. Continuous ECG and pulse recordings were not performed due to the time limitation of recording using Biopac Student Lab (BSL) software. Being energized, ECG and pulse recordings were performed discretely, i.e. with some interval of time. The recordings of ECG and pulse for a Subject at energized condition are showed in Figure 4.8 and Figure 4.9 respectively.

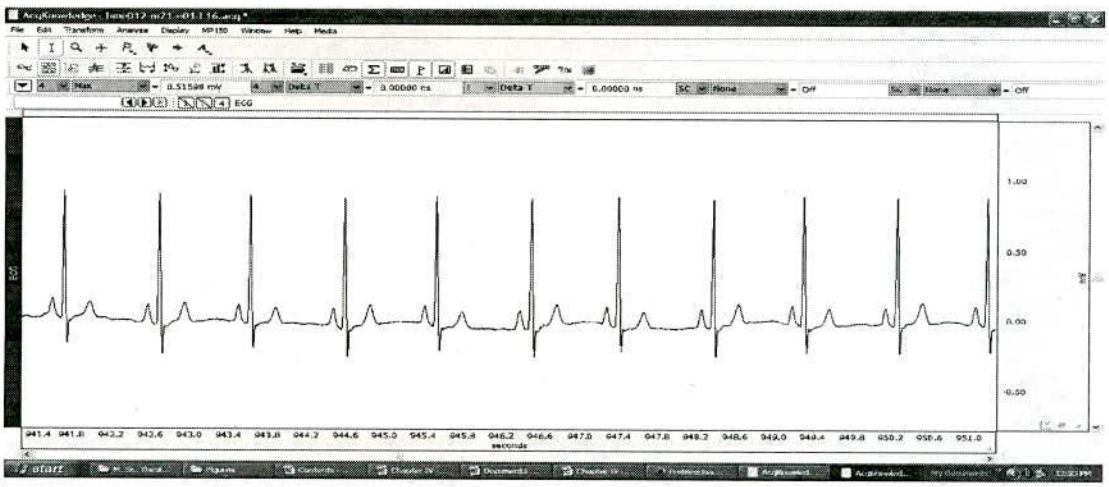

Figure 4.8: ECG recording after having ED.

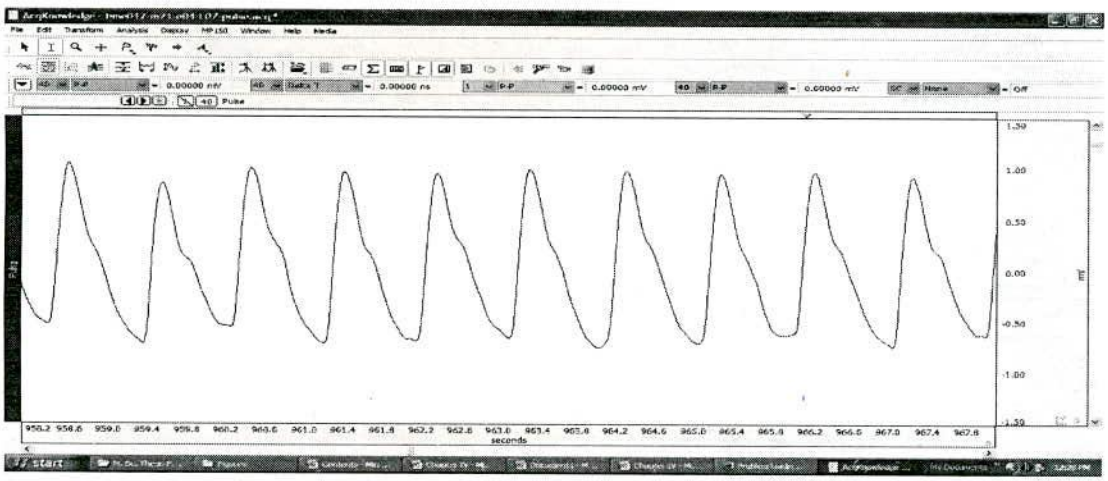

Figure 4.9: Pulse recording after having ED.

4.5 Influence of ED on Cardiac Signals

Influence of energy drinks consumption on cardiac signals can be subdivided into three categories as:

- Influence of ED consumption on ECG
- Influence of ED consumption on PPG
- Influence of ED consumption on ECG & PPG parameters

4.5.1 Influence on ECG

A typical recording of ECG for a subject at normal (before having ED) and energized (after having ED) condition is showed in Figure 4.10 and Figure 4.11 respectively.

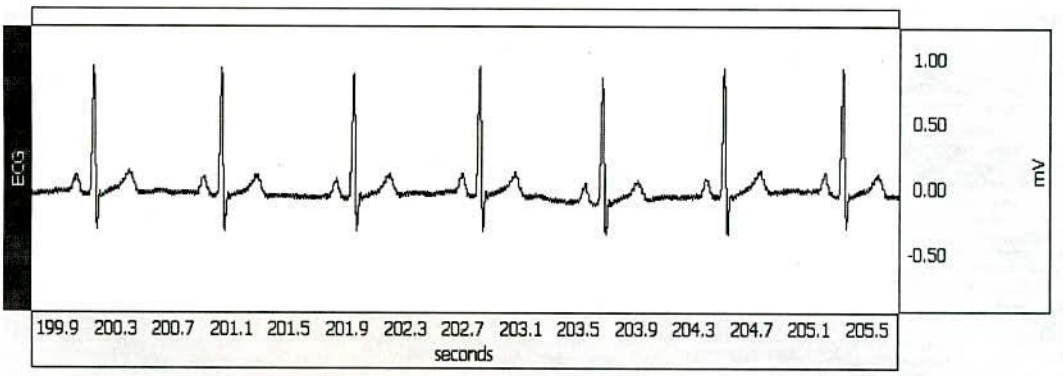

Figure 4.10: ECG recording before having ED for a typical subject.

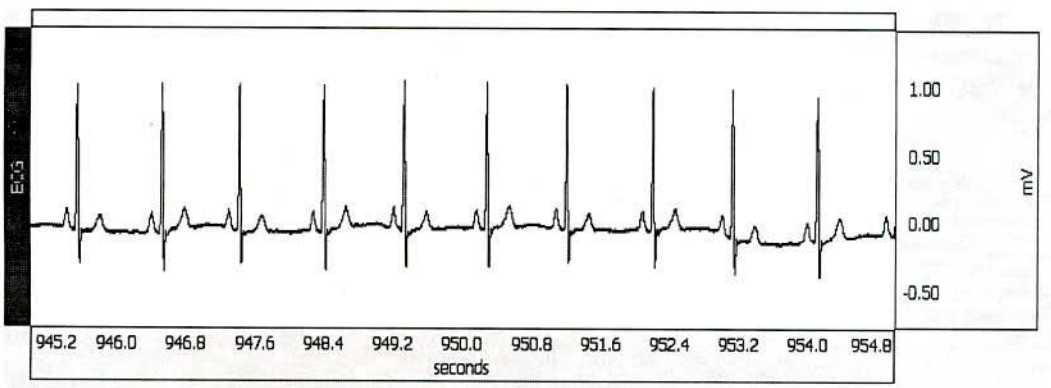

Figure 4.11: ECG recording after having ED for a typical subject.

At normal condition, the maximum R peak amplitude of ECG, average R-R interval of ECG and heart rate are found about 0.952 mV, 879 ms and 68 BPM respectively. After

having ED, the maximum R peak amplitude of ECG, average R-R interval of ECG and heart rate are found about 1.056 mV, 937 ms and 64 BPM respectively. Heart rates have been calculated from average R-R interval of ECG. There is an increment in maximum R peak amplitude of ECG, average R-R interval of ECG and decrement in heart rate due to consumption of ED.

A single ECG signal recording for a typical subject at before and after having ED is shown in Figure 4.12. ECG recording before having ED is indicated by Normal ECG (00) using pure line and after having ED is indicated by Energized ECG (05) using dotted line. Energized ECG (05) indicates the ECG recording after five (05) minutes from the instant of having ED. Due to the consumption of ED, the electrocardiographic parameters such as peak amplitude of P, Q, R, S, & T waves as well as their segments & intervals are changed to a notable value. These changes can be noticed after 20, 40, 65, & 90 minutes of having ED as well. ECG parameters mentioned above before and after having ED are comparable from Figure 4.12. There is a notable incremental change in peak amplitude of P, Q and S wave; significant increment in peak amplitude of R wave; notable decremental change in peak amplitude of T wave are observed due to the consumption of ED.

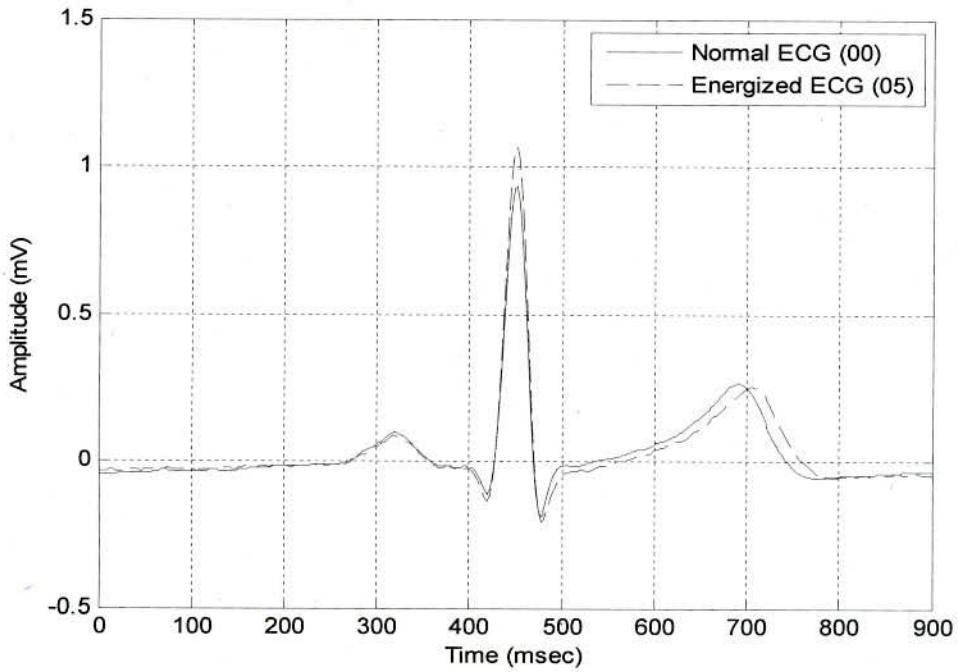

Figure 4.12: ECG signal comparison before and after having ED.

Peak amplitude based ECG parameters variation with time for a typical subject is shown in Figure 4.13. Data at time 0 min indicates the peak amplitude for normal condition. Data after 0 min to 90 min indicate the peak amplitude for energized condition. Due to having ED, peak amplitude of P and Q wave shows a notable decrement with time. In case of S and T waves, both incremental and decremental changes are observed in their peak amplitude. The highest decrement in peak amplitude of S and T waves are observed within about 30 to 50 min from the instant of having ED. There is more significant change in peak amplitude of R wave. After having ED, significant increment in R peak amplitude is observed with time and it gets maximum increment at about 20-40 min and then shows a tendency to decrease. These significant changes in ECG parameters prove that the effect of having ED lasts some interval of time and then finished.

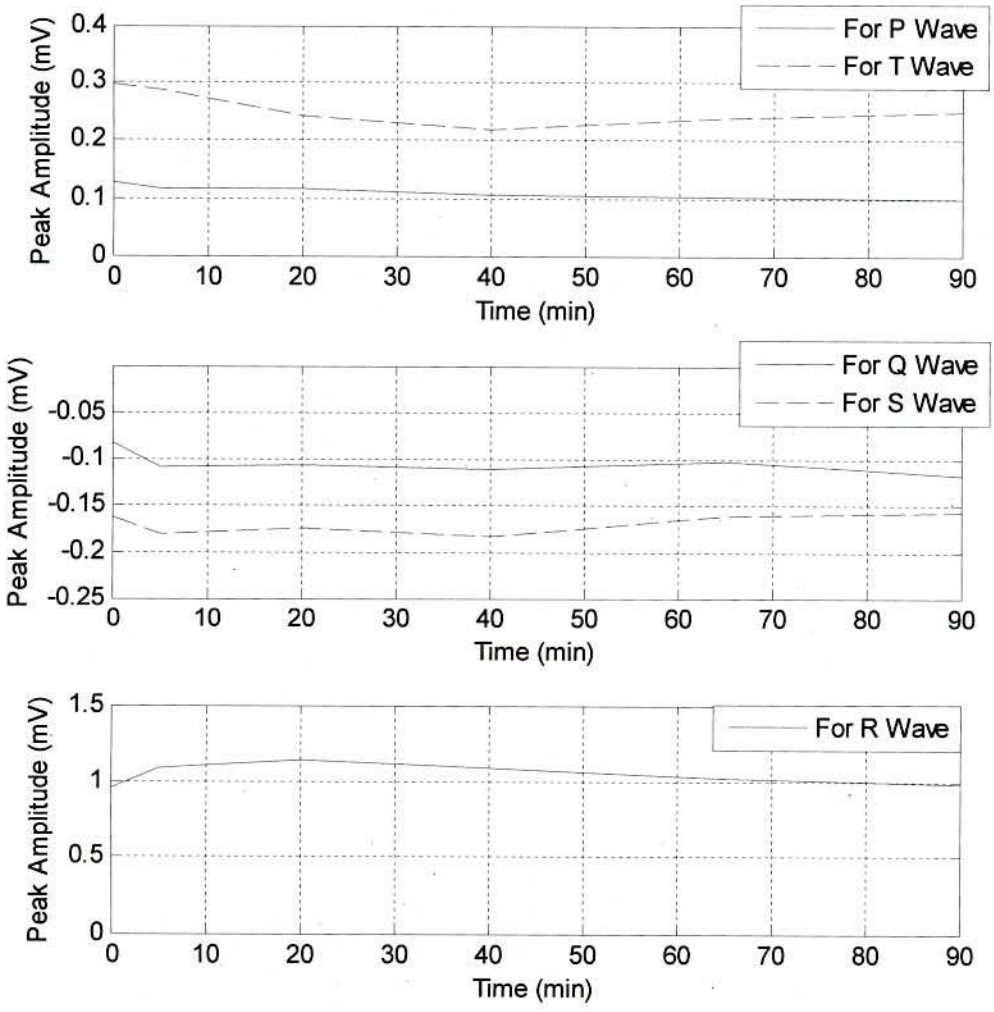

Figure 4.13: Amplitude variation of different waves of ECG signal due to having ED

The average changes in peak amplitude of different waves of ECG signal with time due to the consumption of ED are shown in Table 4.4. The readings (range) at time 00 minute indicate the average value of peak amplitude of corresponding waves at normal condition. Average values of peak amplitude at energized condition are shown in some interval of time (i.e. after 05, 20, 40, 65 and 90 minutes from the instant of being energized). The ranges of readings of peak amplitude of corresponding waves are presented as mean ± standard deviation (SD). The average peak amplitude of P wave decreases with time which is notable. Besides, a significant decrement in average peak amplitude of T wave is also noticed due to having energized. In case of Q and S waves, a variable (random) change is noticed with time. Though there are less significant changes in peak amplitude of P, Q, S and T wave; change in peak amplitude of R wave with time is more significant. The peak amplitude of R wave increases after having energized and it gets maximum increment at about 20-40 min from the instant of drinking and then shows a tendency to decrease to reach at normal condition.

Table 4.4: Average changes in peak amplitude of ECG signal components

Time (min)	Peak amplitude of ECG Signal components (mV)[a]				
	P wave	Q wave	R wave	S wave	T wave
00	0.11649 ± 0.02461	0.05479 ± 0.03490	1.12127 ± 0.55469	-0.22759 ± 0.08750	0.23686 ± 0.07307
06	0.11577 ± 0.03183	0.06332 ± 0.04827	1.18797 ± 0.57099	-0.22684 ± 0.09150	0.22928 ± 0.07080
21	0.11456 ± 0.02263	0.05843 ± 0.04866	1.23395 ± 0.57775	-0.22489 ± 0.08887	0.21403 ± 0.04650
40	0.11168 ± 0.02548	0.06213 ± 0.04274	1.22629 ± 0.56285	-0.24712 ± 0.10554	0.17944 ± 0.05021
60	0.11025 ± 0.02510	0.06059 ± 0.03892	1.18709 ± 0.56459	-0.21941 ± 0.09584	0.20487 ± 0.04886
90	0.10730 ± 0.01911	0.06437 ± 0.04168	1.15502 ± 0.55503	-0.22107 ± 0.09353	0.20269 ± 0.06453

[a]Values are Mean ± SD

The percentage changes in average peak amplitude of different waves of ECG signal with time are shown in Table 4.5. The readings at time 00 minute indicate the percentage changes in average peak amplitude of different waves at normal condition. Percentage changes in average peak amplitude at energized condition are shown in some interval of time (i.e. after 05, 20, 40, 65 and 90 minutes from the instant of being energized). Minus (-) sign indicates the decrement in peak amplitude with respect to normal condition. In case of P wave, the decremental percentage change is observed i.e. the peak amplitude of P wave decreases with time. Also the percentage change in peak amplitude of Q, S and T waves are variable and the highest increment or decrement in peak amplitude of these waves are found within 20 to 40 min from the instant of being energized. Though there are less significant percentage changes in peak amplitude of P, Q, S and T wave; percentage change in peak amplitude of R wave with time is more significant. The percentage increment in peak amplitude of R wave after having energized and it gets maximum percentage increment at about 20-40 min from the instant of drinking and then shows a tendency to decrease to reach at normal condition.

Table 4.5: Percentage changes in average peak amplitude of different waves of ECG signal

Time (min)	% Change in average peak amplitude of different waves of ECG signal with time				
	P wave	Q wave	R wave	S wave	T wave
00	0%	0%	0%	0%	0%
06	-2.10%	1.15%	6.16%	-0.05%	-3.07%
21	-0.40%	-26.06%	11.18%	-1.48%	-5.97%
40	-3.23%	14.05%	10.82%	7.49%	-23.36%
60	-4.20%	14.46%	6.44%	-4.93%	-7.96%
90	-6.37%	34.68%	3.77%	-3.12%	-11.61%

ECG parameters such as RR, RT and PR intervals were evaluated from ECG recording for both before and after having ED. Interval based ECG parameters variation with time for a typical subject is shown in Figure 4.14. Data at time 0 min indicates the intervals for normal condition. Data after 0 min to 90 min indicate the intervals for energized condition. Due to having ED, no significant change is found in RT and PR intervals but notable

change is found in RR interval of ECG signal. RR interval increases with time for this typical subject and hence heart rate of this subject decreases after consuming ED.

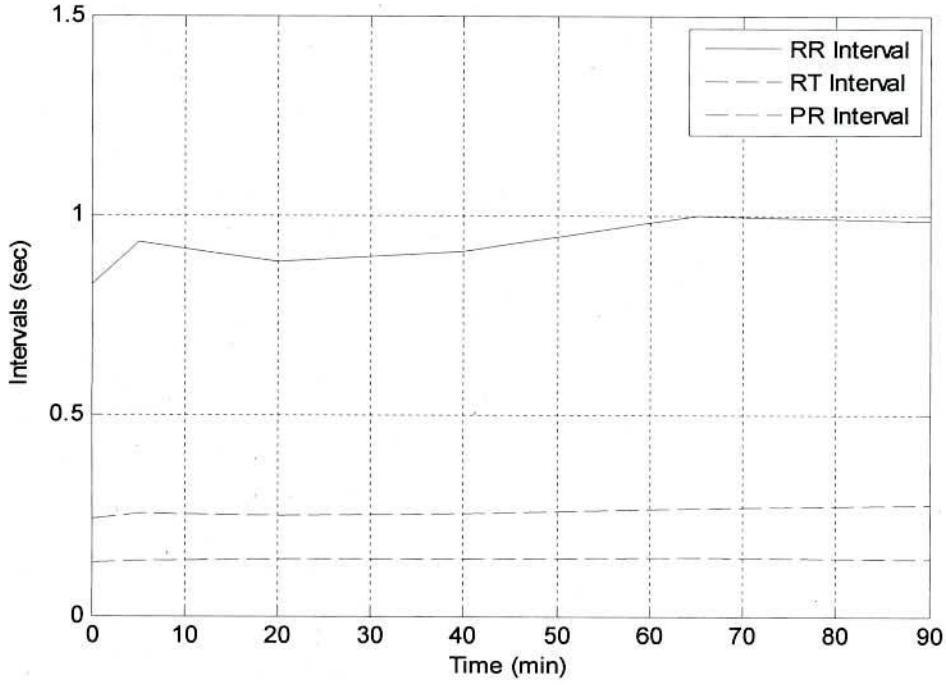

Figure 4.14: Variation of different intervals of ECG signal with time due to having ED.

Average changes in different intervals of ECG signal with time due to the consumption of ED are shown in Table 4.6. The readings (range) at time 00 minute indicate the average value of different intervals at normal condition. Average values of different intervals at energized condition are shown in some interval of time (i.e. after 05, 20, 40, 65 and 90 minutes from the instant of being energized). The ranges of readings of different intervals of ECG signal are presented as mean ± standard deviation (SD). It shows less significant increment in PR interval, moderately significant increment in RT interval and more significant increment in RR interval. Due to the consumption of ED, increments in different intervals are noticed but RR interval increment is remarkable. In this study, the time interval between two successive R peaks is assumed as RR interval. Heart rate (HR) decreases as the RR interval increases and vice versa i.e. heart rate is inversely proportional to the RR interval. RR interval increases or heart rate decreases with time due to the consumption of ED.

Table 4.6: Average changes in different intervals of ECG signal with time

Time (min)	Change in different intervals of ECG Signal (sec)[a]		
	RR Interval	RT Interval	PR Interval
00	0.8522 ± 0.0536	0.2244 ± 0.0162	0.1184 ± 0.0131
06	0.8530 ± 0.0544	0.2328 ± 0.0162	0.1216 ± 0.0159
21	0.8478 ± 0.0571	0.2332 ± 0.0199	0.1206 ± 0.0178
40	0.8736 ± 0.0822	0.2340 ± 0.0194	0.1228 ± 0.0177
60	0.8720 ± 0.1162	0.2378 ± 0.0185	0.1248 ± 0.0197
90	0.8860 ± 0.0913	0.2438 ± 0.0197	0.1258 ± 0.0192

[a]Values are Mean ± SD

Power spectrum density of ECG recording for a certain interval of time (about 30 seconds) at both normal and energized condition is showed in Figure 4.15 and Figure 4.16 respectively.

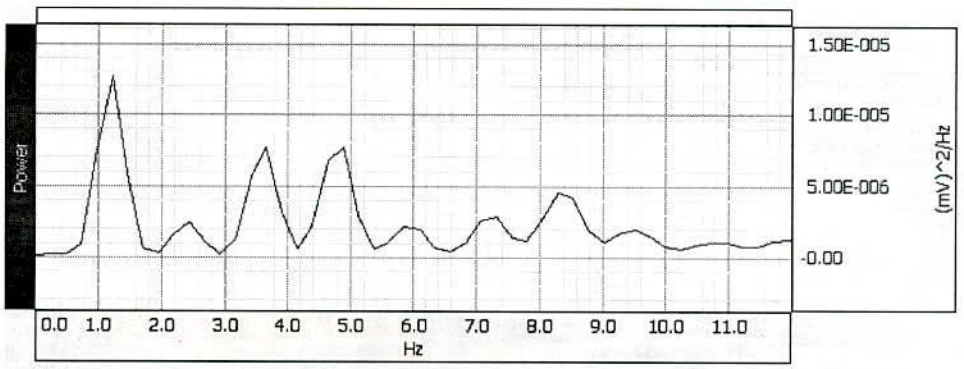

Figure 4.15: Power spectrum density of ECG signal before having ED.

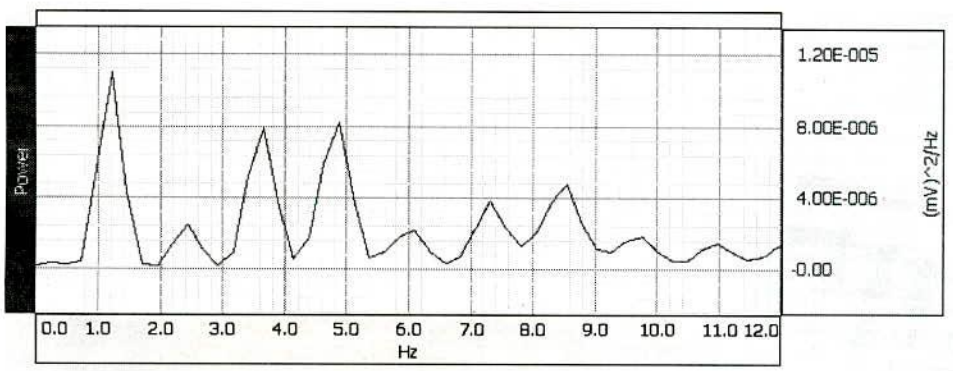

Figure 4.16: Power spectral density of ECG signal after having ED.

At normal condition, the maximum power of spectrum density is found as 1.26E-005 (mV)^2/Hz at 1.22 Hz. After being energized, the maximum power of spectrum density is found as 1.10E-005 (mV)^2/Hz at 1.22 Hz. It is observed that, the power of spectrum density which occurs within frequency range of cardiac activity decreases about 13 percent with respect to the normal condition due to the consumption of ED.

Fast Fourier Transform (FFT) of ECG recording for a certain interval of time (about 30 seconds) at both normal and energized condition is showed in Figure 4.17 and Figure 4.18 respectively. At normal condition, the maximum amplitude of FFT is found as 0.01684 mV at 1.22 Hz. After being energized, the maximum amplitude of FFT is found as 0.01377 mV at 1.22 Hz. It is observed that, the amplitude of FFT which occurs within frequency range of cardiac activity decreases about 18 percent with respect to the normal condition due to the consumption of ED.

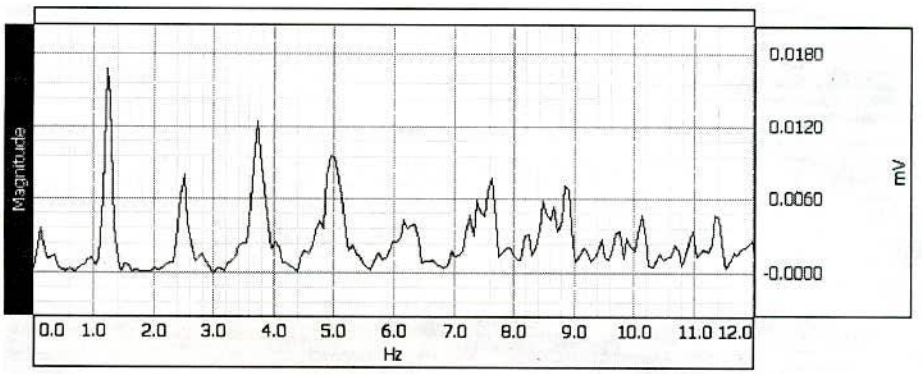

Figure 4.17: Fast Fourier Transform of ECG signal before having ED.

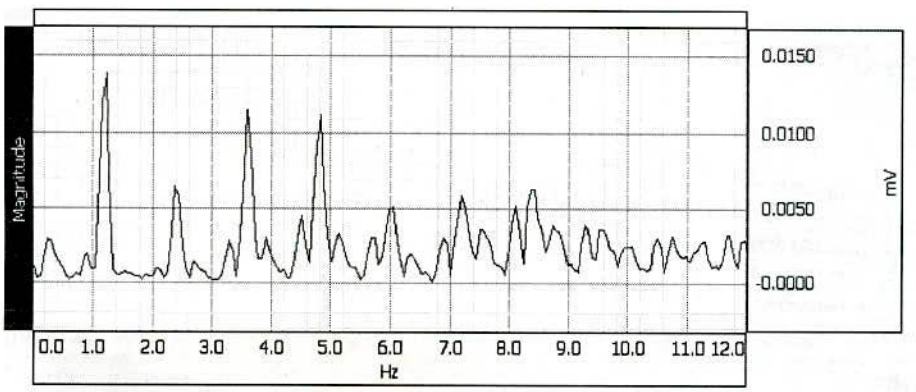

Figure 4.18: Fast Fourier Transform of ECG signal after having ED.

4.5.2 Influence on PPG

A typical recording of pulse (PPG) for a subject at normal and energized condition is showed in Figure 4.19 and Figure 4.20 respectively. At normal condition, the maximum peak to peak amplitude of PPG is about 1.793 mV. After having ED, the maximum peak to peak amplitude of PPG is about 1.751 mV. There is a little decrement in maximum peak to peak amplitude of PPG for this subject. An effective decrement in maximum peak to peak amplitude of PPG is found in our study for other subjects due to consumption of ED.

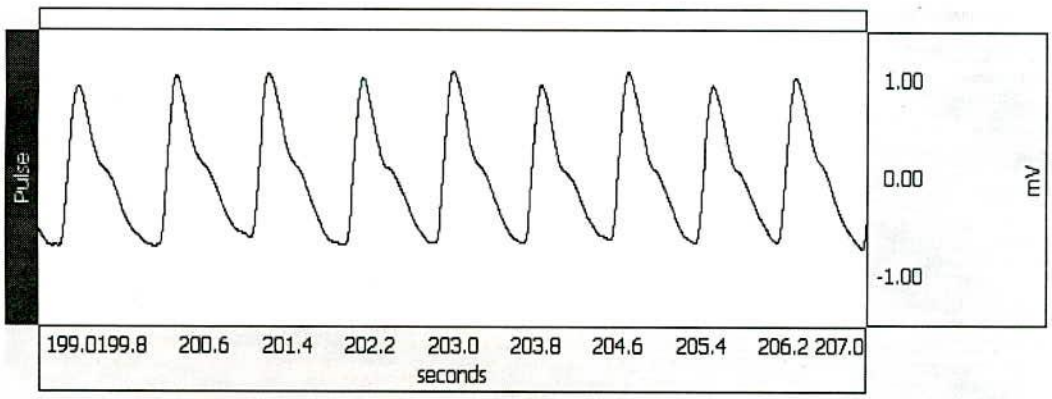

Figure 4.19: Pulse (PPG) recording before having ED.

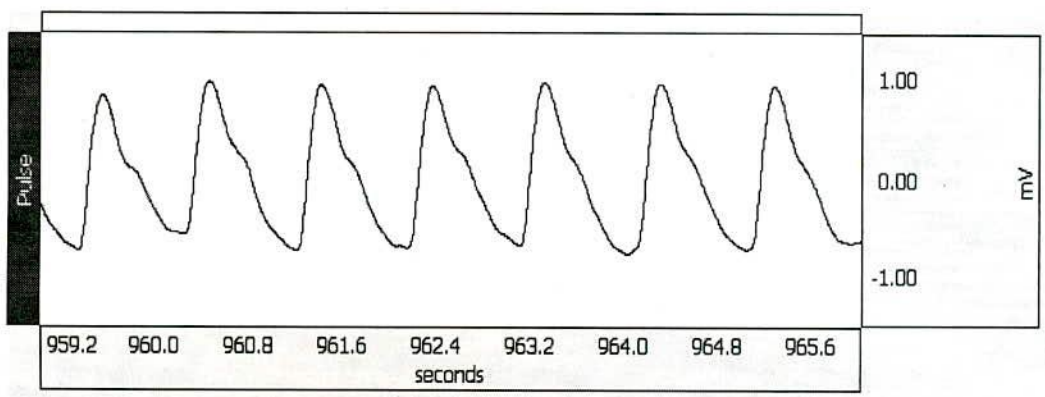

Figure 4.20: Pulse (PPG) recording after having ED.

Power spectrum density of PPG recording for a certain interval of time (about 30 seconds) at both normal and energized condition is showed in Figure 4.21 and Figure 4.22 respectively. At normal condition, the maximum power of spectrum density is found as 0.00346 (mV)^2/Hz at 1.17 Hz. After being energized, the maximum power of spectrum density is found as 0.00255 (mV)^2/Hz at 1.07 Hz. We know that, the frequency range for

cardiac activity is about 0.6 to 1.6 Hz. It is observed that, the power of spectrum density which occurs within frequency range (cardiac activity) mentioned above decreases about 26 percent with respect to the normal condition due to the consumption of ED.

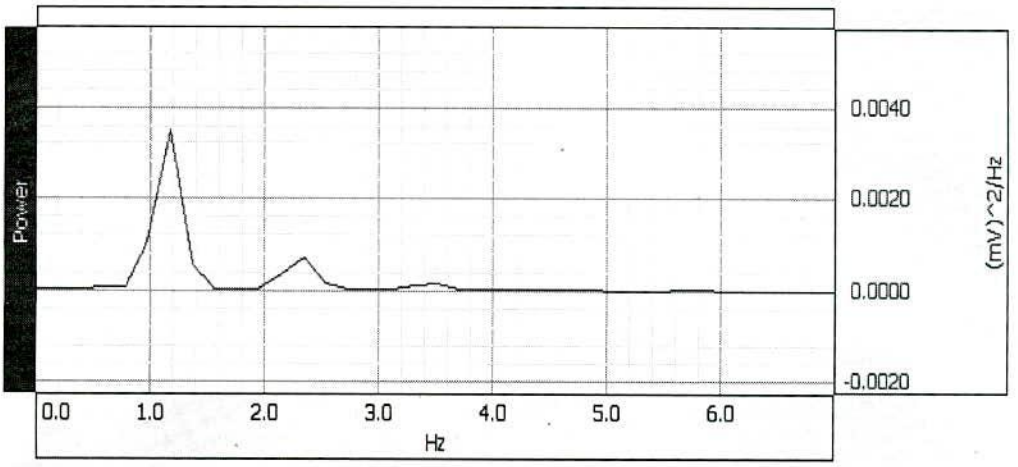

Figure 4.21: Power spectrum density of PPG signal before having ED.

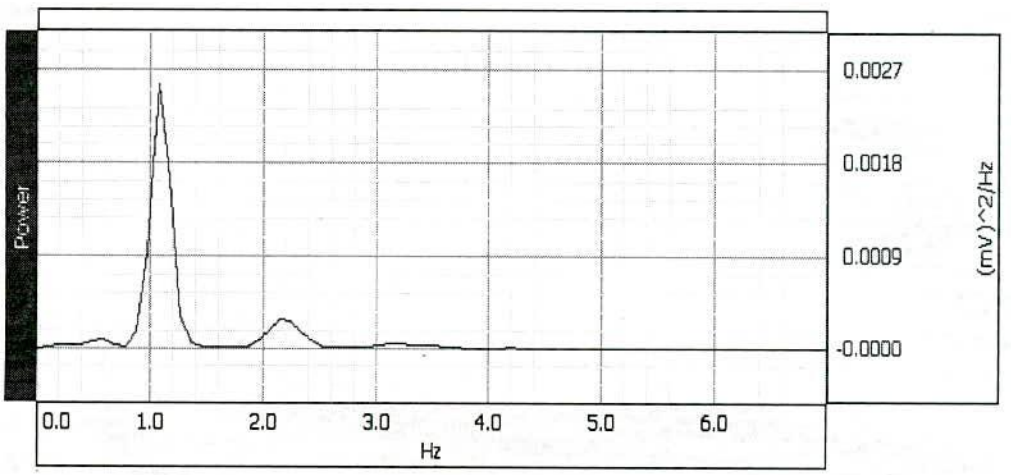

Figure 4.22: Power spectrum density of PPG signal after having ED.

Fast Fourier Transform (FFT) of PPG recording for a certain interval of time (about 30 seconds) at both normal and energized condition is showed in Figure 4.23 and Figure 4.24 respectively. At normal condition, the maximum amplitude of FFT is found as 0.11879 mV at 1.15 Hz. After being energized, the maximum amplitude of FFT is found as 0.08046 mV at 1.10 Hz. It is observed that, the amplitude of FFT which occurs within

frequency range of cardiac activity decreases about 32 percent with respect to the normal condition due to the consumption of ED.

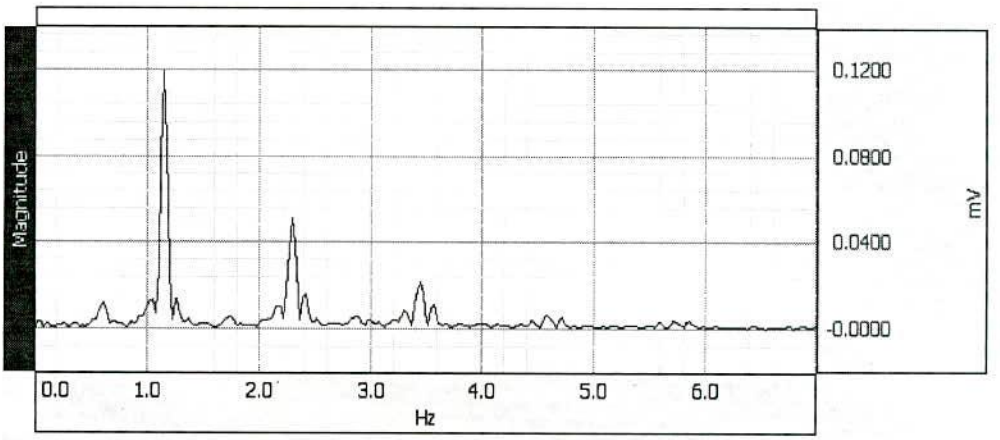

Figure 4.23: Fast Fourier Transform of PPG signal before having ED.

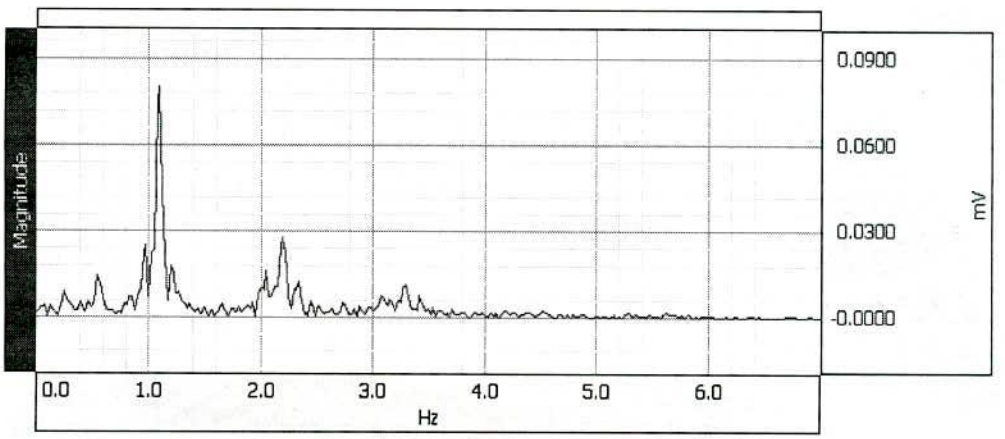

Figure 4.24: Fast Fourier Transform of PPG signal after having ED.

4.5.3 Influence on ECG & PPG Parameters

Figure 4.25 shows the changes in heart rate of different subjects with time which is calculated using RR intervals of ECG signal. Table 4.7 shows the average values of R peak amplitude of ECG, peak to peak amplitude of pulse and heart rate for twelve healthy young male adults with some interval of time. The readings at time 0 minute indicate the average values of electrocardiographic and pulse plethysmographic parameters at normal condition. Average values of electrocardiographic and pulse plethysmographic parameters at

energized condition are shown in some interval of time (i.e. after 6, 9, 12, etc. minutes of having energy drinks). Average data showed here upto 95 minutes from the instant of having energy drinks. It is observed that, R peak amplitude of ECG increases and this increment continues upto about 95 minutes from the instant of being energized. Also an effective decrement in peak to peak amplitude of pulse and heart rate is observed due to having ED.

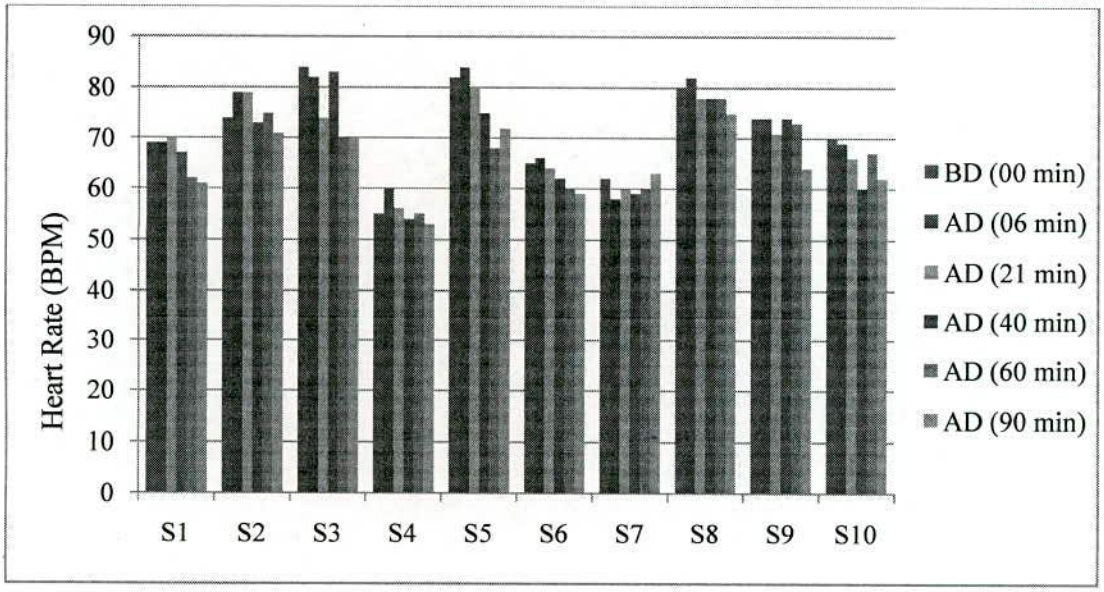

Figure 4.25: Changes in heart rate of different subjects with time.

The percentage changes in average R peak amplitude of ECG with time are shown in Figure 4.26. The percentage change at time 0 minute is zero which indicates the normal condition. After having energized, the maximum increment in average R peak amplitude of ECG is about 4.8%. Graph shows that about 0 to 2.7% increment in 0 to 21 minutes duration, 0.7% to 4.8% increment in 21 to 55 minutes duration, 1.6% to 4.4% increment in 55 to 90 minutes duration occurs in average R peak amplitude of ECG approximately. After 90 minutes, increment in average R peak amplitude of ECG is below 2% and tries to go to become normal rapidly at about 95 minutes. The total effective increment (>1%) in average R peak amplitude of ECG lasts about 90 to 95 minutes.

The percentage changes in peak to peak amplitude of pulse (PPG) and heart rate (HR) with time are shown in Figure 4.27 and Figure 4.28 respectively. After having energized, the percentage changes in peak to peak amplitude of PPG are irregular and hold average normal value upto about 40 minutes. After 40 minutes, there is a significant decrement in

peak to peak amplitude of PPG due to consumption of ED. An insufficient increment in HR (about 0 to 1.4%) lasts about 8 minutes and then decrement with a higher rate starts due to having ED. About 0 to 4.2% decrement in HR is found within 8 to 60 minutes interval. A higher decrement about 4% to 7.2% in HR is found within 60 to 90 minutes interval. Graph shows a negative impact on peak to peak amplitude of PPG and HR due to the consumption of ED.

Table 4.7: Average changes in ECG and PPG parameters with time

Time (min)	Average R Peak Amplitude of ECG (mV)	Average p-p amplitude of pulse (mV)	Average Heart Rate (BPM)
00	0.939	2.31	72
06	0.943	2.33	73
09	0.949	2.14	71
12	0.955	2.29	71
15	0.965	2.44	70
18	0.961	2.28	69
21	0.946	2.46	70
24	0.953	2.19	70
27	0.959	2.23	69
30	0.959	2.33	70
35	0.970	2.46	69
40	0.971	2.18	70
45	0.982	2.11	69
50	0.984	2.30	69
55	0.970	1.94	69
60	0.969	2.07	69
70	0.975	2.09	67
80	0.981	2.10	67
85	0.973	2.14	67
90	0.957	2.06	67
95	0.940	1.89	68

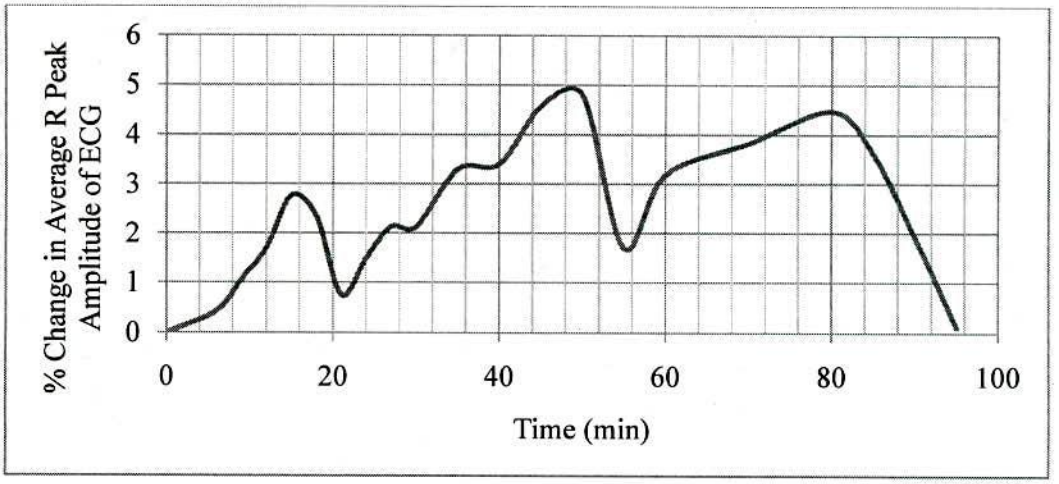

Figure 4.26: Percentage changes in average R peak amplitude of ECG signal.

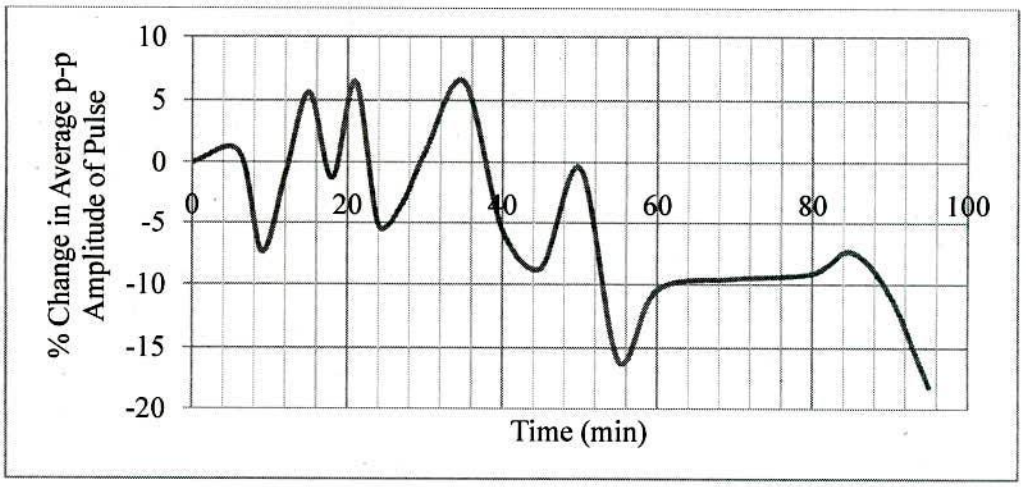

Figure 4.27: Percentage changes in average p-p amplitude of pulse (PPG).

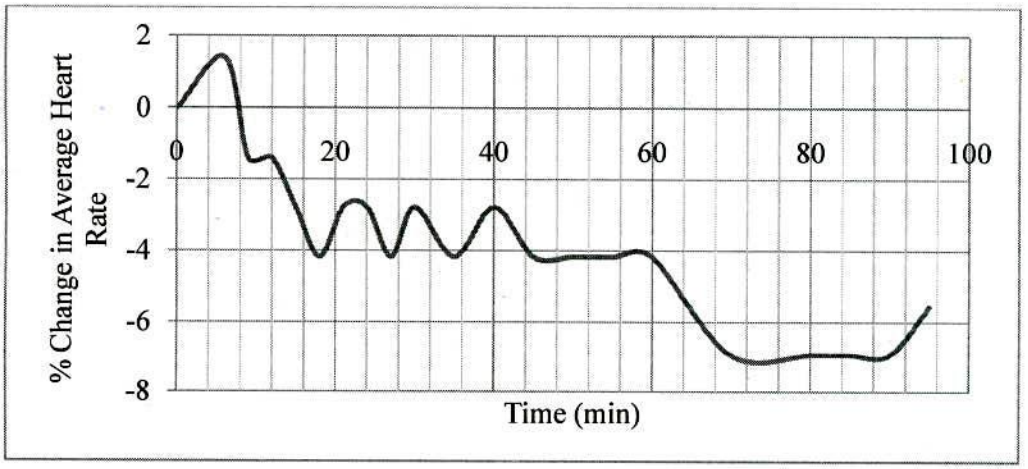

Figure 4.28: Percentage changes in average heart rate (HR) or pulse rate (PR).

Figure 4.29 and Figure 4.30 shows the changes in power of spectral density of ECG signal and amplitude of FFT of PPG signal of different subjects with time respectively. Table 4.8 shows the average values of spectrum or frequency components occur within the frequency range of heart activity for twelve healthy male adults with some interval of time. The readings at time 0 minute indicate the average value of spectrum or frequency components at normal condition. Average values of spectrum or frequency components at energized condition are shown in some interval of time (i.e. after 6, 9, 12, etc. minutes from the instant of being energized). Average data showed here upto 95 minutes from the instant of having ED. It is observed that, the spectrum or frequency components for PPG signal decreases with a significant rate from the instant of being energized. Though there is an insufficient incremental change in spectrum or frequency components for a short interval about 15 to 20 minutes, the effective decrement in spectrum components starts after that increment for ECG signal due to the consumption of ED.

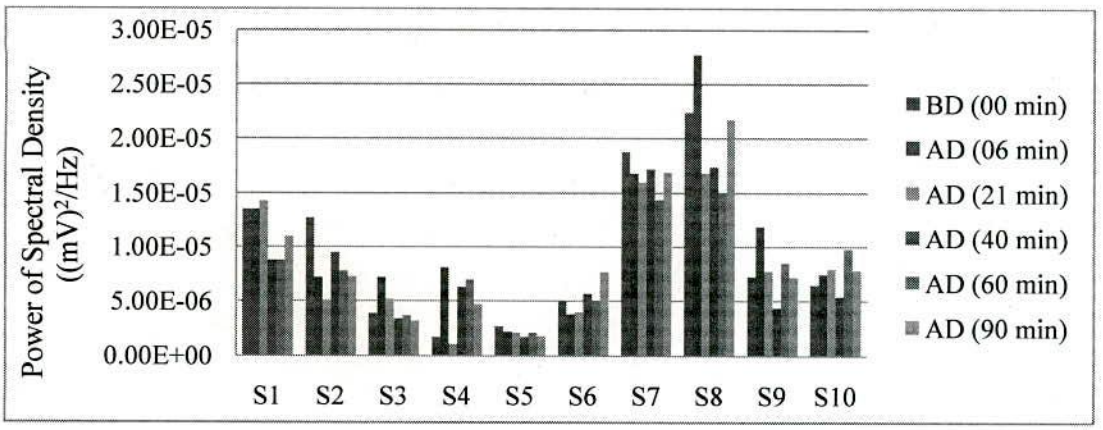

Figure 4.29: Changes in power of spectral density of different subjects for ECG signal.

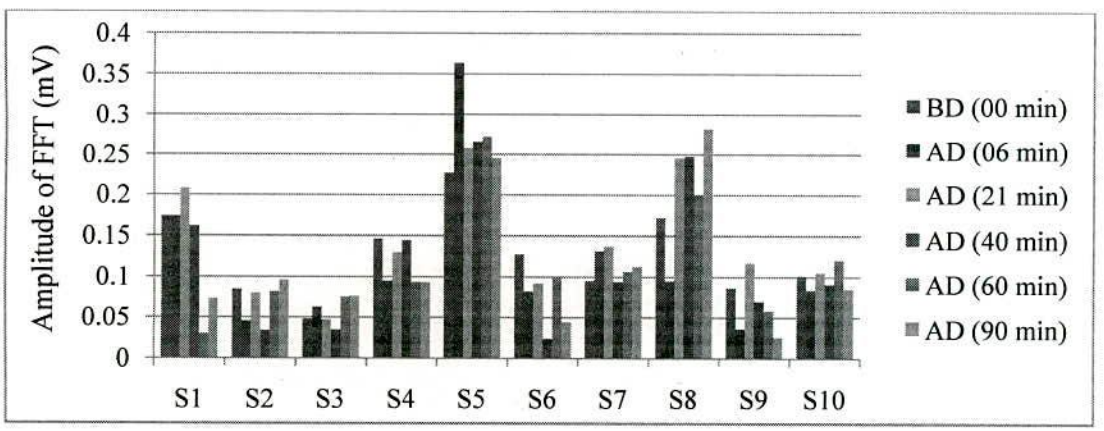

Figure 4.30: Changes in amplitude of FFT of different subjects for PPG signal.

Table 4.8: Average changes in spectrum or frequency components with time

Time (min)	For Pulse		For ECG	
	Power of Spectral Density $((mV)^2/Hz)$	*Magnitude of FFT (mV)*	*Power of Spectral Density* $((mV)^2/Hz)$	*Magnitude of FFT (mV)*
00	0.00799	0.15267	1.08E-05	0.01016
06	0.00772	0.12668	1.19E-05	0.01091
09	0.00726	0.12891	1.12E-05	0.01038
12	0.00744	0.11252	1.21E-05	0.01031
15	0.00784	0.15309	1.26E-05	0.01092
18	0.00762	0.12633	1.14E-05	0.00918
21	0.00666	0.14351	0.97E-05	0.00830
24	0.00652	0.12815	1.15E-05	0.00908
27	0.00613	0.12849	1.00E-05	0.00902
30	0.00646	0.11760	1.11E-05	0.01035
35	0.00681	0.13278	0.99E-05	0.01086
40	0.00429	0.11201	0.98E-05	0.00967
45	0.00495	0.09693	1.10E-05	0.00943
50	0.00477	0.12612	1.10E-05	0.00969
55	0.00540	0.10940	1.11E-05	0.00935
60	0.00530	0.11364	1.07E-05	0.01070
70	0.00548	0.13198	1.11E-05	0.01045
80	0.00467	0.11130	1.13E-05	0.01032
85	0.00553	0.13640	1.09E-05	0.01029
90	0.00521	0.12304	1.06E-05	0.01034
95	0.00488	0.12967	0.93E-05	0.01037

The percentage changes in average power of spectrum density and average amplitude of FFT for PPG signal are showed in Figure 4.31 and Figure 4.32 respectively. The percentage change at time 0 minute is zero which indicates the normal condition. After having energized, the maximum decrement in average power of spectral density and average amplitude of FFT for PPG signal is about 47% and 37% respectively with respect

to the normal condition. Graph shows irregular rapid decrement in power of spectral density and amplitude of FFT upto the time about 40-45 minutes and then shows a tendency to reach to the normal condition due to having ED.

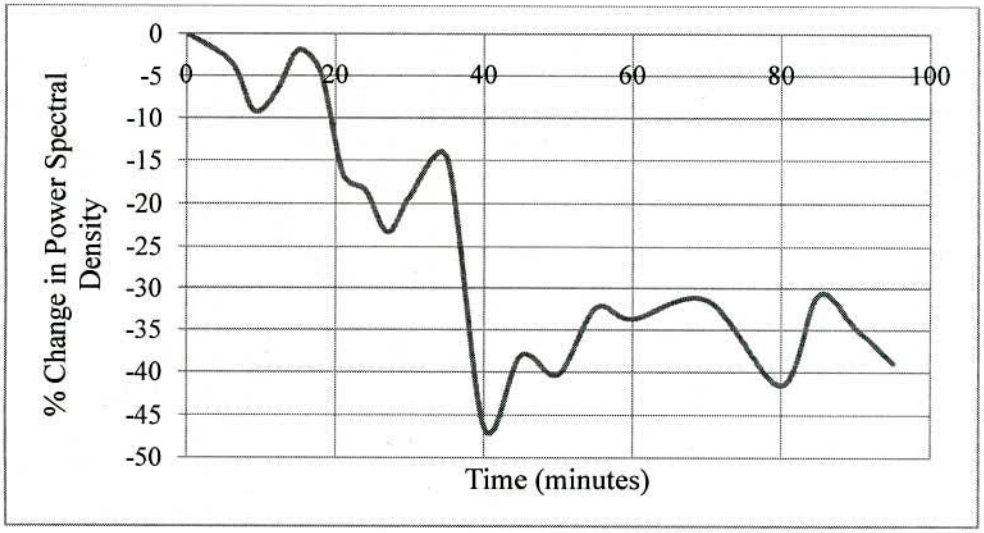

Figure 4.31: Percentage changes in power of spectrum density with time for PPG.

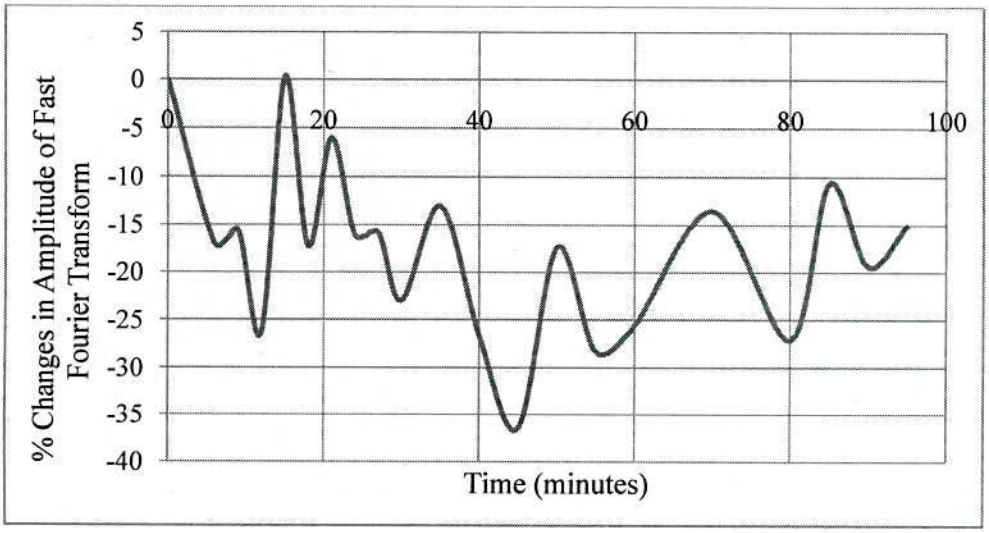

Figure 4.32: Percentage changes in amplitude of FFT with time for PPG.

For ECG signal, the percentage changes in average power of spectrum density and average amplitude of FFT are showed in Figure 4.33 and Figure 4.34 respectively. The percentage change at time 0 minute is zero which is the normal condition. After having ED, the maximum increment in average power of spectral density and average amplitude of FFT

for ECG signal is about 17% and 8% respectively with respect to the normal condition. This increment continues upto about 15-20 minutes from the instant of being energized. The above short time increment in spectral components indicate a positive impact on heart activity due to the consumption of ED. After this short interval (about 0-20 minutes), the maximum decrement in average power of spectral density and average amplitude of FFT for ECG signal is about 10% and 18% respectively with respect to the normal condition. Graph shows both irregular increment and decrement in power of spectral density and amplitude of FFT within the specified time period.

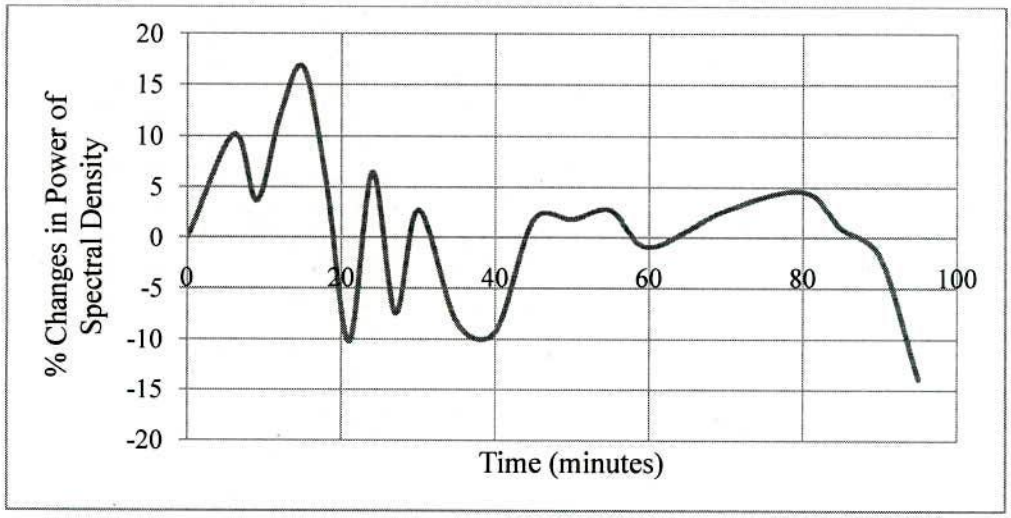

Figure 4.33: Percentage changes in power of spectrum density with time for ECG.

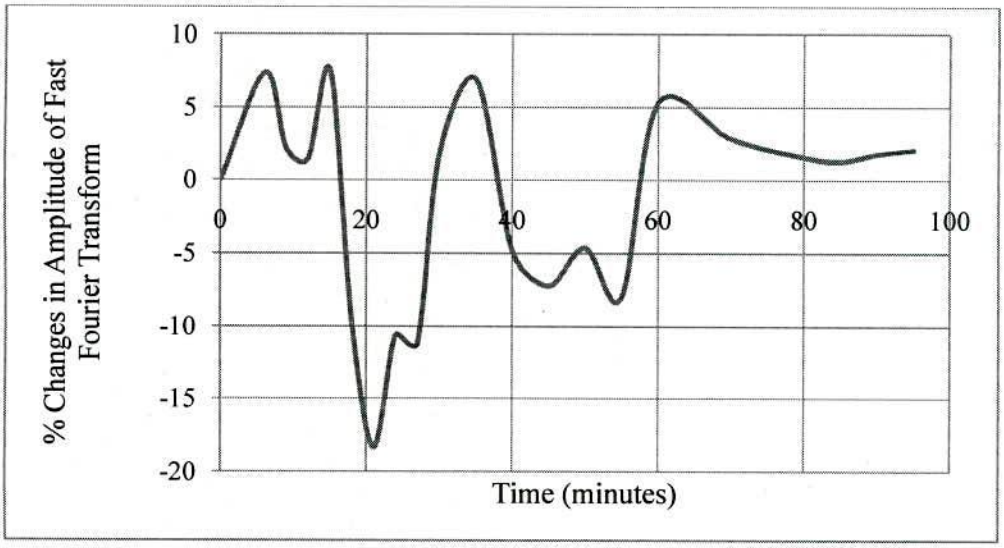

Figure 4.34: Percentage changes in amplitude of FFT with time for ECG.

4.6 Evaluation of Cardiac Signals Modeling

Electrocardiogram (ECG) modeling is proposed in this study as a part of thesis work and finally we have proposed an approximate mathematical model to generate ECG at both before and after the consumption of ED. Cardiac performances are evaluated using this mathematical model analyzing different error evaluating parameters. We have evaluated the performance of proposed model as well as modified proposed model of ECG.

4.6.1 Evaluation of Proposed Model

Using proposed model the individual P, Q, R, S, T waves as well as complete ECG signal can be generated using shifting and zero padding method as shown in Figure 4.32. To generate Figure 4.32 we have used model parameters as:

$A_P = 0.25$	$A_Q = -0.10$	$A_R = 1.0$	$A_S = -0.25$	$A_T = 0.35$
$B_P = 220$	$B_Q = 370$	$B_R = 420$	$B_S = 460$	$B_T = 700$
$C_P = 25$	$C_Q = 10$	$C_R = 15$	$C_S = 10$	$C_T = 35$
$D_P = 0$	$D_Q = 0$	$D_R = 0$	$D_S = 0$	$D_T = 0$

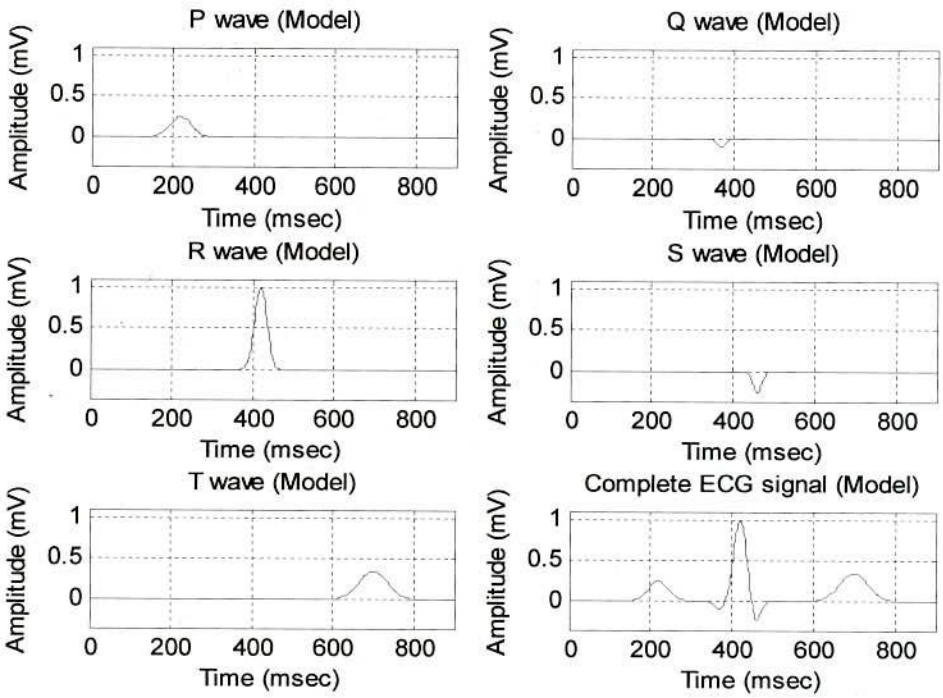

Figure 4.35: Modeling of different waves of ECG and complete ECG signal.

A comparison between real ECG and model ECG is shown in Figure 4.33. Real ECG recorded by BIOPAC data acquisition system is represented by pure line whereas ECG generated by our proposed model is represented by dotted line. To fit our Model ECG with Real ECG we have varied the constants or variable parameters of our model. For some real parameters our Model ECG is best fitted with Real ECG. Then it is possible to find out peak amplitude based model parameters (A_i) and its comparison with real amplitudes of different waves of Real ECG. It is important to mention that the proposed model is also suitable to fit real ECG signal for other subjects.

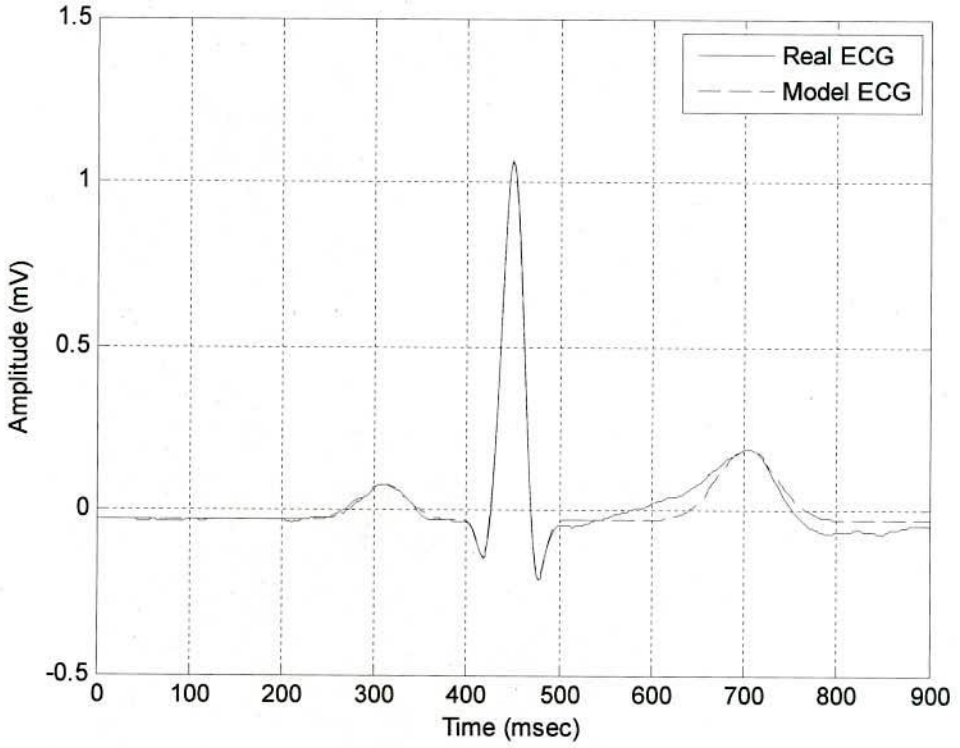

Figure 4.36: Comparison of real ECG and model ECG of a typical subject.

Error analysis for a typical subject at a certain time is noted in Table 4.9. MSE, NMSE, RMSE, NRMSE and PNRMSE for P, R and T waves are very low but PNRMSE for Q and S waves are very high. PNRMSE is less than 1% for P, R and T waves but for Q and S waves it is more than 10%. Error analysis for a typical subject with time is noted in Table 4.10. For this subject, with varying time PNRMSEs are almost less than 1% for P, R and T waves but for Q and S waves it is varying around 20% and 30% respectively.

Table 4.9: Error Analysis for model ECG of a typical subject

Name of Waves	Peak Amplitude (mV)		MSE	NMSE	RMSE	NRMSE	PNRMSE
	Real ECG	Model ECG					
P	0.10773	0.107	5.33E-07	4.59E-05	0.00073	0.00678	0.67762
Q	-0.11230	-0.130	0.000315	0.024972	0.01774	0.15803	15.8026
R	1.09102	1.100	8.06E-05	6.77E-05	0.00898	0.00823	0.82308
S	-0.18330	-0.234	0.002572	0.076544	0.05071	0.27667	27.6665
T	0.21761	0.217	3.72E-07	7.86E-06	0.00061	0.00280	0.28032

Table 4.10: PNRMSE analysis for a typical subject with time

Name of Waves	PNRMSE with time						Average PNRMSE
	00 min	05 min	20 min	40 min	65 min	90 min	
P	0.89	0.51	0.68	0.68	0.52	0.40	0.61
Q	23.94	11.34	9.21	15.80	27.24	16.37	17.32
R	0.88	0.93	0.53	0.82	0.77	0.83	0.79
S	55.88	21.82	15.88	27.67	37.39	26.94	30.93
T	0.16	0.13	0.96	0.28	0.30	0.12	0.33

We have selected about five subject's ECG recordings for modeling which are best suited to the practical ECG requirements. Error analysis for these recordings with time is noted in Table 4.11.

Table 4.11: Mean of PNRMSE analysis with time

Name of Waves	Mean of PNRMSE with time						Average of Mean PNRMSE
	00 min	05 min	20 min	40 min	65 min	90 min	
P	0.35	0.22	0.40	0.47	0.36	0.46	0.45
Q	18.18	15.27	17.41	17.30	21.86	14.73	20.95
R	1.07	1.17	0.91	0.76	0.60	0.65	1.03
S	31.01	35.79	29.51	25.50	29.52	25.90	30.27
T	0.49	0.35	0.30	0.39	0.45	0.33	0.46

It is seen that, for all selected subjects, average PNRMSEs are almost around or less than 1% for P, R and T waves but for Q and S waves it is more than 20% and 30% respectively.

4.6.2 Evaluation of Modified Proposed Model

To evaluate the performance of our proposed model we have compared our ECG model with some healthy subject's ECG recordings. Peak amplitude based model parameters have been noted after fitting the model ECG with Real ECG with varying time. This model is better for P, R and T waves modeling but not suitable for Q and S waves.

Table 4.12: Variation of PNRMSE with varying M_Q and M_S

M_i $(i=Q)$	Mean ± SD of % Error	M_i $(i=S)$	Mean ± SD of % Error
1.00	24.54 ± 3.47	1.00	32.67 ± 5.53
1.05	19.84 ± 3.10	1.05	26.40 ± 5.50
1.10	14.85 ± 3.02	1.10	20.66 ± 5.22
1.15	9.86 ± 2.95	1.15	15.23 ± 4.74
1.20	4.86 ± 3.14	1.20	10.15 ± 4.46
1.25	2.65 ± 2.29	1.25	5.80 ± 3.68
1.30	3.94 ± 2.40	1.30	3.73 ± 1.82
1.35	7.14 ± 2.55	1.35	3.57 ± 2.71
1.40	10.78 ± 2.07	1.40	5.42 ± 3.82
1.45	13.66 ± 2.19	1.45	8.55 ± 3.77
1.50	16.64 ± 2.16	1.50	11.73 ± 3.58
1.55	19.28 ± 2.08	1.55	14.62 ± 3.49
1.60	21.58 ± 1.84	1.60	17.44 ± 3.35
1.65	23.83 ± 1.68	1.65	19.84 ± 3.20
1.70	26.04 ± 1.60	1.70	22.24 ± 3.13
1.75	28.25 ± 1.54	1.75	24.43 ± 3.08
1.80	30.26 ± 1.48	1.80	26.47 ± 3.04
1.85	32.28 ± 1.44	1.85	28.52 ± 2.90
1.90	34.05 ± 1.42	1.90	30.36 ± 2.77
1.95	35.79 ± 1.49	1.95	32.19 ± 2.74
2.00	37.65 ± 1.59	2.00	33.89 ± 2.63

We can plot mean percentage error with varying M_i (i ∈ Q, S) as shown in Figure 4.34 using Table 4.12.

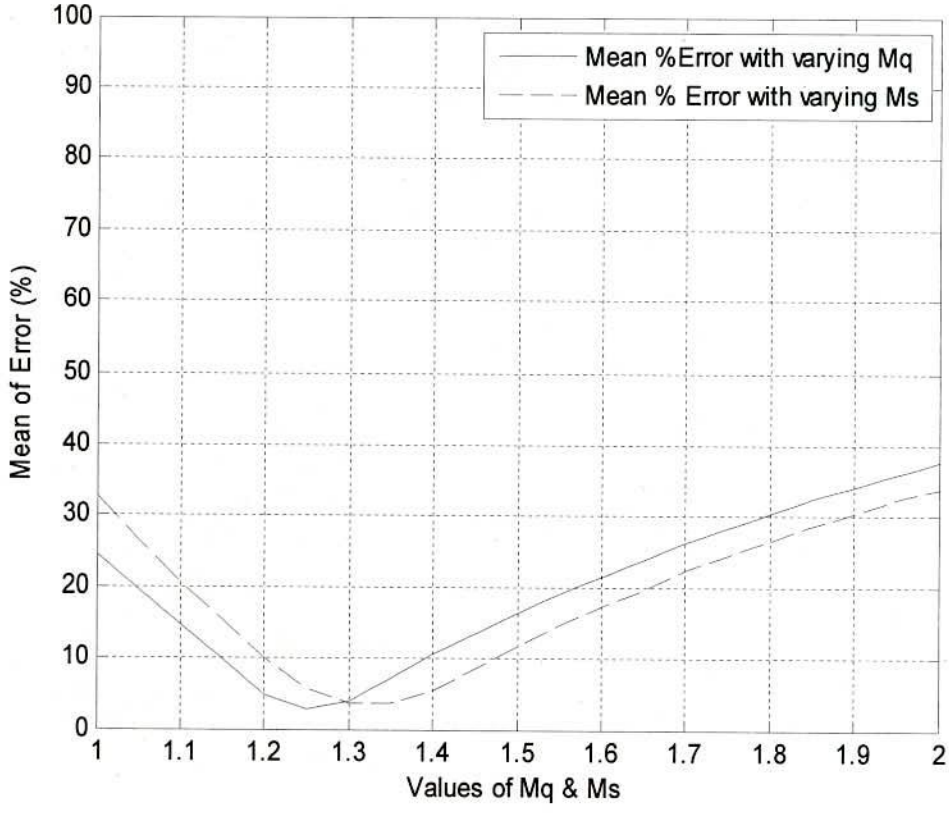

Figure 4.37: Changes in mean percentage error with varying M_q and M_s.

It is seen that, mean percentage error is minimum at M_Q = 1.25 and M_S = 1.35. So we can select these values for our modified model to minimize error. Besides, we can define a range for M_i (i ∈ Q, S) for which error lies within acceptable range. From Figure 5.3, it is seen that error is around or less than 5% within the range 1.20 to 1.30 (for Q wave) and 1.25 to 1.40 (for S wave). If we consider the acceptable range of percentage error is around or less than 5%, then the acceptable range of M_i (i ∈ Q, S) can be noted as:

$$M_i(\text{i} \in \text{Q}) = 1.20 \text{ to } 1.30$$

$$M_i(\text{i} \in \text{S}) = 1.25 \text{ to } 1.40$$

Using these ranges, we have evaluated the performance of our modified proposed model as explained below:

Real ECG is represented by pure line whereas ECG generated by our modified proposed model is represented by dotted line as shown in Figure 4.35. To fit our Modified Model ECG with Real ECG we have varied the constants or variable parameters of our modified proposed model. For some real parameters (M_Q = 1.20, M_S = 1.35), our Modified Model ECG is best fitted with Real ECG. Then it is possible to find out peak amplitude based modified model parameters (A_i) and its comparison with real amplitudes of different waves of Real ECG.

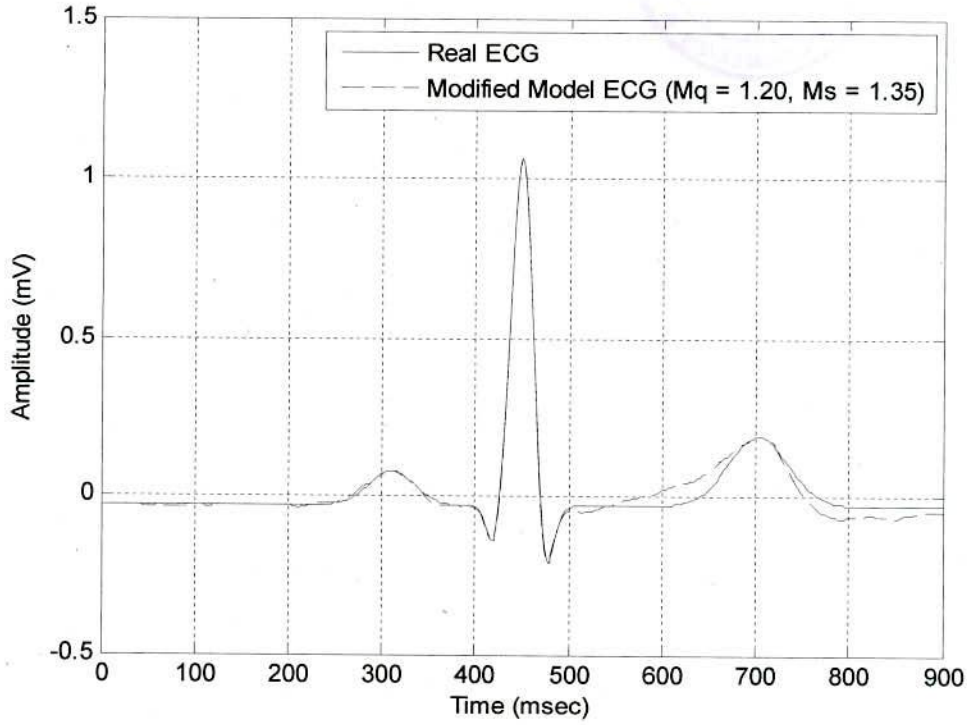

Figure 4.38: Comparison of real ECG and modified model ECG of a typical subject.

For modified proposed model, error analysis for a typical subject at a certain time is noted in Table 4.13. MSE, NMSE, RMSE, NRMSE and PNRMSE for P and T waves are very low but PNRMSE for Q, R and S waves are around or less than 2% that is within the acceptable range of error. The change in M_i (i ∈ Q, S) shows a little impact on peak amplitude of R wave. Hence percentage error in R peak has increased by a little value than before which is also acceptable.

Error analysis for a typical subject with time is noted in Table 4.14. For this subject, with varying time PNRMSEs are almost less than 1% for P and T waves but for Q, R and S waves its average value is around or less than 2%.

Table 4.13: Error analysis for modified model ECG of a typical subject

Name of Waves	Peak Amplitude (mV)		MSE	NMSE	RMSE	NRMSE	PNRMSE
	Real ECG	Modified Model ECG					
P	0.10773	0.107	5.33E-07	4.59E-05	0.00073	0.006776	0.67762
Q	-0.1123	-0.115	7.51E-06	0.000596	0.00274	0.02441	2.44076
R	1.09102	1.106	0.000224	0.000189	0.01498	0.01373	1.37303
S	-0.1833	-0.187	1.38E-05	0.00041	0.00371	0.02024	2.02411
T	0.21761	0.217	3.72E-07	7.86E-06	0.00061	0.002803	0.28032

Table 4.14: PNRMSE for a typical subject with time for modified model ECG

Name of Wave	PNRMSE with time						Average PNRMSE
	00 min	05 min	20 min	40 min	65 min	90 min	
P	0.89	0.51	0.68	0.68	0.52	0.40	0.61
Q	3.87	3.26	0.97	2.44	4.11	2.18	2.81
R	1.09	0.93	0.80	1.37	1.94	1.24	1.23
S	2.70	5.07	3.63	2.02	0.26	1.62	2.55
T	0.16	0.13	0.96	0.28	0.30	0.12	0.33

Table 4.15: Mean of PNRMSE with time for modified model ECG

Name of Waves	Mean of PNRMSE with time						Average of Mean PNRMSE
	00 min	05 min	20 min	40 min	65 min	90 min	
P	0.35	0.22	0.40	0.47	0.36	0.46	0.38
Q	3.03	2.90	2.43	1.51	2.70	2.15	2.45
R	1.15	1.20	0.97	1.12	1.32	1.13	1.15
S	3.03	2.46	3.28	2.99	2.37	3.06	2.87
T	0.49	0.35	0.30	0.39	0.45	0.33	0.39

For modified model, we have selected about five subject's ECG recordings for modeling which are best suited to the practical ECG requirements as before. Error analysis for these recordings with time is noted in Table 4.15. It is seen that, for all selected subjects, average PNRMSEs are almost around or less than 1% for P and T waves but for Q, R and S waves its average value is around or less than 2%.

To evaluate the performance of our modified proposed model we have compared our modified ECG model with some healthy subject's ECG recordings. Peak amplitude based model parameters have been noted after fitting the modified model ECG with Real ECG with varying time. This modified model is better for P, Q, R, S and T waves modeling i.e. complete ECG modeling than before due to less error.

4.6.3 Evaluation with Consuming ED

At first we have selected ECG signal at normal condition (before having ED) of five subjects as before. It is already seen that, the effect of energy drinks consumption is more or less significant at duration about 30 to 40 minutes from the instant of having ED. To get almost maximum effect, we have also selected ECG signal at energized condition (after having ED) of those five subjects. By varying the value of M_i ($i \in Q, S$) within the predefined range, we have evaluated the percentage error at both before and after having ED as shown in Table 4.16 and Table 4.17.

Table 4.16: PNRMSE in peak amplitude of Q wave before and after having ED

Condition	Before having ED (at 00 min)			After having ED (at 40 min)		
M_Q	1.20	1.25	1.30	1.20	1.25	1.30
PNRMSE (S1)	0.49	2.44	7.32	9.17	4.77	7.40
PNRMSE (S2)	3.42	0.34	4.10	10.66	5.43	0.03
PNRMSE (S3)	3.05	1.09	4.86	4.13	0.36	3.88
PNRMSE (S4)	2.56	1.96	5.73	0.15	4.06	8.65
PNRMSE (S5)	3.40	7.34	10.79	8.05	3.45	3.45

The average percentage error (PNRMSE) at both before and after having ED with varying M_i ($i \in Q, S$) is shown in Table 4.18 and Table 4.19. It is seen that before having ED, minimum percentage error for Q and S wave modeling is found at M_Q = 1.20 and M_S =

1.25 respectively. Besides after having ED, minimum percentage error for Q and S wave modeling is found at M_Q = 1.25 and M_S = 1.35 respectively.

Table 4.17: PNRMSE in peak amplitude of S wave before and after having ED

Condition	Before having ED (at 00 min)				After having ED (at 40 min)			
M_S	1.25	1.30	1.35	1.40	1.25	1.30	1.35	1.40
PNRMSE (S1)	0.61	4.14	7.67	10.95	6.29	2.19	1.59	5.10
PNRMSE (S2)	1.58	2.32	5.93	9.27	9.38	5.14	0.96	1.47
PNRMSE (S3)	10.64	6.36	2.69	0.06	11.78	7.47	3.49	0.16
PNRMSE (S4)	3.67	0.17	2.74	6.23	2.84	1.15	4.79	8.18
PNRMSE (S5)	6.15	9.77	13.13	16.23	2.78	6.31	9.84	13.76

Table 4.18: Average PNRMSE in peak amplitude of Q wave before and after having ED

Condition	Before having ED (at 00 min)			After having ED (at 40 min)		
M_Q	1.20	1.25	1.30	1.20	1.25	1.30
Average PNRMSE	2.58	2.63	6.56	6.43	3.61	4.68

Table 4.19: Average PNRMSE in peak amplitude of S wave before and after having ED

Condition	Before having ED (at 00 min)				After having ED (at 40 min)			
M_S	1.25	1.30	1.35	1.40	1.25	1.30	1.35	1.40
Average PNRMSE	4.53	4.55	6.43	8.55	6.61	4.45	3.73	5.73

Chapter V

Performance Validation Analyzing LDF Signal

5.1 What is LDF?

Laser Doppler Flowmetry (or simply "LDF") is an established and reliable method for the measurement of blood perfusion in microvascular research. Most LDF applications are concerned with monitoring the competence of regional (microvascular) blood supply following trauma, degenerative and pathological disease, surgical intervention and drug therapy.

5.2 Previous Works on LDF

Periodic oscillations in the microvasculature are detected by the noninvasive technique of LDF. The spectral analysis of the LDF signal from human forearm skin has revealed five characteristic frequencies [24]-[25]. In addition to the cardiac and respiratory rhythms around 1 and 0.3 Hz, respectively [25]-[26], three frequencies have been detected in the regions around 0.1, 0.04, and 0.01 Hz in human skin [24]-[26]. It is suggested that periodic oscillations with a frequency of around 0.1 Hz (a-waves) reflect intrinsic smooth muscle (myogenic) activity of blood vessels [93], whereas the frequency around 0.04 Hz (b-waves) represents neurogenic stimulation of resistance vessels [94]. Golenhofen suggested that oscillations of around 0.01 Hz (minute-rhythm) resulted from changes in metabolism of the perfused tissue [95]. The different spectral components are thought to modulate vascular smooth muscle cell activity. This results in a specific level of vascular tone, which in combination with the rheological properties and the active dilator activity, determines vascular resistance. The aim of the study is to determine the microvascular changes in the periodic oscillations of cutaneous blood perfusion after having energy drinks using laser Doppler flowmetry technique. We hypothesized that having energy drinks changes in microvascular control mechanisms of the skin would result in differences in the spectral components and their corresponding amplitudes of laser Doppler flowmetry.

5.3 Working Principle of LDF Module

The LDF100C is a laser Doppler microvascular perfusion module that is capable of monitoring red blood cell (erythrocyte) perfusion in the microcirculation of a tissue. This module uses a Laser Doppler Flowmetry technique. Laser Doppler flowmetry provides a semi quantitative as-assessment of microvascular blood perfusion, which is expressed in arbitrary units Blood Perfusion Unit (BPU). LDF measurements from the skin reflect blood flow in capillaries, arterioles, venules, and dermal vascular plexa. They also reflect a small nutritive and a large thermoregulatory aspect of perfusion [96]. Laser Doppler signals from the tissue are recorded in BPU which is a relative units scale defined using a carefully controlled motility standard comprising a suspension of latex spheres undergoing Brownian motion. The LDF technique offers substantial advantages over other methods in the measurement of microvascular blood perfusion. This technique provides promise and opportunity to adapt the methodology in various fields of research for example in cerebral monitoring (stroke, in- jury ...), transplantation surgery (skin grafts, free flaps ...), vital organ monitoring (organ viability), tumor vascular research (angiogenesis) and peripheral vascular research (diabetes). Studies have shown that it is both highly sensitive and responsive to local blood perfusion and is also versatile and easy to use for continuous monitoring [97]-[98].

The LDF100C laser Doppler microvascular perfusion module works by illuminating tissue with low power laser light using a probe (TSD140 series) containing optical fiber light guides. Laser light from one fiber is scattered within the tissue and some is scattered back to the probe. Another optical fiber collects the backscattered light from the tissue and returns it to the module. The light is scattered by the static tissue structures and moving blood cells; the moving blood cells impart a Doppler Shift; an adjacent fiber detects light returned from the tissue; this light contains Doppler shifted and unshifted light. Most of the light is scattered by tissue that is not moving but a small percentage of returned light is scattered by moving red blood cells. The light returned to the module undergoes signal processing to extract the signal related to the moving red blood cells. The principle of laser Doppler flowmetry technique is shown in Figure 5.1.

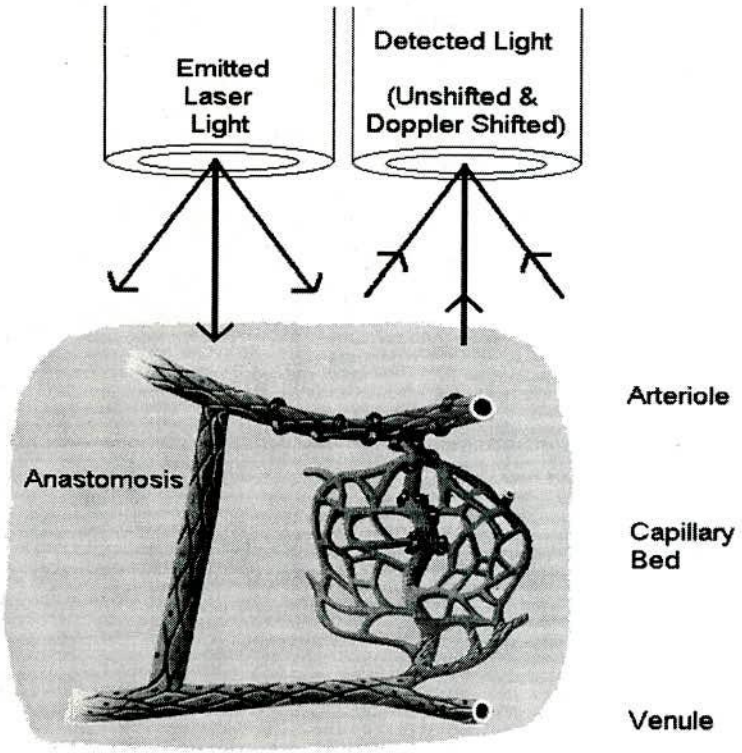

Figure 5.1: Laser Doppler flowmetry technique [99].

5.4 LDF Recording

To validate our experimental results (shown in chapter IV) we have selected two subjects from previous 12 subjects and their LDF signal is recorded before and after having ED. Applying same conditions we have done LDF recording as before. LDF measurements were performed with the Laser Doppler Flowmetry module (LDF100C) and a wide range of fiber-optic based probes (TSD140 series) in order to access the tissue. Probe include small and lightweight probes for (non-invasive) skin and tissue surface measurements and needle type probe for direct (invasive) measurements within tissue, such as muscle and organ. Double-sided adhesive rings (ADD200 series) can be used to attach surface type probes to tissue; one size of ring fits both standard and miniature surface probes. LDF measurements were carried out in a room in which the temperature was maintained constant at 22°C (21-23) with the subjects in a supine position. At least 20 min were allowed for acclimatization before the LDF measurements were performed on the skin of middle finger tip. Skin perfusion was measured immediately before and from 30 min after the taking of energy drinks.

LDF recordings before and after having ED for a typical subject is shown in Figure 5.2 and Figure 5.3 respectively. Before having ED the maximum, minimum and average flows are 1315 BPU, 585 BPU and 972 BPU respectively. After having ED the maximum, minimum and average flows are 1487 BPU, 888 BPU and 1210 BPU respectively. We can see that, due to having ED the maximum, minimum and average flows are increasing but the peak to peak flow decrement is more significant.

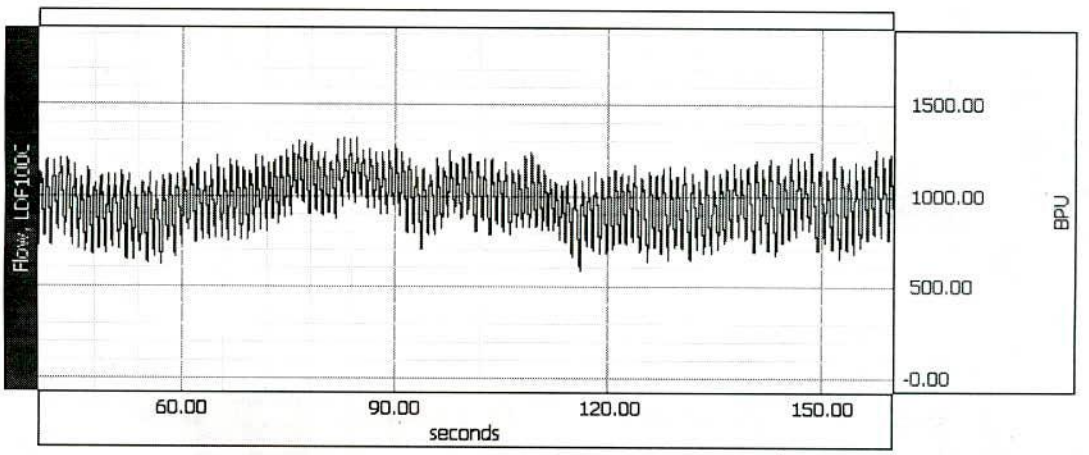

Figure 5.2: LDF recording of a typical subject before having ED.

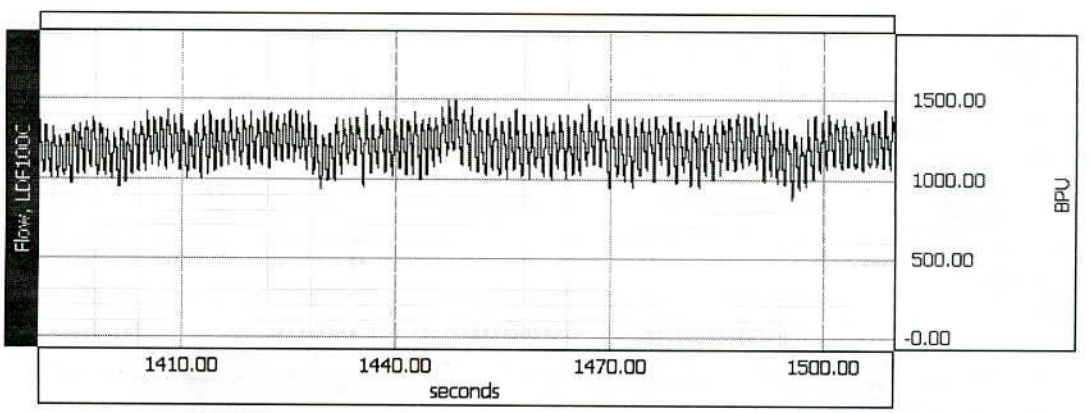

Figure 5.3: LDF recording of a typical subject after having ED.

5.5 Spectrum Analysis of LDF

Spectrum analysis of skin LDF signal is performed by means of Biopac AcqKnowledge software. The frequency spectrum of the same LDF signal is calculated by Fast Fourier transform (FFT) and Power Spectral Density (PSD). For obtaining better spectral resolution in FFT and PSD we have used hamming window function. Following recent

studies [24]-[25], the frequency interval studied (from 0.009 to 1.6 Hz) was divided into five subintervals as shown in Table 5.1.

Table 5.1: Frequency interval of skin LDF signal

Origin of Oscillation (Activities)	Frequency Range (Hz)
Metabolic	0.0095-0.02
Sympathetic	0.02-0.06
Myogenic	0.06-0.20
Respiratory	0.20-0.60
Heart/Cardiac	0.60-1.60

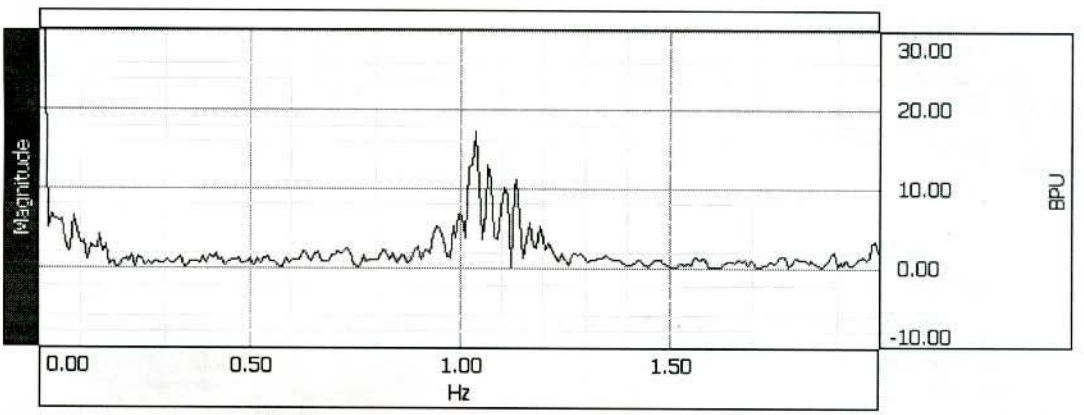

Figure 5.4: FFT of LDF recording of a typical subject before having ED.

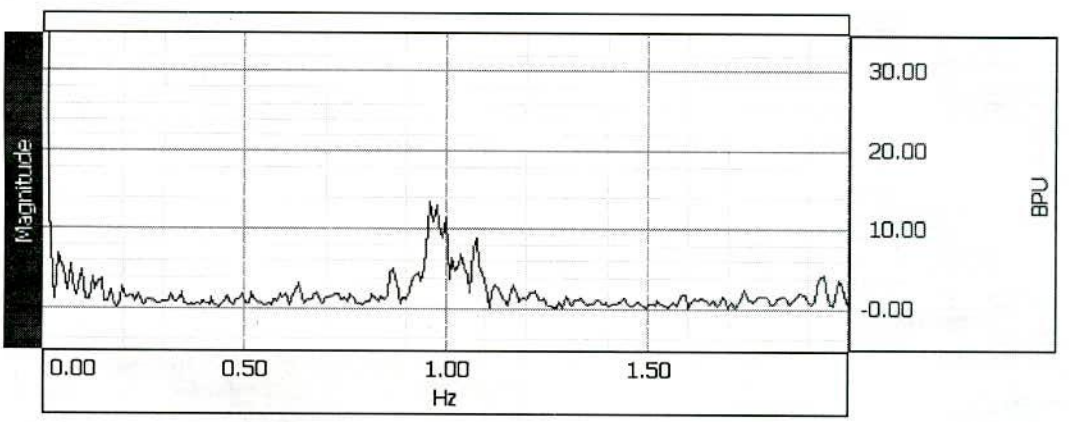

Figure 5.5: FFT of LDF recording of a typical subject after having ED.

FFT analysis of LDF signal before and after having ED for a typical subject is shown in Figure 5.4 and Figure 5.5 respectively. Before having ED the peak magnitude of FFT within cardiac activity is 17.37 BPU, occurs at 1.04 Hz. After having ED the peak magnitude of FFT within cardiac activity is 13.52 BPU, occurs at 0.96 Hz. We can see that, due to having ED the peak magnitude of FFT within cardiac activity is decreasing. The reason behind this decrement may be the decrement in peak to peak flow of LDF signal.

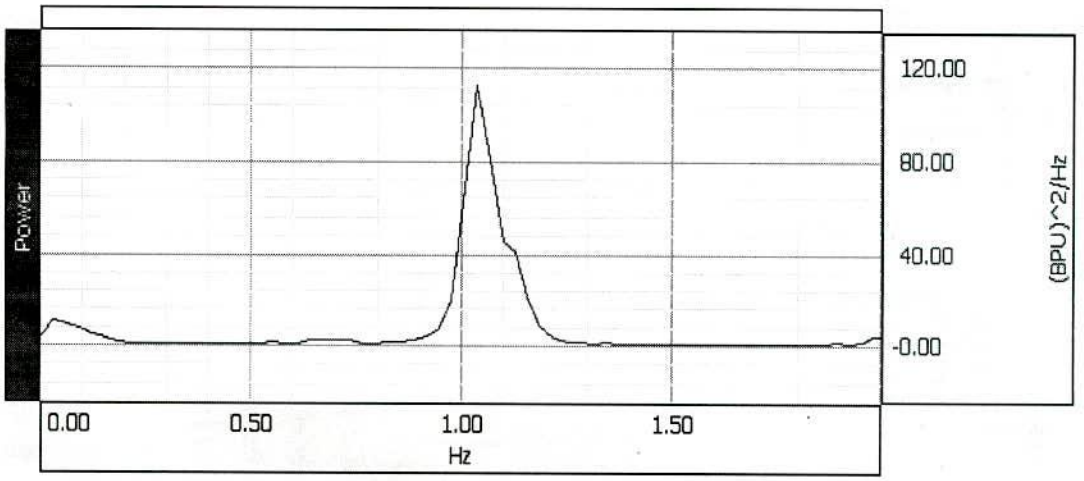

Figure 5.6: PSD of LDF recording of a typical subject before having ED.

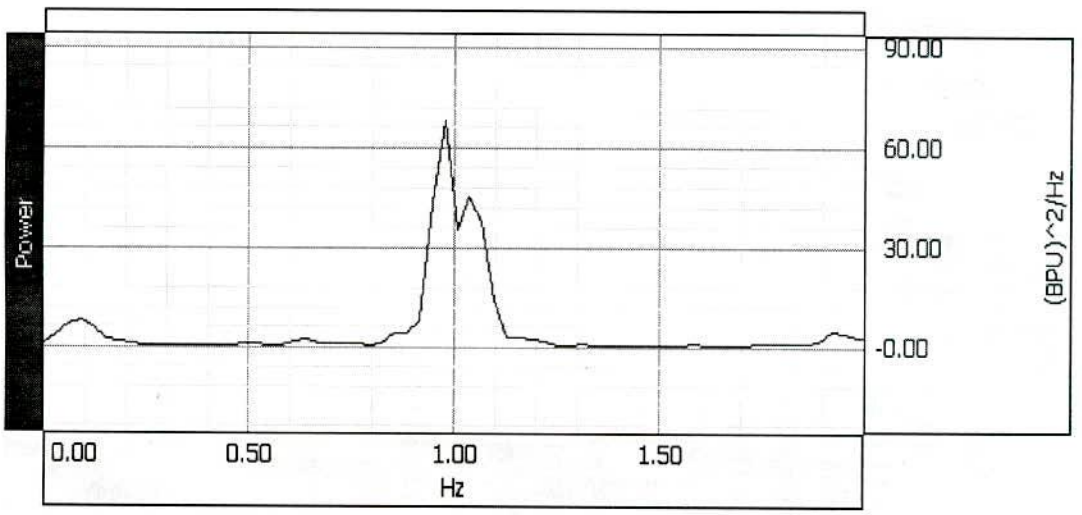

Figure 5.7: PSD of LDF recording of a typical subject after having ED.

PSD analysis of LDF signal before and after having ED for a typical subject is shown in Figure 5.6 and Figure 5.7 respectively. Before having ED the peak power of PSD is 111.8 $(BPU)^2/Hz$ occurs at 1.04 Hz which is also within cardiac frequency range. After having ED the peak power of PSD is 67.77 $(BPU)^2/Hz$ occurs at 0.98 Hz which is also within cardiac frequency range. We can see that, due to having ED the peak power of PSD within cardiac activity is decreasing. The reason behind this decrement may be also the decrement in peak to peak flow of LDF signal.

The changes in FFT and PSD parameters of LDF signal due to having ED for a typical subject are listed in Table 5.2.

Table 5.2: Cardiac function evaluation using frequency spectrum of LDF signal

Spectrum type	Frequency band	Before having ED		After having ED	
		Peak occurs at (Hz)	Peak magnitude (BPU)/power $((BPU)^2/Hz)$	Peak occurs at (Hz)	Peak magnitude (BPU)/power $((BPU)^2/Hz)$
FFT	Cardiac (0.6-1.6 Hz)	1.04	17.37	0.96	13.52
PSD		1.04	111.8	0.98	67.77

The changes in average FFT and PSD parameters of LDF signal due to having ED are listed in Table 5.3. It is seen that for both FFT and PSD, frequency parameters of LDF signal decreases within frequency range of cardiac activity due to having ED.

Table 5.3: Average cardiac function evaluation using frequency spectrum

Spectrum type	Frequency band	Before having ED		After having ED	
		Peak occurs at (Hz)	Peak magnitude (BPU)/power $((BPU)^2/Hz)$	Peak occurs at (Hz)	Peak magnitude (BPU)/power $((BPU)^2/Hz)$
FFT	Cardiac (0.6-1.6 Hz)	1.06	17.95	1.02	11.81
PSD		1.06	97.6	1.00	63.79

5.6 Validation of Previous Analysis

We have compared the frequency spectrum related results of ECG and PPG signals with LDF signal which is shown in Table 5.4. Frequency spectrum analysis of LDF signal shows that about 34% decrement in FFT and PSD parameters due to the consumption of ED. In previous chapter we have got about 35% decrement in FFT and PSD parameters for PPG signal and about 15% decrement in FFT and PSD parameters for ECG signal.

Table 5.4: Performance comparison of LDF analysis with previous results

Signal type	Spectrum type	Frequency band	Peak magnitude (BPU)/power ((BPU)^2/Hz) before having ED	Peak magnitude (BPU)/power ((BPU)^2/Hz) after having ED	% Change due to having ED
ECG	FFT	Cardiac (0.6-1.6 Hz)	0.01016	0.00830	- 18.30%
	PSD		1.08E-05	0.97E-05	- 10.19%
PPG	FFT		0.15267	0.09693	- 36.51%
	PSD		0.00799	0.00429	- 46.31%
LDF	FFT		17.95	11.81	- 34.21%
	PSD		97.60	63.79	- 34.64%

In both analysis (ECG, PPG Vs LDF), the net change is negative which is also identical (approximately) in some cases. The LDF signal analysis also shows similar results as in case of ECG and PPG signal analysis. Since the nature of signals is different, it is impossible to get 100% identical results. Finally it can be say that our experimental results are nearly matched.

Chapter VI

Conclusions and Future Works

6.1 Conclusions

The cardiac functions are clearly evaluated due to the consumption of ED analyzing different cardiac signals. Consumption of ED affects heart activity that is determined in this study using electrocardiographic and photo plethysmographic parameters variation. The average peak amplitude of P and T wave decreases significantly with time due to having energized. In case of Q and S waves, a variable (random) change is noticed with time. Though there are less significant changes in peak amplitude of P, Q, S and T wave; change in peak amplitude of R wave with time is more significant. The peak amplitude of R wave increases after having energized and it gets maximum increment at about 20-40 min from the instant of drinking and then shows a tendency to decrease to reach at normal condition. The average changes in different intervals of ECG signal with time due to the consumption of ED are also more or less significant. Due to the consumption of ED, increments in different intervals are noticed but RR interval increment is remarkable. Hence the heart rate decreases with time due to the consumption of ED. Besides, an effective decrement in peak to peak amplitude of PPG is observed due to having ED.

The spectral analysis of cardiac signals is also significant to evaluate cardiac functions. The spectrum or frequency components for PPG signal decreases with a significant rate from the instant of being energized. Also a net decrement in spectrum components is noticed for ECG signal due to the consumption of ED. By analyzing spectrum components of LDF signal we have found approximately same results as in case of ECG and PPG. Thus our experimental results are verified with LDF analysis.

The effects of ED consumption on cardiac functions are evaluated by analyzing peak amplitude variation of different waves and their corresponding intervals of ECG signal, peak to peak amplitude of PPG signal, heart rate as well as their frequency components. There are less significant positive impacts which may give short term boost of energy but

other impacts on cardiac parameters are not in favor to the human being due to having ED. It is the time to be concern about the negative aspects of energy drinks consumption.

ECG signal modeling using proposed model is done in this study and peak amplitude based model parameters have been noted after fitting the model ECG with Real ECG. This model is better for P, R and T waves modeling but not suitable for Q and S waves modeling for more error. The performance of modified proposed model to generate ECG signal is better than proposed model due to low error in P, R, T waves as well as Q and S waves modeling. The complete ECG signal modeling using modified proposed model in both before and after the consumption of ED results good fitting as well as low error with real ECG signal. This model is essential to evaluate cardiac functions comparing model parameters with real parameters with consuming ED.

6.2 Future Works

Cardiac functions are evaluated using different cardiac signal parameters with consuming a specified type (fixed amount of ingredients) of ED. In future, cardiac functions can be evaluated with consuming different type (varying the amount of ingredients- basically caffeine and sugar) of ED. The modified proposed model can be used to model cardiac signal with varying the amount of caffeine which is under consideration.

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APPENDIX I

Sample File Naming Rule

Data Collection Number:-01

File naming rule for capturing data:

File Name: DCN-SAg-PcSi.Ext
Example: bme001-m25-n01.acq
bme002-f25-n04.acq

Symbol Explanation:

Symbol	Meaning	Example
DCN	Data collection number	(bme001, bme002, …….)
S	Sex	(M, F)
Ag	Age	(00, …….., 99))
Pc	Patient condition	(N, E)
Si	Signal index	(01, 04)
Ext	File extension	(acq, txt, …..)

Note:

Signal Index:

01 – BP, Stethoscope, ECG
04 – Pulse (PPG), Respiration, LDF

Patient Condition:

N: Normal (Before having energy drinks)
E: Energized (After having energy drinks)

APPENDIX II

Sample Data Collection Sheet

Data Collection Number:-

Department of Biomedical Engineering

Khulna University of Engineering and Technology (KUET)

Khulna-9203, Bangladesh

Data Collection Information Sheet

1. **Subject Name:** Dip Mazumder
2. **Age:** 21 (years)
3. **Height:** 5'7" (cm)
4. **Weight:** 61 (kg)
5. **Gender:** M ✓ /F (Male/ Female)
6. **Address:** AEH (Attached), KUET
7. **Mobile Number:** 01675277485
8. **E-mail:** dip.kuet.cse.16@gmail.com
9. **Other information (if required):**
10. **Collected data information:**

Si. No.	Signal Type	Physical Condition	Data Condition	
			Normal (Before having energy drinks)	Energized (After having energy drinks)
1	BP	At Rest (Lying & Relaxed)	✓	✓
2	Stethoscope		✓	✓
3	ECG		✓	✓
4	Pulse		✓	✓
5	Respiration		✓	✓

11. **Subject's blood pressure (at normal):**
12. **Subject's heart rate (at normal):**
13. **Subject's respiration rate (at normal):**
14. **Subject's blood pressure (at energized):**
15. **Subject's heart rate (at energized):**
16. **Subject's respiration rate (at energized):**

17. **Declaration:**

I hereby declare that the data taken can be used without my permission for any revised or extended derivative work based on data and/or any associated written, audio and/or visual presentation or other for research and/or publication.

Signature: Dip Mazumder

Date: 15-07-2013 (DD/MM/YYYY)

Data Captured by: 15.07.2013

APPENDIX III

Sample Data Collection Sheet

Data Collection Number:-

Department of Biomedical Engineering
Khulna University of Engineering and Technology (KUET)
Khulna-9203, Bangladesh

Data Collection Information Sheet

1. **Subject Name:** Nahid Hasan
2. **Age:** 22 (years)
3. **Height:** 66 (cm)
4. **Weight:** 58 (kg)
5. **Gender:** M ✓ /F (Male/ Female)
6. **Address:** EEE, KUET
7. **Mobile Number:**
8. **E-mail:**
9. **Other information (if required):**
10. **Collected data information:**

Si. No.	Signal Type	Physical Condition	Data Condition	
			Normal (Before having energy drinks)	**Energized** (After having energy drinks)
1	LDF	At Rest (Lying & Relaxed at Supine position)	Captured (OK)	Captured (OK)

11. Declaration:

I hereby declare that the data taken can be used without my permission for any revised or extended derivative work based on data and/or any associated written, audio and/or visual presentation or other for research and/or publication.

Signature: Nahid 14.11.13
Date: (DD/MM/YYYY)

Data Captured by: 14.11.13