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Signal processing the human circulatory system for stability and regulation

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Abstract

During this project the components of the circulatory profile of a patient before a cardiac surgery have been analyzed and compared to the perturbed circulatory profile components of the same patient after having a cardiac surgery. All this data is compared to the usual values of a healthy person as well.

The data recorded previous to the surgery, is used as a baseline and compared to the data after the surgery. The data is studied and analyzed in order to create a connection between those two profiles. Making use of the comparison between the two types of data patterns, a characterizing profile and patterns are tried to find to understand the regulation of the circulatory system and try to relate them to control theory techniques. For that purpose frequency and time analysis is performed.

At the beginning of the project, the information regarding the different medicines that were applying to the patients after having the surgery, in order to see how the body was reacting to the drugs was expected. But that information has not been available, so it has not be possible to predict when giving certain drugs to the human being, how the body was going to react. For example if a vasodilator was giving to a patient, its effects should be visible in the immediate time period, and based on that and using control theory techniques a model could be made. As the necessary information to perform that model was not given, other features have been analyzed in the available data and control theory has been studied.

From the analysis of the results it has been observed that there are some common aspects in all the patients before and after the surgery, for example the low values of the R wave amplitude and the diastolic blood pressure. In the frequency domain how most of the energy is around 0-1Hz as expected, can be seen.

In total, the data recorded from 6 patients has been analyzed. All the patients that have collaborated to collect data for this purpose suffer from heart diseases and are considered stable Coronary Artery Bypass Grafting (CABG) patients to standard elective and urgent operation, and are signing a written consent.

CABG is a kind of surgery which aim is to improve the blood flow to the heart. All the recordings have been performed at St Olav Hospital Cardiothoracic Intensive Care Unit and a consulting cardiothoracic anesthesiologist is present at all moment. The study has been approved by the Norwegian Regional Ethics Committee and the data is registered in the ClinicalTrial.org database.

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1 Introduction

1.1 Project scope and objectives

The monitoring of a patient with cardiac problems before and after having a cardiac surgery is necessary to evaluate how the patient is reacting to the medicines that are being applied to their bodies, and whether the evolution of its recovery is going in a correct way or there is any problem. The monitoring is the observation of several parameters over time, it can be done continuously or repeatedly performing medical tests [1]. During this project, data from monitored patients is recorded before and after a cardiac surgery. This is done by applying sensors in different parts of the patients and recording the data using the Powerlab sampling system.

The data before the surgery of each patient is used as a baseline, and compared to the data collected after the operation. This is done to determine if it is possible to predict the reaction that the different aspects of the cardiovascular circulatory profile are going to have in the patients with cardiac problems, and therefore to be able to anticipate the reactions and necessities that another patient under the same cardiac surgery conditions may have.

In order to try to predict the behavior of the different components of the cardiovascular system, control theory techniques are studied in this project. The control theory deals with the behavior of the dynamical systems with inputs, and how their behavior is modified by feedback, specifically in the engineering field. The control system is used to maintain or alter any quantity in accordance to a desired manner, so the obtained results are controlled within a range of values [2].

At the beginning of the this work different aspects where expected to be studied but due to type of data available and timing, not all the desired work has been possible to achieve, and it will be considered as further work to be developed.

1.2 Motivation

For a human body, to deal with large challenges on the circulatory system, in this case having a cardiac surgery, and the stress and fatigue that it implies can exhaust the self-ability of the circulatory system to compensate all the changes that is suffering. As a result the circulatory system may collapse, or as it is termed, decompensation may occur. Decompensation is defined as the deterioration of a previously working structure or system [3].

This particular group of patients which data is recorded from is composed by individuals with some problems in their circulatory resilience because of the cardiac disease they suffer, which has an impact on the pumping function of their hearts. Those patients are suitable to give a better understanding of how the circulatory system is able to adapt to challenges and how it is regulated, due to the amount of fatigue and stress their circulatory system is suffering.

The regulation of the circulatory system is carried out by homeostatic mechanisms which function is to constantly monitor and adjust organs, tissues, cells and glands, to enable the body to function at an optimum steady state [4].

Cardiac or cardiovascular surgery is an intervention performed on the heart or on the proximal great vessels, and there are several risks attached to it. Those risks have to be taken seriously into account [5].

Taking this in mind and due to increasing number of people undergoing cardiac surgery in Norway, more than 4000 interventions are made every year [6]. It is a necessity to minimize the risks and anticipate to the problems that could happen.

2 Theory

The control theory and the hemodynamics are tightly related. The hemodynamics are the part of our body able to control the features of the body and adjust them to the corresponding levels that the human being needs, which is what the control system does in the engineering field. In this section the important aspects of both themes are explained.

2.1 Control Theory

2.1.1 Introduction

The control system in engineering was first described in 1868 by the physicist James Clerk Maxwell, when in the centrifugal governor the phenomenon of the self-oscillation was analyzed leading to dynamic control [7]. Since then, the application of the control theory has been studied and used in different areas, as for example in manned flight by the Wright Brothers, fire-control, guidance systems and electronics during the Second World War, or most recently in ship stabilizers and missiles.

The control theory as known nowadays, deals with the behavior of the dynamical systems with inputs, and how their behavior is modified by feedback. It is used to maintain or alter any quantity in accordance to a desired manner. For that purpose, feedback loops are utilized. Close loop systems are useful to design stable systems, without oscillations, and can achieve the steady state easily. [2]

The transfer function or system function describes mathematically the existing relation in the system between the input and the output variables, making use of differential equations.

The main advantage of using feedback control systems is that the system performance regarding to the variations of the variables and the unwanted disturbances is less sensitive. On the other hand the drawbacks are that the instability is a concern and that in order to have the feedback loop, more components are needed.

The control system can be said to have four major functions; measuring, comparing, computing and adjusting values. Those functions are described using a block diagram as it follows: [2]

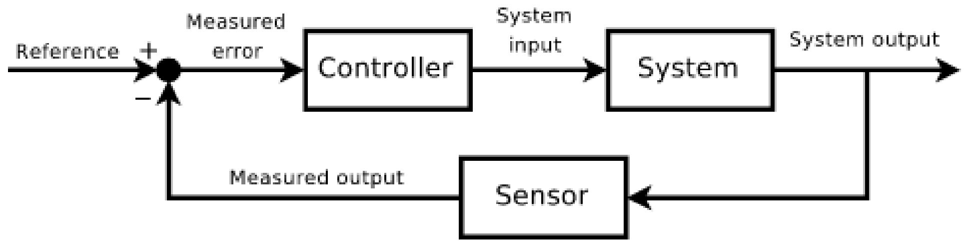

Figure 1. - Control system block diagram

Reference: is the value that the measured output wants to achieve, it can either be a fixed or a variable value.

Measured error: is the existing difference between the measured output and the reference value, and it applied as feedback.

The controller: is the responsible of adjusting dynamically the behavior of the different elements taking into account the measured outputs. It controls the values of the system input in order to achieve the reference value.

System input: it can be adjusted in a dynamical way and is it manipulates the behavior of the system.

The system: it manipulates the elements to get the wanted output.

The system output: is a characteristic that can be measured of the system.

The sensor: is the responsible of transforming the measured output in order to be compared to the reference [8][9].

The major properties that control theory deals with are:

Observability: when by regarding the output values of the system, the behavior of the whole system can be determined.

Stability: if the input is bounded, the output is as well bounded.

Controllability: when an output is suitable to be changed by an external input value from any initial condition to any final condition in a certain period of time.

The control specification: there exist several control strategies that are explained later on this text which differences depends on which criteria are following. They all have in common the stability criterion; the close-loop has always to be stable no matter how the open-loop stability is.

Robustness: is the ability to the properties do not change, even if the system is not exactly the same as mathematical one, that is, it can cope with errors.[9][10]

2.1.2 Classification

There exist three main aspects when classifying a control system, linearity, type of domain and number of inputs and outputs.

Linear: the superposition principle is applied in those types of systems; the input and the output are proportional due to the linear equations they are governed by. Linear Time Invariant (LTI) systems are of this kind.

Non-linear systems: the output is not proportional to the input and therefore the superposition principle is not followed. Usually non-linear differential equations describe those systems and are more difficult to handle them. They are used to model real world systems which require specific techniques.

Frequency domain: the variables are displayed as frequency functions, so some kind of transform has to be used, Laplace Transform, Fourier Transform… in order to change from time domain to frequency domain the inputs and the transfer function. As a consequence the system is not described by differential equations, but by algebraic equations, being easier to solve them. As a disadvantage, linear systems can only support the frequency domain techniques.

Time domain systems: the variables are displayed as time functions and differential equations are used to describe the system. They are used to describe real world systems, which are more difficult to analyze.

SISO systems: stands for Single Input Single Output, and it describes the situation of having a single output which is controlled by a unique control signal. It is the simplest type of control theory systems and also the most common one.

MIMO systems: stands for Multiple Input Multiple Output systems. Those kinds of systems are used in nuclear reactors and telescopes [9] [11].

2.1.3 Approaches

Classical control theory: a feedback is introduced to the open-loop controller, getting over to the limitations that the open-loop controller has. Those are the main advantages the feedback introduced:

- The tracking of the reference input is better; as a consequence there exists better tracking performance.
- The sensitivity is reduced.
- Stabilization is improved.
- The performance is guaranteed even when there are mismatches between the model structures.

Modern control theory: is characterized because of the use of the time domain state space representation, which is a mathematical model of a set of input, output and state variables related by first-order differential equations. This representation is a suitable way to model and study systems that consist on more than one inputs or outputs because they can be displayed as vectors, and therefore the representation is not only able for linear systems [10].

2.1.4 Control strategies

One of the most important aspects, as mentioned before, is to maintain the stability of the close-loop. In order to control that, there are several different control techniques that are going to be explained above.

Hierarchical control: a hierarchical tree composed of nodes in different levels (subordinates and superiors); each of them with its own features is used to perform the feedback loop.

Intelligent control: is characterized because of the use of Artificial Intelligence (AI) computing in order to be able to control the dynamic system.

Robust control: initially there is some uncertainty on the parameters but as it is bounded, stability can be achieved. This is the case of the high gain feedback where if the gain is high enough the variation of the variables will not almost affect the result. It is usual in systems using this technique to have multiple feedback loops.

Stochastic control: the model is supposed to have an amount of uncertainty which the system will handle. It is assumed to have disturbances as well as random noise, so the deviations that might occur have to be taken into account.

Adaptive control: it is based on the estimation of the parameters that are used. The variables are not known at the beginning and there is no initial information regarding the bounds, so the controller has to adapt to a controlled system. The most important adaptive control techniques are feedback adaptive control or feedforward adaptive control.

Optimal control: it is one of the most used techniques; it is based on optimizing the output having chosen a criterion. There exists two main methods, Model Predictive Control (MPC) and Linear Quadratic Gaussian control (LQG) [10] [12].

2.1.5 Systems classifications

Decentralized systems control: it is called this way when there are many controllers, they have to be constantly communicating in order to coordinate their actions, and one of the main advantages is that in that way, the system covers a bigger area.

Linear systems control: characterized by its homogeneity and its additivity, they are easy to analyze.

Nonlinear systems control: it is real world base, but difficult to manage, linearization techniques are used to linearize then but in most of the cases each non-linear system has to be analyzed from the very beginning.

Deterministic system control: it does not depend on external parameters.

Stochastic systems control: it depends on external random parameters [12].

2.2 Hemodynamics

2.2.1 Introduction

The term hemodynamics is defined as the study of the movements of the blood flow and the forces concerned therein. It explains which are the laws that control the flow of the blood in the blood vessels. The circulation of the blood in the cardiovascular system is called blood flow, and it is necessary to carry the nutrients, hormones etc. from one part of the body to the other. The blood vessels are part of that circulatory system and have the responsibility of transporting the blood throughout the whole body. There exist three main types which are arteries, they take the blood from the heart to the rest of the body, the veins, that take the blood to the heart and the capillaries that are responsible of exchanging the chemicals between the tissues and the blood.

The hemodynamic response is the responsible of monitoring and adjusting the necessary parameters in the body according to its environment. To have a correct blood circulation or blood flow is synonymous of good quality of live, longevity and cardiovascular health due to the fact that all tissues are supplied by an adequate amount of oxygen. During this project hemodynamics of the patients are analyzed due to the fact that a big amount of cardiovascular problems are related to hemodynamic dysfunction. The study of the hemodynamics and its homeostatic mechanisms is a challenging role due to the complexity of the blood vessels [13].

2.2.2 Homeostatic mechanisms and modulators

The homeostatic mechanisms are the parameters that control the circulatory system, they are classified mainly on cardiac hemodynamics and arterial hemodynamics, even though there are many of them, in this document a brief description of some the basic ones is presented.

Velocity of blood flow: the amount of blood that comes to the heart is similar to the amount of blood that the heart pumps out every minute, because of this the velocity can be calculated by the cross sectional area.

$$Velocity(cm/s) = \frac{Blod\ flow\ (ml/s)}{Cross\ sectional\ areacm^2)}$$

Blood Pressure (BP): is a consequence of the pumping of the heart that makes to variate the systemic arterial blood pressure. The maximum value of that variation is called systolic pressure (BPsys) and minimum variation of it is called diastolic pressure (BPdia). Both parameters are used to obtain the Mean Arterial Pressure.

$$MAP = \frac{2}{3}BPdia + \frac{1}{3}BPsys$$

Turbulence: depending on the level of smooth of the vessels, the blood flow can behalf as turbulent or laminar flow, that is chaotic or smooth flow. The smooth flow can be change to turbulence due to the amount of fat in the arterial walls. This parameter can be characterized by the Reynold's Number (RN), where the density of the blood (ρ), the mean velocity of the blood (v), the diameter of the vessel (L) and the viscosity of the blood (μ) take part. If the result obtained is above 2200, there is turbulence, if it is below, the flow is laminar.

$$NR = \frac{\rho v L}{\mu}$$

Resistance (R): is the relation between pressure and blood flow. It can be described using the Hagen-Poiseuille equation where ΔP is the pressure gradient, μ is the viscosity, l is the length of the vessel, Q is the flow rate of the blood and r is the radius of the vessel.

$$\Delta P = \frac{8\mu l Q}{\pi r^4}$$

$$R = \frac{\Delta P}{Q}$$

As mentioned before, in order to have a healthy cardiovascular system, and adequate supply of oxygen is required in all tissues, no matter under which metabolic condition they are, this is achieved thanks to four modulators, which values are corrected every hear beat according to the necessities of the body. Those modulators are the responsible of the changes in the blood pressure and in the blood flow and are known as intravascular volume, inotropy, vasoactivity and chronotropy, and their disorder can be modified by pharmacological agents as volume-reducing drugs, positive and negative chronotropes, positive and negative inotropes and vasodilators and vasoconstrictors [14].

2.2.3 Electrocardiogram (ECG)

It is a test based on the measurements of the electrical activity of the heart during a certain period of time placing electrodes on the patient. The electrodes are able to detect the electrical differences on the skin that the heartbeat makes. Regarding to the information that it gives, it is possible to detect whether or not the patient has a cardiovascular disease. The ECG is characterized by five or six peaks, the PQRST and sometimes U waves. The wave that is analyzed in this project is the R that represents the electrical stimulus as it goes through the ventricular walls, that are thick and as a consequence, the voltage is higher [15].

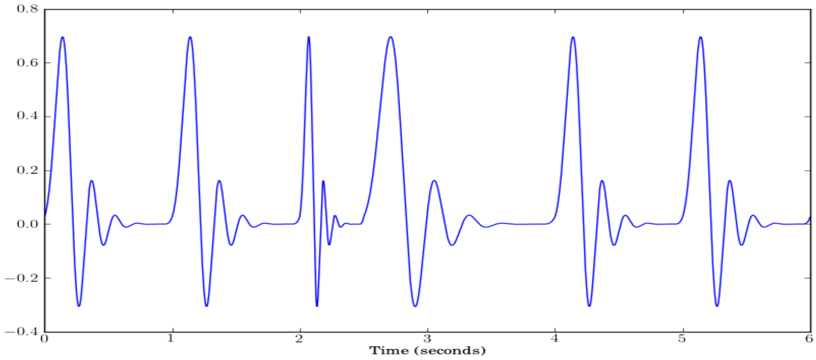

Figure 2.-ECG signal

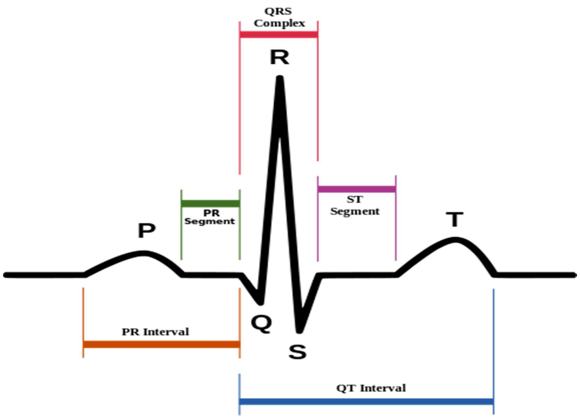

Figure 3.-QRST wave

3 Procedure

3.1 Equipment

In order to analyze and study the data during the project, Matlab program has been used.

The data that has been managed in this project has been collected using PowerLab sampling system that is a high performance data acquisition hardware. This equipment has been handled by medicine students in St. Olav hospital in Trondheim in order to collect reliable data and then it has been given to the university in order to analyze it.

Figure 4.-Powerlab sampling system [16]

3.2 Available data

During the realization of the project several changes have been had regarding how the available data was going to be and which information was going to contain.

At the beginning of the project, there was several information to be analyzed, ECG, heart rate, blood pressure, laser Doppler flow, spirometry and finger pressure, but lately it was decided to focus on analyzing the data corresponding to ECG and blood, due to the difficulties of getting correctly the other data. It was also going to be available the information regarding when the patient was given medicines, in order to predict depending on the type of medicine what changes were expected in the homeostatic mechanisms, even though finally this data could not be available, specific time periods have been asked to analyze.

The results in this project have been obtained by analyzing data that corresponds to patients that are having a cardiac surgery. There is around one hour of data recorded previous to the surgery, called baseline, and around 13 to 17 hours of recordings after the surgery. There was not available the same amount of data for each patient, so the number of post-surgery hours that are analyzed variate.

The sample frequency in all the cases is the same 400Hz. Regarding to the ECG and blood pressure, all the hours are analyzed in the time domain but due to the big amount of data in the post-surgery data, specifically in the frequency domain three periods of time are analyzed in each case, those periods last each of them an hour and have been chosen by a doctor to be analyzed. As drawback the type of cardiac surgery that the patients are having is unknown.

In order to analyze and compare how the body reacts before and after a cardiac surgery, data collected before the surgery has been studied and taken as a baseline and then compared to the data recorded during post-surgery hours. All the data is also compared to the data corresponding to a healthy person, to see if it variates between the usual values of a sane person. In order to achieve that aim, different techniques have been used, for example the Fast Fourier Transform (FFT) of the ECG signal and the power spectral density of a healthy ECG are computed in order to compare it to the data collected.

The table above shows those usual values of a healthy person regarding blood pressure, R peak and the energy of an ECG signal during an hour.

Systolic blood pressure	Diastolic blood pressure	RR peaks interval time	R peak amplitude	Energy
90 -140 mmHg	60 -90 mmHg	0.6-1.2 s	2,5-3mV	$2{\cdot}10^{-4}$-$2{\cdot}10^{-5}$ J

Table 1.-usual values [14]

3.3 Methodology

In this section the different techniques that have been used In order to compare the information about ECG and blood pressure are explained briefly. Some techniques have been useful and conclusions have been obtained, but other techniques that have been used are not explained due to the lack of effectiveness when trying to obtain information using them. For example the correlation between the baseline and the post-surgery signal has been analyzed every hour, but the similarity between them has not been included in the results, it did not give any relevant information.

Periodogram: a method to identify and describe which are the dominant cycles or frequencies in a time series. It is used as a tool to examine the cyclical behavior of a signal in a time series [17]. The Bartlett's method and Welch's overlapped segment averaging estimator have been used.

Fast Fourier Transform or FFT: is an algorithm for computing the DFT with fewer multiplications, that is, it computes fewer operations. Using this technique the signal changes from time domain in this case to frequency domain representation. By its use it is possible to analyze which are the main frequencies [18].

During this project, as the FFT of a long signal (an hour) needed to be analyzed, so the procedure of doing it has been this one. First the signal has been cut in segments of 10 minutes each, for each value in a certain position of the signals the average value has been calculated, and the FFT of the resulting signal of 10 minutes made of averages of the whole hour has been calculated.

Energy of the signal: it is defined as the area under the squared signal [19].

$$E_s = \int_{-\infty}^{\infty} |x(t)|^2 dt$$

Regarding ECG signal in the time domain, the distance between the consecutive P, Q, R, S, and T peaks and the amplitude of each peak value is obtained. When analyzing the data corresponding to the blood pressure, the values of the amplitude of the systolic and diastolic blood pressure is analyzed. It can be seen in the next figure in red color the peaks corresponding to the systolic blood pressure and in blue the peaks corresponding to the diastolic blood pressure.

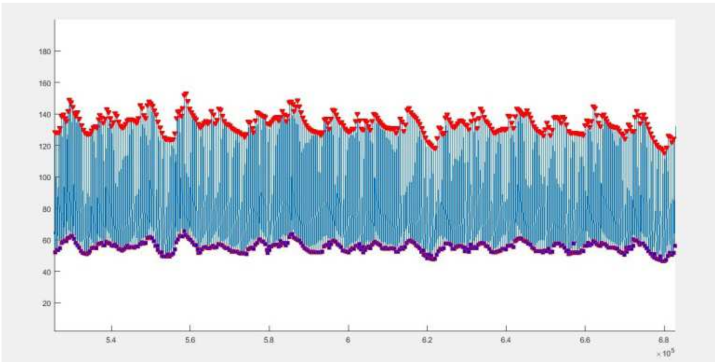

Figure 5.-Peak detection

When analyzing the ECG signal in the time domain, only the results of the values corresponding to the distance between R peaks and their amplitudes it is analyzed. The data corresponding to P, Q, S and T peaks does not give medical relevant information, so it is not included. Regarding to periodogram, the Pwelch results are included, technique that gives more useful results than the Bartlett's method.

In the figure below the relevant peaks of the ECG signal are pointed, that is the R peaks.

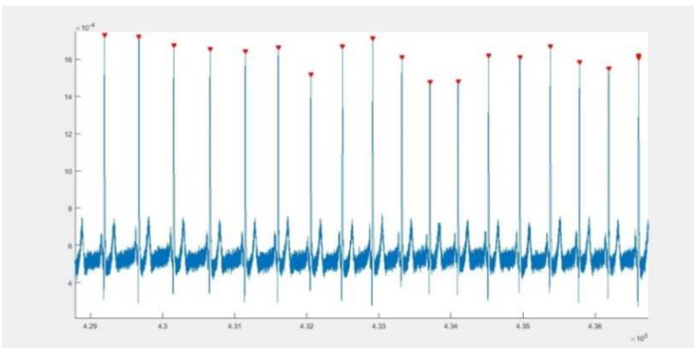

Figure 6.-R peak detection

4 Results and discussion

Before the surgery the data corresponding to the baseline of each patient is exposed in a table, as well as the graphics corresponding to the FFT and the periodogram. After the surgery the results of each patient and the evolution of the blood pressure and the amplitude and interval between the R peaks is analyzed during each hour of recording and plotted. The graphics corresponding to the three periods of one hour each that are analyzed using FFT and periodogram are also included. The energy of the signal is also analyzed.

4.1 First patient

4.1.1 Baseline

Systolic blood pressure	Diastolic blood pressure	RR peaks interval time	R peak amplitude	Energy
138.5 mmHg	57 mmHg	1.0883 s	0.0016 V	8.0191·10^-5 J

Table 2.-Baseline values patient 1

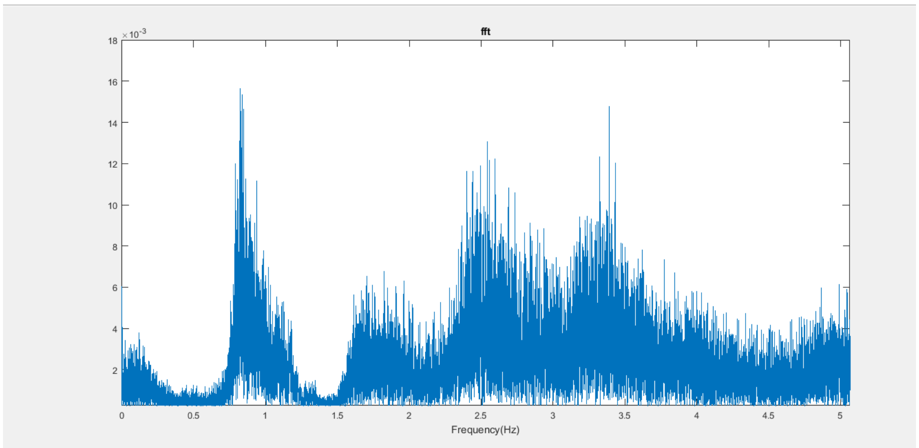

Figure 7.-FFT baseline patient 1

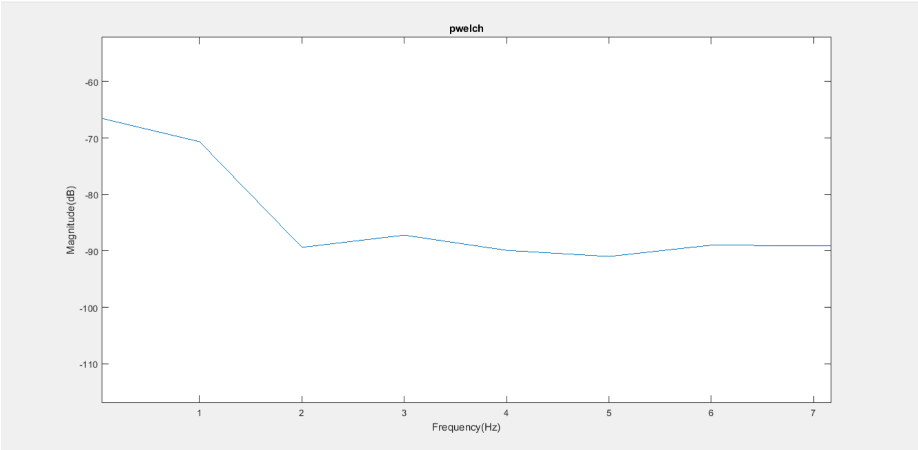

Figure 8.-Periodogram baseline patient 1

4.1.2 After surgery

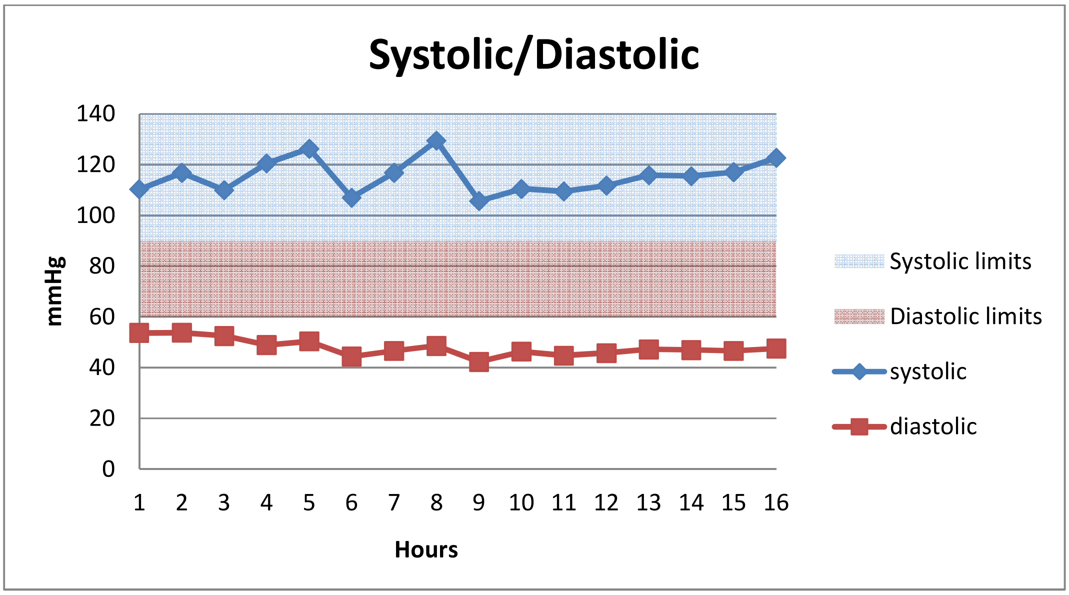

Figure 9.-Systolic/diastolic values patient 1

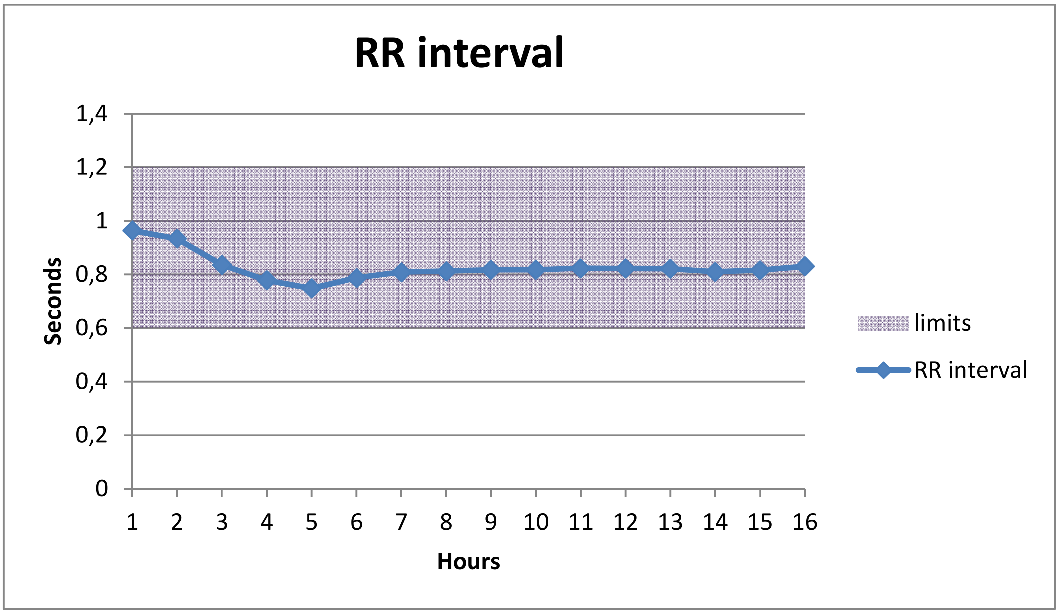

Figure 10.-RR interval patient 1

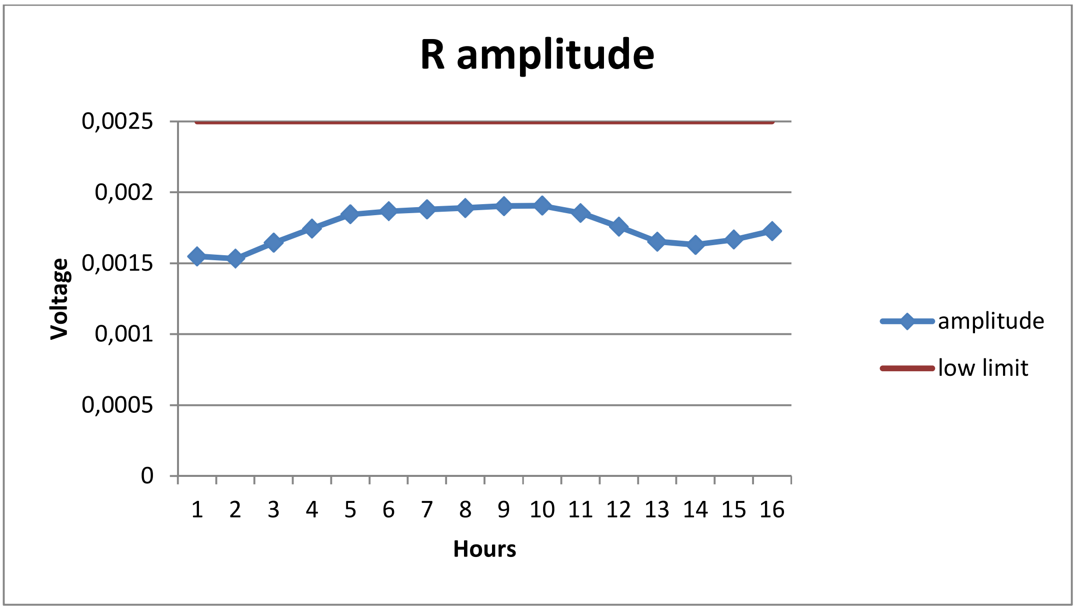

Figure 11.-R amplitude patient 1

	Period 1	Period 2	Period 3
FFT max. Value(v^2)	0.01	0.02	0.03
Frequency(Hz)	1.1	1.25	1.25

Table 3.-FFT values of the periods patient 1

	Period 1	Period 2	Period 3
Periodogram (dB)	-62	-63	-67

Table 4.-Periodogram values of periods patient 1

Period 1 (30.00 - 1.30.00)	Period 2 (2.00.00 - 3.00.00)	Period 3 (15.45.00 - 16.45.00)
3.3875e-05 J	9.5833e-05 J	1.1707e-04 J

Table 5. - Energy of the periods patient 1

4.1.3 Discussion

The baseline indicates that all the values are in the appropriate range except the one corresponding to the amplitude of the R signal. Even though the diastolic blood pressure is a little bit low, the data analyzed after the surgery indicates a low diastolic pressure and low R wave amplitude, the same as seen in the baseline. Regarding to the periodogram the results are similar to the baseline, and the energy also gives similar values. The Fourier transform maintains also similar values in the different periods of time, so no significant changes are appreciated. The energy stands between usual values.

4.2 Second patient

4.2.1 Baseline

Systolic blood pressure	Diastolic blood pressure	RR peaks interval time	R peak amplitude	Energy
209.4 mmHg	69.7 mmHg	0.6917 s	- V	6.8158·10^-5 J

Table 6.-Baseline values patient 2

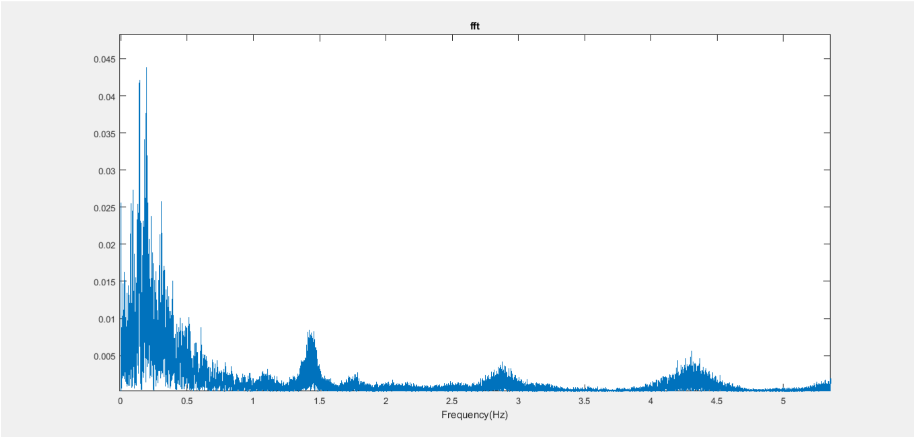

Figure 12.-FFT baseline patient 2

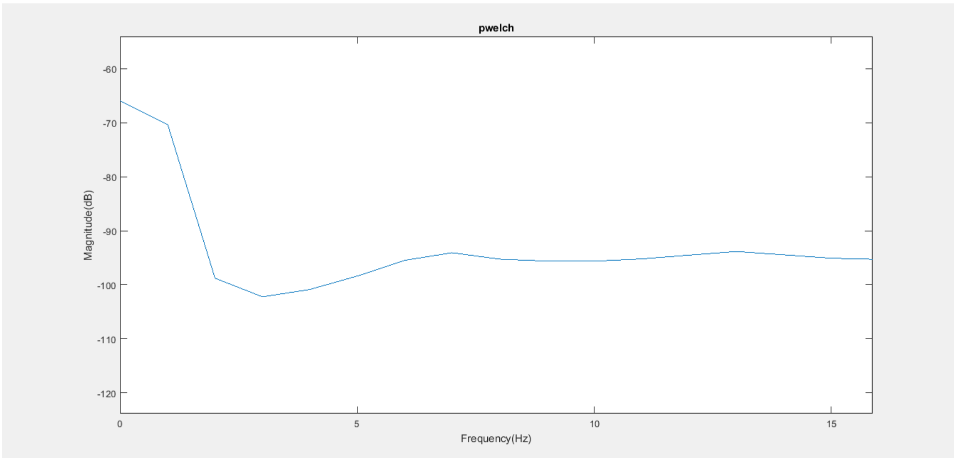

Figure 13.-Periodogram baseline patient 2

4.2.2 After surgery

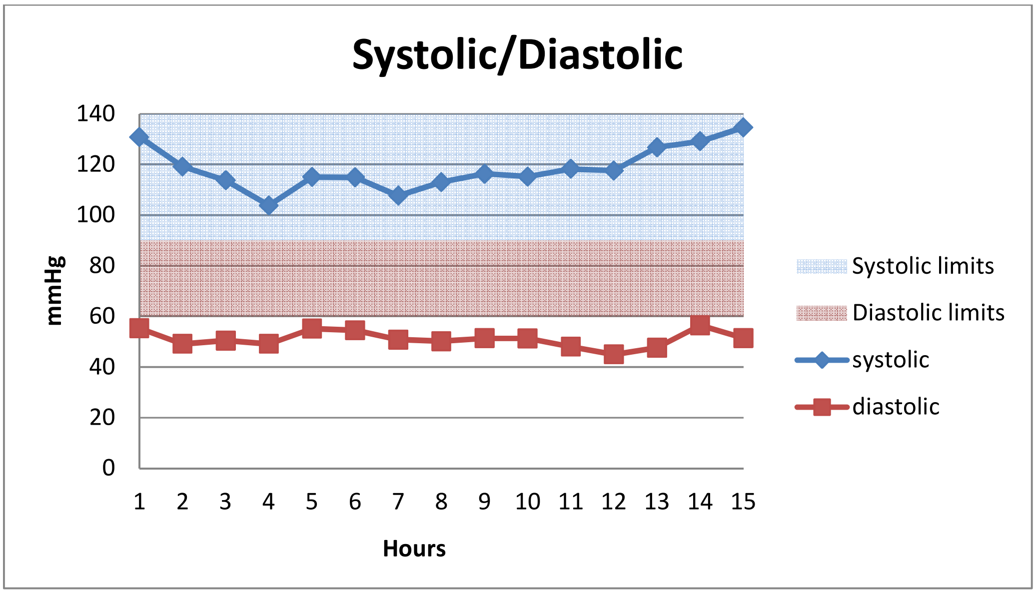

Figure 14.-Systolic/diastolic values patient 2

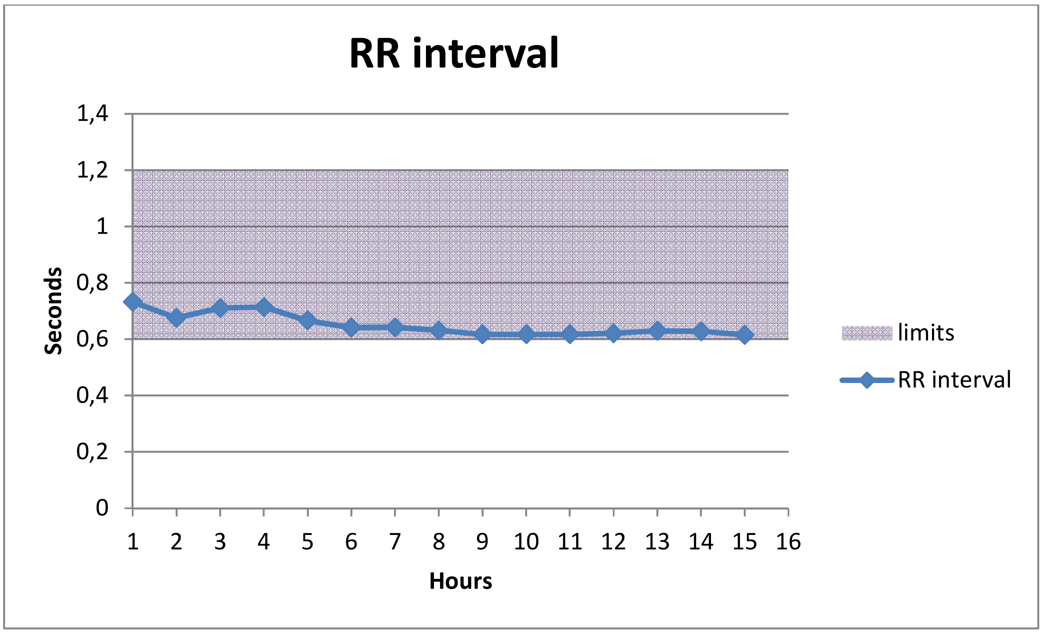

Figure 15.-RR interval patient 2

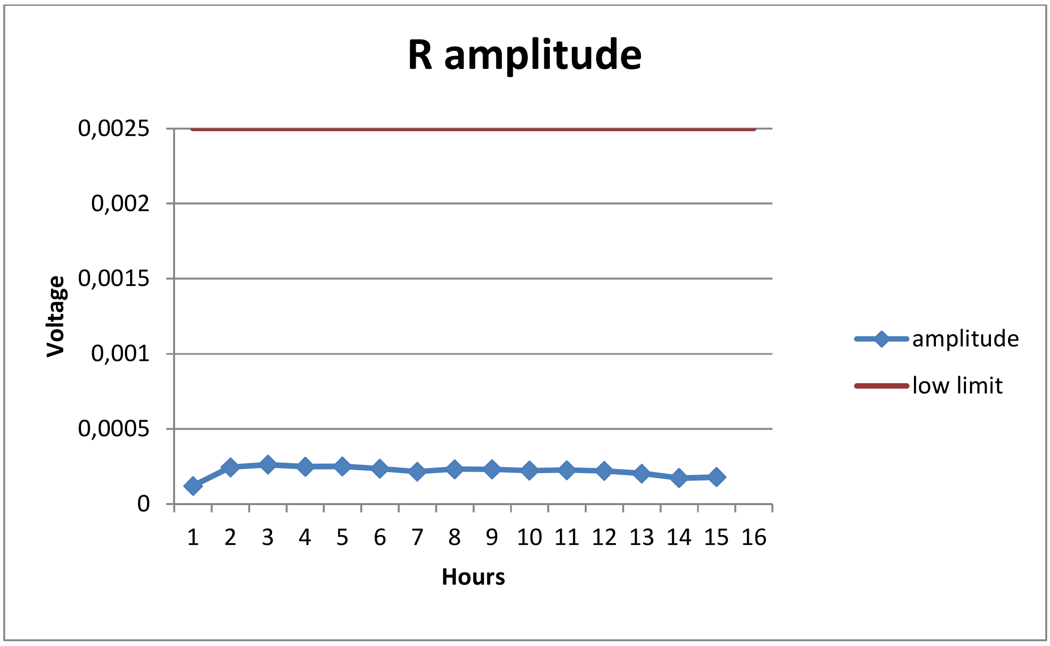

Figure 16.-R amplitude patient 2

Period 1 (42.00 - 1.42.00)	Period 2 (2.07.00 - 3.07.00)	Period 3 (15.15.00 - 16.15.00)
1.195e-05 J	4.4708e-05 J	3.852e-05 J

Table 7. - Energy of the periods patient 2

	Period 1	Period 2	Period 3
FFT max. Value(V^2)	0.01	0.026	0.01
Frequency(Hz)	0.2	0.1	0.2

Table 8.-FFT values of the periods patient 2

	Period 1	Period 2	Period 3
Periodogram (dB)	-79	-78	-78

Table 9.-Periodogram values of periods patient 2

4.2.3 Discussion

The systolic pressure in the baseline is high, but in the post-surgery hours that problem does not appear. The diastolic pressure is low after the surgery and the RR interval lies on the limit. The periodogram values are lower in the post-surgery hours, but in the three periods of time they maintain similar values, around -80. The FFT maximum values are also similar in the periods of time, they occur in similar frequencies, close to zero Hertz, and in the baseline occurs the same thing. The value of the energy of the first period is a little bit lower comparing to the baseline and other periods, but it is not a problem. The R value cannot be calculated due to noises, nonsense value.

4.3 Third patient

4.3.1 Baseline

Systolic blood pressure	Diastolic blood pressure	RR peaks interval time	R peak amplitude	Energy
133.3 mmHg	64.7 mmHg	0.7976 s	0.0016 V	1.3767e-4 J

Table 10.-Baseline values patient 3

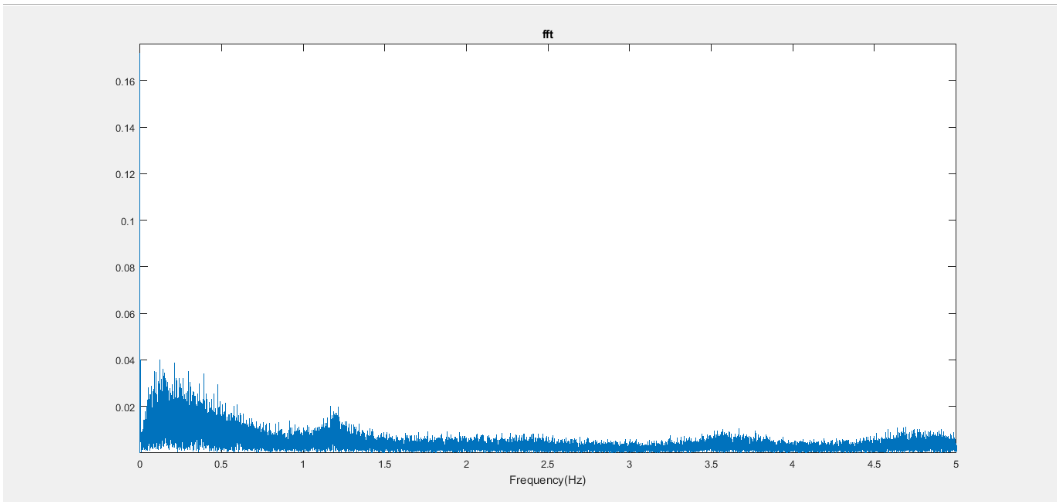

Figure 17.-FFT baseline patient 3

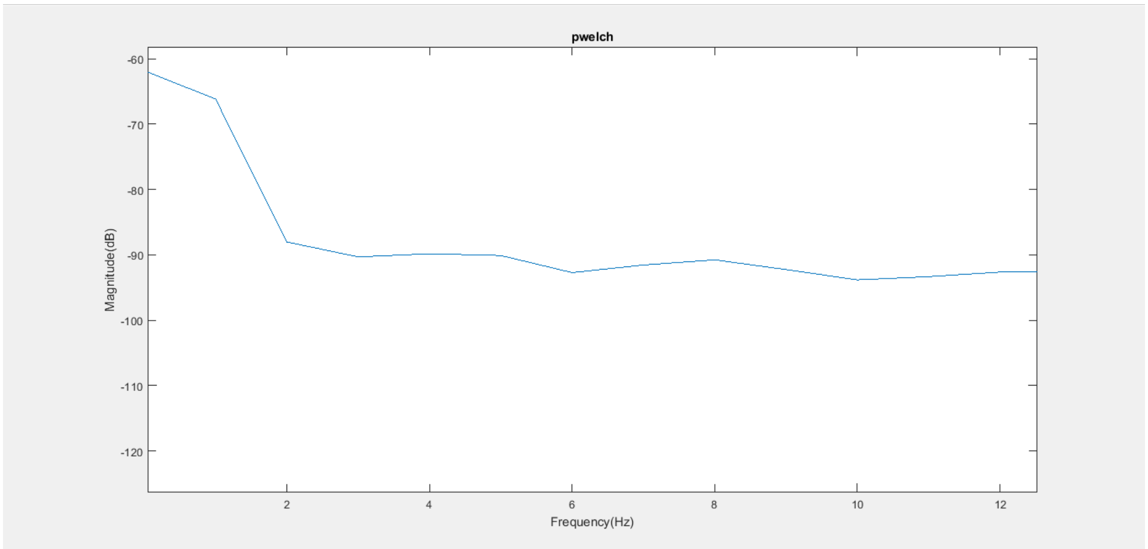

Figure 18.-Periodogram baseline patient 3

4.3.2 After surgery

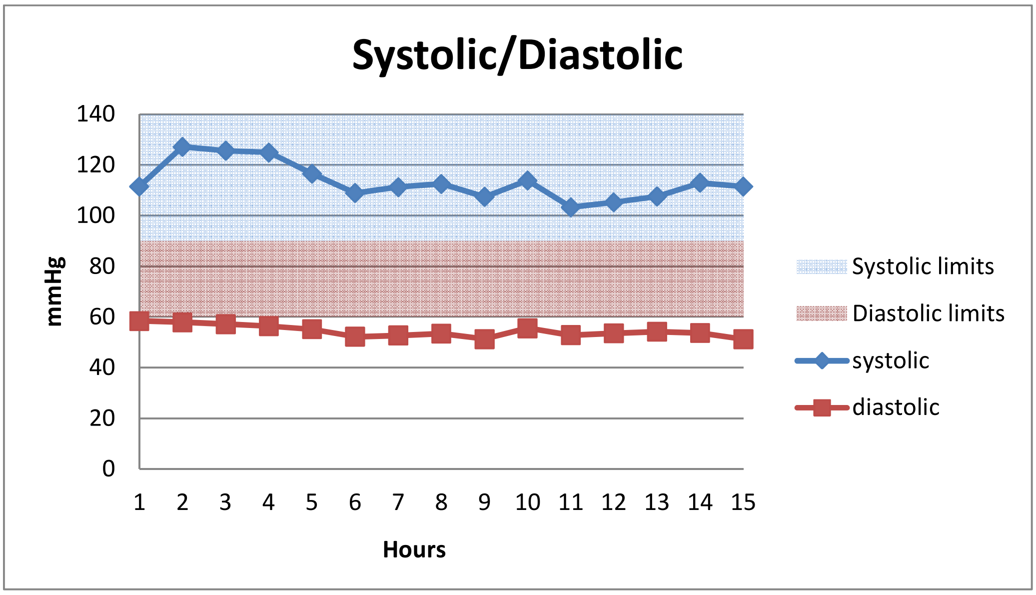

Figure 19.-Systolic/diastolic values patient 3

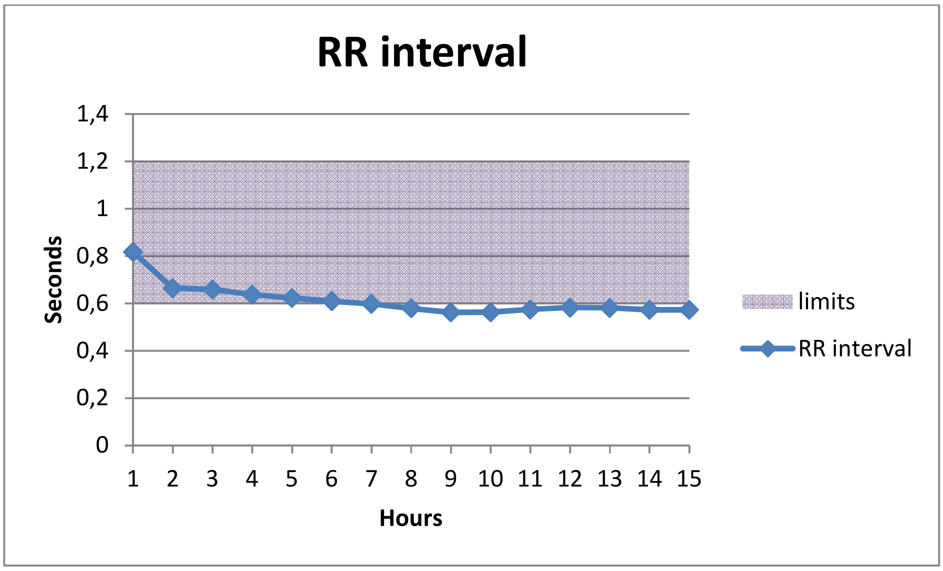

Figure 20.-RR interval patient 3

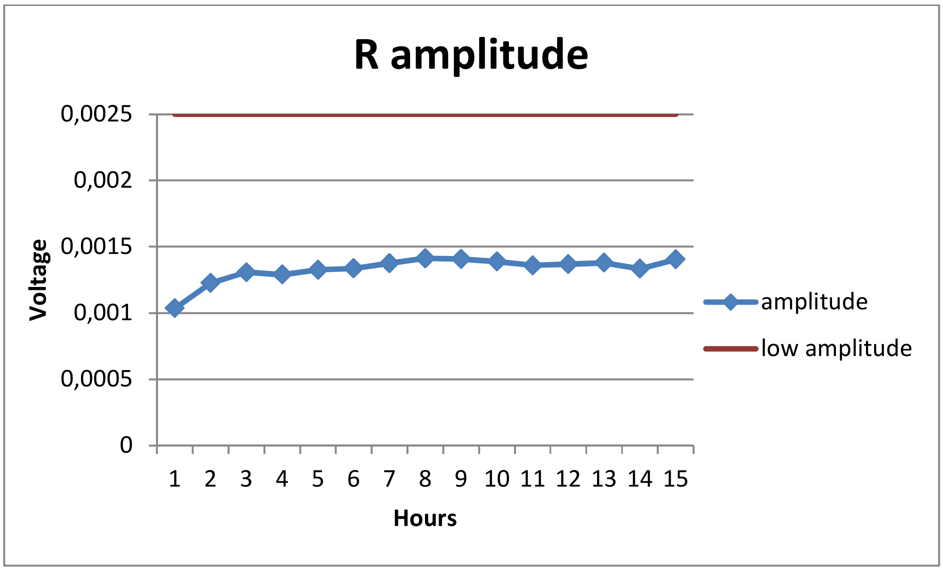

Figure 21.-R amplitude patient 3

Period 1 (52.00 - 1.52.00)	Period 2 (2.00.00 - 3.00.00)	Period 3 (14.30.00 - 15.30.00)
2.0595e-05 J	4.7788e-05 J	0.0092 J

Table 11.-Energy of the periods patient 3

	Period 1	Period 2	Period 3
FFT max. Value(V^2)	0.04	0.03	-
Frequency(Hz)	1.1	1.5	-

Table 12.-FFT values of the periods patient 3

	Period 1	Period 2	Period 3
Periodogram (dB)	-68	-69	-63

Table 13.-Periodogram values of periods patient 3

4.3.3 Discussion

The values corresponding to the diastolic blood pressure and the R amplitude are low. The FFT maximum values around the same frequencies in all the periods except in the baseline, which maximum values are around 0.14 and is around 0 Hz. The periodogram shows similar values in all the cases. Regarding the energy, the signal shows a high energy level in the third period. The value of the RR interval decreases the last post-surgery hours, and the same happens to the diastolic and systolic blood pressure. The values corresponding to the third period cannot be calculated due to noise.

4.4 Fourth patient

4.4.1 Baseline

Systolic blood pressure	Diastolic blood pressure	RR peaks interval time	R peak amplitude	Energy
125.2 mmHg	68.5 mmHg	0.6525 s	0.0013 V	1.0071e-4 J

Table 14.-Baseline values patient 4

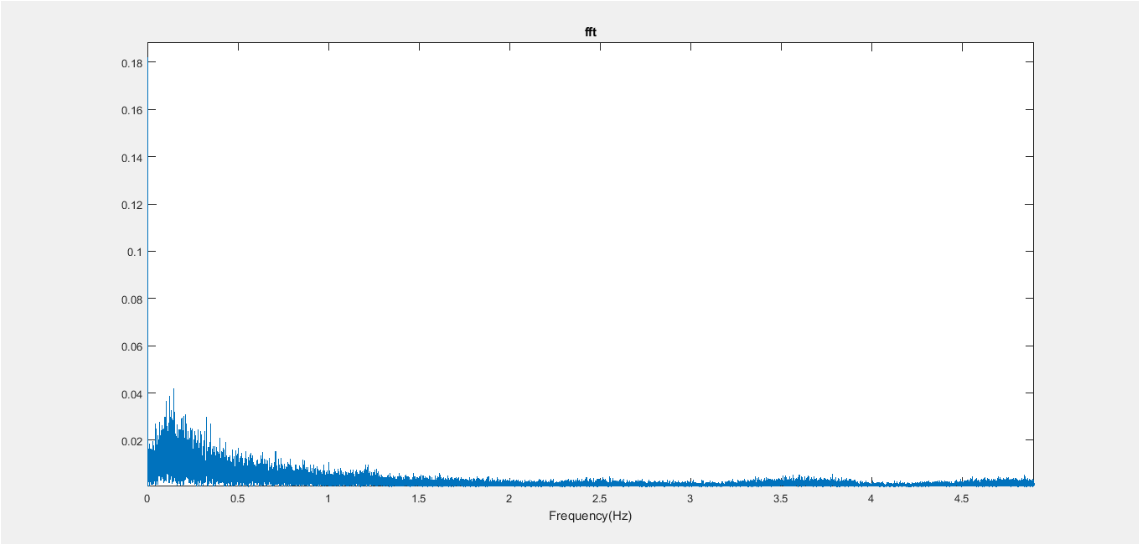

Figure 22.-FFT baseline patient 4

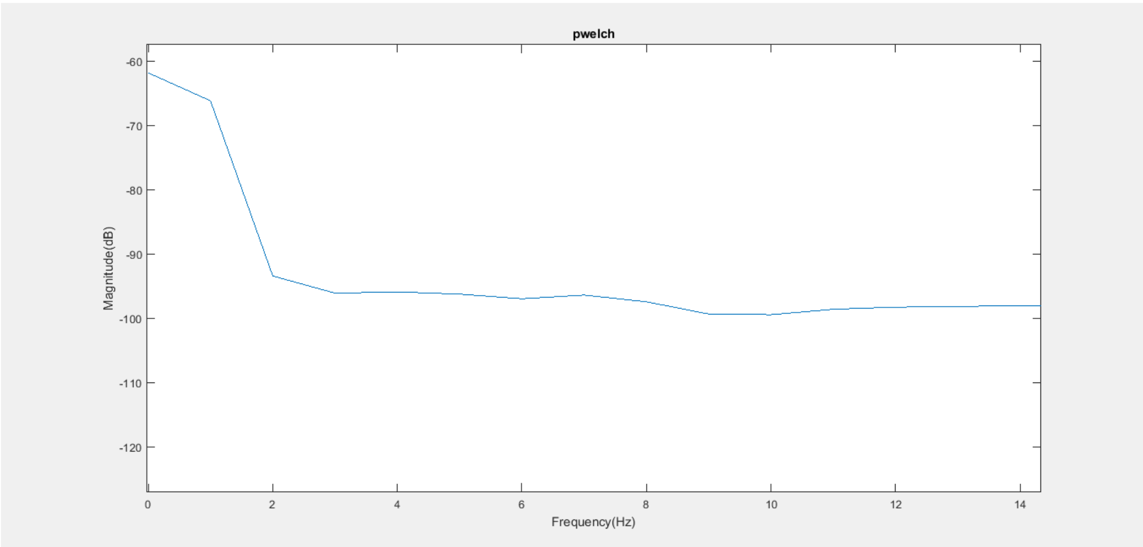

Figure 23.-Periodogram baseline patient 4

4.4.2 After surgery

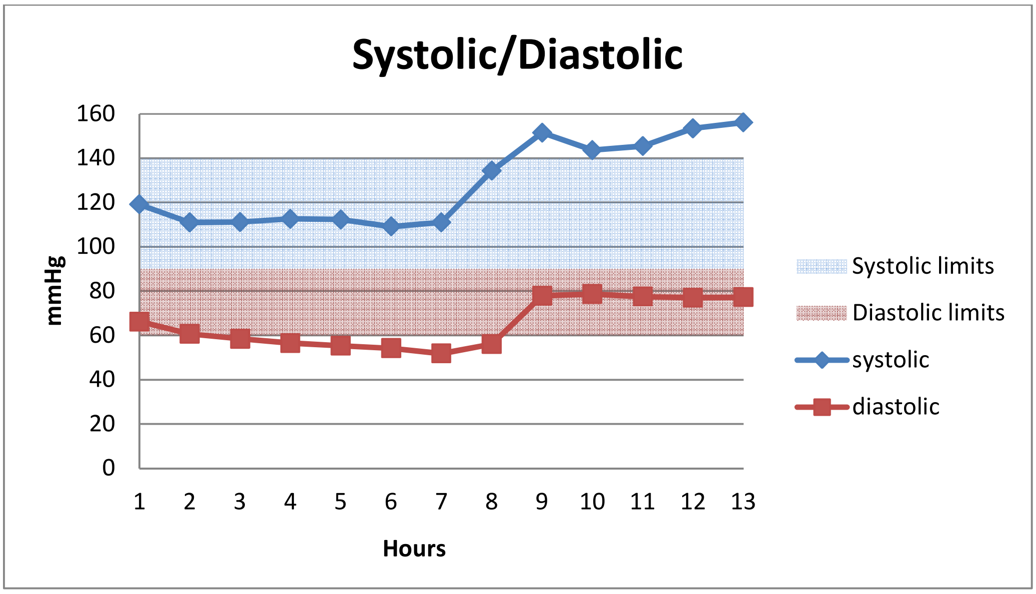

Figure 24.-Systolic/diastolic values patient 4

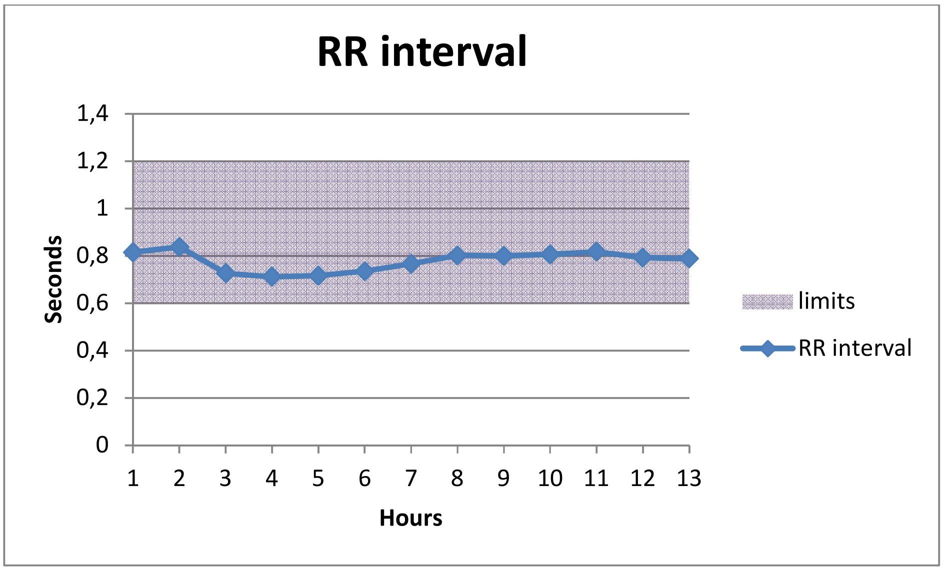

Figure 25.-RR interval patient 4

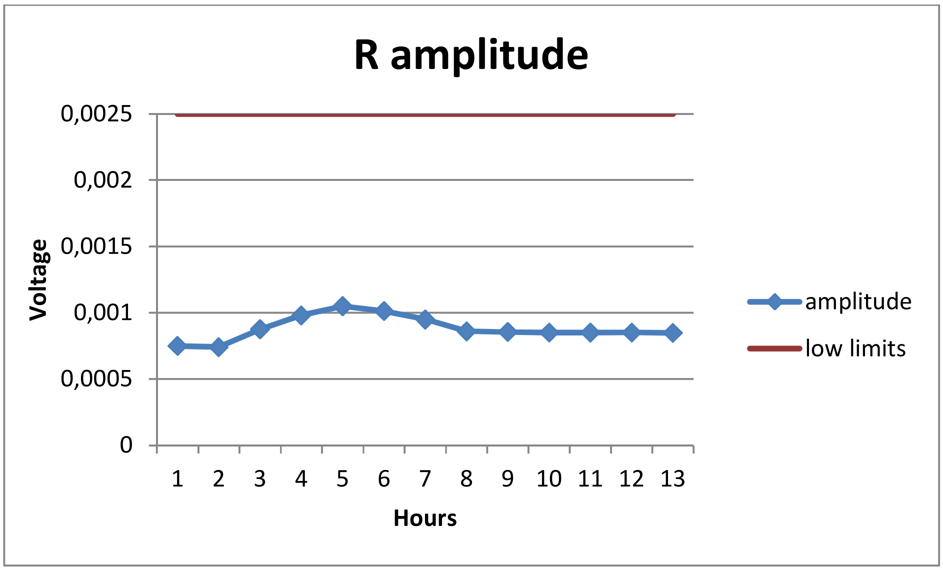

Figure 26.-R amplitude patient 4

Period 1 (1.50.00 - 2.50.00)	Period 2 (3.00.00 - 4.00.00)	Period 3 (11.00.00 - 12.00.00)
8.1102e-06 J	2.2983e-05 J	1.2232e-05 J

Table 15.-Energy of the periods patient 4

	Period 1	Period 2	Period 3
FFT max. Value(V^2)	0.0018	0.03	0.014
Frequency(Hz)	0.1	1.5	1.4

Table 16.-FFT values of the periods patient 4

	Period 1	Period 2	Period 3
Periodogram (dB)	-68	-69	-68

Table 17.-Periodogram values of periods patient 4

4.4.3 Discussion

The last hours after the surgery it is appreciated how there is a significant change in the blood pressure. All the periodogram values are similar and the R amplitude is low in all the cases. The values corresponding to the energy of the signal are lower in the post-surgery periods than in the baseline, especially in the first period. The values corresponding to the maximum FFT values vary a little in this case. In the baseline the maximum value is achieved around 0Hz and is higher than the values in the post-surgery periods that are lower. The first period is around 0Hz, like the baseline but the other two cases lie around 1Hz.

4.5 Fifth patient

4.5.1 Baseline

Systolic blood pressure	Diastolic blood pressure	RR peaks interval time	R peak amplitude	Energy
150.3 mmHg	75.3 mmHg	1.0046 s	0.0018 V	1.1046e-4 J

Table 18.-Baseline values patient 5

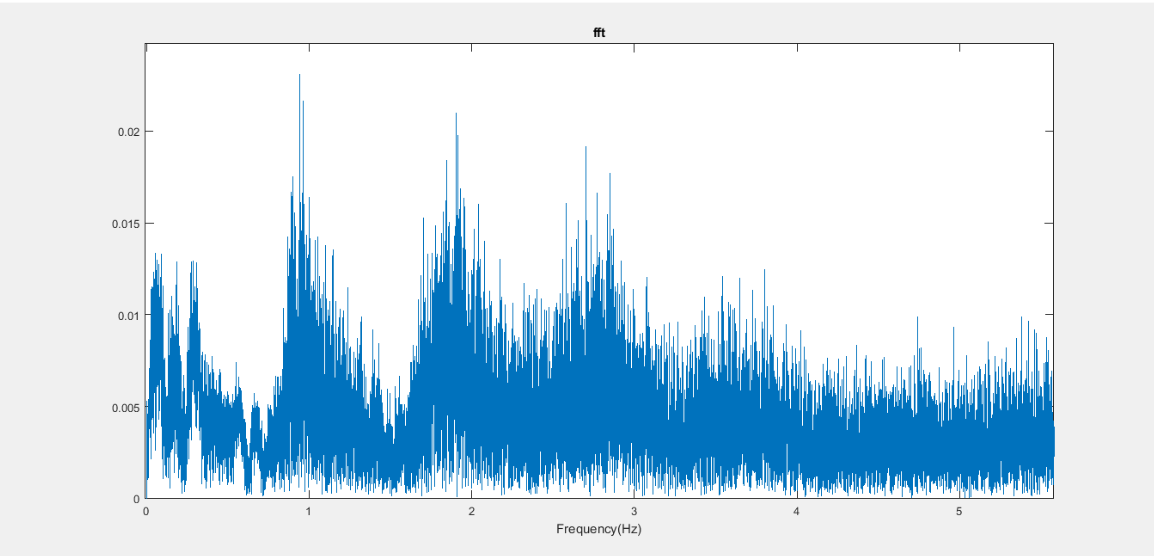

Figure 27.-FFT baseline patient 5

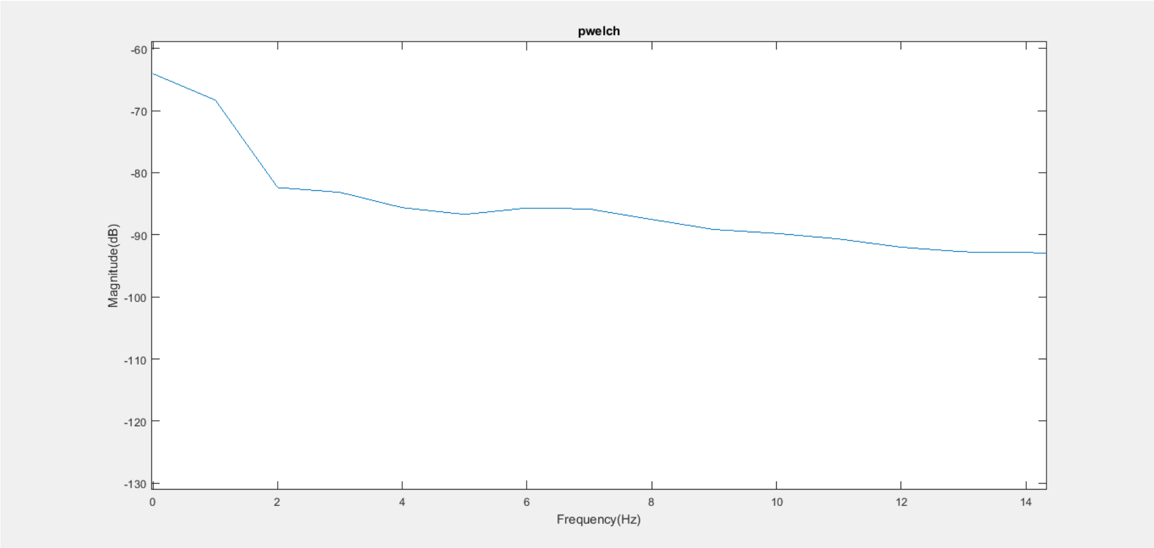

Figure 28.-Periodogram baseline patient 5

4.5.2 After surgery

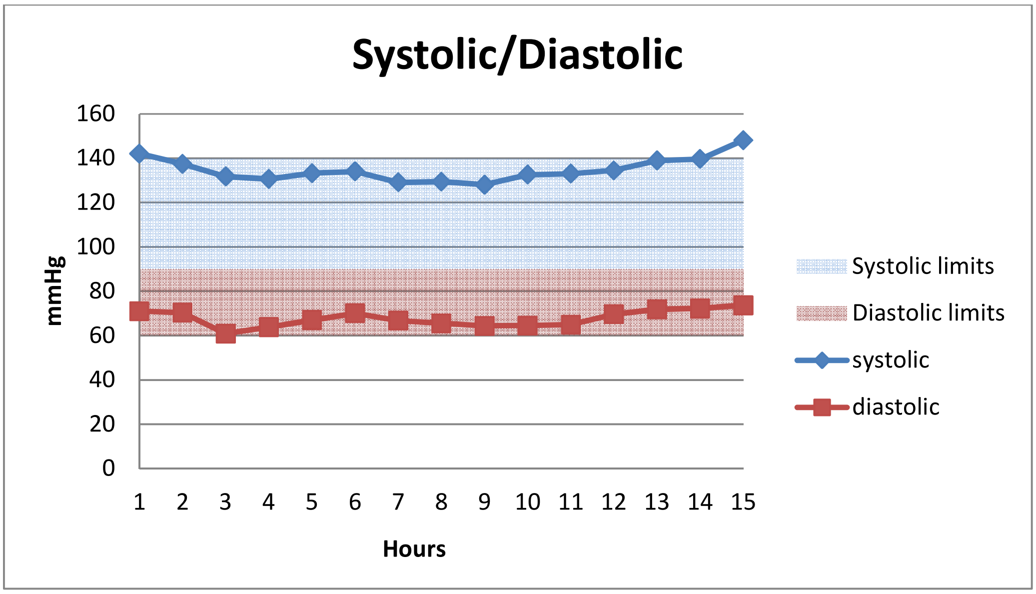

Figure 29.-Systolic/diastolic values patient 5

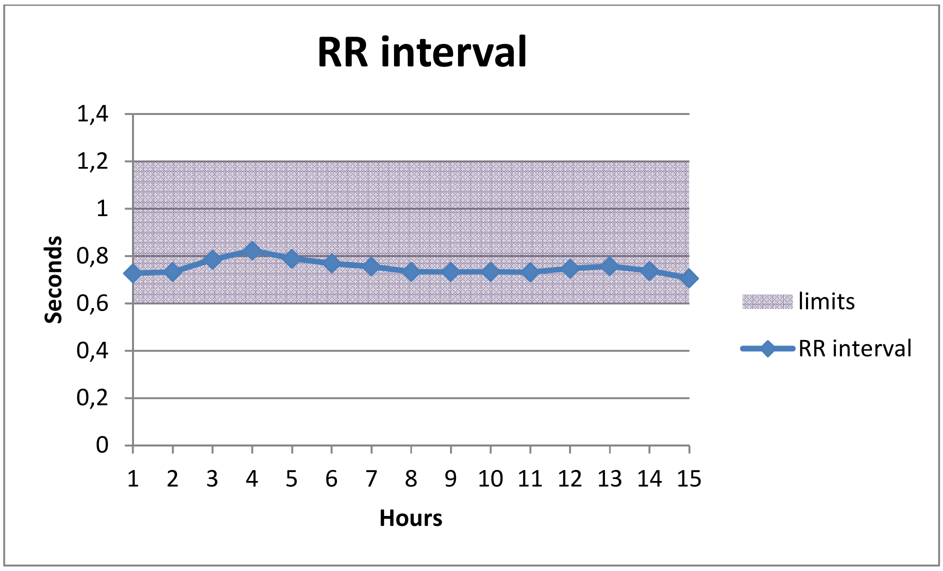

Figure 30.-RR interval patient 5

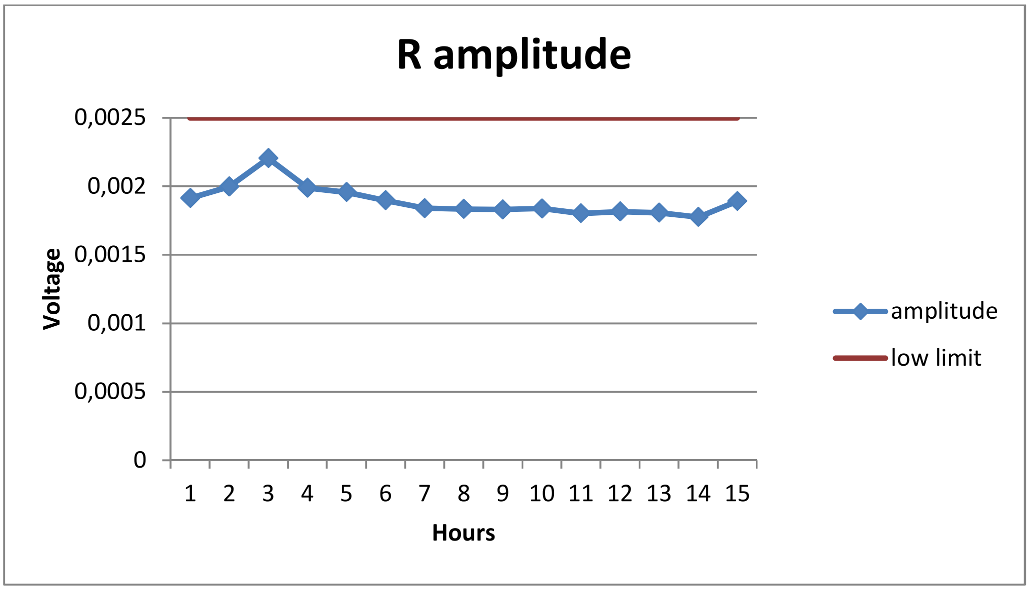

Figure 31.-R amplitude patient 5

Period 1 (1.24.00 - 2.24.00)	Period 2 (2.40.00 - 3.40.00)	Period 3 (17.16.00 – 18.16.00)
1.8247e-04 J	6.2724e-04 J	2.8079e-04 J

Table 19.-Energy of the periods patient 5

	Period 1	Period 2	Period 3
FFT max. Value(V^2)	0.06	0.05	0.05
Frequency(Hz)	1.25	1.4	1.4

Table 20.-FFT values of the periods patient 5

	Period 1	Period 2	Period 3
Periodogram (dB)	-68	-67	-68

Table 21.-Periodogram values of periods patient 5

4.5.3 Discussion

Both the diastolic and the systolic blood pressure are in the appropriate range before and after the surgery. The R amplitude is low and the periodogram maintains its values in all the cases. The values corresponding to the maximum FFT values are similar in all the cases and the same happen with the frequencies where the maximum can be seen, that is around 1Hz. The energy levels are similar in all the cases.

4.6 Sixth patient

4.6.1 Baseline

Systolic blood pressure	Diastolic blood pressure	RR peaks interval time	R peak amplitude	Energy
157.5 mmHg	70.3 mmHg	0.6977 s	0.0014 V	1.2304e-4 J

Table 22.-Baseline values patient 6

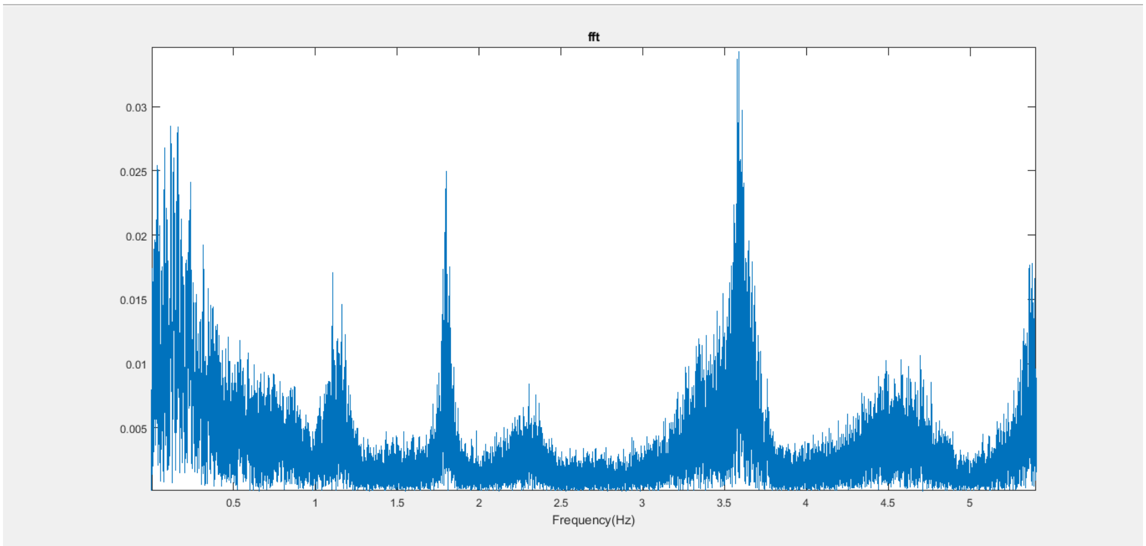

Figure 32.-FFT baseline patient 6

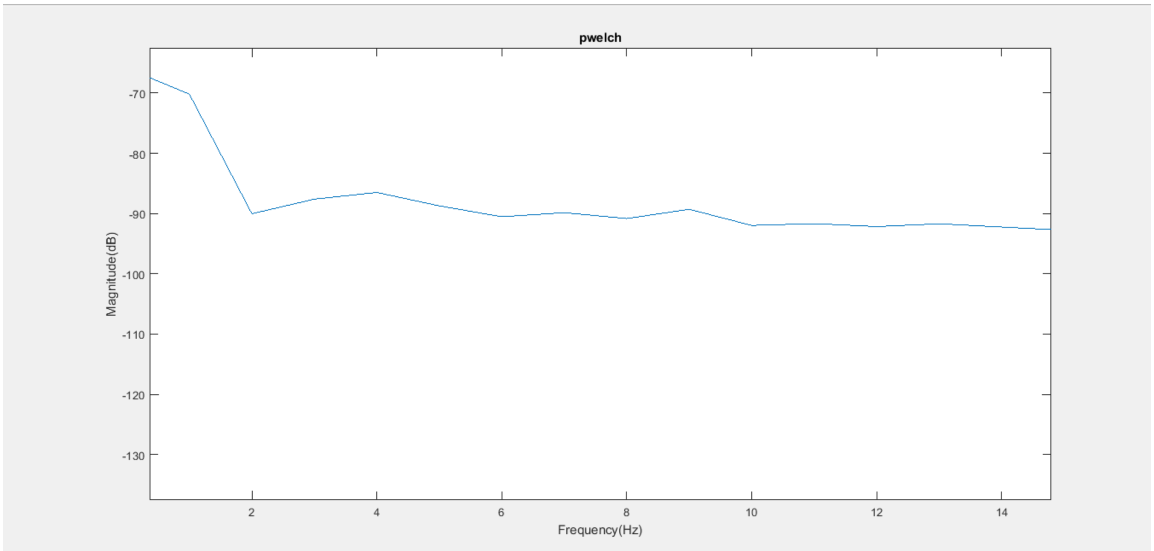

Figure 33.-Periodogram baseline patient 6

4.6.2 After surgery

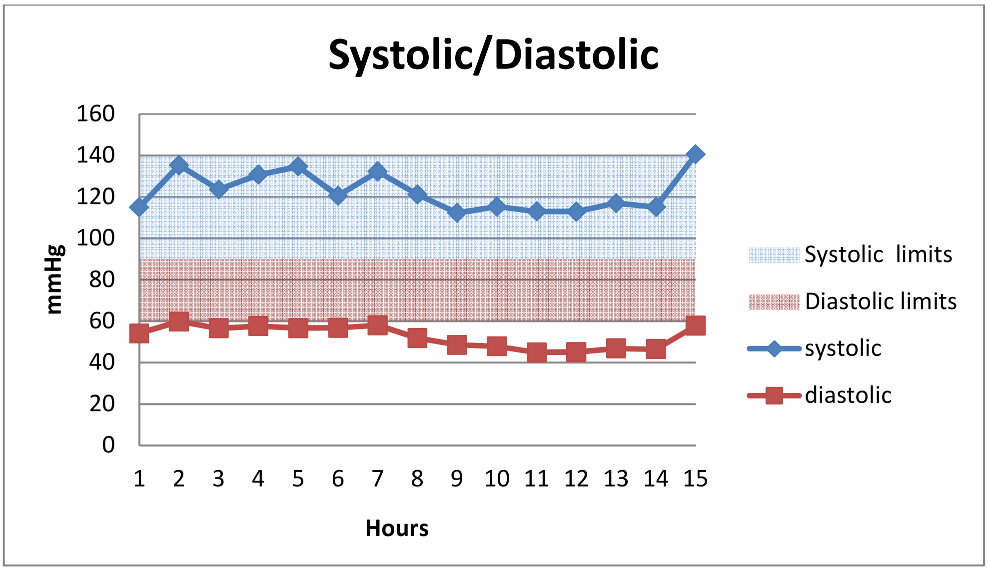

Figure 34.-Systolic/diastolic values patient 6

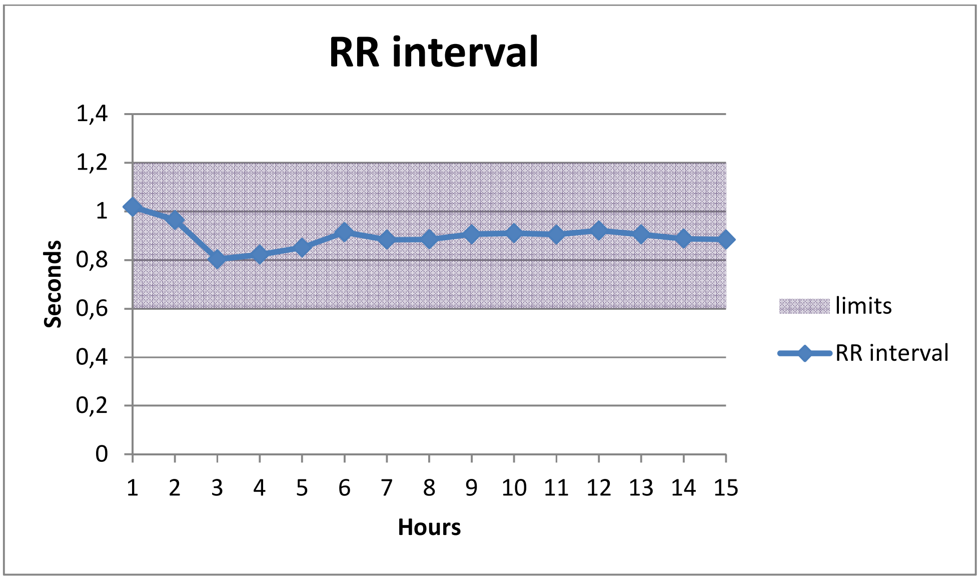

Figure 35.-RR interval patient 6

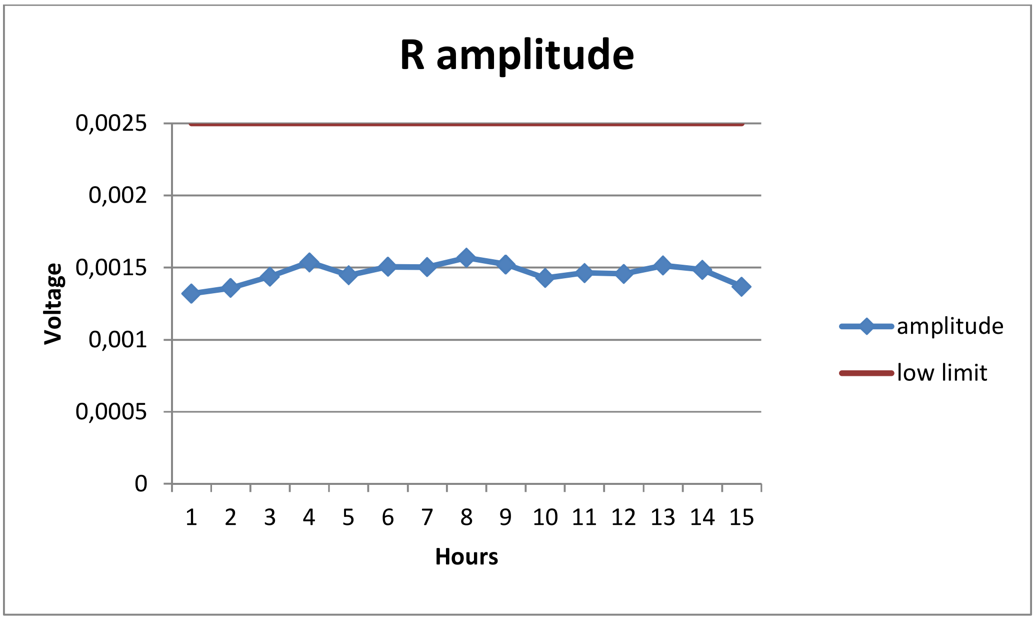

Figure 36.-R amplitude patient 6

Period 1 (1.20.00 - 2.20.00)	Period 2 (2.40.00 - 3.40.00)	Period 3 (14.28.00 – 15.28.00)
5.2659e-05 J	1.2795e-04 J	7.7455e-05 J

Table 23.-Energy of the periods patient 6

	Period 1	Period 2	Period 3
FFT max. Value (V^2)	0.025	0.034	0.039
Frequency(Hz)	1	0.3	1

Table 24.-FFT values of the periods patient 6

	Period 1	Period 2	Period 3
Periodogram (dB)	-69	-68	-69

Table 25.-Periodogram values of periods patient 6

4.6.3 Discussion

The energy values and the periodogram values are similar in all the cases. Some differences can be appreciated in the FFT values. In the baseline the maximum peak occurs around 3.5Hz, while in the post-surgery periods it occurs around 1Hz in the first and third cases and around 0Hz in the second period. Having in all the cases similar maximum values. The R amplitude and the diastolic pressure in this patient are low after the surgery hours, and the energy levels are in the usual range.

5 Conclusion

Due to the different noises that appear in the recorded data the results obtained are not as accurate as desired even though they have been pre-process in order to eliminate the undesirable components. The noise came from different sources, the sensors are moved, the intubation is taken off, some other medicines are applied to the patients… This is the reason why in a few cases it has not been possible to obtain a coherent result o not expected values are obtained.

In the six patients similarities are appreciated. When comparing the time interval between the RR peaks, in all six cases and both, in the baseline values and in the post-surgery data the values are the same as a healthy individual, there exists some variations during the post-surgery hours but are not significant.

On the other hand, regarding to the amplitude of the R peaks, in all the patients the amplitude is lower than the usual one before and after the surgery. Most of the values oscillate between 0.001 and 0.002, when the usual minimum is 0.0025. The values obtained about the second patient are especially low, the value obtained in the baseline is not mentioned due to the nonsense value obtained (negative value).

In respect of the changes between the baselines values compared to the post-surgery data, all the patients have a correct systolic value but a low diastolic value, in all the cases around 50mmHg. The exception is the fourth one, where it can be appreciated that from the eighth hour on, both the diastolic and systolic increase but continue between the normal values.

This occurs due to the anesthesia, while the recordings are measured, the patients are under the effects of the anesthesia, and it affects those features [20].

Furthermore, when analyzing in the frequency domain the signals, in a healthy individual most of the energy is around the first Hz, in the FFT of the baseline signals it can be seen how most of the energy is between zero and the first Hz but in the fifth and the sixth patients the energy is more spread along those first five Hz. The energy values in most of the cases stand between the usual values.

Computing the power spectral density, it can be seen how the signal has more power in the low frequencies, as expected from the healthy individual, and how the maximum value of it and its variation along the frequencies is very similar in all the cases.

6 Recommendation for further work

The corresponding information regarding what medicine is giving to the patient at each moment is expected to be provided in those 6 patients that have been analyzed in a future. It is expected also to have information regarding more patients, so a big amount of data available can be provided for further work. So even though it has not been possible to realize the expected work due to the type of data provided, it will be possible in a short period of time to predict, knowing which medicine has been given to the patient, the effect that this is going to have in the ECG and blood pressure. This can be done by using control theory techniques as it was expected. As other type of data is expected also to be available, spirometry, laser Doppler flow etc., the analysis of those aspects can also be done as a continuation of this work.

7 References

[1] William B. White, *Blood Pressure Monitoring in Cardiovascular Medicine and Therapeutics (Contemporary Cardiology),* ISBN 978-0-89603-840-0

[2] Tarek Abdelzaher, Yixin Diao, Joseph L. Hellerstein, Chenyang Lu,Xiaoyun Zhu, *Introduction to Control Theory and its applications to Computing Systems,* available at www.eecs.umich.edu/courses/eecs571/reading/control-to-computer-zaher.pdf

[3] Joseph; et al. (2009), *Acute Decompensated Heart Failure,* Texas Heart Institute Journal, Retrieved 18 October 2012.

[4] Homeostasis. (2015). *Cause/Effect Homeostasis not Maintained Properly*. Available at: http://homeostasiseleishabiology.weebly.com/causeeffect-homeostasis-not-maintained-properly.html

[5] Cardiac surgery. (n.d.) 2009. *Medical Dictionary*. Retrieved April 4 2016 available on http://medical-dictionary.thefreedictionary.com/cardiac+surgery

[6] Norwegian registry for cardiac surgery in collaboration with Norwegian association for cardiothoratic surgery,Available at http://legeforeningen.no/PageFiles/20098/Heart%20Surgery%20in%20Norway%202014.pdf

[7] Maxwell, J.C. (1868). *"On Governors". Proceedings of the Royal Society of London* 16:p. 270–283.

[8] Harald Paulitsch, *A brief introduction to control theory*, Technische universitat Wien.

[9] Terrell, William (1999). *"Some fundamental control theory I: Controllability, observability, and duality —AND— Some fundamental control Theory II: Feedback linearization of single input nonlinear systems".* Amer. Math. Monthly 106: p.705–719 and 812–828

[10] Katsuhiko Ogata (1997). *Modern Control Engineering (3rd ed.).* Upper Saddle River, NJ: Prentice-Hall. ISBN 0-13-227307-1.

[11] Phillips, C.l., Parr, J.M., & Riskin*, E.A (2007).* Signals, systems and Transforms. Prentice Hall. ISBN 0-13-041207-4.

[12] Katalin M. Hangos, R. Lakner, and M. Gerzson *(2001). Intelligent Control Systems: An Introduction with Examples.* Springer. *p. 254.*ISBN 9781402001345.

[13] Internation hemodynamics society glossary, available at www.hemodynamicsociety.org/hemodyn.html

[14] Nicolaas Westerhof,Nikolaos Stergiopulos, Mark I.M. Noble,(2010) *Snapshots of Hemodynamics* (2nd ed.),Springer

[15] Hemodynamics. (n.d.) *Miller-Keane Encyclopedia and Dictionary of Medicine, Nursing, and Allied Health, Seventh Edition*. (2003). Retrieved April 8 2016 , available at http://medical-dictionary.thefreedictionary.com/hemodynamics

[16] ADI instruments, available at www.adinstruments.com/products/powerlab

[17] The periodogram, available at https://onlinecourses.science.psu.edu/stat510/?q=book/export/html/52

[18] Karl L. Stratos, (2010)*The Fast Fourier Transform and its applications,* University of Rochester

[19] Melissa Selik, Richard Baraniuk, Adam Blair (2013), *Synal Energy vs Signal Power*, available at https://cnx.org/contents/IufvMRKP@11/Signal-Energy-vs-Signal-Power

[20] G.M. Woerlee,(2008) *Anesthesia and Hypotension*, available at www.anesthesiaweb.org/hypotension.php

8 Appendix

8.1 Patient 1 after surgery FFT and periodogram graphics

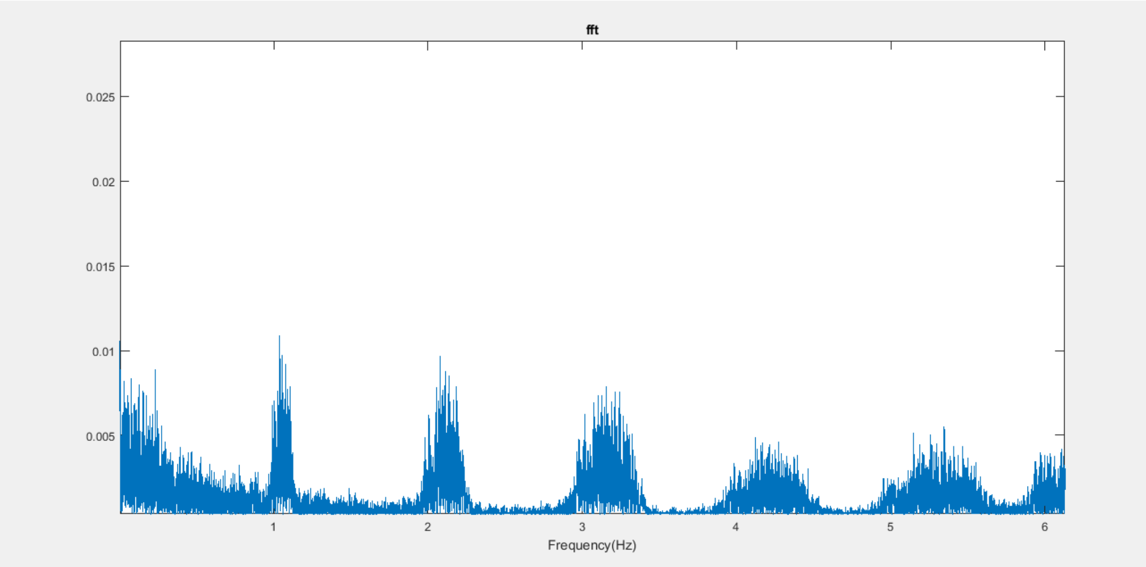

Figure 37.-FFT period 1 patient 1

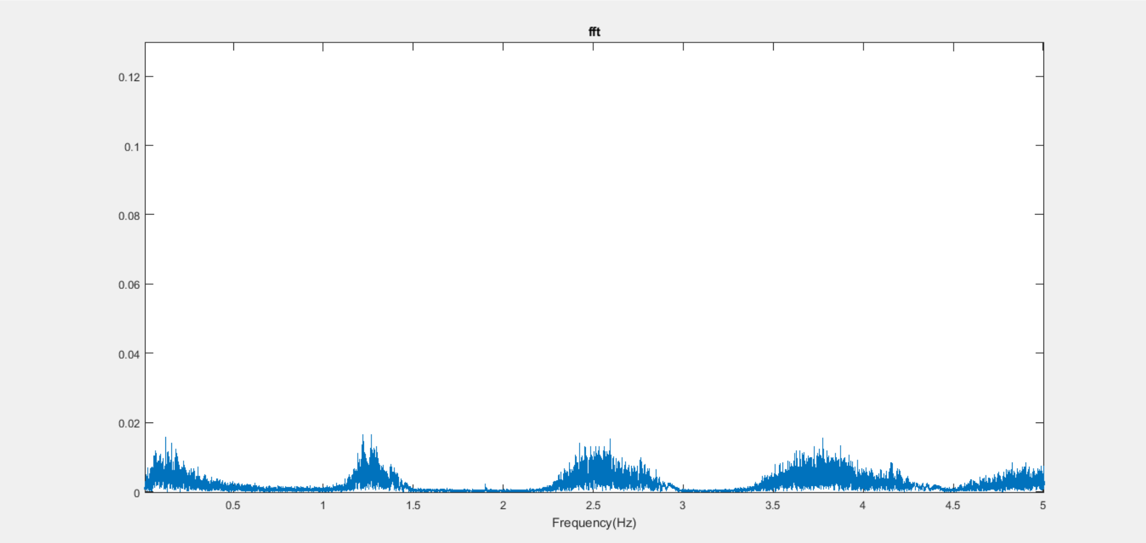

Figure 38.-FFT period 2 patient 1

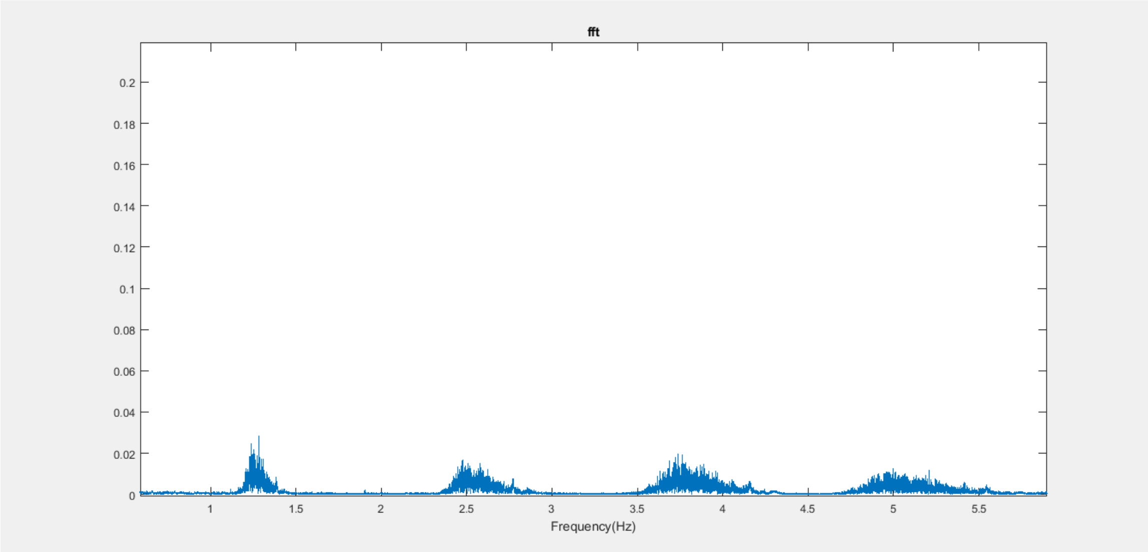

Figure 39.-FFT period 3 patient 1

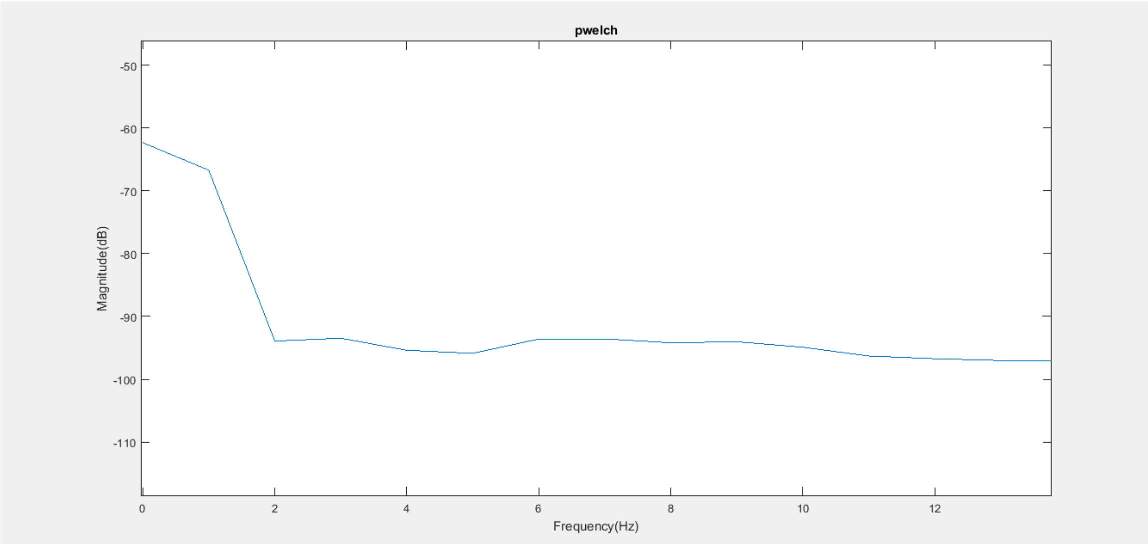

Figure 40.-Periodogram period 1 patient 1

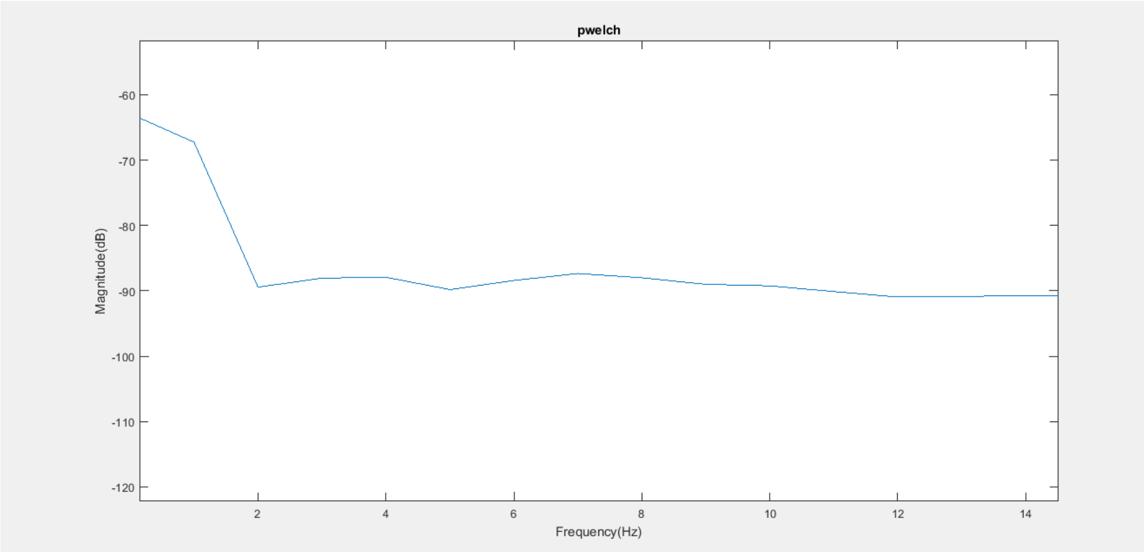

Figure 41.-Periodogram period 2 patient 1

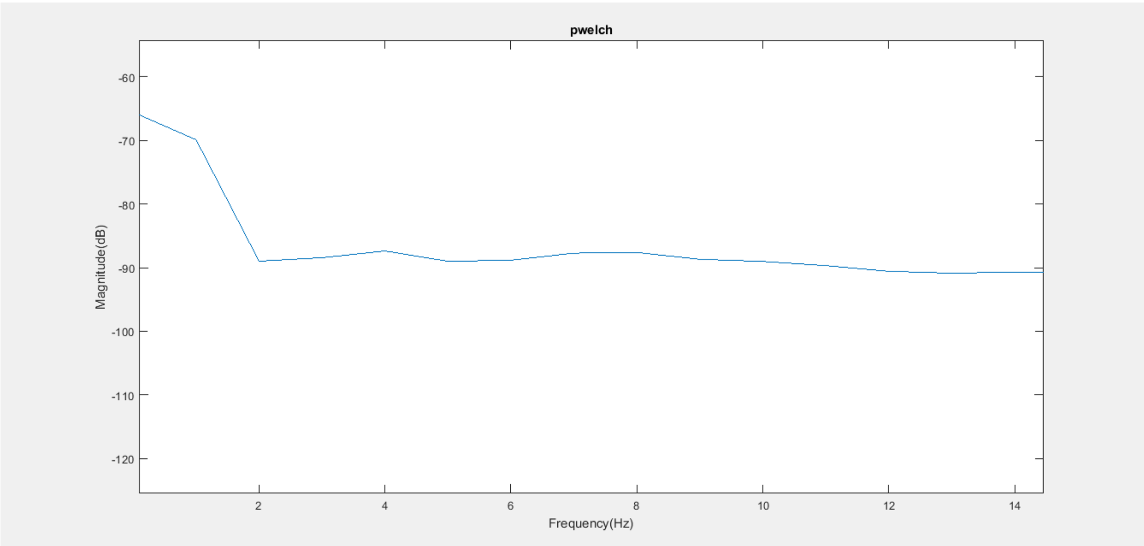

Figure 42.-Periodogram period 3 patient 1

8.2 Patient 2 after surgery FFT and periodogram graphics

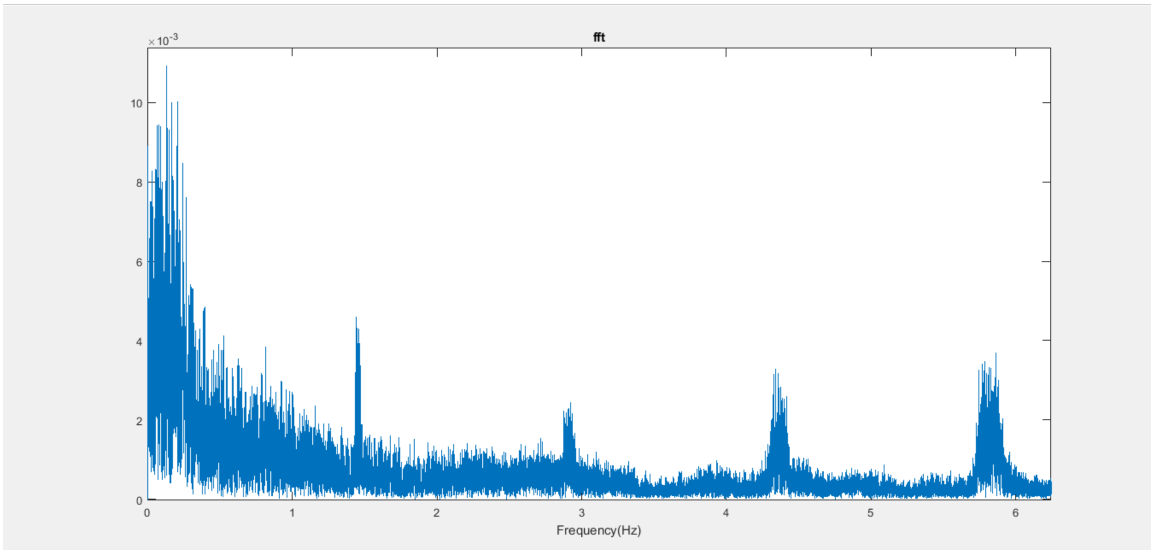

Figure 43.-FFT period 1 patient 2

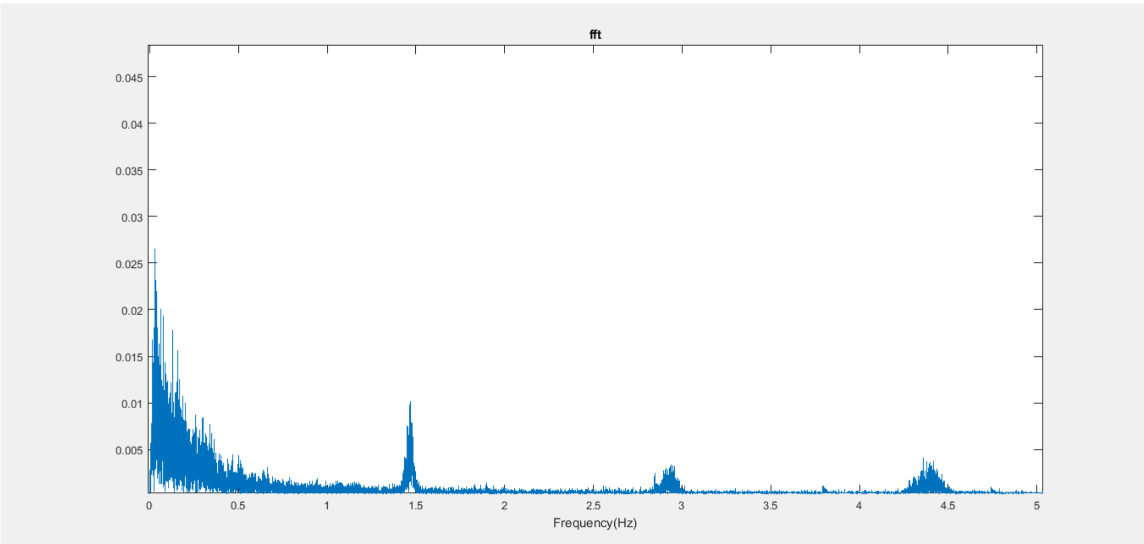

Figure 44.-FFT period 2 patient 2

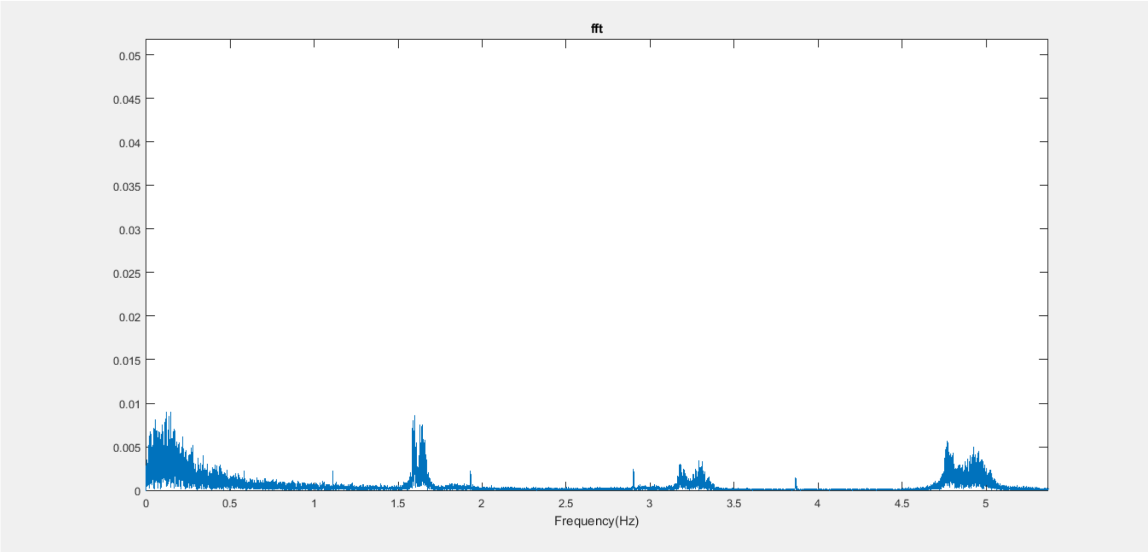

Figure 45.-FFT period 3 patient 2

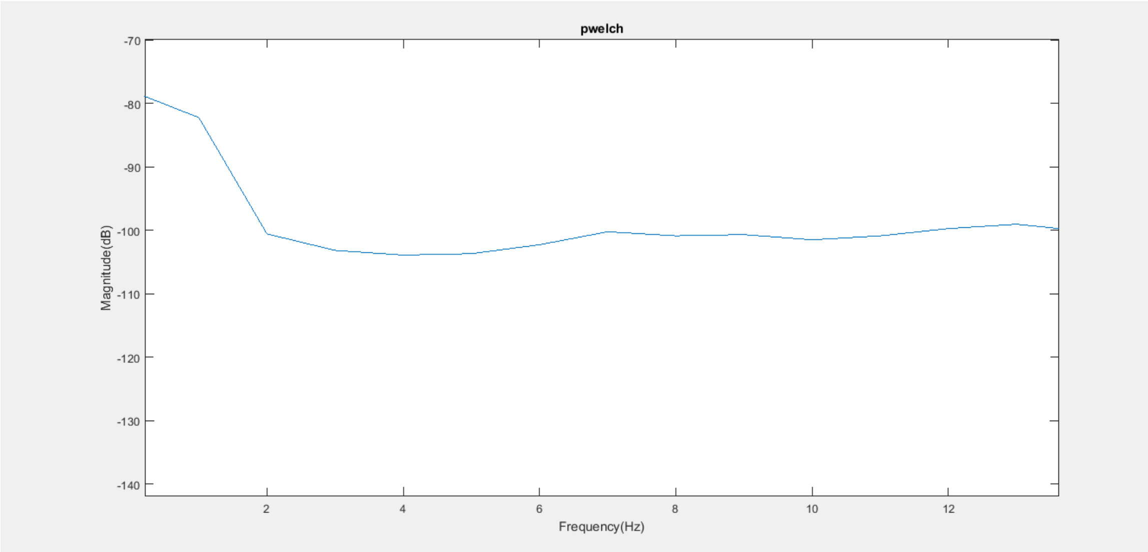

Figure 46.-Periodogram period 1 patient 2

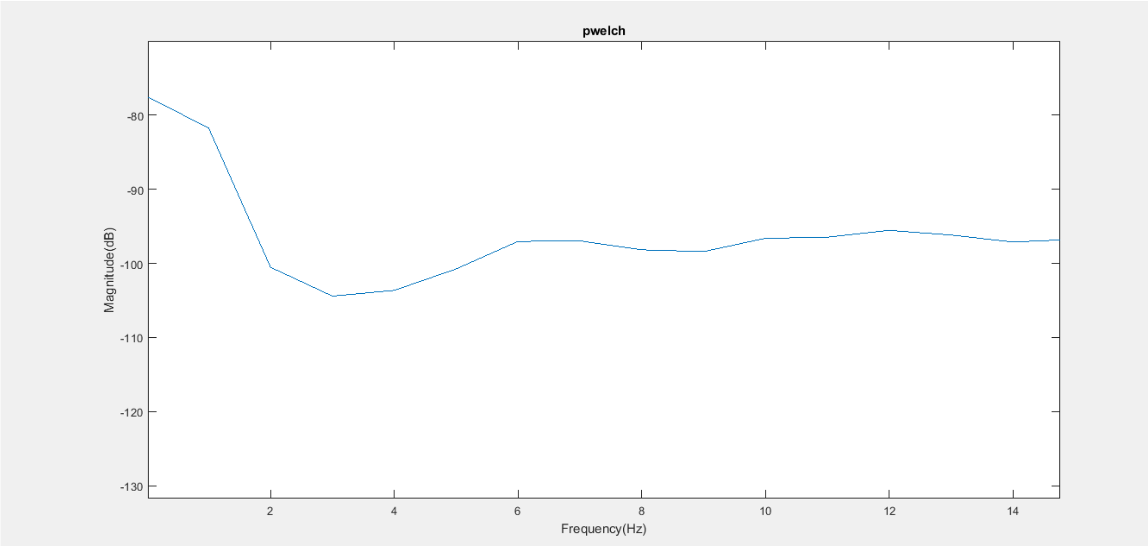

Figure 47.-Periodogram period 2 patient 2

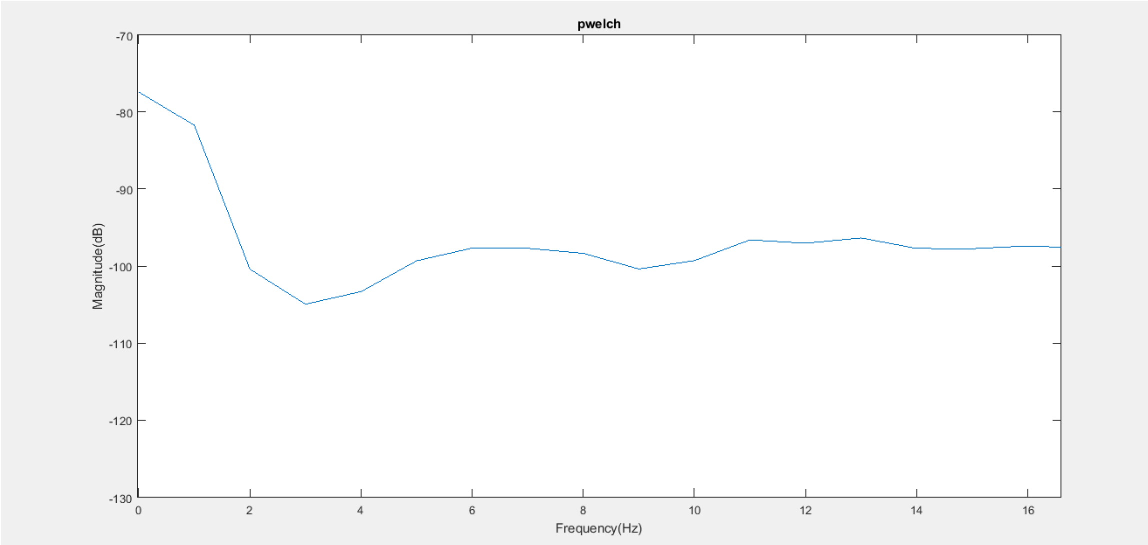

Figure 48.-Periodogram period 3 patient 2

8.3 Patient 3 after surgery FFT and periodogram graphics

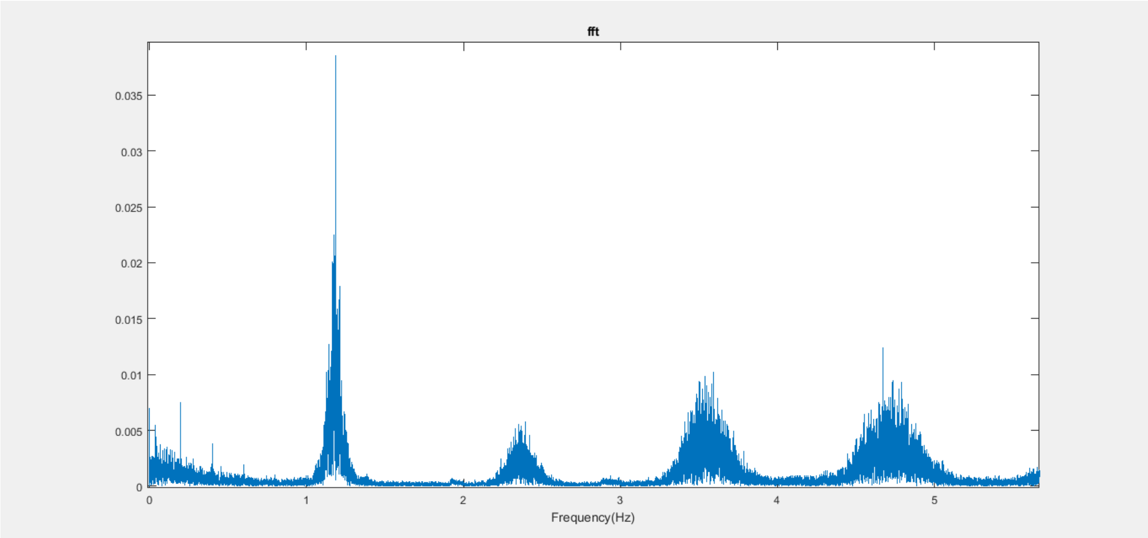

Figure 49.-FFT period 1 patient 3

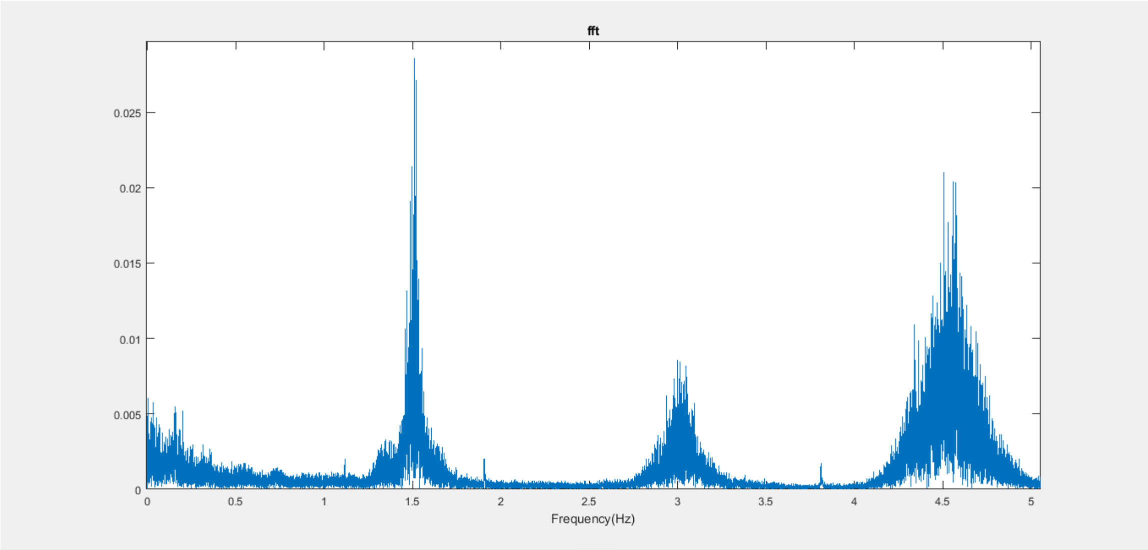

Figure 50.-FFT period 2 patient 3

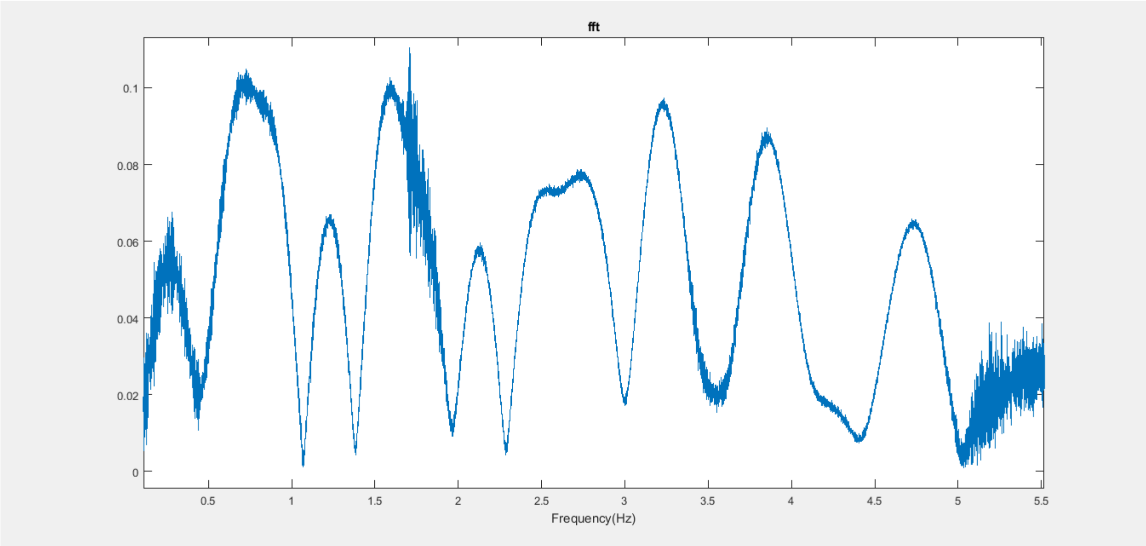

Figure 51.-FFT period 3 patient 3

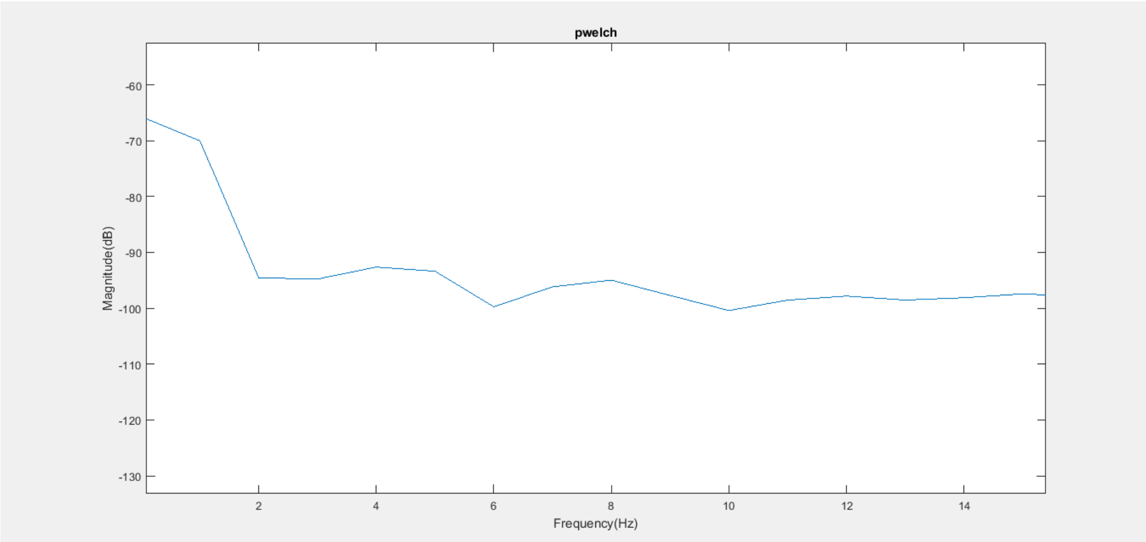

Figure 52.-Periodogram period 1 patient 3

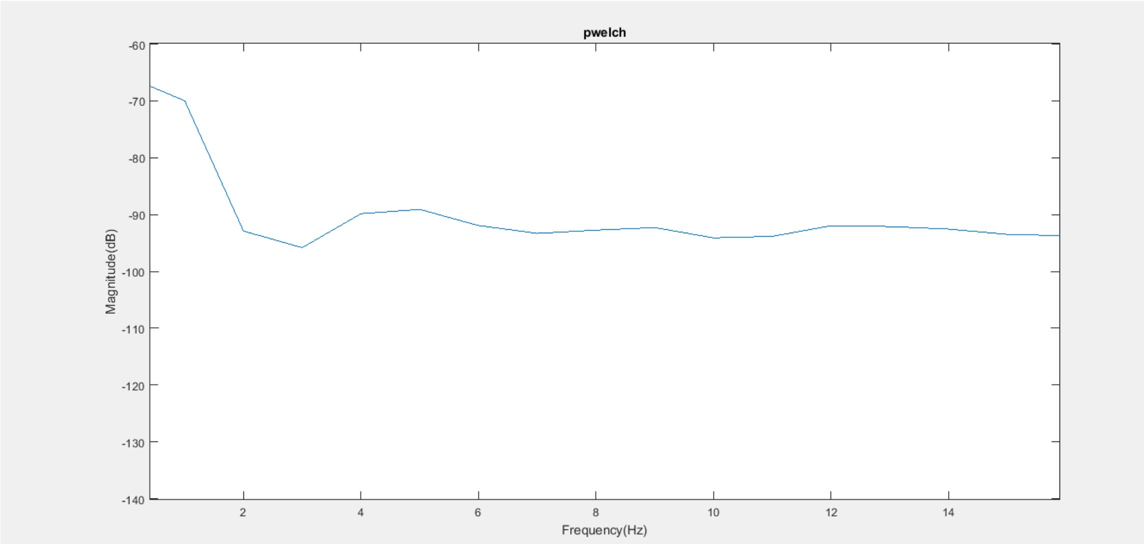

Figure 53.-Periodogram period 2 patient 3

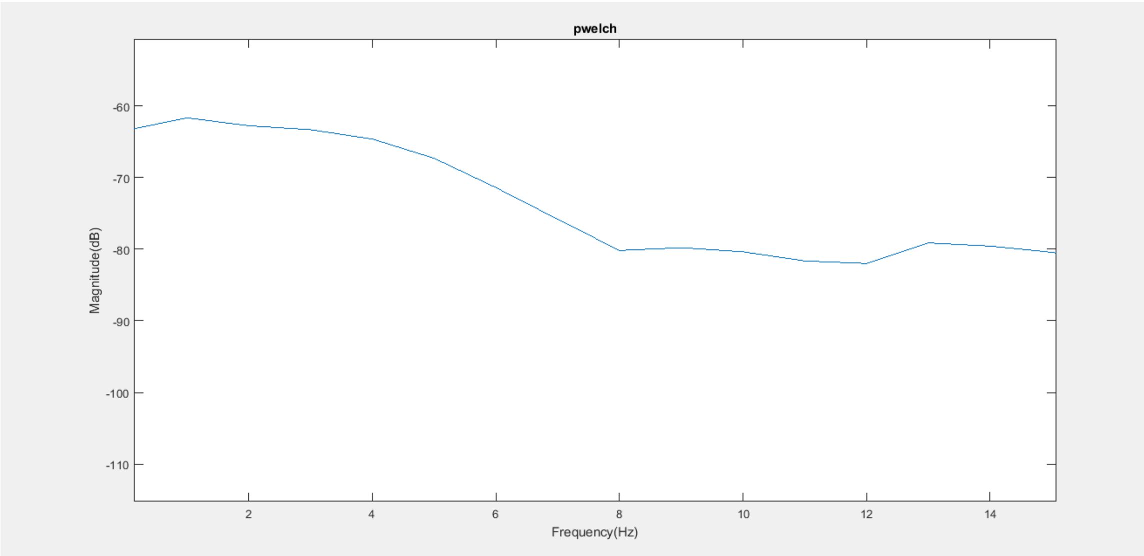

Figure 54.-Periodogram period 3 patient 3

8.4 Patient 4 after surgery FFT and periodogram graphics

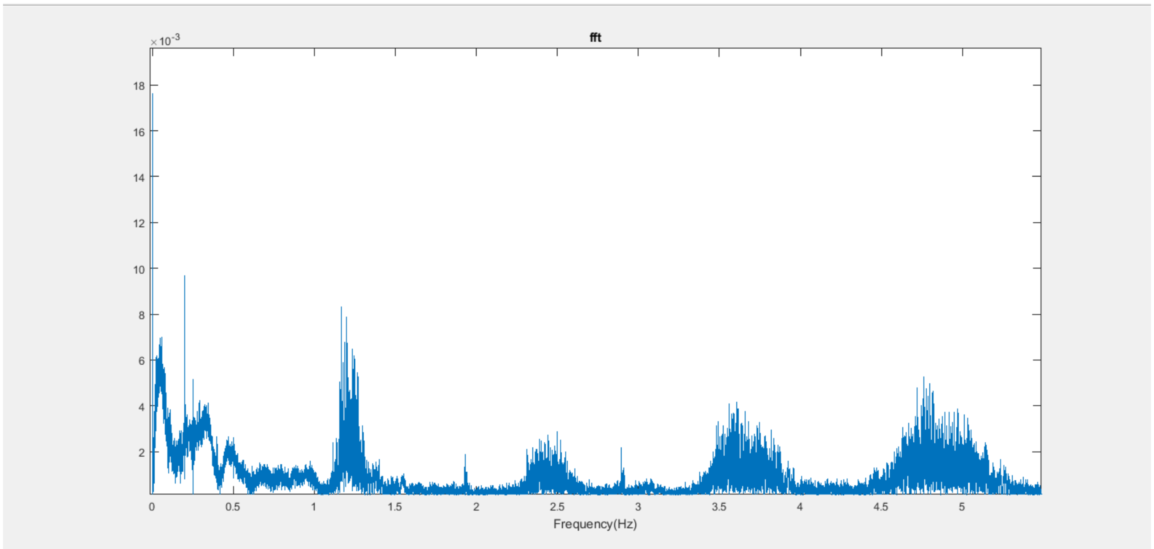

Figure 55.-FFT period 1 patient 4

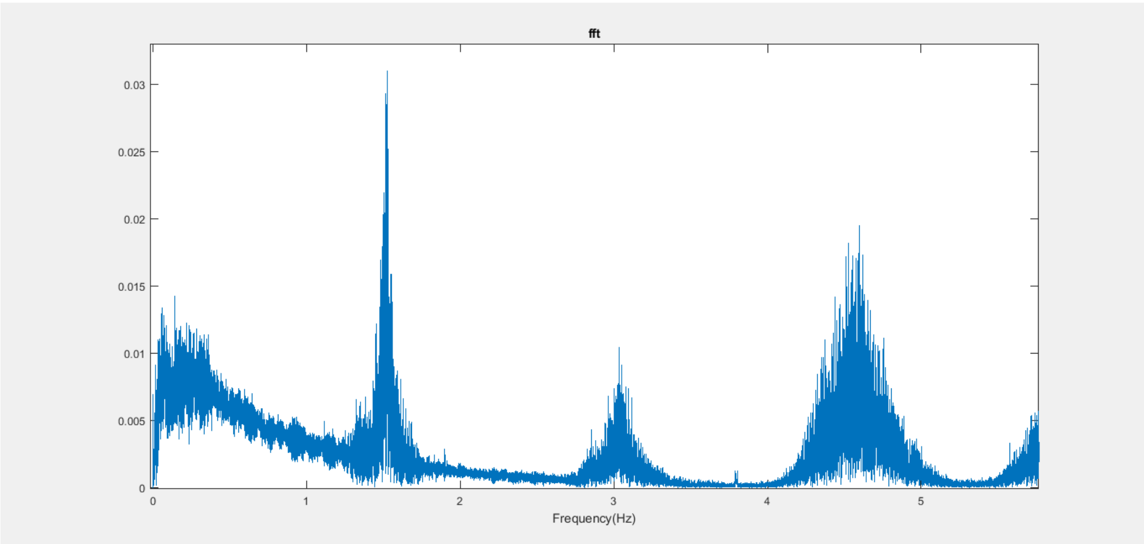

Figure 56.-FFT period 2 patient 4

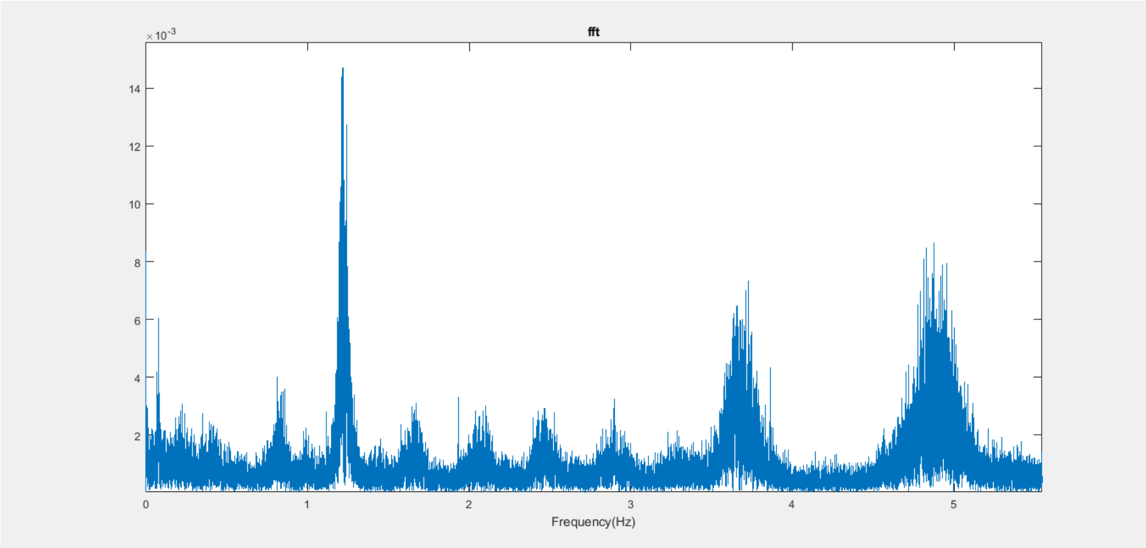

Figure 57.-FFT period 3 patient 4

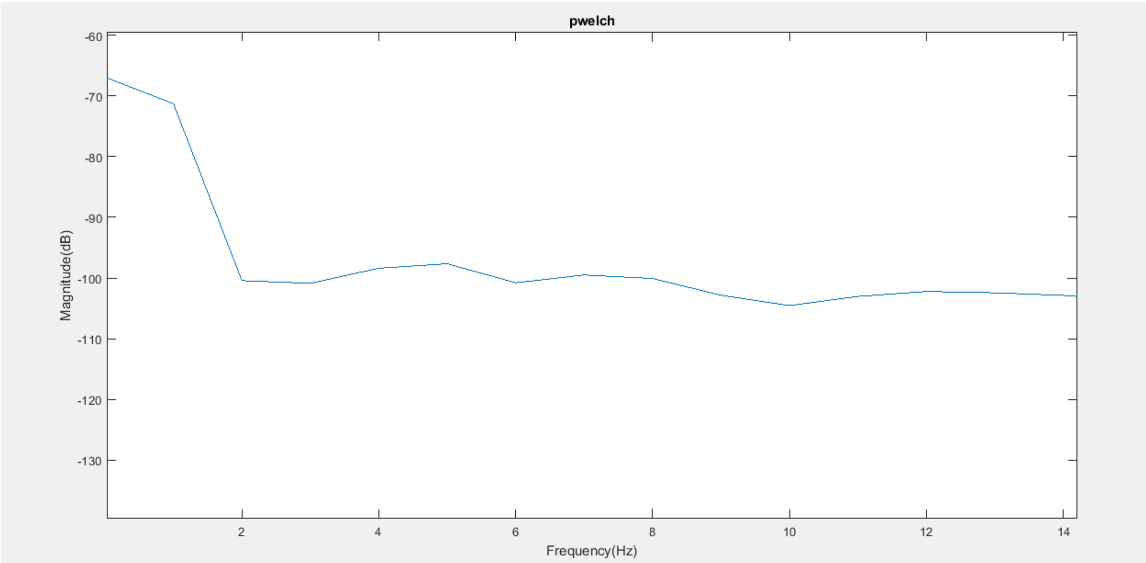

Figure 58.-Periodogram period 1 patient 4

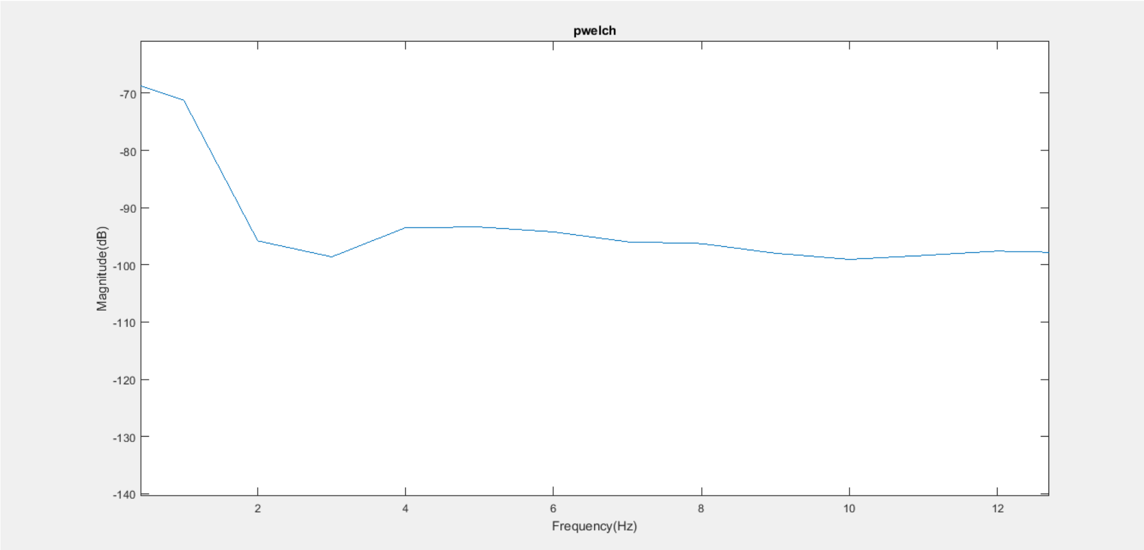

Figure 59.-Periodogram period 2 patient 4

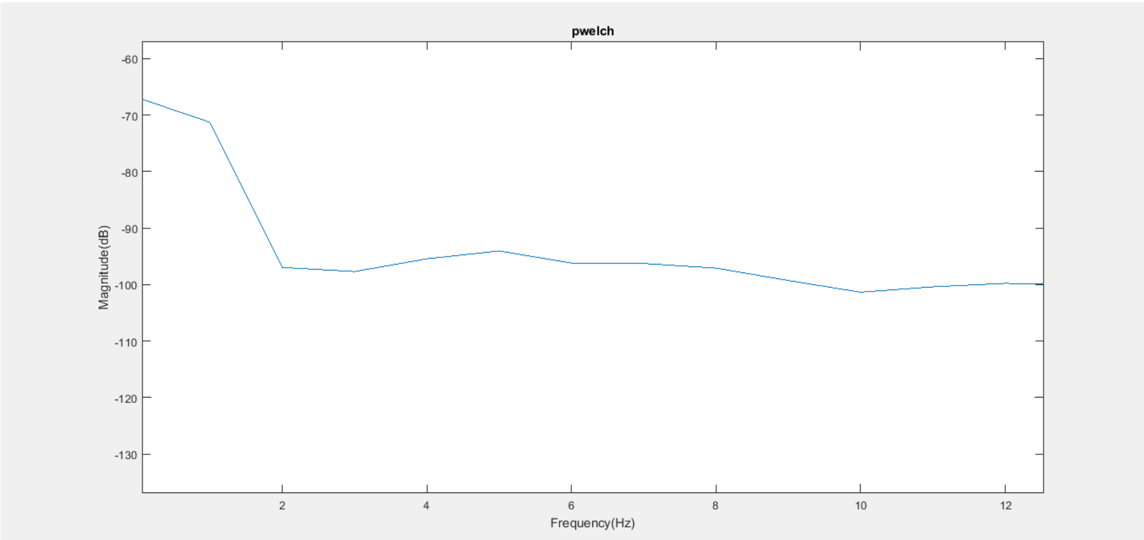

Figure 60.-Periodogram period 3 patient 4

8.5 Patient 5 after surgery FFT and periodogram graphics

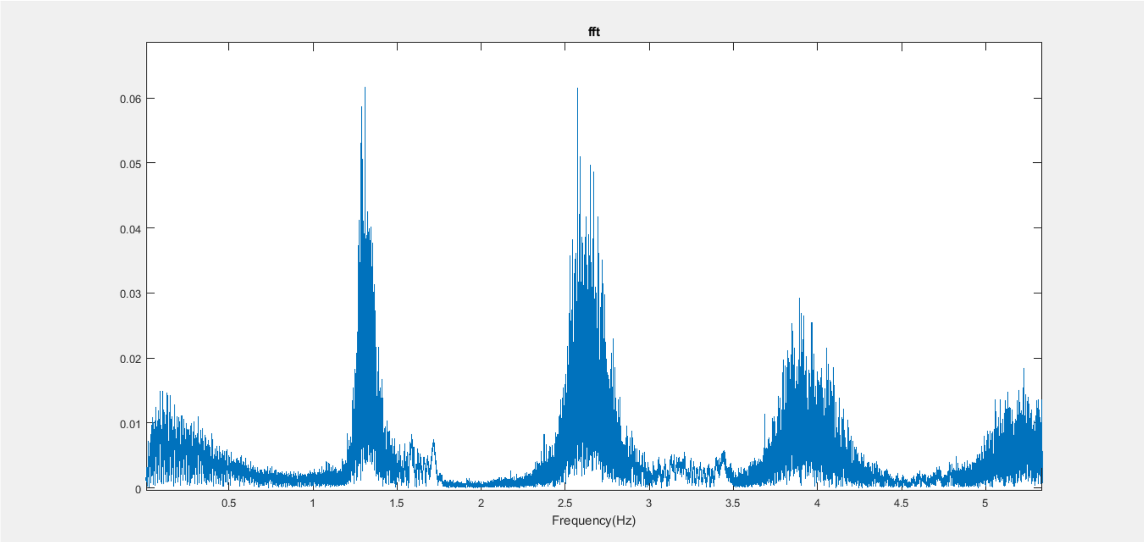

Figure 61.-FFT period 1 patient 5

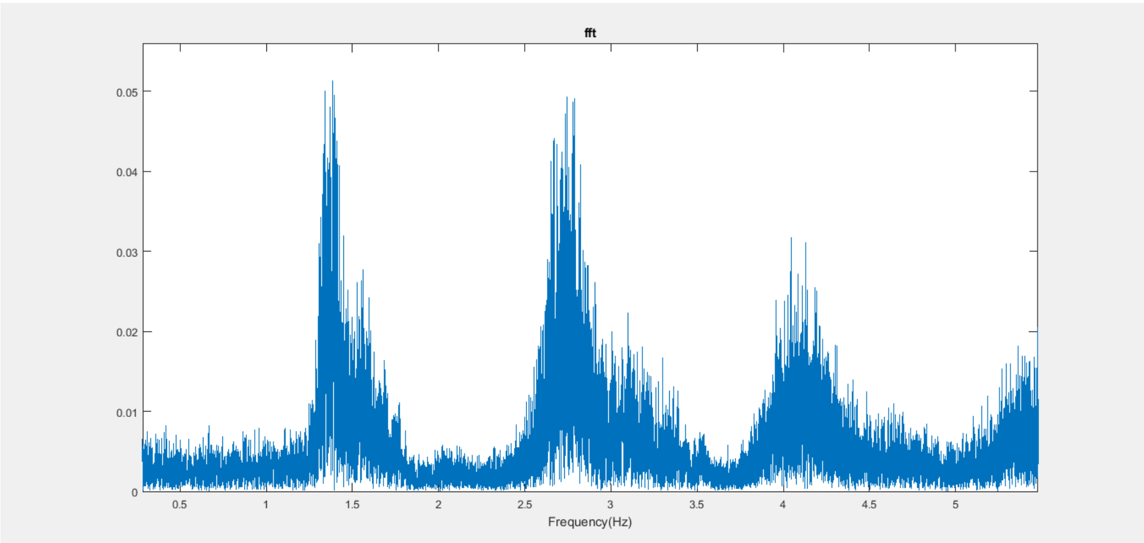

Figure 62.-FFT period 2 patient 5

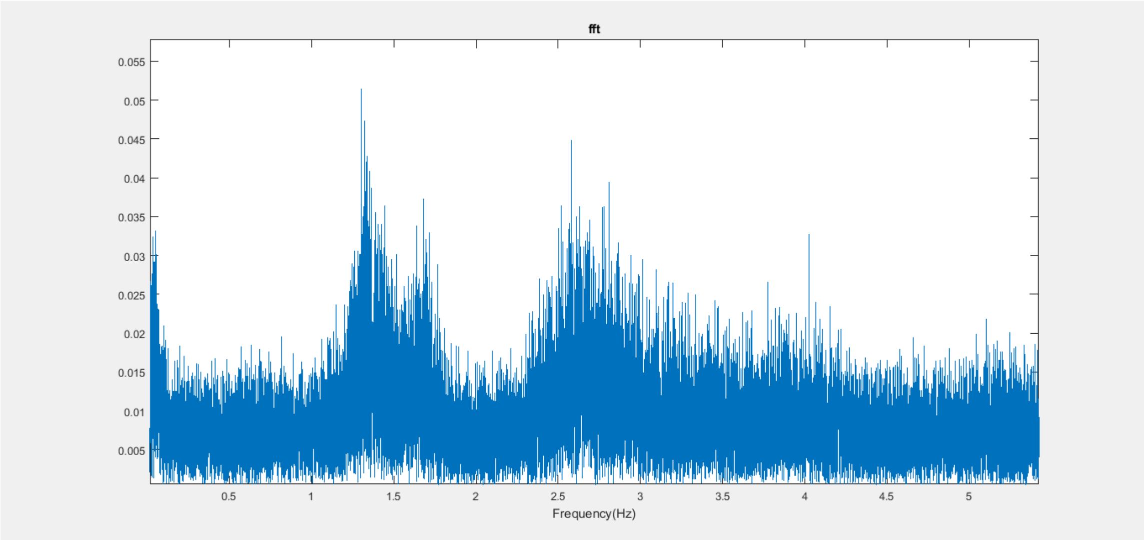

Figure 63.-FFT period 3 patient 5

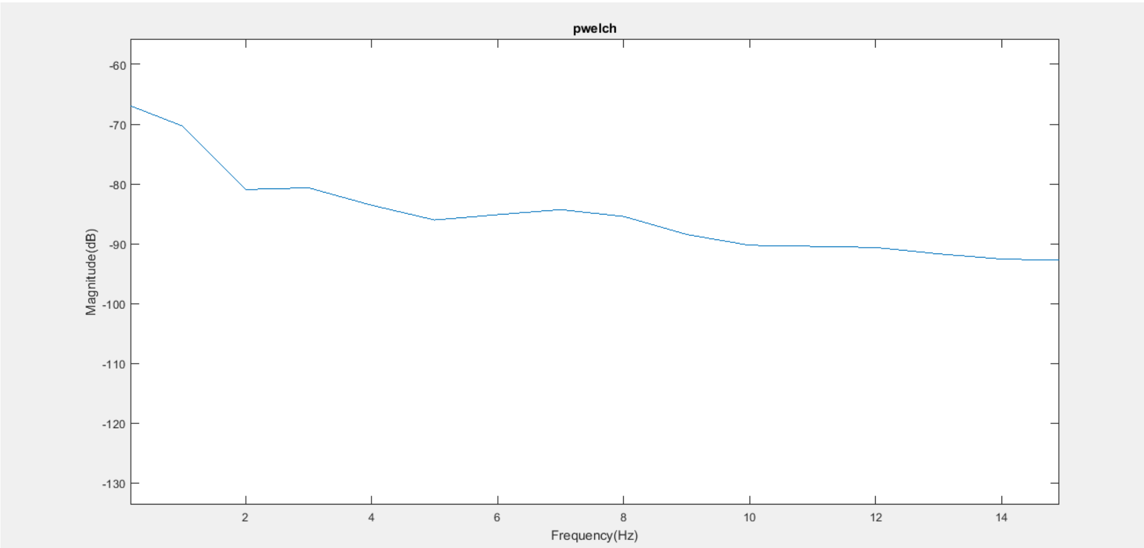

Figure 64.-Periodogram period 1 patient 5

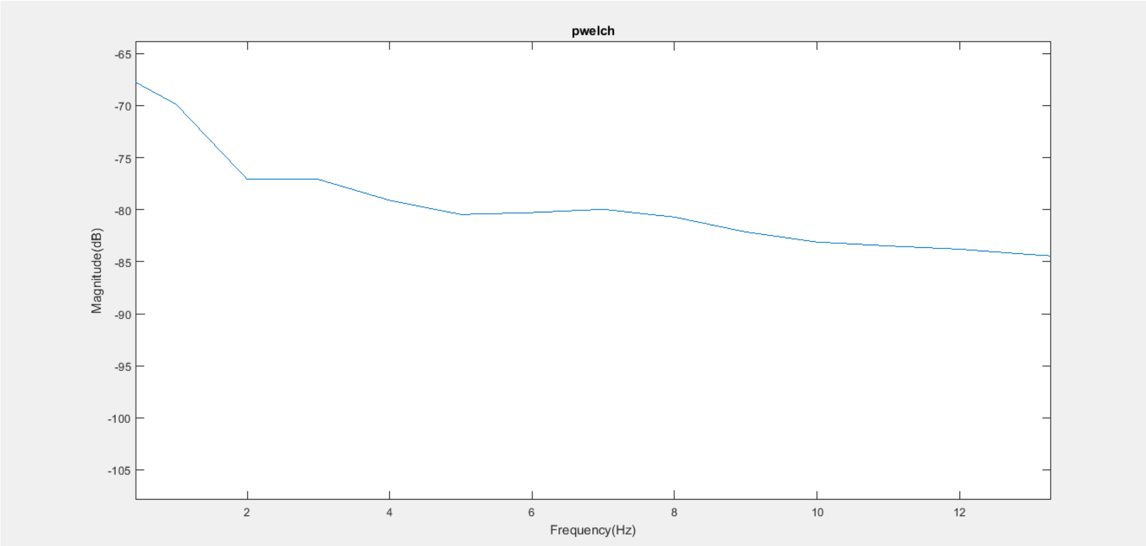

Figure 65.-Periodogram period 2 patient 5

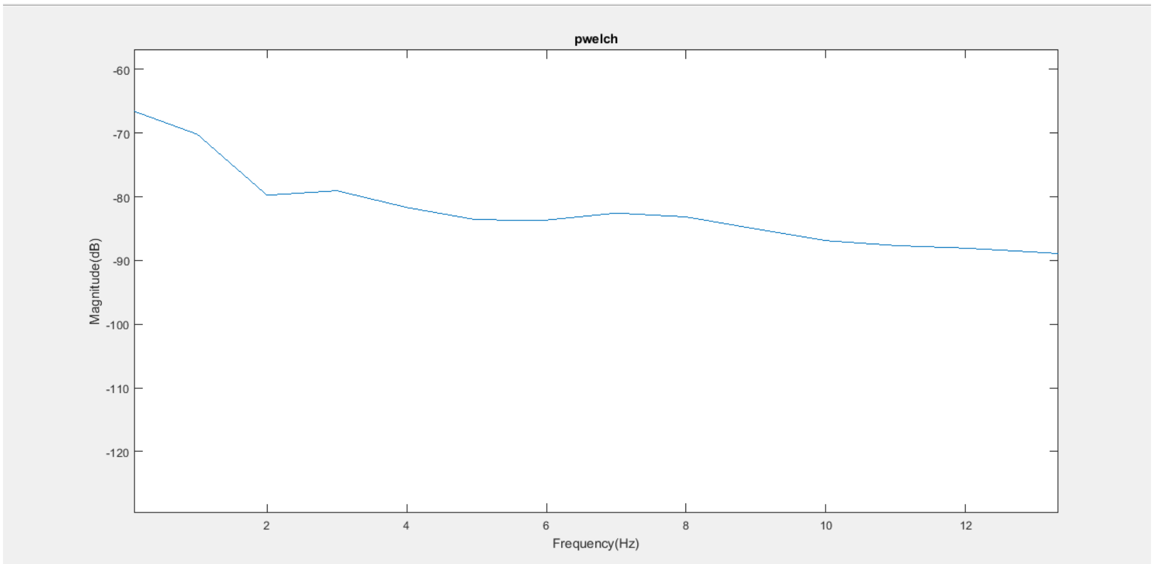

Figure 66.-Periodogram period 3 patient 5

8.6 Patient 6 after surgery FFT and periodogram graphics

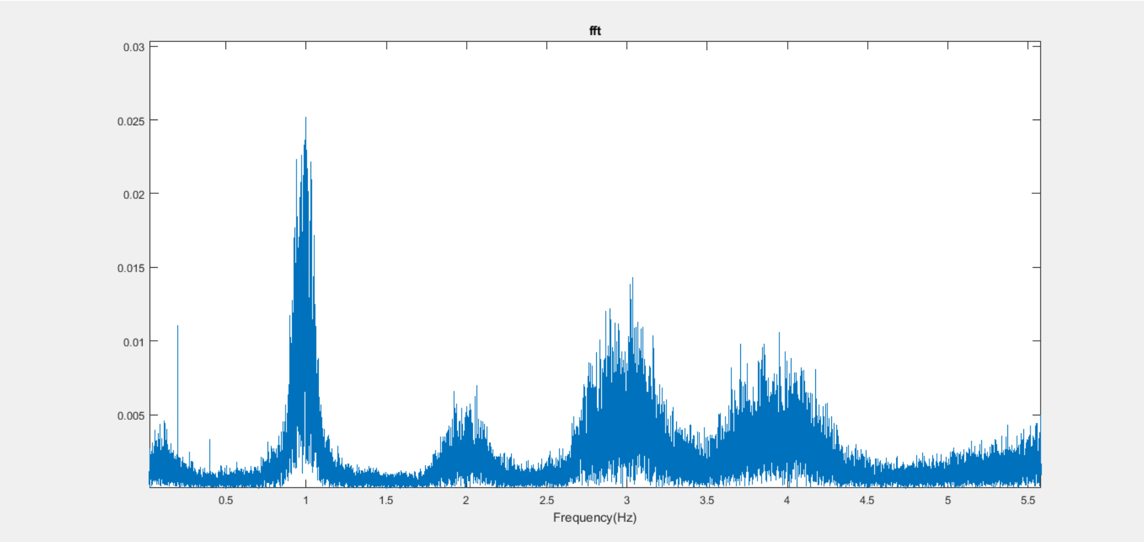

Figure 67.-FFT period 1 patient 6

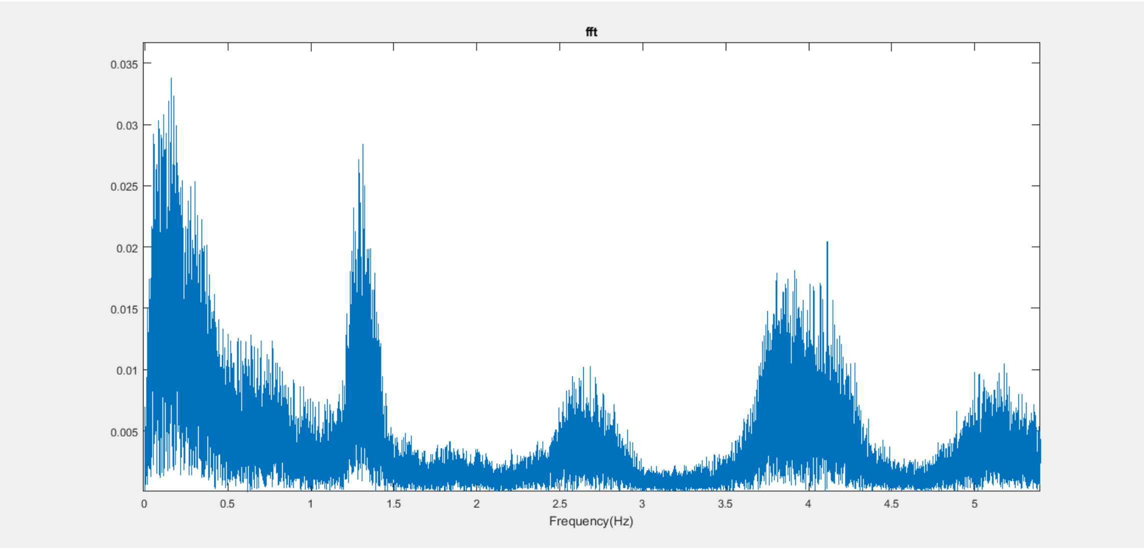

Figure 68.-FFT period 2 patient 6

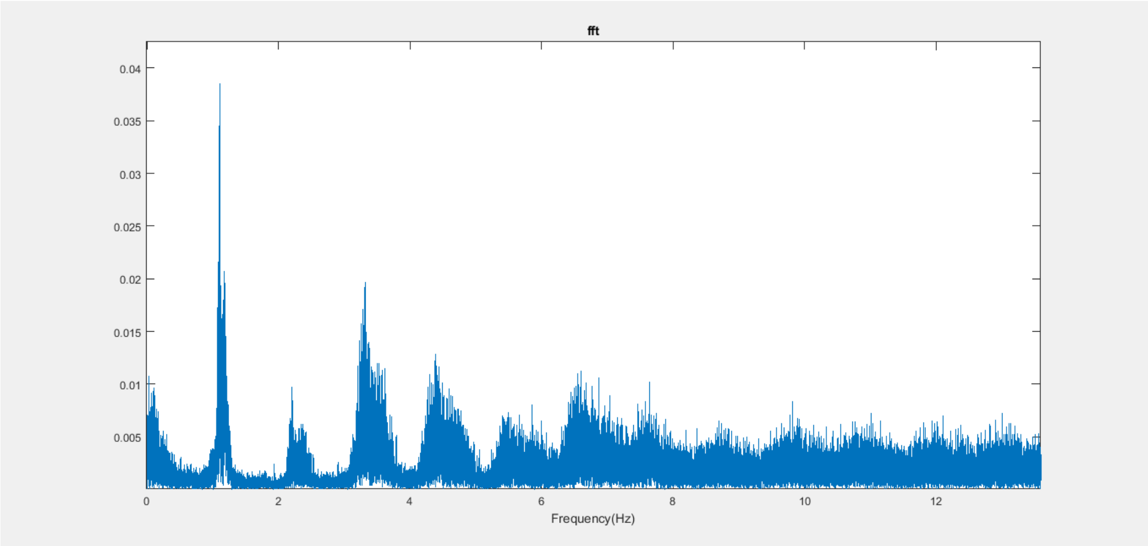

Figure 69.-FFT period 3 patient 6

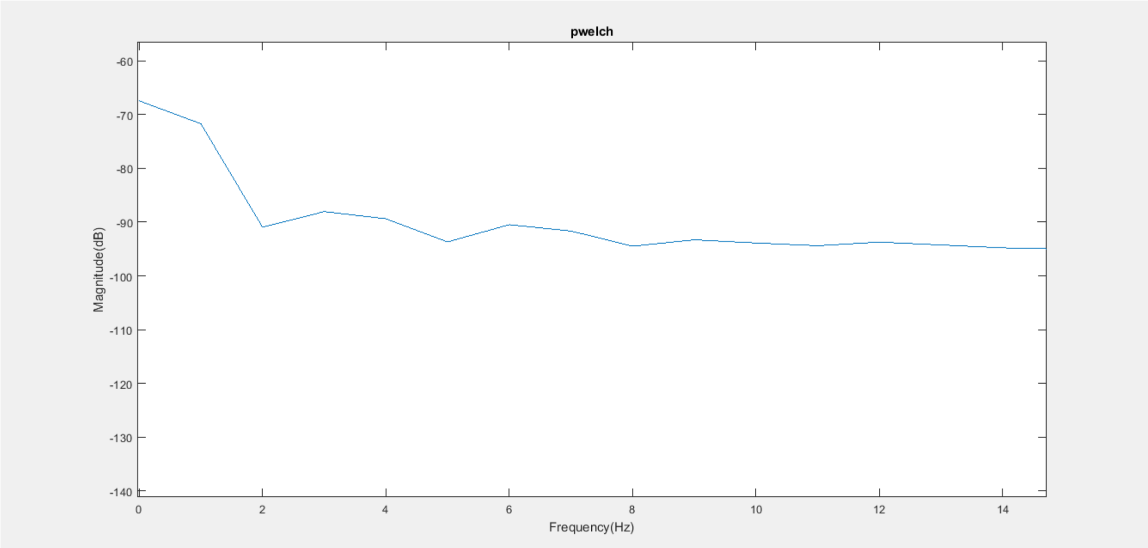

Figure 70.-Periodogram period 1 patient 6

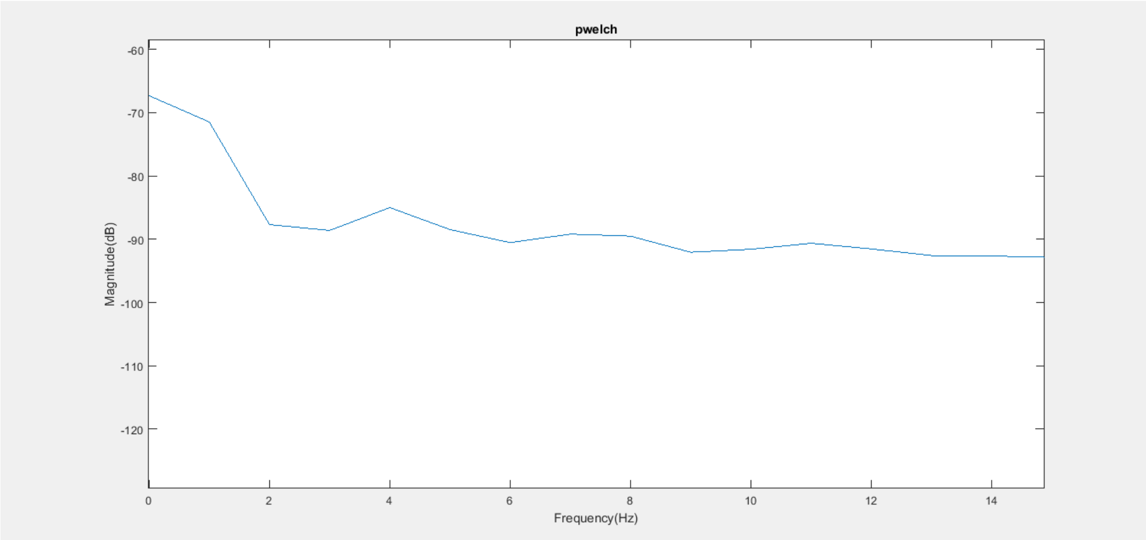

Figure 71.-Periodogram period 2 patient 6

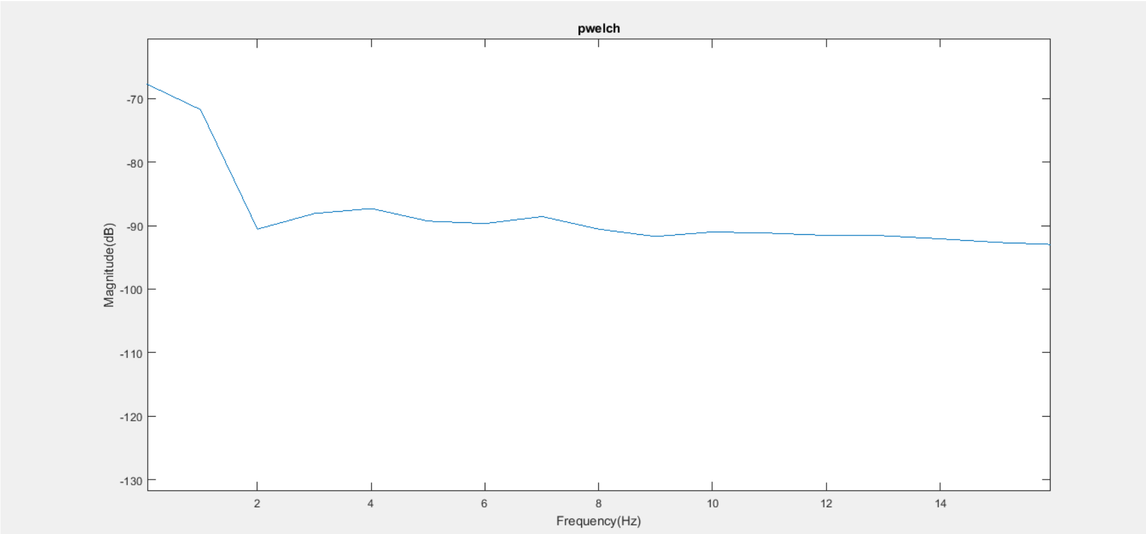

Figure 72.-Periodogram period 3 patient 6