ABSTRACT

EFFECTS OF SLEEP DEPRIVATION ON AUTONOMIC NERVOUS SYSTEM

by

Jaeyeaon Cho

Sleep deprivation (SD) has been thought a potential factor to trigger cardiovascular events by increasing the sympathetic nervous system activity. The aim of the present study was to evaluate the relationship between sleep deprivation and the autonomic nervous system activity by means of heart rate variability (HRV) and blood pressure variability (BPV). All data were acquired in the sleep lab of Columbia University.

Data were acquired from the two groups, SD and control. Subjects in the SD group did not sleep for thirty-six hours but subjects in the control group slept at night as usual. There were five different data acquisition stages; baseline (stage 0 and stage 1), twelve hours of sleep deprivation (stage 2), twenty-four hours of sleep deprivation (stage 3) and thirty-six hours of sleep deprivation (stage 4). ECG and blood pressure were measured for one hour in each stage. Data were acquired in the supine and sitting positions and volunteers were then asked to use a computer to study the SD effects on cognitive performance. Sleep deprivation produces negative effects on cognitive performance. Cognitive performance deficits involved reduced ability to pay attention and impairment of the ability to think quickly and not make mistakes. In this study, we tested whether the negative effects reflect on the autonomic nervous system (ANS).

The low frequency (LF) area and the high frequency (HF) area were calculated using the Power Spectrum Analysis of HRV and BPV. The LF area of HRV is associated with the sympathetic nervous system activity plus the parasympathetic nervous system activity but the HF area of HRV is associated with only the parasympathetic nervous system activity. The LF area of BPV is believed to be related purely only to the sympathetic nervous system activity, rather than to a mixture of sympathetic and parasympathetic nervous system activities. In this study, the LF and HF areas were time-normalized and the normalized LF and HF areas were averaged for a mean value analysis.

In addition to the mean value analysis, One Factor ANOVA and Two-Factor ANOVA were conducted for the significance comparison tests.

In One Factor ANOVA and the mean value analysis, after thirty-six hours of sleep deprivation, the LF area of HRV increased significantly in the sitting position and when subjects began the cognitive task. No significant increase in the LF area was observed in the supine position and after ten minutes of the cognitive task. The significantly increased LF area could reflect an increased stress level and acts as a predictor of cardiovascular events. Sleep deprivation can cause negative effects on cognitive performance especially at the beginning state of the cognitive task. The LF area of BPV did not change significantly in the supine and sitting positions during thirty-six hours of sleep deprivation. After thirty-six hours of sleep deprivation, the LF area of BPV increased significantly when people began the cognitive task as did the LF area of HRV. Significant changes were observed after thirty-six hours of sleep deprivation in One Factor ANOVA but a significant change was observed after twelve hours of SD in Two-Factor ANOVA. Although there was a significant change in the LF area, no significant HF change was observed in the control and SD groups.

The negative effect of sleep deprivation reflects on the autonomic nervous system. Sleep deprivation did not affect the HF area significantly but significant LF area changes occurred due to sleep deprivation. HRV responses to SD were different according to positions. Subjects experienced more negative effects in the sitting position then in the supine position. The LF area of HRV and BPV increased significantly at the beginning state of the cognitive task after thirty-six hours. Sleep deprivation may induce the LF area to increase and people can experience a mental stress and cognitive performance deficit at the beginning of cognitive performance.

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This thesis is dedicated to my parents,

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CHAPTER 1

INTRODUCTION

1.1 Sleep Deprivation

Sleep is a state of the unconscious in which the brain is relatively more responsive to internal than to external stimuli. Sleepiness is assumed to be a central nervous system phenomenon, although the physiological substrates of sleepiness have yet to be determined [1]. The brain gradually becomes less responsive to visual, auditory, and other environmental stimuli during the transition from wake to sleep [2]. Probably no single sleep-generating center exists. A more likely mechanism is sleep-generating circuits with inputs from brainstem and hypothalamic neural groups [2]. Different people require different amounts of rest. While the majority of adults should spend between eight to nine hours asleep, a small number of people function perfectly well on only three to four hours of rest. The time a person spends asleep also changes with age [3]. People who are well rested feel alert and do not have the urge to nap [4].

Sleep deprivation is a relative concept. Small amounts of sleep loss (eg, 1hour per night over many nights) have subtle cognitive costs, which appear to go unrecognized by the individual experiencing the sleep loss. More severe restriction of sleep for a week leads to profound cognitive deficits similar to those seen in some stroke patients, which also appear to go unrecognized by the individual [5, 6, 7]. Exhaustion, fatigue and lack of physical energy are common sleep deprivation symptoms [3]. Exhaustion and fatigue affect our emotional moods, causing pessimism, sadness, stress and anger. In humans, sleep deprivation results in a decrease in core body temperature [8], a decrease in

immune system function as measured by white cell count and activity [9], and a decrease in the release of growth hormone [10]. The National Sleep Foundation (NSF) has suggested that social problems such as road rage may be caused, in part, by a national epidemic of sleepiness. The brain's frontal cortex relies on sleep to function effectively. Insufficient rest adversely affects the frontal cortex's ability to control speech, access memory, and solve problems [11, 12, 13]. These physical reactions disappear when the test subject is allowed to rest properly [14].

1.2 Objective and Scope of Study

Effects of sleep deprivation (SD) on neural cardiovascular control may have important clinical implications [15]. Sleep deprivation is a common condition that afflicts 47 million American adults, or almost a quarter of the adult population [3]. In animal studies, several days of complete sleep deprivation results in an increase in mortality [16]. It has been suggested that fragmented sleep or sleep deprivation may increase the incidence of cardiovascular events. Cardiovascular events follow a circadian rhythm, with a high incidence of sudden death, myocardial infarction, and stroke in the early morning [17]. Increased sympathetic activity has been shown to coincide with morning cardiovascular events [18, 19]. Several studies have proposed the attractive hypothesis that activation of the sympathetic nervous system by sleep deprivation may be implicated in triggering cardiovascular events in the morning hours [20, 21, 22]. In 2000, Dr. Kato's research team studied the sympathetic responses to sleep deprivation. They found that sleep deprivation increases blood pressure (BP) but not heart rate and muscle sympathetic nervous activity (MSNA). The relationship between the sympathetic activity and sleep

deprivation is still controversial because there is no result so far to support the concept that sleep deprivation may trigger cardiovascular events by increasing sympathetic drive or potentiating the neural circulatory responses to stressful stimuli.

Sleep deprivation can cause negative effects on cognitive performance. Cognitive performance deficits involved reduced ability to pay attention and impairment of the ability to think quickly and not make mistakes [23]. From this research, we attempted to study sleep deprivation effects on cognitive performance as well as the relation between sleep deprivation and the sympathetic activity.

Two different signals, ECG and blood pressure, were acquired and analyzed to calculate heart rate variability and blood pressure variability. The LF area of the HRV spectrum, in the range between 0.05 and 0.15 Hz, provides an indication of a mixture of sympathetic and parasympathetic activity. The HF area of the HRV spectrum, in the range between 0.15 and 0.4 Hz, provides an indication of the parasympathetic nervous system activity. BPV implies different information from HRV. The LF of BPV is related purely to the sympathetic nervous system activity, rather than to a mixture of sympathetic and parasympathetic nervous system activities [24].

All tests were conducted for thirty-six hours. More than thirty-six hours of SD study is helpful for measurement of sleep deprivation effects but it was almost impossible to go without sleep for over thirty-six hours. Healthy and young (20 ~ 32 years old) people volunteered for this study and data analysis was conducted without sex separations. Volunteers were divided into two groups, SD and control. Subjects in the SD group did not sleep during the tests but people in the control group slept at night as usual. Research members of this study volunteered for the control group. They slept during their

normal sleep time and worked in the lab during the day time. Data were acquired throughout five stages. In each stage, data were acquired in supine and sitting positions and during the computer cognitive tasks. Data from the two groups were analyzed using power spectrum analysis of HRV and BPV. The acquired spectrums of the two groups were analyzed again using ANOVA for the statistical significance studies. The ANOVA results will be presented in Sections 5. 1. 3 and 5. 2. 3.

CHAPTER 2

AUTONOMIC NERVOUS SYSTEM

2.1 Nervous System

Parts of the nervous system are interconnected, but for convenience they can be divided into the central nervous system (CNS) and the peripheral nervous system. Table 2.1 shows the divisions of the nervous system. Branches of the peripheral nervous system go from the base of the spine to the tips of the toes and from the base of the brain to the organs of the digestive system [24]. Like other communication systems such as the endocrine system, the nervous system regulates many internal functions and also coordinates the activities we know collectively as human behavior. These activities include not only such easily observed acts as smiling and walking but also experiences such as feeling angry, being motivated, having an idea, or remembering a long-past event. These phenomena that we attribute to the "mind" are believed to be related to the integrated activities of nerve cells.

2.2 Autonomic Nervous System

The autonomic nervous system (ANS) plays an important role in regulating the heart. The autonomic nervous system is a part of the nervous system which is concerned with the control of involuntary body functions. It helps control the arterial pressure, heart rate, body temperature and many other activities. The autonomic nervous system is activated mainly by centers located in the spinal cord, brain stem, and hypothalamus.

Table 2.1 Nervous System Divisions [25]

Central Nervous system	Peripheral Nervous System
• Brain • Spinal Cord	• Afferent Division • Efferent Division A. Somatic Nervous System B. Autonomic Nervous System 1. Sympathetic Division 2. Parasympathetic Division

The autonomic nervous system (ANS) is made up of two functional divisions: the sympathetic (SMP) division and the parasympathetic (PSMP) division. These two divisions are anatomically, physiologically, and functionally distinct. The nerve fibers of these components leave the CNS at different levels – the sympathetic fibers from the thoracic and lumbar regions of the spinal cord, the parasympathetic fibers from the brain and the sacral portion of the spinal cord (Figure 2.1). In general, the PSMP division enhances activities of energy gain and/or conservation, such as slowing the heart rate. The sympathetic division increases energy expenditures and prepares an individual for action by accelerating the heart. When sympathetic and parasympathetic nerves innervate the same organ, they often (but not always) have antagonistic effects. At rest there is considerably more parasympathetic activity to the heart than sympathetic. Note that the heart and many glands and smooth muscles which are innervated by both sympathetic and parasympathetic fibers.

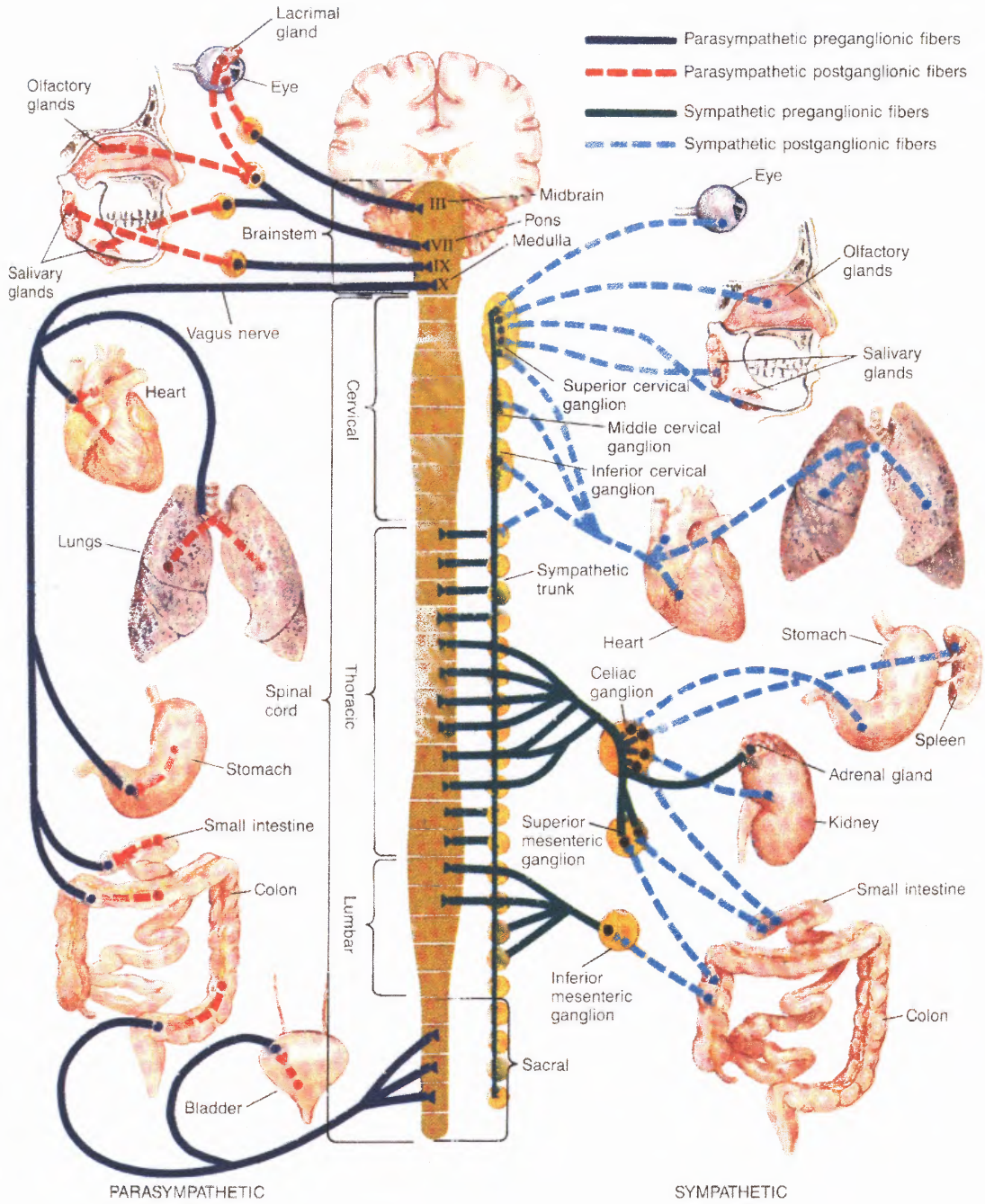


Figure 2.1 The parasympathetic (left) and sympathetic (right) divisions of the autonomic nervous system [25].

Whatever effect one division has on the effecter cells, the other division frequently (but not always) has the opposite effect. Although the inherent rhythm of the heart is due to a natural pacemaker situated in the sinoatrial node, continuous beat-to-beat control of heart rate depend on the relative balance between parasympathetic and sympathetic impulses delivered from the brain to the sinus node.

2.3 The Heart and Electrocardiogram

The heart is a muscular organ enclosed in a fibrous sac, the pericardium, and located in the chest (thorax). The narrow space between the percardium and the heart is filled with fluid that serves as lubricant as the heart moves within the sac [25]. The heart receives a rich supply of sympathetic and parasympathetic nerve fibers, the latter contained in the vagus nerves. Both sympathetic and parasympathetic postganglionic fibers innervate the cells of the conducting system as well as the contractile cells of the atria and ventricles. The sympathetic postganglionic fibers release primarily norepinephrine, and the parasympathetics release primarily acetycholine.

The heart maintains cardiac rhythmicity and transmits the action potentials throughtout the heart muscle to cause periodic heart beats. The action potential in the sinoatrial (SA) node is generated spontaneously and the SA node is designated as a pacemaker. From the SA node, the action potential travels rapidly to the atrioventricular (AV) node activating the bundle of His which divides into two branches serving the right and left ventricles. Through these branches the action potencial finally passes to the ventricles and generates ventricular contraction. (Figure 2.2)

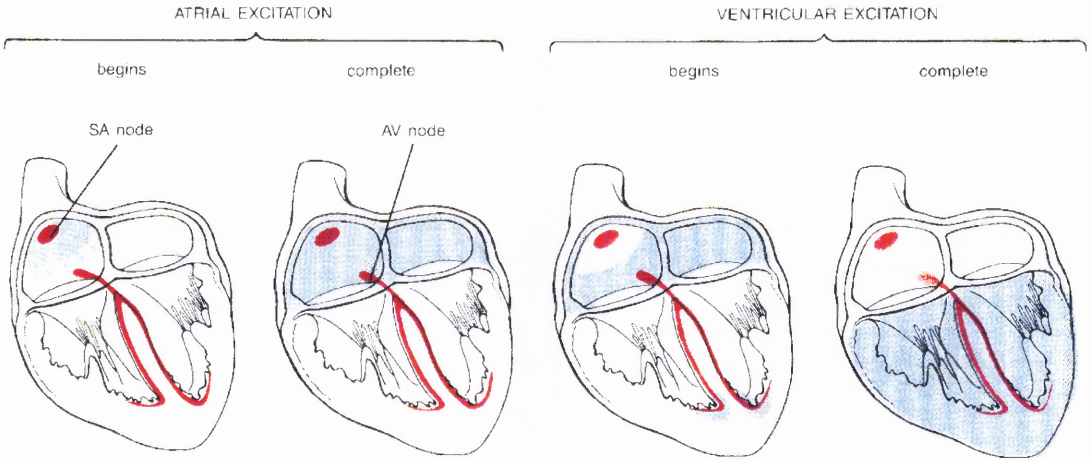


Figure 2.2 Sequence of cardiac excitation. Shading denotes areas that are depolarized [25].

The electrocardiogram (ECG or EKG) is primarily a tool for evaluating the electrical events within the heart. The sum of the action potentials occuring simultaneously in many individual cells can be detected by recording electrodes at the surface of the skin.

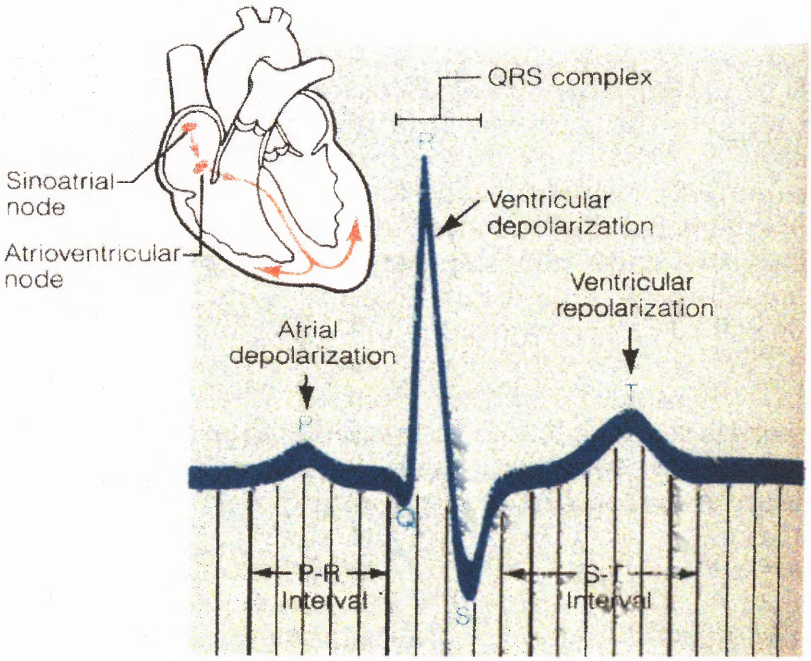


Figure 2.3 A typical normal ECG wave [26].

The first deflection, the P wave, corresponds to artrial depolarization. The second deflection, the QRS complex is the result of ventricular depolarization. It is a complex rather then a single deflection. The final deflection, the T wave, is the result of ventricular repolarization. Figure 2.3 illustrates a typical normal ECG signal.

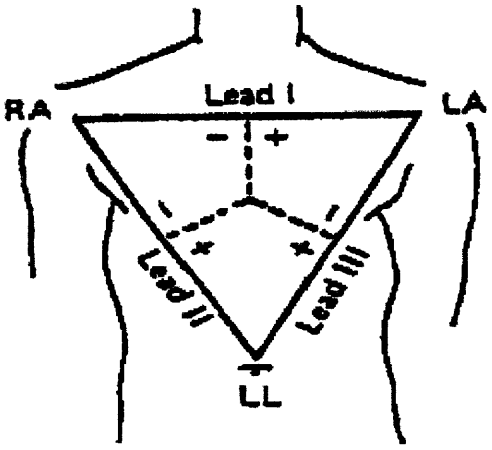


Figure 2.4 Standard bipolar leads for recording ECG [27].

In Figure 2.4, the standard bipolar limb leads for recording the EKG is illustrated. The term "bipolar" means that the ECG is recorded from two specific electrodes on the body. In recording lead I, the negative terminal of the ECG monitor is connected to the right arm and the positive terminal to the left arm. In recording lead II, the negative terminal is connected to the right arm and the positive terminal to the left leg. In recording III, the negative terminal is connected to the left arm and the positive terminal to the left leg. The reference point (ground) is connected to the right leg.

An ECG is very useful in determining whether a person has heart disease. Because many myocardial defects alter normal impulse propagation, and thereby the shape and timing of the waves. the ECG is a powerful tool for diagnosing certain types of heart defects. Figure 2.5 gives one example. According to the type of heart defects, the shape and timing of the waves are changed.

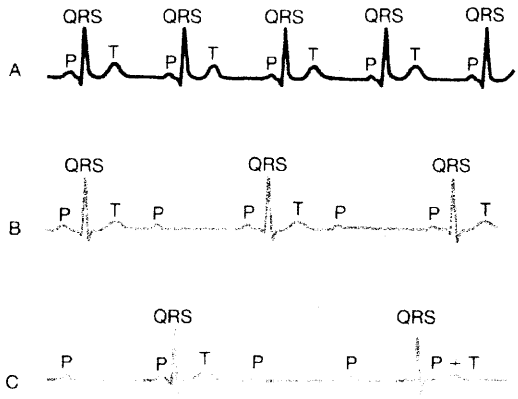


Figure 2.5 Electrocardiograms : (A) Healthy person (B) Partial atrioventricular block (C) Complete atrioventricular block [25].

2.4 Heart Rate Variability

There is a significant relationship between the autonomic nervous system and cardiovascular mortality, including sudden cardiac death. Heart rate variability (HRV) represents one of the most promising quantitative markers of the autonomic activity. With respect to the heart activity, the PSNS slows the heart rhythm while the SNS accelerates it. The interaction between both branches creates the HRV. 'Heart Rate Variability' has become the conventionally accepted term to describe variations of both instantaneous heart rate and RR intervals.

The HRV non-invasively reflects the autonomic nervous system (ANS) activity. If the time interval between beats is measured, it is noticed that the interval is not constant but varies in a cyclical manner. Most measurements of heart rate variability involve the determination of the R wave positions as markers of each beat position. The R wave is used because of its distinctive shape and prominent amplitude making it the easiest part of the beat for a computer to detect.

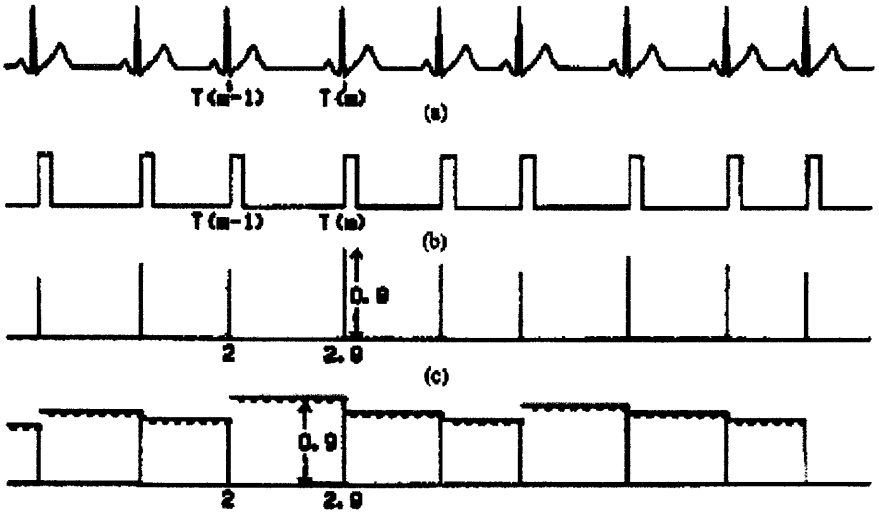


Figure 2.6 Construction of an interpolate interbeat interval (IIBI) signal [28].

The first step to obtain the power spectrum of HRV is to detect every R peaks in the ECG. Figure 2.6 shows the steps involved in constructing an interbeat interval (IBI) signal which will be used to examine the autonomic nervous system. In Figure 2.6 (a), we see a normal ECG. Each R wave is detected and a pulse is produced at the position of each R wave. This pulse train is shown in Figure 2.6 (b). To obtain the IBI signal, the distance in time between a specific beat at T_m and the previous beat at T_{m-1} is calculated. The interval becomes the height of the pulse at time T_m and the pulse wave is interpolated to produce a wave with equally spaced samples. This type of interpolation is called backward step interpolation. The height of the wave in a time intervals is kept constant at the value of the length of the time interval. The wave shown in Figure 2.6 (d) is called an interpolated interbeat interval (IIBI) signal and will become the basis from which information on heart rate variability will be obtained.

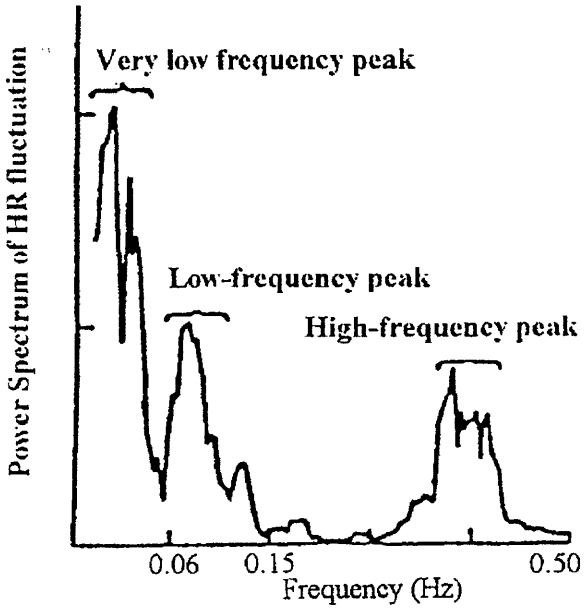


Figure 2.7 Fourier transform of heart rate fluctuations, indicating very-low frequency, low frequency and high frequency peaks [31].

The IIBI signal is then transformed using the Fourier transform to produce a frequency spectrum. Three frequency regions can be identified in the frequency spectrum of heart rate variability. Figure 2.7 is a spectrum of heart rate variability and shows three frequency regions [28]. The area under the spectrum in the band of frequencies between 0.15Hz and 0.4Hz, called the high frequency band, has been shown to be an indicator of the parasympathetic nervous system activity. The major activity in this band is due to respiration and a predominant peak usually occurs at the respiration frequency. The area under the spectrum in the frequency band between 0.05Hz and 0.15Hz, called the low frequency band, has been shown to be influenced by both sympathetic and parasympathetic nervous system activity and is large part due to the variability in the

blood pressure control system. The band between 0.02Hz and 0.05Hz is called the very low frequency band and is due mainly to the activity of the temperature control system. Basic knowledge about heart rate variability follows [29]:

- HRV is measured by the RR intervals in the ECG.
- HRV depends on the activity of both the sympathetic and parasympathetic branches of the autonomic nervous system.
- HRV is affected mainly by respiration (respiratory sinus arrhythmia) and by blood pressure (baroreceptor control system).
- HRV receives effects of respiration through only the parasympathetic nervous system.
- HRV has been shown to be a predictor of the occurrence of cardiac symptoms.
- HRV decreases with age. Therefore, any study involving heart rate variability must use age matched controls.
- HRV decreases in smokers and in sedentary people. Conversely, heart rate variability increases in people who habitually exercise.

2.5 Blood Pressure Variability

2.5.1 Blood Pressure

The force that blood exerts against the walls of a vessel is called blood pressure. The blood pressure also carries information which is useful in the study of heat rate variability. The aortic pressure pattern shown in Figure 2.8 is typical of the pressure changes that occur in all the large systemic arteries. The maximum pressure reached during peak ventricular ejection is called systolic pressure (SP). The minimum pressure occurs just before ventricular ejection begins and is called diastolic pressure (DP).

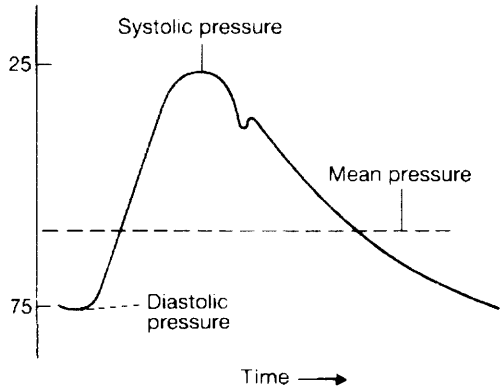


Figure 2.8 A typical arterial pressure fluctuation during the cardiac cycle [25].

2.5.2 Baroreceptor Response

Baroreceptors are receptors sensitive to blood pressure. Figure 2.9 illustrate the locations of arterial baroreceptors and Figure 2.10 illustrates the arterial baroreflex response [25]. The primary control center for the baroreflex is a diffuse network of highly interconnected neurons in the brainstem medulla called the medullary cardiovascular center. The neurons in this center receive input from the various baroreceptors. This input determines the outflow from the center along axons that terminate upon the cell bodies and dendrites of the parasympathetic neurons to the heart and sympathetic neurons to the heart, arterioles, and veins. A decrease in blood pressure sensed by the baroreceptors produces an increase in the sympathetic activity and a decrease in the parasympathetic activity, resulting in an increase in heart rate and therefore an increase in blood pressure.

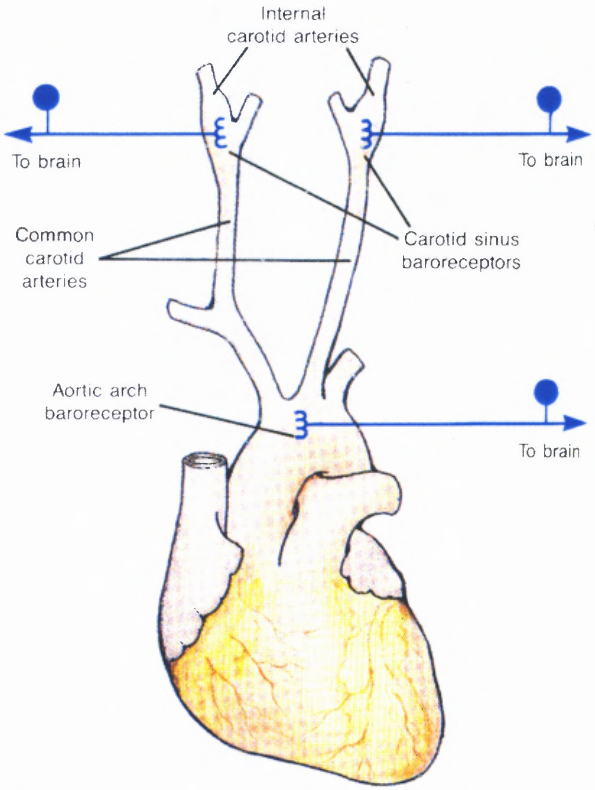


Figure 2.9 Locations of arterial baroreceptors [25].

An increase in blood pressure sensed by the baroreceptors produces an increase in the parasympathetic activity and a decrease in the sympathetic activity, resulting in a decrease in heart rate and therefore a decrease in blood pressure. The oscillations resulting from this negative feedback loop have been shown to occur in the mid-frequency range between 0.1Hz and 0.15Hz.

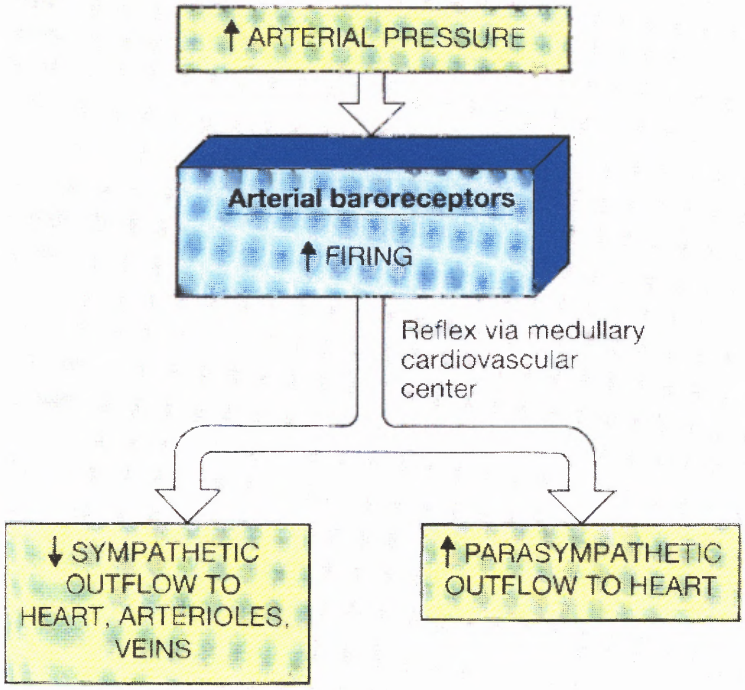


Figure 2.10 Neural components of the arterial baroreceptor reflex [25].

CHAPTER 3

ENGINEERING BACKGROUND

3.1 Power Spectrum (Frequency Domain) Analysis

Power spectral analysis is a technique which transforms a signal from the time domain to the frequency domain. It is based on the theory proposed by Fourier who states that all periodic functions can be represented as a sum of sines and cosines at a fundamental frequency and its harmonics. If f(t) converges, and f(t) is piecewise continuous, the Fourier transform of f(t) is defined as [30]:

$$F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t} dt \tag{3.1}$$

3.1.1 HRV Spectrum

The power spectrum of heart rate variability (PS/HRV) is a potentially powerful tool for exploring neurocardiac dysfunction in patients with a variety of cardiac and autonomic disorders [31]. Power spectrum analysis decomposes the heart rate variability signal into its frequency components and quantifies them in terms of their relative intensity, or power.

Figure 3.1 illustrates a typical HRV spectrum. The area under the spectrum from 0.05 Hz to 0.15 Hz was calculated and indicated as low frequency (LF) area. The area under the spectrum from 0.15Hz to 0.4Hz was calculated and indicated as high frequency (HF) area.

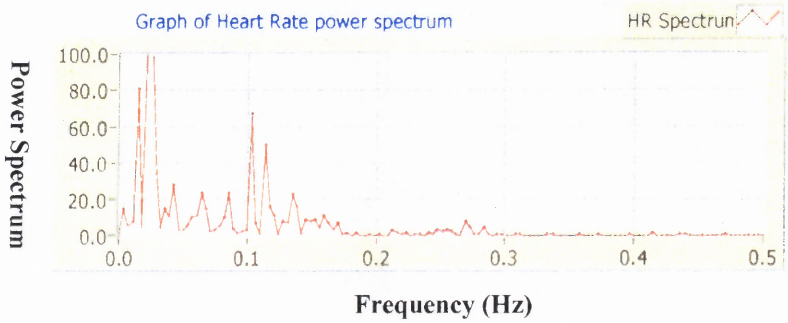


Figure 3.1 Power spectrum of heart rate variability: spectrum of sitting segment in stage 4 (control subject 3).

3.1.2 BPV Spectrum

Similar to the ECG, the systolic peaks are detected and the peak amplitude calculated instead of the time interval between peaks. The first maximum value of amplitude that occurs in the peak is detected and this value is interpolated over the interval until the next successive peak amplitude is detected (Figure 3.2). The blood pressure IIBI file is then calculated using the Fourier transform and the BPV spectrum is obtained (Figure 3.3).

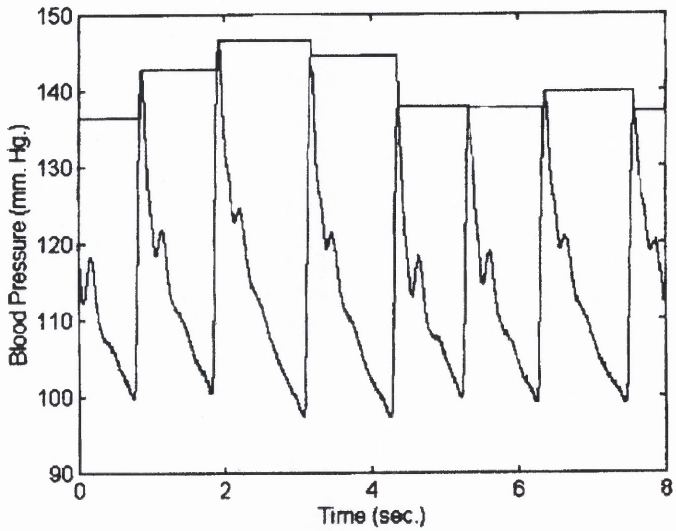


Figure 3.2 Production of a systolic blood pressure variability wave.

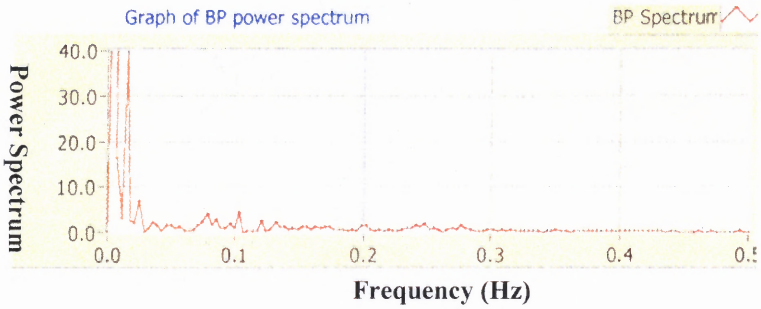


Figure 3.3 Power spectrum of blood pressure variability: spectrum of sitting segment in stage 4 (subject 3 of the control group).

3.2 Statistical Analysis (ANOVA)

Analysis of variance (ANOVA) is used to test hypotheses about differences between two or more means. Analysis of variance can be used to test differences among several means for significance without increasing the Type I error rate. Significance tests are performed to see if the null hypothesis can be rejected. If the null hypothesis is rejected, then the effect found in a sample is said to be statistically significant. If the null hypothesis is not rejected, then the effect is not significant.

$$\text{Null Hypothesis: } \mu_1 = \mu_2 = \mu_3 = \ldots = \mu_n \tag{3.2}$$

(μ_n are the mean of samples)

There are two kinds of errors that can be made in significance tests: (1) a true null hypothesis can be incorrectly rejected and (2) a false null hypothesis can fail to be rejected. The former error is called a Type I error and the latter error is called a Type II error. These two types of errors are defined in the Table 3.1. The probability of a Type I error is designated by the Greek letter alpha (α) and is called the Type I error rate; the probability of a Type II error (the Type II error rate) is designated by the Greek letter beta

probability of a Type II error (the Type II error rate) is designated by the Greek letter beta (ß) [32]. The experimenter chooses a significance level before conducting the statistical analysis. The significance level chosen determines the probability of a Type 1 error.

Analysis of variance assumes normal distributions and homogeneity of variance. Therefore, in One Factor ANOVA, it is assumed that each of the population is normally distributed with the same variance (σ^2). In Two Factors ANOVA, it is assumed that data is sampled randomly and independently [32]. Some experiments have more than one experiment factor. In this study, experiments were conducted in five stages and five segments (Chapter 4.1) so there were two experiment factors, stages and segments. One Factor ANOVA was used to study significances between stages in the same segment or segments in the same stage. Two-Factor ANOVA was used to study significances between stages or segments.

Table 3.1 Statistical Test Errors [32]

Statistical Decision	True state of null hypothesis	
	Ho True	**Ho False**
Reject Ho	Type 1 error	Correct
Do not reject Ho	Correct	Type 2 error

One Factor ANOVA This tool performs a simple analysis of variance, testing the hypothesis that means from two or more samples are equal (drawn from populations with the same mean).

Two-Factor ANOVA This analysis tool performs an extension of One Factor ANOVA that includes more than one sample for each group of data.

CHAPTER 4

METHODS

4.1 Data Acquisition

The ECG and blood pressure (BP) signals were acquired in five different stages.

Stage 0: the first day, morning (9am)

Stage 1: the first day, night (9pm)

Stage 2: the second day, morning (9am), twelve hours of SD

Stage 3: the second day, night (9pm), twenty-four hours of SD

Stage 4: the third day, morning (9am), thirty-six hours of SD

All data were acquired with the Embla Sx, a bio-signal acquisition instrument. Analog BP and ECG signals were converted into digital signals coincidently with acquisitions. Digitized data were transferred to the computer and displayed on the computer monitor. All tests were conducted in the sleep research lab of Columbia University. Volunteers were divided into the two groups, SD and control. SD subjects were asked to stay in the lab for thirty-six hours and not to sleep. All conditions of the control group were same as for the SD group except that people of the control group went home at night and slept as usual. Ten people volunteered for the SD study and five people volunteered for the control study. Volunteers took a twenty minute break after their arrival, and then BP and ECG were monitored for fifteen minutes in supine and sitting positions. After measurements in two positions, subjects were asked to use a computer

for thirty minutes. They clicked the mouse and used the internet for thirty minutes and the thirty minutes of data were divided into three segments, C1, C2 and C3.

C1: The first ten minutes data after the volunteers started using the computer.

C2: Data taken between ten minutes and twenty minutes after beginning.

C3: Data taken between twenty minutes and thirty minutes after beginning.

There were five segments of data in each stage and the last five minutes of each segment were used for this study. It took a total of one hour for the measurement in each stage. For the control study, ECG and BP were acquired from five volunteers. Volunteers did their usual tasks and came to the lab to have data taken. All data acquisition procedures and methods were same as that of the SD test.

4.2 Data Processing

All signal processing techniques were performed with the LABVIEW graphical programming language. The physiological signals, BP and ECG, were sampled at 200 Hz.

4.2.1 Power Spectrum of Heart Rate Variability

All R peaks of the filtered ECG (Figure 4.1(a)) were detected using the CORRECT.VI, a LABVIEW program block (APPENDIX B). Missed R peaks or wrongly detected R peaks were corrected manually using the CORRECT.VI. Heart rate IBI data (Figure 4.1(b)) were acquired through this procedure and the IBI data flowed into the SPECTRUM.VI block where it was interpolated. The power spectrums were computed as well as LF area, HF area and the length of data file in minutes.

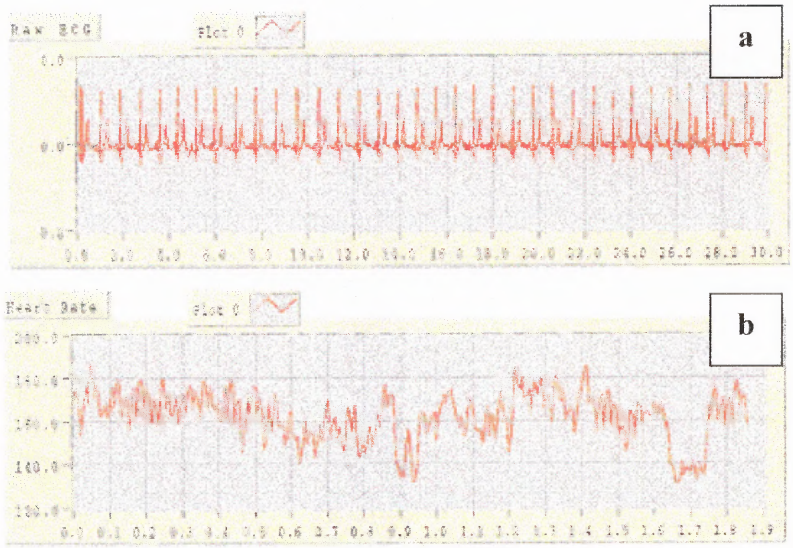


Figure 4.1 (a) Raw ECG (b) Heart Rate IBI file.

4.2.2 Power Spectrum Analysis of Blood Pressure

Blood pressure signals flowed into a peak detection block (CORRECTBP.VI). Unlike the peak detection block for the ECG signal, the locations of each consecutive peak of the blood pressure signal were not important. For blood pressure variability (BPV) analysis, the amplitude of each peak was detected. Detection of the BP peak location is dependent upon the maximum amplitude of the peak. The first amplitude is interpolated over the interval until the next peak amplitude is detected. In this way, the BP IBI is interpolated to generate the BPV IIBI (Figure 4.2). The IIBI array undergoes a series of analyses and mathematical calculations, similarly to the heart rate spectrum.

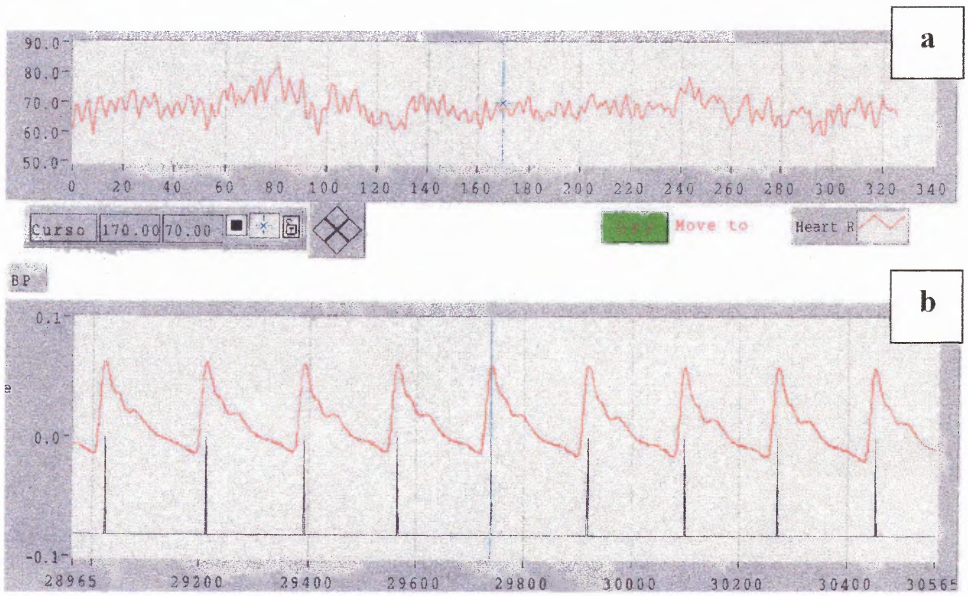


Figure 4.2 (a) BP IIBI data (b) Systolic pressure detection (CORRECTBP.VI).

4.3 ANOVA

One Factor ANOVA and Two Factors ANOVA were conducted for the significance comparison tests. Data in a different segment but in the same stage (Table 4.1(b)) or data in different stages but in the same segment (Table 4.1(a)) were selected for One Factor ANOVA.

Table 4.1 Data Selection for One-Factor ANOVA

C1	Stage 1	Stage 2	Stage 3	Stage 4
1	301	760	1080	2000
2	308	1217	1066	545
3	813	470	1126	2225
4	1135	2880	1978	4989
5	708	1236	2577	750
6	783	1428	793	3469
7	482	1087	929	705
8	385	1278	1202	1107
9	2544	2544	2601	2783
10	1460	4049	4960	1884

(a) SD NLF in the C1 segment

Stage 4	Supine	Sitting	C1	C2	C3
1	876	1348	2000	1951	1866
2	518	714	545	472	674
3	164	1532	2225	718	2880
4	3422	3940	4989	3463	4745
5	1661	1488	750	900	753
6	1673	3794	3469	2242	2498
7	2326	1344	705	520	532
8	560	412	1107	1162	1088
9	1210	1806	2783	3013	2281
10	1473	1814	1884	2016	9464

(b) SD NLF in stage 4

Table 4.1 is an example of data selection for a One Factor ANOVA. Table 4.1(b) is the SD NLF of the C1 segment in four different stages and Table 4.2(a) is the result of the One Factor ANOVA in Table 4.1(a). Stage was the factor in this One Factor ANOVA test. The numbers in the first row in Table 4.2(a) are the numbers of the stages. For example, 1&2 is stage 1 and stage 2. The numbers in the second row are P-values. On the 0.05 significance level, there was a significant difference between stage 1 and stage 4

because the number in 1&4 is less then 0.05. In other stage comparisons, no significant difference was observed. Table 4.1(b) is the NLF of the SD group in stage 4 and Table 4.2(b) is the One Factor ANOVA result of data in Table 4.1(b). Segment was the factor of this One Factor ANOVA test. All P-values in Table 4.2(b) are over 0.05. There was no significant change between segments in stage 4.

Table 4.2 One Factor ANOVA Results of Data in Table 4.1

Stages	1&2	1&3	1&4	2&3	2&4	3&4	1&2&3	1&2&3&4
C1	0.07	0.06	0.03	0.8	0.54	0.73	0.12	0.15

(a) One Factor ANOVA P-values of data in Table 4.1(a)

	Supine&C1	Supine&C2	Supine&C3	Sitting&C1	Sitting&C2	Sitting&C3	C1&C2	C1&C3	C2&C3
Stage 1	0.86	0.13	0.25	0.84	0.21	0.43	0.17	0.35	0.54
Stage 2	0.62	0.26	0.25	0.85	0.31	0.31	0.36	0.44	0.59
Stage 3	0.15	0.11	0.14	0.40	0.23	0.35	0.56	0.87	0.68
Stage 4	0.24	0.58	0.17	0.70	0.73	0.37	0.48	0.52	0.28

	Supine & Sitting	Supine&Sitting&C1	Supine&Sitting&C1&C2	Supine&Sitting&C1&C2&C3
Stage 1	0.69	0.93	0.26	0.35
Stage 2	0.70	0.85	0.42	0.50
Stage 3	0.38	0.27	0.24	0.36
Stage 4	0.38	0.47	0.64	0.45

(b) One Factor ANOVA P-values of data in Table 4.1(b)

Table 4.3 shows an example of data selection for Two Factors ANOVA. Table 4.4 shows the Two Factors ANOVA result of data in Table 4.3. In Table 4.3, the NLF data in stage 1 and stage 2 were selected for the Two Factors ANOVA significance test. There are two factors, segments (Supine, Sitting and three cognitive segments) and stages (stage 1 and stage 2). The degree of freedom of the segments is four and the degree of freedom

of the stages is one. The P-value between the two stages is 0.003 and the P-value between five segments is 0.189 (Table 4.2). On the significance level of 0.05, there was a significant difference between the two stages although no significant change between segments was observed.

Table 4.3 Data Selection for Two-Factor ANOVA: The NLF of the SD Group in Stage 1 and Stage 2

	Supine	Sitting	C1	C2	C3
Stage 1	294	239	301	167	864
	324	236	308	880	353
	598	1592	813	1449	835
	2359	1253	1135	2013	1892
	646	1721	708	2612	2072
	634	481	783	750	747
	359	627	482	361	466
	1112	826	385	845	717
	966	1838	2544	3370	2419
	1105	699	1460	2060	1601
Stage 2	195	562	760	1933	2200
	293	605	1217	1022	1145
	1340	1307	470	528	1034
	877	1122	2880	3141	2636
	978	1572	1236	1223	934
	1586	1583	1428	910	1754
	970	2104	1087	1165	811
	542	1348	1278	1367	2292
	2365	2619	2544	4625	3483
	4938	3299	4049	11653	4989

Table 4.4 Two-Factor ANOVA Results of Data in Table 4.3

Anova: Two-Factor With Replication

SUMMARY	supine	Sitting	C1	C2	C3	Total
stage 1						
Count	10	10	10	10	10	50
Sum	8397	9513.197	8918.203	14507.36	11965.8	53301.56
Average	839.7	951.3197	891.8203	1450.736	1196.58	1066.031
Variance	377979.3	367338.8	475253.9	1082211	536411.7	574499.9
stage 2						
Count	10	10	10	10	10	50
Sum	14084	16121.86	16949.39	27567.5	21279.12	96001.87
Average	1408.4	1612.186	1694.939	2756.75	2127.912	1920.037
Variance	1948479	735905.5	1232674	11294584	1752936	3350742
Total						
Count	20	20	20	20	20	
Sum	22481	25635.06	25867.6	42074.86	33244.92	
Average	1124.05	1281.753	1293.38	2103.743	1662.246	
Variance	1187117	637522.3	978755.3	6311553	1312686	

ANOVA

Source of Variation	*SS*	*Df*	*MS*	*F*	*P-value*	*F crit*
Stages	18233166	**1**	18233166	9.206915	**0.003151**	3.946866
Segments	12444972	**4**	3111243	1.571035	**0.188849**	2.47293
Interaction	1657909	4	414477.3	0.209292	0.932661	2.47293
Within	1.78E+08	90	1980377			
Total	2.11E+08	99				

CHAPTER 5

RESULTS AND DISCUSSION

The HF and LF areas were calculated using power spectrum analysis of HRV and BPV. Calculated HF and LF were normalized for five minutes as shown in equation 5.1 and 5.2. The time-normalized HF and LF areas were indicated as NHF and NLF, respectively.

$$NLF = (LF/time)*5 \tag{5.1}$$

$$NHF = (HF/time)*5 \tag{5.2}$$

The time normalized HF and LF were normalized again by the total power, NLF plus NHF.

$$NNLF = NLF/ (NLF+NHF) \tag{5.3}$$

$$NNHF = NHF/ (NLF+NHF) \tag{5.4}$$

All data were acquired in the sleep lab of Columbia University. Blood pressure and ECG were acquired from the two groups, SD and control. Ten people volunteered for the SD group and five people volunteered for the control group. People in the SD group did not sleep for thirty-six hours but people in the control group slept at night as usual. Research members of this study or their family members volunteered for the control group. Subjects of the control group slept as much as their usual sleep hours at home and they came to the lab and stayed there like subjects of the SD group. Subjects of the SD

group stayed in the lab for over thirty-six hours and were asked to be awake during their stay at the lab.

There were five different data acquisition stages. Data of the SD group were acquired from stage 1 to stage 4. Data in stage 0 were acquired only in the control group in order to study circadian rhythms in the data. It is thought that a circadian pattern pervades human physiological function, including the ANS. It has been reported that the LF area decreases and the HF area increases at night [31]. In consideration of a circadian pattern, data were acquired at twelve hours intervals.

Stage 0: the first test day, morning (9am)

Stage 1: the first test day, night (9pm)

Stage 2: the second test day, morning (9am), twelve hours of SD

Stage 3: the second test day, night (9pm), twenty-four hours of SD

Stage 4: the third test day, morning (9am), thirty-six hours of SD

Signals were acquired in supine and sitting positions and during the thirty minutes of computer tasks. Volunteers clicked the mouse and used the internet during the thirty minutes of cognitive tasks and data during the cognitive tasks were equally divided in time into three segments, C1, C2 and C3. There is no difference between cognitive segments except the data acquisition time.

C1: The first ten minutes data after the volunteers started using the computer.

C2: Data taken between ten minutes and twenty minutes after beginning.

C3: Data taken between twenty minutes and thirty minutes after beginning.

There were five segments in each stage.

Segments: Supine → Sitting → Computer tasks (C1 → C2 → C3)

For the statistical comparison tests, ANOVA were conducted as stated in Chapter 4. The P-value is the smallest level of significance that would lead to the rejection of the null hypothesis. The chosen significance level was 0.05. The P-values were acquired from One Factor ANOVA and Two-Factor ANOVA. If the P-value is less than 0.05, there is a significant change.

5.1 The Heart Rate Variability (HRV)

The NLF and NHF were calculated in all segments and stages. The NLF of the HRV spectrum provides an indication of a mixture of the sympathetic and parasympathetic nervous system activity. The NHF of HRV provides an indication of the parasympathetic activity.

5.1.1 The Heart Rate Variability of the Control Group

Five subjects volunteered for this control study and data were acquired from all subjects in all stages except stage 0. In stage 0, data were acquired in all segments from only three subjects. Table 5.1 shows time normalized (5min) HRV spectra of control subjects.

Table 5.1 The Heart Rate Variability of the Control Group

	NLF					NHF				
Subject 1	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 0	453	526	513	674	222	302	271	288	236	157
Stage 1	302	517	382	508	378	167	135	203	119	134
Stage 2	1163	319	511	750	712	280	234	171	224	491
Stage 3	761	669	491	883	691	135	122	176	746	195
Stage 4	450	330	560	520	594	196	217	229	246	287
Subject 2	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 0	-	-	-	-	-	-	-	-	-	-
Stage 1	179	307	232	440	412	317	534	282	241	317
Stage 2	171	798	259	344	306	129	208	196	179	166
Stage 3	339	245	647	513	831	136	348	487	753	406
Stage 4	523	739	262	631	627	176	444	253	236	475
Subject 3	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 0	648	486	-	-	-	275	143	-	-	-
Stage 1	575	607	799	786	666	482	136	179	100	179
Stage 2	304	414	503	670	721	77	86	60	110	99
Stage 3	308	409	381	378	580	96	98	82	82	96
Stage 4	427	371	609	638	568	183	105	160	89	128
Subject 4	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 0	401	687	455	324	535	328	423	543	478	674
Stage 1	496	610	348	409	301	222	545	432	434	445
Stage 2	385	913	228	320	393	692	542	425	408	343
Stage 3	698	652	533	264	461	870	713	353	383	171
Stage 4	404	410	388	257	340	465	547	339	344	296
Subject 5	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 0	476	458	316	460	361	796	616	557	515	540
Stage 1	474	513	125	343	180	449	539	440	461	507
Stage 2	292	457	288	332	439	596	735	398	559	410
Stage 3	231	348	233	253	315	249	280	370	201	359
Stage 4	422	389	753	676	649	593	611	323	399	410

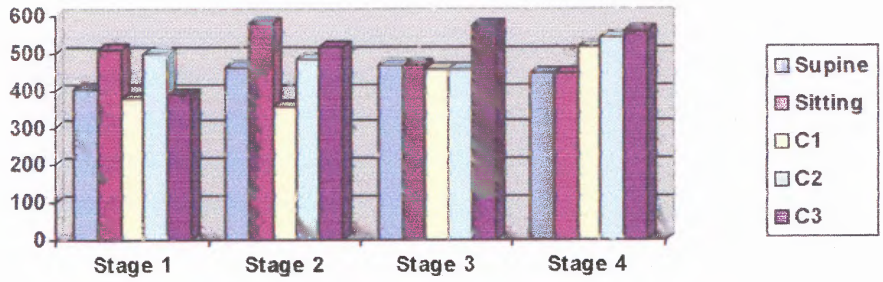
Individual control subject's HRV spectra diagrams are found in Appendix C. Each figure shows the normalized LF (NLF), the normalized HF (NHF), the total power normalized NLF (NNLF), the total power normalized NHF (NNHF) and the NLF/NHF ratio. The sympathetic branch and parasympathetic branch act antagonistically and the ratio is believed to indicate the balance between the two autonomic nervous branches [31].

Table 5.2 shows the mean HRV of the control group. Spectra in the same segment and stage were added together and divided by the number of subjects. There are only three control subject's data in stage 0 so we did not include data in stage 0 for this mean value analysis. The mean NLF was divided by the mean NHF and indicated as MNLF/MNHF ratio. The MNLF/MNHF ratio represents the balance between the sympathetic nervous system activity and parasympathetic nervous system activity. An increased ratio means an increased sympathetic nervous activity.

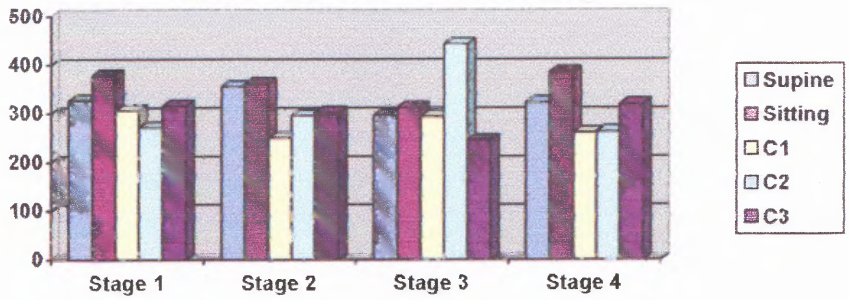
Table 5.2 The Mean HRV of the Control Group

Mean NLF	Stage 1	Stage 2	Stage 3	Stage 4
Supine	405	463	467	445
Sitting	511	580	465	448
C1	377	358	457	514
C2	497	483	458	544
C3	387	514	576	556
Mean NHF	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
Supine	327	355	297	323
Sitting	378	361	312	385
C1	307	250	294	261
C2	271	296	443	263
C3	316	302	245	319
MNLF/MNHF Ratio	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
Supine	1.24	1.30	1.57	1.38
Sitting	1.35	1.61	1.49	1.16
C1	1.23	1.43	1.55	1.97
C2	1.83	1.63	1.03	2.07
C3	1.22	1.70	2.35	1.74

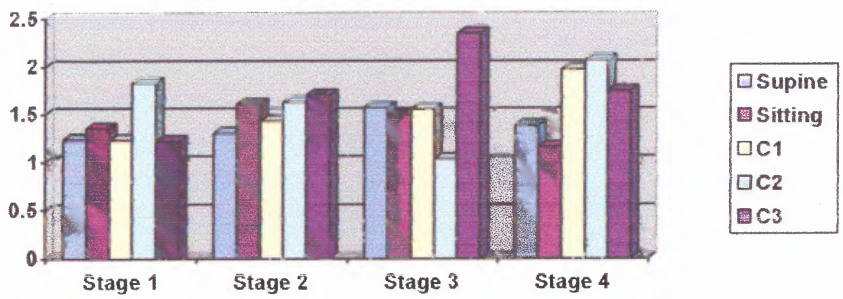
Figure 5.1(a) shows the mean NLF of the control group and Figure 5.1(b) shows the mean NHF of the control group diagrammatically. When subjects changed their position from supine to sitting, the NLF and NHF increased in all stages except the NLF in stage 3. No circadian rhythm was observed in the control group. The NLF and NHF decreased in the C1 segment except the NLF in stage 4. Figure 5.1(c) shows the MNLF/MNHF ratio.



(a) The mean NLF (MNLF)



(b) The mean NHF (MNHF)



(c) The mean NLF/NHF Ratio

Figure 5.1 The mean HRV diagrams of the control group (HRV).

5.1.2 The HRV of the Sleep Deprivation Group

Table 5.3 shows the NLF and NHF of the SD group. Individual spectra diagrams are shown in Appendix D. Ten subjects volunteered for the sleep deprivation study and each volunteer was indicated as SD subject 1, SD subject 2,…., SD subject 10.

Table 5.3 The Heart Rate Variability of the SD Group

	NLF					NHF				
Subject 1	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 1	294	239	301	167	864	375	358	299	296	395
Stage 2	195	562	760	1933	2200	251	608	1236	826	819
Stage 3	388	608	1080	1627	1167	407	996	732	1119	1008
Stage 4	876	1348	2000	1951	1866	686	633	1001	946	919
Subject 2	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 1	324	236	308	880	353	209	288	234	307	234
Stage 2	293	605	1217	1022	1145	190	306	550	385	193
Stage 3	942	754	1066	614	677	211	267	203	266	175
Stage 4	518	714	545	472	674	284	201	128	116	100
Subject 3	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 1	598	1592	813	1449	835	448	738	351	848	540
Stage 2	1340	1307	470	528	1034	1253	846	295	315	571
Stage 3	294	527	1126	2023	1940	395	439	273	590	445
Stage 4	164	1532	2225	718	2880	487	529	436	226	715
Subject 4	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 1	2359	1253	1135	2013	1892	1563	351	286	361	608
Stage 2	877	1122	2880	3141	2636	890	470	608	605	842
Stage 3	2017	1231	1978	1768	2813	2136	633	535	980	981
Stage 4	3422	3940	4989	3463	4745	2798	2555	2157	2014	3048
Subject 5	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 1	646	1721	708	2612	2072	481	923	202	689	452
Stage 2	978	1572	1236	1223	934	486	584	298	222	202
Stage 3	1003	1950	2577	2272	1480	952	1025	870	469	480
Stage 4	1661	1488	750	900	753	741	757	118	130	193
Subject 6	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 1	634	481	783	750	747	147	117	318	210	268
Stage 2	1586	1583	1428	910	1754	664	293	495	448	441
Stage 3	1190	1814	793	2467	1228	346	464	140	242	204
Stage 4	1673	3794	3469	2242	2498	822	486	275	333	359
Subject 7	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 1	359	627	482	361	466	626	448	283	286	224
Stage 2	970	2104	1087	1165	811	560	350	192	294	268
Stage 3	987	1721	929	933	722	518	329	272	334	280
Stage 4	2326	1344	705	520	532	905	508	117	104	131
Subject 8	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 1	1112	826	385	845	717	374	182	193	179	155
Stage 2	542	1348	1278	1367	2292	381	425	444	379	390
Stage 3	317	975	1202	1047	968	440	290	187	157	139
Stage 4	560	412	1107	1162	1088	443	224	343	362	363
Subject 9	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 1	966	1838	2544	3370	2419	3371	2332	2474	2843	3245
Stage 2	2365	2619	2544	4625	3483	1779	1074	1853	2214	1925
Stage 3	1171	1692	2601	2241	2691	1505	1159	1643	1371	2051
Stage 4	1210	1806	2783	3013	2281	1193	1309	1550	1404	1092
Subject10	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 1	1105	699	1460	2060	1601	423	397	616	644	484
Stage 2	4938	3299	4049	11653	4989	1484	867	987	1025	1015
Stage 3	2819	2968	4960	7783	5699	1900	921	2690	1606	1524
Stage 4	1473	1814	1884	2016	9464	555	1175	993	871	3762

Each SD subject has a different HRV sensitivity to sleep deprivation. Individual SD subject's HRV spectra diagrams are in Appendix D. All SD subject's overall NLF/NHF ratio increased in stage 3 and stage 4 except SD subject 4 and SD subject 10. The NLF/NHF ratio increase induced by the position change was observed in all SD subjects.

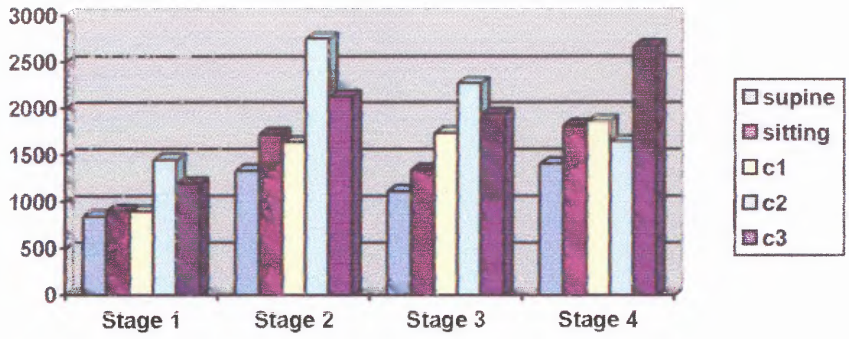
Table 5.4 The Mean HRV of the SD Group

Mean NLF	Stage 1	Stage 2	Stage 3	Stage 4
Supine	840	1408	1113	1388
Sitting	951	1612	1424	1819
C1	892	1695	1831	2046
C2	1451	2757	2278	1646
C3	1197	2128	1939	2678
Mean NHF	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
Supine	802	794	881	891
Sitting	613	582	652	838
C1	526	696	755	712
C2	666	671	713	651
C3	661	667	729	1068
NLF/NHF	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
Supine	1.05	1.77	1.26	1.56
Sitting	1.55	2.77	2.18	2.17
C1	1.70	2.44	2.43	2.87
C2	2.18	4.11	3.19	2.53
C3	1.81	3.19	2.66	2.51

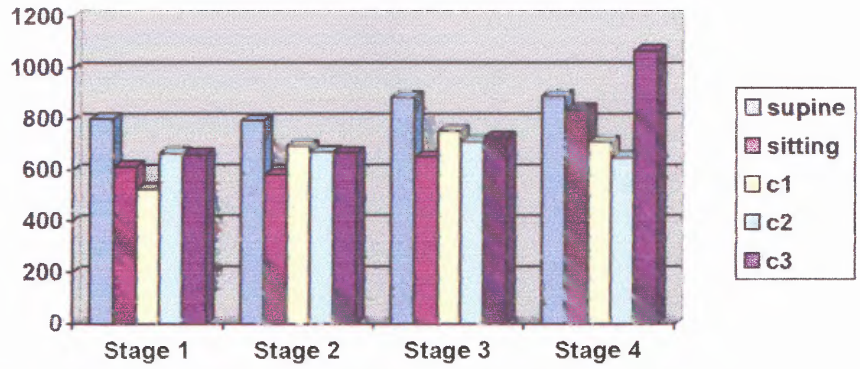
Table 5.4 shows the mean HRV values of the SD group. Figure 5.2(a) is the diagram of the mean NLF and Figure 5.2(b) is the mean NHF diagram. The MNLF increased in the morning (stage 2 and stage 4) and decreased at night (stage 1 and stage 3) in the supine and sitting segments. This circadian rhythm was observed only in the MNLF not in the MNHF. In all stages, the mean NLF increased and the mean NHF decreased when subjects changed their position from supine to sitting. During the cognitive task, the MNLF increased in the C2 segment and decreased in the C3 segment

except in stage 4. In stage 4, the MNLF and the MNHF decreased in the C2 segment and increased in the C3 segment. The MNHF decreased in all stages when subjects changed their position from supine to sitting.

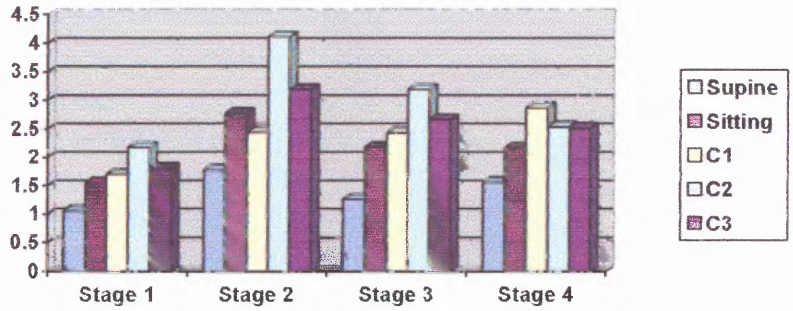
Figure 5.2 (c) shows the diagram of the MNLF/MNHF ratio. Although the NLF/NHF ratio in the control group does not show a circadian rhythm, the NLF/NHF ratio in the SD group shows a circadian rhythm. In all stages, the MNLF/MNHF ratio was increased by the position change from supine to sitting. During the cognitive task, the ratio increased in the C2 segment and decreased in the C3 segment in all stages except stage 4. In stage 4, the ratio increased in the C1 segment and then decreased in the C2 and C3 segments. We suppose that the subjects received mental stress at the point of the NLF/NHF ratio peak while the cognitive task. From stage 1 to stage 3, subjects received mental stress between ten minutes and twenty minutes after starting the cognitive task. In stage 4, after thirty-six hours of sleep deprivation, subjects received mental stress within ten minutes after starting the cognitive task.



(a) The mean NLF (MNLF)



(b) The mean NHF (MNHF)



(c) The mean NLF/mean NHF ratio (MNLF/MNHF)

Figure 5.2 The mean spectra diagrams of the SD group (HRV).

5.1.3 HRV Analysis of Variance (ANOVA)

In addition to the mean values analysis, One Factor ANOVA and Two-Factor ANOVA were conducted for the significance comparison tests.

5.1.3.1 One Factor ANOVA. Table 5.5 shows the NLF P-values of the control group (a) and the SD group (b). Data in the same segment but in different stages were compared. Stage is the factor of this One Factor ANOVA. Numbers in the first row are the stage number. For example, the control supine P-value between stage 1 and stage 2 (1&2) is 0.77.

Table 5.5 P-Values between Stages in the Same Segment (NLF of the HRV, One Factor ANOVA)

	1&2	1&3	1&4	2&3	2&4	3&4	1&2&3	1&2&3&4
Supine	0.77	0.65	0.61	0.98	0.92	0.85	0.93	0.98
Sitting	0.60	0.66	0.51	0.44	0.36	0.88	0.66	0.70
C1	0.89	0.57	0.37	0.32	0.18	0.62	0.69	0.55
C2	0.91	0.79	0.67	0.87	0.63	0.55	0.96	0.93
C3	0.31	0.16	0.12	0.63	0.70	0.85	0.32	0.36

(a) The Control Group

	1&2	1&3	1&4	2&3	2&4	3&4	1&2&3	1&2&3&4
Supine	0.25	0.40	0.15	0.57	0.97	0.49	0.45	0.54
Sitting	0.06	0.14	**0.05**	0.61	0.66	0.38	0.14	0.16
C1	0.07	0.06	**0.03**	0.80	0.54	0.73	0.12	0.15
C2	0.26	0.27	0.68	0.70	0.33	0.39	0.46	0.50
C3	0.07	0.18	0.11	0.77	0.57	0.46	0.22	0.30

(b) The SD Group

All P-values in Table 5.5 (a) are over 0.05. No significant change was seen in the control group. Even though there was no significant change in the control group, significant changes were observed in the SD group after thirty-six hours of sleep deprivation in the sitting segment and the C1 segment. P-values in sitting and C1 of 1&4

Table 5.6 P-Values between Stages in the Same Segment (NHF of the HRV, One Factor ANOVA)

	1&2	1&3	1&4	2&3	2&4	3&4	1&2&3	1&2&3&4
Supine	0.85	0.85	0.97	0.77	0.84	0.88	0.94	0.99
Sitting	0.92	0.67	0.96	0.77	0.88	0.63	0.91	0.96
C1	0.54	0.89	0.49	0.68	0.89	0.69	0.82	0.89
C2	0.83	0.33	0.93	0.42	0.74	0.28	0.51	0.55
C3	0.89	0.47	0.98	0.57	0.86	0.40	0.75	0.85

(a) The Control Group

	1&2	1&3	1&4	2&3	2&4	3&4	1&2&3	1&2&3&4
Supine	0.98	0.84	0.82	0.76	0.74	0.97	0.96	0.99
Sitting	0.89	0.87	0.47	0.62	0.30	0.46	0.94	0.70
C1	0.54	0.51	0.56	0.85	0.95	0.90	0.75	0.89
C2	0.99	0.88	0.96	0.87	0.94	0.81	0.98	1.00
C3	0.99	0.85	0.43	0.82	0.37	0.47	0.97	0.71

(b) SD Group

are equal or less then 0.05. Sleep deprivation more then thirty-six hours may increase the LF area in the sitting position and when people begin a cognitive task.

Table 5.6 shows NHF P-values of the control group (a) and the SD group (b). All P-values in Table 5.6 are greater then 0.05 so no significant change of the HF area was observed in the control group and the SD group.

Table 5.7 P-Values between Segments in the Same Stage (HRV)

(a) The Control Group

NLF	Supine&C1	Supine&C2	Supine&C3	Sitting&C1	Sitting&C2	Sitting&C3	C1&C2	C1&C3	C2&C3
Stage 1	0.84	0.41	0.87	0.32	0.89	0.24	0.41	0.94	0.35
Stage 2	0.59	0.92	0.80	0.13	0.53	0.66	0.30	0.18	0.81
Stage 3	0.94	0.96	0.46	0.95	0.97	0.39	0.99	0.33	0.45
Stage 4	0.46	0.25	0.10	0.57	0.39	0.28	0.80	0.70	0.91
NHF	Supine&C1	Supine&C2	Supine&C3	Sitting&C1	Sitting&C2	Sitting&C3	C1&C2	C1&C3	C2&C3
Stage 1	0.81	0.58	0.91	0.55	0.42	0.63	0.71	0.92	0.68
Stage 2	0.48	0.70	0.72	0.45	0.67	0.68	0.68	0.62	0.96
Stage 3	0.98	0.52	0.75	0.89	0.51	0.61	0.40	0.62	0.25
Stage 4	0.52	0.57	0.97	0.26	0.30	0.58	0.98	0.41	0.50

NLF	Supine & Sitting	Supine&Sitting&C1	Supine&Sitting&C1&C2	Supine&Sitting&C1&C2&C3
Stage 1	0.28	0.52	0.60	0.67
Stage 2	0.59	0.49	0.64	0.73
Stage 3	0.98	1.00	1.00	0.88
Stage 4	0.97	0.71	0.68	0.65
NHF	Supine & Sitting	Supine&Sitting&C1	Supine&Sitting&C1&C2	Supine&Sitting&C1&C2&C3
Stage 1	0.68	0.79	0.79	0.89
Stage 2	0.97	0.72	0.85	0.92
Stage 3	0.94	0.99	0.82	0.81
Stage 4	0.65	0.54	0.58	0.71

(b) The SD Group

NLF	Supine&C1	Supine&C2	Supine&C3	Sitting&C1	Sitting&C2	Sitting&C3	C1&C2	C1&C3	C2&C3
Stage 1	0.86	0.13	0.25	0.84	0.21	0.43	0.17	0.35	0.54
Stage 2	0.62	0.26	0.25	0.85	0.31	0.31	0.36	0.44	0.59
Stage 3	0.15	0.11	0.14	0.40	0.23	0.35	0.56	0.87	0.68
Stage 4	0.24	0.58	0.17	0.70	0.73	0.37	0.48	0.52	0.28
NHF	Supine&C1	Supine&C2	Supine&C3	Sitting&C1	Sitting&C2	Sitting&C3	C1&C2	C1&C3	C2&C3
Stage 1	0.48	0.74	0.74	0.77	0.87	0.90	0.68	0.72	0.99
Stage 2	0.69	0.64	0.60	0.55	0.67	0.66	0.92	0.90	0.99
Stage 3	0.72	0.55	0.62	0.72	0.76	0.75	0.89	0.94	0.95
Stage 4	0.58	0.44	0.71	0.69	0.54	0.63	0.84	0.45	0.37

NLF	Supine & Sitting	Supine&Sitting&C1	Supine&Sitting&C1&C2	Supine&Sitting&C1&C2&C3
Stage 1	0.69	0.93	0.26	0.35
Stage 2	0.70	0.85	0.42	0.50
Stage 3	0.38	0.27	0.24	0.36
Stage 4	0.38	0.47	0.64	0.45
NHF	Supine & Sitting	Supine&Sitting&C1	Supine&Sitting&C1&C2	Supine&Sitting&C1&C2&C3
Stage 1	0.62	0.73	0.89	0.96
Stage 2	0.28	0.60	0.82	0.92
Stage 3	0.37	0.74	0.87	0.95
Stage 4	0.87	0.84	0.86	0.83

Table 5.7 shows the P-values between HRV in different segments but in the same stage. The NLF and NHF spectra between different segments but in the same stage were compared. All P-values in the control group and the SD group are greater then 0.05. Although the NLF in the sitting and C1 segments significantly increased after thirty-six hours of sleep deprivation (Table 5.6), there was no significant difference between segments in stage 4.

5.1.4.1 Two-Factor ANOVA. Two-Factor ANOVA tests were conducted in addition to One Factor ANOVA. Table 5.8 shows the result of Two-Factor ANOVA. The numbers in the first row are the number of the stage. For example, 1&2 is stage 1 stage 2. The numbers in the segment row are the P-values between segments. Spectra in the same segment were added together and compared. In all segment tests, the degree of freedom is four.

Table 5.8 Two- Factor HRV ANOVA

(a) The Control Group

NLF	1&2	1&3	1&4	2&3	2&4	3&4	1&2&3	1&2&3&4
Segment	0.48	0.91	0.76	0.72	0.79	0.67	0.60	0.63
Stage	0.49	0.39	0.17	0.94	0.71	0.75	0.69	0.70
NHF	**1&2**	**1&3**	**1&4**	**2&3**	**2&4**	**3&4**	**1&2&3**	**1&2&3&4**
segments	0.81	0.94	0.57	0.87	0.66	0.89	0.89	0.75
Stages	0.90	0.95	0.83	0.96	0.96	0.92	0.99	1.00

(b) The SD Group

NLF	1&2	1&3	1&4	2&3	2&4	3&4	1&2&3	1&2&3&4
Segment	0.19	0.11	0.34	0.14	0.38	0.23	0.04	0.05
Stage	0.003	0.004	0.001	0.53	0.99	0.51	0.007	0.01
NHF	**1&2**	**1&3**	**1&4**	**2&3**	**2&4**	**3&4**	**1&2&3**	**1&2&3&4**
segment	0.90	0.90	0.84	0.81	0.84	0.85	0.79	0.74
Stage	0.83	0.53	0.29	0.58	0.28	0.57	0.78	0.61

Degree of Freedom = total sample number -1

4 = 5 (supine, sitting, C1, C2 and C3) - 1

The degree of freedom of stages depends on the number of compared stages. For example, the degree of freedom of 1&2 is one and the degree of freedom of 1&2&3&4 is three.

The NHF did not change significantly in the control group and the SD group. No significant NLF change was observed in the control group but there were significant NLF changes between stages in the SD group. The NLF P-values in 1&2, 1&3 and 1&4 are less then 0.05. There was a significant change in overall NLF between stages after twelve hours of SD. In addition to this significant overall NLF change between stages, in the SD group, there were significant segment changes in 1&2&3 and 1&2&3&4. This significant change was not observed in the control group.

Two-Factor ANOVA and One Factor ANOVA show that sleep deprivation can change significantly the LF area but does not affect significantly the HF area. The sleep deprivation effects are seen after twelve hours of sleep deprivation and people receive the negative effects easily in the sitting position and at the beginning of a cognitive task.

5.2 The Blood Pressure Variability (BPV)

The change of blood pressure modifies the ANS activity to decrease the change as a feedback system. It was reported that blood pressure is increased by sleep deprivation [20] so BPV is expected to be affected by SD. BPV contains different information from HRV. The LF of BPV is related purely to the sympathetic nervous system activity, rather than to a mixture of sympathetic and parasympathetic nervous system activity. The HF of BPV is also different from the HF of HRV.

5.2.1 The Blood Pressure Variability of the Control Group

The BPV were acquired in all segments and stages as the HRV. Table 5.9 shows BPV of the control group.

Table 5.9 The Blood Pressure Variability of the Control Group

	NLF					NHF				
Subject 1	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 0	239	1171	283	578	51	92	443	151	184	32
Stage 1	1132	522	831	1303	230	855	222	265	560	57
Stage 2	315	265	176	277	304	318	67	76	50	130
Stage 3	725	956	354	315	295	257	221	197	169	95
Stage 4	259	45	880	1005	3448	211	23	544	137	966
Subject 2	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 1	105	70	795	419	646	120	50	633	280	552
Stage 2	29	1235	1082	505	941	48	1755	1422	626	1207
Stage 3	3050	750	32	153	3901	3611	891	20	176	3446
Stage 4	358	414	1336	106	62	374	379	1843	119	90
Subject 3	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 0	61	86	-	-	-	69	77	-	-	-
Stage 1	191	94	1067	554	56	282	73	1404	426	85
Stage 2	510	175	351	873	325	728	122	123	388	135
Stage 3	31	222	147	47	101	14	167	70	32	42
Stage 4	114	41	116	330	334	75	48	90	163	226
Subject 4	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 0	681	2048	1173	585	150	1325	3514	2331	1248	189
Stage 1	357	935	18	124	10	705	1160	35	207	18
Stage 2	17	224	71	85	590	20	262	185	129	757
Stage 3	321	588	835	58	652	495	943	1491	103	838
Stage 4	479	185	79	259	925	754	376	126	597	1686
Subject 5	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 0	442	740	105	1132	115	562	930	97	1619	162
Stage 1	129	171	35	524	164	206	120	46	614	288
Stage 2	94	7627	971	890	215	130	10596	1625	1383	360
Stage 3	75	26	603	340	695	111	19	831	452	1069
Stage 4	255	1022	451	1375	177	450	1241	774	2288	336

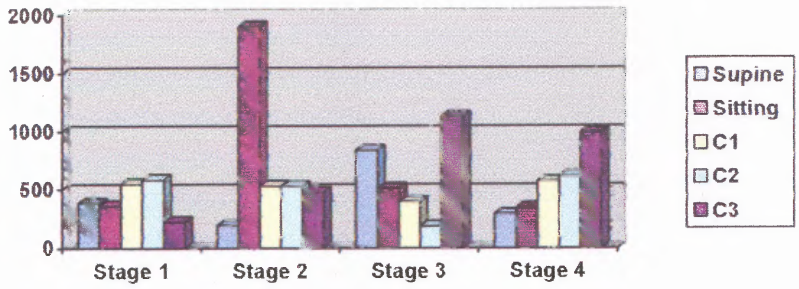
Five control subject's BPV spectra diagrams are in Appendix E. In all control subjects, the NNLF was increased and the NNHF was decreased due to the position change from supine to sitting. The NLF/NHF ratio was also increased due to the position change from supine to sitting except in subject 4. During the cognitive task, the NLF/NHF ratio of the BPV increased in the C2 segment and decreased in the C3 segment like the NLF/NHF ratio of the HRV.

Table 5.11 The Mean BPV of the Control Group

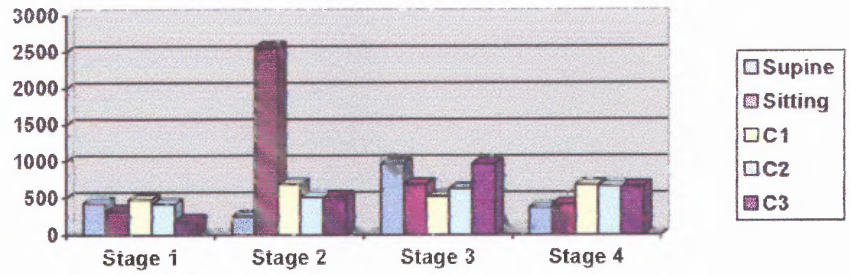
Mean NLF	Stage 1	Stage 2	Stage 3	Stage 4
Supine	383	193	840	291
Sitting	358	1905	508	341
C1	549	530	394	572
C2	585	526	183	615
C3	221	475	1129	989
Mean NHF	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
Supine	434	249	965	373
Sitting	325	2560	684	413
C1	477	686	521	675
C2	417	515	625	661
C3	200	518	970	661
NLF/NHF Ratio	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
Supine	0.88	0.78	0.87	0.78
Sitting	1.10	0.74	0.74	0.83
C1	1.15	0.77	0.76	0.85
C2	1.40	1.02	0.29	0.93
C3	1.11	0.92	1.16	1.50

Each subject's BPV in the same segment and stage was added and divided by the total group number. Table 5.11 shows the mean BPV of the control group. Data in stage 0 was not considered in this mean value analysis.

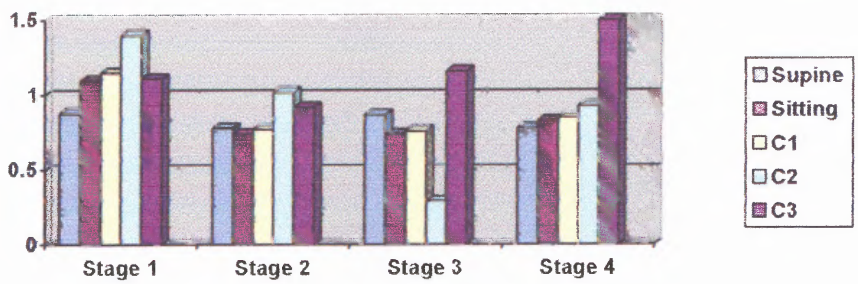
Figure 5.3 (a) shows the mean NLF of BPV and Figure 5.3 (b) shows the mean NHF of BPV diagrammatically. When subjects changed their positions, from supine to sitting, the mean NLF increased in all stages except in stage 3. Figure 5.3 (c) shows the MNLF/MNHF ratio of the control group. During the cognitive task, in stage 1 and stage 2, the MNLF/MNHF ratio increased in the C2 segment and decreased in the C3 segment. In stage 3 and stage 4, the MNLF/MNHF ratio increased in the C3 segment. Participating in a test can cause an increase of stress level. The MNLF/MNHF ratio increase in the C3 segment is possibly due to the increased stress level.



(a) The mean NLF (MNLF)



(b) The mean NHF (MNHF)



(c) The mean NLF/mean NHF ratio (MNLF/MNHF)

Figure 5.3 The mean BPV of the control group.

5.2.2 The Blood Pressure Variability of the SD Group

Table 5.10 shows the BPV of the SD group.

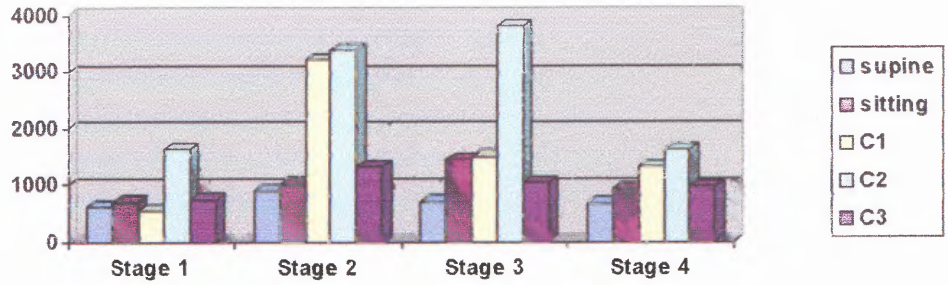
Table 5.10 The Blood Pressure Variability of the SD Group

	NLF					NHF				
Subject 1	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 1	128	79	134	354	1110	138	53	150	399	957
Stage 2	33	188	123	1672	2584	49	204	29	1046	2309
Stage 3	574	2090	740	422	931	662	1260	210	111	364
Stage 4	142	490	194	1243	172	57	269	45	1171	167
Subject 2	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 1	910	3509	962	3648	276	1748	5897	1811	6164	291
Stage 2	2252	699	17128	6058	2189	1742	1019	22371	9442	2973
Stage 3	1615	5732	2106	334	282	1553	9682	2980	434	374
Stage 4	230	1909	991	188	1294	220	2707	528	92	528
Subject 3	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 1	218	216	228	8552	283	175	200	282	10726	523
Stage 2	721	699	328	294	1029	705	1071	421	441	1704
Stage 3	165	687	537	972	998	147	879	587	805	766
Stage 4	1814	621	1408	271	1372	2156	1023	951	394	1897
Subject 4	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 1	2419	48	942	1786	1415	2496	28	1448	976	671
Stage 2	3186	312	3227	3048	3145	3350	356	2313	1712	1255
Stage 3	1523	1357	1904	2040	3299	852	1357	1464	910	2843
Stage 4	1329	1266	3401	8788	2408	981	867	1669	6936	1758
Subject 5	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 1	343	1564	882	1097	284	206	1329	1369	454	139
Stage 2	238	889	672	1012	445	197	345	414	458	225
Stage 3	292	856	3146	1369	1110	293	645	1645	801	616
Stage 4	688	1975	1279	1871	1616	317	848	361	1039	1044
Subject 6	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 1	341	188	456	207	228	147	78	266	152	210
Stage 2	520	1005	331	184	1767	452	386	237	123	642
Stage 3	694	1895	476	2798	1891	368	1371	386	2007	613
Stage 4	767	3165	1236	3780	1735	722	712	662	2172	1134
Subject 7	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 1	127	234	82	78	55	234	290	110	52	38
Stage 2	299	2227	1530	2373	281	326	661	823	1059	277
Stage 3	562	397	6721	814	819	556	105	7917	553	530
Stage 4	445	158	2121	771	116	158	66	1427	368	99
Subject 8	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 1	143	807	23	207	303	89	744	17	50	110
Stage 2	398	494	435	436	409	541	301	211	135	124
Stage 3	100	62	668	308	112	84	21	476	112	16
Stage 4	28	239	152	404	946	31	201	92	302	750
Subject 9	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 1	1218	192	1056	672	1318	2031	329	993	669	780
Stage 2	586	409	1090	1003	1096	175	83	485	988	897
Stage 3	443	594	596	1571	1325	451	543	229	818	676
Stage 4	256	434	1284	522	739	159	307	706	236	292
Subject 10	**Supine**	**Sitting**	**C1**	**C2**	**C3**	**Supine**	**Sitting**	**C1**	**C2**	**C3**
Stage 1	167	162	925	240	2068	163	153	1129	255	2328
Stage 2	757	1311	5937	18727	728	624	1150	2811	12338	431
Stage 3	1096	1686	282	28274	452	980	1127	288	22941	212
Stage 4	820	1032	2351	402	950	1045	1384	2254	591	776

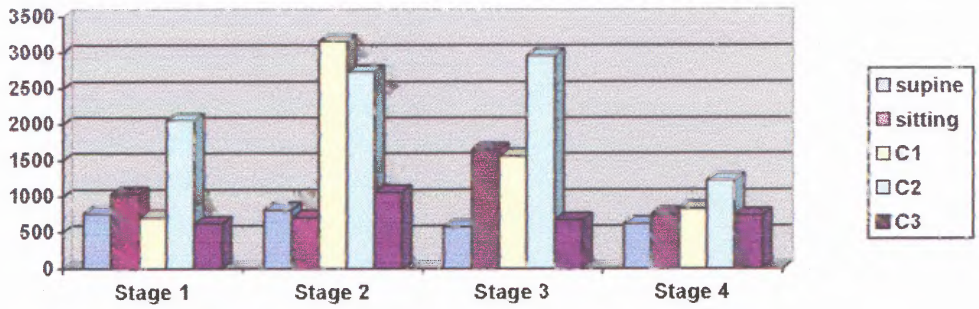
Table 5.12 The Mean BPV of the SD Group

NLF	Stage 1	Stage 2	Stage 3	Stage 4
Supine	608	897	694	662
Sitting	696	1020	1457	931
C1	546	3217	1507	1314
C2	1641	3380	3815	1637
C3	735	1323	1043	973
NHF	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
Supine	767	816	581	622
Sitting	1032	708	1643	754
C1	709	3158	1561	833
C2	2052	2728	2956	1226
C3	624	1061	680	740
NLF/ NHF Ratio	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
Supine	0.79	1.10	1.19	1.06
Sitting	0.67	1.44	0.89	1.24
C1	0.77	1.02	0.97	1.58
C2	0.80	1.24	1.29	1.34
C3	1.18	1.25	1.53	1.32

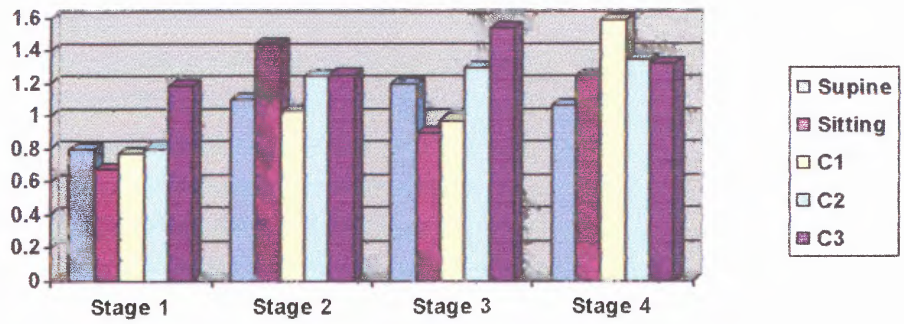
Individual SD subject's BPV spectra diagrams are shown in Appendix F. In many subjects, the NLF/NHF ratio increased in the C1 segment of stage 4. Figure 5.4 (a) shows diagrammatically the mean NLF and Figure 5.4 (b) shows the mean NHF. When subjects changed their positions, from supine to sitting, the mean NLF values increased in all stages. The mean NLF and NHF show a similar response during the cognitive tasks. The MNLF and MNHF increased in the C2 segment and decreased in the C3 segment. The mean NLF and the mean NHF increased over three times in the C1 segment of stage 2 compared to the previous sitting segment in the same stage. Figure 5.4 (c) shows the MNLF/MNHF ratio diagram of BPV. Although there were great increases in the C1 segment of stage 2, the MNLF/MNHF ratio decreased in the C1 segment of stage 2. The MNLF/MNHF ratio increased in the C1 segment of stage 4 like the MNLF/MNHF ratio of HRV.



(a) The mean NLF (MNLF)



(b) The mean NHF (MNHF)



(c) The mean NLF/mean NHF ratio (MNLF/MNHF)

Figure 5.4 The mean BPV of the SD group.

5.2.3 BPV Analysis of Variance (ANOVA)

5.2.3.1 One Factor ANOVA of BPV. Table 5.13 shows the NLF P-values of the control group (a) and the SD group (b). Like the HRV One Factor ANOVA test (Table 5.5), numbers in the first row represent the stage number. Spectra in the same segment but in different stages were compared. For example, the number in the second column and the second row is the P-value of the supine segments in stage 1 and stage 2. Because the P-value in supine 1&2 is 0.40, there was no significant difference in the supine position after twelve hours of SD.

All P-values in Table 5.13(a) are greater then the chosen significance level. No significant change occurred due to SD between same segment NLF spectra in different stages. All P-values in table 5.13 (b) are also greater then 0.05 except the C1 P-value in 1&4. The BPV P-value of the C1 segment in 1&4 is less then 0.05 so the LF area changed significantly when subjects started the cognitive task after thirty-six hours of sleep deprivation. The MNLF and MNLF/MNHF ratio (Figure 5.4) increased so sleep deprivation increased the LF area at the beginning of the cognitive task. This result suggests that mental stress can be increased by sleep deprivation and people can experience difficulties at the beginning of a cognitive task. Unlike the result of the HRV ANOVA, P-value of the sitting segment in 1&4 is not less then 0.05 so there was no significant NLF change of BPV in the sitting segment.

Table 5.13 One Factor ANOVA of the NLF (BPV)

	1&2	1&3	1&4	2&3	2&4	3&4	1&2&3	1&2&3&4
Supine	0.40	0.47	0.67	0.29	0.40	0.36	0.43	0.47
Sitting	0.32	0.55	0.95	0.36	0.31	0.52	0.39	0.40
C1	0.95	0.57	0.94	0.61	0.90	0.54	0.83	0.93
C2	0.82	0.08	0.93	0.08	0.77	0.13	0.16	0.32
C3	0.18	0.24	0.27	0.39	0.45	0.89	0.32	0.52

(a) The Control Group

	1&2	1&3	1&4	2&3	2&4	3&4	1&2&3	1&2&3&4
Supine	0.46	0.72	0.87	0.60	0.51	0.83	0.69	0.82
Sitting	0.76	0.19	0.36	0.21	0.41	0.50	0.25	0.37
C1	0.15	0.09	**0.02**	0.45	0.35	0.70	0.24	0.28
C2	0.37	0.45	0.91	0.90	0.41	0.48	0.70	0.74
C3	0.12	0.30	0.21	0.58	0.56	0.97	0.29	0.42

(b) The SD Group

Table 5.14 shows the result of One Factor NHF ANOVA. All P-values in the control group (a) and SD group (b) were greater then 0.05 so there was no significant change in the NHF of BPV.

Table 5.14 One Factor ANOVA of the NHF (BPV)

	1&2	1&3	1&4	2&3	2&4	3&4	1&2&3	1&2&3&4
Supine	0.37	0.53	0.75	0.38	0.50	0.47	0.53	0.61
Sitting	0.31	0.68	0.78	0.33	0.32	0.91	0.36	0.38
C1	0.64	0.91	0.64	0.72	0.98	0.73	0.87	0.94
C2	0.71	0.06	0.58	0.22	0.77	0.29	0.32	0.59
C3	0.20	0.19	0.18	0.40	0.70	0.54	0.28	0.39

(a) The Control Group

	1&2	1&3	1&4	2&3	2&4	3&4	1&2&3	1&2&3&4
Supine	0.87	0.66	0.67	0.53	0.55	0.97	0.84	0.89
Sitting	0.55	0.47	0.91	0.23	0.32	0.37	0.42	0.51
C1	0.32	0.29	0.72	0.55	0.34	0.35	0.49	0.50
C2	0.67	0.71	0.62	0.95	0.36	0.49	0.91	0.85
C3	0.22	0.77	0.42	0.35	0.52	0.66	0.40	0.55

(b) The SD Group

5.2.3.2 Two-Factor ANOVA Of BPV. Two-Factor BPV ANOVA was conducted as stated in Chapter 4.

Table 5.15 Two-Factor ANOVA of BPV

(a) The Control Group

NLF	1&2	1&3	1&4	2&3	2&4	3&4	1&2&3	1&2&3&4
Segments	0.44	0.88	0.73	0.55	0.56	0.40	0.69	0.74
Stages	0.32	0.35	0.40	0.74	0.62	0.84	0.57	0.73
NHF	1&2	1&3	1&4	2&3	2&4	3&4	1&2&3	1&2&3&4
segments	0.45	0.77	0.89	0.58	0.52	0.74	0.63	0.73
Stages	0.22	0.23	0.23	0.55	0.43	0.76	0.38	0.48

(b) The SD Group

NLF	1&2	1&3	1&4	2&3	2&4	3&4	1&2&3	1&2&3&4
Segments	0.14	0.2	0.13	0.11	0.12	0.22	0.05	0.02
Stages	0.05	0.12	0.17	0.86	0.2	0.36	0.19	0.21
NHF	1&2	1&3	1&4	2&3	2&4	3&4	1&2&3	1&2&3&4
segments	0.26	0.12	0.07	0.25	0.31	0.4	0.26	0.25
Stages	0.27	0.56	0.45	0.85	0.17	0.25	0.37	0.73

Table 5.15 shows the P-values from the Two-Factor ANOVA. There was no significant change in the control group (a) but there were in the SD group (b). There was a significant change between stage 1 and stage 2. Unlike the HRV, there was no significant change in 1&3 and 1&4. The NLF P-values in 1&2&3 and 1&2&3&4 are greater then 0.05 like the NLF P-values of SD HRV.

The ANOVA results of BPV were similar to that of HRV except in the sitting segment of stage 4 and no significant stage P-values in 1&3 and 1&4.

CHAPTER 6

CONCLUSION AND SUGGESTIONS FOR FUTURE RESEARCH

A summary of the results of this research and recommendations for future work will be the focus of this chapter.

6.1 Summary of Results

Using power spectrum analysis of HRV and BPV, we investigated the sleep deprivation effects on the autonomic nervous system. For the significance tests, One Factor ANOVA and Two-Factor ANOVA were conducted.

In the control group study, no significant change was observed in both NLF and NHF. The individual spectra diagrams and the mean value study also did not show a significant change.

In the SD group study of HRV, the LF area increased significantly in the sitting position and at the beginning of a cognitive task after thirty-six hours of SD. In Two-Factor ANOVA tests, there were overall LF significant changes between stages after twelve hours of SD.

There was no significant HF change in the control group and the SD group but significant LF increases were observed in the SD group. Sleep deprivation increased the LF area and subjects could experience the negative effects due to sleep deprivation after twelve hours of sleep deprivation. As the amount of sleep deprivation was increased (from stage 1 to stage 4), more significant changes in the LF area were observed. A significant NLF/NHF ratio increase was observed only in the sitting position not in the supine position.

This suggests that people can receive negative effects easier in the sitting position then in the supine position.

It has been believed that the blood pressure variability (BPV) contains different information from the heart rate variability (HRV) and sleep deprivation may have effects on the BPV. In addition to the HRV, the BPV was studied for the sleep deprivation effects on the autonomic nervous system activity. No significant change was observed in the control group. No significant HF change was observed in the SD group but the LF area increased significantly in the C1 segment after thirty-six hours of SD. No significant LF change was observed in the sitting segment of stage 4. The Two-Factor ANOVA tests show overall NLF significant change between stage 1 and stage 2 but this significant change was observed only between stage 1 and stage 2, unlike Two-Factor HRV ANOVA. In Two-Factor HRV ANOVA, overall NLF significant change was also observed between stage 1 and two other stages, stage 3 and stage 4.

In conclusion, the low frequency (LF) area increased due to sleep deprivation. Significant change in the LF area was observed in both HRV and BPV. The increased LF area reflects an increased stress level and decreased ability to perform a cognitive task. Subjects experienced the negative effects due to sleep deprivation after thirty-six hours of sleep deprivation. Sleep deprivation can cause a stress level increase during a cognitive task especially within ten minutes of cognitive task. The stress level could be different according to the position. People can experience negative effects more easily in the sitting position then in the supine position. The Two-Factor ANOVA test suggests that people can receive negative effects earlier then expected from One Factor ANOVA. The significant

LF change occurred after thirty-six hours in One Factor ANOVA but the significant overall LF change was observed after twelve hours of SD in Two-Factor ANOVA.

6.2. Suggestions for Future Work

It was observed that sleep deprivation affects the autonomic nervous system and increases the sympathetic nervous system activity. The long-term implications of this increase in SNS activity remain unclear. A question that remains unanswered is whether these changes may be corrected by a period of sleep immediately following the deprivation. Further, a study of the optimal duration of sleep following the deprivation would yield greater insights into recovery patterns of the ANS. For a deeper study of sleep deprivation effects on the autonomic nervous system, recovery studies are suggested.

Sleep deprivation effects will be different according to subject's conditions such as different ages, life styles and health conditions. The significantly increased LF area could be serious to some people and could be slight to some people. All our subjects were healthy and young (around thirty years old). This study could be used as control data for the sleep deprivation study which has differently conditioned subjects.

APPENDIX A

POWER SPECTRUM. VI

This program was written in LABVIEW. Filtered ECG and blood pressure signals flow into each CORRECT.VI block and CORRECTBP.VI block. From the CORRECT.VI block, the heart rate IBI file is acquired and displayed on the heart rate control panel. From the CORRECTBP.VI block, the blood pressure IIBI file is acquired and displayed on the BP IIBI control panel. The interpolated BP IBI file and the heart rate IBI file goes into the SPECTRUM.VI block, where the heart rate data is interpolated and spectra of BP and HRV are calculated.

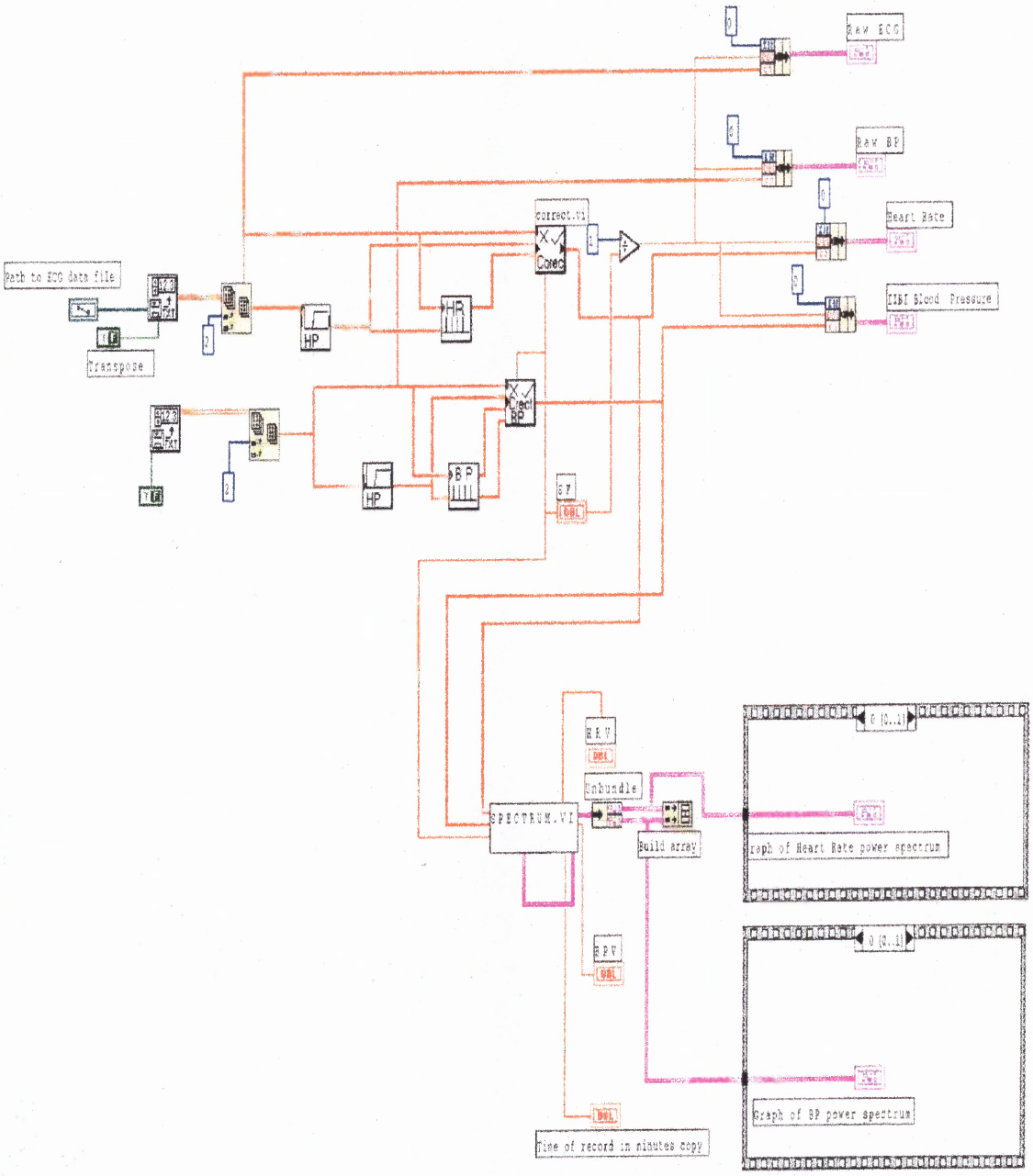


Figure A.1 Power spectrum. Vi (All R peaks were detected using the CORRECT.VI. Missed R peaks or wrongly detected R peaks were corrected manually. Heart rate IBI data were acquired through this procedure and the IBI data flowed into the SPECTRUM.VI block to acquire IIBI data).

APPENDIX B

SPECTRUM.VI

The BP IIBI and the heart rate IBI data flow into this block. The heart rate IBI file is interpolated from this program block. Spectra of BPV and HRV are acquired using each IIBI data and values of BPV and HRV are calculated.

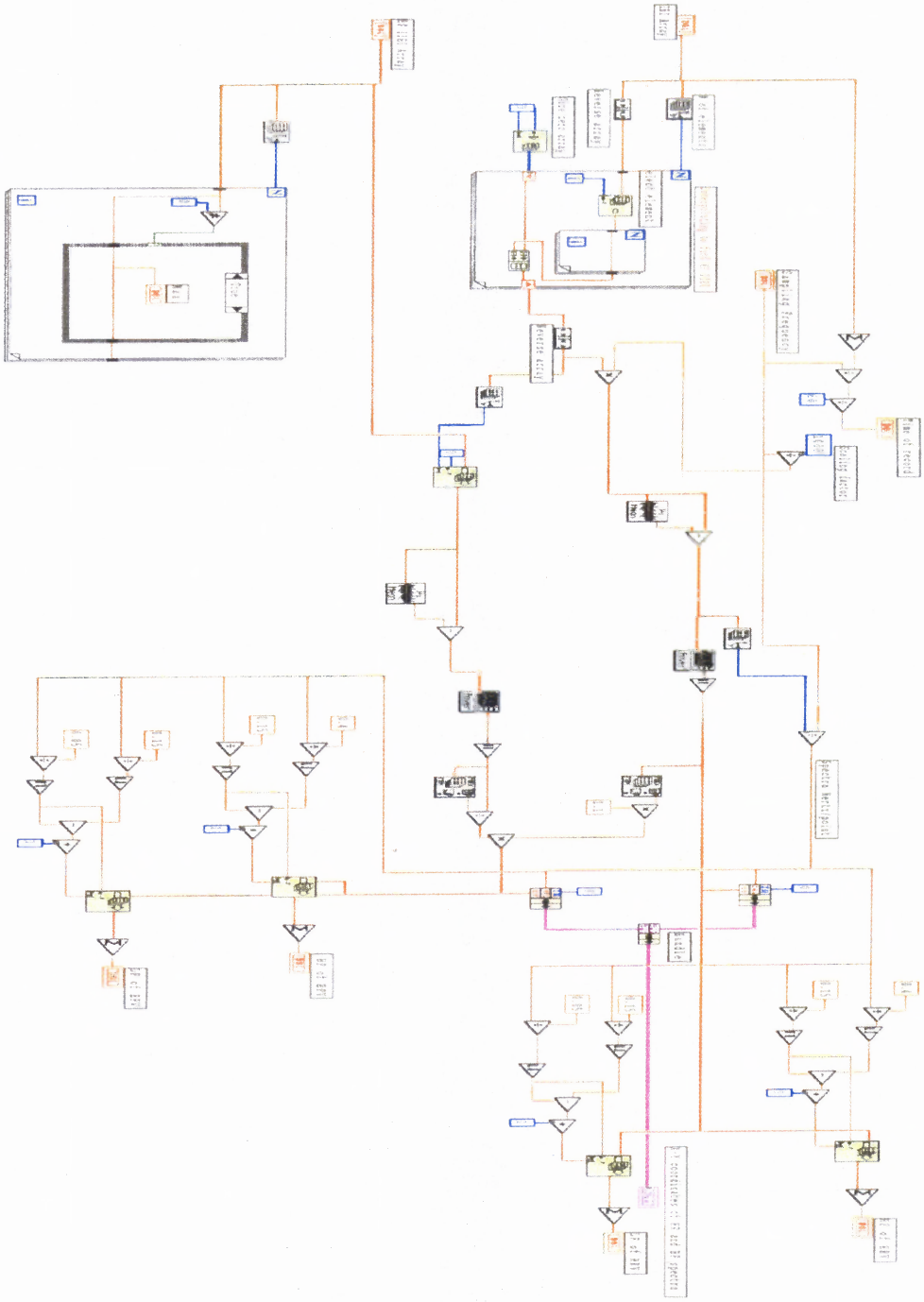
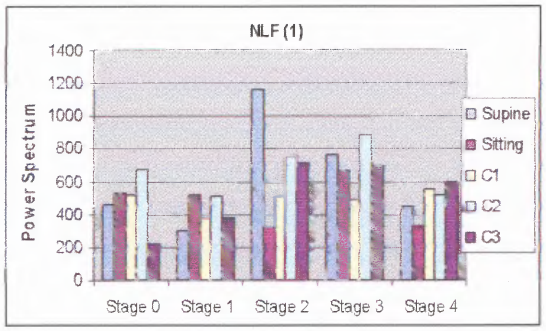


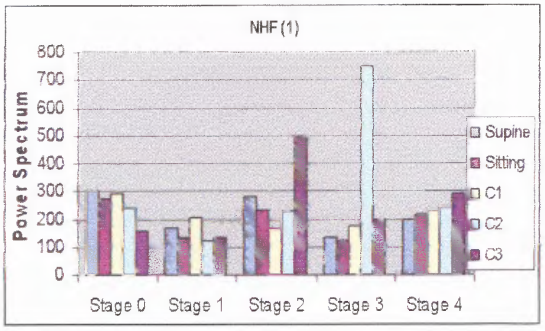
Figure B.1 Spectrum.vi (IBI data was interpolated through this procedure and power spectrum areas were calculated).

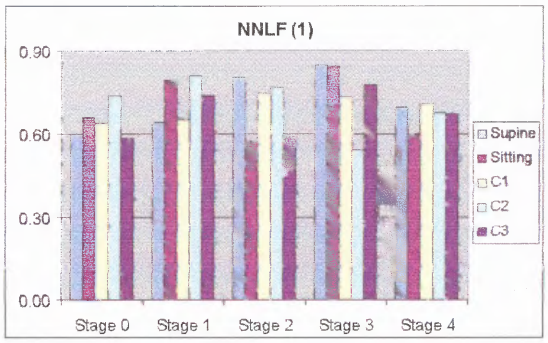
APPENDIX C

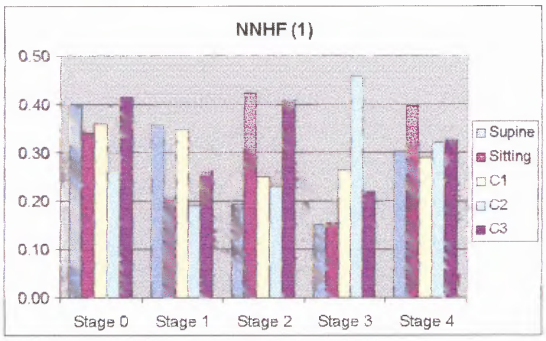
HRV SPECTRA DIAGRAMS OF THE CONTROL GROUP

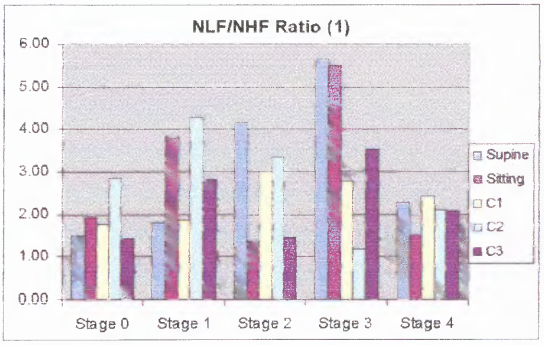
The following figures are HRV spectra diagrams of the control group. There were five subjects in the control group and each subject's HRV spectra diagrams are shown from Figure C.1 to Figure C.5. Each Figure has five diagrams, which show the NLF, the NHF, the NNLF, the NNHF and the NLF/NHF ratio.









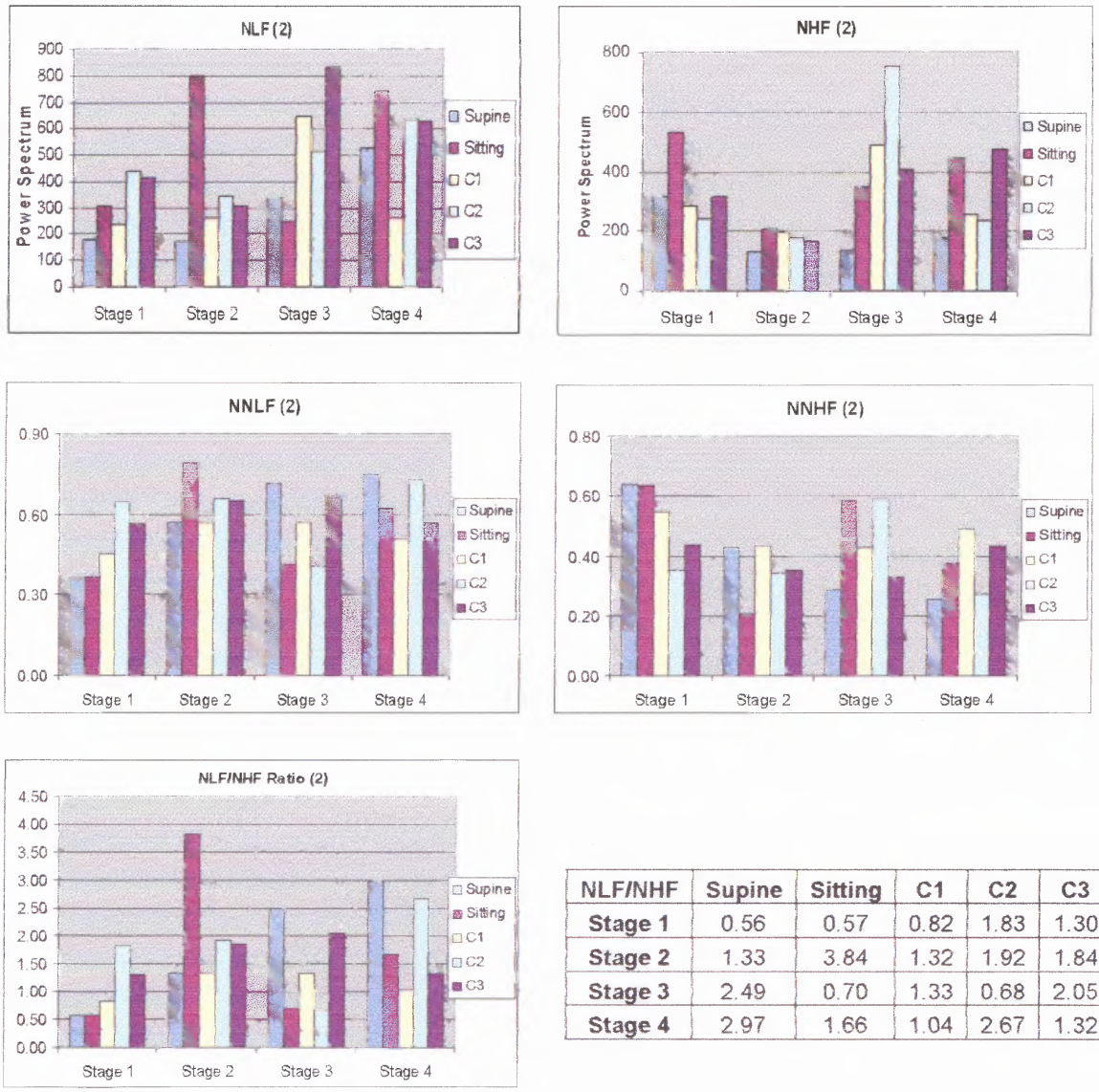


NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 0	1.50	1.94	1.78	2.86	1.41
Stage 1	1.81	3.83	1.88	4.27	2.82
Stage 2	4.15	1.36	2.99	3.35	1.45
Stage 3	5.64	5.48	2.79	1.18	3.54
Stage 4	2.30	1.52	2.45	2.11	2.07

Figure C.1 HRV spectra diagram of subject 1.

Figure C.1 show HRV spectra diagrams of subject 1. While supine, the NLF of subject 1 increased in the morning (stage 0 and stage 2) and decreased at night (stage 1 and stage 3). Although the supine NLF shows a circadian rhythm, the supine NLF/NHF ratio shows a continuous increase until stage 3. The supine NNHF shows a decreasing trend from stage 0 to stage 3 and the supine NNLF shows an increasing trend from stage 0 to stage 3.

Although the NLF/NHF ratio was increased by the position change on the first test day (stage 0 and stage 1), the ratio was decreased by the position change in other stages. During the cognitive task, the NLF/NHF ratio increased in the C2 segment and decreased in the C3 segments except stage 3 and stage 4.



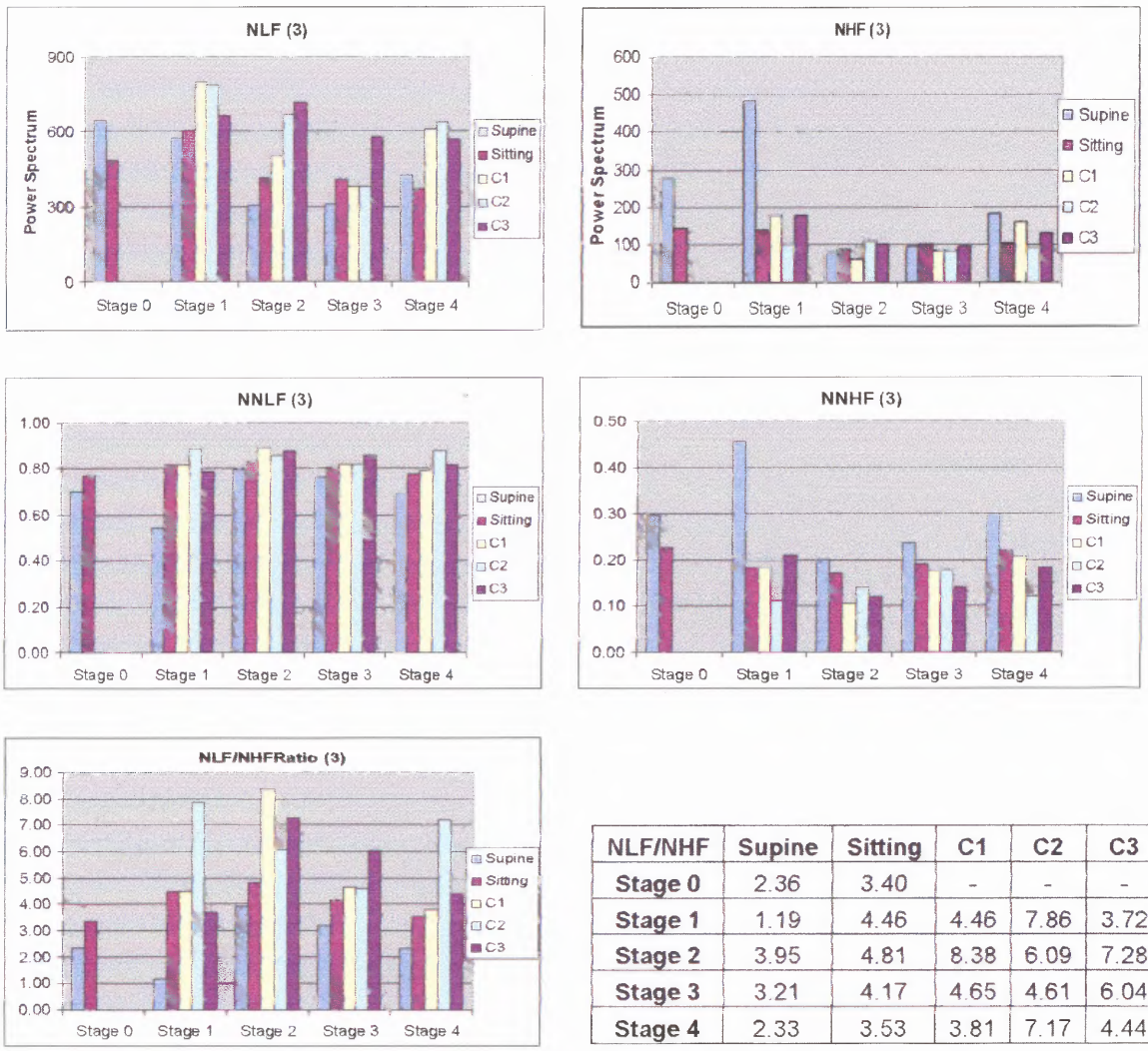
NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 1	0.56	0.57	0.82	1.83	1.30
Stage 2	1.33	3.84	1.32	1.92	1.84
Stage 3	2.49	0.70	1.33	0.68	2.05
Stage 4	2.97	1.66	1.04	2.67	1.32

Figure C.2 HRV spectra diagrams of subject 2.

Figure C.2 show HRV spectra diagrams of subject 2. We did not observe a circadian rhythm in the supine position but a circadian rhythm in the sitting position was observed. In the sitting position, the NLF, the NNLF and the NLF/NHF ratio increased in the morning and decreased at night. During the cognitive task, the NLF/NHF ratio shows the following except in stage 3.

C1 segment to C2 segment: The ratio increases.

C2 segment to C3 segment: The ratio decreases.

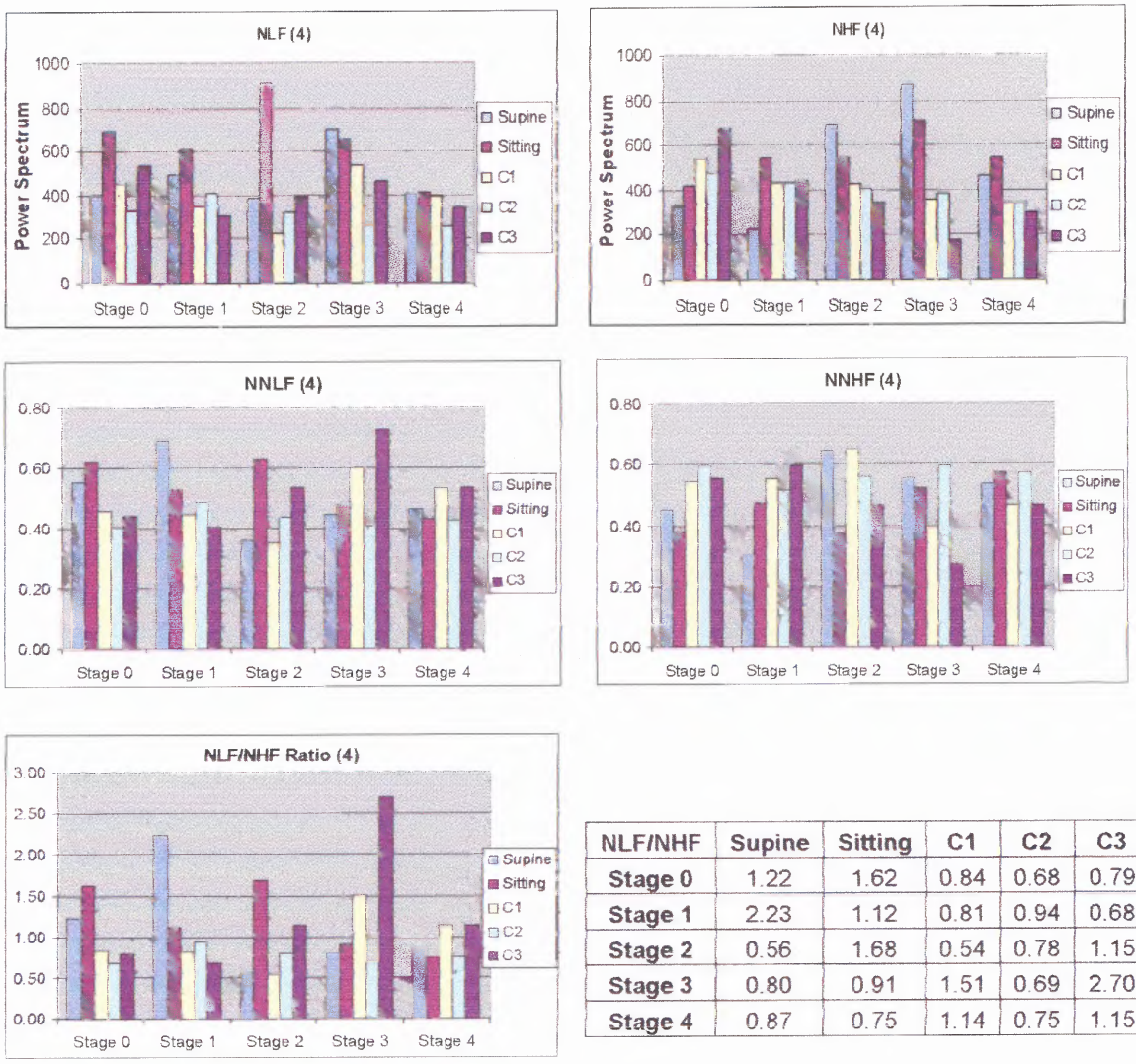


NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 0	2.36	3.40	-	-	-
Stage 1	1.19	4.46	4.46	7.86	3.72
Stage 2	3.95	4.81	8.38	6.09	7.28
Stage 3	3.21	4.17	4.65	4.61	6.04
Stage 4	2.33	3.53	3.81	7.17	4.44

Figure C.3 HRV spectra diagrams of subject 3.

Figure C.3 show HRV spectra diagrams of subject 3. In the supine segment, the NNLF and the NLF/NHF ratio increased in the morning and decreased at night but the NLF does not show this trend. In the sitting segment, the NLF/NHF ratio does not show a circadian rhythm and the NLF/NHF ratio shows an increase trend by position change from supine to sitting in all stages.

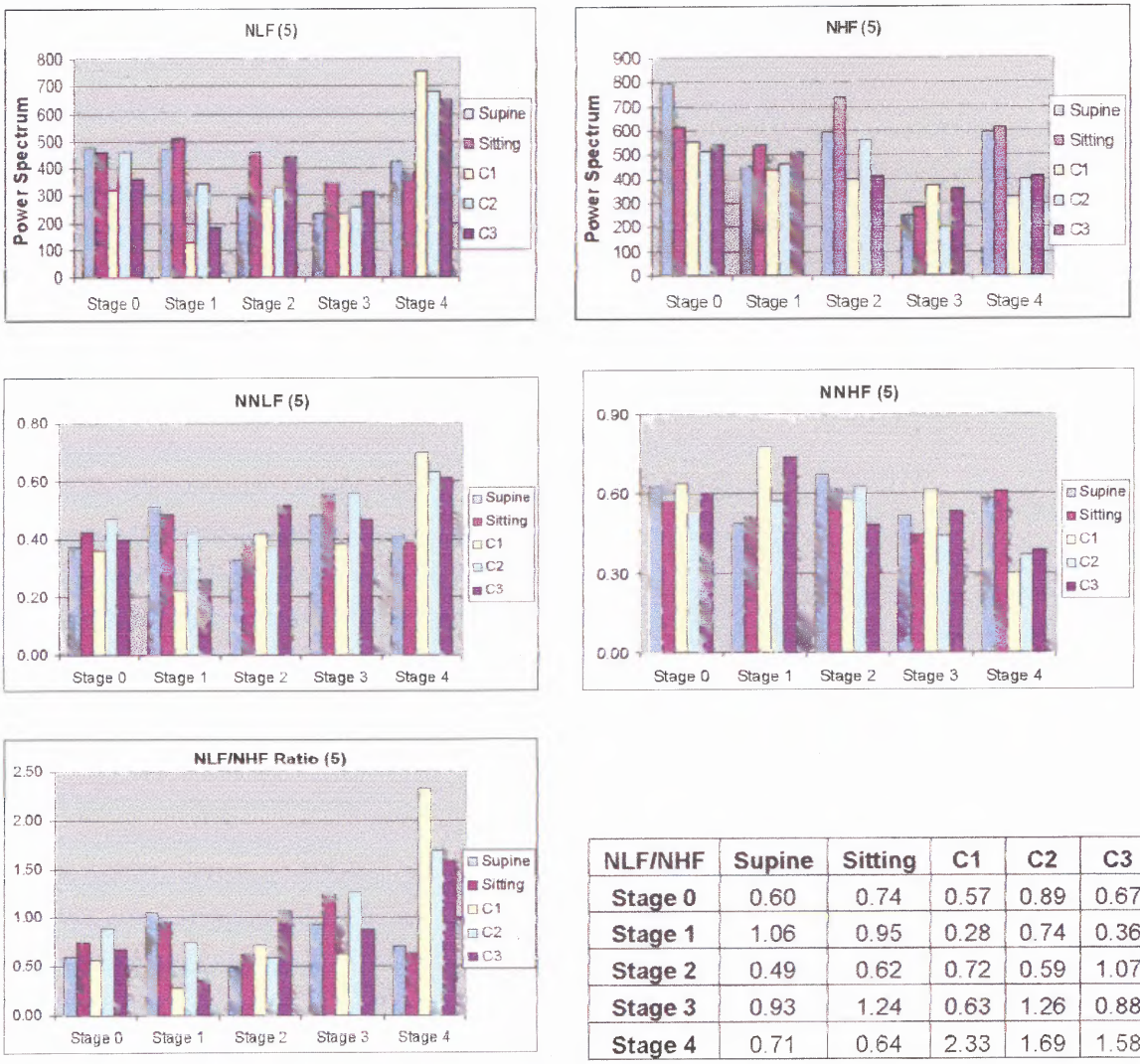
During the cognitive task, the NLF/NHF ratio increased in the C2 segment and decreased in the C3 segment in only stage 1 and stage 4. In stage 2 and stage 3, the ratio shows an increase in the C1 segment, a decrease in the C2 segments and then an increase in the C3 segment.



NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 0	1.22	1.62	0.84	0.68	0.79
Stage 1	2.23	1.12	0.81	0.94	0.68
Stage 2	0.56	1.68	0.54	0.78	1.15
Stage 3	0.80	0.91	1.51	0.69	2.70
Stage 4	0.87	0.75	1.14	0.75	1.15

Figure C.4 HRV spectra diagrams of subject 4.

Figure C.4 show HRV spectra diagrams of subject 4. The NLF/NHF ratio in the sitting segments shows a circadian rhythm but the ratio in the supine segments show an opposite trend to a circadian rhythm. During the cognitive task, the ratio increased in the C2 segment and decreased in the C3 segment only in stage 1. In other stages, the ratio shows an increasing trend in the C3 segment.



NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 0	0.60	0.74	0.57	0.89	0.67
Stage 1	1.06	0.95	0.28	0.74	0.36
Stage 2	0.49	0.62	0.72	0.59	1.07
Stage 3	0.93	1.24	0.63	1.26	0.88
Stage 4	0.71	0.64	2.33	1.69	1.58

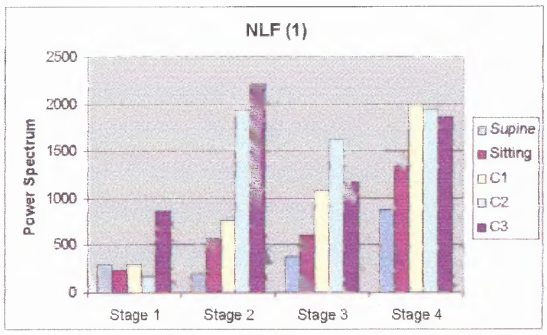
Figure C.5 HRV spectra diagrams of subject 5.

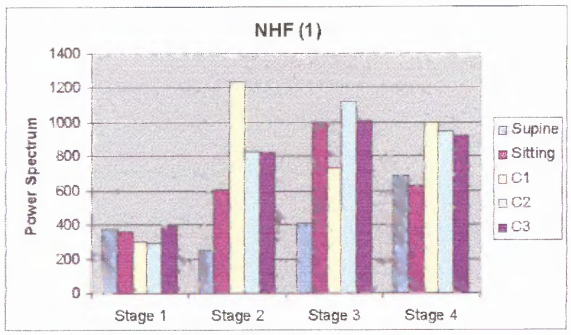
Figure C.5 shows HRV spectra diagrams of subject 5. In supine and sitting, the NLF/NHF ratio increased at night and decreased in the morning. During the cognitive task, the NLF/NHF ratio increased in the C2 segment and decreased in the C3 segment in stage 0, stage 1 and stage 3. In stage 4, the overall NNLF increased but the overall NNHF decreased during cognitive task. The NLF/NHF ratio in the C1 segment of stage 4 was over three times greater compared to the NLF/NHF ratio in the C1 segment of previous stages, from stage 0 to stage 3.

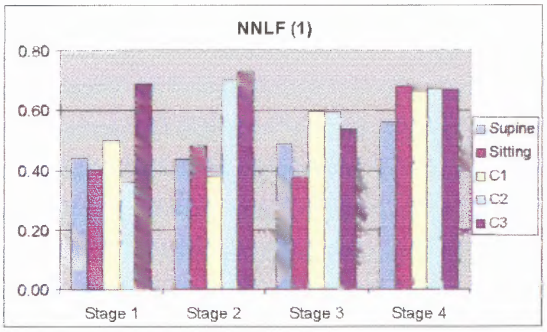
APPENDIX D

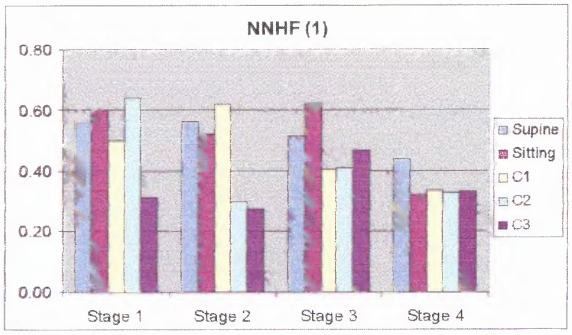
HRV SPECTRA DIAGRAMS OF THE SD GROUP

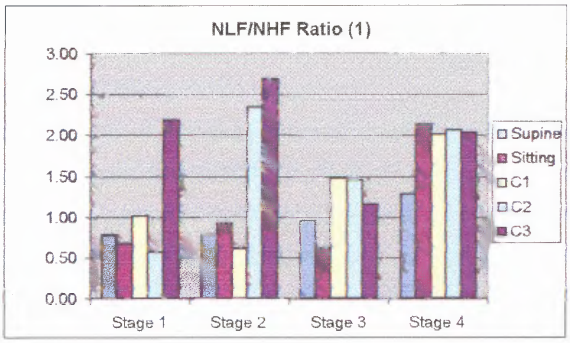
The followings figures are HRV spectra diagrams of the SD group. There were ten subjects in the SD group and each subject's HRV spectra diagrams are shown from Figure D.1 to Figure D.10. Each Figure has five diagrams, which show the NLF, the NHF, the NNLF, the NNHF and the NLF/NHF ratio.







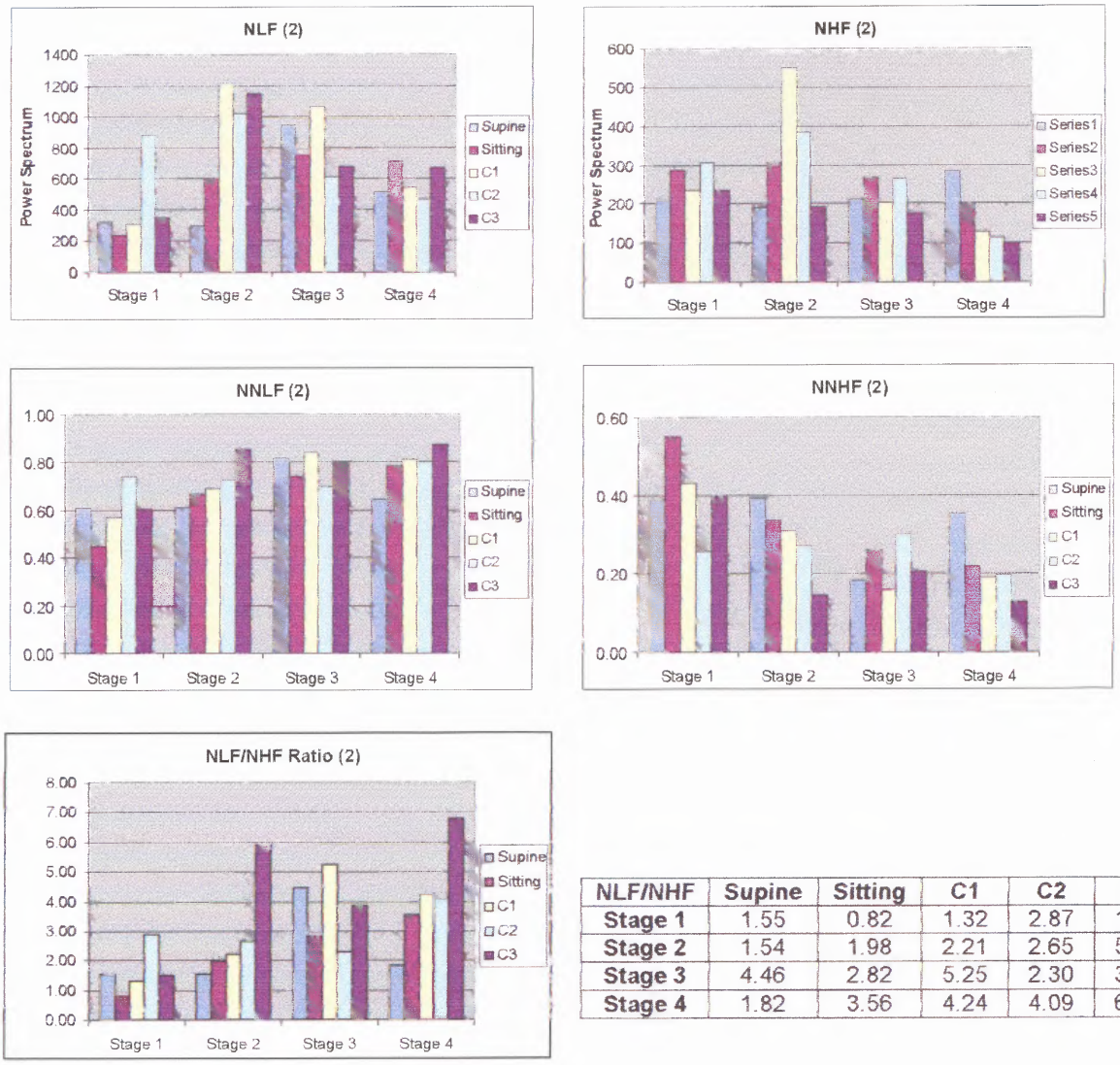




NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 1	0.78	0.67	1.01	0.56	2.19
Stage 2	0.78	0.92	0.62	2.34	2.69
Stage 3	0.95	0.61	1.47	1.45	1.16
Stage 4	1.28	2.13	2.00	2.06	2.03

Figure D.1 HRV spectra diagrams of SD subject 1.

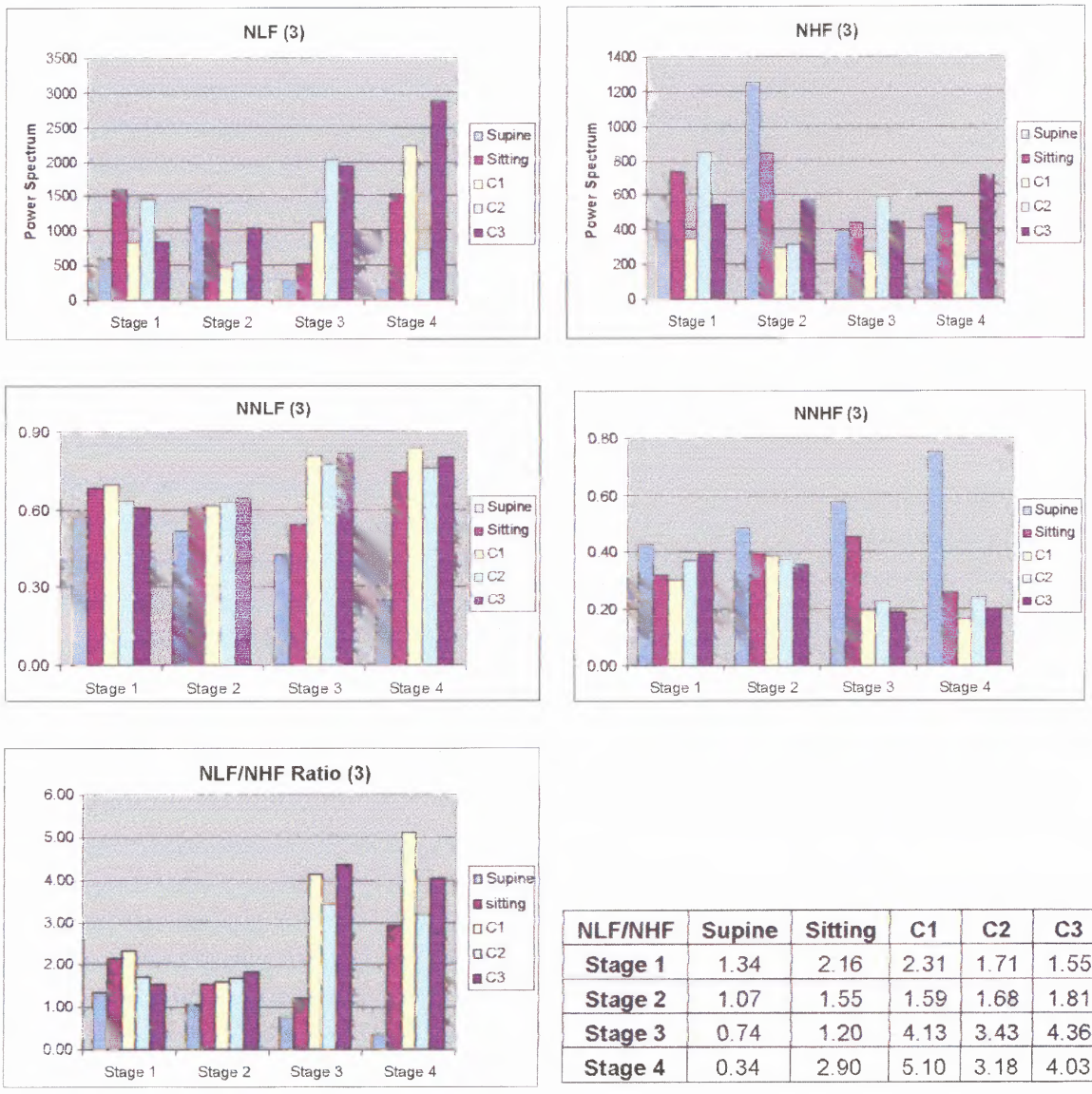
Figure D.1 shows HRV spectra diagrams of SD subject 1. Although the NLF/NHF ratio increased continuously from stage 1 to stage 4 while supine, the ratio while sitting shows a circadian rhythm. During the cognitive task, the range of the NLF/NHF ratio change decreased in stage 3 and stage 4.



NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 1	1.55	0.82	1.32	2.87	1.51
Stage 2	1.54	1.98	2.21	2.65	5.92
Stage 3	4.46	2.82	5.25	2.30	3.88
Stage 4	1.82	3.56	4.24	4.09	6.77

Figure D.2 HRV spectra diagrams of SD subject 2.

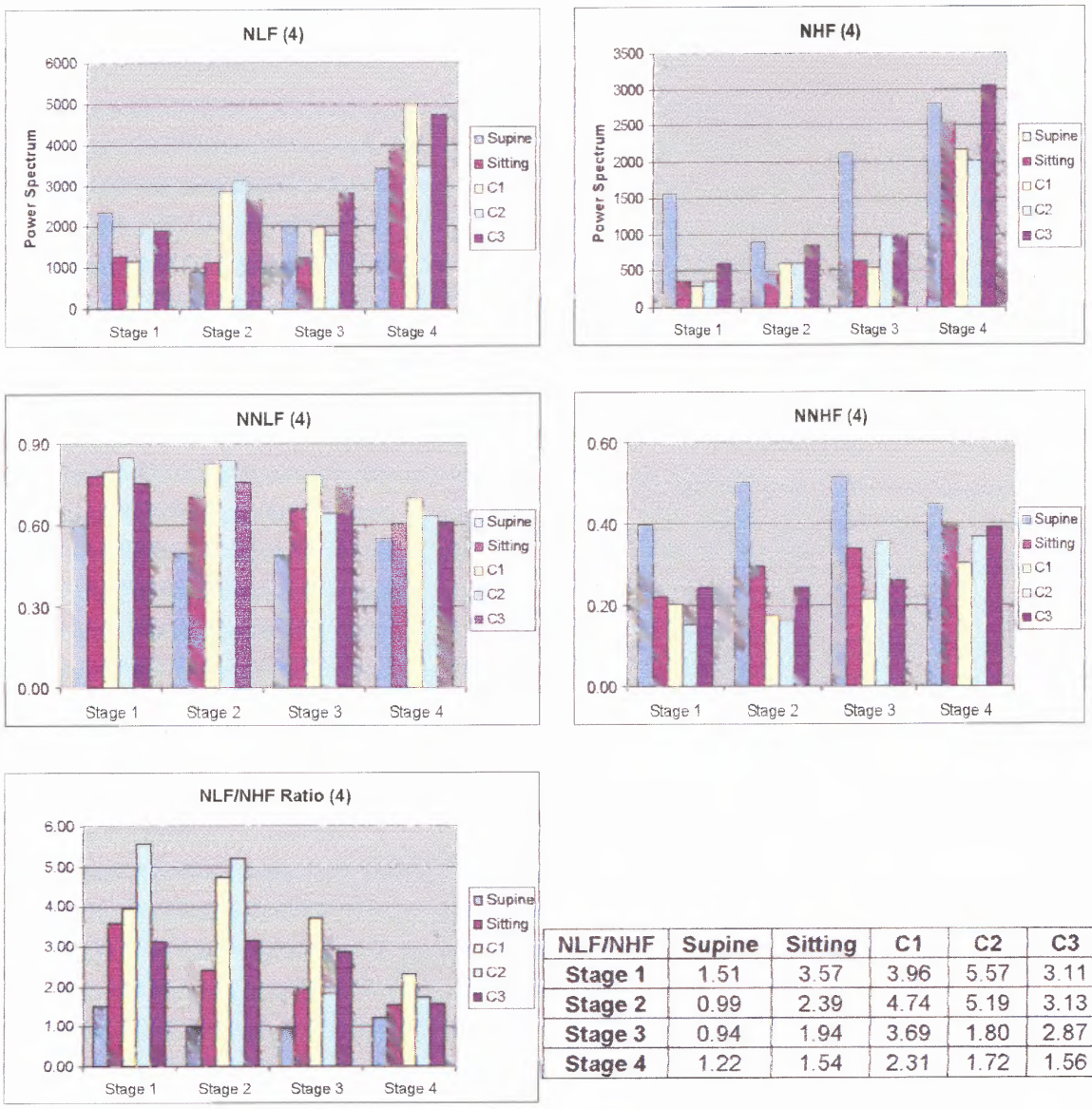
Figure D.2 shows HRV spectra diagrams of SD subject 2. The overall NLF/NHF ratio shows a continuous increase from stage 1 to stage 4. The NLF/NHF ratio during the cognitive task in stage 3 was greater then the cognitive NLF/NHF ratio in stage 1 and the cognitive NLF/NHF ratio in stage 4 was greater then the cognitive NLF/NHF ratio in stage 2. In only stage 1, the NLF/NHF ratio increased in the C2 segment and decreased in the C3 segment. In other segments, the ratio showed an increased trend in the C1 segment



NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 1	1.34	2.16	2.31	1.71	1.55
Stage 2	1.07	1.55	1.59	1.68	1.81
Stage 3	0.74	1.20	4.13	3.43	4.36
Stage 4	0.34	2.90	5.10	3.18	4.03

Figure D.3 HRV spectra diagrams of SD subject 3.

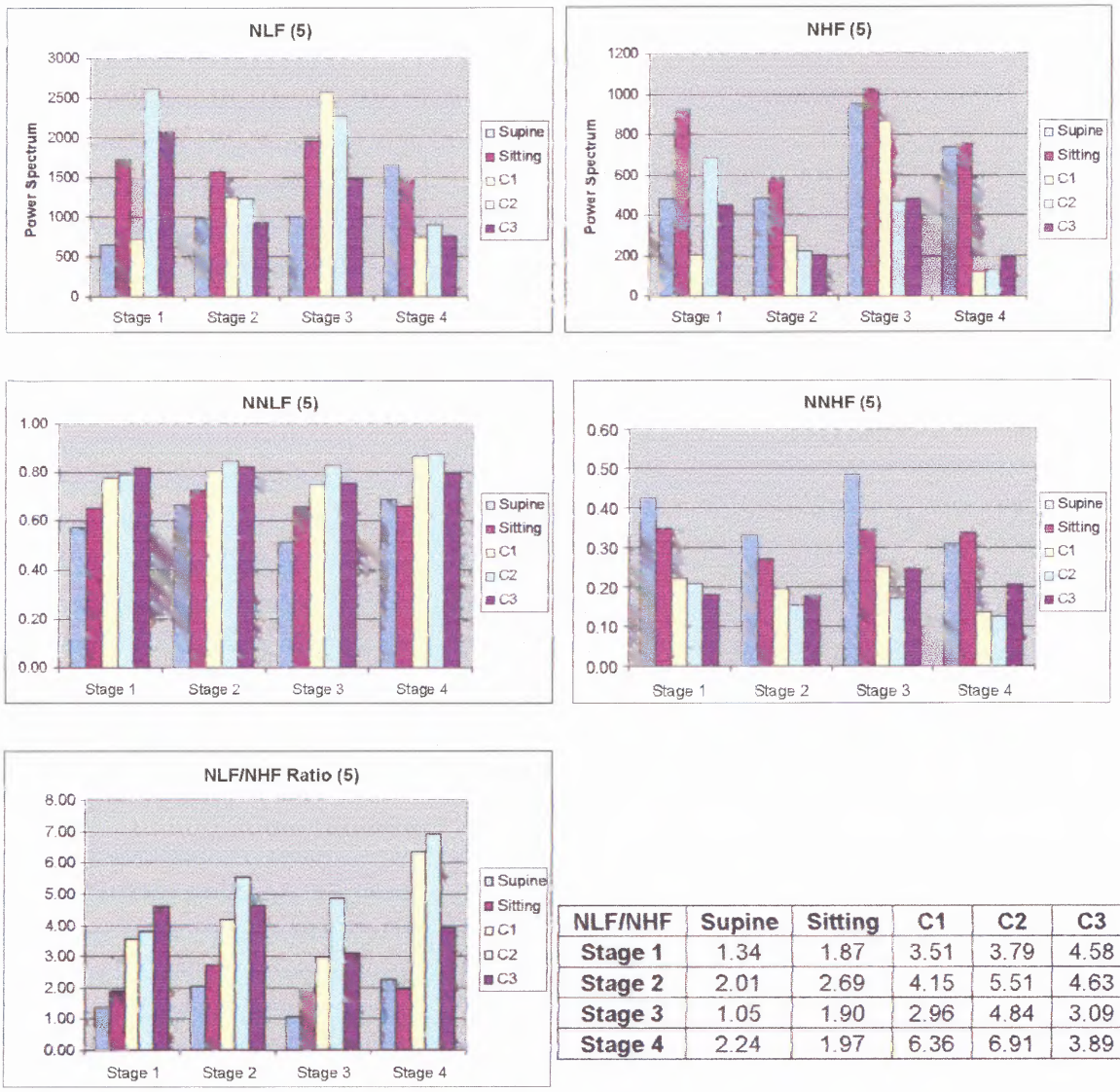
and the C3 segment. The sitting NLF/NHF ratio increased continuously from stage 1 to stage 4. Figure D.3 shows HRV spectra diagrams of SD subject 3. When SD subject 3 changed his position from supine to sitting, the NLF/NHF ratio increased in all stages. No circadian rhythm was observed in both supine and sitting segments. The overall NLF/NHF ratio during the cognitive task increased significantly in stage 3 and stage 4.



NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 1	1.51	3.57	3.96	5.57	3.11
Stage 2	0.99	2.39	4.74	5.19	3.13
Stage 3	0.94	1.94	3.69	1.80	2.87
Stage 4	1.22	1.54	2.31	1.72	1.56

Figure D.4 HRV spectra diagrams of SD subject 4.

Figure D.4 shows HRV spectra diagrams of SD subject 4. The overall NLF/NHF ratio decreased continuously from stage 1 to stage 4. This trend is opposite to the previous three SD subjects. The NLF/NHF ratio was increased by the position change from supine to sitting in all stages. In all stages, the ratio increased in the C1 segment. Although the increased NLF/NHF ratio increased more in the C2 segment in stage 1 and



NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 1	1.34	1.87	3.51	3.79	4.58
Stage 2	2.01	2.69	4.15	5.51	4.63
Stage 3	1.05	1.90	2.96	4.84	3.09
Stage 4	2.24	1.97	6.36	6.91	3.89

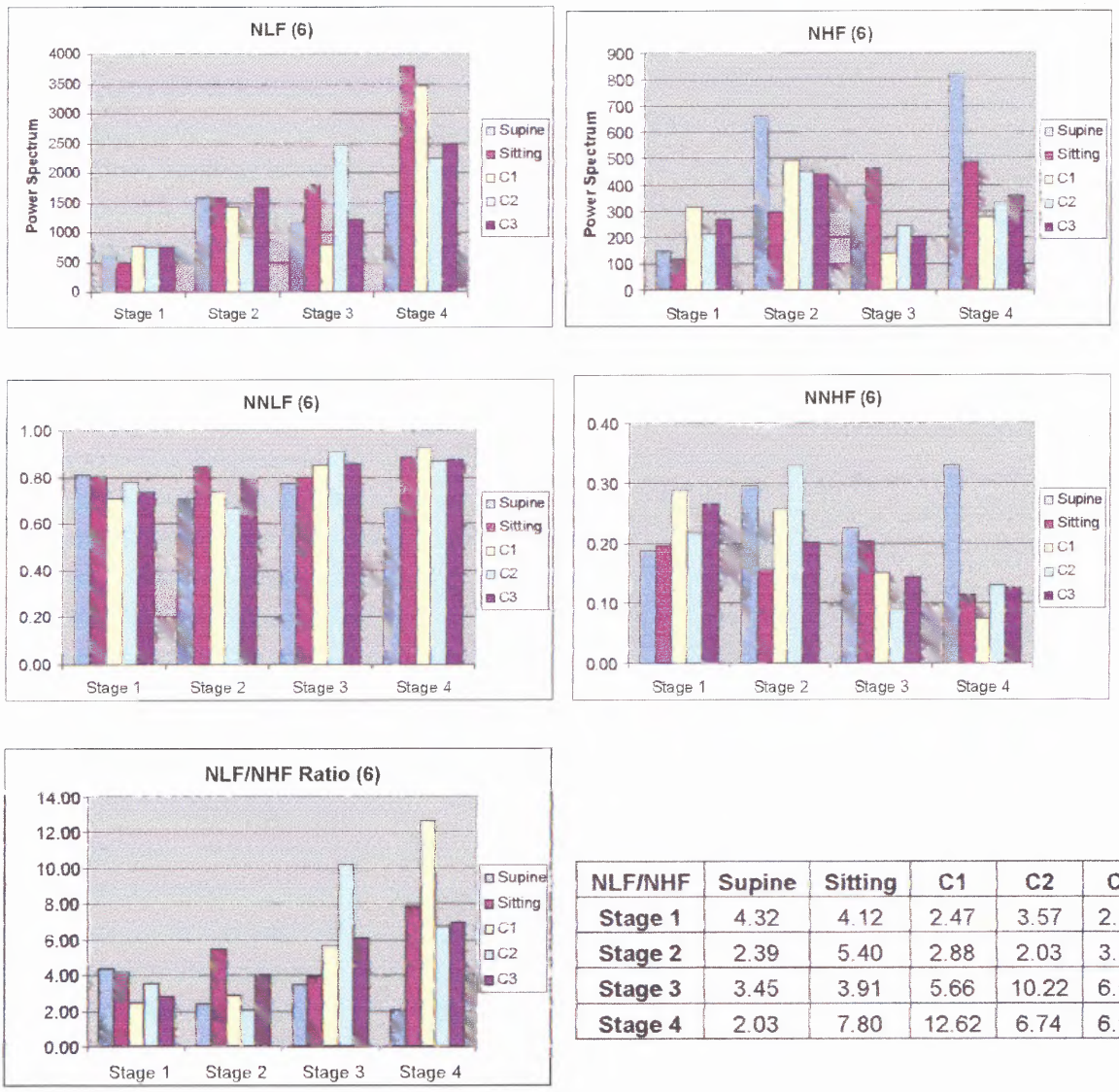
Figure D.5 HRV spectra diagrams of SD subject 5.

stage 2, the ratio decreased in the C2 segment in stage 3 and stage 4. The ratio decreased in the C3 segments in all stages except in stage 3.

Figure D.5 shows HRV spectra diagrams of SD subject 5. When SD subject 5 changed his position from supine to sitting, the NLF/NHF ratio increased in all stages except in stage 4. The NLF/NHF ratio in supine and sitting segments shows a circadian

rhythm. The ratio increased in the morning (Stage 2 and Stage 4) and decreased at night (Stage 1 and Stage 3).

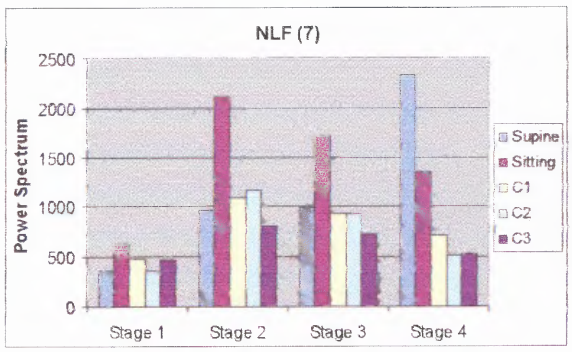
The NLF/NHF ratio increased in the C1 segment in all stages and, especially in stage 4, the increase in the C1 segment was significant. The ratio shows an increasing trend in the C2 segment and a decreasing trend in the C3 segment except in stage 1.

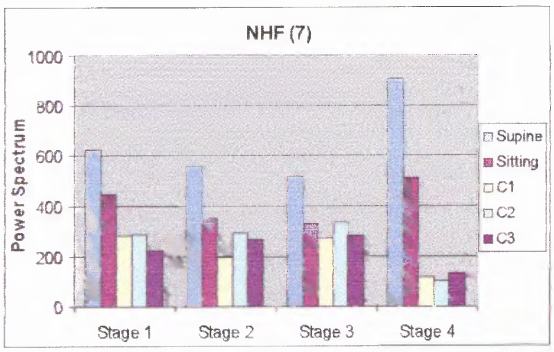


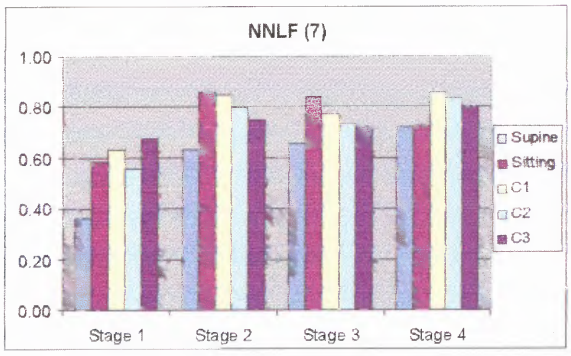
NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 1	4.32	4.12	2.47	3.57	2.78
Stage 2	2.39	5.40	2.88	2.03	3.98
Stage 3	3.45	3.91	5.66	10.22	6.03
Stage 4	2.03	7.80	12.62	6.74	6.96

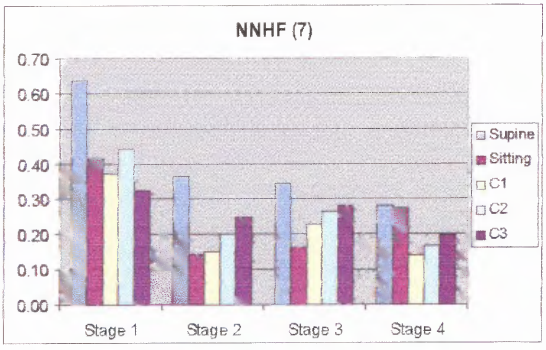
Figure D.6 HRV spectra diagrams of SD subject 6.

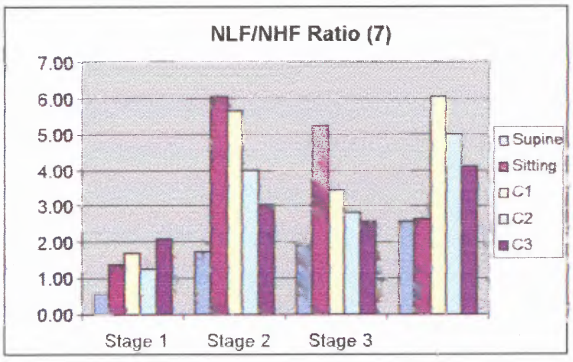
Figure D.6 shows HRV spectra diagrams of SD subject 6. Although the NLF/NHF ratio shows a circadian rhythm in the sitting segment, it shows an opposite trend in the supine segment. The overall NLF/NHF ratio increased significantly in stage 3 and stage 4 and the ratio was increased by the position change from supine to sitting in all stages except stage 1.







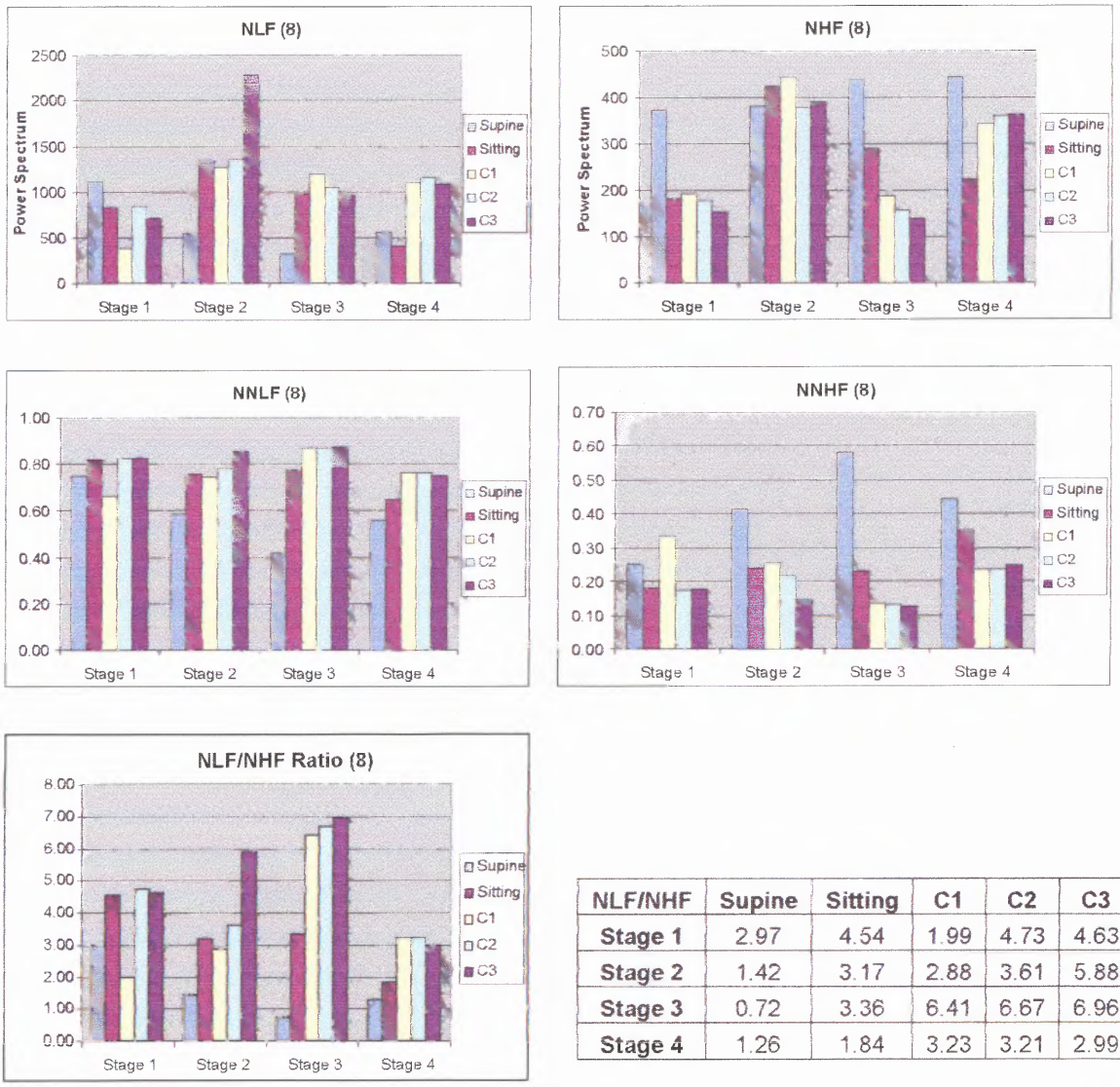




NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 1	0.57	1.40	1.70	1.26	2.08
Stage 2	1.73	6.02	5.65	3.97	3.02
Stage 3	1.91	5.22	3.41	2.79	2.58
Stage 4	2.57	2.65	6.04	4.99	4.07

Figure D.7 HRV spectra diagrams of SD subject 7.

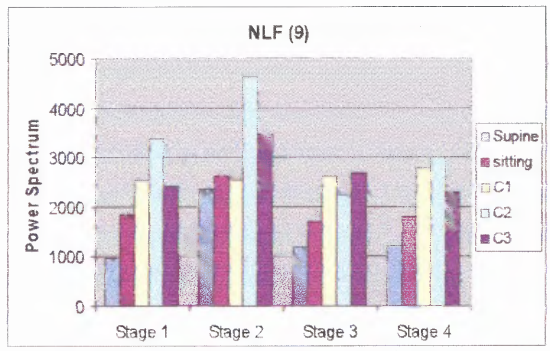
Figure D.7 shows HRV spectra diagrams of SD subject 7. The ratio was increased by the position change in all stages and shows a significant increase in the C1 segment of stage 4. During the cognitive task, the overall ratio in stage 4 is greater then that of stage 3 and the overall ratio in stage 3 is greater then that of stage 1.

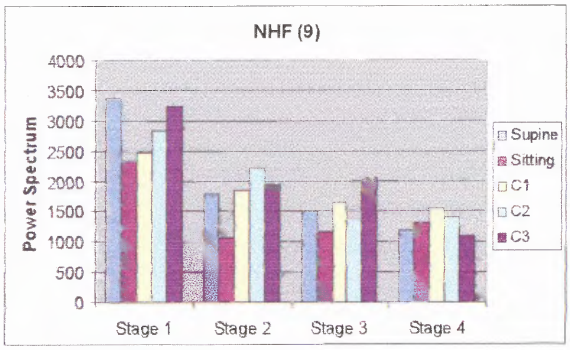


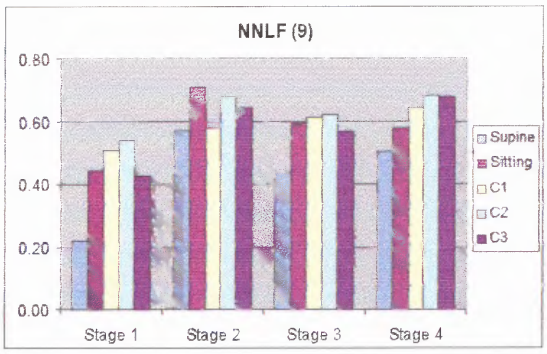
NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 1	2.97	4.54	1.99	4.73	4.63
Stage 2	1.42	3.17	2.88	3.61	5.88
Stage 3	0.72	3.36	6.41	6.67	6.96
Stage 4	1.26	1.84	3.23	3.21	2.99

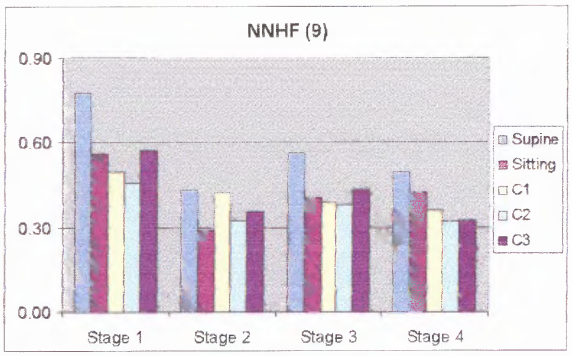
Figure D.8 HRV spectra diagrams of SD subject 8.

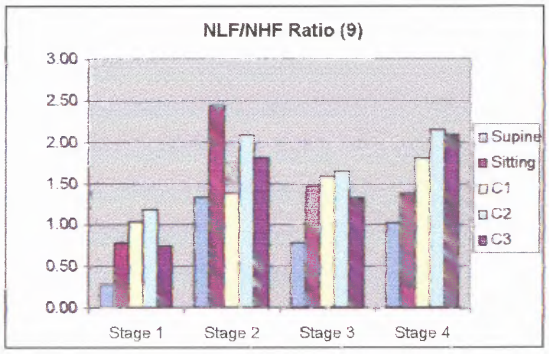
Figure D.8 shows HRV spectra diagrams of SD subject 8. The NLF/NHF ratio was increased by the position change from supine to sitting in all stages. During the cognitive task, the ratio shows a continuous increasing trend in all stages except stage 4. In stage 3 and stage 4, there was a significant NLF/NHF ratio increase in the C1 segment.







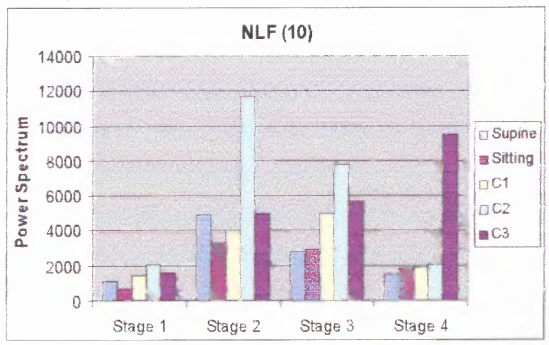


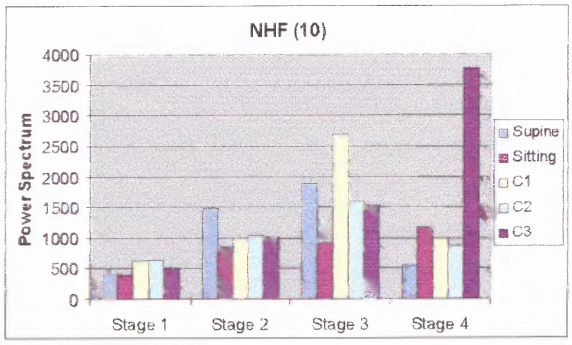


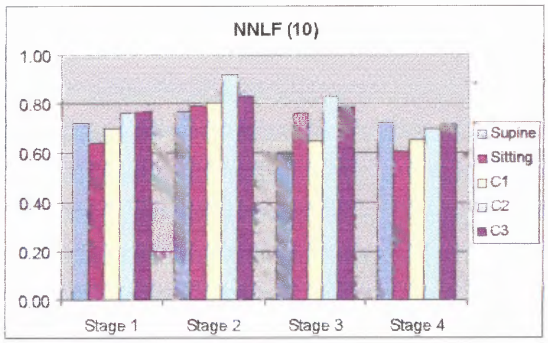
NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 1	0.29	0.79	1.03	1.19	0.75
Stage 2	1.33	2.44	1.37	2.09	1.81
Stage 3	0.78	1.46	1.58	1.64	1.31
Stage 4	1.01	1.38	1.80	2.15	2.09

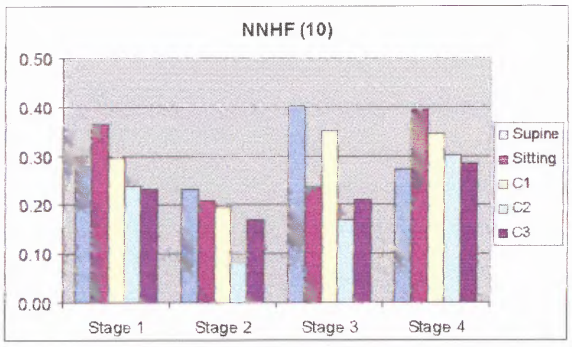
Figure D.9 HRV spectra diagrams of SD subject 9.

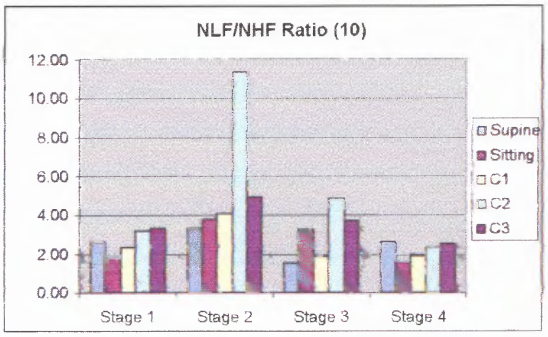
Figure D.9 shows HRV spectra diagrams of SD subject 9. A circadian rhythm was observed in both supine and sitting segments. The NLF/NHF ratio was increased by the position change from supine to sitting in all stages. During the cognitive task, the NNLF and the ratio increased in the C2 segment and then decreased in the C3 segment in all stages. The overall NLF/NHF ratio in stage 3 is greater then the overall ratio in stage 1 and the overall ratio in stage 4 is greater then overall ratio in stage 2.











NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 1	2.61	1.76	2.37	3.20	3.31
Stage 2	3.33	3.80	4.10	11.36	4.92
Stage 3	1.48	3.22	1.84	4.85	3.74
Stage 4	2.65	1.54	1.90	2.32	2.52

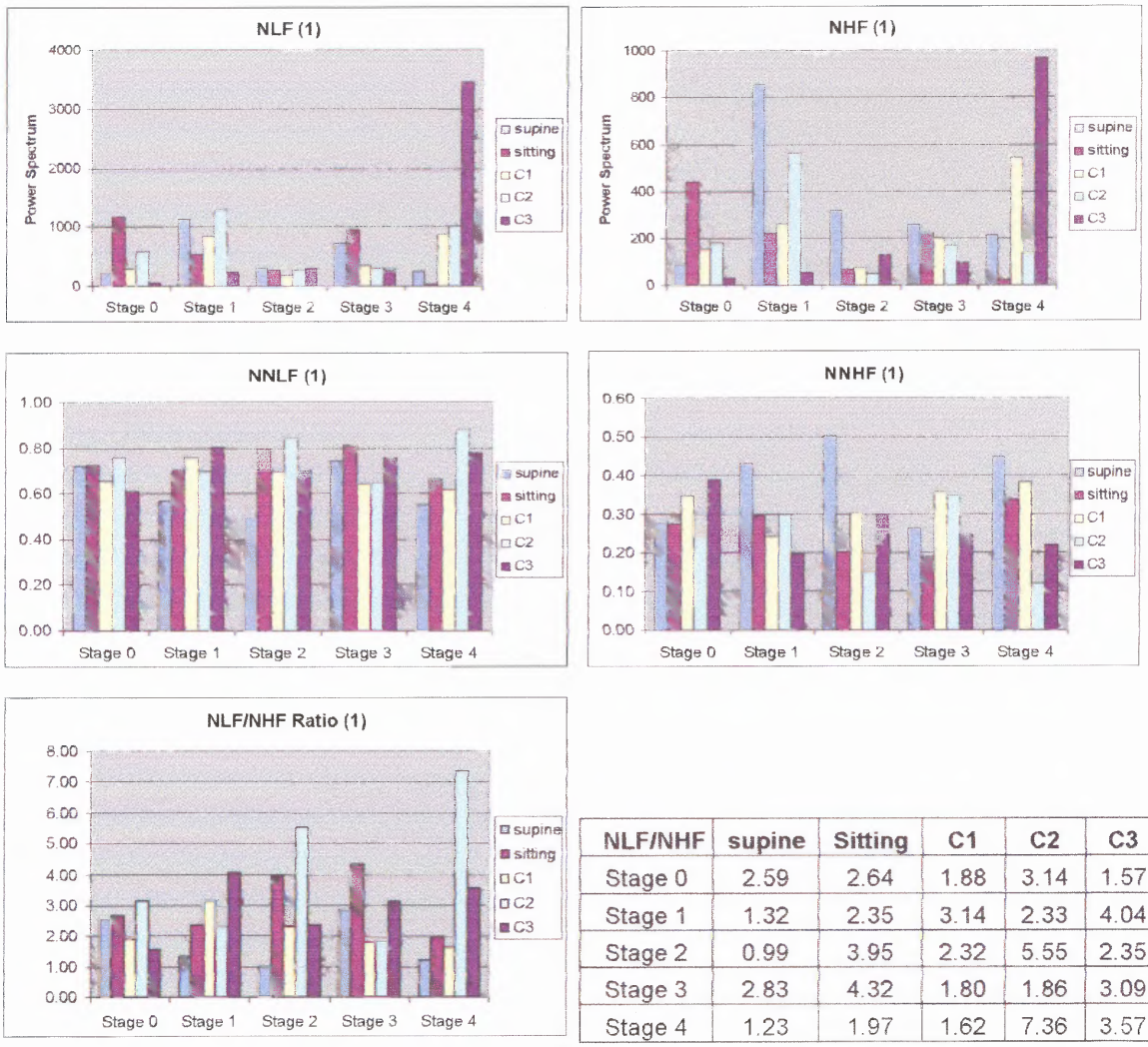
Figure D.10 HRV spectra diagrams of SD subject 10.

Figure D.10 shows HRV spectra diagrams of SD subject 10. In both supine and sitting segments, the NLF/NHF ratio increased in the morning and decreased at night. During the cognitive task, the NLF/NHF ratio increased in C2 segment the overall ratio increase in stage 4 and stage 3 was not observed in SD subject 10.

APPENDIX E

BPV SPECTRA DIAGRAMS OF THE CONTROL GROUP

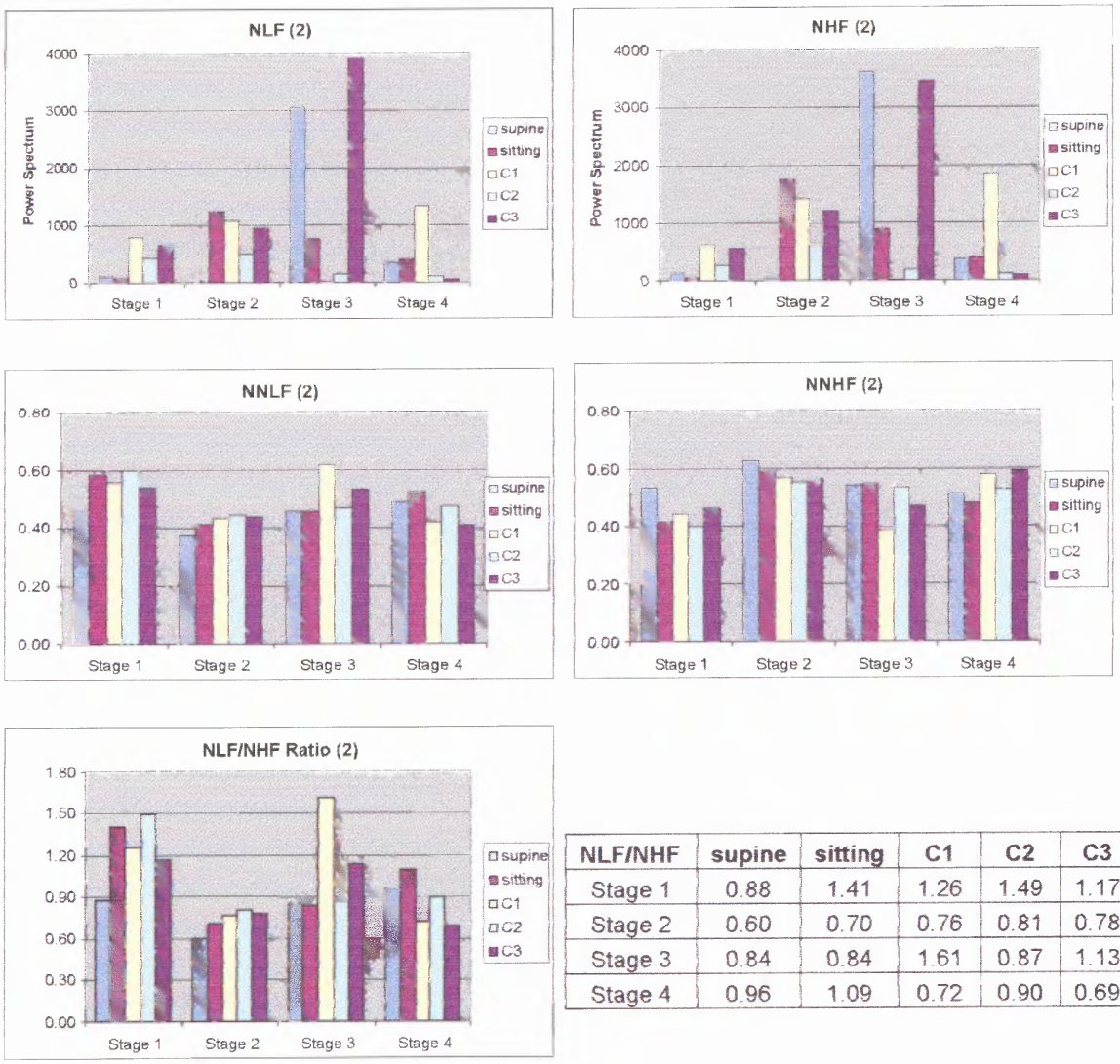
The Following figures are BPV spectra diagrams of the control group. There were five subjects in the control group and each subject's BPV spectra diagrams are shown in Figure E.1 to Figure E.5. Each Figure has five diagrams, which show the NLF, the NHF, the NNLF, the NNHF and the NLF/NHF ratio.



NLF/NHF	supine	Sitting	C1	C2	C3
Stage 0	2.59	2.64	1.88	3.14	1.57
Stage 1	1.32	2.35	3.14	2.33	4.04
Stage 2	0.99	3.95	2.32	5.55	2.35
Stage 3	2.83	4.32	1.80	1.86	3.09
Stage 4	1.23	1.97	1.62	7.36	3.57

Figure E.1 BPV spectra diagrams of subject 1.

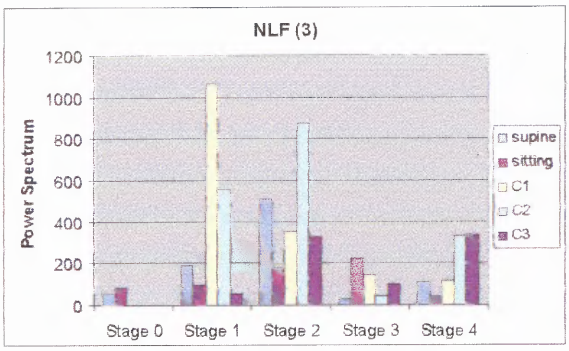
Figure E.1 shows BPV spectra diagrams of subject 1. The NLF/NHF ratio was increased by the position change from supine to sitting. During the cognitive task, the NLF/NHF ratio increased in the C2 segment and then decreased in the C3 segment. The NLF and the NHF show a similar trend but the NNLF and the NNHF show an antagonistical activity to each other.

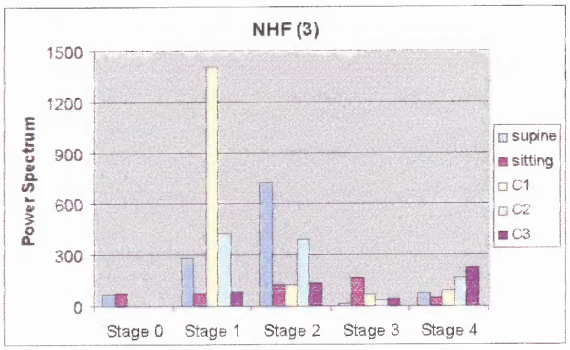


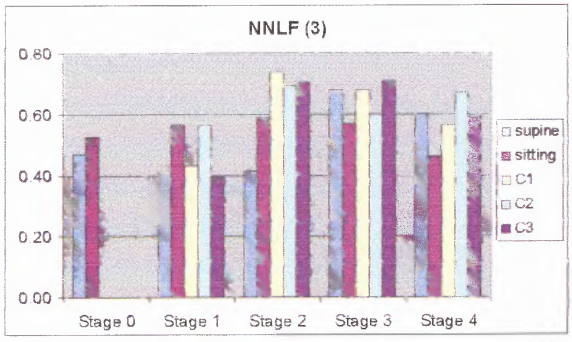
NLF/NHF	supine	sitting	C1	C2	C3
Stage 1	0.88	1.41	1.26	1.49	1.17
Stage 2	0.60	0.70	0.76	0.81	0.78
Stage 3	0.84	0.84	1.61	0.87	1.13
Stage 4	0.96	1.09	0.72	0.90	0.69

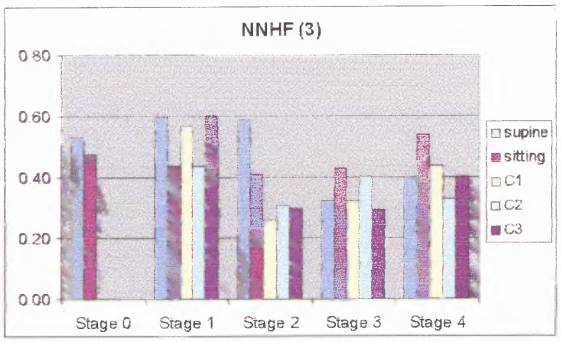
Figure E.2 BPV spectra diagrams of subject 2.

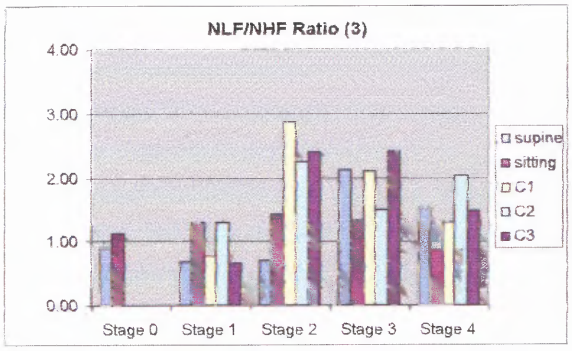
Figure E.2 shows BPV spectra diagrams of subject 2. The NLF/NHF ratio was increased by the position change from supine to sitting in all stages except in stage 3. The normal cognitive ratio trend (increase in C2 segment and decrease in C3 segment) was observed in stage 1, stage 2 and stage 4. The NLF and the NHF show a similar trend but the NNLF and the NNHF show an antagonistical activity to each other.







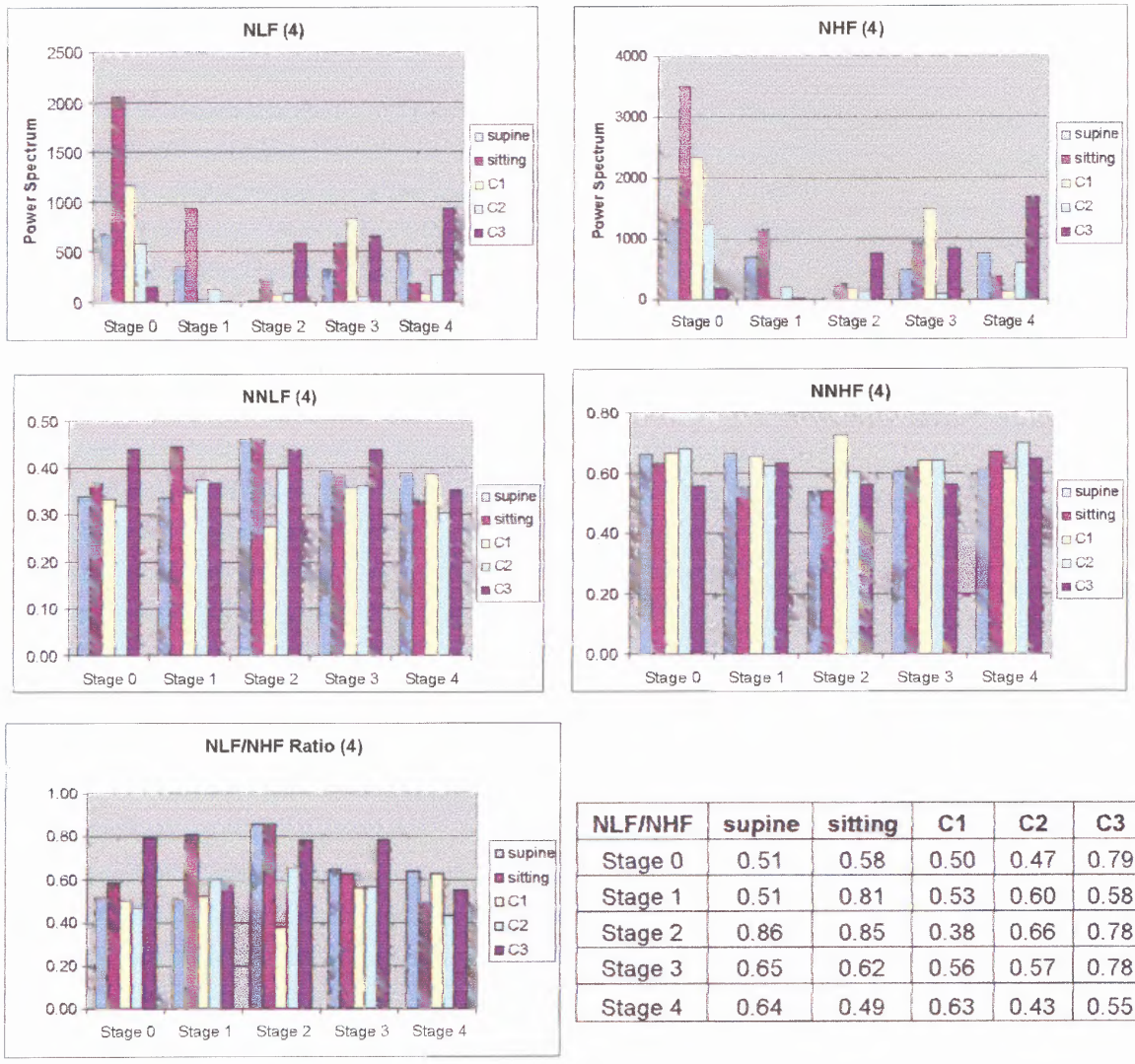




NLF/NHF	supine	sitting	C1	C2	C3
Stage 0	0.89	1.12	-	-	-
Stage 1	0.68	1.29	0.76	1.30	0.66
Stage 2	0.70	1.43	2.86	2.25	2.40
Stage 3	2.11	1.33	2.10	1.50	2.41
Stage 4	1.52	0.85	1.29	2.02	1.48

Figure E.3 BPV spectra diagrams of subject 3.

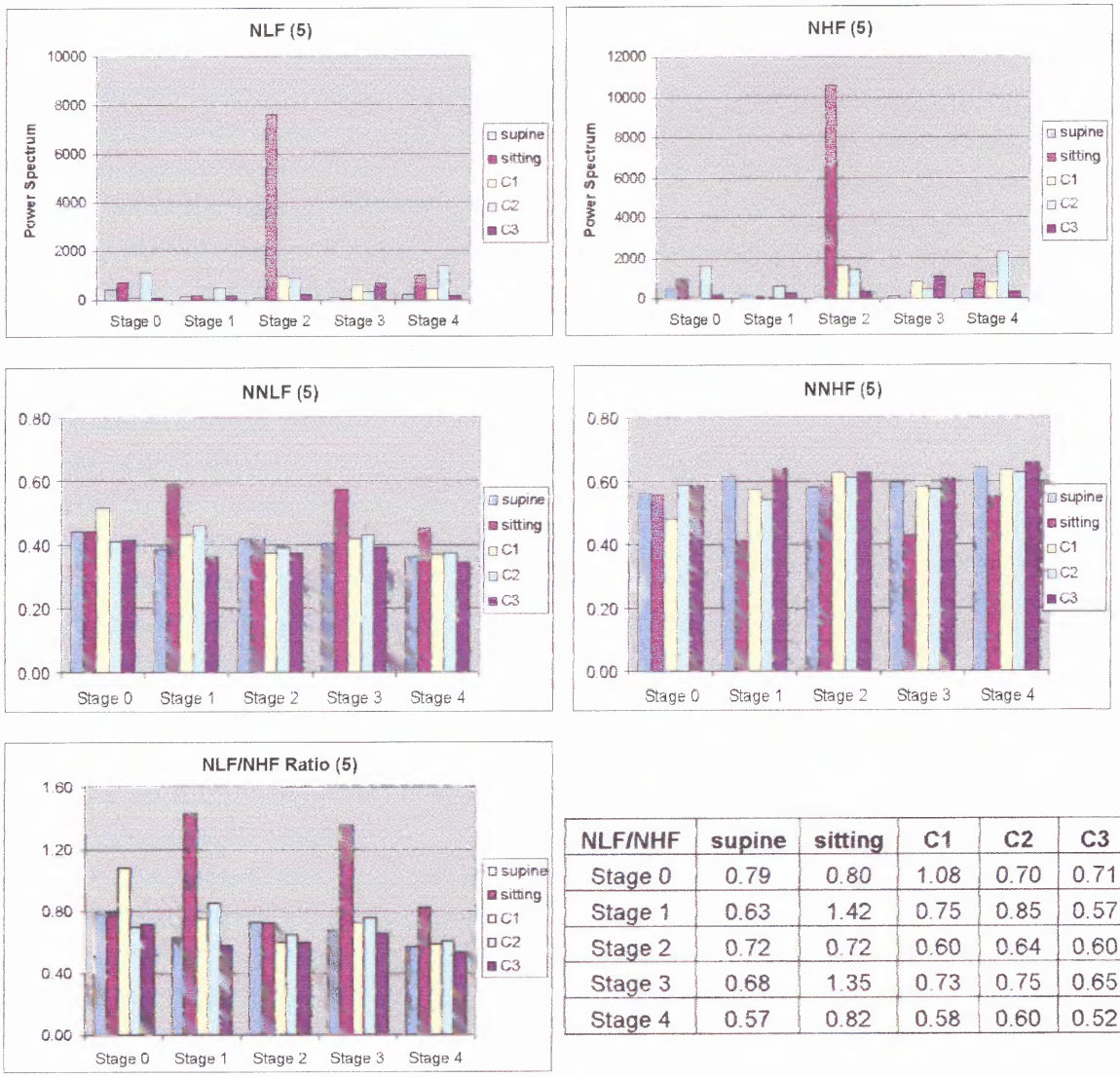
Figure E.3 shows BPV spectra diagrams of subject 3. The NLF/NHF ratio was increased by the position change except in stage 3 and stage 4. The normal cognitive ratio trend (increase in the C2 segment and decrease in the C3 segment) was observed only in stage 1 and stage 4. The NLF and the NHF show a similar trend but the NNLF and the NNHF show an antagonistical activity to each other like previous two control subjects.



NLF/NHF	supine	sitting	C1	C2	C3
Stage 0	0.51	0.58	0.50	0.47	0.79
Stage 1	0.51	0.81	0.53	0.60	0.58
Stage 2	0.86	0.85	0.38	0.66	0.78
Stage 3	0.65	0.62	0.56	0.57	0.78
Stage 4	0.64	0.49	0.63	0.43	0.55

Figure E.4 BPV spectra diagrams of subject 4.

Figure E.4 shows BPV spectra diagrams of subject 4. The position change induced NLF/NHF ratio increase was observed only in stage 0 and stage 1. During the cognitive task, the NLF/NHF ratio did not follow the normal cognitive trend and the ratio shows an increasing trend. The NLF and the NHF show a similar trend but the NNLF and the NNHF show an antagonistical activity to each other.



NLF/NHF	supine	sitting	C1	C2	C3
Stage 0	0.79	0.80	1.08	0.70	0.71
Stage 1	0.63	1.42	0.75	0.85	0.57
Stage 2	0.72	0.72	0.60	0.64	0.60
Stage 3	0.68	1.35	0.73	0.75	0.65
Stage 4	0.57	0.82	0.58	0.60	0.52

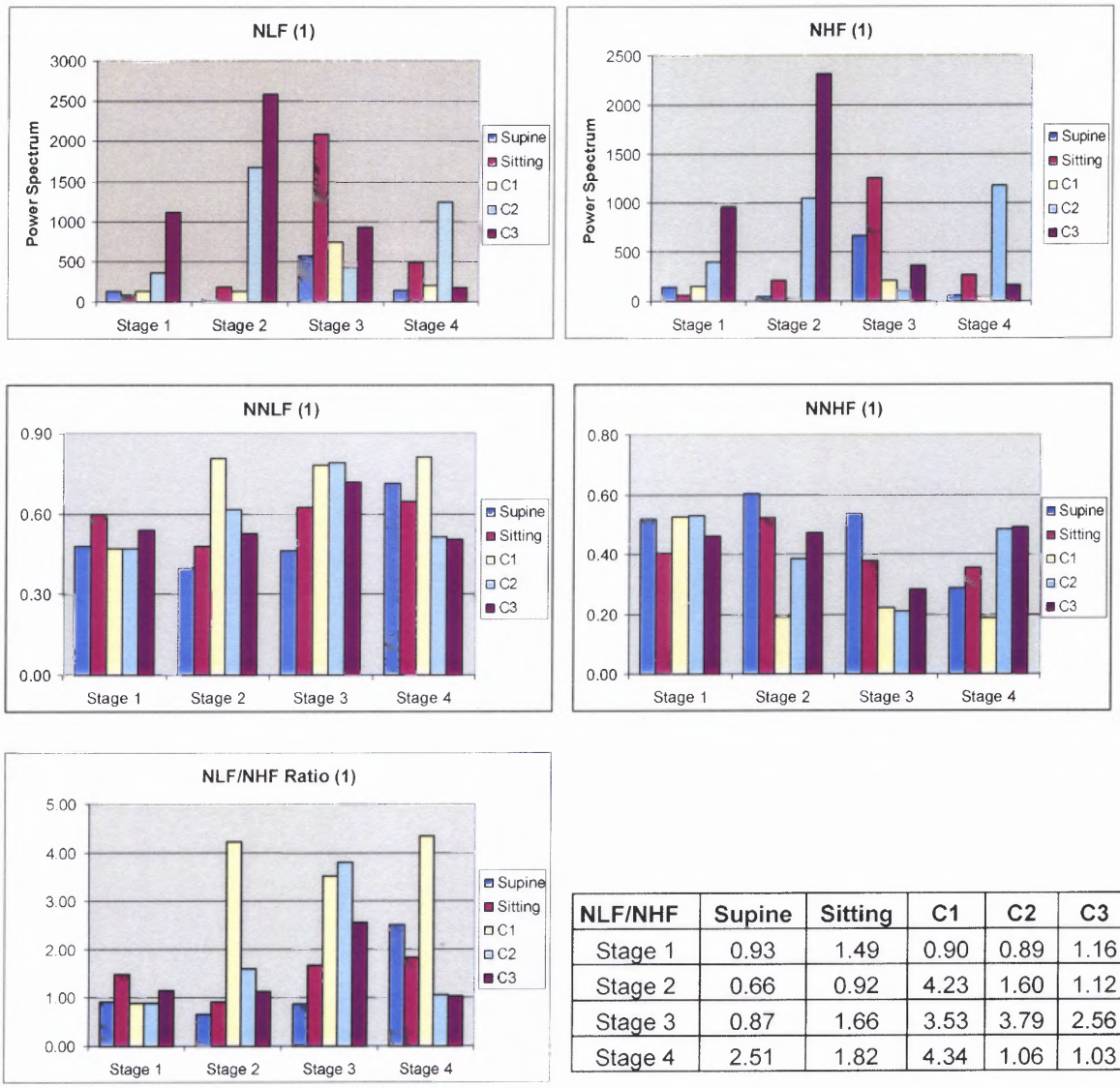
Figure E.5 BPV spectra diagrams of subject 5.

Figure E.5 shows BPV spectra diagrams of subject 5. The NLF/NHF ratio was increased by the position change from supine to sitting. The ratio followed the normal cognitive trend during the cognitive task except in stage 0. The NLF and the NHF show a similar trend but the NNLF and the NNHF show an antagonistical activity to each other.

APPENDIX F

BPV SPECTRA DIAGRAMS OF THE SD GROUP

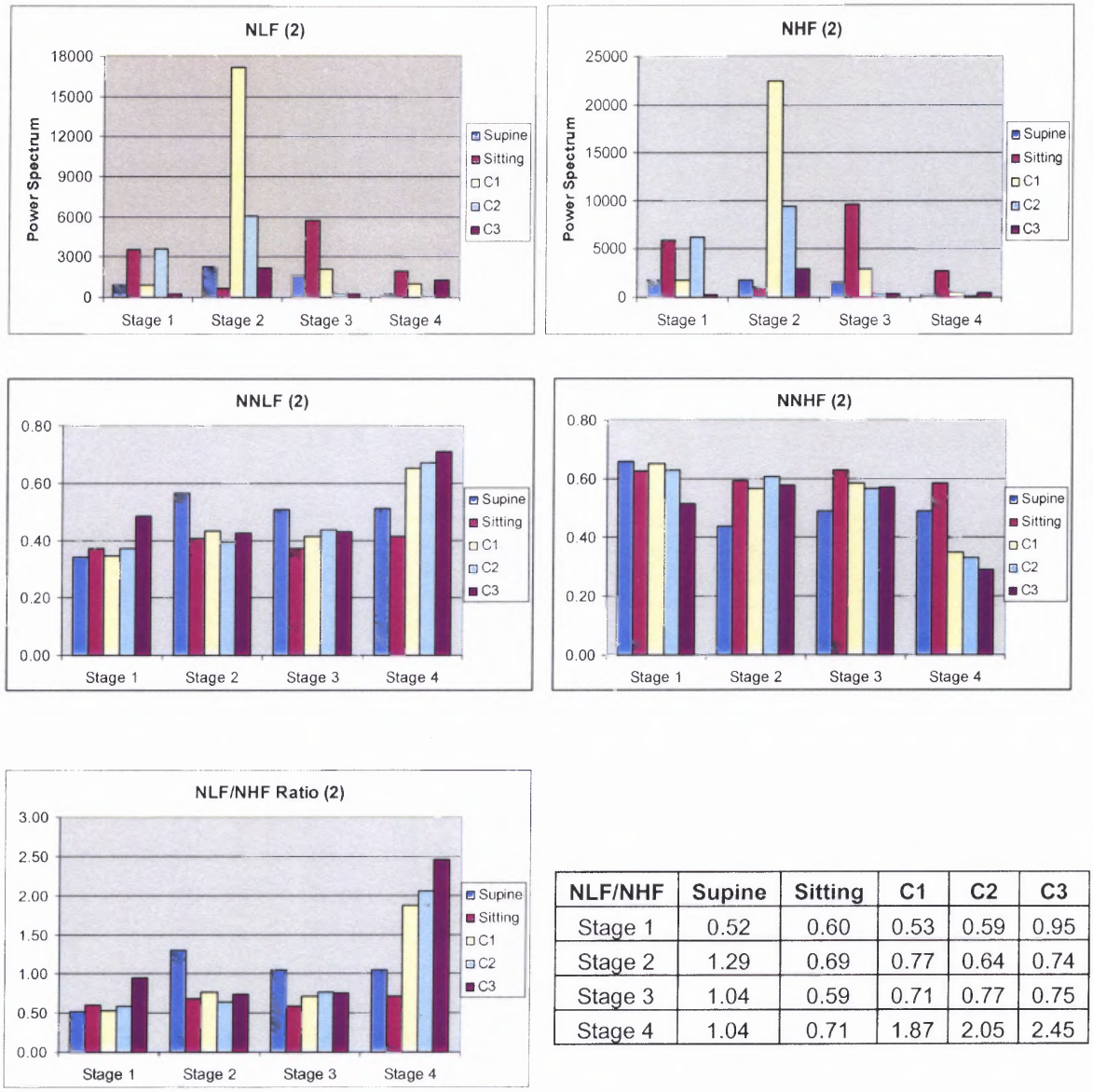
The following figures are BPV spectra diagrams of the SD group. There were ten subjects in the SD group and each subject's BPV spectra diagrams are shown in Figure F.1 to Figure F.10. Each Figure has five diagrams, which show the NLF, the NHF, the NNLF, the NNHF and the NLF/NHF ratio.



NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 1	0.93	1.49	0.90	0.89	1.16
Stage 2	0.66	0.92	4.23	1.60	1.12
Stage 3	0.87	1.66	3.53	3.79	2.56
Stage 4	2.51	1.82	4.34	1.06	1.03

Figure F.1 BPV spectra diagrams of SD subject 1.

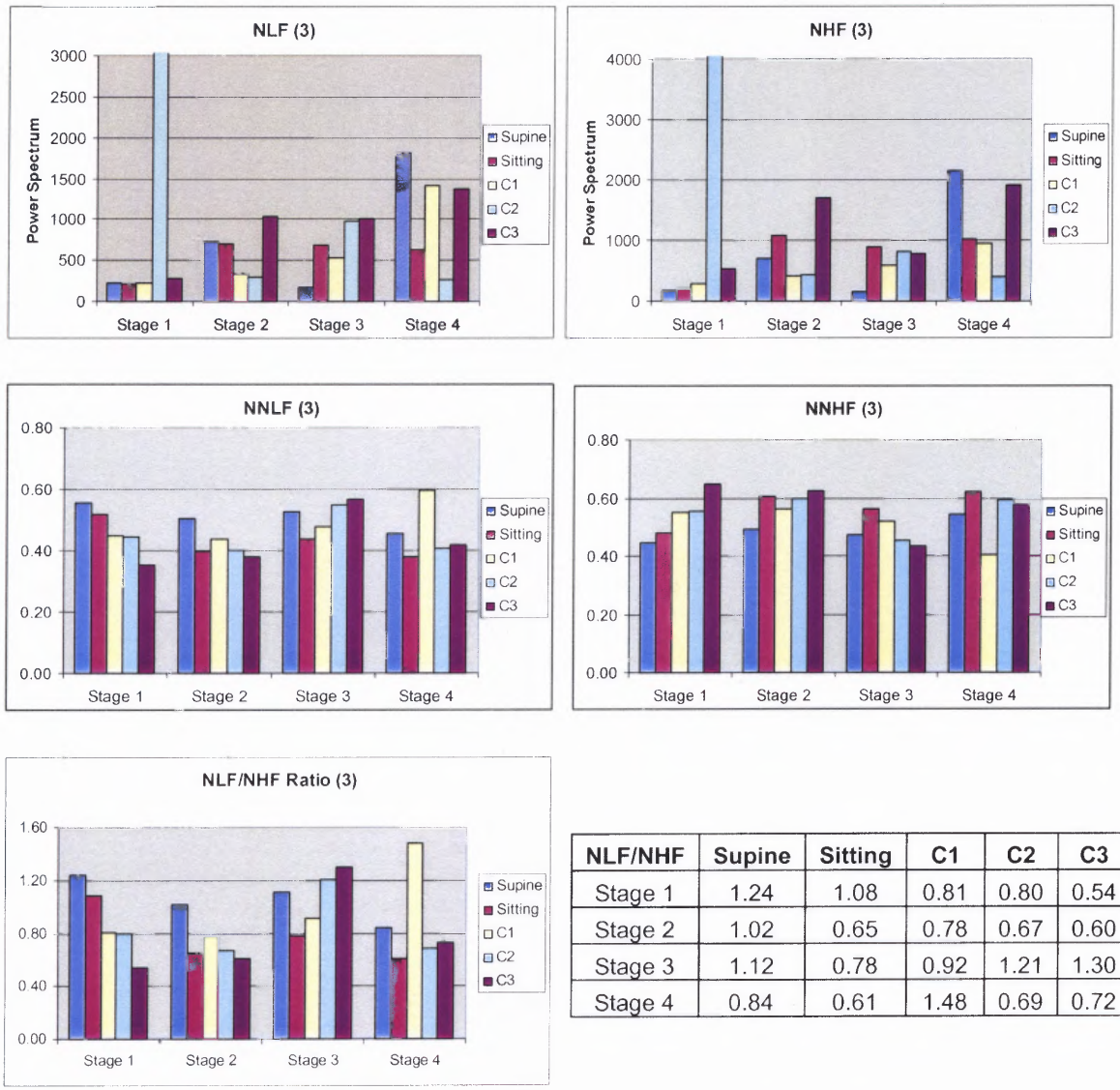
Figure F.1 shows BPV spectra diagrams of SD subject 1. The NLF/NHF ratio was increased by the position change from supine to sitting except in stage 4. During the cognitive task, the NLF/NHF ratio increased significantly in the C1 segment of stage 2 and this increasing trend in the C1 segment was also observed in stage 3 and stage 4.



NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 1	0.52	0.60	0.53	0.59	0.95
Stage 2	1.29	0.69	0.77	0.64	0.74
Stage 3	1.04	0.59	0.71	0.77	0.75
Stage 4	1.04	0.71	1.87	2.05	2.45

Figure F.2 BPV spectra diagrams of SD subject 2.

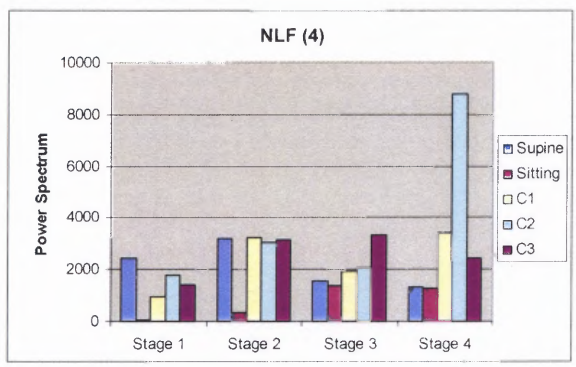
Figure F.2 shows BPV spectra diagrams of SD subject 2. Position change induced NLF change was observed only in stage 1. Overall NLF/NHF ratio of cognitive segments of stage 4 increased significantly and shows a continuous increasing trend.

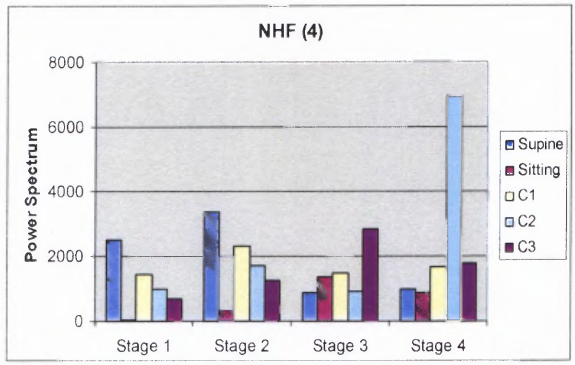


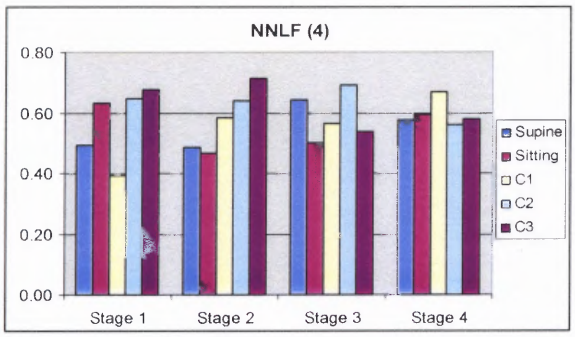
NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 1	1.24	1.08	0.81	0.80	0.54
Stage 2	1.02	0.65	0.78	0.67	0.60
Stage 3	1.12	0.78	0.92	1.21	1.30
Stage 4	0.84	0.61	1.48	0.69	0.72

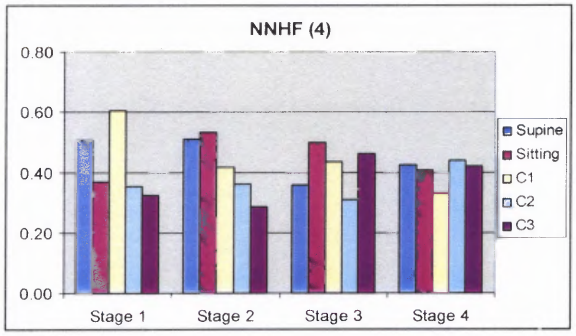
Figure F.3 BPV spectra diagrams of SD subject 3.

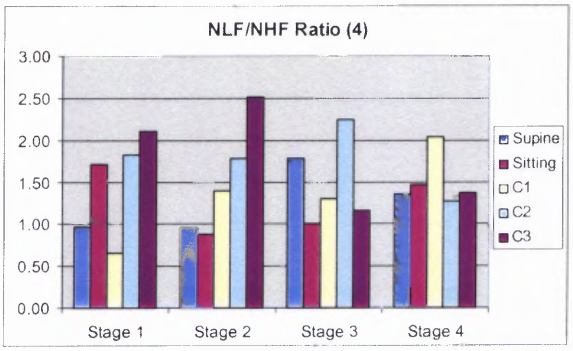
Figure F.3 shows BPV spectra diagrams of SD subject 3. The HRV of SD subject 3 was increased in all stages by the position change but the BPV of the same person was decreased by the position change. Like previous two SD subjects, the ratio increased significantly in C1 segment of stage 4.







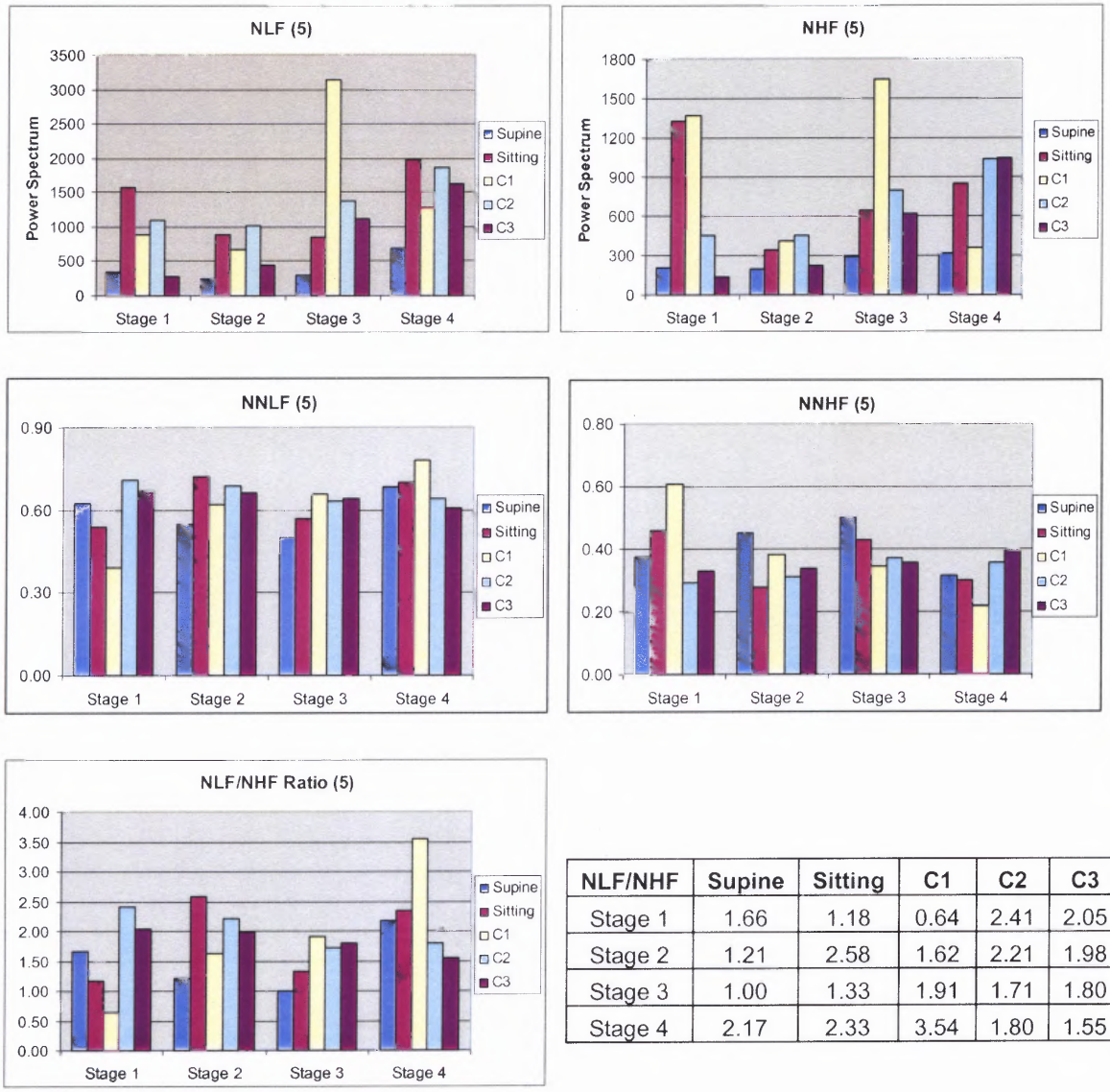




NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 1	0.97	1.71	0.65	1.83	2.11
Stage 2	0.95	0.88	1.39	1.78	2.51
Stage 3	1.79	1.00	1.30	2.24	1.16
Stage 4	1.35	1.46	2.04	1.27	1.37

Figure F.4 BPV spectra diagrams of SD subject 4.

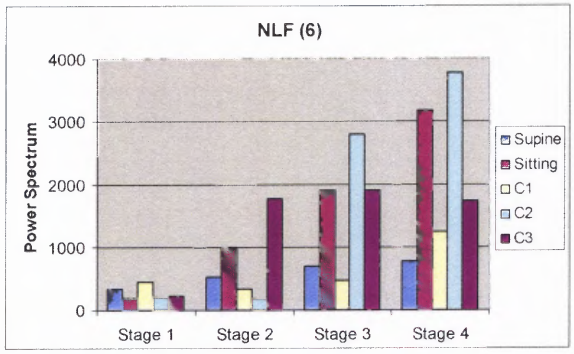
Figure F.4 shows BPV spectra diagrams of SD subject 4. The position induced NLF/NHF ratio increase was observed only in stage 1 and stage 4. Like other subjects, there was a significant increase in the C1 segment of stage 4.

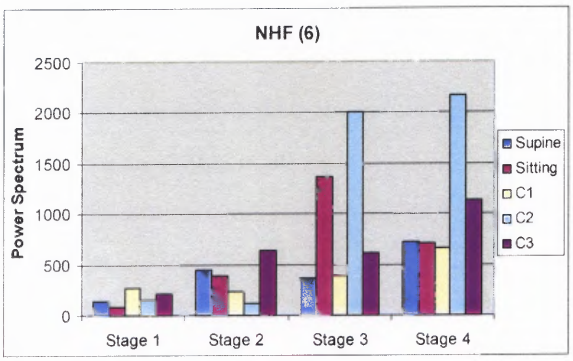


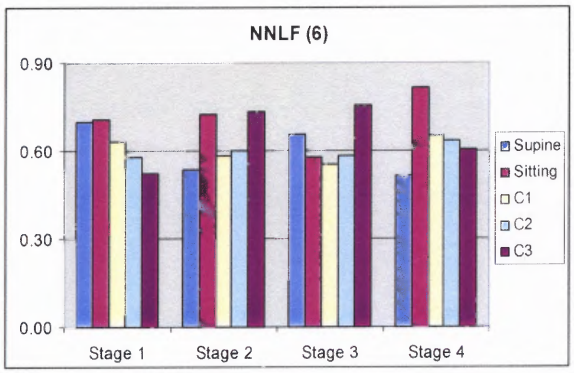
NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 1	1.66	1.18	0.64	2.41	2.05
Stage 2	1.21	2.58	1.62	2.21	1.98
Stage 3	1.00	1.33	1.91	1.71	1.80
Stage 4	2.17	2.33	3.54	1.80	1.55

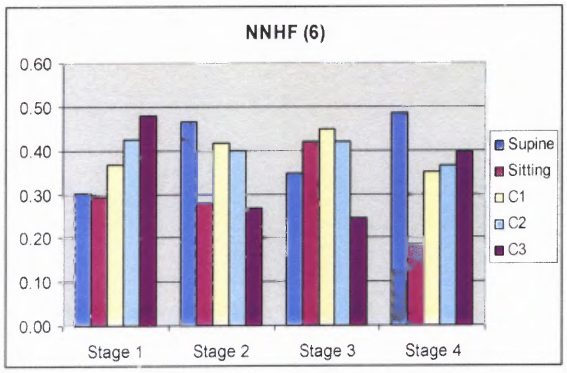
Figure F.5 BPV spectra diagrams of SD subject 5.

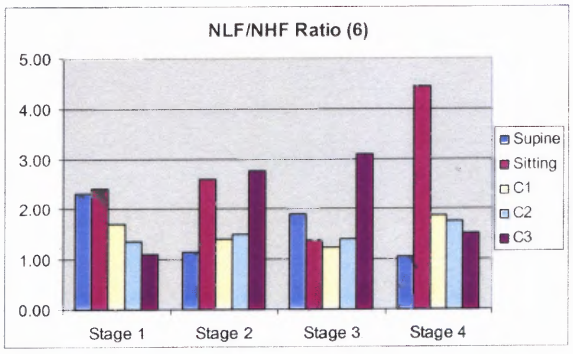
Figure F.5 shows BPV spectra diagrams of SD subject 5. The NLF/NHF ratio was increased by the position change except in stage 1. Like other subjects, the ratio increased significantly in the C1 segment of the stage 4.







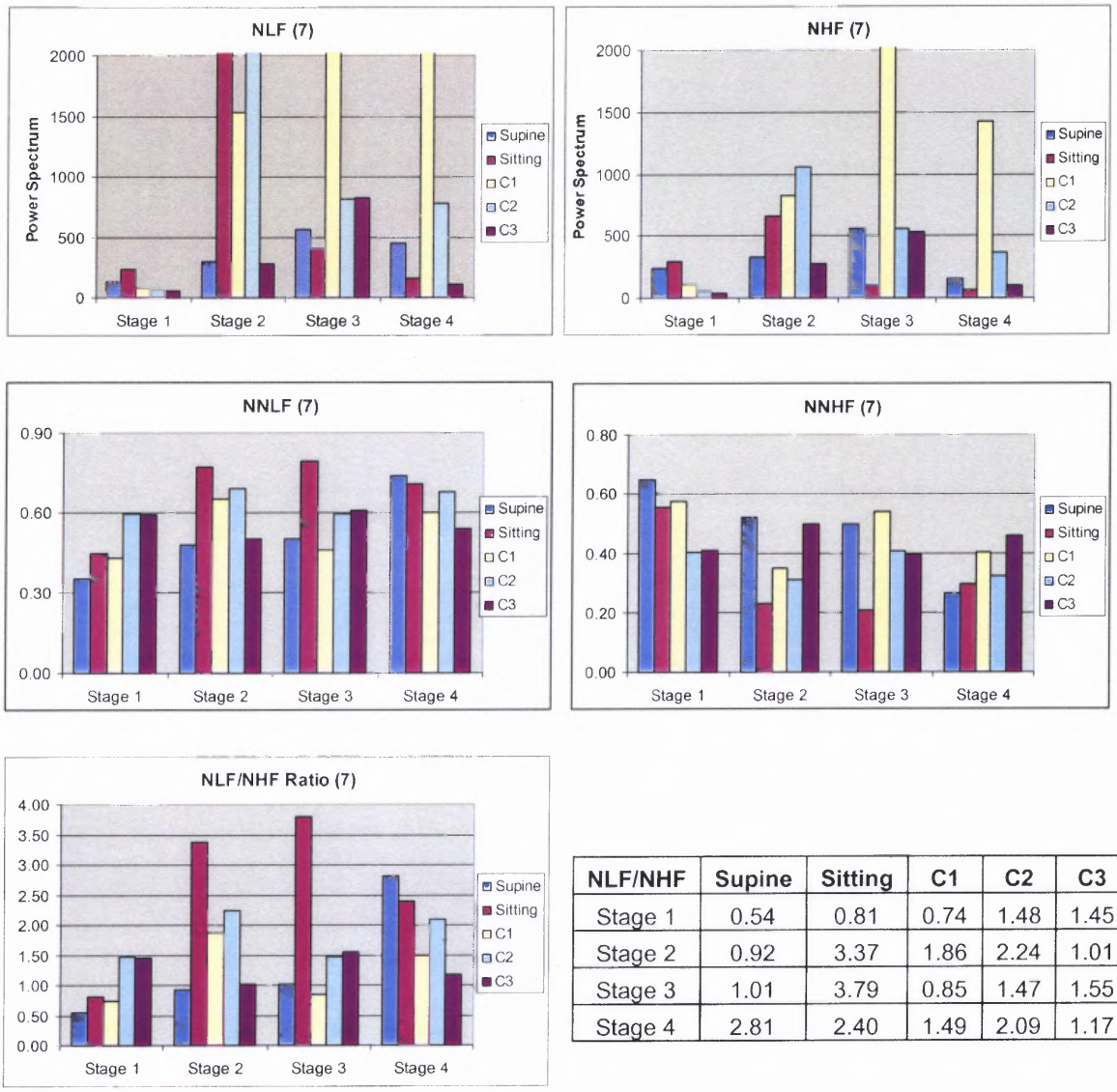




NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 1	2.32	2.40	1.72	1.36	1.09
Stage 2	1.15	2.60	1.40	1.50	2.75
Stage 3	1.89	1.38	1.24	1.39	3.09
Stage 4	1.06	4.44	1.87	1.74	1.53

Figure F.6 BPV spectra diagrams of SD subject 6.

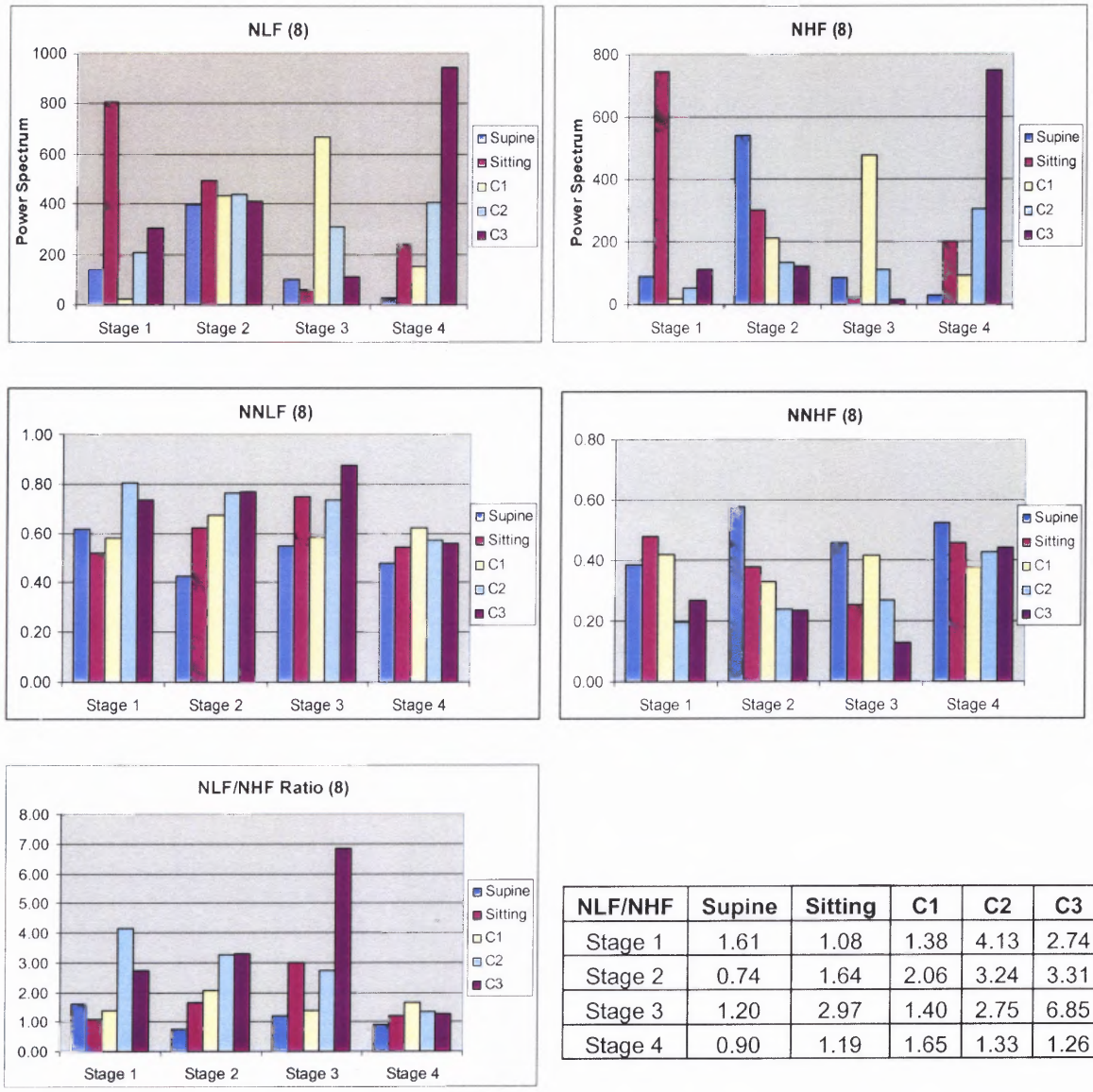
Figure F.6 shows BPV spectra diagrams of SD subject 6. The NLF and the NLF/NHF ratio show an increasing trend due to the position change from supine to sitting. The significant increase in the C1 segment of stage 4 was not observed.



NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 1	0.54	0.81	0.74	1.48	1.45
Stage 2	0.92	3.37	1.86	2.24	1.01
Stage 3	1.01	3.79	0.85	1.47	1.55
Stage 4	2.81	2.40	1.49	2.09	1.17

Figure F.7 BPV spectra diagrams of SD subject 7.

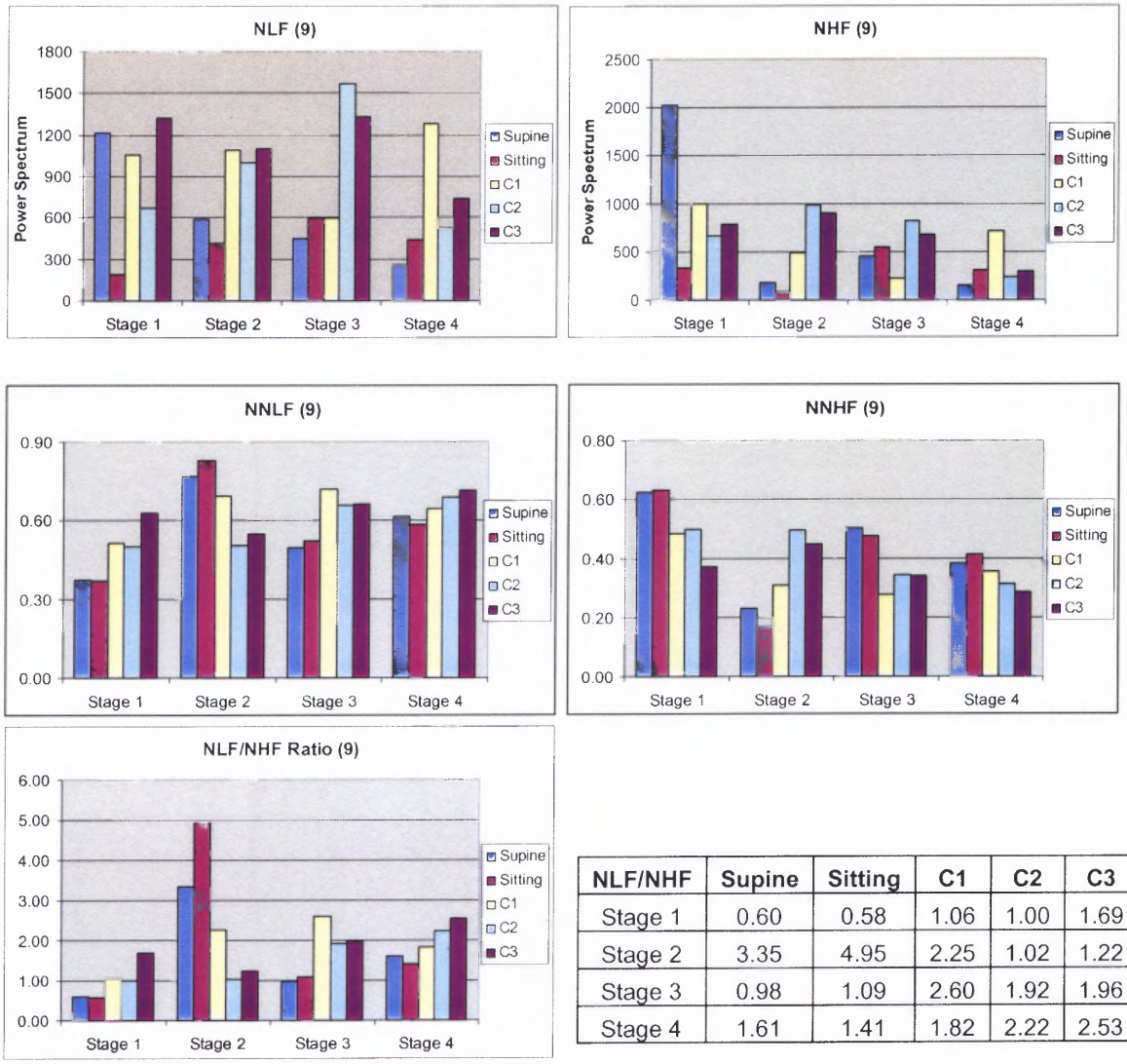
Figure F.7 shows spectra diagrams of SD subject 7. Position change induced NLF/NHF ratio change was observed except in stage 4. There was a significant ratio increase in supine segment of stage 4. The normal cognitive trend (increase in the C2 segment and decrease in the C3 segment) was observed in all stages except stage 3. The overall NLF/NHF ratio during the cognitive task decreased at night (stage 1 and stage 3) and the overall cognitive ratio increased in the morning (stage 2 and stage 4).



NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 1	1.61	1.08	1.38	4.13	2.74
Stage 2	0.74	1.64	2.06	3.24	3.31
Stage 3	1.20	2.97	1.40	2.75	6.85
Stage 4	0.90	1.19	1.65	1.33	1.26

Figure F.8 BPV spectra diagrams of SD subject 8.

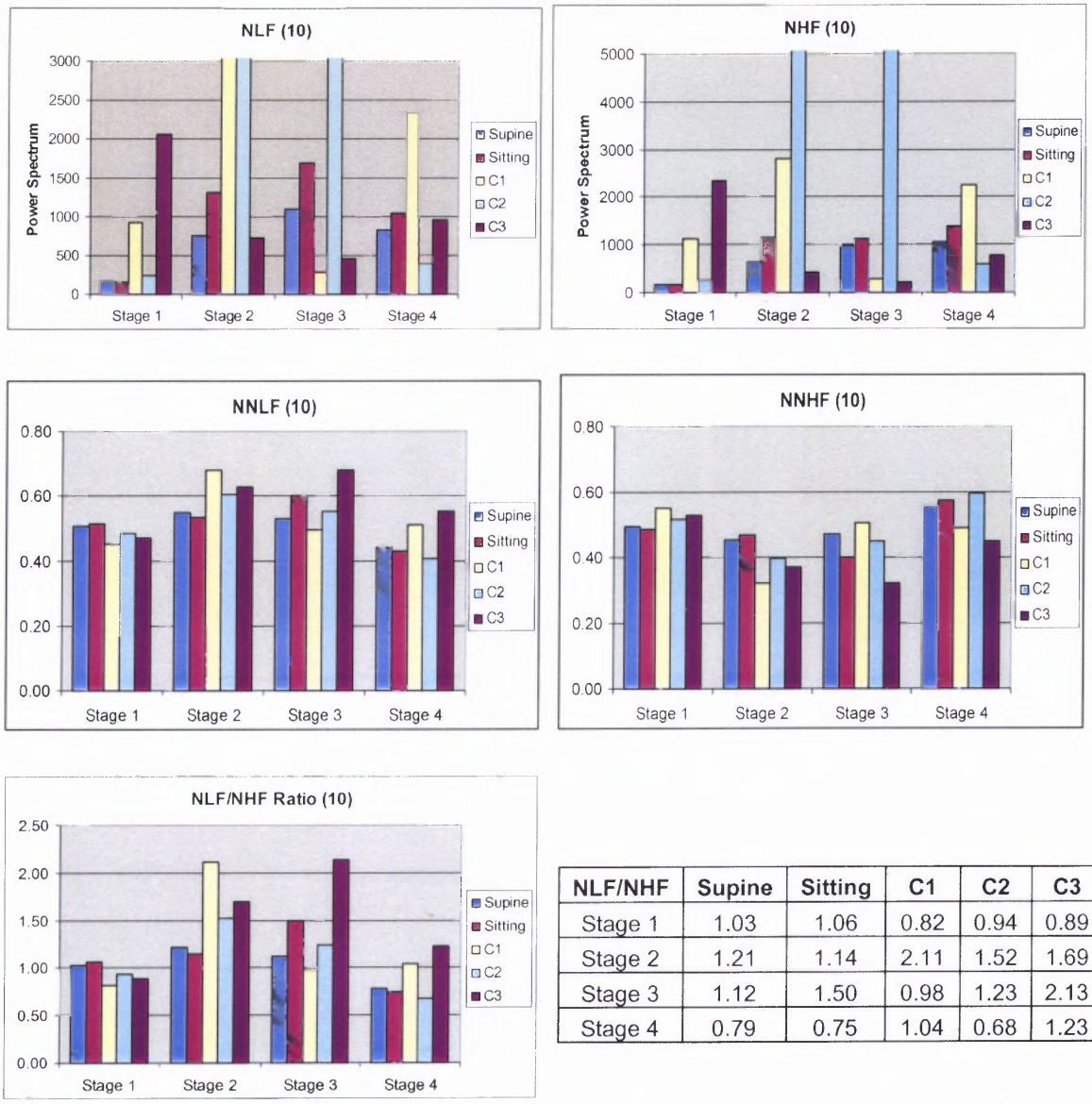
Figure F.8 shows BPV spectra diagrams of SD subject 8. Position induced NNLF and NLF/NHF ratio increases were observed in all stages except in stage 1. The overall NLF/NHF ratio decreased in stage 4.



NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 1	0.60	0.58	1.06	1.00	1.69
Stage 2	3.35	4.95	2.25	1.02	1.22
Stage 3	0.98	1.09	2.60	1.92	1.96
Stage 4	1.61	1.41	1.82	2.22	2.53

Figure F.9 BPV spectra diagrams of SD subject 9.

Figure F.9 shows BPV spectra diagrams of SD subject 9. The NLF/NHF ratio shows a circadian rhythm. The NLF/NHF ratio increased in the morning and deceased at night. No particular trend during the cognitive task was observed.



NLF/NHF	Supine	Sitting	C1	C2	C3
Stage 1	1.03	1.06	0.82	0.94	0.89
Stage 2	1.21	1.14	2.11	1.52	1.69
Stage 3	1.12	1.50	0.98	1.23	2.13
Stage 4	0.79	0.75	1.04	0.68	1.23

Figure F.10 BPV spectra diagrams of SD subject 10.

Figure F.10 shows BPV spectra diagrams of SD subject 10. The NLF/NHF ratio shows an increasing trend in the C3 segments in all stages except stage 1. In the morning (stage 2 and stage 4), the NLF/NHF ratio shows an increasing trend in the C1 segment. The overall HRV of SD subject 10 increased in stage 4 but the overall BPV of SD subject 10 did not increase in stage 4.

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