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Fetal cardiac arrhythmia detection by Heart rate variability (HRV) signal analysis

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الإهداء

الحمد لله الذي هدانا لهذا وما كنا لنهتدي لولا ان هدانا الله، فالحمد لله الذي أنار لي طريقي وكان لي خير عون .

لم تكن الرحلة قصيرة ولا ينبغي لها ان تكون. لم يكن الحلم قريباً ولا الطريق كان محفوفاً بالتسهيلات لكني فعلتها! اليوم: و بادئ ذي بدء أحب أن أهدي عملي هذا الى روح عمي الذي وافته المنية خلال فترة تواجدي في الجزائر.

الى بؤرة النور التي عبرت بي نحو الاملِ و الاماني الجميلة وإتسع قلبه ليحتوي حلمي حين ضاقت الدنيا ف روضَ الصعاب من أجلي وسار في حلكتِ الدربِ ليغرس معاني النور و الصفاء في قلبي وعلمني معنى أن نعيش من أجل الحق و العلم لنظل أحياء حتى لو فارقت أرواحنا أجسادنا ولطالما تفطر قلبه شوقا وحنت عيناه الوضاءتان إلى رؤيتي متقلداً شهادة الماجستير وها هي قد أينعت لأقدمها الان بين يديك والدي الحبيب ها أنا اليوم اقدم مذكرة الماجستير بإسمك انت واعلم أنها لطالما كانت حلما لك لكنك آثرت من تحب على ما تحب وعشت من أجلنا من أجل أن نحيا حياة كريمة وفي بيتٍ كريم وفي أحضان علمٍ نافعٍ كريم ومن أجل أن أمثل أمامك الآن بشهادتي التي تعترف كل قصاصةٍ فيها بأنك سبب وجودها وسبب خلودها في مدارك العلم بإذن الله وقد كان إرضاءك جزءاً من طموحي وجزءاً من سيري في طريق الماجستير حتى ترى ثمرة جهدك وطيب غرسك فكنت معنى الحياة لي وقد أرضاني الله فيك يا ابتِ فهلا رضيت عني .

وإلى من تتسابق الكلمات لتخرج معبرتً عن مكنون ذاتها إلى التي تمتهن الحب وتغزل الامل في قلبي عصفورا يرفرف فوق ناصية الأحلام فتبقى روحي متلألئةً ومشرقةً طالما كانت دعواتها عنوان دربي وتبقى أمنياتي على وشك التحقق طالما يدها في يدي وسنارةُ جهدها وسهرها تصطاد لي الراحة وتخطف التعب والألم من قلبي وعندما تكسوني الهموم أسبح في بحر حبها وحنانها ليخفف بل ويزيل من آلامي إلى امي التي مهما كبرت ف سأبقى طفلها الذي يكتب اسمها على دفتر قلبه ساعة حزنه ويهتف بفضلها حين يتقدم في علمه درجات لك يا والدتي الحبيبة يا سيدة القلب و الحياة أهديك رسالتي لتهديني الرضا و الدعاء.

وإلى الذين ظفرت بهم هدية من الأقدار إخوة فعرفوا معنى الأخوة، إخوتي الأحباء : وأخص بالذكر سندي الثاني بعد أبي اخي محمد(أبا يحيى) و إلى رفيق الطفولة و أول الأصدقاء زكريا اهديكم هذا العمل. وفي مقام الأخوة لا يمكنني أن انسى من تقاسمت معهم الغربة فكانوا بحق سندا في هذه الغربة ، لكم يا رفاقي : معاذ النجار ، صهيب ابو مصطفى ، علاء مصطفى ، وعلاء أبو دهيس وطبعا دون أن انسى محمد قفه.

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Abstract

The fetal electrocardiogram (ECG) signal is one of the most important vital parameters in clinical practice for the evaluation of the fetus. This signal represents the difference in the electrical activity of the fetal heart as a function of time.

Obtaining a fetal ECG in a way that satisfies scientific passion is a difficult task.

In this thesis, we propose a method to perform a non-invasive fetal electrocardiogram (NI-FECG) using an algorithm we have developed. An algorithm was first implemented to eliminate all interferences from the mother's side, and then the fetal QRS complexes were detected. The experimental results obtained by testing the proposed approach on non-invasive fetal ECG data from the PhysioNet database show its efficiency in diagnosing fetal arrhythmias when compared to other methods found in the literature.

Keywords

Electrocardiogram, ECG, Foetal ECG, NI-FECG, QRS complex, Filtering, Fetal Arrhythmias, Extraction

RESUME

Le signal de l'électrocardiogramme fœtal (ECG) est l'un des paramètres vitaux les plus importants en pratique clinique pour l'évaluation du fœtus. Ce signal représente la différence d'activité électrique du cœur fœtal en fonction du temps.

Obtenir un ECG fœtal d'une manière qui satisfasse la passion scientifique est une tâche difficile.

Dans cette thèse, nous proposons une méthode pour réaliser un électrocardiogramme fœtal non invasif (NI-FECG) en utilisant un algorithme que nous avons développé. Un algorithme a d'abord été mis en œuvre pour éliminer toutes les interférences du côté de la mère, puis les complexes QRS fœtaux ont été détectés. Les résultats expérimentaux obtenus en testant l'approche proposée sur les données ECG fœtales non invasives de la base de données PhysioNet montrent son efficacité dans le diagnostic des arythmies fœtales par rapport aux autres méthodes trouvées dans la littérature.

Mots Clés

Électrocardiogramme, ECG, ECG fœtal, NI-FECG, Complexe QRS, Filtration, Arythmies fœtales, Extraction

ملخص الأطروحة

تعتبر اشارة مخطط كهربية القلب للجنين (م ك ق) من اهم المعلمات الحيوية في الممارسة السريرية من أجل تقيم للجنين . تمثل هذه الاشارة اختلاف النشاط الكهربائي لقلب الجنين كدالة للوقت.

يعد الحصول على مخطط كهربية القلب للجنين بطريقة ترضي الشغف العلمي مهمة صعبة .

في هذه الاطروحة ، نقترح طريقة لتنفيذ تخطيط القلب الكهربائي غير الغازي للجنين باستخدام خوارزمية قمنا بتطويرها. تم أولا تفيذ خوارزمية ل التخلص من كل التداخلات من جهة الام ، من ثم القيام إكتشاف معقدات QRS للجنين.

تظهر النتائج التجريبية التي تم الحصول عليها عن طريق اختبار النهج المقترح على بيانات تخطيط القلب الكهربائي غير الغازي للجنين من قاعدة بيانات كفاءته في تشخيص عدم انتظام ضربات القلب لدى الجنين عند مقارنته بالطرق الأخرى الموجودة في الادبيات.

الكلمات الدالة

تخطيط القلب الكهربي، تخطيط كهربية القلب للجنين، الفلتره، عدم انتظام ضربات القلب لدى الجنين، استخلاص

CONTENTS

ECG	Electrocardiogramme
LA	Left Atrium
LV	Left Ventricle
RA	Right Atrium
RV	Right Ventricle
AV	Atrioventricular
SA	Sinoatrial
SV	Stroke Volume
HR	Heart Rate
CO	Cardiac Output
FHR	Fetal Heart Rate
bpm	Beats Per Minute
ARR	Arrhythmia
NR	Normal Rhythm
FECG	Fetal Electrocardiogramme
IUGR	Intrauterine Growth Restriction
SVES	Supraventricular Extrasystole
UC	Uterine Contractions
EFM	Electronic Fetal Monitoring
CTG	Cardiotocography
PPG	Photoplethysmography
NIR	Near-Infrared
LED	Light-Emitting Diode
FMCG	Fetal Magnetocardiogram
SQUID	Superconducting Quantum Interference Device
pT	Pico Tesla
fT	Femto Tesla
MSR	Magnetically Shielding Room
US	Ultrasound
PW	Pulsed Wave
GA	Gestational Age
BMI	Body Mass Index
FIGO	Federation of Obstetrics and Gynecology
FM	Fetal Movement
FOV	Field of View
MHR	Mother Heart Rate
FSE	Fetal Scalp Electrode
HIV	Human Immunodeficiency Virus
CSF	Cerebrospinal Fluid
NI-ECG	Non-invasive Fetal Electrocardiography
HRV	Heart Rate Variability
MECG	Maternal Electrocardiogram

AECG	Abdominal Electrocardiogram
ICA	Independent Component Analysis
EKF	Enhanced Kalman Filter
TS	Template Subtraction
AF	adaptive filtering
SNR	Signal-To-Noise Ratio

General Introduction

General Introduction

The first challenge that a person faces in his life is his birth because when moving from the inside to the outside of the womb, the newborn has to adapt to this new environment, and sometimes this transition is accompanied by temporal hypoxia, which can be defined by a decrease in the level of oxygen in the surrounding tissues. However, in most cases, the newborn can pass this crisis through protection mechanisms that enable him to deal with it.

But in some cases, these mechanisms fail to protect the newborn, either because they have not yet developed or for any reason. In this case, the risk is great, up to death. In other cases, it can be treated if it is discovered in the early stages of pregnancy.

With the continuous increase in pregnancies in general, there is also an increase in dangerous pregnancies, as they constitute nearly 20% of pregnancies. Therefore, it was necessary to find a method that allows early detection of these cases, and perhaps the best way is monitoring, which represents the main tool for evaluating the clinical situation of pregnant women and thus gives the ability to intervene on time.

The intended monitoring here is related to the physiological signals and their characteristics and classification; In order to monitor Pathological cases. To obtain information about the disease state, the monitoring system must consist of advanced technological tools with a mechanism for signal analysis. As a result of the technological development that enabled us to collect and interpret data, this has resulted in a complete renewal of the monitoring systems. For example, the heart and blood vessels are monitored by a heart rate change signal (HRV), as any change in the activity of the heart leads to a variance in the HRV signal.

Coming back to the monitoring of dangerous pregnancies that suffer from obstacles to the application of technological monitoring to pregnant women, among these obstacles is the inability to apply it for long periods, invasive, unreliable and imprecise.

The most common method used nowadays to monitor the fetus and the change in its heart rate is electrocardiography (CTG); But during the labour process, there are two techniques: Doppler ultrasound over the mother’s abdomen by a probe, which is characterized by being non-invasive and can be used almost throughout pregnancy, or by using an electrode attached to the head of the fetus, but unlike the first, it represents accuracy and specific at the time of use. Returning to the most widely used technique (CTG), known for its high sensitivity, but it suffers from low specificity, meaning that it can only recognize specific patterns of heart rate change, which makes accurate diagnosis difficult and unreliable.

According to all of the above, there is a need for new technology to record the fetal electrocardiogram without surgical intervention from the mother's abdominal (NI-FECG), and like other techniques, it faces challenges. One of the most important of these difficulties is that the recorded signal-to-noise ratio (SNR) is low, and the position of the fetus is not fixed, so the forms of signals and the intensity of the signal received from the fetus vary.

1. Objective

This thesis aims to evaluate whether the non-invasive fetal electrocardiogram (NI-FECG) allows the diagnosis of arrhythmia in the fetus, work to improve this technique and address potential difficulties and extract as much information as possible about the fetus and its heart performance.

The objectives of the thesis are divided as follows:

- Conduct a literature study.
- Identify the methods used to monitor the fetus.
- Conducting a comparative study between the methods used and identifying the advantages and disadvantages of each one.
- NI-FECG Technology Application and Implementation Mechanism.
- Development and construction of algorithms in MATLAB® to extract fetal electrocardiograms from recordings taken from the mother's womb.
- Study and analyze the results after implementing the algorithm on a database.

2. Outline

This document is divided into three chapters:

The first chapter briefly presents the functioning of the cardiovascular system, and the heart in particular, and examines the difference between the adult heart and the fetal heart. It provides an overview of the basics of electrocardiography, helps to understand the origin and nature of the electrical signals recorded by the ECG, and provides analysis and clarification of the ECG signal.

As for the second chapter of this thesis, it touched on the technical aspect of fetal monitoring methods, as it included a complete comparison of fetal monitoring methods with a detailed explanation of the methods currently used frequently, in addition to clarifying the new. Technology (NI-FECG) and its most important pillars.

The last chapter included the mechanism of work and implementation, as well as building a detection algorithm using a working environment compatible with this work and applying it to a database to ensure its efficiency.

Chapter I

Cardiac system and measurement of the ECG signal

In this chapter, we present the overall performance of the cardiac system from the medical side followed by the measurement of the ECG signal. We explain the importance of measuring the ECG signal in general and the embryo in particular, and the importance of fully extracting this signal without losing any part of it. And that's for the proper diagnosis of the fetal condition.

I. 1. The Heart

The heart is a hollow muscle organ, the primary organ of the circulation system, where it pumps blood into the human body, through a regular contraction. With every precision, the blood necessary for life is driven through the human body. Blood provides the body with oxygen and nutrients and helps to remove the body's waste.

As for its size, it is slightly larger than the handgrip, weighing between 200- 450(g), and the normal rate of the human pulse of 70 pulses per minute, during which 4.5 (L) of blood is pumped throughout the body.

I. 1.1 Heart Function

The heart can be said to be one of the most important organs of the human body; because it is mainly responsible for pumping blood and distributing oxygen and nutrients around body parts, radical changes in human body organs can occur once there are abnormalities or heart disorders regardless of their severity.

I. 1.2 Heart Anatomy

The heart is located between the lungs in the middle of the chest, specifically behind the sternum, and is indicated to be slightly left-leaning. The weight of the heart is 0.5% of the weight of the human body, i.e., it is about 350 grams per person weighing 70 kg. This increase in weight is accompanied by an increase in the volume of blood pumped into a pulse. What is increased in athletes is the amount of blood pumped, not the number of pulses (Figure I.1).

When defining a human heart, it is necessary to talk about what it contains:

a. **Middle Muscular Layer:** It's called cardiac muscle and it's made up of cardiac muscle cells, and an inner lining called the endocardium, which is the thickest layer.

b. **Heart Chambers (Heart Cavity):** Inside your heart are four rooms called atrium upper stones where the atrium receives blood from other parts of the body. The lower two stones are called ventricles, and they pump blood into other parts of the body, which is why the walls of the ventricles are thicker, and contain more heart muscles.

c. **Heart Chambers (Heart Cavity):** Inside your heart are four rooms called atrium upper stones where the atrium receives blood from other parts of the body. The lower two stones are called ventricles, and they pump blood into other parts of the body, which is why the walls of the ventricles are thicker, and contain more heart muscles.

As for the nutrition of the heart, like other parts of the body, the tissues of the heart need nutrition and oxygen. Although the heart cavity is constantly filled with blood, they cannot obtain nutrition from the blood. Its nourishment occurs through special blood vessels and special capillary networks called coronary arteries.

I. 1.2.1 Atria and Ventricles

The heart is composed of two functional and anatomically distinct parts; the right heart and the left heart. Each of these two parts is subdivided into atria and ventricle and works synchronously. There is a valve system between these different parts of the heart that prevents blood from flowing back (Figure I.1).

The atria obtain blood returning to the heart, even as the ventricles obtain blood from the atria – thru the atrioventricular valves – and pumps it into the lungs and the relaxation of the frame. The left atrium (LA) and left ventricle (LV) are separated from the right atrium (RA) and right ventricle (RV) with the aid of using a band of tissue known as the septum.

The RA gets deoxygenated blood from the pinnacle and neck and from the relaxation of the frame thru the advanced and inferior vena cava, respectively. The RV then pumps blood into the lungs (thru the pulmonary trunk, which divides into the proper and left pulmonary arteries), wherein it's far oxygenated. The oxygenated blood is again to the LA thru the pulmonary veins and passes into the LV thru the cardiac valves. From the LV, it's far added to the entire frame thru the aorta.

The RV does now no longer want a massive quantity of pressure to pump blood into the lungs, in comparison with the LV, which has to pump blood into the relaxation of the frame. The LV has a thicker wall and its hollow space is circular, even as the RV hollow space is crescent-fashioned with a thinner wall.

I. 1.2.2 Heart Valves

The RA and RV are separated via way of means of the tricuspid valve, which has 3 leaflets. The tricuspid valve lets in deoxygenated blood to transport from the RA into the RV. From the RV, blood passes via the pulmonary valve (located among the RV and the pulmonary artery), permitting deoxygenated blood to go into the lungs. On the left aspect of the heart, oxygenated blood from the lungs enters the LA from the pulmonary vein. The LA is separated from the LV via way of means of the mitral valve (additionally referred to as a bicuspid valve, because it has leaflets and blood flows via this valve into the LV. It then passes via the aortic valve into the aorta, which transports oxygenated blood in the course of the body (Figure I.1).

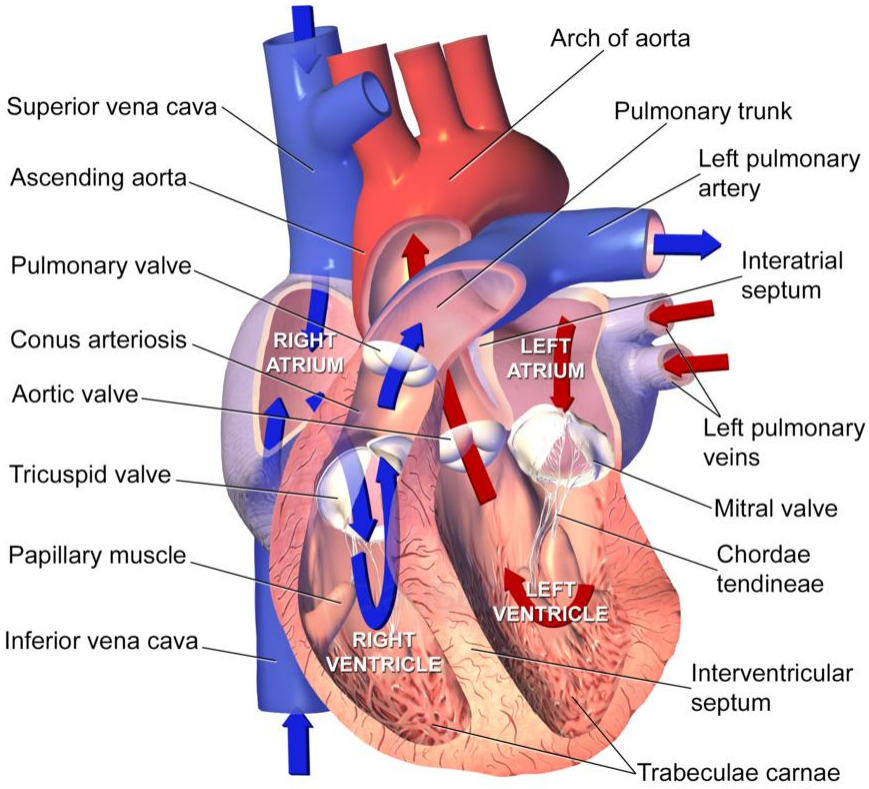

Figure I.1: Heart Anatomy.

I. 1.3 Conduction system of the heart

The heart has a specialized system for the self-excitation of the rhythm and regular contraction of the muscle, which will cause the heart muscle to contract rhythmically and quickly transmit these impulses to the entire heart. When this system is operating normally, the atria contract some time ahead of the ventricles, allowing the additional filling of the ventricles before they thrust the blood through the lungs and peripheral circulation. Another feature of this system is that all parts of the ventricles can contract almost simultaneously, which is important for generating effective pressure in the ventricular cavity.

I. 1.3.1 Definition

It is a group of cardiac muscle structures whose function is to generate and initiate the electrical impulses responsible for the coordinated contractions of each heart cycle and to transmit electrical excitement from its original location to the myocardium (cardiac muscle tissue) that leads to every contraction (contraction). These specialized cells can generate an action potential on their own (self-excitation) and transfer it to other neighbouring cells (conduction), including heart muscle cells, (Figure I.2).

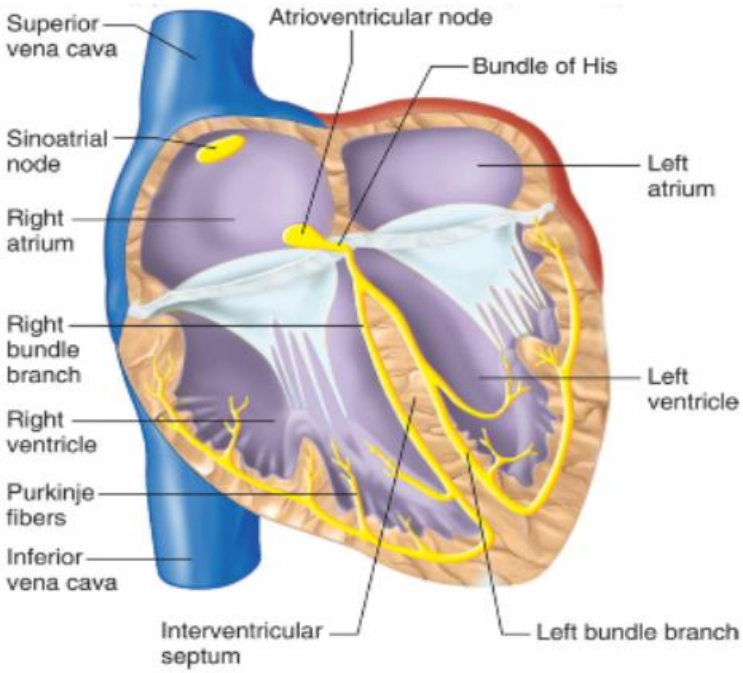

Figure I.2: Basic anatomy of the human adult heart with the electrical conduction system indicated**.**

I. 1.3.2 The main parts of the cardiac conduction system

Its components, which are arranged spatially, which are activated in sequence and which take place at different speeds, are essential for the formation (initiation) of cardiac excitation and for the coordination and rhythm of the mechanical activity of the various regions of the myocardium during cardiac cycles. These components, which have been named sequential activation order during the cardiac cycle, are the sinoatrial node, three internal bundles, the atrioventricular (AV) node, the His bundle with its right and left branches, and Purkinje fibers (Figure I.3).

A. Sinoatrial Node (SA node)

The sinus node is a small, oval-shaped anatomical structure about 15 mm in length, 5 mm in height and about 3 mm in thickness, and is located in the posterior part of the right atrium, near the start of the vena cava in this chamber. and it is responsible for the rhythm of the heart, which is expressed by the rate of the heartbeat. The sinus node produces about 60-80 signals per minute (Figure I.3).

It is made up of a few hundred modified cardiomyocytes that have lost their constricting apparatus and have developed a speciality that allows them to experience gradual depolarization spontaneously during diastole that ends up firing an actual potential in them. This generated excitement spontaneously spreads and reaches the atrial myocardium and the ventricular myocardium, and it excites and forces them to contract, and repeats as many times per minute as the heart rate value. Cells of the sinoatrial node directly communicate with and excite adjacent atrial myocardium cells; this excitement spreads to the rest of the atria to produce atrium constriction. The conduction velocity here is 0.3 m / s and atrial depolarization is completed in 0.07-0.09 (s).

B. Internodal and intra-atrial conduction

The internodal conduction pathways are a part of intra-atrial conduction. Not only do these pathways travel within the right atrium, but they also form direct points of communication between the sinoatrial and atrioventricular nodes. The internodal conduction pathway is divided into anterior, middle and posterior branches.

These conduction pathways transmit the action potential slightly faster than the surrounding cardiomyocytes. This ensures that the action potential arrives at the AV node at an appropriate time [Lib'07].

C. Atrioventricular node (AV node)

It is the nucleus of cells located in the posterior wall of the right atrium, in the lower part of the septum between the atria, behind the tricuspid valve. This is the obligatory excitation pathway that goes into the ventricles and cannot use the non-excitable fibrous tissue that gets in the way.

After the electrical impulses propagate through the atria, they converge at the atrioventricular node - located inside the atrioventricular septum, near the opening of the coronary sinus. The cranial segment or upper segment has a conduction velocity of 0.04 m/s and a more caudal segment with a speed of 0.1 m / s. This decrease in conduction velocity delays the passage of excitation into the ventricles. The conduction time through the AV node is 0.1 sec. This relatively long time represents a delay that allows the atria to complete depolarization and pre-ventricular contractions, and to complete filling of these chambers before they contract.

The AV node deactivates the electrical signal by approximately 120 milliseconds, to ensure the atria have sufficient time to eject all blood into the ventricles before ventricular contractions. Without this disruption, the atria and ventricles would contract at the same time, and blood would not flow efficiently from the atria to the ventricles. Inactivation in the AV node represents most of the interval between the two P-R waves on the ECG, and the other portion represents repolarization in the atria. Then the excitation wave travels from the atrioventricular node to the atrioventricular bundle (Figure I.3).

D. Atrioventricular bundle (bundle of His)

The atrioventricular bundle (His bundle) is a continuation of the specialized tissues of the AV node and serves to transmit electrical impulses from the atrioventricular node to the Purkinje fibres in the ventricles.

The distal portion of the AV node is known as the HIS bundle. The HIS bundle divides into two branches in the interventricular septum: the left branch and the right branch. The left branch activates the left ventricle, while the right branch activates the right ventricle (Figure I.3).

E. Purkinje fibers

These cells are located in the subendocardial surface of the ventricular walls and can rapidly transmit cardiac action potentials from the atrioventricular bundle to the myocardium of the ventricles. And it is noted that it is more branching in the left ventricle due to the force of contraction that it needs to pump blood around the body (Figure I.3).

This rapid conduction allows for coordinated ventricular contraction (ventricular systole) and for blood to travel from the left and right ventricles to the pulmonary and aorta, respectively. Total excitation is reached in approximately 0.06 (s).

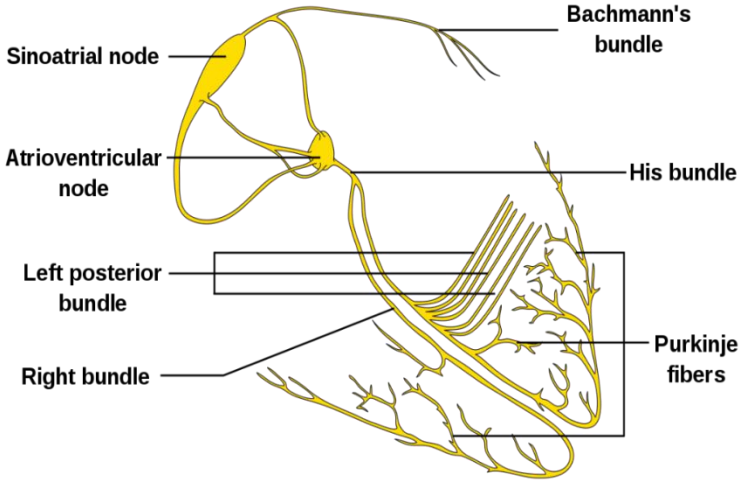

Figure I.3: the main components of the conduction system of the heart.

I. 1.3.3 Rapid depolarization of heart cells

The conduction velocity in the atrial myocardium is 0.3 m / s and the atrium completes depolarization in a period between 0.07 and 0.09 s. In intramuscular beams, the velocity is 1 m / s and excitation takes about 0.03s to reach the AV node when it begins in the sinus node.

In the AV node, the velocity is between 0.04 and 0.1 m / s. The excitation takes 0.1 seconds to pass through the node. The velocity in HIS bundle and its branches is 1 m / s and rises to 4 m / s in PURKINJE fibres. The delivery time for its branch route - Purkinje is 0.03 seconds.

The conduction velocity in the ventricular contractile fibres is 0.5-1 m / s and the total excitation, once initiated, is completed in 0.06 s. The addition of appropriate times demonstrated that ventricular excitation reached 0.22 s after initial SA node activation.

The consequences of combining the velocities and times at which excitation passes through the different components of the system are 1. The two atria are excited first, then the ventricles and 2. They are simultaneously activated. Effective contraction to expel blood.

I. 1.3.4 The mechanism of action

The heart's electrical conduction system transmits the signals normally generated by the sinoatrial node to cause the heart muscle to contract. The pacemaker signal generated by the sinoatrial node travels through the right atrium to the atrioventricular node, along with the bundle of His and across the branches of the bundle to cause the myocardium to contract. This signal stimulates contraction first of the right and left atria and then the right and left ventricles. This process allows blood to be pumped throughout the body.

Although all parts have the ability to generate action potentials and thus produce heart contractions, the sinoatrial node (SA node) is the main initiator and regulator of impulses in a healthy heart. This is one aspect that makes SA node a physiological pacemaker. And conduct the pulse from the SA node, and then deliver it to the cardiomyocytes. When cardiomyocytes are stimulated by an action potential, they contract synchronously, causing a heartbeat.

The sequence of electrical events during one full contraction of the heart muscle:

- The fibers in this particular conducting system have the capability of self-excitation, a process that can cause automatic rhythmic discharge and subsequent contraction. The fibers of the sinoatrial node (SA) exhibit this capability to the largest extent, so the SA node ordinarily controls the rate of contractions of the complete heart. Specifically, the fibers of the SA node self-excite at the highest rate and the impulses generated by the SA node subsequently propagate throughout the entire heart. After the cell is depolarized, it shows a refractory period during which no excitement occurs. At the end of the refractory period, the SA node is usually the first to reactivate itself, so the SA node is responsible for the heart rate.

- The nodular fibers of the SA node discharge spontaneously, causing the action potential to rapidly propagate through the two atria and from there to the ventricle through the atrioventricular (AV) bundle. It is primarily this AV (or His) bundle that delays the transmission of action potentials from the atria into the ventricles, allowing time for the atria to empty their contents into the ventricles before a ventricular contraction begins. Figure I.2 shows a diagram of the action potential pathway through the heart.

- After the fibrous tissue passes between the atrial and ventricular muscles, the distal end of the atrioventricular bundle downward descends into the ventricular septum and is divided into left and right branches. Each branch descends to the apex of the ventricle and gradually divides into smaller branches, encircling each ventricular cavity and returning to the bottom of the heart. The Purkinje terminal fiber penetrates about a third of the way into the muscular mass and then become continuous with the cardiac muscle fibers.

- Purkinje fibers pass through the atrioventricular bundle from the atrioventricular node and branch to the ventricles, which has opposite characteristics to the atrioventricular node. For all muscle fibers of the ventricle to contract almost simultaneously, the cardiac impulse has to appear at each muscle fiber at approximately the same time. Therefore, Purkinje fibers are relatively large fibers that transmit action potentials at approximately six times the rate of transmission in cardiac fibers.

I. 1.4 Cardiovascular system

The circulatory system consists of the heart, blood vessels and blood. The heart is divided into two parts, each part is composed of atria and ventricles. The blood flows through the body under the pressure created by the heart-pumping action. The cardiovascular system forms a closed circuit composed of two circuits; pulmonary and systemic. The blood is pumped from the right ventricle, through the lungs, and then into the left atrium, which is called the pulmonary circulation. Then blood is pumped from the left ventricle through the systemic circulation to all organs and tissues of the body except the lungs and right atrium [Raf'14].

I. 1.5 Physiology of The Heart

In the following, we will study the healthy and proper function of the heart in general and the heart of the fetus and pregnant woman in particular.

I. 1.5.1 The adult heart

The adult heart is a muscular organ composed of two independent pumps: the right side of the heart pumps blood through the lungs, and the left side of the heart pumps blood through peripheral organs, each of which is a pulsatile two-chamber pump composed of an atrium and a ventricle. The atria mainly act as weak pumps, pumping the ventricles and helping the blood flow into the ventricles. In turn, the ventricles provide the main force that allows blood to flow through the pulmonary or peripheral circulation.

The cardiac cycle refers back to the alternating contraction and rest of the myocardium withinside the partitions of the coronary heart chambers, coordinated with the aid of using the conduction system, at some stage in one heartbeat. Systole is the contraction segment of the cardiac cycle, and diastole is the rest segment. At a normal coronary heart rate, one cardiac cycle lasts for 0.8 second.

Although the right side of the heart is separated from its left side, they work together in the sense that they contract and expand together. The blood is released through the chambers as a result of the contraction of the cardiac muscles, which begins with the two upper chambers or the thin-walled atria, which takes about 0.1 seconds.

This is followed by the contraction of the two thick-walled ventricles below the atria for a period of about 0.3 seconds. This active phase of the heart is called systole, which is followed by a rest period called diastole, which takes 0.4 seconds.

Thus, in the cardiac cycle, with its two phases, systole and diastole, it takes about 0.8 seconds. And from here it can be concluded that the number of heart cycles per minute mathematically is equal to 75 revolutions per minute, and in fact, it was found that the average number of heart cycles is between 70 and 72 revolutions per minute for a normal person while it changes in some pathological conditions, and the amount of blood can be estimated Which flow out of each ventricle at a specific time during different physiological conditions.

It was found that each ventricle pumps an amount of blood estimated at 70 millilitres per stroke, known as stroke volume S.V. Since the heart rate (average number of beats per minute) HR equals 70 times per minute, the volume of blood released by each ventricle per minute under normal conditions is 70 times x 70 millilitres = 4900 millilitres/minute, meaning an infusion of approximately five litres per minute This is known as cardiac output (CO).

I. 1.5.1.1 HEART CYCLE

Ensures the heart thanks to its role as a double suction pump (Double Pump) the circulation of blood in the body to provide oxygen and nutrients to the tissues. There are two types of circulation: pulmonary circulation and systemic circulation.

The systemic circulation ensures the general distribution of blood to tissues throughout the body and back to the heart. Here, the left heart acts as a pump. The reoxygenated blood enters the left atrium and then passes to the left ventricle, which ejects it by contraction into the aortic artery. From there, it is distributed to the various organs and tissues of the body. It is then brought back to the right heart by the venous network.

As shown in (Figure I.4), the sequence of phases of contraction (systole) and relaxation (diastole) observed at the heart are summarized as follows:

- The phases of activity (systole) and rest (diastole) are contemporary in the transverse direction of the organ, that is to say that the right and left homologous cavities contract and relax synchronously.
- The phases of activity and rest are successive in the longitudinal direction of the organ in the right as in the left heart. The atrial systole precedes the ventricle systole.
- There is a period during which the atria and ventricles are simultaneously in a relaxed state: this is the general diastole.
- In a normal heart, these phases of activity and rest are repeated in an unchanging order. In resting subjects, this frequency varies in the same subject under certain extreme physiological conditions [Mar'14].

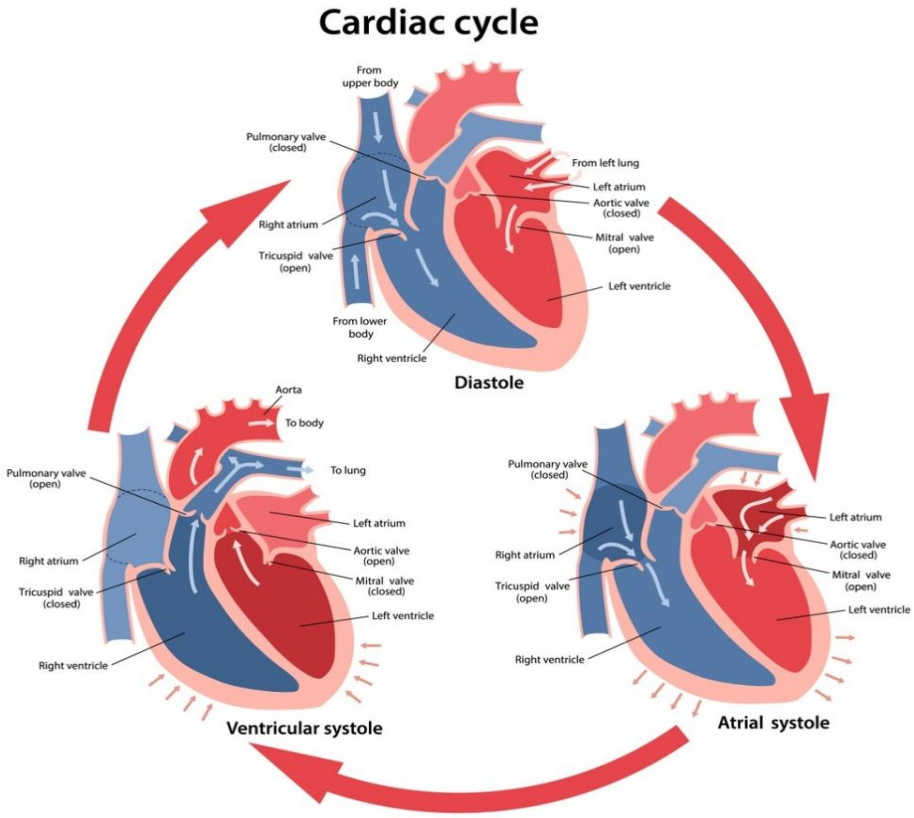

Figure I.4: Cardiac cycle.

A. Pulmonary circulation

The function of the pulmonary circulation or small circulation is to transport blood to the lungs to ensure gas exchange and then return it to the heart. The right side of the heart is the pump for pulmonary circulation.

The oxygen-depleted and CO2-rich blood enters the body into the right atrium through the upper and lower vena cava veins. Then it descends into the right ventricle which ejects it into the two pulmonary arteries (pulmonary trunk). They carry blood to the lungs where it gets rid of CO2 and absorbs oxygen. It is then redirected to the heart, in the left atrium, through the pulmonary veins.

B. Systemic Circulation

Greater circulation supplies all body tissues with oxygenated blood and nutrients and rids them of carbon dioxide and other waste products. Oxygenated blood travels from the left ventricle through the arteries to the capillaries in the tissues of the body. The deoxygenated blood then returns from the capillaries to the tissues of the heart, where gaseous exchange occurs in the veins that converge to form larger and larger veins until the blood reaches either the superior vena cava or the inferior vena cava, which ends in the right atrium. The aorta is the main artery in the systemic circulation, and all other major arteries are direct or indirect branches of the aorta.

I. 1.5.1.2 Cardiac cycle from the perspective of electrical activity

Effective blood pumping requires the orderly contraction of arteries and ventricles. First, the atria contract and then immediately contract the ventricles. The contraction of the myocardium is caused by the depolarization of the plasma membrane. Remember the electrical conduction system of the heart (Figure I.2). The initial depolarization occurs in the sinoatrial node (SA), where the discharge rate of the sinoatrial node controls the heart rate. Depolarization first spreads to the muscles of the atria, and conduction occurs fast enough to cause the left and right atria to contract simultaneously. The depolarization will conduct to ventricles through the ventricular (AV) node which is located in the base of the right atrium. After the atrioventricular node, the pulse enters the Hiss bundle located between the walls of the two ventricles, because the atria and ventricles are completely separated by a layer of non-conductive material, the bundle of His is the only electrical conductor between the atria and ventricles. The His bundle divides into the right and left branches of the bundle, and contacts Purkinje fibers, and Purkinje fibers eventually contact ventricular cardiomyocytes. The conduction along Purkinje fibers is very rapid, and the depolarization of all left and right ventricles occurs more or less simultaneously; however, conduction and contraction of the lower ventricles occur earlier, making the contraction more effective [Wid'04].

A normal heartbeat involves a series of mechanical and electrical events (Figure I.5), summarized as follows:

1. The action potential is generated in the SA node and spreads to both atria.
2. Contraction of both atria.
3. The action potential reaches the AV node and trigger it.
4. During the contraction of the atria, blood is forced from the atria into the ventricles.
5. The action potential of the AV node increases the diffusion through the His bundle to the Purkne fiber.
6. Due to the propagation of the AV action potential, the two ventricles are in contact; the left ventricle pumps blood into the systemic circulation, while the right ventricle supplies blood to the lung system.

7. The heart muscle will relax, but due to the elastic rebound of the arterial wall, blood will continue to flow.

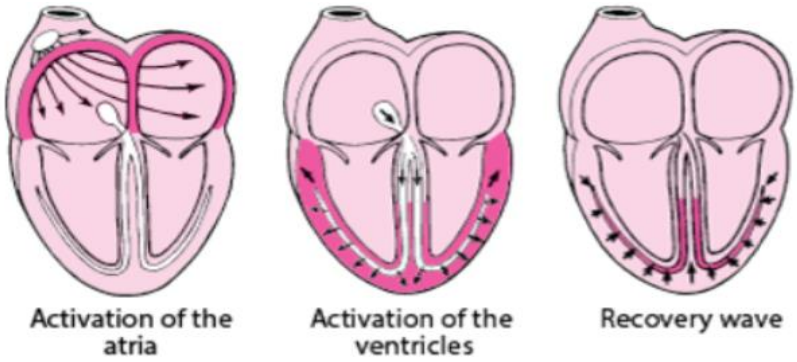

Figure I.5: electrical activity of the Cardiac cycle.

I. 1.5.2 Fetal Heart

The baby growing inside of the mother's uterus (the womb) is called a fetus. The developing fetus is absolutely depending on a unique organ referred to as the placenta for nourishment. One facet of the placenta is hooked up to the uterus, and the alternative facet is hooked up to a liquid-crammed sac that holds the fetus. A unique twine referred to as the umbilical twine hyperlinks the placenta to the fetus. The mom's blood flows thru a skinny layer of cells withinside the wall of the uterus, giving the fetus meals and oxygen whilst getting rid of any wastes like carbon dioxide. There is truly no direct touch among the circulatory structures of the mom and fetus.

The fetus does not use its own lungs until birth, so its circulatory system is different from that of a newborn baby. Before birth, the fetal heart does not have to pump blood to the lungs to pick up oxygen. In other words, the fetal heart does not need a separate pulmonary artery and aorta. In the fetal heart, these two blood vessels are connected by a blood vessel called the ductus arteriosus. After birth, the ductus closes and a separate left pulmonary artery and aorta form.

The heart is one of the first organs to form in the human body, yet it takes a number of weeks for its four chambers to form, and it should be noted that there is a recent study that showed that the embryonic heart rate reaches its maximum when development is complete Morphological of the heart of the fetus.

I. 1.5.2.1 Development of fetal heart shape

A human fetus forms in a very precise order. While the heart is one of the first organs to begin development, it takes several weeks before it resembles the four-chambered structure that we all know. During the fetal heart's developmental stages, the heart actually takes on several distinct appearances. These heart structures resemble other animal hearts.

- When the human heart first begins to form, it looks like a simple tube, much like a fish's heart. However, rapid growth soon causes the tube to bend and twist backwards, beginning the formation of the familiar shape.

- The second phase of heart development creates two chambers. At this time, the heart resembles a frog heart.
- The third phase begins when the two atria (the top chambers of the heart) become completely separate and the ventricles (the bottom chambers) are just beginning to separate. During this three-chambered phase, the fetal heart may appear similar to a snake or a turtle heart.
- Finally, the ventricles separate completely. The final four-chambered heart structure distinguishes the human heart from other living creatures.

I. 1.5.3 Differences between the adult heart and the fetal heart

The electrical activity of the fetal heart is similar to that of the adult heart, but the electrical axis of the fetal heart points in a different direction than the electrical axis of the adult heart. There are some functional and physiological differences between the fetal heart and the adult heart. These differences are due to the difference in the circulatory system of the heart and blood vessels of the fetus from the circulatory system of the adult.

In adults, gas exchange (that is, the release of carbon dioxide from the blood and the supply of oxygen from the blood) occurs in the lungs. Oxygenated blood flows from the lungs through the left side of the heart to the peripheral circulation. Since this peripheral circulation is greater than the pulmonary circulation, the left ventricle must generate significantly higher pressure than the right ventricle to ensure that there is sufficient blood flow to the organs. Therefore, the muscle mass of the left ventricle is greater than the muscle mass of the right ventricle. This causes the electrical axis to be directed towards the left ventricle.

In the fetus, gas exchange occurs in the placenta and not in the lungs. The concomitant higher load that must be exerted by the right ventricle - as opposed to the left ventricle - causes a shift in the electrical axis of the fetus towards the right ventricle. Therefore, the pulmonary circulation is bypass by using two shunts, namely the foramen ovale and ductus arteriosus which links outgoing vessels of booth ventricles. A similar shunt is called ductus venosus, which allows blood to bypass the liver. This different circulation manifests itself, among other differences, by interconnections between the left and right parts of the heart. These interconnections consist of the foramen ovale, a gap in the septum dividing both sides of the heart, and the ductus arteriosus, a shunt between the pulmonary artery and the aorta. The foramen ovale and ductus arteriosus are shown in (Figure I.6).

It transports blood containing oxygen and nutrients from the umbilical cord directly to the right side of the fetal heart. The foramen ovale is closed during the first breath after birth, and the arterial duct is partially closed 10-15 hours after birth. After a while, the ductus venosus will also be closed. when the umbilical cord is cut, the blood flow between the mother and the fetus stops.

Because of these interconnections, the left and right ventricles produce the same pressure; however, in the fetal circulation, the right ventricle accounts for about 60% of total cardiac output, and the left ventricle accounts for about 40% of the remaining. Due to this increased production, the right ventricle of the fetal heart has more muscle mass than the left ventricle [Yag'09].

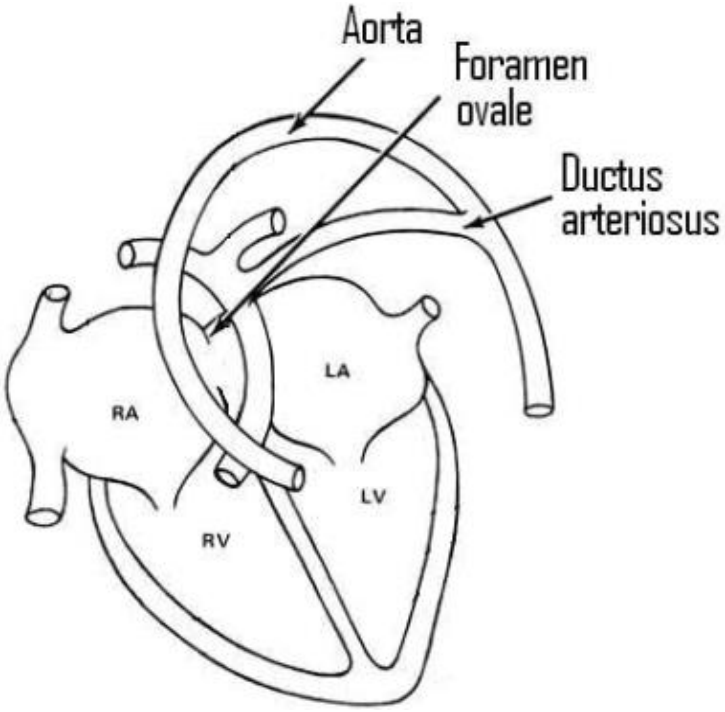

Figure I.6: Basic anatomy of the human fetal heart with the main differences with respect to the adult heart.

I. 1.5.4 The physiology of the pregnant woman's heart

Pregnancy brings lots of changes. Besides the obvious ones like a growing belly, there are some that aren't as noticeable. One example is an increased amount of blood in the body.

As the first months of pregnancy pass and the fetus grows month after month, the uterus needs more blood flowing inside it to provide the necessary nutrients for the growth and development of the fetus, and as a result, the percentage of blood pumped by the heart increases 30-50% more than a person's normal rate.

During pregnancy, the woman's heart must work harder because as the fetus grows, the heart must pump more blood to the uterus. By the end of pregnancy, the uterus is receiving one-fifth of the woman's prepregnancy blood supply. During pregnancy, the amount of blood pumped by the heart (cardiac output) increases by 30 to 50%. As cardiac output increases, the heart rate at rest speeds up from a normal prepregnancy rate of about 70 beats per minute to 80 or 90 beats per minute. During exercise, cardiac output and heart rate increase more when a woman is pregnant than when she is not. At about 30 weeks of pregnancy, cardiac output decreases slightly. Then during labour, it increases by an additional 30%. After delivery, cardiac output decreases rapidly at first, then more slowly. It returns to the prepregnancy level about 6 weeks after delivery.

In the second trimester, the blood vessels in a woman's body begin to dilate or widen. This causes your blood pressure to drop slightly, but may return to a normal prepregnancy level in the third trimester.

The volume of blood increases by almost 50% during pregnancy. The amount of fluid in the blood increases more than the number of red blood cells (which carry oxygen). Thus, even though there are more red blood cells, blood tests indicate mild anemia, which is normal. For reasons not clearly understood, the number of white blood cells (which fight infection) increases slightly during pregnancy and increases markedly during labor and the first few days after delivery.

Certain heart murmurs and irregularities in heart rhythm may appear because the heart is working harder. Sometimes a pregnant woman may feel these irregularities. Such changes are normal during pregnancy. However, other abnormal heart sounds and rhythms (for example, diastolic murmurs and a rapid, irregular heart rate), which occur more often in pregnant women, may require treatment.

Heart palpitations can be normal and non-harmful during pregnancy. But there's always a chance they could mean you have a more serious, underlying health condition.

I. 2. Fetal pulse

The fetal pulse is the sign that indicates the formation of the heart and the circulatory system of the fetus, it is the first sign of the heart's work, so that the heart takes a shape closer to the tube, and pumps blood which is the "pulse" at the beginning of the fifth week of the fetus's formation, even though the heart is incomplete in The body at this time, which is the beginning of the second month or in the fifth week, the pulse is complete and begins to rise as the weight and growth of the fetus increases in the following weeks.

In the fifth week of pregnancy, the heart of the fetus begins to beat, but it is difficult at this stage to hear it through the fetus monitor, so you should wait for the fetus's growth a little until its heart is fully formed, the first time the fetus's heartbeat is detected via ultrasound during the sixth week And the seventh of pregnancy.

The baby's heart begins to form in the third week of pregnancy, out of two blood vessels, but it does not begin to function immediately. As the pumping of blood to the heart begins in the fifth week of pregnancy, and with the beginning of the sixth week the first heartbeat of the fetus begins, and its blood begins to circulate, and then the sound of the baby's heartbeat can be heard by examining sound waves by the ultrasound device, and by the end of the twentieth week, a heartbeat can be heard Fetus with a stethoscope.

I. 2.1 Fetal heart rate

A normal fetal heart rate (FHR) generally stages from 120 to 160 beats per minute (bpm) in the in-utero period. It is measurable sonographically from around 6 weeks and the everyday variety varies all through gestation, growing to around 170 bpm at 10 weeks and lowering from then to around 130 bpm at term.

I. 2.2 Evolution through gestation

Although the myocardium begins to contract rhythmically by 3 weeks after conception (from spontaneously depolarising myocardial pacemaker cells in the embryonic heart) it is first visible on sonography around 6 weeks of gestation. The FHR is then usually around 100 to 120 beats per minute (bpm).

FHR then increases progressively over the subsequent 2-3 weeks becoming:

~110 bpm (mean) by 5-6 weeks

~170 bpm by 9-10 weeks

This is followed by a decrease in FHR becoming on average:

~150 bpm by 14 weeks

~140 bpm by 20 weeks

~130 bpm by term

Although in the healthy fetus the heart rate is usually regular, a beat-to-beat variation of approximately 5 to 15 beats per minute can be allowed [1].

I. 2.3 Fetal heart rate diseases

A slow fetal heart rate is named fetal bradycardia and is typically described as:

- FHR <100 bpm before 6.3 weeks gestation,
- FHR <120 bpm between 6.3 and 7.0 weeks

A fast fetal heart rate is named a fetal tachycardia and is commonly described as:

- FHR >160-180 bpm
- FHR around 170 bpm may be classified as borderline fetal tachycardia

A rapid and irregular fetal heart rate is usually termed a fetal tachyarrhythmia [Dou'00] [Hor'07].

I. 3. Electrocardiogram

Electrocardiography is a technique for exploring myocardial activity, based on the recording and interpretation of ECGs.

The electrocardiogram (ECG) is the most important tool for assessing the heart's electrical events from one point in time to the next; therefore, the electrocardiogram is a graph of the relationship between heartbeat and time and voltage, Or it is a scalar tracing that records over time the variations in potentials induced in different points of the body (especially on the surface of the skin) by active myocardial fibres. The examination is an important part of clinical diagnosis. The action potential of the myocardium generates a current that generates an electric field that can be sensed by pick-up electrodes that are selectively placed on the body surface. (Figure I.7) shows the one cycle of ECG waveform.

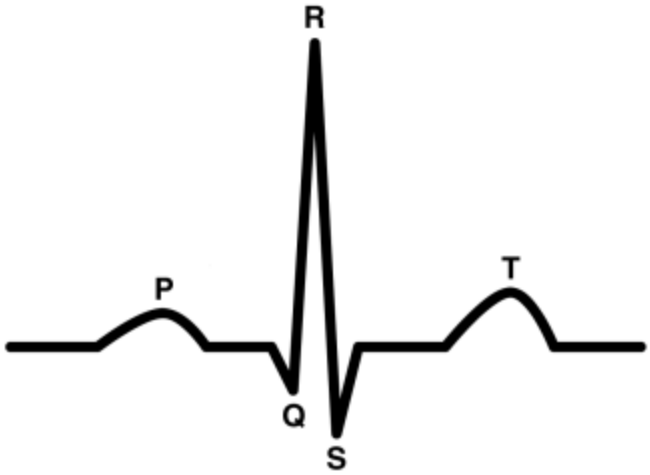

Figure I.7: The waveform of typical ECG which can be recorded during one cardiac cycle.

This electrical recording (electrocardiogram) provides information about the part of the heart that stimulates each heartbeat (the sinoatrial or sinus node), the heart's nerve conduction pathways, and the rate and rhythm of the heartbeat.

From the sinus node, conduction takes place step by step and radially in the atria; it thus reaches the atrioventricular node where it slows down, the bundle of His then its branches, the Purkinje network and the ventricular cells are then excited.

I. 3.1 Electro-genesis of the signal

Each heartbeat begins with a pulse or signal from the pacemaker (the sinoatrial or sinus node). This signal stimulates the two upper chambers of the heart (atria). The first wave is called the P wave, which corresponds to the current flowing during an atrial depolarization.

Then, electrical current flows into the lower chambers of the heart (the ventricles). The second deflection Represent the QRS complex, which is related to ventricular depolarization (the activation of the ventricles) in the ECG. The electric current then spreads back to the ventricles in the opposite direction. This activity is called the recovery wave, which is represented by the T wave.

Clinical ECG is usually done using several combinations of limb and chest recording points called ECG leads. The shape and size of the P wave, QRS wave group, and T wave vary depending on the electrode position. The relationship between heart rate and ECG curve and interval is shown in (Figure I.8).

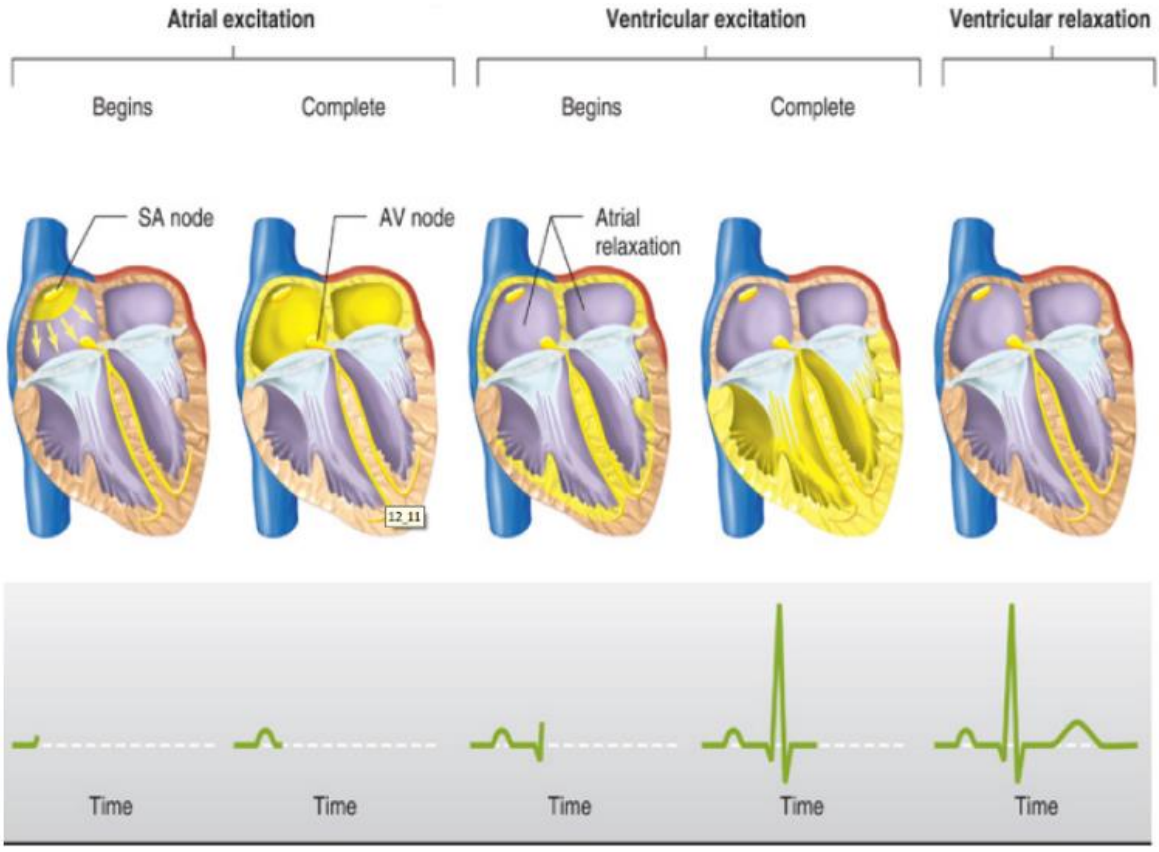

Figure I.8: The ECG waves compare to the heart electrical activities.

I. 3.2 Waves recorded on a normal ECG

On the electrocardiogram signal of the electrocardiogram, it can be observed that the contraction and relaxation process of the myocardium is represented by a series of positive and negative deviations superimposed on the zero-potential line (baseline), which corresponds to the absence of a cardiac event. As shown in Figure 1.9.

The letters P, Q, R, S, T, and U are usually assigned to the main ECG waves:

- **P wave:** The P wave is a kind of atrial depolarization, which propagates from the SA node to the AV node, and from the right atrium to the left, and is within a range of 0.08 to 0.12 seconds and its amplitude is less than 0.25 mv.
- **QRS Complex:** The QRS complex represents the rapid depolarization of the left and right ventricles. Compared with the atrium, the muscle mass of the ventricle is greater, so the amplitude of the QRS complex is usually much larger than that of the P wave. QRS duration should usually be 0.06 to 0.10 seconds and its variable amplitude is between 5 and 20 (mV) [Ken'11].

- **Q wave:** Represents the depolarization of the interventricular septum, and the range is 0.03-0.04 seconds.
- **PR interval:** The PR interval is measured from the beginning of the P wave to the beginning of the QRS wave. This interval represents the time it takes for electrical pulses to pass through the AV node from the sinoatrial node.
- **R wave:** Represents the disappearance of ventricular wall polarization, about 0.05-0.08 seconds.
- **S wave:** This represents the depolarization of Purkinje fibers and **is** 0.03-0.08 seconds.
- **T-wave:** Represents the repolarization of the ventricle**,** which is 0.16 seconds.
- **U wave:** It is believed that the U wave is caused by the repolarization of the interventricular septum. The amplitude is usually small and usually disappears completely (three times smaller than the T wave amplitude). U waves are more common in athletes with low heart rate. (Figure I.9). in the table I.1 shows ECG waves and intervals [Ben'13].

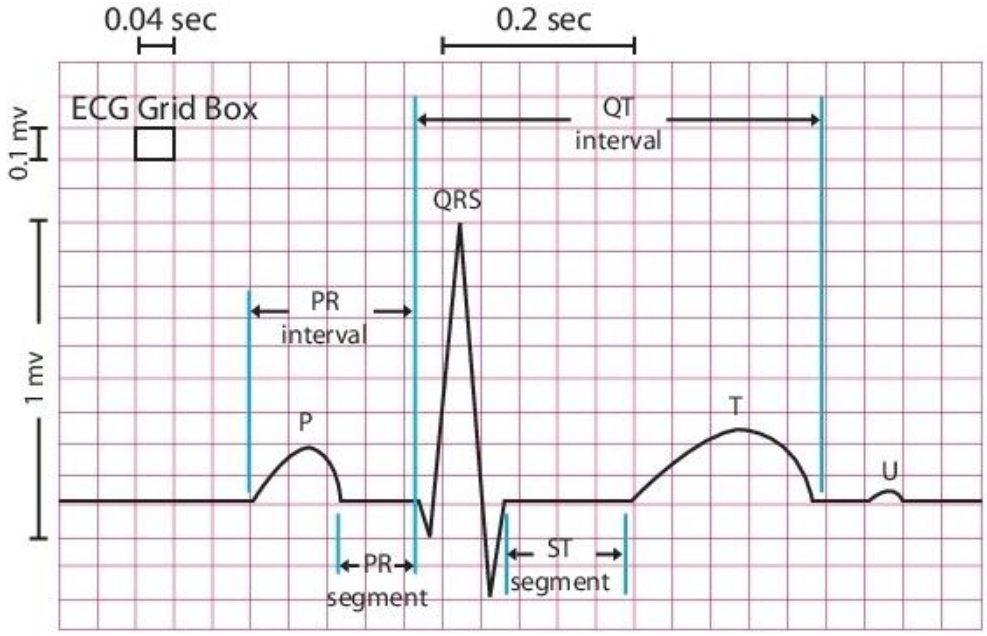

Figure I.9: the morphology of the normal ECG signal over a cardiac cycle.

Wave/Interval	Corresponded Heart Activity	Estimated duration
P-Wave	Atrial Depolarization	100 ms
PR interval	Time action potential moves from atria to ventricles	120-200 ms
QRS complex	Ventricular depolarization	60-100 ms
ST interval	Time between ventricular depolarization and re polarization	120 ms
T-Wave	Ventricular re-polarization	200 ms

Table I.1: ECG waves and intervals.

I. 3.3 Heartbeat

Heart rate is related to the origin of electrical activity in the heart and the regularity or irregularity of its distribution. Therefore, when it comes to the following, we will talk about regular sinus rhythm:

- Regular: The R-R interval is almost constant over the entire trace, with similar QRS complexes.
- **Sinus:** Electrical activity is produced by the sinoatrial node.

The analysis of the heart rhythm from the electrocardiogram signal is accomplished by checking the regularity of the rhythm and its origin which can be:

- **Sinus** (from sinoatrial node: P wave precedes each QRS complex).
- **Junctional** (atrioventricular node: fine QRS complexes and retrograde P wave).
- **Ventricle** (ventricular cardiomyocytes: QRS complex without P wave increases).
- **Ectopic** (from atrial myocytes**:** abnormal P wave and normal QRS wave).
- **Artificial** (pacemaker).

In the case of the pacemaker, the heart rate is imposed by a pacemaker implanted in the vicinity of the heart [Ben'13].

I. 3.4 The frequency characteristics of the ECG

- In the study of **Thakor et al**, the spectrum analysis of electrocardiogram and the spectrum analysis of isolated QRS complexes and various noise sources are introduced. The frequency components of a normal ECG have been shown to have the following properties, in table I.2 shows normal values of events on the ECG according to the age of the fetus.:

- The ECG spectrum ranges from zero frequency to approximately 100 Hz.
- The P wave is characterized by a low-frequency spectrum band with low amplitude: its frequency components are in the range of 0.5 Hz to 10 Hz.
- T wave has a spectrum band similar to the P wave spectrum band, between 0.5 Hz and 10 Hz.
- The frequency components of QRS complexes are much higher than other ECG waves, and the frequency components range from 10 Hz to 30 Hz.
- The frequency components of the baseline and any motion artifacts are between 0.5 Hz and 7 Hz [Siy'15].

Age	HR (bpm)	PR interval (sec)	QRS interval (sec)
1st wk	90-160	0.08-0.15	0.03-0.08
1-3 wk	100-180	0.08-0.15	0.03-0.08
1-2 mo	120-180	0.08-0.15	0.03-0.08
3-5 mo	105-185	0.08-0.15	0.03-0.08
6-11 mo	110-170	0.07-0.16	0.03-0.08

Table I.2: ECG: normal value by age**.**

I. 4. The Fetal ECG Morphology

The fetal heart is one of the earliest developing organs of the fetus. After 7 weeks of pregnancy, its anatomical shape is similar to that of an adult heart (four chambers, two atria and two ventricles). Therefore, from a morphological point of view, fetal and adult ECG signals are quite similar, containing the same fundamental waves: P waves, which are related to atrial depolarization; QRS complexes, which are related to ventricular depolarization; and the T wave, associated to ventricular repolarization. However, due to some structural differences required for different blood circulation in the prenatal period, the mechanical function of the fetal heart is different from that of an adult. As we all know, after birth, the left ventricle pumps blood into the body to deliver oxygen, while the right ventricle pumps blood into the lungs for oxygen. In the fetus, oxygen is released from the placenta, so blood is not pumped into the lungs for this purpose. Both ventricles pump blood throughout the body (including the lungs).

In particular, the left ventricle provides blood for the heart and brain, while the right ventricle provides blood for all lower parts of the body. The cardiac output of the right ventricle is greater than the cardiac output of the left ventricle, which results in a large amount of cardiac muscle in the right part of the fetal heart. Thus, in the fetus, the electrical axis of the heart points to the right ventricle, while in adults it points to the left ventricle (the ventricular mass is very large). And each fetal ECG representation -being the projection of the fetal ECG onto the appropriate lead vector- differs from the corresponding adult ECG representation [Vul'10].

Therefore, the direction of the fetal electrocardiogram (ECG; that is, the vector representing the magnitude and direction of the power generated by the heart throughout the cycle) is different from that of the adult electrocardiogram, and each fetal ECG representation -being the projection of the fetal ECG onto the appropriate lead vector- differs from the corresponding adult ECG representation [Vul'10].

I. 4.1 Clinical significance of the fetal ECG

Various clinical evaluations can be obtained, and these evaluations are not necessarily directly related to the fetal heart, can be derived from the analysis of the FECG signal. For example, based on the length of the intervals in the ECG, the size of the fetal heart can be estimated, thereby estimating the size of the fetus, and it can also identify signs of fetal hypoxia.

- **Fetal heart arrhythmia**

Any abnormality in a baby's heart rate is referred to as fetal arrhythmias (ARRs). An irregular heart rate, a slowed heart rate, or a daily rhythm outside the reference range are examples of this abnormality. ARRs are found in about 1% of all fetuses, with about 10% of these being considered possible morbidity sources (Figure I.10).

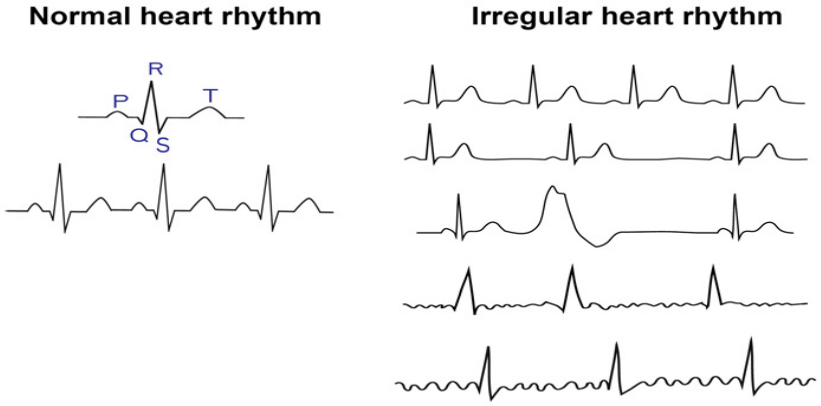

Figure I.10: Normal and Irregular heart rhythm

- **Fetal Growth Parameters**

Intrauterine growth restriction (IUGR) refers to the poor development of babies in the mother's uterus during pregnancy, which is a dangerous condition of hypoxia. Since FECG provides information about fetal growth rate and oxygenation, it can also be used to estimate IUGR. The FECG signal, P wave duration, and QRS complex wave duration indicate the time required to depolarize the atria or ventricles; these intervals are determined by the size of the myocardium and the transmission rate of the action potential. The duration of each wave depends on the dimension of the related cardiac rooms. Since the growth of the heart is proportional to the fetus, the length of the P wave and the duration of the QRS complex can be used to estimate the size of the fetus and therefore assess the existence of IUGR [Vul'10] [Bas'03].

- **Supraventricular Arrhythmias**

In the FECG signal, supraventricular extrasystole (SVES) appears as a widened QRS complex with the opposite sign without P wave, usually sporadic and asymptomatic; however, in the cases in which the SVES are due to congenital heart diseases (for example, Supraventricular tachycardia, bradycardia or premature atrial contraction) is caused, the FECG is very important, because it can detect fetal congenital heart disease early and may be treated during pregnancy or Immediately after birth [Hor'07].

- **ST Segment Variability**

The balance between energy production and use controls the fetal heart's ability to distribute blood throughout the body. Usually, the availability of oxygen exceeds its need, and the fetal heart uses aerobic (ie, dependent on oxygen) metabolism to produce energy. In this case, the energy balance is positive, and the FECG is normal. On the contrary, if the available oxygen is reduced but the required oxygen is maintained, the energy balance becomes negative, and myocardial hypoxia occurs. In the FECG, the effect of myocardial hypoxia is commonly usually reflected in the morphological changes of the ST segment, increasing or decreasing. The fetus responds to the negative energy balance, and adrenaline suddenly spikes to initiate glycogen breakdown, a process that uses stored glucose as energy. The changes in ST segment indirectly reflect the fetal metabolism [Spi'13].

- **Fetal Movements**

The mother's perception of fetal movement is the oldest and most widely used method for assessing the health of the fetus from the 20th week of pregnancy. Fetal movements are violent and infrequent at first, but in the second half of pregnancy, they become stronger and more frequent, and are increasingly associated with fetal heart rate patterns and eye movements, and identify fetal behavioral states that are indicators of maturity and integrity of the fetal nervous system. The sharp and continuous reduction in fetal movement indicates fetal stress, which usually precedes fetal death. Fetal movement only temporarily affects the shape of the Fetal electrocardiogram, and fetal distress associated with a continuous decrease in fetal movement can cause long-term fluctuations on FECG, especially ST-segment. ST-segment abnormalities longer than 15 seconds are related to severe fetal conditions and shorter episodes of fetal movement [Vul'10] [Sad'77].

I. 5. Methods of measuring the fetal heartbeat

There are 2 ways to do fetal heart monitoring, external and internal:

I. 5.1 External fetal heart monitoring

This method uses a device to listen to and record the baby's heartbeat through the abdomen. One type of monitor is the Doppler ultrasound machine. It is often used during antenatal visits to calculate a baby's heart rate. It can also be used to check the heart rate of the fetus during labour. The health care provider may also check the baby's heart rate continuously during labour and delivery. To do this, an ultrasound probe (transducer) is attached to the abdomen. It sends your baby's heart sounds to the computer. Your baby's heart rate and pattern are displayed on a screen and printed on paper.

I. 5.2 Internal fetal heart monitoring

This method uses a thin wire (electrode) that is placed on the child's scalp. The wire passes from the baby through the cervix. It is connected to the screen. This method gives better readings because things like motion do not affect it. But this can only be done if the fluid-filled sac that surrounds the baby during pregnancy breaks (the amniotic sac) and the cervix opens. Internal monitoring is used when the external monitoring does not give a good read. Or to closely monitor the baby during labour.

The following is a mention of some tools that are used in the process of hearing the heartbeat of the fetus in the doctor's office, or even at home as well. table I.3 [2]:

Tools and devices	**The usual time of application**
Stethoscope	Between week 18 and week 22
Fetoscope	Between week 18 and week 22
Pinard Horn	Between week 18 and week 22
Amplifiers	Between week 8 and week 22
Doppler	From the eighth week of pregnancy
Fetal Monitor	From the twentieth week of pregnancy

Table I.3: Instruments used to listen to the fetal heartbeat

I. 6. Conclusion

Despite the rapid technological development in the field of medical equipment, electrocardiography has been important research in cardiology for many years.

Using this method, the electrical activity of the myocardium can be monitored from the outside. This is achieved by collecting electrical signals called ECG signals using electrodes attached to the surface of the skin.

The study conducted in this first chapter provides research on the anatomy and physiology of the heart, as well as the electrical properties of cardiac cells, a better understanding of the nature and origin of the ECG signal, in addition to a special study of both the mother's and the baby's heart during pregnancy.

It also provided a full examination of the electrocardiogram (ECG) signal, as well as a thorough understanding of the nature and causes of that signal and an explanation of all parts of it.

In the next chapter, the different methods will be presented to acquire a fetal ECG, passing through invasive devices, to the newly used algorithms and making a comprehensive comparison, in addition to developing one of these algorithms and obtaining a reliable method for obtaining a complete fetal ECG without losing any part of it.

Chapter II

Methods for acquiring an ECG of the fetus

II. 1. Introduction

Electrical signals are potential differences that vary with time in a non-periodic way, their form can be characterized by the frequencies of components that constitute them, and a fetal electrocardiogram is one of those signals.

Monitoring biomedical signals by measuring, quantifying, evaluating and classifying signal characteristics is one of the main tools for studying the development of pathological conditions. The overall architecture of the surveillance system should combine technical tools with signal analysis techniques to extract useful information to determine the patient's condition.

In these procedures, it is very important to select processing methods that improve the characteristics of pathophysiological signals, so parameters can be linked to physiological events and possible physical quantities.

Traditional surveillance systems have been fundamentally improved by new technical equipment that allows longer and deeper data collection and advanced clinical tools for data interpretation.

In this chapter, the methods currently used in obtaining the electrocardiogram of the fetus will be presented in both the invasive and non-invasive sections, and the methods and algorithms used to obtain this signal will be presented and compared to each other, in addition to developing one of these algorithms and obtaining a reliable method for obtaining a complete fetal ECG without losing any part of it.

In this chapter, we present the overall performance of the cardiac system from the medical side followed by the measurement of the ECG signal. We explain the importance of measuring the ECG signal in general and the embryo in particular, and the importance of fully extracting this signal without losing any part of it. And that's for the proper diagnosis of the fetal condition.

II. 2. History of fetal heartbeat monitoring

The history of fetal heart rate monitoring is a combination of the simultaneous development of biomedicine and obstetric technology.

According to reports, fetal heart sounds were first discovered by **Marsac** in the 17th century. By 1818, Mayor and **Kergaradec** described a method of hearing fetal heart sounds by bringing the ear close to the mother's stomach. **Kergaradec** also suggested that the heart sounds of the fetus can be used to determine the vitality of the fetus. In 1833, British doctor **Evory Kennedy** recommended auscultating the fetal heart rate as a monitoring tool during childbirth [Wul'85].

David Hillis first described the fetal stethoscope or fetal scope in 1917. In 1922, **Joseph DeLi** described the device again and prioritized its development. The device was eventually called the DeLi-Hillis fetal scope and has been at the forefront of fetal monitoring during delivery for the next half-century.

Technical trends variety from the primary obstetric stethoscopes through the second-generation cardiotocographs to the cutting-edge computer-operated cardiotocograph assessment structures of our, because it was, third-generation obstetric tracking equipment. The significance of fetal coronary heart tracking for obstetrics has extended with technical progress (Figure II.1) [Jud'00].

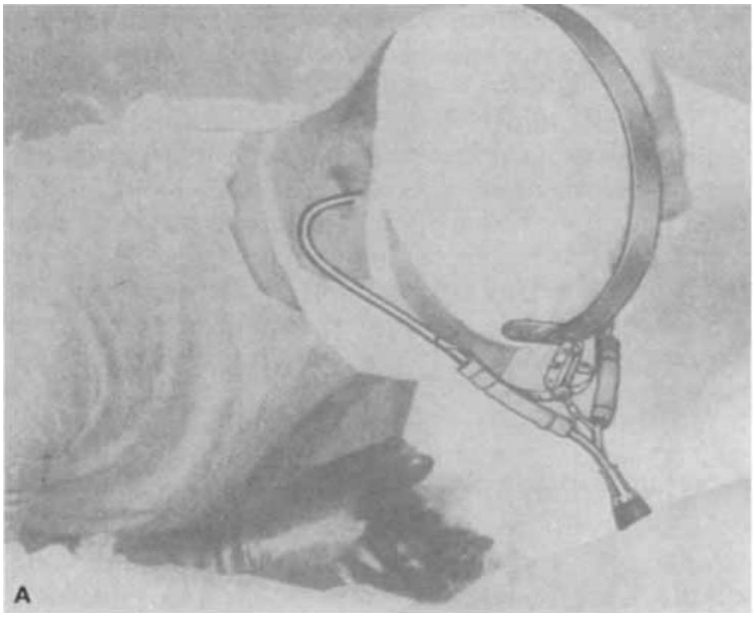

Figure II.1: illustration of the head attachment for the stethoscope later called a fetoscope

Then, electronic devices appeared strongly and the accompanying signal processing, as medical devices appeared and were able to memorize and enlarge these signals and initially process them and were better than the primitive tools that preceded them.

The use of electronic methods to obtain and record fetal heart rate (FHR) and uterine contractions (UC) signals has become a recent phenomenon. **Edward Hon**, **Roberto Caldeyro-Barcia** and **Konrad Hammacher** first described sequential techniques for acquiring FHR and UC signals in the 1950s and 1960s, which eventually led to the development of the first commercial fetal monitor in 1966 (Figure II.2) [Mae'02].

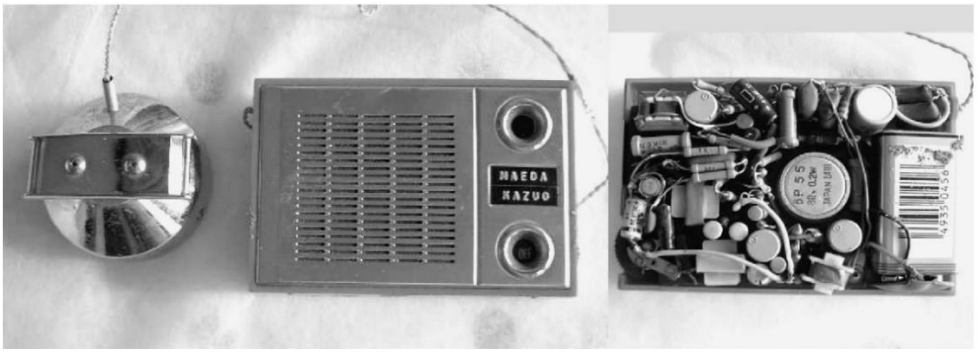

Figure II.2: Fetal heart tone was listened to by a tiny radio-sized electric stethoscope.

The previous device (somewhat primitive) only had the ability to record the fetal heart sound and enlarge it to a certain amount, as this recording needed other devices such as an oscilloscope to display this recording on paper.

Although it is sometimes recommended to auscultate the fetal heart during postpartum, it is difficult to determine the health of the fetus just by listening to the heart. In the past, many cases of neonatal asphyxia were not predicted by using the stethoscope. In 1968, A sinusoidal pattern was not observed when hearing the heart sound during fetal abdominal transfusion. Recently, a correct diagnosis was made by using a modern FHR monitor to process the recorded sound (Figure II.3). The condition of the fetus can be judged by the heartbeat of the fetus but It is difficult to correctly judge the condition of the fetus by listening to heart sounds with an electronic stethoscope [Zus'79].

Figure II.3: the first commercially available fetal monitor, released in 1968

An instant heart rate device with direct FECG recorded the most accurate heart rate. The fetal QRS peak was recorded with minimal error, the peak-to-peak interval was measured, the inverse of the interval was maintained and recorded until the next QRS, and the chart recorded an FHR tracing.

Electronic fetal monitoring (usually shortened to EFM) was the natural name given within the Nineteen Sixties and Nineteen Seventies to explain the new technology of ceaselessly monitoring fetal heart rate and uterine contraction signals. The age of electronics was at its peak, and it was vital to differentiate this technology from antecedently existing mechanical methods.

Over time, the term "electronic fetal monitoring" has been unused. If it was the only form of electronic monitoring of the fetus at first, several other technologies for monitoring the fetus were later developed: ultrasound, portable Doppler ultrasound, and fetal electrocardiogram. and many more.

II. 3. Modern methods for monitoring fetal heart rate

Due to the continuous emergence of children's health problems during the birth or prenatal period, and the huge technological advancement in the field of electronic devices, this has led to the development of medical equipment that specializes in the study of fetal conditions throughout pregnancy. the number of deaths between pregnancy and one month after birth has reached half a million mothers and one million children each year, and most of these deaths occur in developing countries, so many of them can be prevented by detecting complications on time.

Two types of devices have been manufactured, some of which are indirect and non-invasive to the body used during pregnancy, the other is classified as an invasive device used on the body at the end of pregnancy, auscultation technology (such as ultrasound Doppler and fetoscope) or electronic fetal monitoring technology, the latter can be divided into external equipment (including ultrasound Doppler and tocodynamometer) and internal equipment (including direct fetal electrodes and intrauterine pressure catheters). And each of them you have a method of exploration and a different principle from the other.

II. 3.1. Cardiotocography

Cardiotocography (CTG), developed by Dr: Konrad Hammacher in the 1970s, is one of the most advanced non-invasive prenatal diagnosis methods in clinical practice. It is used to monitor fetal health and record the measured values of fetal heart rate and uterine contractions during pregnancy, including pre-delivery and During childbirth. Prenatal care of the fetus is an important part of the management of high-risk pregnancy care standards, including maternal hypertension, intrauterine growth restriction, decreased fetal mobility, and other pathophysiological diseases of the mother and fetus [Wil'04].

cardiotocography is used to monitor fetal heart rate and uterine muscle activity. The latter is sensed by two sensors placed on the mother's abdomen: one above the fetal heart and the other at the fundus. This is recorded on a paper strip called a fetal heart rate monitor (CTG).

The interpretation of the CTG curve requires a qualitative and quantitative description of uterine activity, initial fetal heart rate, baseline FHR variability, presence of acceleration, periodic deceleration, and the change or trend of the final heart rate pattern over time. in recent years, have reached a consensus on stating the standardized nomenclature of fetal heart rate models (Figure II.4).

Figure II.4: cardiotocography (CTG)**.**

II. 3.2. Photoplethysmography (PPG)

Photoplethysmography (PPG) was first introduced in the 1930s. It is a non-invasive optical technology used to detect changes in blood vessel volume to detect heart rate based on changes in tissue absorption of light at or near wavelengths of specific red wavelengths. This method can also be used to measure the fetal heart rate through the mother's abdomen. The received PPG signal is composed of AC components that represent blood volume changes and DC components that represent baseline heart rate and low-frequency noise components.

Fetal heart rate is measured non-invasively by emitting near-infrared (NIR) light with a wavelength of 650 to 950 (nm), which can be measured by a photodetector that to measure reflected light through human tissue with the peak penetration being at 890 (nm). The study recommended the use of four 20 (W) halogen lamps and two 0.575 (W) tungsten lamps as light sources and two photomultiplier tubes as photodetectors. This method is energy-intensive, generates heat, is expensive and difficult to use. because the main problem of fetal monitoring is temperature rise, another method is proposed, using a low-power light-emitting diode (LED) with a maximum power of 68 (mW) as the light source, and placing the low-cost silicon photodetector directly on the mother's abdomen [Nit'02].

The light beam received by the photodetector is modulated by the pulsation of maternal and fetal blood, and a reference signal from the mother is needed to extract the desired foetal heart rate signal. The required signal is usually received by a PPG sensor connected to the mother's index finger (Figure II.5).

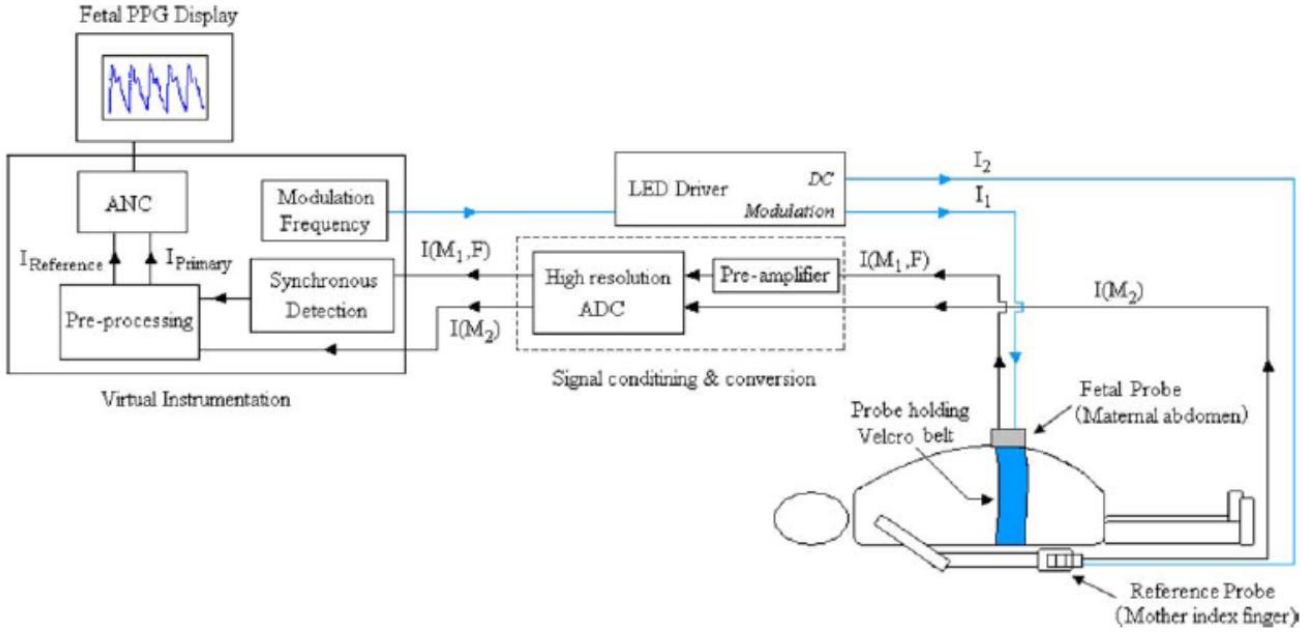

Figure II.5: Photoplethysmography system.

II. 3.3. Fetal Magnetocardiography

Fetal Magnetocardiogram (FMCG) is a non-invasive method of recording the magnetic field generated by the heart's electric field. FMCG does not emit magnetic fields or energy, so it is very safe. recorded the first one (FMCG) with a superconducting quantum interference device from 1974 (SQUID). FMCG is a weak signal of the order of 10-12 (Tesla), which is much smaller than the surrounding magnetic signal just like the earth's magnetic field; it is recorded in a protected space.

FMCG can be used to monitor the fetus during delivery, determine the status of the fetus, monitor fetal arrhythmia, automatically detect fetal movement, and monitor fetal heart rate. On the other hand, FMCG can be used to monitor fetal heart activity at the beginning of the second trimester.

When FMCG monitoring, no part of the magnetometer system is in contact with the body; this means that the resistance of the tissue does not significantly affect the magnetic field of the fetal heart. However, FMCG has several disadvantages, such as size, cost, the complexity of the magnetometer system, and the need to minimize object movement. Based on FMCG, low computational complexity and processing delay are required, and rapid changes in the heartbeats must be recognized. FMCG registration depends on gestational age (GA), fetal behavioural status, fetal presentation, fetal movement and fetal breathing rate [Str'08].

The superconducting quantum interference system SQUID used can detect very weak biomagnetic fields ranging from Pico tesla (pT) to Femto tesla (fT). There are two different SQUID systems: SQUID magnetometers for indoor measurements with the super magnetically shielding room (MSR) and SQUID gradiometers with different antennas. Used for measurement in environments with medium or unshielded MSR.

The FMCG device should be as close as possible to the mother's abdomen because the fetus's signal is strongest in the abdomen and decreases with the increase of distance, while the noise at both distances is the same. The amplitude and shape of FMCG depend on the distance between them. The position of the fetal heart and the measuring magnetic field (Figure II.6).

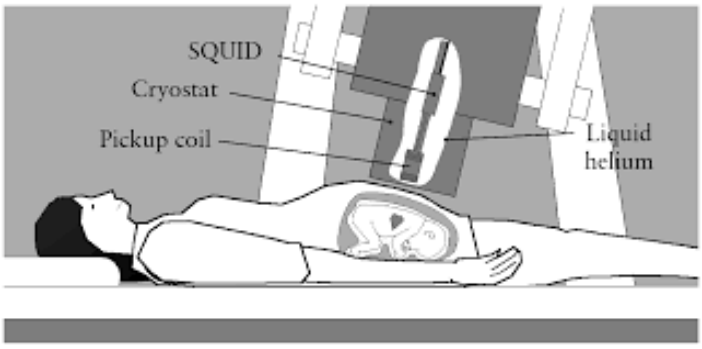

Figure II.6: Fetal Magnetocardiography.

Due to the availability of newer and cheaper technologies, the above three technologies are rarely used today. The following techniques are the most commonly used.

II. 3.4. Echocardiography: Doppler ultrasound device

One in 100 babies is born with a congenital heart defect, which is a common birth defect. To reduce the risk of heart defects at birth, the health of the fetus should be evaluated and any problems should be diagnosed early in pregnancy. Fetal echocardiography is one of the most important procedures and examinations that must be performed when a fetal heart defect is suspected.

Fetal echocardiography is an important tool for screening the anatomical structure of the fetal heart. Congenital heart disease is the most common pathology in human fetuses. 2D imaging is still the gold standard and is widely used for fetal echocardiography.

II. 3.4.1. Definition

Fetal echocardiography or fetal echocardiogram is the name of a test used to diagnose heart disease in the fetal stage. This is a non-invasive external ultrasound examination that can assess the position, size, structure, function and rhythm of the fetal heart. Using an echocardiogram of the fetus, you can evaluate your child's heart condition in detail. It is usually performed in the second trimester of pregnancy, between the 18th and 24th weeks of pregnancy. If necessary, it can be done in the later stages of pregnancy (Figure II.7) [Car'13].

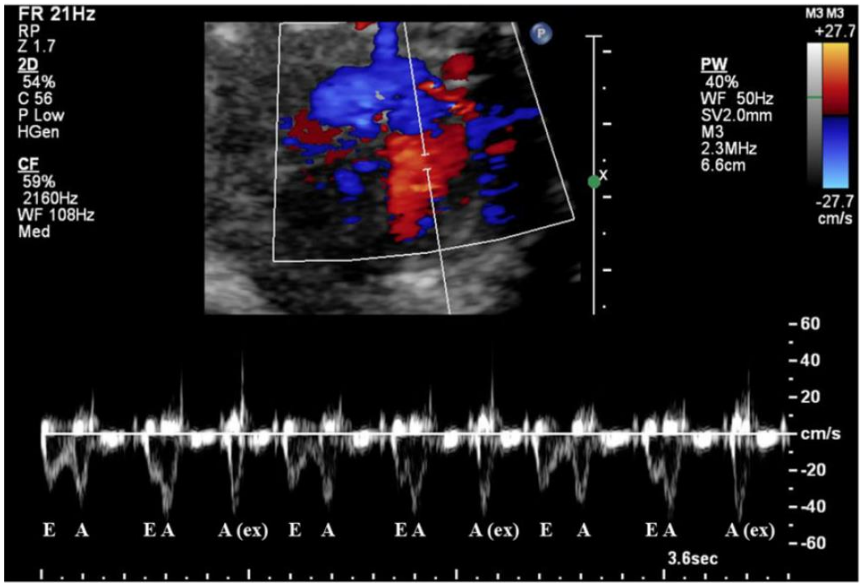

Figure II.7: fetal echocardiography, Doppler mode (pulsed wave (PW)), left ventricular inflow pattern.

Heart defects are one of the most common birth defects, Diagnosis at the fetal stage is important because it can help plan the baby and guide the delivery process. This is a test that must be done during pregnancy to determine or rule out the presence of congenital heart defects.

Diagnostic ultrasound is an advanced electronic technology that uses high-frequency sound pulses to create images. A transducer moving over the region of interest emits ultrasound pulses that propagate through the tissue, some pulses are reflected back to the sensor. This converts these reflected echoes into electrical signals.

The intensity of the reflected echo is determined by the properties of the tissue interface. The return signal is processed by the computer, and the computer displays the intensity and position of each echo as an image on the screen. It depends not only on the technical skills of the ultrasound equipment, but also on the experience and knowledge of the operator, and the standards vary [Car'13].

A pregnancy ultrasound was introduced about 25 years ago. Initially, this technique was mainly used for suspected morbidity or fetal malformations. With the development of ultrasound technology, the indications for this examination have also expanded. It can be used in various situations during pregnancy, such as after clinical complications or where there are concerns about fetal growth, and since there may be negative results even in pregnancy even in the absence of clear risk factors, it is a recognized standard procedure The use of ultrasound is beneficial to all pregnant women, so all pregnant women are now offered an ultrasound examination at least once during their pregnancy.

II. 3.4.2. Doppler ultrasound technology

The fetal heart rate (FHR) is usually monitored to assess the health of the fetus. In clinical practice, the de facto standard heart rate monitoring technique is based on Doppler ultrasound (US).

The Doppler principle was first discovered by the Austrian physicist Christian Doppler in 1842. It describes the relationship between the speed of an object and the frequency of the received wave. This method is used to measure the mechanical activity of the heart, such as the opening and closing of the valve in each cardiac cycle, to evaluate the fetal heart rate signal.

Before that, the most commonly used method was cardiotocography (CTG), which included a simultaneous and continuous recording of fetal heart rate (FHR) and uterine contractions (UC). The CTG method was independently described in the late 1950s and early 1960s. Since then, CTG has become a standard method to assess the condition of the fetus before and during labour (Figure II.4).

The main goal of CTG was to reduce fetal mortality and morbidity by identifying vulnerable fetuses and determining the optimal birth time. The use of CTG is associated with a reduction in neonatal mortality. However, the interpretation of CTG recordings is often challenging. Therefore, computer analysis of CTG records was introduced.

During pregnancy, the fetal heart begins to beat spontaneously in the 5th week of gestational age (GA), which can be measured by a trained ultrasound technician using an ultrasound imaging system and an abdominal ultrasound transducer.

Currently, the most common heart rate measurement technique is based on Doppler ultrasound, in which an ultrasound transducer is attached to the maternal abdomen for recording. However, there are known technical limitations, such as inaccurate heart rate estimation FHR and frequent signal loss periods. Signal loss is particularly serious in premature babies, mothers with high body mass index (BMI), and multiple pregnancies, which makes FHR records difficult to analyze. If the loss of the FHR signal recording time does not exceed 20%, then the Federation of Obstetrics and Gynecology (FIGO) recommends that FHR recordings be used for clinical analysis [Mar'18].

Below will find a schematic diagram of the technical components of the Doppler ultrasound equipment (Figure II.8) and the typical signals of each part (Figure II.9).

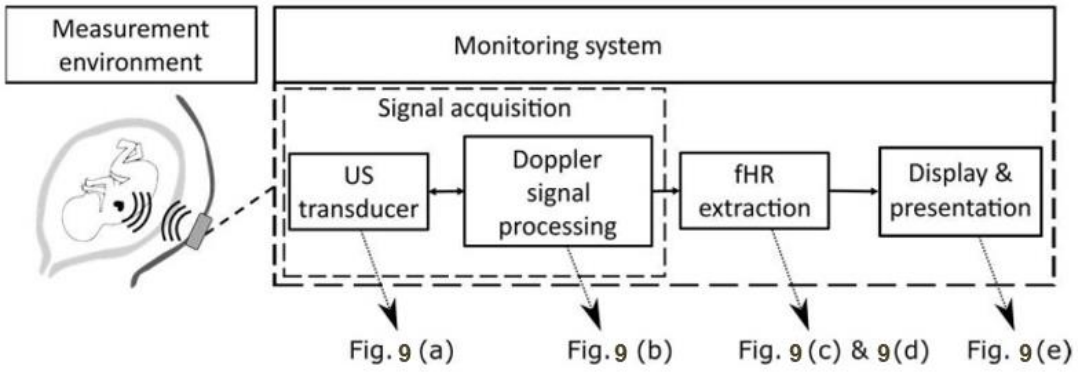

Figure II.8: Technical building blocks of a Doppler-based fetal heart rate monitoring system

The following figure shows an example signal after intermediate signal processing steps: (a) raw radiofrequency US signal, (b) non-directional Doppler signal, (c) Doppler signal envelope, (d) autocorrelation function and (e) tracking the FHR signal. as that the units are different on the x-axis.

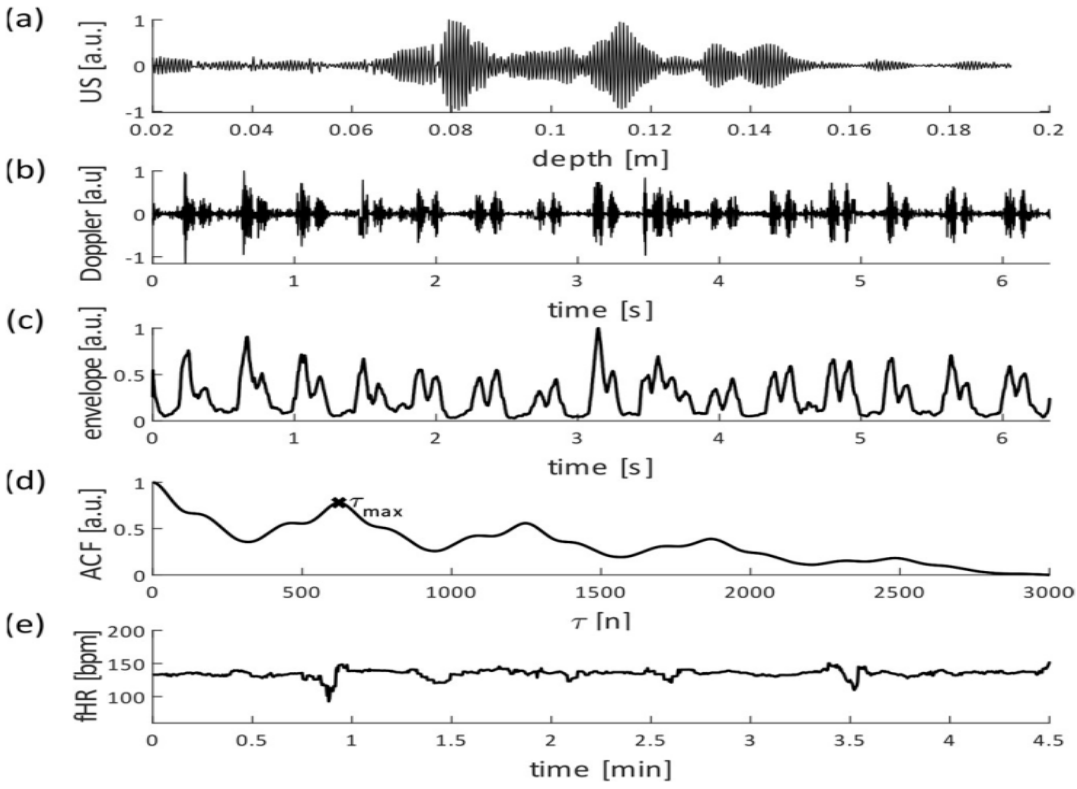

Figure II.9: exemplary signals after intermediate signal processing steps.

II. 3.4.3. Measurement Environment

A. Clinical environment

To obtain FHR signals in clinical practice, well-trained staff will scan the fetus's performance and move the ultrasound transducer over the mother's abdomen while listening to the Doppler signal reproduced by the FHR monitoring system. Between the mother's skin and the ultrasound transducer, a US gel applied. If the heart is within the measuring range of the sensor, the doctor will fix the position of the sensor and start to continuously record the heart rate.

B. The maternal abdomen

Various anatomical structures and tissue types are located between the fetal heart and the ultrasound transducer. The transmitted ultrasound passes through the mother's skin and subcutaneous tissue, uterine muscles, an amniotic sac filled with amniotic fluid, and the chest of the fetus. When they finally reach the heart of the fetus, they will reflect back to the ultrasound transducer in the opposite order along the same acoustic path. A representation of the anatomical structure of the maternal abdominal cavity is shown (Figure II.10) [Mar'07].

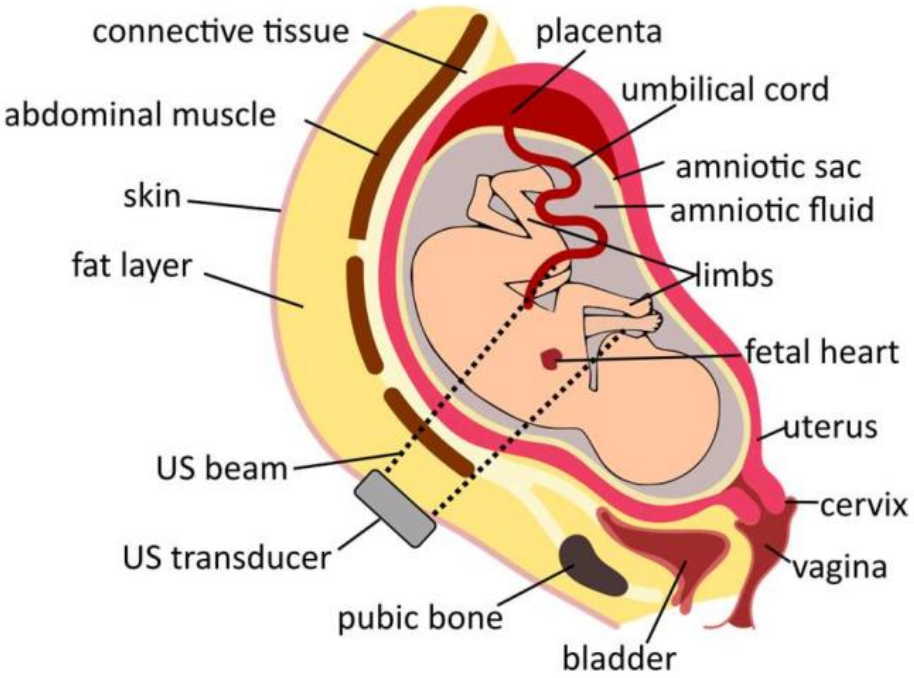

Figure II.10: A schematic diagram of the anatomical structure of the abdominal cavity of a pregnant woman. Please note that the ultrasonic transducer is located in the typical location.

Adequate imaging of the heart is essential for a successful cardiac examination. The imaging of the heart depends on the distance between the ultrasound transducer and the fetal heart, which is mainly determined by the thickness of subcutaneous fat, which varies greatly between the mothers, in addition to some technical limitations (e.g. abdominal or uterine scars, uterine myomas, oligohydramnios, anterior placentation, and late gestation).that can make a proper detailed heart evaluation very difficult due to acoustic shadowing, especially in late pregnancy. Likewise, the width of the fetus affects this distance and determines the specific tilt angle of the heart. For mothers with an average BMI, the distance from the fetal heart to the transducer is usually 4 to 18 cm [Mar'07].

When the apex of the heart is aligned with the front wall of the mother, then Optimal views of the fetal heart are obtained. If the position of the fetus interferes with the satisfactory visualisation of the cardiac anatomy, please wait for the fetus to move spontaneously, undertake such measures as asking the mother to twist or tilt the abdomen, or gently manipulate the mother's abdomen to change the fetal position, or reschedule the examination time. Although the fetus can move freely in the uterus at the beginning of GA, the most common representation of the fetus at birth is the cephalic representation ("head down" and the frequency of overall body movement is reduced). Therefore, the electrocardiogram is usually performed between the 18th to 22nd week.

II. 3.4.4. Ultrasound Transducer

A device that generates sound waves that bounce off body tissues and produces echoes. The transducer also receives echoes and sends them to a computer, which uses them to create images called ultrasound maps. The sensors have different shapes and sizes and can detect different parts of the human body, it can pass through the surface of the body.

a. Physics of ultrasound propagation

When the ultrasound transducer is placed on the mother's abdominal cavity, the transmitted ultrasound passes through the mother's abdominal cavity and interacts with the tissue structures described previously. The transmission and specular reflection of ultrasonic waves at the boundary between two media with different acoustic properties can be characterized by their difference in acoustic impedance *Z* [Ham'17].

$$Z = \rho * c$$

ρ : medium density

c : US propagation velocity

Except for specular reflection, when the US wave interacts with a structure whose wavelength is shorter than the US wavelength, US scattering occurs in all directions:

$$\lambda = c / f_0$$

f_0 : transmission frequency

The reflection and scattering contribute to the echo of the ultrasonic wave, which is finally received by the transducer on the surface of the abdomen. An example of such a received US signal is shown in (Figure II.7a).

The intensity of a propagating US wave decreases as a function of depth z when propagating through the abdomen as:

$$I_{(Z)} = I_{(0)} e^{-\alpha f_0 Z}$$

α : attenuation coefficient

the attenuation coefficient represents the energy loss due to absorption and scattering.

The attenuation coefficient is usually approximated as a linear function of the US frequency f_0, expressed in dB/cm/MHz, although the actual relationship is mostly non-linear. Since the fetus can be located deep in the uterus, American sensors for measuring FHR and measuring fetal movement (FM) usually work in the low-frequency range: f_0 = 1 -3 (MHz). This is especially important for measurement on mothers with high BMI because the fat layer increases the US transducer to fetal heart distance and is characterized by high US attenuation.

b. Transducer Geometry

To monitor the fetal heart rate, the fetal heart must be in the field of view (FOV) of the transducer used. Generally, the ultrasonic transducer used for Doppler probe measurement uses a single circular piezoelectric transmission element.

The choice of transducer frequency is a trade-off between beam penetration and resolution. Therefore, an increase in f_0 will result in a decrease in penetration depth, and vice versa, because a decrease in f_0 will reduce the sensitivity of tissue flow and velocity measurement. The 3 - 5 (MHz) abdominal probes provide sufficient penetration for most mothers and have sufficient resolution. A lower frequency transducer (2 - 2.25 MHz) may be required to provide sufficient penetration for abdominal imaging in obese mothers. The 5 MHz sensor provides excellent resolution while having sufficient penetrating power [Mar'07] [Ham'17].

After conducting simulations to make an optimized and easy-to-use FHR monitoring transducer, they concluded that a single convex sensor with a width of 10mm, a radius of curvature of 100mm, and f_0 = 2MHz produces a divergent beam that can be used in the signal strength and stable movement of the fetus and maternal.

c. Transducer Positioning

The field of view depends on the geometry and frequency of the ultrasound probe. Due to the movement of the fetus and the contraction of the uterus, the heart of the fetus can be out of the field of vision of the sensor. In addition, the filling of the bladder will also change the position of the fetal heart. Therefore, the correct position of the sensor is essential for FHR monitoring.

The doctor swipes the ultrasound transducer around the mother's abdomen, listened to the Doppler signal, and then fixes the US transducer. This can improve signal quality, reduce the possibility that the fetal heart moves out of the FOV during monitoring, and improve clinical workflow in the case of loss of FHR signal [Pal'09].

Several ultrasound transducers are connected to the mother's abdomen for twin monitoring. Careful positioning is required to ensure that the two FHRs are registered correctly and that the same fetus cannot be monitored repeatedly. When the FHRs are too similar, an alarm is triggered to avoid measuring the fetal heart rate of the same fetus twice.

Another consequence of improper positioning of the ultrasound transducer is the ability to record the mother's heart rate (MHR) instead of FHR. This usually occurs after the patient's position changes, after the fetus moves, or during delivery.

The sonographer should optimize the image by adjusting the image magnification (the image should be magnified so that the heart occupies at least one-third or half of the screen), signal amplification, acoustic focusing, frequency selection, and Doppler configuration and other technical parameters to optimize the image. System settings should emphasize a high frame rate, higher contrast, and higher resolution. he should also use a relatively narrow field of view.

d. Ultrasound safety in obstetrics and gynaecology

When ultrasound interacts with tissues with high enough strength, it can cause biophysical damage due to heat, mechanical effects, cavitation, or chemical effects. Therefore, until the mid-1970s, fetal Doppler ultrasound monitors were rarely introduced to the market for safety reasons. These effects require special attention because the fetus is particularly sensitive in the early stages of pregnancy; however, there is no clinical evidence that the use of ultrasound in obstetrics and gynaecology can have harmful effects on the fetus if the recommendations of the international expert group are followed [Ena'14].

The experimental results confirmed that the threshold of ultrasound intensity required to produce a bioeffect was 1 W / cm^2 for continuous-wave ultrasound and 240 mW / cm^2 for pulsed wave ultrasound. the Industrial Standard on the fetal monitor stated that the ultrasound intensity should be below 10 mW/ cm^2 in 1994. US systems for FHR monitoring generate significantly low acoustic output powers. Therefore, there are no contraindications to use it. However, ultrasound should not be performed for non-medical reasons and US exposure should be as low as reasonably. The Doppler Ultrasound Fetal Monitor has been widely used after confirmation of safety.

II. 3.4.5. The efficiency of doppler ultrasound

In this review, the Doppler US technology for FHR monitoring is thoroughly described. Over the years, various transducer designs, signal processing technologies and heart rate extraction technologies have been developed for more accurate and reliable FHR monitoring. It is the most widely used technique in clinical practice. It can accurately determine atrial and ventricular activity, and as technology advances, it will continue to be an important tool for assessing fetal health [Ena'14].

However, the main limitation of using Doppler ultrasound is its sensitivity to motion and the fact that it is not suitable for continuous monitoring (continuous echocardiogram recording is usually short), requires the doctor to manually manipulate the probe and can only be used clinically. The average heart rate is also given, and cannot give the beat-to-beat variability due to the average nature of the autocorrelation function used to estimate the fetal heart rate. Due to the complexity of the signal and the influence of fetal and maternal respiration, it is not always reliable.

II. 3.5. Fetal Scalp Electrode

Fetal heart rate monitoring is the most common obstetric practice. Approximately 85% of fetuses are monitored internally or externally during delivery, sometimes it is impossible to obtain continuous and reliable Fetal heart rate records when an external device is placed on the abdominal cavity during childbirth. Therefore, electronic fetal monitoring (EFM) became possible in the 1950s due to electrodes directly connected to the fetus designed by Edward Hon. EFM was widely used in clinical practice in the late 1960s, and the spiral electrode or fetal scalp electrode used today introduced by Hon in 1972. In 1975, only over 20% of labour were controlled by EFM; today it is over 80% (Figure II.11).

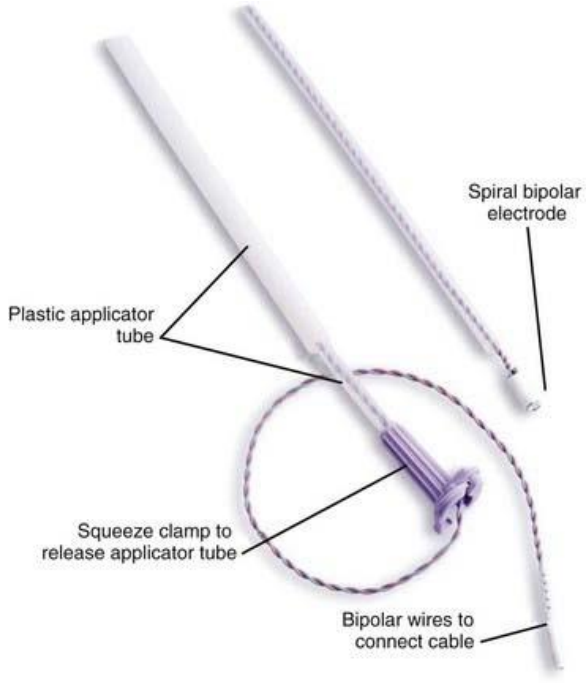

Figure II.11: Fetal scalp electrode with applicator tube.

Continuous EFM can be obtained through external or internal monitoring. Above we mentioned the external monitoring and the internal monitoring, which records the fetal ECG directly from a single electrode (electrode on the fetal scalp) connected to the fetal scalp. Bipolar spiral electrodes connected directly to the fetal scalp. An electrical circuit is formed between the twisted wire electrodes on the fetal skull and the metal wings on the electrodes. The vaginal fluid forms an electrical salt bridge and closes the circuit. The voltage difference (fetal heart rate signal) is amplified and transmitted to the heart meter that calculates the heart rate. The bipolar lead is also connected to the reference electrode on the mother's thigh to minimize electrical noise.

II. 3.5.1. Definition

The fetal scalp electrode (FSE) is a spiral wire that can be placed on the scalp of the fetus to monitor their heart rate and ensure their well-being and it's a technique whereby an electrode is attached to the fetal scalp, is accepted obstetric practice during the time the mother is in labour. Placing electrodes on the fetal skull is an important part of directly observing the fetus in the womb (internal monitoring of the fetus). It also helps to assess the fetal heart rate as well as the variations in the fetal heartbeat, especially due to uterine contractions during childbirth [ACOG'09].

If the cervix is medium enough (1 to 3 cm), the amniotic sac is no longer intact and more accurate results are required. For example, if the fetus is suspected of hypoxia, insert a small electrode into the vagina. The fetal scalp and catheter are inserted into the uterus to measure the contraction force. The measured value can be displayed on the display connected to the electrode cable. Electrodes on the scalp can provide accurately, that is not affected by factors such as movement.

II. 3.5.2. Indications

Whenever other monitoring methods are not satisfactory, the electrodes on the fetal scalp will be instructed to monitor the fetal heart rate. Studies have confirmed that external monitoring can intermittently record the fetal heart rate during delivery, especially during the second stage of labour. Loss of signal is unacceptable in a patient with an at-risk fetus. In addition, for certain patient categories, it may be difficult to monitor the fetal heart rate when using an external monitor.

Internal cardiac monitoring with scalp electrodes is used to identify fetuses at risk of severe hypoxia complications during delivery. Delivery is a unique burden on the fetus in the womb. Uterine contractions reduce the mother's blood flow to the placenta, which in some cases uncovering a deficit in placental capacity. In addition, childbirth and related chorioamnionitis rupture may be related to many other pregnancy risks, including intrauterine bacterial infection, umbilical cord compression, and placental detachment.

Fetal electrodes are needed to reliably estimate fetal heart rate variability (an important part of explaining fetal heart rate during delivery). The internal scalp electrodes provide more accurate information about the development of the fetal heart rate. It's faster than external. The electrode is removed at the time of delivery. The lead can be taken out in advance during the cesarean section, evacuation, or when the lead stops working.

II. 3.5.3. The Equipment

The most common fetal scalp electrode consists of an ECG electrode on the scalp, called Goldtrace, which consists of a needle-shaped spiral electrode and reference hub. The spiral electrode is connected to the fetal skull and the reference hub is located in is inside uterus amniotic fluid. An electrode that extends outside the mother's vagina and inserted into the ground plate, which is usually connected to the mother's thigh. The wires of the ground plate then transmit the ECG signal to the fetal monitor. When inserted, the electrodes are placed in the introducer, which is a tube that protects the mother's vagina from needle injuries. There is a device for the surgeon to rotate the electrode from outside the vagina and pierce the fetal scalp with a needle (Figure II.12) [Ana'12].

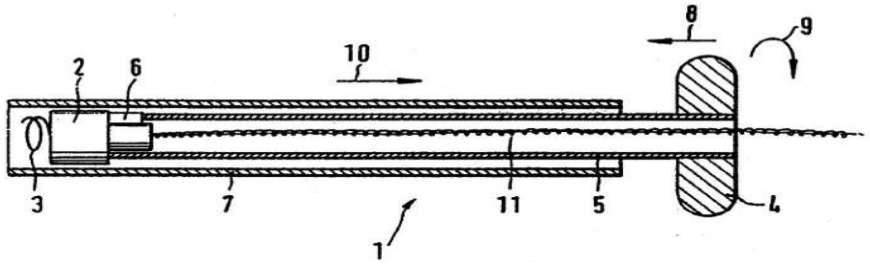

Figure II.12: Parts of a fetal scalp electrode (the remaining elements after inserting the electrode are marked with an asterisk (*) as 2, 3, and 11) 1: Common electrode with insertion aid 2: Electrode hub* 3: Spiral electrode* 4: Handle (used to turn the electrode assembly during application) 5: Sheath (transfer the rotation movement to the electrode connection) 6: Connection between sheath and hub 7: Tube (to protect the tissue of the maternal when inserting the electrode) 8: Direction of motion of tube during introduction 9: Direction adjustment of the rotation direction of the electrode 10:Direction of motion for removal of introducer after the electrode is seated 11: Electrode wires*

Insert the needle into the fetus's scalp to hold the electrode in place. Other types of scalp electrodes (such as clips) are also used.

II. 3.5.4. Application of the scalp electrode

The insertion of the fetal electrode requires a membrane rupture and sufficient dilation of the cervix to insert the device. The presentation of the fetus must be known and the mother must verbally agree to the procedure.

After the system is inserted into the mother's vagina, the introducer is placed on the parietal or occipital bone (inset) against the fetal head. Apply pressure to the electrodes and use a twisting motion to insert the needle electrodes into the fetus (the scalp), Then remove the introducer and keep the electrodes in place.

Sometimes it is difficult to remove the electrodes before birth; this is usually because the electrodes become entangled in the fetus's hair. In these cases, it is possible to cut the electrode leads and remove the electrode left until after delivery. Attempting to disconnect the electrode by pulling is inappropriate because it may damage the fetal scalp.

II. 3.5.5. The efficiency of fetal scalp electrode

Applying electrodes to the fetus's scalp is an invasive procedure, but does not use sharp instruments or radiation. Although the internal monitor provides more accurate fetal heart rate and heart rate records than the external monitor, it is only used when necessary because it does bring some risk. These risks are divided into:

1. **Mother**

Fetal electrodes can cut off the mother's vagina or cervix during insertion or accidentally connected to the mother instead of the fetus. This complication is rare in experienced people. The use of internal monitors also increases the risk of maternal chorioamnionitis, endometritis or cause bleeding. In addition to restricting the mother's activities, this can make childbirth more painful and difficult. If the mother has human immunodeficiency virus (HIV), this should not be done because it can be transmitted to the baby during the operation.

The extent of this risk is difficult to assess because mothers undergoing fetal scalp screening have several risk factors for infection, especially when followed by cesarean delivery. The additional risk may be small. In general, patients delivering after internal monitoring are managed the same as other patients. Whereas it is recommended that all caesarean section patients use prophylactic antibiotics.

2. **Fetus**

Improper placement of fetal electrodes may result in injury to the baby (fetal scalp rupture). The use of electrodes on the fetal scalp is associated with fetal cerebrospinal fluid (CSF) leakage and the risk of neonatal infection. Eventually, the needle electrode may break and part of the needle will remain in the fetal scalp, but these complications are rare (Figure II.13) [Ken'09].

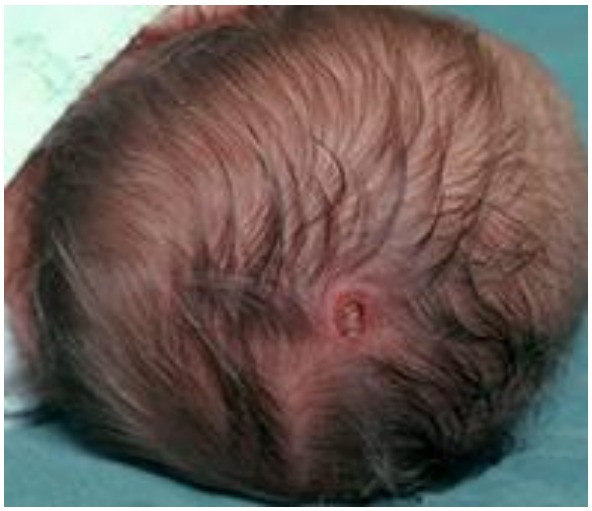

Figure II.13: The lesion on the baby's scalp.

II. 3.6. Non-invasive Fetal Electrocardiography (NI-ECG)

Fetal distress is a common sign that requires a caesarean section. This is described as a breathing restriction between the mother and the fetus. The value and regularity of the fetal heart rate (HR) are considered to be parameters indicative of fetal distress. So, it is very important to obtain highly accurate fetal heart rate estimation. Today's fetal monitoring is based entirely on fetal heart rate (HR) monitoring and does not include the FECG waveform characteristics. The fetal ECG signal contains valuable information for characterizing the fetal heart rate variability and further evaluating cardiac functions. Fetal arrhythmias, such as bradycardia, tachycardia, asphyxia, congenital heart defects and other abnormal conditions can also be detected by the FECG (Fetal cardiac waveforms) analysis.

II. 3.6.1. Introduction

The most common birth defects in babies are related to the heart. The current fetal monitoring is mainly based on fetal heart rate monitoring, that is, simultaneous recording of fetal heart rate and uterine activity. In current clinical practice, the fetal heart rate is determined via either an invasive scalp electrode. Scalp electrodes can only be used during labour and after rupture of the fetal membranes, or with non-invasive ultrasound Doppler. This method is not accurate and can cause signal loss, especially in women with high body mass, during motion, or early in pregnancy [Vul'10].

However, limitations related to invasiveness and the need for technology that can also be used during pregnancy have led to the introduction of non-invasive or indirect ECG, which is why the new technology is called non-invasive fetal Electrocardiogram (NI-FECG).

II. 3.6.2. Definition

Non-invasive fetal electrocardiography (NI-FECG) is a technique used to measure the electrical activity of the fetus's heart using surface electrodes placed on the mother's abdomen and processing them in the algorithm to obtain a suitable signal away from the noise to avoid all previous negative effects. The NI-FECG can be monitored during pregnancy and/or childbirth and used to detect abnormal fetal heart rate (FHR) or patterns; such as rapid heartbeat, bradycardia, or tachycardia, which may be due to ischemia or other pathological reasons. Its non-invasive nature makes indirect electrocardiography a promising method in the field of prenatal diagnosis [Vul'10] [Pet'01].

Therefore, this technology (NI-FECG) is the future of fetal electrocardiogram detection. in addition, that it is expected to be able to detect the physiological changes of the heartbeat interval or the so-called arrhythmia, which is scientifically called heart rate variability (HRV).

II. 3.6.3. Non-Invasive FECG Recording Techniques

➢ Electrode characteristics

Non-invasive FECG signals are obtained by placing standard ECG electrodes on the abdomen of pregnant women. Ag/AgCl electrodes are used as electrodes. The lead electrode is actively shielded to minimize the loss of signal quality during the ECG signal transmission from the lead to the acquisition system. The skin area under the electrode should be gently scraped to remove the shallower, poorly conductive stratum corneum. Usually, a transparent electrolyte gel containing Cl- is used to maintain good contact, and to reduce the impact of the skin on impedance by making the dry outer layer ionic conduction. This minimizes the contact resistance between the sensor and the skin and optimizes the quality of the recorded signal [Lee'08].

➢ Electrode configuration

The morphology of the non-invasive abdominal FECG signal depends not only on the position of the electrodes but also on the position of the fetus, which is not always predicted accurately. Choosing this special electrode configuration, on the one hand, represents a compromise between patient comfort and signal processing capabilities and the recorded amount of information on the other hand. to assess the health of the fetus as accurately as possible, it is best to use as many fetal ECG signals as possible. However, such a large number of fetal electrocardiogram signals require multiple electrodes and multiple signals on the maternal abdomen for processing. To avoid patient discomfort caused by the use of all these electrodes and to facilitate real-time analysis of the recorded information, the number of abdominal electrodes should be small enough.

Therefore, it is impossible to determine the optimal configuration of the electrode; however, several different configurations have been proposed to standardize the registration procedure, some of which are based on the most probable fetal position and allow a small number of leads (4-8) to optimize application simplicity. Others try to cover as many fetal positions as possible and consider using a large number of leads (> 8) to optimize signal reception. The fetal electrocardiogram record contains 8 bipolar signals, all of which have a common reference near the maternal umbilicus. The ground electrode with the right foot is placed near the side of the mother to minimize electrical noise. Therefore, the number of electrodes is chosen as (8), in order to Make sure that no matter what the position of the fetus in the womb, at least some of the electrodes are close to the fetal heart, to record the fetal ECG with sufficient amplitude [Sam'10].

Due to the circular shape of the abdomen, this circular structure exists in three-dimensional space. In particular, the electrodes on the abdomen side (ie, electrodes 1, 4, 5, and 8) are closer to the mother's back than the centre electrodes (ie, electrodes 2, 3, 6, and 7). This third dimension (the transversal direction; from front to back) can be used for a three-dimensional assessment of the fetal ECG, but for pregnancies at low gestational ages, the roundness of the abdomen is small, the accuracy of the three-dimensional electrode positions is relatively low (Figure II.14) [Cli'11].

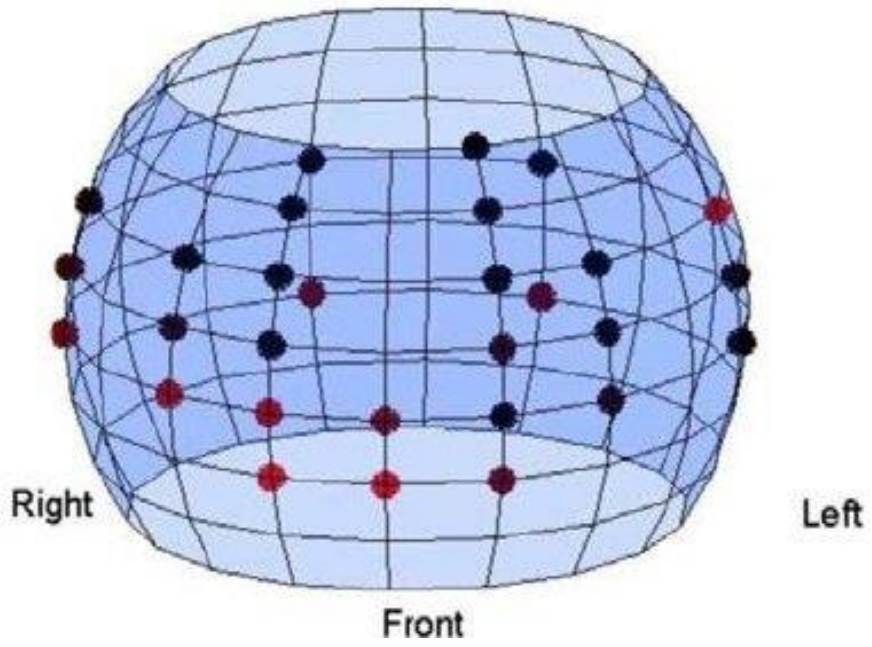

Figure II.14: suggested locations of abdominal electrodes

Globally, electrode configurations used for non-invasive FECG recording can be divided into two categories: pure abdominal configuration and mixed configuration. In contrast to the former, the latter also provides clean maternal electrocardiogram (MECG) records.

A. Pure Abdominal Electrode Configurations

- Four-electrode configuration in this configuration, the only common electrode is on the symphysis pubis, and the other three are on the left, above, and right side of the navel.
- Six-electrode configuration in this configuration, three electrodes are aligned at the umbilicus (two on the right and one on the left), one above the umbilicus, one at the pubic symphysis a reference, and one common-mode reference signal, with an active-ground signal on the left thigh or on the back.
- 10-electrode configuration: This configuration allows 10 electrodes, four of which are arranged vertically in the centre of the mother's abdomen (two above the navel and two below the navel), two pairs of left and right lines of the four lines indicated previous, the reference one located at the abdomen centre near the navel, and the ground one located on the right thigh.
- It is equipped with 13 electrodes. The six-pointed star electrode configuration is obtained by connecting 13 abdominal electrodes. The average of all recorded potentials is a common reference.
- 32 Electrode Configuration. In this configuration, a set of 32 abdominal electrodes based on anatomical landmarks (the navel, xiphoid process, pubic symphysis, axilla, and spine) are placed to cover the mother's abdomen, side and back [War'11].

B. Mixed Electrode Configurations

- A hybrid configuration with eight electrodes. This configuration enables eight electrodes, five of which are located on the abdominal around the navel and three pectorals below the left udder.
- Nine-electrode mixture configuration This configuration includes nine electrodes, six abdominal electrodes placed around the umbilicus, and three thoracics vertically aligned in correspondence of the maternal heart (one above the heart and two below the heart;).
- A mixed configuration of 14 electrodes. In this configuration, 12 electrodes are placed on two horizontal lines on the mother's abdomen, one below and above the navel, and one electrode on each shoulder of the mother [Cli'11].

The division of the electrode configurations used in the NI-FECG extraction is based on the acquisition of the maternal ECG, whether it is included or not. When only abdominal electrocardiogram (AECG) is extracted, the configuration is pure, and the configurations are mixed configuration when the electrodes are placed for the acquisition of AECG and MECG together.

II. 3.6.4. Methodology

The resulting abdominal electrocardiogram (AECG) mainly contains maternal electrocardiogram (MECG) with high amplitude, Fetal electrocardiogram (FECG) with relatively small amplitude, and additional unwanted bioelectrical noise (generated by muscle movement, etc.). Mathematically, the abdominal record is the sum of three signal components: the Fetal electrocardiogram signal (the signal to be retrieved), the abdominal maternal ECG, and noise. Automatic FECG extraction includes pre-filtered abdominal signal noise suppression and MECG suppression (Figure II.15) [Raj'14] [Beh'16].

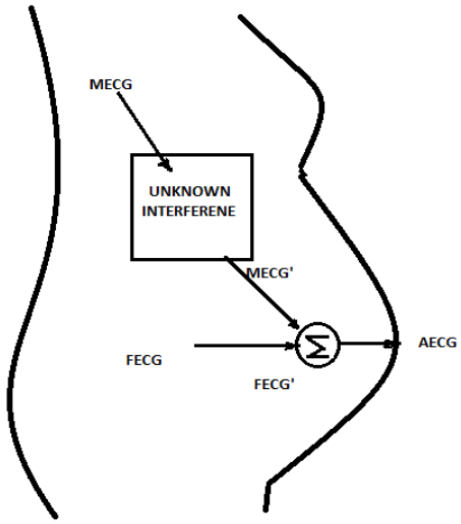

Figure II.15: AECG & its components Source of FECG.

AECG= FECG +MECG + Noise.

In order to extract the FECG signal, the electrodes are placed according to the electrodes configuration to be worked in it (either a pure abdominal configuration or a mixed configuration), where the electrodes configuration plays a major role in the nature of the later stages, and then pass these signals to the processing algorithm and process them at various stages of the algorithm to finally obtain the desired signal. It should also be noted that the processing steps are determined according to the configuration of the electrodes (Figure II.16).

In general, we can define an algorithm as a set of logical and sequential steps that are applied to a set of available data, which is known as the inputs, in this case, the inputs are the AECG signal, to get a result from it, which is known as the outputs (FECG).

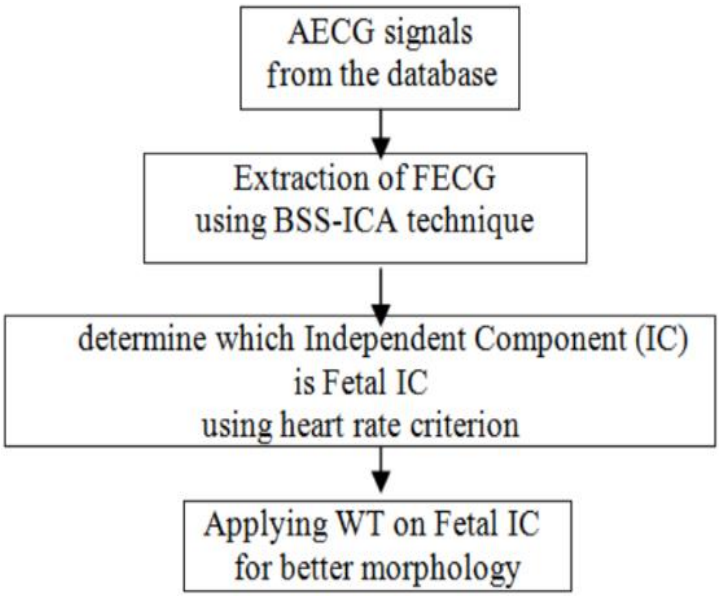

Figure II.16: An example of an algorithm for FECG extraction**.**

The detection of non-invasive fetal electrocardiogram (NI-FECG) from abdominal electrocardiogram records relies heavily on typical statistical signal processing techniques such as independent component analysis (ICA), adaptive noise filtering, QRS detection, and multi-channel blind deconvolution. The latest single-channel FECG extraction schemes, such as enhanced Kalman filter (EKF), template subtraction (TS), and many other modern techniques.

The difference between the methods used depends on the different techniques of FECG extraction, for example, when using a pure abdominal electrode configuration, the ECG is obtained directly from the abdominal recordings through independent component analysis (ICA) or template subtraction (TS), and if use a mixed electrode configuration the foetal electrocardiogram can be retrieved through adaptive filtering (AF) based on the mother's electrocardiogram recorded by electrodes on the mother's chest or shoulders [Iva'14].

There are many different non-invasive FECG signals acquisition algorithms, but each algorithm differs according to the typical statistical signal processing techniques used therein; this will result in differences in the effectiveness of each algorithm and changes in the final signal quality. Algorithms usually involve several steps: pre-processing, scoring, QRS detection, and removal of the maternal electrocardiogram (MECG), which is the main component in AECG and, estimation of FECG.

The algorithm that we will work on will be explained in addition to the signal processing techniques used in it sufficiently in the next chapter.

Although the use of Non-Invasive fetal electrocardiogram (NI-FECG) is inexpensive and easy to use, it is the same as other forms of monitoring, which means that it has some technical problems and has been limited for a long time, mainly due to its low signal-to-noise ratio (SNR) to the FECG signal (low signal quality) due to low electrical amplitude (1/50 of MECG signal), large maternal electrocardiogram (MECG) and background noise. There are also some reservations on how to receive the signal, but the advancement of signal analysis technology has promoted the clinical use of NI-FECG, especially HRV analysis. So, extracting fetal ECG from abdominal ECG requires effective algorithms to provide accurate cardiograph (morphology).

II. 3.6.5. The efficiency of Non-invasive Fetal Electrocardiography

First of all, we must agree that these performance indicators and results are based on the results of algorithms discovered by researchers in previous literature and previously used; therefore, this method is considered cheap, easy to use, suitable for long-term tracking fetuses, and monitoring the difference in the fetal heartbeat. In addition, this technology enables you to accurately assess the fetal heart rate, and many studies have shown that information about conductivity can be retrieved from the morphology of the reconstructed NI-FECG. It can also reduce the confusion between MHR and FHR and better control women with a high body mass index (BMI). However, the potential of NI-FECG to provides clinically useful information has rarely been evaluated [Has'09] [Pet'01].

NIFECG promises to evaluate the rhythm and shape of the FHR. Additional information can also be obtained from the signal, such as the orientation and motion assessment of the fetus. With this technological advance, NIFECG can provide higher-quality FHR information in comparison to existing monitoring modalities.

This is what is known about this technique to this day. In the following chapter, the effects of our improvement of this method can be presented.

II. 4. The basic method of electronic fetal monitoring

The following is a comparison of the methods used to assess the condition of the fetus during pregnancy (Table II.1):

Method	System	Advantages	Disadvantages	Gestational Age
(CTG)	Fetal heart rate and uterine muscle activity are recorded by two sensors in the mother's abdomen. This information is provided by Doppler ultrasound and recorded on a strip of paper called a cardiotocograph (CTG).	Measures uterine contractions, provides continuous FHR tracings.	Short-term variability cannot be observed, difficult to interpret, limited accuracy.	⩾24 weeks
(PPG)	Detection of changes in the size of blood vessels and thus measurement of heart rate based on changes in tissue absorption of light of specific wavelengths in the red or near-infrared range.	Low cost, low power consumption, harmless, easy to handle, suitable for long-term recording, suitable in a clinical setting, can be designed to be portable, can be used in an MRI environment.	-Dependency on the source-detector separation. -dependency on fetal orientation in utero.	⩾24 weeks
(FMCG)	Recording the magnetics field generated by the heart's electric field.	Low cost, easy to handle, suitable for long-term recording, beat-to beat variability monitoring.	Complex design requirements, dependency on fetal orientation in utero.	20-40 weeks
(US)	-The ultrasound beam generated by the ultrasound transducer placed on the mother's abdomen penetrating the tissue and reaching the internal structure of the body. - The reflected echo is received by the US transducer.	-Low cost, easy to handle. -It is the most widely used technique in clinical practice.	-Short-term variability cannot be observed, not suitable for continuous monitoring. -Its sensitivity to motion.	⩾20 weeks
(FSE)	-An electrode is placed on the scalp of the fetus.	-Provides more accurate fetal heart rate and heart rate records than the external monitor.	-An invasive procedure. -It is only used when necessary because it does bring some risk.	During labour
(NI-ECG)	-Standard ECG electrodes with varying preparation methods, it is placed on the mother's abdomen to record AECG and then treat systematically.	-Low cost, easy to handle, suitable for long-term recording, beat-to-beat variability monitoring. – FHR and possibly morphological analysis.	-Low SNR. -Complex design requirements, dependency on fetal orientation in utero.	⩾18 weeks until birth

Table II.1: Comparison between FHR monitoring systems.

II. 5. Conclusion

In summary, the ultrasound method can determine the fetal heart rate, but it suffers from a shortcoming in giving variation in the fetal heart rate, the recordings are relatively short, and there are some disadvantages mentioned previously.

Therefore, it is necessary to develop a new method to eliminate the shortcomings of ultrasound technology, as the fetal scalp electrode technology appeared and it can give the most accurate results in the fetal electrocardiogram (FECG), but it is an invasive technology, and its period of use is limited only during labour.

Due to the danger of the last method, it is necessary to develop a new method to solve all the problems of the previous method and add new functions, such as the ability to record the fetal electrocardiogram in a longer period.

A technology (NI-FECG) has been developed that uses electrical signals from the mother's abdomen (AECG) and extracts the fetal electrocardiogram (FECG). This technique has attracted the attention of researchers and the scientific community, as it is the most promising method for analysing and studying the electrocardiogram of the fetus and making it the main method in the future.

Therefore, this technology (NI-FECG) is the future of fetal ECG detection. In addition, it is also expected to detect the physiological change in the interval between heartbeats or so-called arrhythmias, which is scientifically known as variability Heart rate (HRV).

This technology, like other technologies, initially has some technical problems, the most important of which is the low signal-to-noise ratio and others. Therefore, it is necessary to solve these problems to become a very reliable and widely used technology.

The next chapter introduces the mechanism of constructing and implementing this technique, in addition to explaining the database used and the working and development environment, and then moving to the selected algorithm and its implementation in the work environment and applying it to the existing data, and at the last stage of collecting and analysing the results.

Chapter III

Executing the algorithm and analysing the results

This chapter will present the working mechanism starting with the work environment, development and software used, then explain the database used, then develop and implement the proposed algorithm for extracting the fetal electrocardiogram with an explanation of the toolbox used to detect FECG. And as a final stage, analysis and study of the results.

III. 1. Introduction

As with most pattern recognition applications, the characterization step is necessary for automatic heartbeat recognition.

This stage of characterization is important for the rest of the work, since it, first of all, will allow the extraction of useful information from the ECG signal and make it convenient for both doctors and algorithms for automatic data processing.

This information is consistent with the metrics used by cardiologists to describe cardiac cycles, namely the periods and amplitudes of the waves that make up the electrocardiogram signal, as well as the heart rate.

In this work, the characteristic of ECG signals is to detect the QRS complex of each contraction in order to obtain the necessary representative parameters, which later will make it possible to accurately recognize normal and normal heartbeats, pathological heartbeats.

The characterization process was carried out in two stages:

- Signal pre-processing, its role is to get rid of unwanted frequencies that may interfere with the impulses.
- Detection QRS complexes by locating the R peaks in the ECG signal.

In general, the operation of characterizing an electrocardiogram signal can be divided into two stages, shown in (Figure III.1).

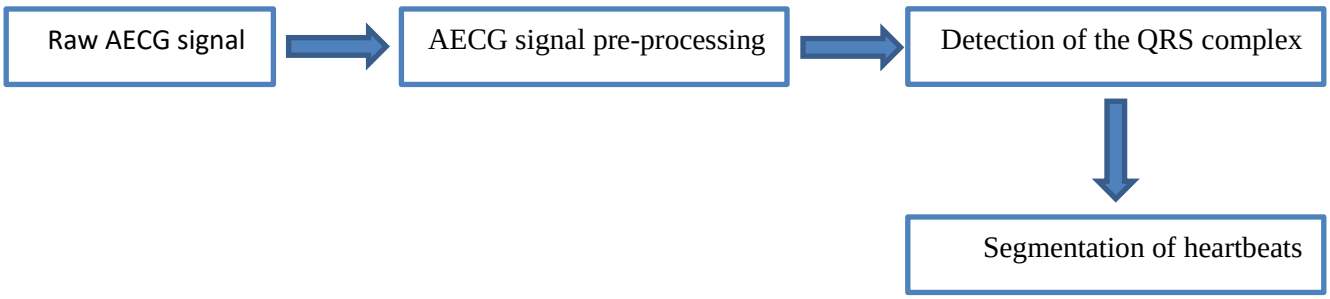

Figure III.1: Stages of ECG signal segmentation.

III. 1.1 signal pre-processing

Due to the presence of noise, it works to damage the ECG signal by altering clinical information by increasing or decreasing; Hence, there must be a pre-processor.

In addition, difficulties in detecting the QRS complex are mainly associated with a large spread in the waveform and the presence of these unnecessary noises from different sources on the electrocardiogram. Therefore, it is important to know what types of noise can spoil the ECG signal.

III. 1.1.1 Types of noise present in the ECG signal

After receiving an ECG signal, unwanted events may appear on the ECG waveform. The problem is often posed during the automatic processing of the signal, where the presence of these noises can generate errors in the diagnosis. but often the treatment of these noises is still difficult to carry out automatically.

These noises can be classified according to their origin into two broad categories: the noise of technical origin and noise of material origin.

1. **The Technical noise:** The noise of technical origin is noise caused by the equipment used during recording.

A. Noise from the 50/60 Hz network

50/60 Hz noise is the noise it comes from the electrical distribution network, it contaminates the ECG signal with oscillations of which the fundamental harmonic is 50/60 Hz, usually, this noise is present in all recordings and can be quite high, however, it is easy to eliminate using the selective filtering operation.

B. Noise due to poor contact of the electrodes with the skin

When the electrodes used to collect the ECG signal diverge or the gel between the electrode and the skin dries up, noise can occur, causing abrupt changes in the amplitude of the ECG signal. This type of noise is very difficult to remove. because its energy is in the same frequency range as the QRS complex.

C. Other noises: Other common technical noises include artefacts caused by:

1.movement of power cables.
2.saturation of measuring instruments.
3.poor wiring quality.
4.the use of common clothing.
5.radio frequency waves emitted by electrosurgical equipment.

2. **Physical noise:** Physically derived noises are artefacts caused by electrical activity in the human body, such as muscle contractions or breathing movements.

A. Baseline fluctuations

The baseline is a horizontal line used as a guide to study the shape and amplitude of various heart waves.

This fluctuation within the baseline corresponds to a low-frequency deviation of the ECG amplitude, primarily associated with the movement of the patient during breathing.

This is because, during the recording of the ECG signal, respiratory activity can cause constant fluctuations in the baseline of the signal. In general, these noises do not cause much discomfort when analyzing the ECG signal, as they can be filtered because their energy is at low frequencies.

B. Noises due to the EMG electromyogram signal

Although the ECG machine is designed to be primarily sensitive to the contractions of the heart muscle, the ECG machine can also record contractions of other skeletal muscles.

This noise is caused by the contraction of muscle tissue, which emits an electromyogram signal, which superimposes the electrocardiogram signal in the form of high-frequency oscillations, these disturbances are quite annoying, especially when the patient is moving or shaking a lot.

III. 1.2 Detection of the QRS complex

For automatic analysis of the ECG signal, a very important step is the detection of QRS complexes.

Usually, detection of QRS complexes can be achieved with a simple signal threshold, since the R wave is usually larger than other waves in amplitude, but sometimes in some cases, the amplitude of the T wave can be comparable to the amplitude of the R wave, which can cause one of the errors in the final detection result (Figure III.2).

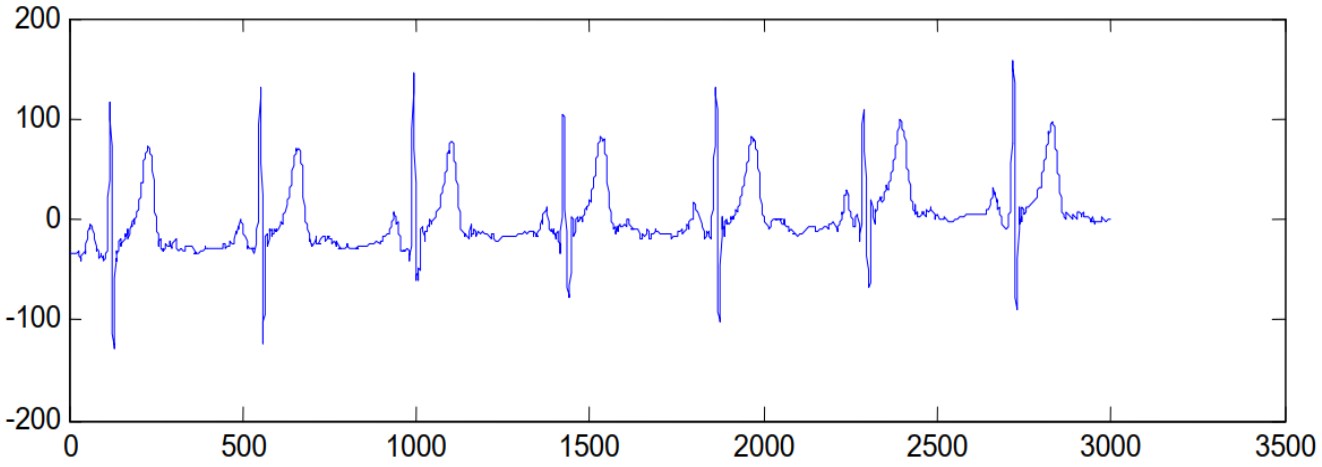

Figure III.2: An ECG signal from a patient in which there is an increase in the amplitude of the T wave.

In addition, R waves can sometimes be of low amplitude and morphology varies greatly from cycle to cycle, therefore good detection of QRS complexes is necessary. Consequently, this requires a very complete signal processing due to the difficulties encountered.

III. 2. Working environment and development

Since it is an accurate physiological signal (AECG), in addition to the interference it contains; Therefore, it is necessary to select a development environment that contains toolboxes capable of processing signals, analyzing data, and developing algorithms with advanced filtering and processing techniques. Therefore, MATLAB® was chosen.

MATLAB® is developed by MathWorks. MATLAB® is an acronym for MATrix LABoratory, technical computing, computation, programming, and visualization tool in an integrated environment used by engineers and scientists to analyze data, develop algorithms, and create models.

MATLAB® is considered one of the high-level programming languages and it is an interactive environment that is relied upon in developing algorithms and doing data analysis. It is an integral part of creating applications and models and provides the user with a set of tools and mathematical functions that help in finding quick solutions based on spreadsheets or even traditional programming languages. MATLAB® is increasingly used among programmers of control systems, computational biology and other fields.

And due to the presence of a graphical interface for ease of use and simplicity of the programming language, the MATLAB® program was chosen to implement the FECG extraction algorithm from AECG.

III. 3. Database

In this work, the open-access database provided by PhysioNet is used to evaluate the performance of the proposed method. PhysioNet Database This is a global database containing a large number of physiological signals collected by researchers for use as reference information to validate research and development algorithms

III. 3.1 Description of the PhysioNet database

The original and current mission of the database is to lead and partially stimulate biomedical research and education by providing free access to large sets of physiological and clinical data as well as related open-source software.

The main advantage of this database is that it is divided into closely related components**:**

1. **PhysioBank:** An extensive archive of widely available digital recordings of physiological signals, time series and related data for use by the biomedical research community.
2. **PhysioToolkit:** A large and constantly growing library of software for processing and analyzing physiological signals, detecting physiologically important events using both classical and new methods.
3. A **collection of popular tutorials and educational materials** that provide expert guidance on an approach to detecting and analyzing health data and physiological signals.

As noted, PhysioNet is not only the name of a research resource on complex physiological signals but also its website physionet.org.

III. 3.2 Data Acquisition

The PhysioNet database provides a series of NI-FECG records collected during a routine medical visit to a group of pregnant women in a clinical setting, collected using non-invasive fetal ECG techniques.

During the same visit, the doctor diagnosed a group of pregnancies as an arrhythmia fetus and the second as a normal rhythm fetus.

A total of 26 recordings were obtained, it was found that the number of fetal arrhythmias recordings = 12, the median gestational age was = 32 weeks (range 22-41 weeks), and the number of normal rhythm recordings = 14, and the median gestational age = 23 weeks (range 20-36 weeks). Therefore, the records were divided into:

- ARR: arrhythmia fetus.
- NR: normal rhythm fetus.

III. 3.3 Data Description

For each of the previous recordings, a set of five abdominal channels and one maternal thoracic channel was recorded, as well as the presence of two additional channels: a common reference and an active ground (Figure III.3).

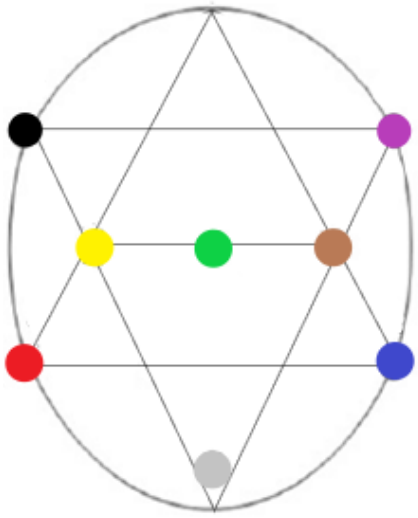

Figure III.3: Distribution of electrodes on the abdomen of mothers from whom recordings were made. 5 abdominal electrodes (red, yellow, green, brown and blue) with a common reference (grey), active ground (black) and one chest electrode (purple).

It is worth mentioning that the mother's thoracic channel is responsible for recording the mother's electrocardiogram (MECG), while the ventricular channels are responsible for recording all electrical signals from the mother's abdominal cavity (AECG). As mentioned in the previous chapter, a mixed electrode configuration was used.

As for the sampling frequency, it is 500 Hz for part of the recordings and 1 kHz for the other part, with a resolution of 16 bits and in the range of [-8,8] mV. The data recording process was carried out continuously and for varying periods, with a minimum of 7 minutes and up to 32 minutes (Table III.1).

Cases	Gestational age (weeks)	Record Length (m:s)	sampling frequency (Hz)
ARR1	38	10:00	1000
ARR2	22	10:04	1000
ARR3	25	12:37	1000
ARR4	35	10:05	1000
ARR5	37	8:01	1000
ARR6	36	32:03	500
ARR7	37	10:18	500
ARR8	23	22:01	500
ARR9	35	11:05	500
ARR10	41	10:07	1000
ARR11	31	10:05	1000
ARR12	23	10:05	1000
NR1	20	10:05	1000
NR2	21	10:05	1000
NR3	32	10:07	1000
NR4	21	10:20	1000
NR5	23	10:05	1000
NR6	22	10:27	1000
NR7	20	10:10	1000
NR8	21	10:00	1000
NR9	36	12:34	1000
NR10	20	10:00	1000
NR11	21	10:02	1000
NR12	24	7:20	1000
NR13	22	10:04	1000
NR14	20	10:10	1000

Table III.1: Description of recordings

III. 3.4 NI-FECG database files

Records are saved in the database as files with different extensions, at least a pair of files for each record, so that each record has two different files with the following extensions: dat and hea.

- **Data file (.dat):** Contains digital data for signals. This file stores electrical signals.

- **Header file (.hea):** It contains the interpretation parameters of the corresponding data file that allow the program to use, such as (the signal name for each signal in the data file, sampling frequency, number and nature of channels used in addition to accuracy and information about the baseline).

III. 4. The Algorithm

In the previous chapter, we mentioned that an algorithm is a systematic series of steps to achieve a specific goal, and it should be noted that the obtaining of the FECG signal itself goes through three main stages (Figure III.4).

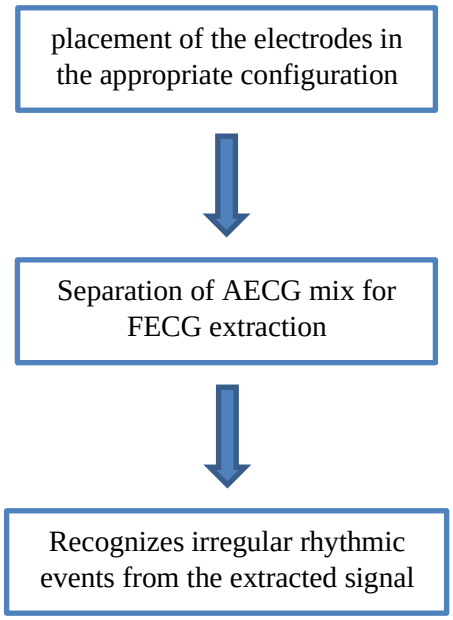

Figure III.4: Application Methodology of NI-FECG Technology

After determining the composition of the electrodes and their placement, we can now move on to the process of extracting FECG from AECG, which will be by developing and implementing an algorithm through the working environment that we mentioned above, and this algorithm is responsible for separating the mixture of signals and detecting the fetal electrocardiogram and identifying abnormal rhythms. The following image shows the steps of this algorithm. The stages of the algorithm's work will be clarified by implementing it on a data file and clarifying the role of each step on the AECG signal (Figure III.5).

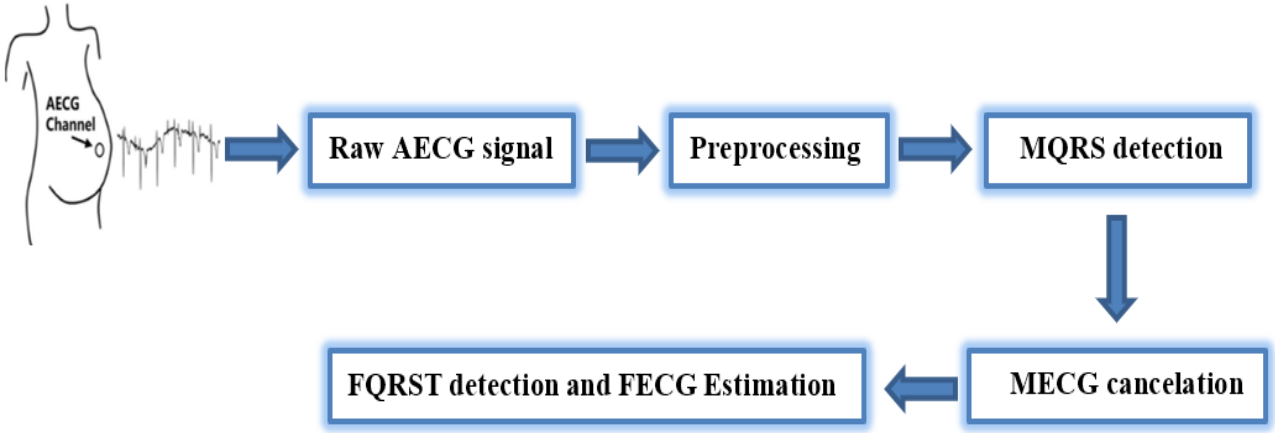

Figure III.5: The algorithm used to extract the FECG and MECG signal and detect the heart rate of each

III. 4.1 Raw AECG

The raw signal (AECG) is received through the electrodes installed in its place, that register five channels in the abdomen and one for the mother's chest, and these channels work by registering changes in the electric field between two electrodes. And this is what is called the derivations (leads) on an electrocardiogram.

As shown in (Figure III.3), we can define the expected derivations or leads as follows (Figure III.6):

VAb1 = **V** red − **V** grey

VAb2 = **V** yellow − **V** grey

VAb3 = **V** Green − **V** grey

VAb4 =**V** Brown − **V** grey

VAb5 = **V** Blue − **V** grey

VTh1 = **V** purple − **V** grey

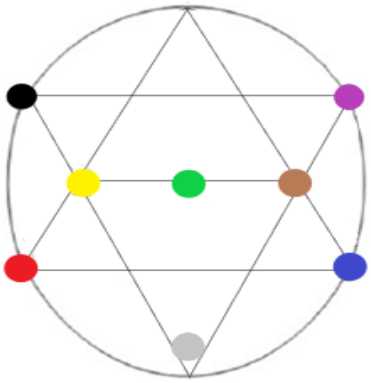

Figure III.6: Derivatives of NI-FECG channels (Ab: abdominal, Th: thorax)

These six derivations and channels are obtained by opening data files (.dat and .hea) in the working environment (MATLAB®), and thus the first step in exploration and analysis is to open the data file and extract the raw signals from those files in order to start the processing stage (Figure III.7).

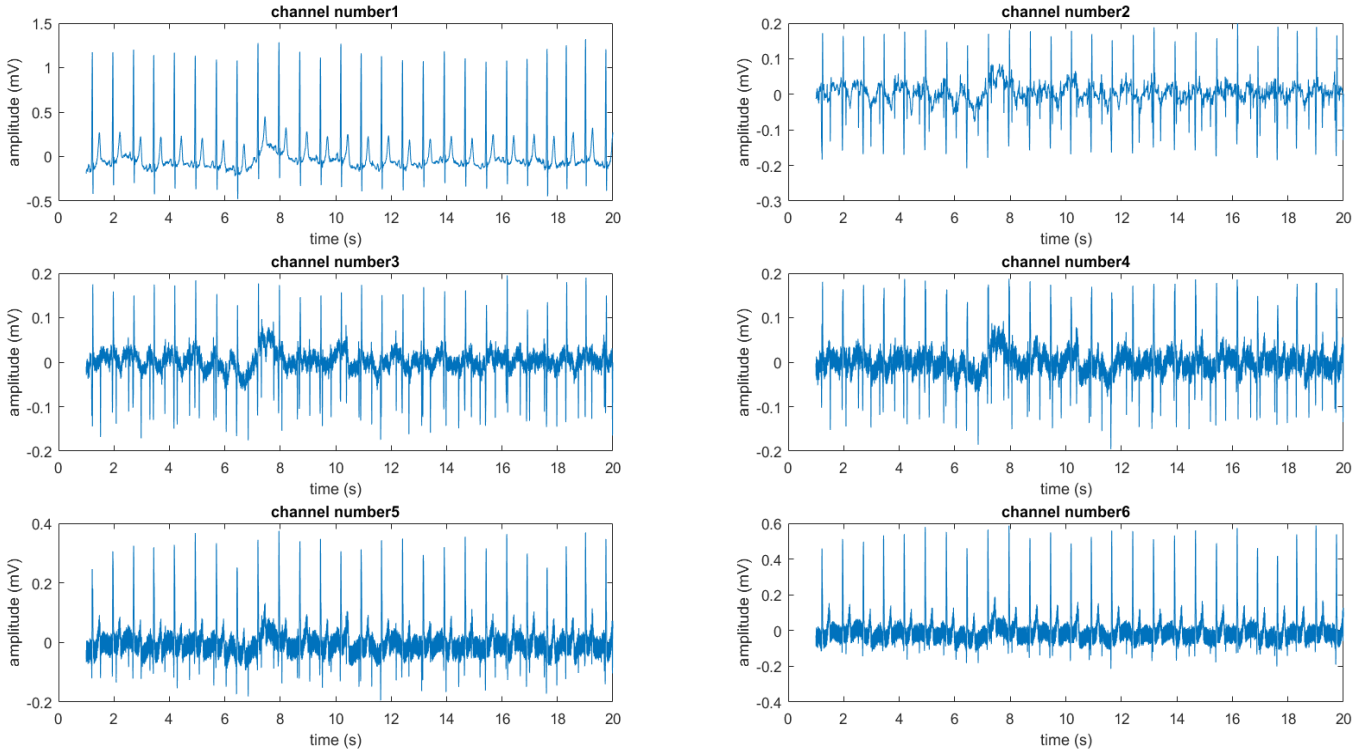

Figure III.7: Signal acquired for each channel within the first 20 seconds of recording (case ARR1 analysis example)

From the above image, we see the channels (1-6) previously defined and the electrical signal extracted from each channel. It is worth mentioning the lack of clarity of these signals and their need for pre-processing before studying and this is the next step in the algorithm.

III. 4.2 Preprocessing

Data pre-processing refers to correcting this data before using it to obtain more accurate results and prevent external influences, such as abdominal muscles, baseline wandering and power line frequency, this must be done because when collecting data, out-of-range values are collected or parts of the data are lost, which is an important step in the data extraction process.

For each of the AECG channels, it is a set of interferences and signals as follows:

$$AECG = FECG + MECG + Noise$$

The first step is to eliminate baseline wander (usually due to breathing) and power line noise and normalize the data, it is worth noting that MECG and FECG are the two main components remaining in the AECG after eliminating noise and have the same bandwidth (1-100) Hz (Figure III.8).

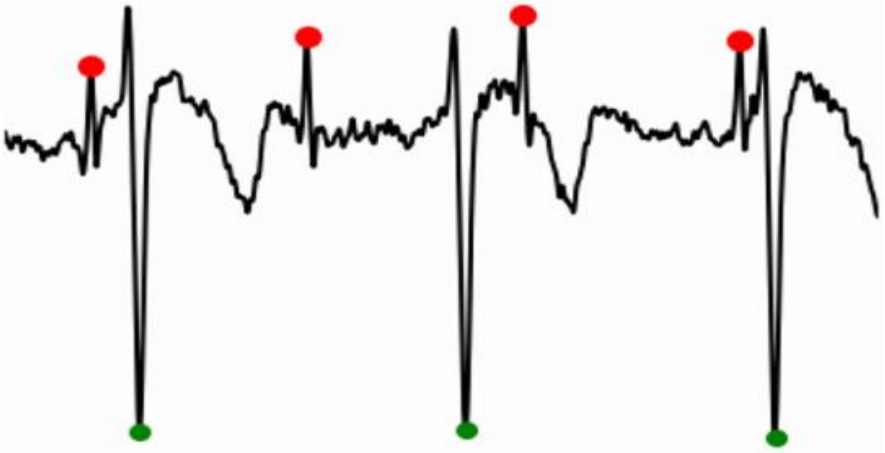

Figure III.8: Part of the abdominal ECG after noise elimination. Green dots represent MECG R peaks and red dots represent FECG R peaks

Three procedures were used for pre-processing the received signals (Figure III.9):

- **Filtering power interferences:** Because it comes from the electricity network feeding the recording device (Holter), this noise is characterized by a sinusoidal interference of 50 or 60 Hz depending on the geographic location and can be accompanied by some harmonics, these frequencies are removed from the signal.

- **Filtering high frequencies:** The movements of the abdominal muscles and the body as whole cause values that are outside the frequency ranges of both the AECG and the FECG, so either make a filter for out-of-bounds frequencies or using knowledge about the spectral properties of the QRS complex in particular and the ECG in general and define them in the program and cancel the rest.

- **Normalization:** The database normalization phase is an additional pre-processing phase to organize data and the relationships between them and to increase the flexibility of the database by compensating for any data corruption or loss and removing duplicates.

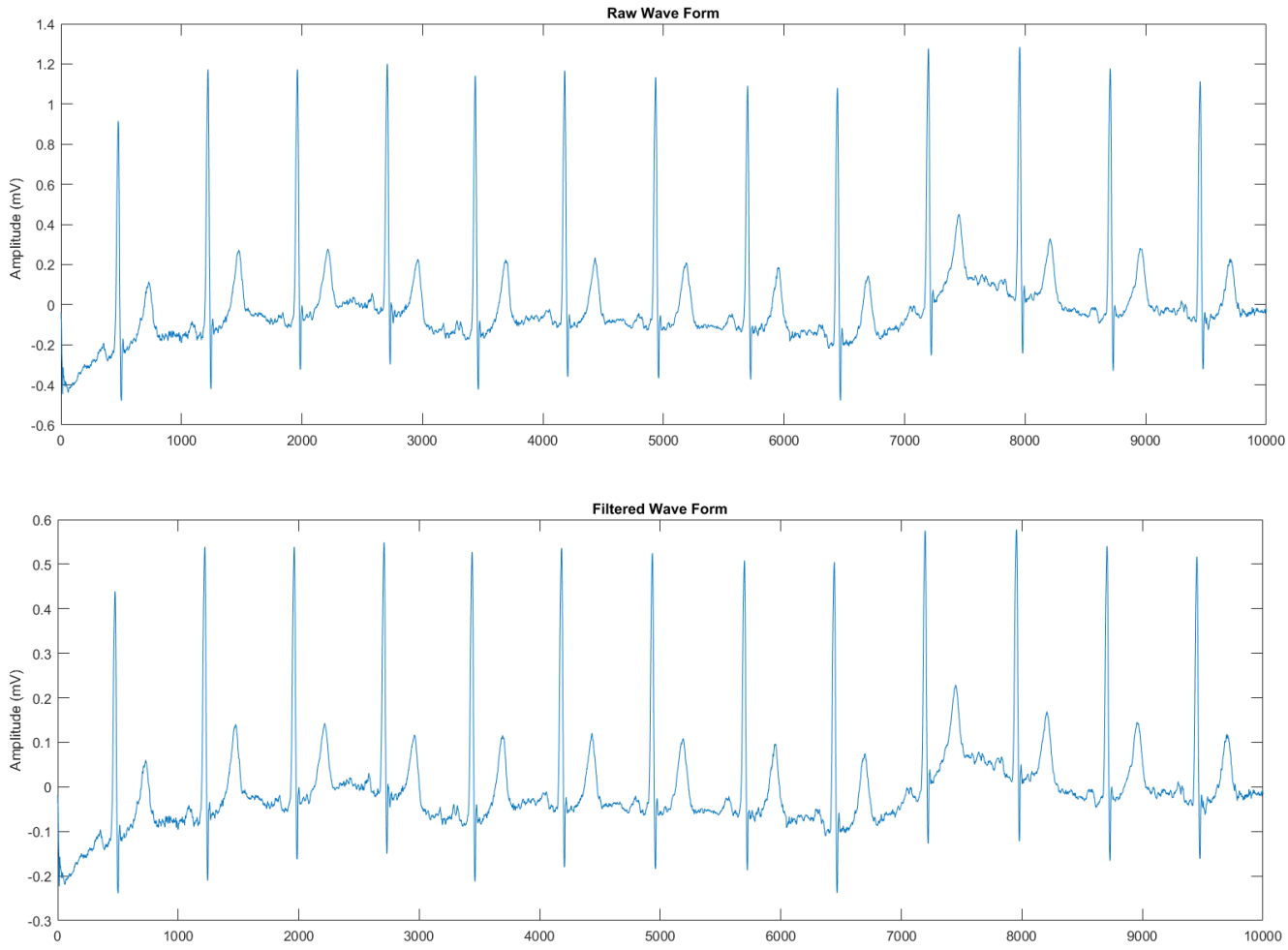

Figure III.9: From top to bottom, the figure shows the raw waveform (part of the ARR1 record) and the filtered waveform

III. 4.3 MQRS Detection

After pretreatment, the primary intervention in the AECG recording is the mother's electrocardiogram MECG, and in general, the QRS complex is the most striking waveform on the electrocardiogram, as it reflects the electrical movement in the heart and the energy of the impulses on mainly. therefore, accurate QRS determination with high temporal accuracy is important for automatic calculation of pulse variability and its shape, which provides a large amount of data on the current state of the heart and is the main part of the electrocardiogram.

Noise and interference are inherent in the AECG signal acquisition method as detailed extensively previously, so QRS recognition is relatively difficult due to given the fact that rhythm morphology changes over time, however, the term "noise" has a broader meaning in terms of QRS detection, so the P and T waves should be considered treated as noise for QRS detection, although they are part of the physiological content of the ECG

signal. During the QRS complex detection phase, the main task is to provide a boundary and use procedures to separate the T and P waves. There are two types of signal and noise problems (Figure III.10):

1. Morphological changes in QRS are of the physiological origin or changes due to artefacts.
2. Noise occurs: large P or T waves, muscle activity, or temporary effects.

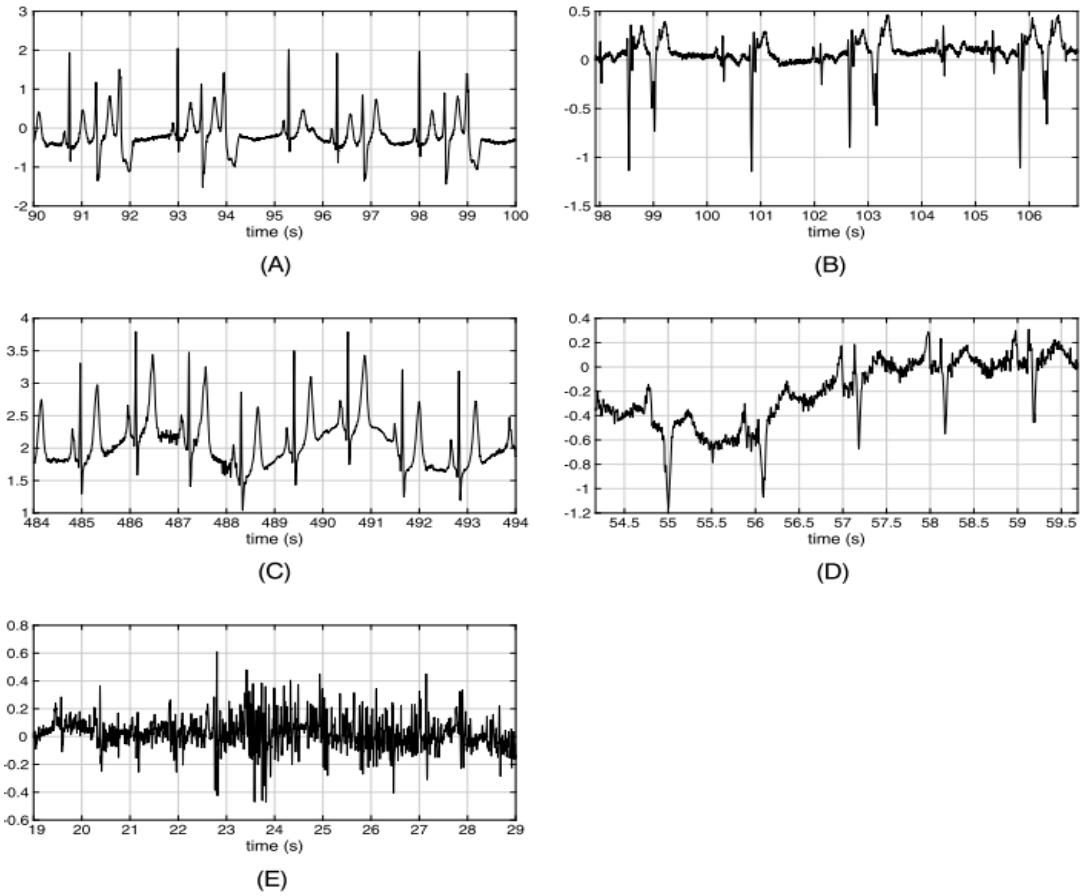

Figure III.10: Types of issues and noise in the ECG from a QRS-detection point of view. (A) QRS morphology alternance. (B) QRS morphology and amplitude changes. (C) High-amplitude T-waves. (D) High-amplitude P-waves. (E) Burst of noise of muscular origin and artifacts similar to QRS.

So, accurate identification of three waves (Q, R, S) representing fulcrums points for identifying normal and abnormal QRS complexes. Since the R wave has the largest amplitude, the focus is to find an acceptable R point. To find a reasonable R point, four QRS waveforms are proposed, as shown in (Figure III.11). At this point, the search will look for Ra, Q, S and R gradually, where Ra is the imprecise R point, to find a reasonable R point.

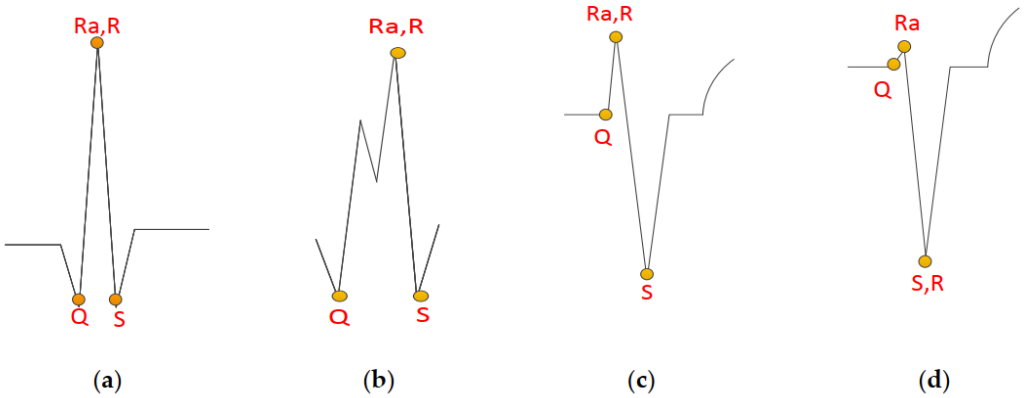

Figure III.11: QRS waveform templates of four desired recognition features: (a) normal QRS waveform, (b) fork-like crests, (c) deep S wave with small R wave, (d) deep S wave with tiny or hidden R wave.

There are many methodologies for QRS complex detection, inclusive of wavelet changes, bandpass filter application, etc. Most of those techniques perform well sufficient and do not cause a significant substantial deterioration in AECG quality.

It is known that there is one cardiac cycle that occurs every certain period (beat). So in this work and the MATLAB® environment we used a sliding window with a length of 500 samples (Figure III.12) can be used that moves continuously along the signal that has been previously processed, and this window works to detect MQRS complexes by detecting the R peak using a coupling present in the MATLAB® environment so that this window splits the signal into parts according to The length of this window (500 samples per window) and the finding of every peak in it.

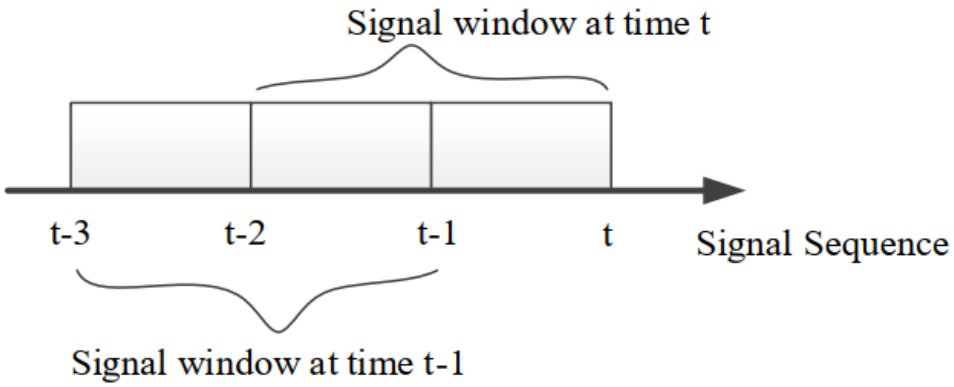

Figure III.12: Represent the window used to extract QRS complexes

In addition to the function that captures the R peaks in each window, many functions are used to get good MQRS captures In this part of the program, such as having a function to check the algorithm if the average power around the MQRS site matches the morphological specifications (checking if this is a QRS pool or another), a high pass filter (order 4) and another function to ensure that T or P waves are not counted as peaks and others. This leads to better MQRS detection.

At the end of this stage, the output is the number of times a mother's QRS complex occurs after the inside was a previously processed digital AECG signal. It is known that each QRS complex results from a pulse, so in the output the number of mother pulses in this part of the signal.

III. 4.4 MECG Cancelation

After the detection of the MQRS complex, the MECG cancellation algorithm was applied. The entire MECG erasure process is illustrated in (Figure III.13). The algorithm works with windows of 20 MQRS and treats each window separately when creating the MECG estimate.

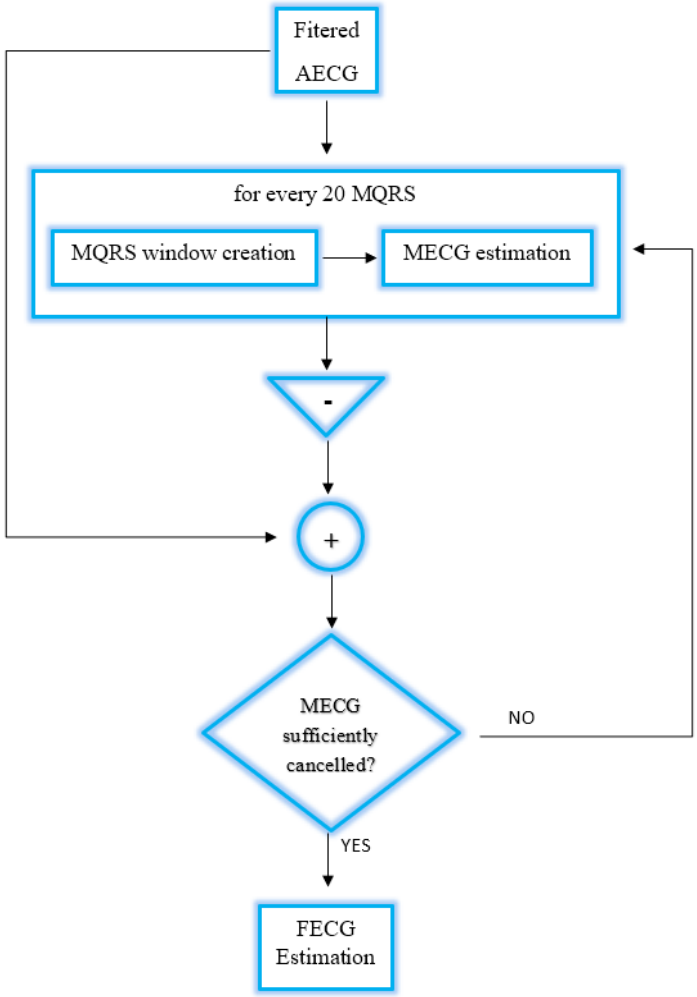

Figure III.13: MQRS cancellation process

The first MQRS model is created using the average of the MQRS complexes in the window. Next, the MECG estimate is created in the MQRS window 20 using the model and the locations of the detected MQRSs. After the build process, the estimated MECG is subtracted from the AECG and the decision on the quality of the erasure is made. The decision algorithm checks if the average energy around the MQRS positions is small enough (average energy per beat of 700 samples) and if not, the MECG cancellation algorithm restarts. This leads to better MECG repression in the presence of noise.

And as the initial output of this phase of the algorithm, the first output will be the mother electrocardiogram produced by MQRS and the signal that has been previously Preprocessed, as the basic inputs for this step-in addition to the inputs specific to the work programme (Figure III.14).

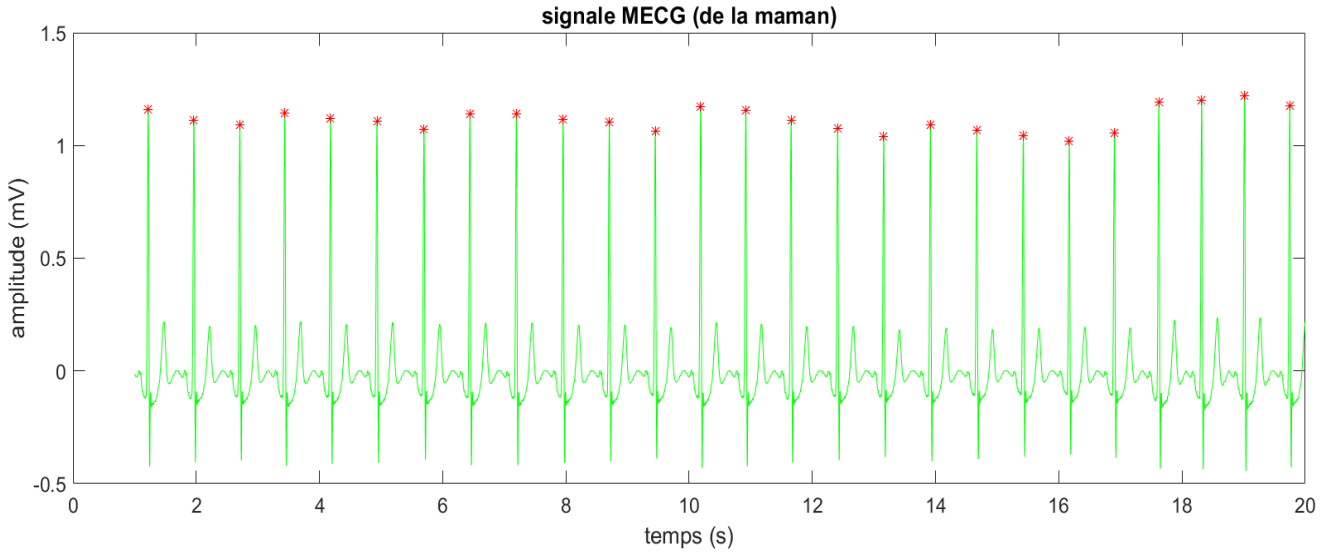

Figure III.14: Maternal ECG signal extraction from the abdominal signal for the first 20 seconds (case ARR1 analysis example)

III. 4.5 FQRST Detection and FECG Estimation

Since FHR is generally not associated with the mother's heart rate, fetal QRS complexes occur at random locations in maternal ECG segments. Because it is known that the amplitude of the fetal ECG signal is low and the number of its heartbeats is high, the extraction and estimation of the FECG and the subsequent discovery of FQRS complexes, taking into account as much as Possible preservation of signal morphology represent a challenge, and therefore there is a slight difference in the detection method of the FQRS complexes, and a filter will be used in place of the window used previously.

The last step of our method involves the detection of FQRS complexes on pre-processed abdominal ECG signals using two order 12 filters because FQRS complexes are more than adults: the low pass filter and the high pass filter. In addition to the selection of the peaks, there is a step of validating the choices, such that the peak is greater than 0.6 of the average maximum values, which leads to better detection of the FQRS complexes.

At the end of the last stage of the work, its output is the electrocardiogram of the fetus, with the identification of QRS peaks (Figure III.15).

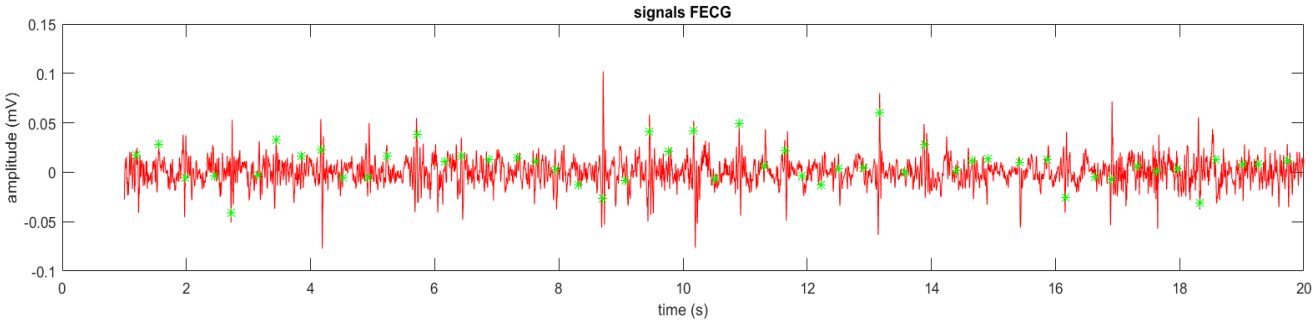

Figure III.15: FECG signal with identification of FQRS complexes for the first 20 seconds of the signal (example ARR1 analysis of the case)

At the end of the work, after determining the QRS complexes for both mother and fetus, the heart rate of each of them can be found, since it was found that the mother's heart rate = (bpm), and fetal heart rate = 176 (bpm) (for the case of the ARR1 study), which are somewhat acceptable values if Compared to the doctor's diagnosis at the time of the recording process.

An image showing the processing steps used in the algorithm for the same study case ARR1 (Figure III.16).

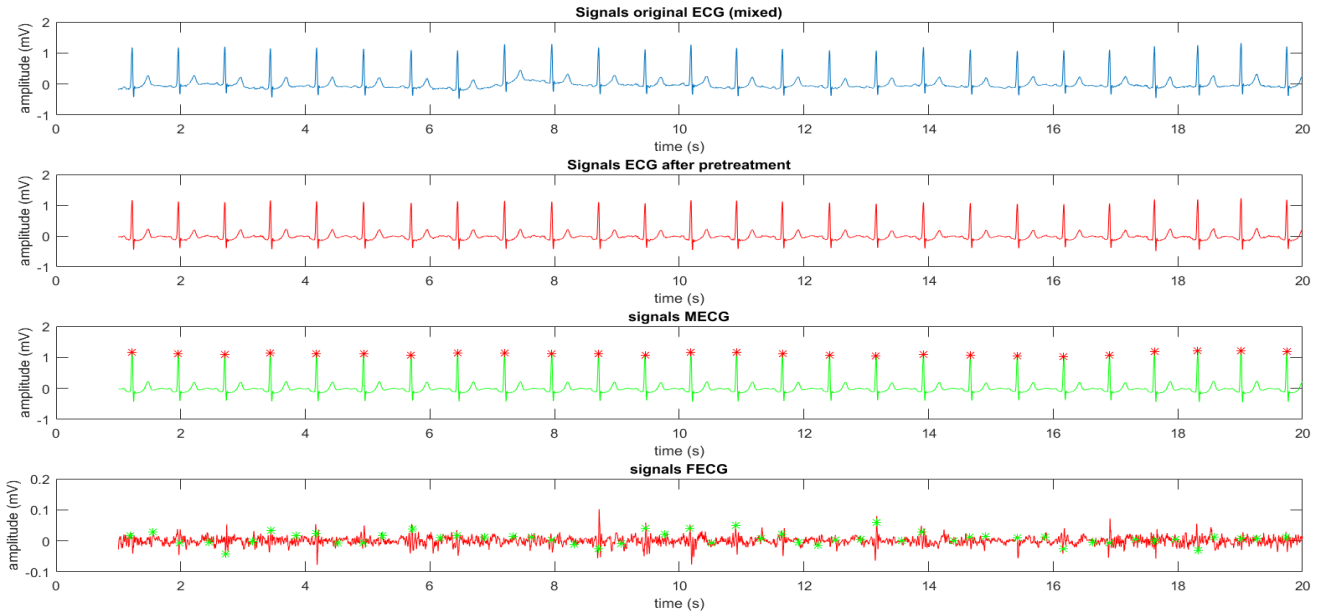

Figure III.16: Stages of the processing process

We applied the algorithm to the database and the result was as follows (Table III.2)**:**

Cases	Gestational age (weeks)	fetal heart rate (bpm)
ARR1	38	176
ARR2	22	180
ARR3	25	187
ARR4	35	177
ARR5	37	189
ARR6	36	163
ARR7	37	175
ARR8	23	179
ARR9	35	156
ARR10	41	176
ARR11	31	178
ARR12	23	177
NR1	20	135
NR2	21	130
NR3	32	142
NR4	21	133
NR5	23	130
NR6	22	135
NR7	20	130
NR8	21	141
NR9	36	138
NR10	20	140
NR11	21	136
NR12	24	136
NR13	22	130
NR14	20	130

Table III.2: Fetal heart rate per case per case in the database

NI-FECG and fetal echocardiography were consistent in all cases on the presence or absence of arrhythmia. Except for the two cases (ARR6 and ARR9) which were described as normal fetal heart rate, contrary to clinical examination.

III. 5. Conclusion

In this study, we developed a method to derive the fetal ECG and find its heart rate by building a precise algorithm that handles this signal, and the FHR was extracted from all the abdominal ECGs.

And after implementing the algorithm, we were able to determine the advantages and disadvantages of this work. Although the morphology of the FECG signal was not clear after isolation, it gave very satisfactory results regarding the calculation of the number of fetal heartbeats, and this is by the way the subject of research, as we can determine which of these fetuses has arrhythmias and those with a normal heart rate.

Indeed, the results showed that the proposed method can be considered an effective way to classify fetal arrhythmias. We have already known in the first chapter the normal heart rate during each period of gestational age.

These results acquired are very promising and inspire us to increase Work and expansion of this technology to use it and work on its practical application through a built-in portable device that works to record and process signals and perform better extraction of pulses with the ability to present these recordings to the medical specialist and other different biomedical applications.

So we can be said that our main conclusion related to the non-invasive fetal electrocardiography (NI-FECG) technique allowed us to present a new technology for the diagnosis of fetal arrhythmias, as this algorithm has demonstrated its ability to diagnose arrhythmias fetuses using NI-FECG technology, However, it should be borne in mind that this algorithm needs to be developed to achieve better accuracy of the fetal ECG signal and its general shape.

General Conclusion and Future Directions

General Conclusion

Timely recognition of fetal distress is important to ensure that treatment or monitoring of pregnancy can be undertaken effectively. Currently, the most widely used method to assess the condition of the fetus in the womb is the Doppler ultrasound. Unfortunately, this method has enough drawbacks, the most important of which is the inability of continuous recording and is performed only in the clinical setting and its inability to give pulse contrast and therefore this method since its introduction has not significantly reduced perinatal mortality. Therefore, the Fetal Scalp Electrode technique was introduced and this method can only be used during labour and after the cervix is sufficiently dilated; Therefore, it was necessary to measure the electrocardiogram of the fetus invasively.

Therefore, we can perform non-invasive fetal ECG monitoring, in principle, during gestational age and therefore it can be a mainstay of fetal monitoring. However, before a non-invasive fetal ECG can be applied in practice, several important aspects of this ECG need to be improved and investigated. For example, the signal quality of non-invasive recordings needs to be improved to ensure that signal-based diagnostics can be performed reliably at all times. In addition, it is necessary to study the appropriate physiological context and the background of the acquired signals to allow a correct general diagnosis. This thesis aims to share in the technological aspect of this technique, such as the quality of the signal and the improvement of non-invasive fetal ECG signals.

The main signal quality problems are caused by interference, which must be removed. The maternal ECG is the dominant interference, but interference from the uterus, abdominal muscles, maternal fetal movements, and the electrical network also obscures the fetal ECG and must be suppressed.

In this thesis, we address the problem of evaluating the feasibility of using the NIFECG technique in the diagnosis of fetal arrhythmias and the development of the algorithm responsible for the capture and determination of FECG.

The first chapter of this thesis dealt with the medical and anatomical aspect of the heart, by studying the difference between the heart of an adult and that of a fetus, and analyzing the electrical activity of the heart with an explanation of the electrocardiogram signal and clarification of its importance and clinical value in the diagnosis of arrhythmia; The ECG signal was used as a starting point to study the physiological aspects of fetal ECG monitoring. The most important conclusions were the importance of the fetal electrocardiogram signal in particular, and it is the only way to know the health status of the fetus.

Regarding the second chapter of this thesis, it touched on the technical aspect of the methods of fetal monitoring, as it contained a complete comparison of the methods of fetal monitoring with a detailed explanation of the methods currently frequently used, in addition to clarifying the new technology (NI-FECG) and its most important pillars. and It was concluded that NI-FECG technology is a promising future for continuous fetal monitoring and diagnosis of arrhythmia.

The last chapter included the working and implementation mechanism, as well as building a detection algorithm using a working environment compatible with this work and applying it to a database to ensure its efficiency. Therefore, we can say that our main conclusion is that the technology (NI-FECG) represents the future of fetal monitoring, as it has demonstrated its ability to diagnose arrhythmias in fetuses; However, more studies are needed to obtain better precision of the FECG signal.

Future Directions

Nowadays, the sole purpose of a fetal ECG (by US) is to extract the fetal heart rate as well as perform an ST analysis. Until now, the non-invasive fetal electrocardiogram has not been used in specialist clinics, despite the success achieved by some researchers. But we hope to provide a step in this direction that demonstrates the possibility of non-invasive ECG recording. This direction allows monitoring of the fetal ECG during pregnancy and facilitates the clinical identification and diagnosis of parameters and signals other than heart rate and ST-segment alone. Examples of these signals are fetal movement and ECG of the fetus a 12-lead.

However, for non-invasive fetal ECG monitoring to be applied effectively in clinics, some improvements need to be made.

The most important improvement is the detection of fetal QRS complexes, as the applied algorithm was able to extract them but we are not sure of its ability to extract them. If the signal-to-noise rate (SNR) is low, the sensitivity of the algorithm is expected to decrease. In addition, an understandable FECG signal must be obtained in order to deal with it.

In general, the ultimate goal of further technological development should be to improve the reliability of signal measurement and analysis, so that home monitoring of potential patients becomes a normal routine procedure. In addition to saving on the costs of visiting a specialist doctor and monitoring pregnant women, this technology improves the lives of these women and reduces the chances of illness.

In order to ensure the practical application of this technology, this technology must provide all the required medical information about the fetus and its condition at all times and for each pathological condition. However, it is necessary to conduct more studies and research in the areas of specialization suitable for health care in order for everything related to this topic to be completely clear.

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