MASTER'S THESIS

Comparison of Conduction Pacing, Conventional RV Pacing, and CRT (Biventricular) Pacing Parameters

Supervisors:
ao. Univ.-Prof. i.R. Dr. Winfried **MAYR**
Prof. Dr. Sandro **BRUSICH**

Author:
Oltion **RAMADANI**
oltion.ramadani@gmail.com
Matrikelnummer: 11919884

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

in the

Technical University of Vienna
Master's Programme Biomedical Engineering

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

I confirm, that the printing of this thesis requires the approval of the examination board.

Affidavit

I declare in lieu of oath, that I wrote this thesis and carried out the associated research myself, using only the literature cited in this volume. If text passages from sources are used literally, they are marked as such.

I confirm that this work is original and has not been submitted for examination elsewhere, nor is it currently under consideration for a thesis elsewhere.

I acknowledge that the submitted work will be checked electronically-technically using suitable and state-of-the-art means (plagiarism detection software). On the one hand, this ensures that the submitted work was prepared according to the high-quality standards within the applicable rules to ensure good scientific practice "Code of Conduct" at the TU Wien. On the other hand, a comparison with other student theses avoids violations of my personal copyright.

Place and Date	**Signature**

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Abstract - English

The comparative analysis of Right Ventricular (RV), Left Bundle Branch (LBB), and Cardiac Resynchronization Therapy (CRT) pacing modalities is pivotal for optimizing patient outcomes in individuals requiring cardiac pacing. This study evaluates key parameters—QRS duration, impedance, sensing, and threshold values—across these pacing methods, highlighting their physiological and clinical impacts. Data were collected during both implant procedures and routine follow-ups. During the implant phase, measurements were obtained in a sterile environment with patients connected to a 12-lead ECG and the EP Tracer system, while pacing lead positioning was guided by signals derived directly from the lead. Key parameters such as pacing threshold, sensing, and impedance were measured using the Medtronic CareLink™ 2090 programmer. For follow-up data, patients were connected to a 12-lead ECG, and pacing was temporarily disabled to capture native QRS durations, followed by measurements under RV, LV, or LBB pacing.

RV pacing, while widely used, often results in prolonged QRS duration, leading to interventricular dyssynchrony and potential long-term adverse outcomes, including pacing-induced cardiomyopathy. The non-physiological activation sequence associated with RV pacing raises concerns about its long-term efficacy. In contrast, LBB pacing represents an innovative approach aimed at achieving more physiological ventricular activation by directly stimulating the conduction system. This method has demonstrated shorter QRS durations compared to RV pacing, mitigating the risks of dyssynchrony and improving ventricular function. However, the technical challenges associated with LBB lead placement highlight the importance of operator experience and patient selection.

CRT remains the gold standard for patients with heart failure and wide QRS complexes, particularly those with left bundle branch block (LBBB). The

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

ability of CRT to resynchronize ventricular contraction and reduce QRS duration has been associated with significant improvements in cardiac function, reduced hospitalization rates, and enhanced survival. This study confirms the efficacy of CRT in achieving optimal resynchronization, though it also emphasizes the need for careful patient selection and consideration of anatomical factors that may influence lead placement and overall device performance.

The findings of this research underscore the critical role of individualized pacing strategies in optimizing cardiac function and patient outcomes. While LBB pacing offers a less invasive and potentially more physiological alternative to CRT, particularly in patients with narrow QRS complexes, CRT remains indispensable for those with significant dyssynchrony.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Abstract - Deutsch

Die vergleichende Analyse der Stimulationsmodalitäten des rechten Ventrikels (RV), des linken Schenkelkamms (LBB) und der kardialen Resynchronisationstherapie (CRT) ist entscheidend für die Optimierung der Patientenergebnisse bei Personen, die eine Herzstimulation benötigen. Diese Studie bewertet Schlüsselparameter – QRS-Dauer, Impedanz, Wahrnehmung und Schwellenwerte – für diese Stimulationsmethoden und hebt ihre physiologischen und klinischen Auswirkungen hervor. Daten wurden sowohl während der Implantationsverfahren als auch bei Routinenachuntersuchungen gesammelt. Während der Implantationsphase wurden Messungen in einer sterilen Umgebung durchgeführt, wobei die Patienten an ein 12-Kanal-EKG und das EP Tracer-System angeschlossen waren, während die Positionierung der Stimulationsleitung durch Signale gesteuert wurde, die direkt von der Leitung abgeleitet wurden. Schlüsselparameter wie Stimulationsschwelle, Wahrnehmung und Impedanz wurden mit dem Programmiergerät Medtronic CareLink™ 2090 gemessen. Für Nachuntersuchungsdaten wurden die Patienten an ein 12-Kanal-EKG angeschlossen und die Stimulation wurde vorübergehend deaktiviert, um native QRS-Dauern zu erfassen, gefolgt von Messungen unter RV-, LV- oder LBB-Stimulation.

Obwohl die RV-Stimulation weit verbreitet ist, führt sie häufig zu einer verlängerten QRS-Dauer, was zu interventrikulärer Dyssynchronie und möglichen langfristigen negativen Folgen, einschließlich einer durch die Stimulation verursachten Kardiomyopathie, führt. Die mit der RV-Stimulation verbundene nicht-physiologische Aktivierungssequenz gibt Anlass zu Bedenken hinsichtlich ihrer langfristigen Wirksamkeit. Im Gegensatz dazu stellt die LBB-Stimulation einen innovativen Ansatz dar, der darauf abzielt, durch direkte Stimulation des Reizleitungssystems eine physiologischere ventrikuläre Aktivierung zu erreichen. Diese Methode hat im Vergleich zur RV-Stimulation

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

kürzere QRS-Dauern gezeigt, wodurch die Risiken einer Dyssynchronie gemindert und die ventrikuläre Funktion verbessert werden. Die technischen Herausforderungen im Zusammenhang mit der Platzierung der LBB-Leitung unterstreichen jedoch die Bedeutung der Erfahrung des Bedieners und der Patientenauswahl.

CRT bleibt der Goldstandard für Patienten mit Herzinsuffizienz und breiten QRS-Komplexen, insbesondere für Patienten mit Linksschenkelblock (LBBB). Die Fähigkeit der CRT, die ventrikuläre Kontraktion zu resynchronisieren und die QRS-Dauer zu verkürzen, wurde mit signifikanten Verbesserungen der Herzfunktion, niedrigeren Krankenhauseinweisungsraten und einer längeren Überlebensdauer in Verbindung gebracht. Diese Studie bestätigt die Wirksamkeit der CRT bei der Erzielung einer optimalen Resynchronisation, betont jedoch auch die Notwendigkeit einer sorgfältigen Patientenauswahl und der Berücksichtigung anatomischer Faktoren, die die Platzierung der Elektroden und die Gesamtleistung des Geräts beeinflussen können.

Die Ergebnisse dieser Forschung unterstreichen die entscheidende Rolle individueller Stimulationsstrategien bei der Optimierung der Herzfunktion und der Patientenergebnisse. Während die LBB-Stimulation eine weniger invasive und möglicherweise physiologischere Alternative zur CRT darstellt, insbesondere bei Patienten mit schmalen QRS-Komplexen, bleibt die CRT für Patienten mit erheblicher Dyssynchronie unverzichtbar.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Acknowledgements

I would like to express my deepest gratitude to all those who have supported and guided me throughout the course of this study.

First and foremost, I would like to thank my professors, whose expertise, guidance, and encouragement were invaluable in the completion of this thesis. Your dedication to teaching and research has greatly inspired me, and I am deeply grateful for the knowledge and insights you have shared with me.

I am also profoundly thankful to my family for their unwavering support and love throughout this journey. To my parents, thank you for always believing in me and for your unwavering encouragement, even in the face of your own health challenges. Despite the difficulties you've faced over the years, your strength and resilience have been a constant source of inspiration. Your support has been a pillar of strength that has carried me through the most challenging times, and I am forever grateful for the love and determination you've shown throughout this journey.

To my brother and sister, I am especially grateful for your understanding, patience, and for always being there when I needed you. Your words of encouragement and the bond we share have been a source of comfort and motivation, reminding me that I was never alone in this journey.

To my beloved wife, your *patience*, *understanding*, and endless support have been crucial to the completion of this work. I am forever grateful for the sacrifices you made to allow me to focus on my studies. Your love and encouragement have been my motivation throughout this journey. And just so you know, there's no more university work left to do!

Lastly, I want to dedicate this work to our daughter, Nina, who was not yet born when this study began. Although you were not physically present during the early stages of this work, your arrival brought a new sense of purpose and joy to my life. Nina, you are my inspiration to continue striving

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

for excellence, and I look forward to sharing my achievements with you as you grow.

To anyone who was part of this journey, thank you.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Contents

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

List of Abbreviations

AF	**A**trial **F**ibrillation
AV	**A**trioventricular
AVB	**A**trioventricular **B**lock
CIED	**C**ardiac **I**mplanted **E**lectronic **D**evice
CRT	**C**ardiac **R**esynchronization **T**herapy
ECG	**E**lectrocardiogram
HBP	**H**is- **B**undle **P**acing
HF	**H**eart **F**ailure
LBB	**L**eft **B**undle **B**ranch
LBBA	**L**eft **B**undle **B**ranch **A**rea
LBBP	**L**eft **B**undle **B**ranch **P**acing
LBBB	**L**eft **B**undle **B**ranch **B**lock
LVEF	**L**eft **V**entricular **E**jection **F**raction
NASPE	**N**orth **A**merican **S**ociety of **P**acing and **E**lectrophysiology
NS-VT	**N**on- **S**ustained **V**entricular **T**achycardia
NSR	**N**ormal **S**inus **R**hythm
PiCM	**P**acing- **I**nduced **C**ardiomyopathy
PR	**PR** interval
pQRSd	**P**aced **QRS** **D**uration
RV	**R**ight **V**entricular
RVP	**R**ight **V**entricular **P**acing
SSS	**S**ick **S**inus **S**yndrome
UCCK	**U**niversity **C**linical **C**enter of **K**osovo

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

VF	**V**entricular **F**ibrillation
VT	**V**entricular **T**achycardia

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Chapter 1

Introduction

When talking about cardiac stimulation and pacemakers, Mr. Larsson, a Swedish engineer is one of the names that history won't forget. History will remember Mr. Larsson not for his profession as an engineer, but as the first person to receive an implantable pacemaker on October 8, 1958—often referred to as the D-Day of implantable pacemakers. Mr. Larsson had more than 20 pacemakers replaced in his last 43 years of his life, before his death from melanoma in 2001.[7]

The journey from that seminal "D-Day" for implantable pacemakers to the present has been characterized by remarkable advancements in the field of heart stimulation and the application of Cardiac Implantable Electronic Devices (CIEDs). These devices have transcended their initial purpose of regulating slow cardiac rhythms, evolving into versatile tools capable of addressing a spectrum of cardiac anomalies, including rapid rhythms and chronic heart failure.

To fully appreciate the scope and impact of these developments in CIEDs, it is essential to first understand the underlying anatomy of the heart and its natural conduction system. The ensuing discussion will delve into these foundational aspects, setting the stage for a comprehensive exploration of the evolution of cardiac pacing technologies.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

1.1 Anatomy and Physiology of the Heart

The heart is a muscle which is pumping blood throughout the body. This vital function facilitates the delivery of oxygen and nutrients to various tissues, as well as the removal of carbon dioxide and other waste products. Pumping blood out of the heart is done through blood vessels, which fall into three categories: arteries - transporting blood from the heart to the body; veins - sending back blood to the heart; capillaries - which are connecting arteries and veins, and oxygen and other nutrients are exchanged within the tissue.

As a muscle, heart consists of four chambers: right atrium, left atrium, right ventricle, and left ventricle. They are all separated from each other by a valve, which is preventing the back flow of the blood.

Anatomically, the heart is comprised of four distinct chambers: the right atrium, left atrium, right ventricle, and left ventricle. These chambers are integral to the heart's function, each playing a specific role in the cardiac cycle. The separation of these chambers by valves is crucial; these valves ensure the unidirectional flow of blood through the heart, preventing any backward movement. The orchestration of the heart's structural components and their synchronized function underpins the continuous, efficient circulation of blood, vital for sustaining life and ensuring the health of the organism.

- the right heart (right atrium and right ventricle) receives deoxygenated blood from the body and then pumping deoxygenated blood to the lungs where blood gets oxygenated - this is known as pulmonary circulation

- the left heart (left atrium and left ventricle) receives oxygenated blood from the lungs and pumps it out to the body - this is known as systemic circulation

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

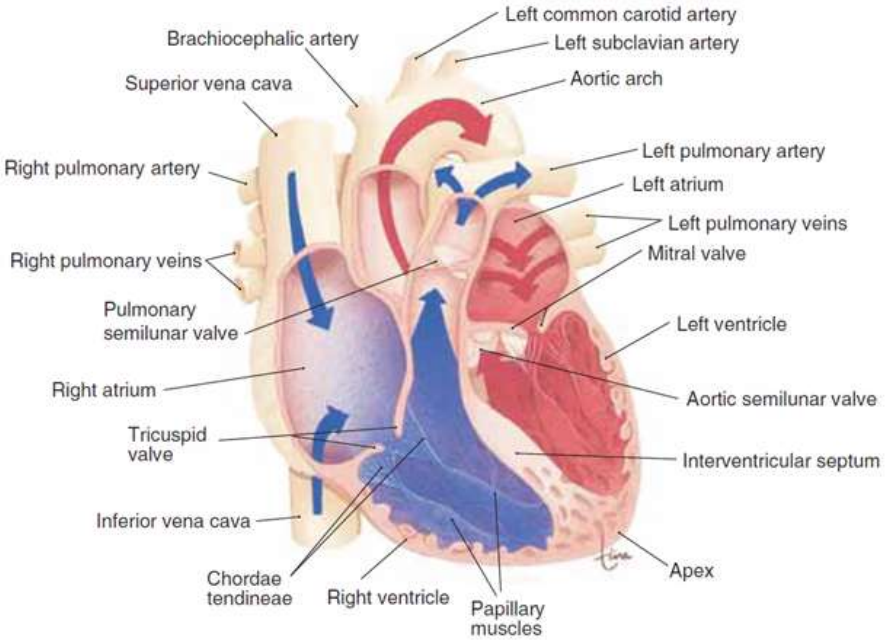

FIGURE 1.1: Frontal section of the heart in anterior view, showing internal structures [17]

The blood flow and other structures of the heart are shown in the figure 1.1. As seen the in the figure, the right heart shows the flow of blue blood which means deoxygenated, meanwhile the left heart shows the flow of red blood which is oxygenated.[5]

1.2 Conduction system of the Heart

The "pump effect" of the heart would not be possible without the triggering mechanism which is making the muscles contract. This mechanism is known as "The Cardiac Conduction System". The Cardiac Conduction System refers to the regulated transmission of electrical impulses through a network of cardiac muscle cells, which make the atria and ventricles contract.

The Cardiac Conduction System starts in the sinoatrial node (SA node), which is located on the "roof" of the right atrium at the junction of superior vena cava, the right atrial appendage, and the culcus terminalis. It is described to be around 1 mm below the epicardium, 10-20 mm long and up to

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

5 mm thick. The sinoatrial node is considered the natural pacemaker of the heart, which is responsible for generating the normal cardiac rhythm. [10]

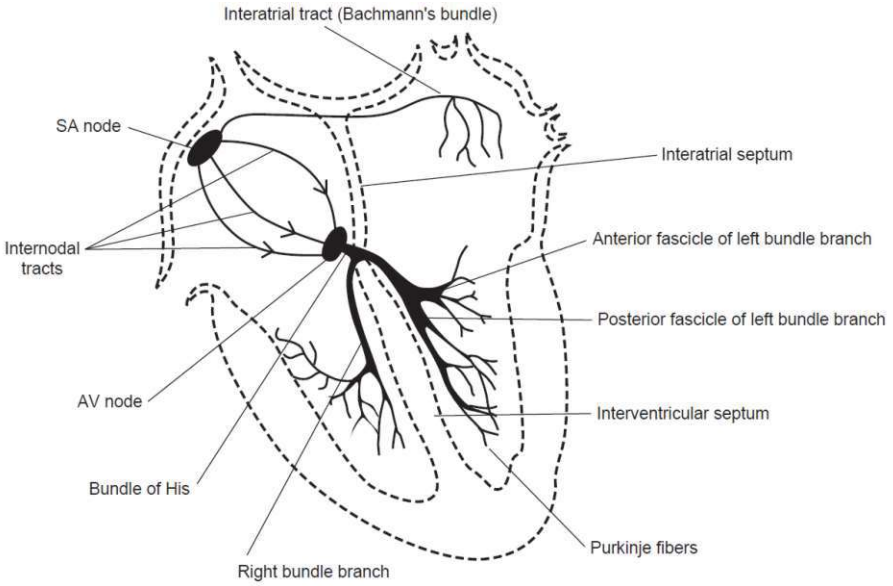

FIGURE 1.2: Electrical conduction system of the heart. [9]

Once the sinoatrial node fires, the signal is spread throughout the atria, making both left and right atria to contract. Toward the end of atrial depolarization the electrical signal reaches the atrioventricular node (AV node) which is the point between atria and ventricles. When the signal reaches the atrioventricular node, it gets excited and then the impulses are conducted to the His Bundle (known also as common bundle). After His bundle is excited, the wave propagates towards the ventricles through the right bundle branch and left bundle branch, where both right and left ventricles are depolarized. The impulse continues toward the last part of the conduction system, which are the Purkinje fibers and ventricular myocardial depolarization spreads. [10]

The above described cycle represents one complete heart beat, following the normal conduction system. The visual conduction system can be seen in figure 1.2. It is worth mentioning that each node/part of the conduction

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

system has it's own pacemaker rate. The sinoatrial node (the natural pacemaker) leads with pacemaker rate of 60 to 100 beats per minute under normal physiologic conditions. In case of sinoatrial failure, the other structures follow with lower pacemaker rate which is critical for patient survival as it maintains some degree of cardiac output.[10]

1. Sinoatrial node: 60-100 beats/min
2. Atrioventricular node: 40-55 beats/min
3. Bundle of His: 25-40 beats/min
4. Bundle branches: 25-40 beats/min
5. Purkinje fibers: 25-40 beats/min

The lower-rate rhythms are usually known as **ventricular escape rhythms**.

The recording of this electrical activity of the heart can be presented by a simple machine capable of recording electrocardiograms (ECG). This will be presented by three different waveforms described by the letters PQRST: the P-wave, the QRS complex, and the T-wave. Although the letters do not have any correlation or meaning, each of them refer specific activity of the heart or create a specific interval between each other. A basic example of an ECG is shown in the figure 1.3.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

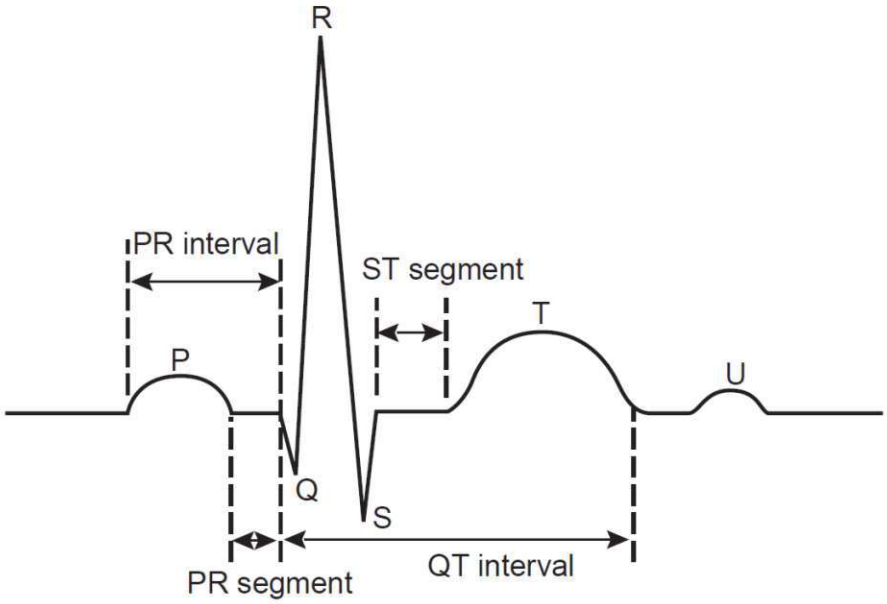

FIGURE 1.3: Relationship of the electrical conduction system to the ECG.. [9]

The **P-wave** in the figure represents atrial depolarization, where the sinoatrial node fires up and the signal is spread throughout the atria. The **QRS complex** represents the ventricular depolarization, where the signal is conduction from His bundle towards the ventricles. Last but not least, it's the **T-wave** which is the final step of one heart beat and represents ventricular repolarization. In some rare cases, **U-wave** is also present, which represents late ventricular repolarization.[9]

The waveforms mentioned are creating the segments and intervals which have specific meaning:

- the **PR interval**: the time from the beginning of atrial depolarization till the beginning of ventricular depolarization
- the **PR segment**: the time between the end of P-wave to the beginning of QRS complex
- the **ST segment**: it's a segment between the S and T wave, which shows potential elevation or depression of the ST segment

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

– the **QT interval**: the interval of full ventricular activity, starting from depolarization o the end of repolarization

It's worth clarifying that atrioventricular node is more complicated that only a node which is separating the atria from the ventricle. More over, the AV node has three main functions: [9]

– It delays the electrical impulse which is coming from the atrium in order to allow more time for the atria to "kick-out" blood and fill up the ventricles. This is know as the PR interval, described above.

– In case of sinoatrial node failure, the atrioventricular node serves as back-up pacemaker providing 40 to 60 beats per minute

– It serves as a safety mechanism which block fast impulses from being conducted to the ventricles if the sinoatrial rate or atrial rate is rapid

The rhythm which is following the Cardiac Conduction System is also known as Normal Sinus Rhythm (NSR).

1.3 Heart Arrhythmia

Any rhythm that it's not following the Cardiac Conduction System it's considered an arrhythmia. Arrhythmia is a very general term, which is including all rhythms other than the normal sinus rhythm. Arrhythmia are caused by any electrical abnormality of disruption of the signal. [9]

Arrhythmias are different, they could be: life threatening or non-life threatening; in the sinoatrial node, atria, AV node, or ventricles.

Sinus arrhythmias can be grouped into:

– **Sinus bradycardia**: A rhythm where the sinoatrial node fires at a lower rate compared to its normal rate. This rate it's between 40-60 beats per minute. It's a normal response of the heart the body is at rest or

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

sleeping. The conduction it's the same as in normal sinus rhythm, we have one atrial contraction followed by one ventricular contraction.

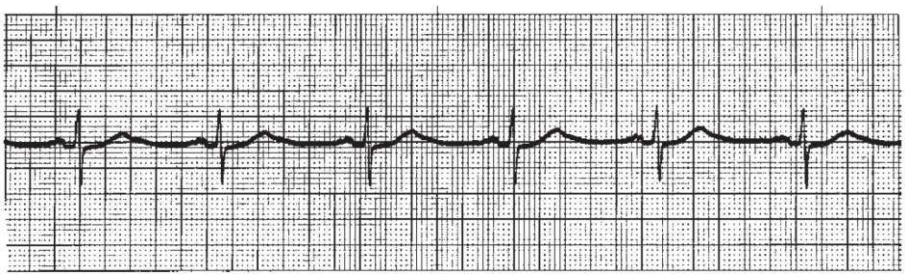

FIGURE 1.4: ECG example of Sinus Bradycardia - 54 beats/minute and regular rhythm.[9]

– **Sinus tachycardia:** A rhythm where the sinoatrial node fires at a higher rate compared to its normal rate. This rate it's between 100-160 beats per minute. It's a normal response of the heart when there's an increase in blood flow in the body. The conduction it's the same as in normal sinus rhythm, we have one atrial contraction followed by one ventricular contraction.

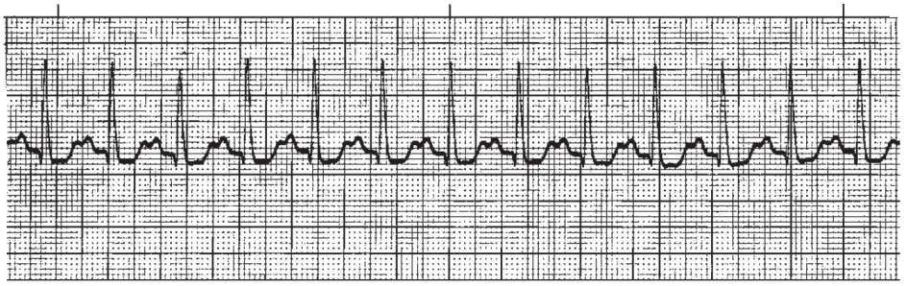

FIGURE 1.5: ECG example of Sinus Tachycardia - 115 beats/minute and regular rhythm.[9]

– **Sinus arrhythmia**: A rhythm that fires in the sinoatrial node but irregularly. It's considered normal and should not be treated. The conduction it's the same as in normal sinus rhythm, we have one atrial contraction followed by one ventricular contraction.

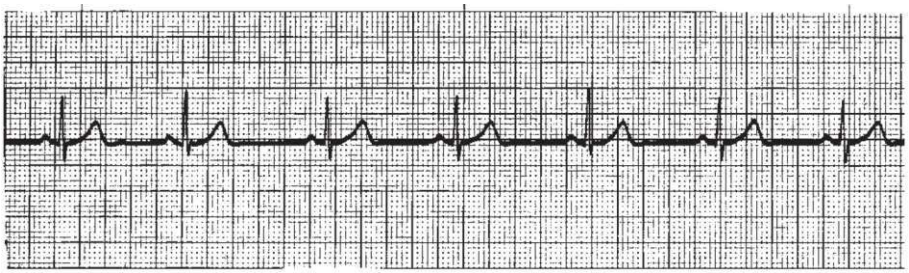

FIGURE 1.6: ECG example of Sinus Arrhythmia - 60 beats/minute and irregular rhythm.[9]

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

– **Sinus arrest**: A rhythm where the sinoatrial node fails to fire suddenly. It has a regular R-R interval and it resumes on time after pause.

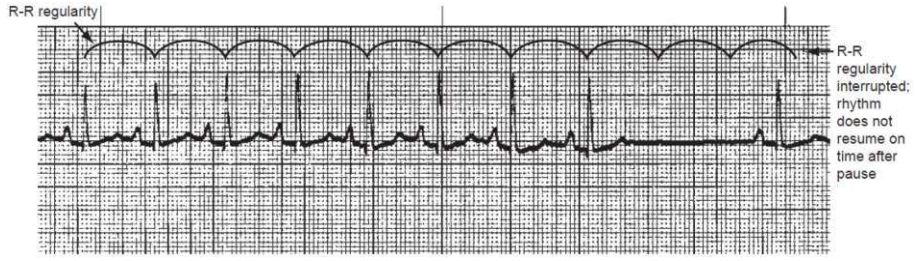

FIGURE 1.7: ECG example of Sinus Arrest - 94 beats/minute and irregular rhythm only during sinus arrest.[9]

– **Sinus block**: A rhythm where the sinoatrial node fails to fire suddenly. It has a regular R-R interval, but compared to sinus arrest it does not resume on time after pause.

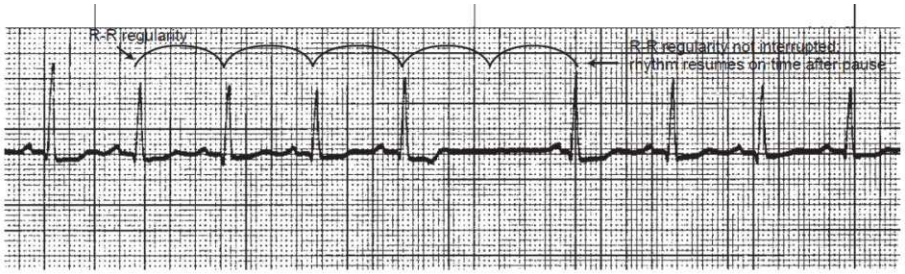

FIGURE 1.8: ECG example of Sinus Arrhythmia - 84 beats/minute and irregular rhythm only during sinus arrest.[9]

Sinoatrial arrhythmias do not belong to the life-threatening arrhythmias, however it could be a sign for underlying heart or lung disease. Similar to sinoatrial arrhythmias, atrial arrhythmias fall into non-life threatening arrhythmias. They could be grouped into three main arrhythmias:

– **Atrial tachycardia**: A point in the atria that is producing a fast rhythm - between 140 to 250 beats per minute. Usually it's regular, it has one atrial contraction followed by one ventricular contraction unless there is no atrioventricular block. Compared to the sinus tachycardia, in atrial tachycardia P-wave is not seen in the ECG since it's hidden in the QRS complex.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

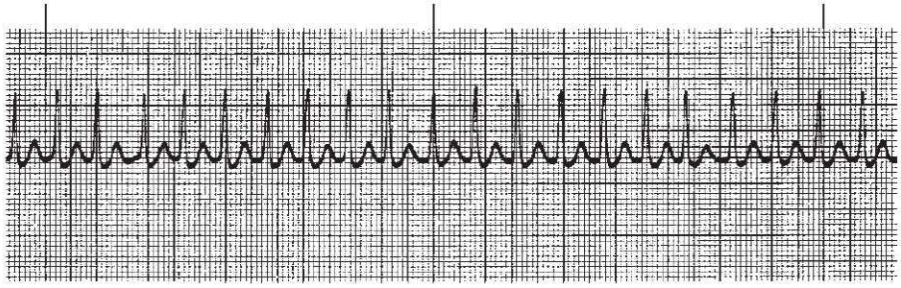

FIGURE 1.9: ECG example of Atrial Arrhythmia - 188 beats/minute and regular rhythm with hidden P-waves.[9]

– **Atrial flutter**: A more advanced atrial tachycardia, where the atria is working at a rate of 250 to 400 beats per minute. In the ECG, atria is producing sawtooth waveforms which are known as flutter waves. In this case atrio-ventricular synchrony is lost, meaning that atria could fire more than one time compared to the ventricles. It could be 2:1, 3:1, 4:1, or if it's irregular different pattern - the first number showing atrial contraction to ventricular response.

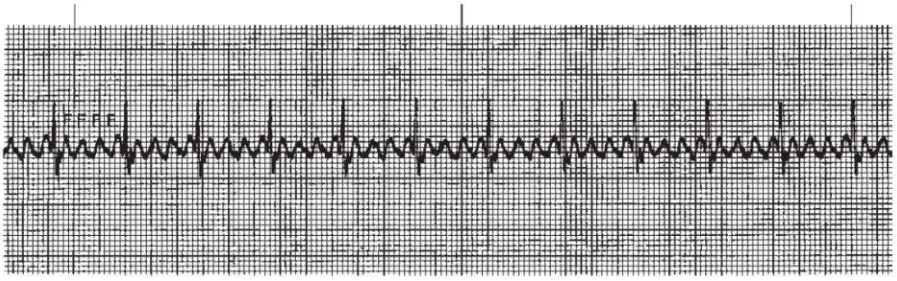

FIGURE 1.10: ECG example of Atrial Flutter - Atrial rate of 428 beats/minute and ventricular rate of 107 beats/minute - 4:1 AV conduction.[9]

– **Atrial fibrillation**: Known as one of the most complicated rhythm to be managed, atrial fibrillation it's a highly irregular and fast rhythm where the impulses in the atria are chaotic with a rate faster than 400 beats per minute. The ventricular rate in atrial fibrillation is highly variable, depending on the signals which manage to pass the atrioventricular node and pass to ventricles. There are cases where there's a fast conduction to the ventricles and the ventricular response is fast; and cases where the conduction to the ventricle is slow and the ventricular rate is low.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

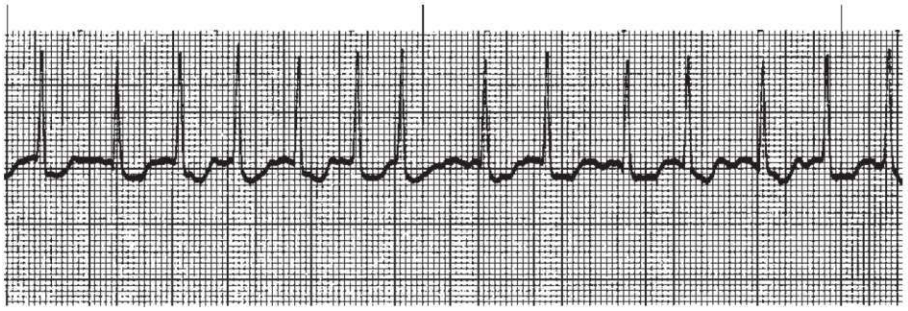

FIGURE 1.11: ECG example of Atrial Fibrillation - Irregular rhythm with ventricular rate of 130 beats/minute.[9]

All arrhythmias generating in the atria need treatment, but they are not life threatening. The first next point after tha atria contract is the atrioventricular node. As described above, the AV node has an important role in the conduction system. The known "heart block" term is indeed related to the AV node, which describes a delay of the signal or a failure of the signal to pass through the AV node. This delay or failure of the signal to pass the AV node, could be potentially a serious condition depending on the ventricular escape rate and patient response to that rate. The clinical effect of the AV block depends on the grade of AV block, which could be:

– **First-degree AV Block**: In this degree of block, the impulse from the atria is conducted to the AV node, but it takes longer to arrive in the ventricles. This makes the PR-interval prolonged (>200 ms), typically in range of 280 to 320 ms. AV Block may produce no symptoms and most of the time it does not require treatment, but it may progress to the higher degrees.

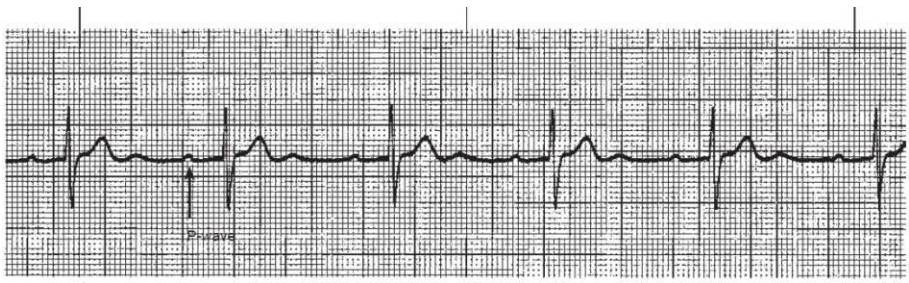

FIGURE 1.12: ECG example of first-degree AV Block - Regular rhythm with ventricular rate of 48 beats/minute.[9]

– **Second-degree AV Block Type I - Mobitz I or Wenckebach**: In this rhythm, the electrical impulse coming from atria is passing through AV

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

node with increased difficulty - which means increased PR-interval after each atrial kick - until one of the impulses do not pass and a pause follows the rhythm. Most of the times it's considered to be temporary as rhythm and patient may not feel it because of stable cardiac output. In case of symptoms, it should be treated with drugs or heart stimulation (pacing).

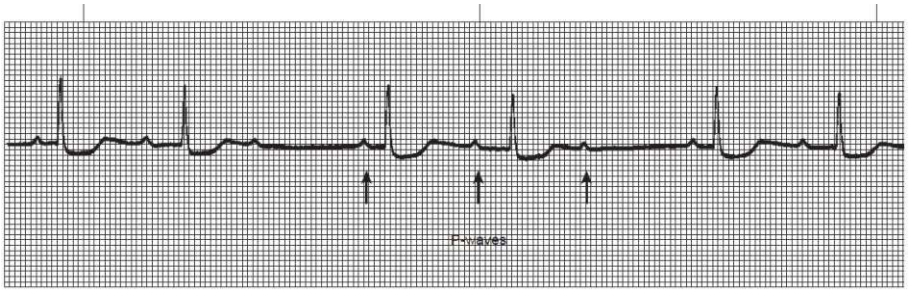

FIGURE 1.13: ECG example of second-degree AV Block Type I - Regular atrial rhythm of 72 beats/minute with irregular ventricular rate of 50 beats/minute.[9]

– **Second-degree AV Block Type II - Mobitz II**: In this type of block, some of the impulses coming from the atria pass through the AV node, and the rest do not. This means that in the ECG, we will have more than one (depending if it's 2:1, 3:1, or 4:1 block) P-wave before QRS. In terms of clinical status of the patient, it depends on the ventricular rate: if the ventricular rate is within normal range, patient will be asymptomatic, but in case it's too low, then symptoms will be present due to reduced cardiac output. Heart stimulation is one of the solution if drugs do not work.

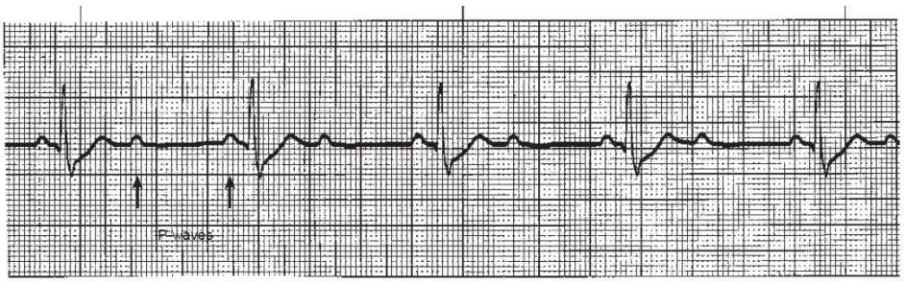

FIGURE 1.14: ECG example of second-degree AV Block Type II - Regular atrial rhythm of 82 beats/minute with regular ventricular rate of 41 beats/minute.[9]

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

– **Third-degree AV Block - Complete Heart Block**: In this rhythm, the upper and lower part of the heart - atria and ventricles - work independently from each other. In this case, all impulses generated in the atria are not conducted to the ventricles. In this case, the ventricular rate will be depended on the rate produced by the AV Junction (40 to 60 beats per minute) or ventricular escape rate which ranges from 30 to 40 beats per minute. When this block occurs, the ventricular rate usually is very low and symptoms are there. It's one of the most typical cases where the permanent heart stimulation (pacemaker) is needed.

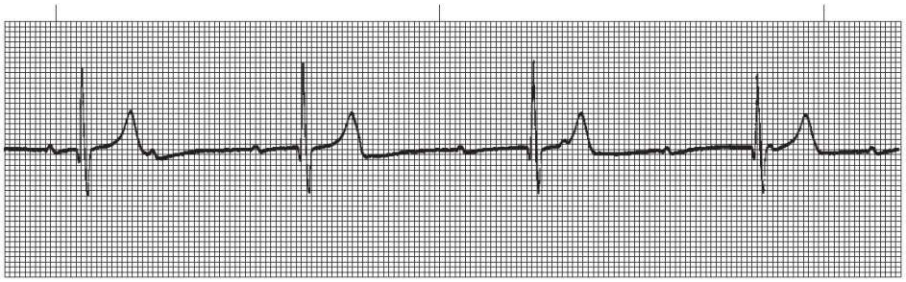

FIGURE 1.15: ECG example of third-degree AV Block - Regular atrial rhythm of 75 beats/minute with regular ventricular rate of 33-34 beats/minute.[9]

The types of arrhythmias mentioned above, are generated in the upper part of the heart and are known as supraventricular arrhythmias. Last but not least, are the ventricular arrhythmias and bundle-branch block, which are generating in the ventricles. Ventricles effect on cardiac output is huge, and for this reason all ventricular arrhythmias can be life-threatening and need treatment immediately. The most dangerous ventricular arrhythmias could be grouped into ventricular tachycardia, ventricular fibrillation, and ventricular asystole or standstill.

– **Ventricular tachycardia (VT)**: A very fast arrhythmia generating in the ventricles with a rate of 140 to 250 beats per minute. It is characterized by wide QRS complex in the ECG, with missing P-waves due to large amplitude of QRS wave. When lasting less than 30 second, it is called

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

non-sustained VT (NS-VT); meanwhile VTs lasting more than 30 seconds are considered sustained VT, which are considered life threatening arrhythmia due to reduced cardiac output and rhythm may escalate to ventricular fibrillation or asystole.

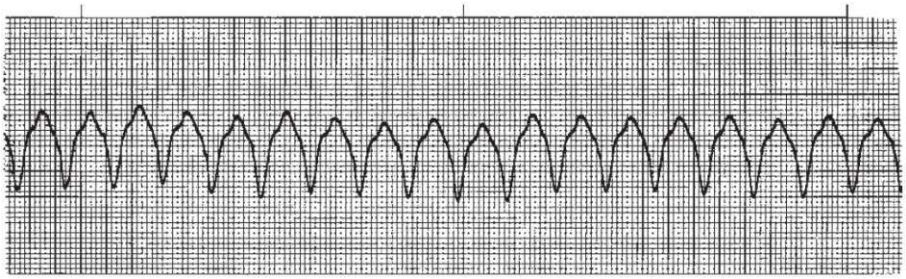

FIGURE 1.16: ECG example of Ventricular tachycardia - Regular rhythm with ventricular rate of 150 beats/minute.[9]

– **Ventricular fibrillation (VF)**: VF is known as most chaotic rhythm, where there's no QRS complexes but only chaotic signals coming from the muscle of the heart. During VF, regular ventricular depolarization and contraction are missing. It's the most common cause of cardiac death and treatment should be done within seconds, as the there's no cardiac output during VF. Cardiopulmonary reanimation and electroshock are the main treatments for this type of arrhythmia.

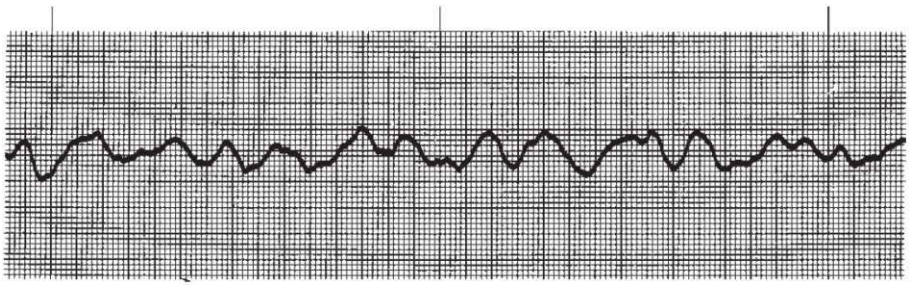

FIGURE 1.17: ECG example of Ventricular fibrillation - Chaotic rhythm with no QRS complex - rate of 0 beats/minute.[9]

– **Ventricular asystole**: Asystole is the "rhythm" where there's no electrical activity in the ventricles, however the atria could produce P-waves. It's the most dangerous rhythm due to the fact that there's no cardiac output and patient becomes unconscious immediately. Treatment should be given immediately to avoid death.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

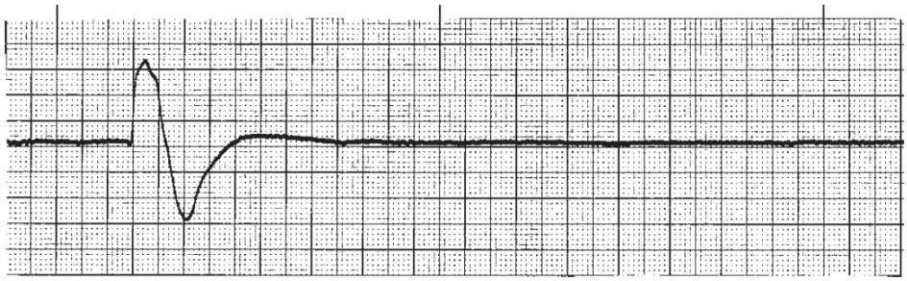

FIGURE 1.18: ECG example of Ventricular Asystole - One very wide QRS Complex followed by ventricular asystole.[9]

A certain issue which is affecting the normal sinus rhythm in a certain way is bundle-branch block. Bundle-branch block may happen in the right- or left bundle-branch. When it happens in one of the branches, the impulse passing through it is making one ventricle contract first (right ventricle in case of left bundle-branch block, or left ventricle in case of right-bundle branch block) and then the same impulse passes through the interventricular septum and depolarizes the other ventricle. This is causing a delay in the signal, taking longer time for the ventricles to contract and thus resulting in wider QRS Complex (more than 120 ms). Bundle branch-block may loose V-V synchrony, which leads to reduced ejection fraction. When the block is affecting the QRS complex duration significantly, treatment may be required.

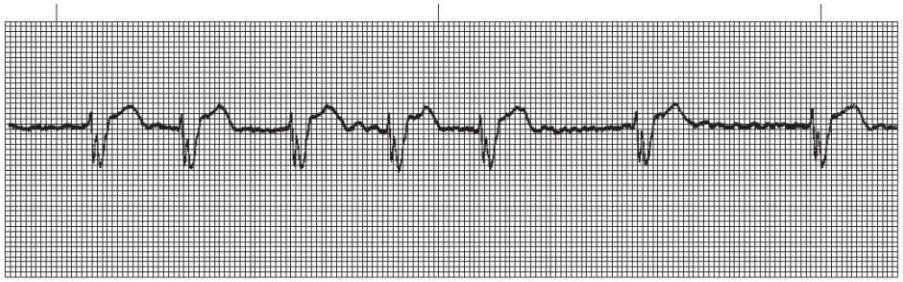

FIGURE 1.19: ECG example of Bundle-Branch Block - Atrial fibrillation with bundle-branch block (QRS Complex from 140 to 160 ms).[9]

1.4 Artificial Heart Stimulation

In addition to the underlying rhythm of the heart, the heart can be stimulated by an artificial electrical stimulus. This artificial stimulation of the heart is done to manage cardiac arrhythmias and conduction failures, described in the chapter above.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

This artificial heart stimulation - also known as pacing - is done using a device known as pacemaker and a cardiac pacing lead, which is implanted in the cardiac muscle. A full circuit consists of patient (body tissue or heart muscle), pacemaker, and electrode.

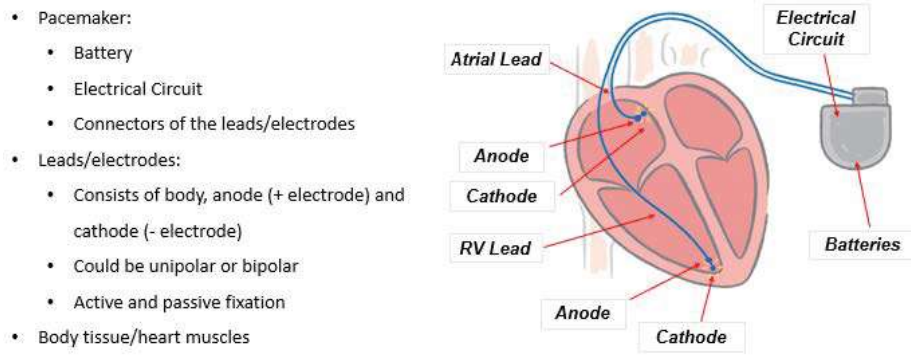

FIGURE 1.20: Pacemaker: Circuit and components

Pacing can be done using two types of electrodes: bipolar electrode, where the cathode and anode are included in the lead; and unipolar mode, where the cathode is located on the lead and the anode is the housing part of the pacemaker, which is in contact with tissue.

The goal of heart stimulation is to treat the abnormal rhythm, which affect patient quality of life and cardiac output. Concluding from the chapter above, we have seen that most life-threatening arrhythmias are coming from the lower part of the heart - ventricles. It's interesting that both extremes of rhythms - very slow and very fast rhythms - fall in life-threatening arrhythmias. However, treatment of these extremes rhythms is completely different. Since in this thesis I've tested different methods on treating ventricular slow rhythms - bradycardia related, treatment of fast arrhythmias won't be discussed.

The typical indications for heart stimulation include, but are not limited to:[16]

- Symptomatic bradycardia from sinus node disease
- Symptomatic bradycardia from atrioventricular node disease

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

- Hypertrophic obstructive cardiomyopathy
- Dilated cardiomyopathy
- During AV node ablation
- Cardiac resynchronization therapy with biventricular pacing
- Advanced 2nd or third-degree heart block
- Recurrent syncope

Implanting a pacemaker sometimes it's an easy decision, as the underlying rhythm of the patient dictates is. However, sometime it may be a very complex decision to be made. The indications for pacing are classified into 5 classes, as explained in the book **Handbook of Cardiac Anatomy, Physiology, and Devices**:[10, p. 550]

- Class I: Benefit »» Risk. Procedure/treatment should be performed/administered.
- Class II: Conditions for which there is conflicting evidence and/or a divergence of opinion about the usefulness/efficacy of a procedure or treatment.
- Class IIa: Benefit » Risk. Additional studies with focused objectives needed. It is reasonable to perform procedure/administer treatment.
- Class IIb: Benefit $\geq$ Risk. Additional studies with broad objectives needed; additional registry data would be helpful. Procedure/treatment may be considered.
- Class III: Classified as "No benefit" (Procedure/test is not helpful with no proven treatment benefit) or "Harm" (Procedure/test is associated with excessive cost without benefit or is harmful and the treatment is harmful to the patient).

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Kenneth A. Ellenbogen and Karoly Kaszala in their book **Cardiac Pacing and ICDs**, have classified indications for pacing in case of AV Block in the following classes: [6, p. 150]

- Class I indication:
  1. Third-degree and advanced second-degree AV block at any anatomical level, associated with any one of the following conditions: Bradycardia with symptoms (including heart failure) presumed to be due to AV block; Arrhythmias and other medical conditions requiring drugs that result in symptomatic bradycardia; Documented periods of asystole of 3.0 s or longer, any escape rate of less than 40 bpm or with any escape rhythm below the AV node in awake, symptom-free patients; Atrial fibrillation and bradycardia with one or more pauses of at least 5 s or longer in awake, symptom-free patients; Following catheter ablation of the AV node; Postoperative AV block that is not expected to resolve after cardiac surgery; etc.
  2. Second-degree AV block regardless of type or site of block, with associated symptomatic bradycardia.
  3. Third-degree AV block with evidence for cardiomegaly or LV dysfunction.

- Class IIa indication:
  1. Persistent third-degree AV block with an escape rate of greater than 40 bpm in asymptomatic adult patients without cardiomegaly.
  2. Asymptomatic type II second-degree AV block at intra-His or infra-His levels found at electrophysiological study.
  3. First- or second-degree AV block with symptoms similar to those of pacemaker syndrome or hemodynamic compromise.
  4. Asymptomatic type II second-degree AV block with narrow QRS. Note that when type II second-degree AV block occurs with wide

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

QRS, including isolated right bundle branch block (RBBB), pacing becomes a class I indication.

– Class IIb indication:

1. Neuromuscular diseases such as myotonic muscular dystrophy, Kearns–Sayre syndrome, Erb muscular dystrophy, and peroneal muscular atrophy with any degree of AV block (including first-degree AV block), with or without symptoms, because there may be unpredictable progression of AV conduction disease.
2. AV block in the setting of drug use and/or toxicity when the block is expected to recur even after the drug is withdrawn.

– Class III (not indicated):

1. Asymptomatic first-degree AV block.
2. Asymptomatic type I second-degree AV block at the AV nodal level or not known to be intra- or infra-Hisian.
3. AV block expected to resolve and/or unlikely to recur (e.g. drug toxicity, Lyme disease, or transient increases in vagal tone or during hypoxia in sleep apnea syndrome in the absence of symptoms).

Besides pacing being used in life threatening arrhythmias, it can be used also to improve patient quality of life and functional status in patients with heart failure. Heart failure (HF) - as a new term in this thesis - it a condition where heart is incapable of pumping enough blood to fulfill the body's need. Heart failure can be described by pump dysfunction, reduced functional capacity, myocardial remodeling, etc. The way to treat heart failure with pacing is Cardiac Resynchronization Therapy (CRT), which is achieved by restoring coordinated contractions between right ventricle and left ventricle.[10, p. 577-592] Similar classification as for AV block is described in the book **Cardiac Pacing and ICDs**: [6, p. 20-21]

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- Class I indication:
  1. Class I indications for sinus node dysfunction or AV block as previously described.
  2. CRT pacing in patients with an LV ejection fraction (LVEF) of 35% or less, sinus rhythm, LBBB, and QRS duration of 150 ms or longer, and NYHA class II, III, or ambulatory IV symptoms on guideline directed medical therapy (GDMT). Most of these patients will qualify for ICD therapy. The choice between a biventricular pacemaker and a biventricular ICD should be made based upon the patient's preference and other clinical factors.
  3. Third-degree AV block with evidence for cardiomegaly or LV dysfunction.

- Class IIa indication:
  1. CRT pacing can be useful in patients with an **LVEF of 35% or less**, sinus rhythm, LBBB with a **QRS duration of 120–149 ms** and NYHA class II, III or ambulatory IV symptoms on GDMT.
  2. CRT can be useful in patients with a **LVEF of 35% or less**, sinus rhythm, non-LBBB pattern with a **QRS duration of 150 ms or longer**, and NYHA class III or ambulatory IV symptoms on GDMT.
  3. CRT can be useful in patients with atrial fibrillation and an **LVEF of 35% or less** on GDMT if: the patient requires ventricular pacing or otherwise meets CRT criteria; AV nodal ablation or pharmacological rate control will allow near 100% ventricular pacing with CRT.
  4. CRT can be useful in patients on GDMT who have an **LVEF of 35% or less** and are undergoing device placement or replacement with anticipated requirement for significant (>40%) ventricular pacing.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- Class IIb indication:
  1. CRT may be considered for patients who have an **LVEF of 35% or less**, ischemic etiology for heart failure, sinus rhythm, LBBB with a **QRS duration of 150 ms or longer**, and NYHA class 1 symptoms on GDMT.
  2. CRT maybe considered for patients who have an **LVEF of 35% or less**, sinus rhythm, non-LBBB pattern with a **QRS duration 120–149 ms**, and NYHA class III/ambulatory class IV symptoms on GDMT.
  3. CRT maybe considered for patients who have an **LVEF of 35% or less**, sinus rhythm, non-LBBB pattern with a **QRS duration of 150 ms or longer**, and NYHA class II symptoms on GDMT.
- Class III (not indicated):
  1. CRT pacing is not recommended for patients with NYHA class I or II symptoms and a non-LBBB pattern with a **QRS duration of less than 150 ms**.
  2. CRT is not indicated in patients whose functional status and life expectancy are limited predominantly by chronic non-cardiac conditions.

Similar classification are available also for other types of arrhythmias and needs for pacing, but since this thesis is oriented on pacing of the ventricle and its outcome, other classifications will not be included here.

Depending on type of arrhythmia, there are cases were you need pacing as much as possible, and there are cases where pacing is needed at certain moments - mainly during pauses. Different types of ventricular pacing will be discussed in the next chapter. As an example, the pacing percentage in cardiac resynchronization therapy should be as high as possible, and possible more than 90% to achieve good results. [10, p. 590]

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

The ideal pacemaker should maintain and optimize heart rate, atrioventricular (AV) synchrony, and ventricular activation to enable cardiac output to meet the metabolic needs of the patient, whether at rest or during exercise. In the current era, the goals of physiological pacing include maintaining heart rate, optimizing AV synchrony, minimizing right ventricular (RV) pacing to avoid ventricular desynchronization, using alternative RV pacing sites for improved hemodynamic performance, and selecting appropriate patients for cardiac resynchronization therapy (CRT). [6, p. 82]

1.4.1 Right Ventricle Pacing

Right ventricular pacing is one of the most important and effective pacing methods, especially for AV Block. Implantation of right ventricular lead is done through the inferior vena cava, then right atrium, and with a stylet with a specific curve (similar to J-shape), passes the tricuspid valve and enters the right ventricle. Afterwards, with a straight stylet, lead is advanced toward the apex of the heart, which the final position is required with proper parameter values. Depending on the preference of the implanter, RV pacing lead may be position in the septum. A special care it's needed in patient with LBBB or AV Block while crossing the tricuspid valve, since touching the right bundle branch may lead to asystole if no back-up temporary pacing is available in the patient.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

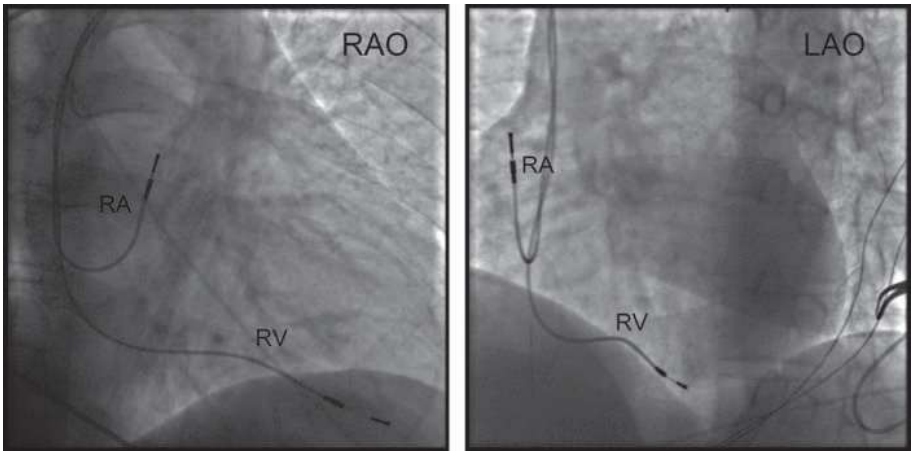

FIGURE 1.21: Right Anterior Oblique (RAO) and Left Anterior Oblique (LAO) views of right ventricular (RV) apical lead positions at the time of implantation. The ventricular lead is positioned with the tip at the RV apex, well beyond the spine shadow, as shown here. The slight downward position of the tip is desirable.[6, p. 168]

A typical ECG example of RV pacing is shown in the 12-lead ECG sample in the figure 1.22.

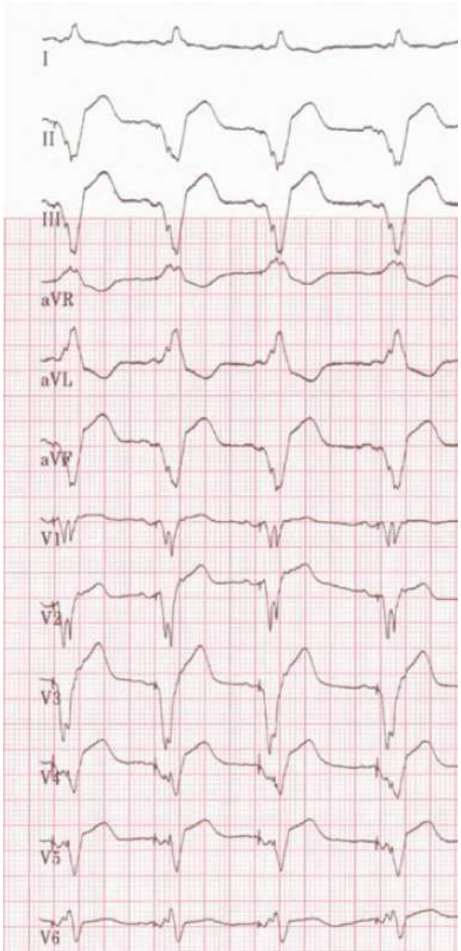

FIGURE 1.22: ECG QRS morphologies during right ventricular (RV).[6, p. 387]

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Besides "easy procedure" of implantation, complications could happen while implanting an RV pacing lead. They include pneumothorax, hemothorax, air embolism, arrhythmia, heart perforation by pacing lead, deep venous thrombosis, etc.[6, p. 180-191]

RV pacing can have detrimental effects on myocardial function and result in progression of heart failure, particularly in patients with pre-existing LV dysfunction, and also can result in a modest detrimental effect on LV function in patients who have normal systolic function. [6, p. 111]

1.4.2 Bi-Ventricular Pacing - CRT

Biventricular pacing - which is also known as Cardiac Resynchronization Therapy (CRT) - it's slightly more complicated method of pacing, compared to right ventricular pacing only. In biventricular pacing, besides the electrode in the right ventricle, a second electrode is implanted in the left side of the heart through the coronary sinus. The idea is to stimulate both ventricles at the same time, maintaining ventricular synchrony and maximizing cardiac output. The goal of biventricular pacing is to improve heart failure symptoms and restore ventricular synchronization. Compared to RV Pacing, as described above, indications for biventricular pacing are more complex. To achieve the best out of ventricular pacing, the QRS duration of a patient should be wider than 150 ms and with left-bundle branch block present. As previously mentioned, biventricular pacing percentage should be as high as possible. For this to be achieved, the intrinsic rhythm of the patient should be controlled. While the criteria for CRT is the QRS complex to be wider than 150 ms, once the CRT is implanted, the goal is to minimize this QRS complex. So, the goal of CRT is achieved by improving QRS complex, which is related to the improvement of heart-failure symptoms. This is the main advantage of CRT compared to RV Pacing, where due to the non-physiological spread

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

of the impulse, the QRS complex is wide.

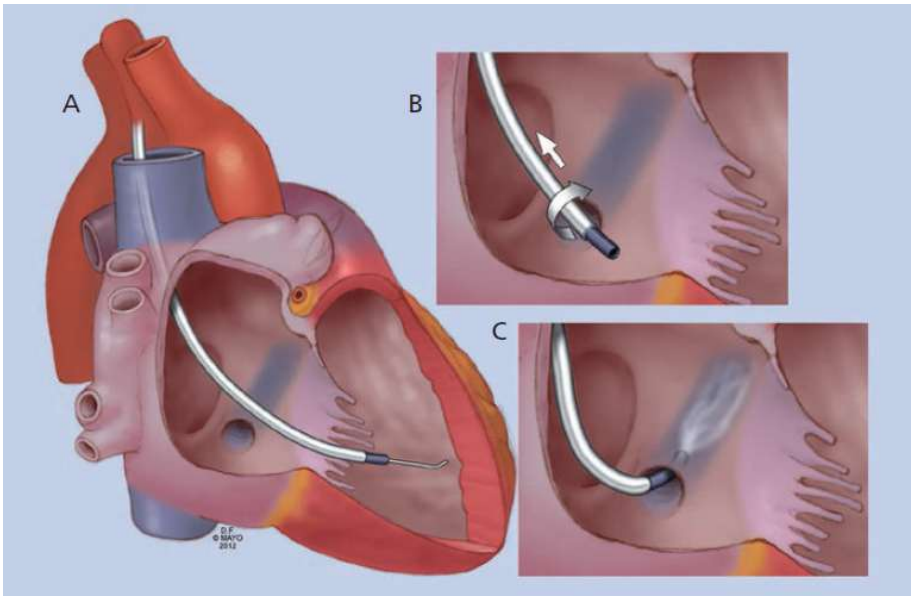

FIGURE 1.23: Engaging the coronary sinus using a long sheath and sub-selecting catheter. (A) The delivery set is first placed into the right ventricle over the wire. (B) The sheath and catheter are slowly pulled back with counter-clockwise rotation, and fall into the coronary sinus ostium. (C) Contract injection confirms the catheter is in the coronary sinus.[6, p. 379]

Compared to right ventricular pacing, implanting a CRT system it is a much more complicated procedure. In CRTs, a third lead is implanted, typically in a posterior or lateral branch of the coronary sinus venous system. The most commonly used method of CRT implantation is the transvenous approach, which utilizes a specially designed delivery system for cannulating the coronary sinus to permit delivery of pacing leads into the branches of the epicardial venous trees.[6, p. 376] Once the lead is placed in the final venous tree of the coronary sinus, the system will have a similar image using x-ray machine:

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

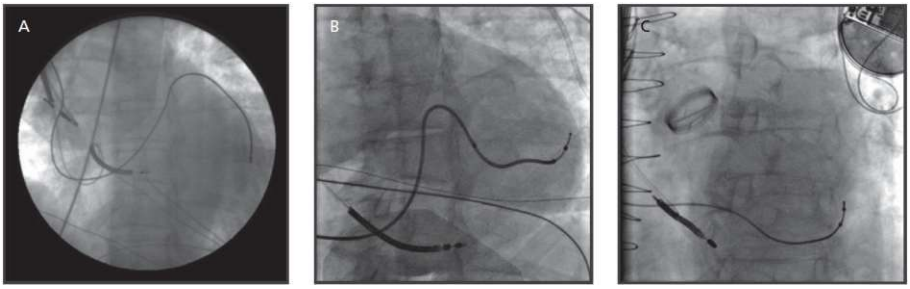

FIGURE 1.24: Fluoroscopy showing placement of the LV lead at the left ventricular lateral wall via (A) anterolateral, (B) lateral, and (C) middle cardiac veins in left anterior oblique review.[6, p. 378]

Due to a more complicated procedure of implantation, complications may happen. Complications include coronary sinus dissection (2–4%) and coronary venous perforation (2%), complications mainly related to coronary sinus venography. Coronary sinus perforation may lead to pericardial tamponade requiring urgent drainage. Extracardiac stimulation from the LV lead (diaphragm and phrenic nerve) may also be problematic and should be sought at the time of implantation. Its occurrence should prompt the search for another lead implant site. This problem may also first appear after implantation and can sometimes be corrected with reprogramming, although lead revision may be required. [6, p. 191]

Different studies has confirmed the improvement on left-ventricular ejection fraction (LVEF) after CRT in patient with heart failure symptoms. This is shown in the following 1.25, where the baseline LVEF is compared with LVEF after CRT therapy is delivered.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

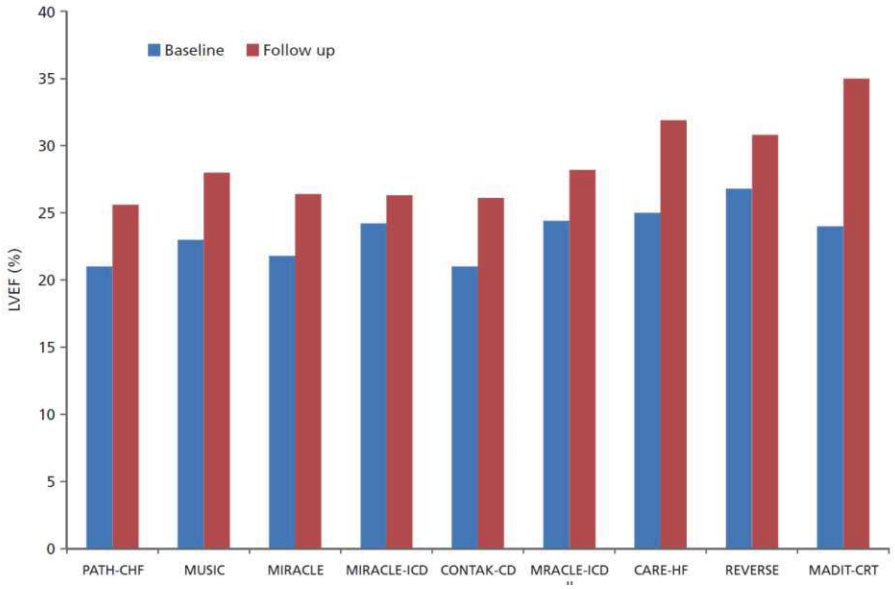

FIGURE 1.25: Change in left ventricular ejection fraction (LVEF) after cardiac resynchronization therapy (CRT) in heart failure patients with different New York Heart Association (NYHA) functional classes. In comparison to LVEF before CRT (blue bar), there was a statistically significant increase of LVEF in all studies after CRT (red bar).[6, p. 396]

1.4.3 Left Bundle Branch Area Pacing

Huang et al. reported a case where pacing of left bundle branch (LBB) was used to correct the impaired His-Purkinje condition system in a patient with heart failure and LBB block.

This case showed that pacing was achieve with a low output, and in 1-year follow-up, the patient had improved clinical outcome and electrocardiographic measurements.[8]

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

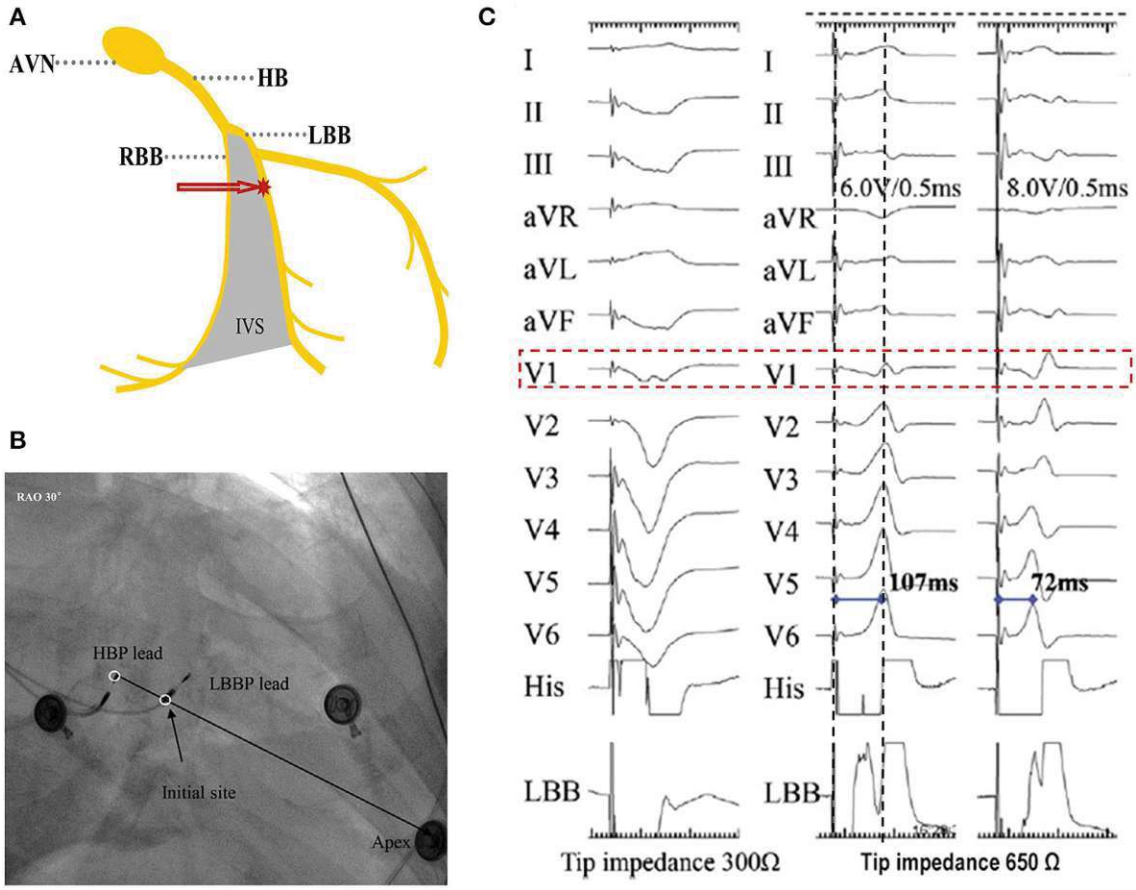

FIGURE 1.26: (A) A photographic representation of LBBP. (B) Location of the HBP lead and LBBP leads in the right anterior oblique 30 degree view. (C) Paced morphology of "W" pattern with a notch at the nadir of the QRS in lead V1 and impedance of 300 Ohms by unipolar tip pacing before fixation (left). Screwing the lead 6–8mm deep, the notch in lead V1 moved up and toward the end of the QRS with impedance of 650 Ohms. Increased output, from 6.0 V/0.5ms (middle) to 8.0 V/0.5ms (right), caused the paced morphology to change to RBBB and the pLVAT to be shortened from 107 to 72ms.[8, p. 4]

While RV Pacing proved to be an important therapy, the long-term side effects are yet to be suppressed. To overcome this, new methods of pacing are needed, and LBB Pacing proved to be one of them.

Implantation of LBBP is slightly more complicated compared to the conventional RV Pacing. It needs more signals from the patient like 12-lead ECG, and intracardiac EGMs - which are not necessary for RV and CRT. LBBP is defined as stimulation of LBB with a pacing lead, which is implanted into the inter-ventricular septum around 10-15 mm and it's located about 10-15

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

mm below the His Bundle region. LBB stimulation may be confirmed by paced QRS morphology, peak left ventricular activation time (pLVAT), LBB potential, retrograde His or anterograde distal LBB potentials, selective or non-selective LBB, etc.: [8, p. 3]

- **Paced QRS Morphology** shows the RBBB in V1 lead or improving the LBB conduction in patients with LBBB. This may not be a good predictor of LBB stimulation as RBBB pattern may not be seen if the pacing site is located in the superior septum or near the distal His bundle, or proximal left bundle.[8, p. 3-4]
- **peak Left Ventricular Activation Time (pLVAT)** - which is the interval between the onside of the pacing spike to the peak of R-wave in the lead V5-6 - it's an indicator of the rapidity of LV free-wall activation used to identify the depth of pacing lead and stimulation of LBB. When the LBB is stimulated, pLVAT is short (lower than 80 ms) and stable with different pacing output; meanwhile an increased pLVAT from high (10 V) to low (2 V) output indicates that the lead is away from the LBB and the electrode should be advanced slowly. pLVAT could be a good indicated on LBB stimulation, however it can be also disturbed by intraventricular conduction defects and ischemic cardiomyopathy with scars.)[8, p. 4]
- **LBB Potential** is a sharp high-frequency deflection distance 15-30 ms to the onset of surface QRS. It confirms lead depth and level of conduction block. It can be recorded in patients without complete heart block of complete LBBB, however in some cases LBB potential can be recorded also in patients with LBBB.[8, p. 4]
- **Retrograde His and Anterograde Distal LBB Potentials** are signals which can be recorded during low-output LBBBP in patients without

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

conduction disease or using multi-polar catheter placed distal to the LBBB lead. [8, p.4-5]

- LBBP can be **Selective or Non-selective**. Selective LBBB refers to the stimulation of LBB as a direct LBB capture sign; while non-selective captures both LBB and the adjacent local septal myocardium. In selective LBB there's always an isoelectric interval between the pacing spike and the onset of surface QRS, while the non-selective LBB does not provide the same. Another difference between the two may be the pLVAT duration which is prolonged in non-selective LBBP when changing the output from high to low. However this is not a strong indicator, as Chen et al.[4] proved that pLVAT is constant at different pacing output.[8, p.5-6]

Implantation of LBB lead is similar to RV lead, with the difference that the lead should be implanted deep in the interventricular septum until LBB is reached. Once it is implanted the depth and stimulation of LBB is confirmed. To indicate the proper placement of the lead, ECG signal will show:

- "W" pattern in the V1 channel of the ECG with a notch at the nadir of QS complex. Note that 20% of patients may not have the "W" pattern in V1.
- Positive QRS in lead II
- Biphasic QRS in lead III

Possible complications of LBBBP could be septal perforation and thromboembolism, RBB caused by manipulation with the catheter and septal arterial injury, and last but not least is lead dislodgement which could be a serious issue in pacemaker dependent patients.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

1.5 Implantable devices

The critical part to achieve the above mentioned pacing are the devices itself, which are connected to the lead(s). A general division of devices is shown in the figure 1.27.

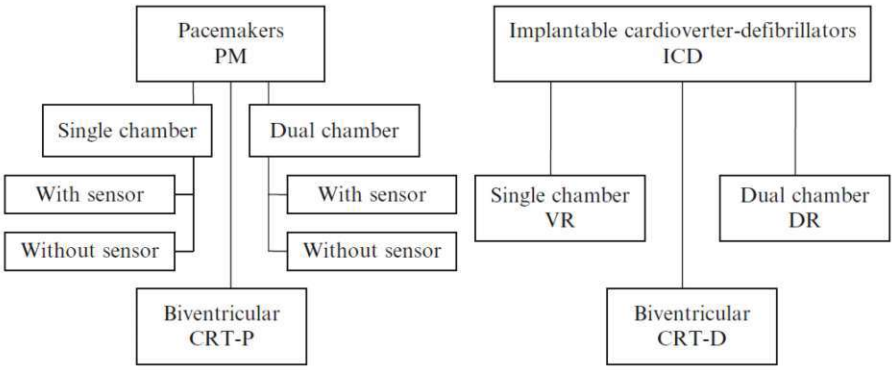

FIGURE 1.27: Division of implantable cardiac devices.[12, p. 8]

As clearly seen in the picture, devices can be divided into two groups: devices without defibrillator and devices with defibrillator. It's worth mentioning that the basic principles of both groups are the same, except that defibrillation function which is used to treat fast arrhythmias. Since this thesis it's only about pacing, defibrillation won't be discussed.

As seen in the figure 1.27, devices can be single chamber, dual chamber, and so-called "triple chamber" or biventricular.

Single chamber devices have only one lead, which can be used to pace right atrium or right ventricle. Single chamber with the electrode in the atrium may be used in patient with Sick Sinus Syndrome (SSS), but due to the risk of having SSS and AV Block, it is rarely seen. Almost all of the single chamber devices have the electrode implanted in the right ventricle. It is worth mentioning that single chamber devices do not maintain AV synchrony. They are usually used in patient with chronic AF and need for pacing in the ventricle, where the patient is not expected to return to the normal sinus rhythm. Single chamber devices when implanted in the ventricle, can be used to perform conventional RV pacing and LBB pacing.[15]

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

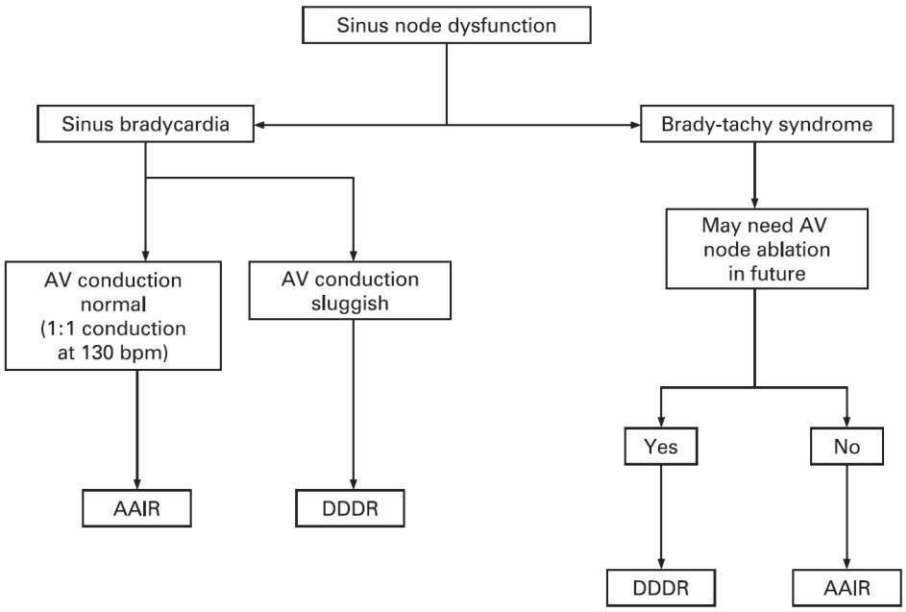

FIGURE 1.28: Selection of the pacemaker mode in sinus node dysfunction.[15, p. 3]

Dual Chamber devices have two lead, one of which is implanted in the right atrium and the other one is implanted in the right ventricle. They are used in patients with AV block and in patient with SSS. The advantage of dual chamber devices is that they provide AV synchrony, and you have information on both (upper and lower) part of the heart. However, having more leads it's not always a benefit, as having two leads may lead to higher chances of complications. Dual chamber devices have always one lead implanted in the right ventricle, and can be used to perform conventional RV pacing and LBB pacing.[15]

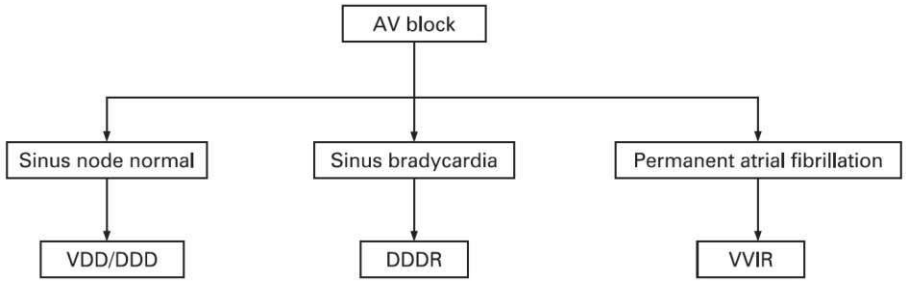

FIGURE 1.29: Selection of the pacemaker mode in atrioventricular (AV) block.[15, p. 4]

Biventricular Devices - also known as CRTs - are similar to dual-chamber devices, with an extra lead which is implanted in the left ventricle through

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

the coronary sinus. A CRT device consists of atrial lead, right ventricular lead, and left ventricle lead. It's a non-pharmacological method of treating heart failure. To be more precise, one of the symptoms of heart failure is the ventricular dyssynchrony, which reduces stroke volume. The CRT delivers pacing pulses to both ventricles (left and right) to make them contract at the same time and increase cardiac output. CRT can be used in devices with defibrillator and without defibrillator, depending on the indication for CRT. Biventricular devices have two leads implanted in the ventricles - one in the right ventricle and one in the left ventricle - and since it has more leads, can be used to provide conventional biventricular pacing (which is conventional RV pacing and LV pacing) or Biventricular pacing via left bundle branch pacing (right ventricular lead performing LBB, and left ventricular lead pacing the left ventricle).[12]

1.5.1 Pacing modes

Each device has many algorithms and programmable modes which are used to achieve the best of out it. The functionality of the device can be best described by North American Society of Pacing and Electrophysiology (NASPE)/British Pacing and Electrophysiology Group (BPEG) codes. The code contain of five characters, each one having it's meaning. This is described in the figure 1.30.

Position:	I	II	III	IV	V
Category:	**Chamber(s) Paced**	**Chamber(s) Sensed**	**Response to Sensing**	**Rate Modulation**	**Multisite Pacing**
	O = None **A** = Atrium **V** = Ventricle **D** = Dual (A + V)	**O** = None **A** = Atrium **V** = Ventricle **D** = Dual (A + V)	**O** = None **T** = Triggered **I** = Inhibited **D** = Dual (T + I)	**O** = None **R** = Rate modulation	**O** = None **A** = Atrium **V** = Ventricle **D** = Dual (A + V)
Manufacturers' designation only:	**S** = Single (A or V)	**S** = Single (A or V)			

FIGURE 1.30: The Revised NASPE-BPEG Generic Code for Antibradycardia Pacing.[2]

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Character I and II indicate the chambers which are being paced and sensed, which could be None (0), Atrium (A), Ventricle (V), or both - Dual (D). **Character III** indicates how the device respond to sensing of the device: None (0), Triggered (T), Inhibited (I), and Dual (D). **Character IV** describes the presence of adaptive-rate mechanism (R) or the absence of it (O). **Character V** describes the presence or not of Multi-site Pacing, which again could be None (O), Atrium (A), Ventricle (V), and Dual (D).

Common modes included in most of devices are VVI(R), AAI(R), SSI(R), V00(R), A00(R), and S00(R) - in single chamber devices; meanwhile dual chamber devices include DDD(R), DDI(R), D00, VDD, VVI, AAI, SSI(R), VOO, AOO, SOO, VVT, AAT, SST, ODO, OSO, and OOO. Bernstein et al. have explained some of the pacing mode and their use in their paper[2, p. 3]:

- **VOO, VOOO, or VOOOO:** Asynchronous ventricular pacing; no sensing, rate modulation, or multi-site pacing.
- **VVIRV:** Ventricular inhibitory pacing with rate modulation and multi-site ventricular pacing (i.e., biventricular pacing or more than one pacing site in one ventricle). This mode is often used in patients with heart failure, chronic AF, and intra-ventricular conduction delay.
- **AAI, AAIO, or AAIOO:** Atrial pacing inhibited by sensed spontaneous atrial depolarization; no rate modulation or multi site pacing.
- **DDD, DDDO, or DDDOO:** Dual chamber pacing (normally inhibited by atrial or ventricular sensing during the alert portion of the VA interval or by ventricular sensing during the alert portion of the AV interval, and with ventricular pacing triggered after a programmed PV interval by atrial sensing during the alert portion of the VA interval); no rate modulation or multi-site pacing.
- **DDI, DDIO, or DDIOO:** Dual chamber pacing without atrium synchronous ventricular pacing (atrial sensing merely cancels the pending

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

atrial output without affecting escape timing); no rate modulation or multi-site pacing.

– **DDDR or DDDRO:** Dual chamber, adaptive-rate pacing; no multi-site pacing.

The NBG Code is used to simplify and understand easily the functionality of device. The most commonly used pacing mode are VVI, VVIR, DDD, DDDR, DDI, and DDIR. A tree of decision for the mode of pacing needed, are simplified in the figure 1.31:

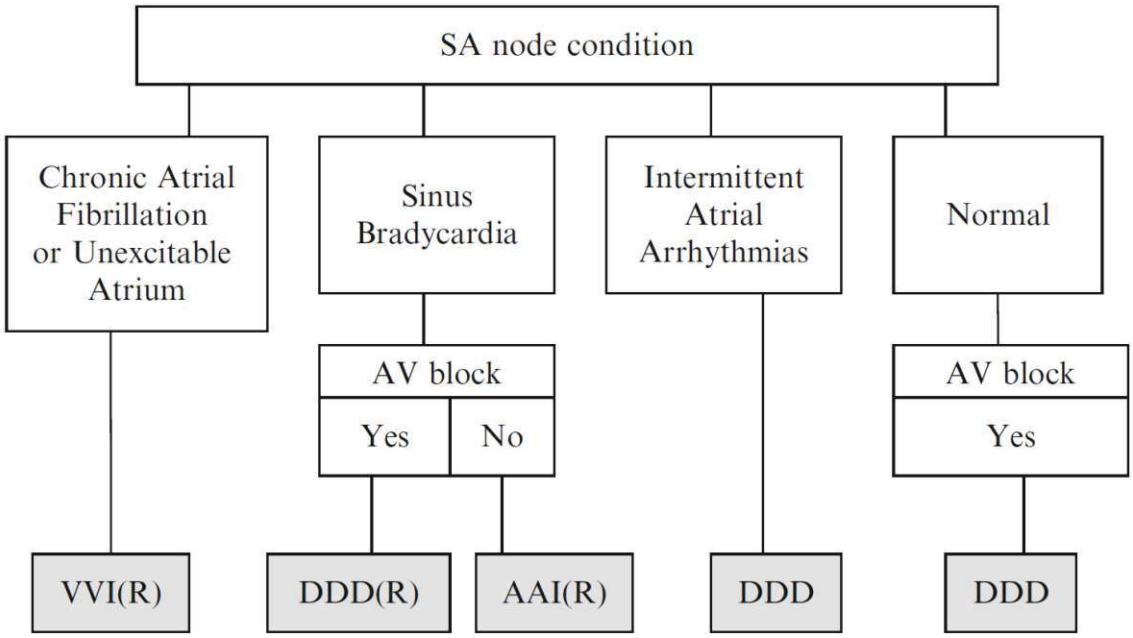

FIGURE 1.31: Reference pacing mode decision tree.[12, p. 28]

1.5.2 Pacing Concepts - Electrical Parameters

Once the device is connected with the lead, there are four parameters which determine "the good" positioning/implant of the lead. These parameters are threshold, sensing, and impedance.

The recommended value of these parameters, can be se in the figure 1.32:

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

	Implant	Chronic
Sensing amplitude		
Atrium	≥ 1 mV	≥ 1 mV
Ventricle	≥ 5 mV	≥ 5 mV
Impedance		
Pacing circuit	300–2,000 Ω	300–2,000 Ω
Shock circuit	20–80 Ω	20–80 Ω
Pacing threshold		
Voltage (at 0.5 ms)		
Atrium	≤ 1.0 V	≤ 1.5 V
Ventricle	≤ 1.0 V	≤ 1.5 V
Current (at 0.5 ms)		
Atrium	≤ 1.5 mA	≤ 6 mA
Ventricle	≤ 1.5 mA	≤ 6 mA
Slew rate		
Atrium	≥ 0.3 V/s (mV/ms)	≥ 0.3 V/s (mV/ms)
Ventricle	≥ 1.0 V/s	≥ 0.5 V/s
Retrograde conduction time	100–400 ms	

FIGURE 1.32: Recommended electrical performance.[12, p. 97]

1.5.2.1 Threshold

Threshold is the minimal electric value which is enough to produce cardiac depolarization. It is one of the most important parameters, which is crucial for making the heart contract. It is measured by decreasing a certain parameter (which could be voltage, current, or pulse width) while pacing the patient at a rate higher than its intrinsic rate. Since the electrode causes a inflammatory reaction when it touches the heart muscle, there's a chance of threshold to increase. For this reason, applying safety margins (2 times or more) is highly recommended. Threshold values depend on positioning of the electrode, heart muscle, and physiological changes over time. Threshold value is measured with Volts at certain pulse width. [6] [12]

1.5.2.2 Sensing and Sensitivity

Sensing defines what the device "sees" when electrode is implanted in the heart muscle. It's an essential parameter for normal operation of the device,

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

as it can inhibit device from pacing when intrinsic cardiac activity is happening; it will make the device "blind" during blanking and refractory period. The proper sensing is when the device "sees" activities that should be seen, like P-wave with atrial lead, QRS in RV lead, etc. It's critical to make sure that device does not sense activities which are real and senses activities which are real. This is termed as oversensing and undersensing. Both cases could lead to serious problems, in all devices (with and without defibrillator). Normal sensitivity values are shown in the figure 1.32.

The proper sensing is achieved by adjusting sensitivity value, which is defined as the lowest input signal waveform amplitude at which device response is induced. Sensitivity should be set to a proper level, so we do not miss any activity and also miss activities we do not want to see. Typical problems related to oversensing are far-field R waves, T-wave oversensing, external noise, myopotentials, external electromagnetic interference, etc. Meanwhile, undersensing may lead to redundant and asynchronous/competitive pacing, or pacing in the vulnerable phase, which could trigger fast arrhythmias like VF.[12]

1.5.2.3 Impedance

Impedance in the pacemaker is the total resistance across the lead conductor, the resistance to the current flow from the lead electrode to the myocardium, and the charge of opposite polarity in the myocardium that develops at the electrode-tissue interface in the context of stimulus delivery. Since devices use direct current (DC), Ohm's law (Voltage (V) = Current Flow (I) x Resistance across the circuit (R)) is applicable, which leads to the impedance and resistance being equivalent. Using Ohm's law, we can conclude that higher impedance means lower current flow when the voltage is constant. As a consequence, the battery longevity is improved. Since impedance is a sum of three components, it's worth mentioning that the highest value must come

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

from the contact of electrode with myocardium; otherwise, if it comes from the resistance across the lead it may lead to drop in the voltage but an increase to heat which may lead to failed stimulation. Smaller electrode have higher impedance, that's why smaller electrodes are higher battery longevity. However, the size of the electrode has a disadvantage which limits the contact of electrode with the muscle and stability. Impedance is measured with Ohms. [6, p. 38]

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Chapter 2

Methods

The objective of this thesis is to undertake a comparative analysis of three distinct pacing methodologies: traditional Right Ventricular (RV) Pacing, Left Bundle Branch (LBB) Pacing, and Biventricular Pacing, also known as Cardiac Resynchronization Therapy (CRT). Particular emphasis is placed on the exploration of LBB Pacing as an emergent technique showcasing considerable potential.

This comparison is operationalized through the assessment of five specific parameters: the duration of the native QRS complex in the absence of pacing, the duration of the QRS complex when paced, pacing threshold, sensing capability, and electrical impedance. These parameters were evaluated using two distinct methodologies:

- During the implant, directly from the operating room. This is considered "invasive" measurement, as the measurements are measured directly from the lead using programmer within the sterile environment of the operating room.

- During routine follow-up, in a normal control room, classified as "non-invasive testing".

It is worth noting that for both invasive and non-invasive testing modalities, a 12-lead Electrocardiogram (ECG) was used to ensure the accuracy of

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

QRS duration measurements. All collected data were integral to the standard patient examination protocol.

2.1 Patient selection

The selection of patients for this study was executed through a randomized process. Any individual scheduled for either a pacing device implantation or a follow-up consultation during my tenure at the Rijeka Clinical Hospital Center and the University Clinical Center of Kosovo was eligible for inclusion.

Given the multifunctional capability of certain devices, such as CRTs, which support multiple pacing modes, a subset of patients was able to contribute data across several pacing methodologies. For instance, a patient with a CRT device might provide insights into LBB Pacing, RV Pacing, and CRT, whereas those with single or dual-chamber devices could only yield information regarding RV or LBB pacing.

Having a larg enough table not to fit a page, for a better view it is separated into two tables, where the first one consists of thirty (30) patients, and the other one twenty nine (29) patients:

A group of 59 patients were involved in this study, categorized as follows based on the pacing modalities available to them:

- Twenty-nine patients had LBB pacing
- Thirty-eight patients had RV pacing,
- Seven patients had CRT or Biventricular pacing.

It is crucial to acknowledge that it was not feasible to measure all parameters across all patients due to various constraints, including but not limited to:

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- Patient is pacemaker depended - no native QRS is available
- Patient is very symptomatic when pacing is stopped - leading to missing information on native QRS and sensing value
- Very poor/noisy ECG signal, which could be either from muscle tremor or faulty device - QRS measurement not possible

2.2 Data Collection and Processing

Data collection for this study was conducted during both implant procedures and follow-up visits. For the implant phase, data were gathered in a sterile environment where patients were connected to a 12-lead ECG using the EP Tracer system. In addition to the standard ECG channels, two channels were derived directly from the lead. These channels were essential for precise lead positioning and were displayed in the EP Tracer system through a Medtronic programmer cable, as seen in Figure 2.1. This Medtronic cable, connected to the pacing lead, was responsible for both pacing and the measurement of critical parameters such as threshold, sensing, and impedance. The signal from the lead was routed into the EP Tracer using a jumper cable to display these measurements on the system.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

FIGURE 2.1: Medtronic CareLink Programmer: Testing cable which is connected to the patient and EP Tracer

Before pacing was initiated, the native QRS duration was measured using the EP Tracer software to establish a baseline for later comparison with the paced QRS duration. Once the pacing lead was positioned optimally, another 12-lead ECG recording was obtained in the EP Tracer, with the writing speed set to 50 mm/s to provide a more detailed ECG trace. The QRS duration was then measured directly from this high-resolution ECG.

Examples of taken ECGs and QRS measurement can be seen on the following three pictures (samples taken from the same patient), where:

- The first picture represents the native QRS, before pacing;
- The second picture represents the RV Paced QRS and its measurement;
- The third picture represents the LBB Paced QRS and its measurement.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

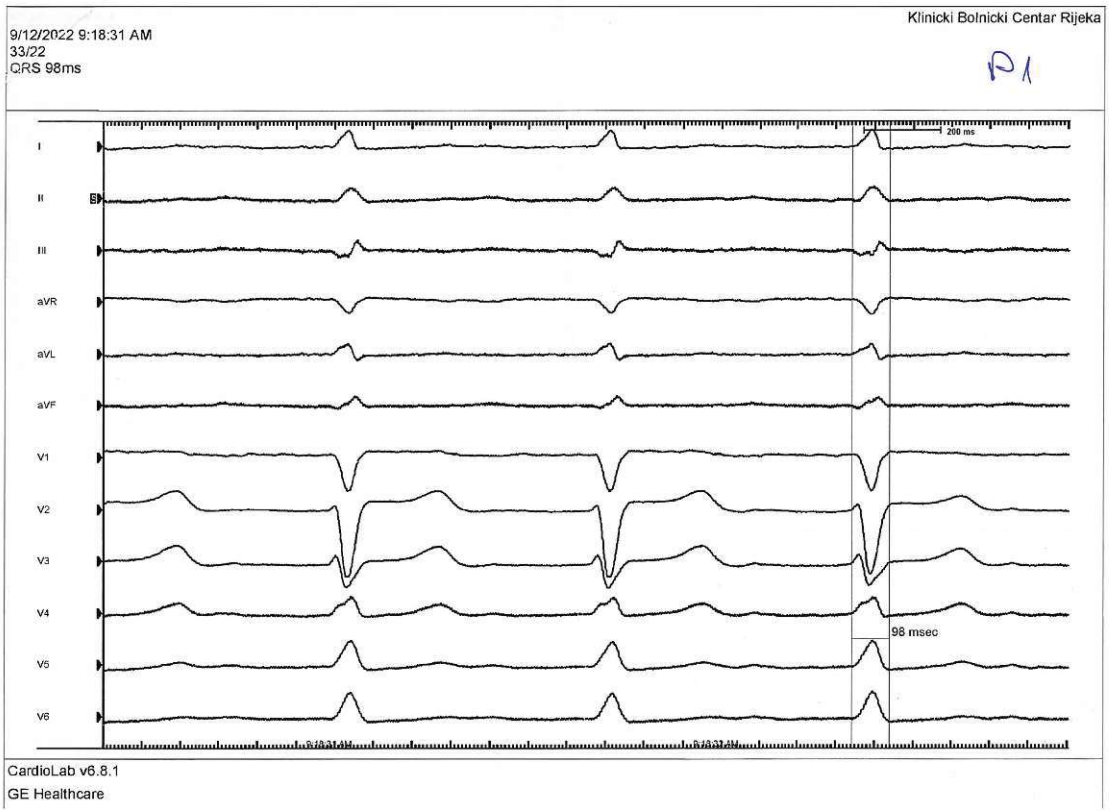

FIGURE 2.2: ECG Example: Native QRS Measurement - Printed on 50mm/s

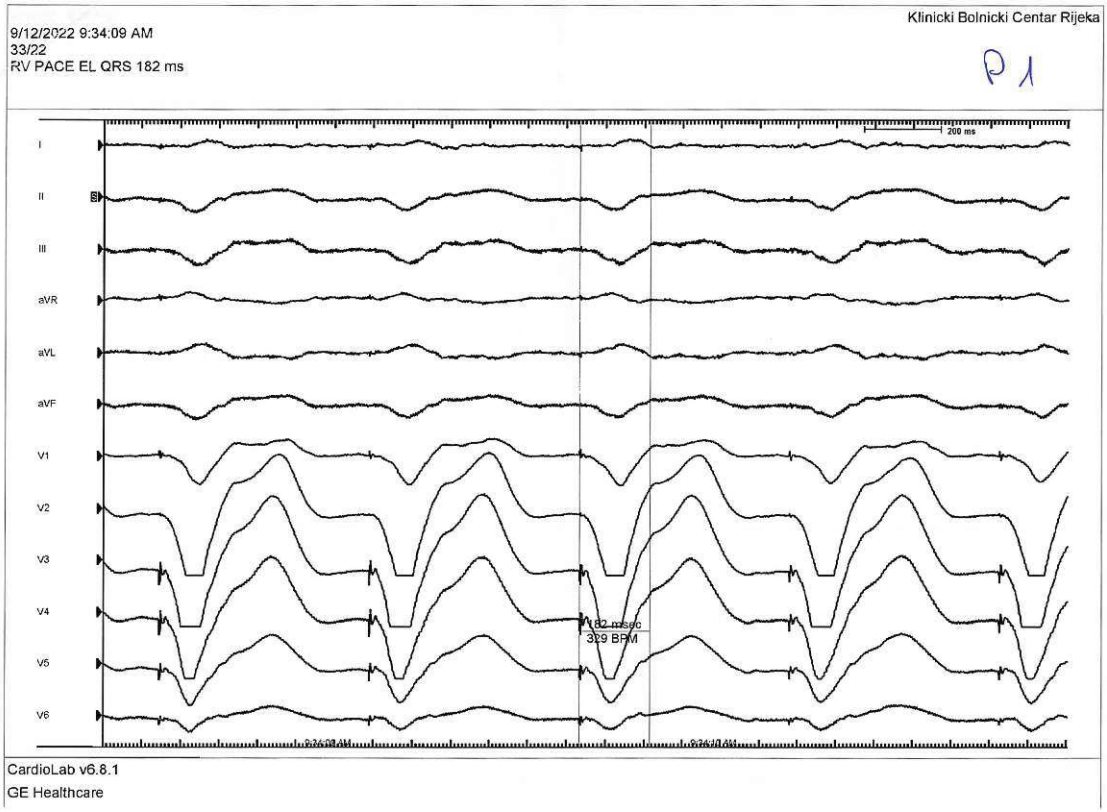

FIGURE 2.3: ECG Example: Native QRS Measurement - Printed on 50mm/s

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

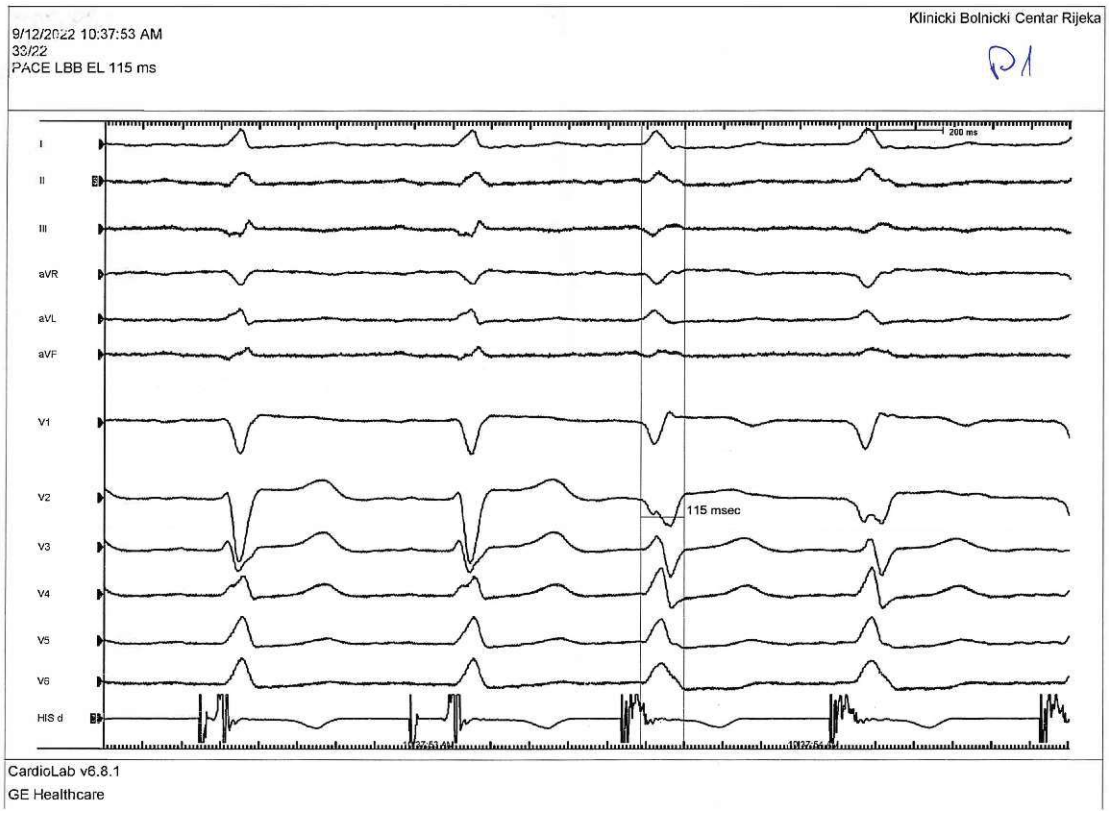

FIGURE 2.4: ECG Example: Native QRS Measurement - Printed on 50mm/s

Following confirmation of lead positioning and acceptable QRS duration, pacing was initiated, and the threshold (via overdrive pacing), sensing, and impedance values were measured using the Medtronic CareLink™ 2090 programmer, which was employed 100% during implants and follow-ups. All values were documented and tabulated for further analysis. The Medtronic CareLink Encore™ 29901 programmer was also used exclusively during follow-up visits to measure these parameters.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

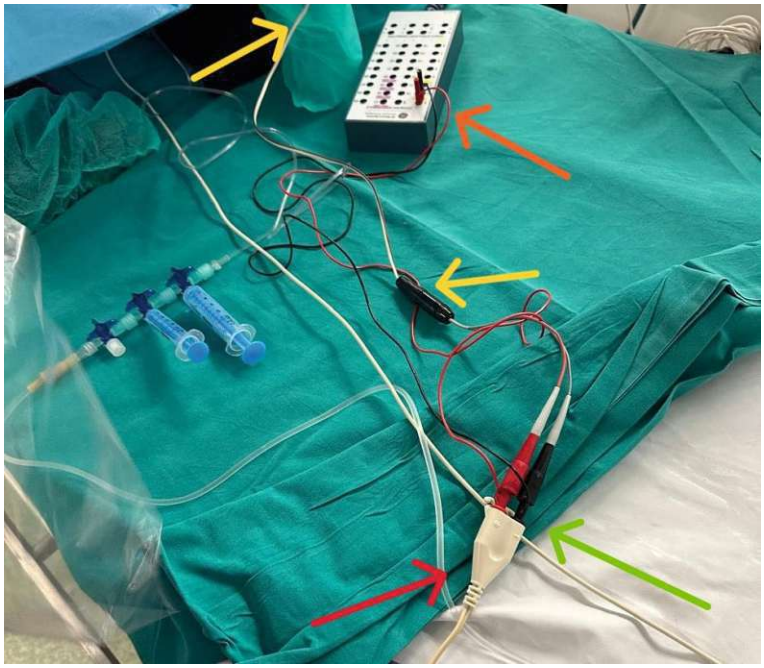

FIGURE 2.5: Cabling to the patient and EP Tracer: Red arrow showing the cable coming from programmer 2.1; Green arrow showing the jumper, which is used to shown the signal in Medtronic programmer and EP Tracer; Yellow arrows show the cable going to the lead directly; Orange arrow show the cables from the jumper to the EP Tracer.

For follow-up data collection, patients visited the clinic and were placed in a bed before being connected to a 12-lead ECG. Once the ECG trace was stable, the patient's device was connected to the Medtronic programmers via the programmer head. Testing began by assessing whether the patient had an underlying rhythm. If present, pacing was briefly disabled to capture a native 12-lead ECG and measure the native QRS duration. Subsequently, the patient was paced using the RV, LV, or LBB lead to obtain a paced 12-lead ECG, from which the paced QRS duration was measured. Following this, the threshold, sensing, and impedance values were measured.

In cases where patients lacked a tolerable underlying rhythm, or had very slow rhythms but could not tolerate pacing deactivation, the measurement

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

of native QRS duration and sensing values was aborted to avoid patient discomfort or risk. Additionally, if a patient was uncomfortable during the testing process or if ECG quality was compromised by noise, only data confirmed to be accurate were used. In instances where the ECG trace was too noisy and measuring QRS duration was difficult or impossible, the patient was excluded from the QRS duration analysis.

Once all tests were completed, the patient was disconnected from the programmer and released from the clinic.

The collected data were put in an excel table, before being processed. The full patient data collected from patients can be seen in Figure 2.6 and Figure 2.7:

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

#	ID	Implant/ Follow-Up	LBBP / RVP / CRT	Electrode/Lead	Threshold	Sensing	Impedance	Native QRS (ms)	Paced QRS (ms)
Patient 1	P1	Implant	LBBP + RVP	RV Lead:	0.5 V	14 mV	630 Ohms	98	188
				LBB Lead:	0.5 V	6.8 mV	722 Ohms		115
Patient 2	P2	Follow-up	LBBP	LBB Lead:	1.0 V	22.4 mV	603 Ohms	167	117
Patient 3	P3	Follow-up	LBBP	LBB Lead:	0.75 V	22.4 mV	750 Ohms	80	100
Patient 4	P4	Follow-up	LBB + RVP	RV Lead:	0.5 V	14.3 mV	863 Ohms	188	185
				LBB Lead:	0.25 V	N/A	1140 Ohms		123
Patient 5	P5	Implant	LBB + RVP	RV Lead:	0.70 V	8.3 mV	437 Ohms	165	177
				LBB Lead:	0.50 V	8.1 mV	560 Ohms		140
Patient 6	P6	Implant	LBBP	RV Lead:	N/A	N/A	N/A	125	
				LBB Lead:	0.30 V	12.0 mV	870 Ohms		100
Patient 7	P7	Follow-up	LBBP	LBB Lead:	0.8 V	14.1 mV	578 Ohms	121	122
Patient 8	P8	Implant	LBBP	LBB Lead:	1.2 V	8.9 mV	870 Ohms	104	87
Patient 9	P9	Follow-up	LBBP + RVP	RV Lead:	0.5 V		745 Ohms	175	153
				LBB Lead:	0.7 V	10.7 mV	952 Ohms		105
Patient 10	P10	Follow-up	LBBP + RVP	LBB Lead:	1.2 V	N/A	570 Ohms	160	155
Patient 11	P11	Implant	LBBP	LBB Lead:	1.0 V	12.5 mV	830 Ohms	133	107
Patient 12	P12	Implant	LBBP	LBB Lead:	1.2 V	10.0 mV	853 Ohms	95	111
Patient 13	P13	Follow-up	LBBP	LBB Lead:	0.5 V	14.9 mV	390 Ohms	98	110
Patient 14	P14	Follow-up	LBBP	LBB Lead:	0.5 V	16.6 mV	839 Homs	114	105
Patient 15	P15	Follow-up	RVP	RV Lead:	1.75 V	9.3 mV	665 Ohms	0	180
Patient 16	P16	Implant	RVP	RV Lead:	0.5 V	15.2 mV	630 Ohms	127	177
Patient 17	P17	Implant	RVP	RV Lead:	0.5 V	5.0 mV	607 Ohms	134	167
Patient 18	P18	Implant	RVP	RV Lead:	0.6 V	8.4 mV	764 Ohms	107	195
Patient 19	P19	Implant	RVP	RV Lead:	0.75 V	20.0 mV	608 Ohms	164	170
Patient 20	P20	Implant	RVP	RV Lead:	0.50 V	12.3 mV	532 Ohms	160	197
Patient 21	P21	Implant	RVP	RV Lead:	0.50 V	10.1 mV	551 Ohms	164	176
Patient 22	P22	Implant	RVP	RV Lead:	0.50 V	12.6 mV	570 Ohms	190	194
Patient 23	P23	Implant	RVP	RV Lead:	0.5 V	10.0 mV	730 Ohms	81	152
Patient 24	P24	Implant	RVP	RV Lead:	0.88 V	4.9 mV	670 Ohms	80	155
Patient 25	P25	Follow-up	CRT	RV Lead:	2.75 V	5.1 mV	456 Ohms	137	160
				CRT:	0.75 V	NA	450 Ohms		125
Patient 26	P26	Follow-up	RVP	RV Lead:	1.0 V	10.0 mV	418 Ohms		177
Patient 27	P27	Implant	LBBP	LBB Lead:	0.5 V	13.7 mV	876 Ohms	160	113
Patient 28	P28	Implant	LBBP	RV Lead:	0.50 V	5.4 mV	380 Ohms	197	
				LBB Lead:	0.75 V	5.4 mV	570 Ohms		131
Patient 29	P29	Implant	LBBP	LBB Lead:	0.60 V	8.3 mV	677 Ohms	95	110
Patient 30	P30	Implant	RVP	RV Lead:	1.25 V	7.6 mV	532 Ohms	120	160

FIGURE 2.6: Dataset: Patient 1 to 30

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

#	ID	Implant/ Follow-Up	LBBP / RVP / CRT	Electrode/Lead	Threshold	Sensing	Impedance	Native QRS (ms)	Paced QRS (ms)
Patient 31	P31	Implant	RVP	RV Lead:	0.5 V	15.68 mV	944 Ohms	95	117
Patient 32	P32	Implant	CRT	RV Lead:	0.5 V	4.4 mV	532 Ohms	132	170
				CRT:	0.75 V		817 Ohms		114
Patient 33	P33	Implant	LBBP	LBB Lead:	1.0 V	15.6 mV	900 Ohms	161	121
Patient 34	P34	Follow-up	LBBP	LBB Lead:	0.5 V	11.2 mV	610 Ohms	115	120
Patient 35	P35	Implant	LBBP	LBB Lead:	1.3 V	8.8 mV	730 Ohms	123	118
Patient 36	P36	Implant	LBBP	LBB Lead:	0.8 V	7.5 mV	685 Ohms	87	95
Patient 37	P37	Implant	CRT	RV Lead:	0.6 V	4.4 mV	688 Ohms	162	194
				CRT:	2.0 V		510 Ohms		140
Patient 38	P38	Follow-up	RVP	RV Lead:	0.6 V	7.6 mV	487 Ohms	120	125
Patient 39	P39	Follow-up	RVP	RV Lead:	0.4 V	8.7 mV	965 Ohms	120	180
Patient 40	P40	Follow-up	LBBP	LBB Lead:	1.0 V	NA	468 Ohms	160	105
Patient 41	P41	Implant	RVP	RV Lead:	0.5 V	11.0 mV	530 Ohms	120	170
Patient 42	P42	Implant	LBBP	LBB Lead:	0.5 V	7.8 mV	691 Ohms	90	98
Patient 43	P43	Implant	LBBP	LBB Lead:	1.2 V	13.0 mV	755 Ohms	97	81
Patient 44	P44	Implant	CRT	RV Lead:	0.5 V	5.0 mV	571 Ohms	162	165
				CRT:	1.25 V				130
Patient 45	P45	Implant	RVP	RV Lead:	0.9 V	17.9 mV	869 Ohms	95	125
Patient 46	P46	Follow-up	LBBP	LBB Lead:	0.5 V	5.6 mV	520 Ohms	145	120
Patient 47	P47	Follow-up	LBBP	LBB Lead:	0.6 V	7.8 mV	526 Ohms	100	110
Patient 48	P48	Follow-up	CRT	RV Lead:	0.8 V	12.1 mV	565 Ohms	142	
				CRT:	1.9 V	5.5 mV	741 Ohms		123
Patient 49	P49	Follow-up	RVP	RV Lead:	0.8 V	8.7 mV	487 Ohms	100	160
				CRT:	1.0 V		399 Ohms		
Patient 50	P50	Implant	CRT	RV Lead:	0.75 V	15.6 mV	810 Ohms		
				CRT:	0.6 V	14.2 mV	1088 Ohms		
Patient 51	P51	Follow-up	LBBP	LBB Lead:	1.0 V	15.6 mV	785 Ohms	123	105
Patient 52	P52	Follow-up	RVP	RV Lead:	0.5 V	10.0 mV	526 Ohms	105	158
Patient 53	P53	Implant	RVP	RV Lead:	0.2 V	8.8 mV	620 Ohms	132	98
Patient 54	P54	Follow-up	RVP	RV Lead:	0.6 V	9.1 mV	546 Ohms	110	161
Patient 55	P55	Follow-up	RVP	RV Lead:	0.5 V	11.2 mV	720 Ohms	102	163
Patient 56	P56	Follow-up	RVP	RV Lead:	0.5 V	5.6 mV	680 Ohms	123	158
Patient 57	P57	Implant	CRT	RV Lead:	0.5 V	8.9 mV	380 Ohms	130	162
				CRT:	0.75 V		430 Ohms		120
Patient 58	P58	Implant	LBBP	LBB Lead:	0.5 V	6.8 mV	856 Ohms	97	103
Patient 59	P59	Implant	LBBP	LBB Lead:	0.5 V	11.2 mV	820 Ohms	153	101

FIGURE 2.7: Dataset: Patient 31 to 59

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

2.3 Statistical Methods

Several statistical methods were applied to analyze the dataset from Chapter 2.2. The primary focus was on comparing different pacing parameters—such as QRS duration, pacing threshold, sensing values, and impedance—across multiple pacing methods including Right Ventricular (RV) Pacing, Left Bundle Branch (LBB) Pacing, and Cardiac Resynchronization Therapy (CRT).

Descriptive statistics were used to summarize the key parameters for each pacing method. The following measures were calculated for each parameter (e.g., QRS duration, pacing threshold, sensing, and impedance):

- Mean: The average value of each parameter.
- Median: The middle value when data is ordered.
- Minimum and Maximum: The smallest and largest values.
- Standard Deviation: The spread of the values around the mean.

This summary provided insight into the central tendencies and variability of the pacing parameters across the different pacing methods.

A key part of the analysis involved comparing different pacing modalities and parameters for each patient. The comparisons focused on parameters such as QRS duration, pacing threshold, sensing values, and impedance across different pacing methods:

- Paired t-tests were used to compare parameters (e.g., native QRS vs. RV-paced QRS) for the same group of patients. This test was applied to determine whether the mean difference between paired observations was statistically significant.
- The statistical significance of the results was evaluated using p-values, with a threshold of $p < 0.05$ indicating a statistically significant difference between the compared groups. This approach allowed for the

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

identification of meaningful differences in pacing parameters across various pacing methods.

RStudio was used for all data processing, statistical analysis, and visualizations. The built-in functions in R were leveraged to calculate descriptive statistics, perform paired t-tests and Wilcoxon tests, and generate visual representations of the data, such as dotcharts and boxplots.

The following R code was used to compare native QRS duration and RV-paced QRS duration for a group of patients. This example illustrates the process used to analyze different pacing parameters in 3.

```
set.seed(1)
patient <- c("Patient 1", "Patient 2", "Patient 3",
"Patient 4", "Patient 5", "Patient 6",
"Patient 7", "Patient 8", "Patient 9",
"Patient 10", "Patient 11", "Patient 12",
"Patient 13", "Patient 14")

QRSduration <- c(98, 188, 165, 175, 0, 127,
        134, 107, 164, 160, 164, 190, 81, 80)

paceQRSduration <- c(188, 185, 177, 153, 180,
        177, 167, 195, 170, 197, 176, 194, 152, 155)

get_statistics <- function(data) {
        mean_val <- mean(data, na.rm = TRUE)
        median_val <- median(data, na.rm = TRUE)
        min_val <- min(data, na.rm = TRUE)
        max_val <- max(data, na.rm = TRUE)
        sd_val <- sd(data, na.rm = TRUE)
```

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

```
        return(data.frame(
        Mean = mean_val,
        Median = median_val,
        Min = min_val,
        Max = max_val,
        Standard_Deviation = sd_val
        ))
}
# Get statistics for QRSduration
QRS_stats <- get_statistics(QRSduration)
print("Statistics for QRSduration:")
print(QRS_stats)

# Get statistics for paceQRSduration
paceQRS_stats <- get_statistics(paceQRSduration)
print("Statistics for paceQRSduration:")
print(paceQRS_stats)

data <- data.frame(patient, QRSduration, paceQRSduration)
dotchart(data$paceQRSduration,
xlim = range(data$QRSduration, data$paceQRSduration) + c(-5, 5),
pch = 21, bg = "green", labels = data$patient,
main="Intrinsic QRS in ms (RED) vs RV Paced QRS in ms (GREEN)",
xlab = "QRS Duration (ms)",
pt.cex = 1.5)
invisible(sapply(1:nrow(data), function(i) {
        segments(min(data$paceQRSduration[i],
```

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

```
        data$QRSduration[i]), i,

        max(data$paceQRSduration[i],
        data$QRSduration[i]), i, lwd = 2)

        text(min(data$paceQRSduration[i],
        data$QRSduration[i]) - 9, i,

        labels = min(data$paceQRSduration[i],
        data$QRSduration[i]))

        text(max(data$paceQRSduration[i],
        data$QRSduration[i]) + 9, i,

        labels = max(data$paceQRSduration[i],
        data$QRSduration[i]) )
}))

points(data$QRSduration, 1:nrow(data),
        col = "red", pch = 19, cex = 1.5)
points(data$paceQRSduration, 1:nrow(data),
        col = "red", pch = 21, bg = "green", cex = 1.5)
```

The code performs three main tasks:

1. Data Initialization: The code first defines data for 14 patients, including their names, QRS durations in two conditions: one with intrinsic (native) QRS (QRSduration) and another with RV-paced QRS (paceQRSduration). These are stored in arrays for use in subsequent calculations and visualization.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

2. Statistical Analysis: A function get statistics is defined to compute basic statistical measures (mean, median, minimum, maximum, and standard deviation) for each dataset. This function is applied separately to both QRSduration and paceQRSduration, generating descriptive statistics that are printed to the console. This helps to summarize the central tendency and dispersion of QRS durations for each pacing mode.

3. Visual Comparison Using a Dot Chart: The code creates a dot chart that visually compares intrinsic QRS durations (plotted in red) and paced QRS durations (plotted in green) for each patient, as in Figure 3.2. It plots these values side-by-side for each patient, connecting the minimum and maximum values with a line for easier comparison. The intrinsic QRS values are displayed in red, while the paced QRS values are highlighted with green-filled circles. The chart includes labels with the exact values, making it easier to interpret differences between the two sets of data for each patient.

This approach of combining statistical analysis and visualization allows for a clear comparison between intrinsic and paced QRS durations, providing both numerical insights and an intuitive graphical summary.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Chapter 3

Results

The objective of this research was to conduct a comparative analysis of five parameters obtained from cardiac stimulation, acknowledging the intrinsic significance of each. Notably, among these parameters, the QRS duration is of primary clinical importance. This is supported by findings from Bongioanni et al., who emphasized the QRS duration related to the cardiovascular mortality. Moreover, the QRS duration has been identified as a critical factor for long-term prognosis in patients with heart disease. A QRS width exceeding 120 ms is a strong and independent predictor of prognosis.[3]

The importance of the other three parameters remains still - and in term of device are critical and should never be neglected. These parameters, while perhaps not as directly correlated with mortality as QRS duration, are indispensable in the comprehensive management and prognostication of cardiac conditions. On the following sections, the results taken from the fifty nine patients will be shown.

3.1 QRS Duration

In this thesis, the comparison of QRS duration is grouped into three distinct categories: comparison between native QRS duration and right ventricular (RV) pacing, comparison between native QRS duration and left bundle

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

branch (LBB) pacing, and comparison between native QRS duration and cardiac resynchronization therapy (CRT) pacing.

As explained earlier, certain patients may present with the feasibility for one or more pacing modalities. This aspect will be further explored through a direct, head-to-head comparative analysis, taking advantage of the chance to evaluate different pacing methods in the same group of patients, allowing for a straightforward comparison of techniques.

3.1.1 Native QRS Duration vs. RV Pacing QRS Duration

Data from thirty-two patients were used to perform the initial comparison between native QRS duration and QRS duration observed during RV Pacing. The data for this analysis were collected during either implantation procedures or subsequent follow-up evaluations. The tabled representation of the initial dataset is provided below:

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

#	ID	Implant/ Follow-up	Native QRS Duration (ms)	RV Paced QRS Duration (ms)	Difference (ms)
1	P1	Implant	98	188	-90
2	P4	Follow-up	188	185	3
3	P5	Implant	165	177	-12
4	P9	Follow-up	175	153	22
5	P15	Follow-up	0	180	-180
6	P16	Implant	127	177	-50
7	P17	Implant	134	167	-33
8	P18	Implant	107	195	-88
9	P19	Implant	164	170	-6
10	P20	Implant	160	197	-37
11	P21	Implant	164	176	-12
12	P22	Implant	190	194	-4
13	P23	Implant	81	152	-71
14	P24	Implant	80	155	-75
15	P25	Follow-up	137	160	-23
16	P26	Follow-up	0	177	-177
17	P30	Implant	120	160	-40
18	P31	Implant	95	117	-22
19	P32	Implant	132	170	-38
20	P37	Implant	162	194	-32
21	P38	Follow-up	120	125	-5
22	P39	Follow-up	120	180	-60
23	P41	Implant	120	170	-50
24	P44	Implant	162	165	-3
25	P45	Implant	95	125	-30
26	P49	Follow-up	100	160	-60
27	P52	Follow-up	105	158	-53
28	P53	Implant	132	98	34
29	P54	Follow-up	110	161	-51
30	P55	Follow-up	102	163	-61
31	P56	Follow-up	123	158	-35
32	P57	Implant	130	162	-32

FIGURE 3.1: Native QRS Duration vs. RV Pacing QRS Duration

It's important to highlight that in cases where native QRS duration couldn't be measured, denoted as 0, due to patient dependency on a pacemaker, a comparison will be made between their RV Pacing QRS Duration and the "normal QRS duration" observed in healthy individuals.

The data set table clearly indicates a consistent trend: in nearly all patients, the QRS duration was shorter prior to right ventricular pacing. Only

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

three patients demonstrated a shorter QRS duration following right ventricular pacing. Notably, in two out of three patients exhibited QRS duration exceeding 170 ms, suggesting potential end-stage heart failure. This will not be part of discussion in this thesis.

Description	Minimum	Median	Mean	Maximum
Native QRS Duration	80 ms	125 ms	129.9 ms	190 ms
RV Paced QRS Duration	98 ms	164 ms	163.7 ms	197 ms
Difference (RVP - Native QRSd)	-90 ms	34 ms	33.8 ms	34 ms

FIGURE 3.2: Summary: QRS Duration vs. RV Pacing QRS Duration

This table presents a summary of the data on native QRS duration, RV paced QRS duration, and the difference between them (RVP - Native QRSd) in this group of pateints. A summary can be summed up as follwoing:

1. Native QRS Duration:
   - The native QRS duration, representing the intrinsic electrical conduction of the heart, ranges from 80 ms to 190 ms across the patient cohort.
   - The median native QRS duration, at 125 ms, indicates that half of the patients have QRS durations shorter than this value, while the other half have longer durations.
   - The mean native QRS duration, calculated at 129.9 ms, provides the average duration across all patients in the sample.
2. RV Paced QRS Duration:
   - The RV paced QRS duration, reflecting the electrical conduction influenced by right ventricular pacing, ranges from 98 ms to 197 ms.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- The median RV paced QRS duration, at 164 ms, suggests that half of the patients exhibit QRS durations shorter than this value, while the remainder have longer durations.
- The mean RV paced QRS duration, calculated at 163.7 ms, represents the average duration of QRS complexes under right ventricular pacing.

3. Difference (RVP - Native QRSd):

- The difference between RV paced QRS duration and native QRS duration varies across the patient cohort.
- The minimum difference of -90 ms indicates cases where RV pacing resulted in a shorter QRS duration compared to the native duration, suggesting potential improvement in electrical conduction efficiency.
- The median difference of 34 ms signifies that, on average, RV pacing leads to an increase in QRS duration compared to the native duration.
- The maximum difference of 34 ms indicates instances where RV pacing did not significantly alter QRS duration compared to the native duration.

Overall, the data suggests that RV pacing generally results in longer QRS durations compared to native QRS durations, with the difference ranging from -90 ms (the case were the RV Paced QRS duration is 90 ms longer than its native QRS) to 34 ms (one of the best cases where RV Paced QRS was better than the native QRS). However, it's worth noting that in some cases, RV pacing led to shorter QRS durations, particularly in patients with longer native QRS durations.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

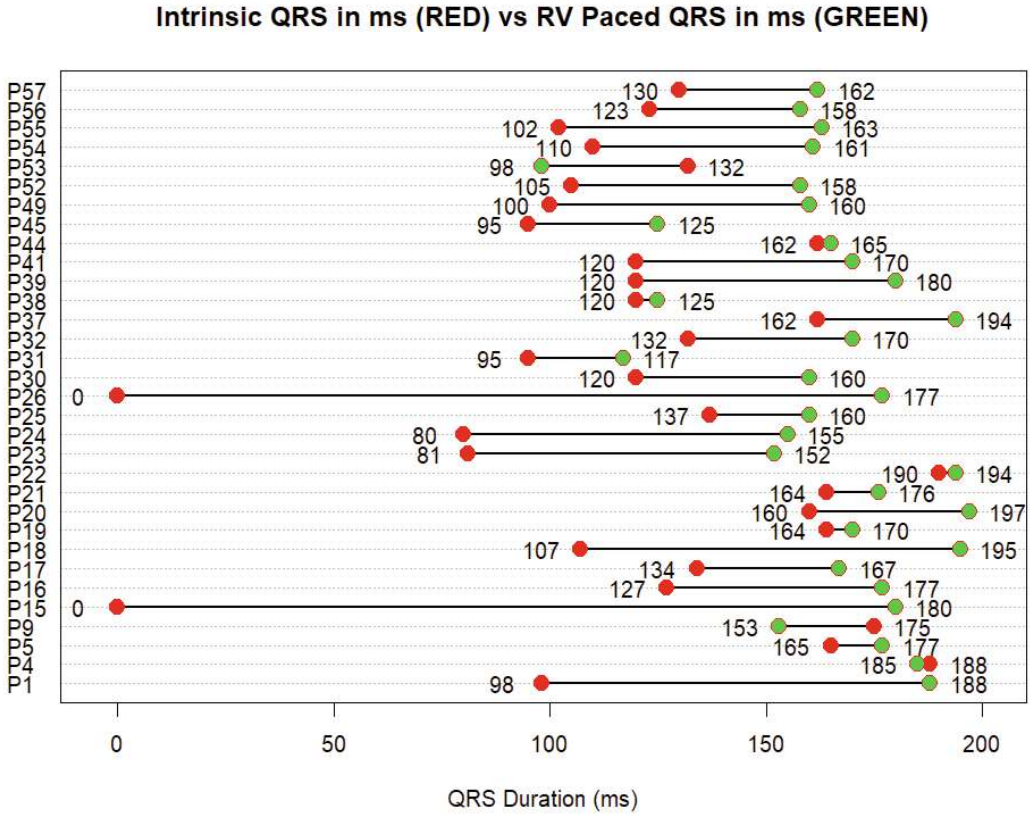

FIGURE 3.3: Native QRS Duratoin vs. RV Pacing QRS Duration.

The chart provided offers another way to show the data. It clearly shows that the red circles, representing native QRS duration, are mostly on the left side of the graph, indicating shorter durations. In contrast, the green circles, representing RV Paced QRS duration, are spread across the graph, suggesting longer durations compared to native QRS.

It is worth analyzing the two cases where the Native QRS measurement was not possible due to patient pacemaker dependency. pecifically, attention is directed towards two such cases, denoted as P26 and P15, wherein the QRS duration measures 177 ms and 180 ms, respectively. These durations are out of the normal range of QRS duration with significant distance. As previously mentioned before, "wide" or prolonged QRS complexes is associated with unfavorable long-term prognostic implications.

Another point to be discussed from the dataset is the variance observed

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

between measurements recorded during the initial implantation phase and those obtained during the follow-up period. In the dataset, 20 out of 32 results are coming from the implant; meanwhile, the other 12 results are coming from follow-ups.

When we look at the group of implant, a significant increase in QRS duration - or a negative difference between Native QRS versus RV Paced QRS - is noticed in patients. Similar results are seen in the follow-up group, with some changes where the QRS duration is either decreased or changes were minimal.

The T-test comes up with a results of T-statistic value 0.97 and a P-value of 0.35. This could be explained as following:

- **T-statistic:** a value near 1 indicates a small difference in the means between the two groups relative to the variability within those groups.
- **P-value:** a value of 0.35 suggests that the observed differences in QRS duration changes between the two groups are not statistically significant.

This absence of significant differences in QRS duration changes between the two groups allows for a generalized comparison without necessitating segmentation of the results. This finding suggests a consistent impact of the intervention over time, reinforcing the stability of the treatment effect observed - whether it's clinically positive or negative.

3.1.2 Native QRS Duration vs. LBB Pacing QRS Duration

Data consisting of twenty-nine patients were used to perform comparison between the native QRS and LBB Paced QRS. Similarly to the comparisson between native QRS and RV Pacing, data for LBB Pacing were collected during either implanation procedure or follow-up evaluations. The tabled representation of this set consisting of twenty-nine patients is provided below:

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

#	ID	Implant/ Follow-up	Native QRS Duration (ms)	LBB Paced QRS Duration (ms)	Difference (ms)
1	P1	Implant	98	115	-17
2	P2	Follow-up	167	117	50
3	P3	Follow-up	80	100	-20
4	P4	Follow-up	80	100	-20
5	P5	Implant	165	140	25
6	P6	Implant	125	100	25
7	P7	Follow-up	121	122	-1
8	P8	Implant	104	87	17
9	P9	Follow-up	175	105	70
10	P10	Follow-up	160	155	5
11	P11	Implant	133	107	26
12	P12	Implant	95	111	-16
13	P13	Follow-up	98	110	-12
14	P14	Follow-up	114	105	9
15	P27	Implant	160	113	47
16	P28	Implant	197	131	66
17	P29	Implant	95	110	-15
18	P33	Implant	161	121	40
19	P34	Follow-up	115	120	-5
20	P35	Implant	123	118	5
21	P36	Implant	87	95	-8
22	P40	Follow-up	160	105	55
23	P42	Implant	90	98	-8
24	P43	Implant	97	81	16
25	P46	Follow-up	145	120	25
26	P47	Follow-up	100	110	-10
27	P51	Follow-up	123	105	18
28	P58	Implant	97	103	-6
29	P59	Implant	153	101	52

FIGURE 3.4: Native QRS Duration vs. LBB Pacing QRS Duration

When starting the analysis of the data shown in the table, a clear observation is that the LBB Paced QRS Duration is generally shorter than the Native QRS Duration, or when longer, the difference is small. This contrast is evident when comparing it to Figure 3.1, where the RV Paced Duration values are significantly higher than the LBB Paced QRS Duration values depicted in Figure 3.4.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Upon examining the final column depicting the difference between Native and LBB Paced QRS Duration, it becomes evident that twelve (12) patients exhibit a negative difference, indicating a longer QRS Duration in LBB Pacing, whereas seventeen (17) patients show a positive difference, suggesting a shorter QRS Duration. This observation underscores the varying effects of LBB Paced QRS Duration relative to Native QRS Duration across the patient cohort. This observation is promising, indicating that LBB Pacing tends to either improve or maintain similar QRS Duration without worsening the condition, unlike RV Pacing.

Description	Minimum	Median	Mean	Maximum
Native QRS Duration	80 ms	121 ms	124.8 ms	197 ms
LBB Paced QRS Duration	81 ms	110 ms	118 ms	155 ms
Difference (LBB - Native QRSd)	-20 ms	9 ms	14.24 ms	70 ms

FIGURE 3.5: Summary: Native QRS Duration vs. LBB Pacing QRS Duration

Table shown in 3.5 provides a summarized data of the dataset. Out of it, we can get the following conclusion:

1. Native QRS Duration:
   - The distribution of Native QRS Duration spans from 80 ms to 197 ms.
   - The median duration (121 ms) indicates that half of the observed durations are below this value.
   - The mean duration (124.8 ms) suggests the average duration across the dataset.
2. LBB Paced QRS Duration:
   - LBB Paced QRS Duration ranges from 81 ms to 155 ms.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- The median duration (110 ms) is notably lower compared to Native QRS Duration, indicating a tendency towards shorter durations with LBB Pacing.
- The mean duration (118 ms) further supports this observation, indicating an overall reduction in QRS duration compared to native conditions.

3. Difference (LBB - Native QRSd):

- The mean duration (118 ms) further supports this observation, indicating an overall reduction in QRS duration compared to native conditions.
- The median difference of 11 ms indicates that, on average, LBB Pacing leads to an improvement or reduction in QRS duration compared to native conditions.
- The positive mean difference (33.8 ms) further supports the observation that LBB Pacing tends to improve or maintain QRS duration relative to native conditions.

The analysis demonstrates that LBB Pacing generally results in shorter QRS durations compared to native QRS duration, with median and mean values supporting this observation. This suggests that LBB Pacing may offer therapeutic benefits in cardiac activity by potentially improving QRS durations.

It is notable that patients exhibiting severe extension of QRS duration, such as those identified by IDs P2, P5, P9, P16, P18, P22, and P29, demonstrate considerable improvements with LBB Pacing, bringing their QRS durations closer to the range considered normal. This observation prompts further discussion on the potential therapeutic role of LBB Pacing in managing

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

heart failure patients with widened QRS durations. However, comprehensive evaluation incorporating additional factors is necessary to fully clarify its clinical implications.

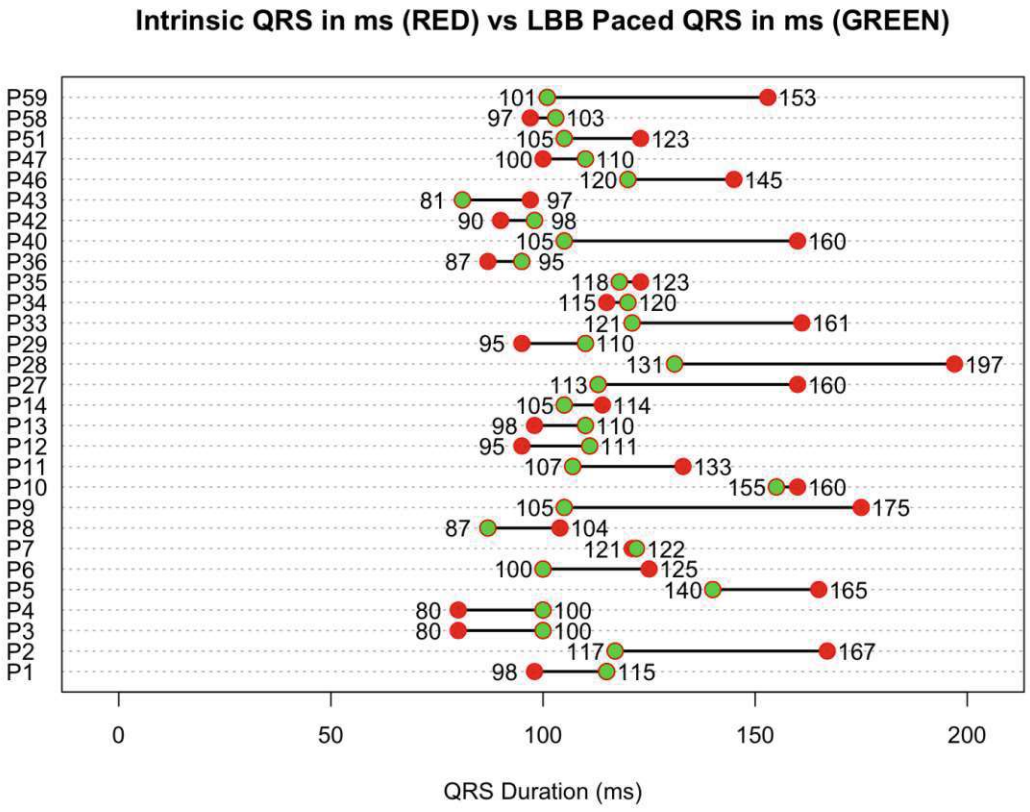

FIGURE 3.6: Native QRS Duratoin vs. LBB Pacing QRS Duration.

Another view of the dataset can be seen in the 3.6. If the green dots - which represent the LBB Paced QRS - are to the left of the red dot - which represent the native QRS duration - it means the QRS duration is shorter after pacing, which is an improvement. On the other hand, if the green dot is to the right of the red dot, the QRS duration is longer after pacing, indicating a worsening or less effective pacing.

Patients where the gap between both dots is the largest, indicates that pacing affected them most, either positively or negatively. Meanwhile in patients where the dots are close to each other, when can conclude that pacing

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

have minimal impact on QRS duration.

The overall effectiveness of LBB pacing in altering QRS duration can be evaluated by examining the distribution of the green and red dots on the graph. If the majority of green dots are positioned to the left of the red dots, it indicates that LBB pacing is effective in reducing QRS duration. Conversely, if green dots are predominantly to the right, this suggests that LBB pacing may not be as beneficial or could potentially worsen the QRS duration in some patients.

The observed data indicate that most of the green dots fall within the range of 80 to 140 ms, suggesting a favorable outcome for LBB pacing. Notably, there is no evidence of a dramatic increase in QRS duration following LBB pacing in any patient. This is different from the effects observed with RV pacing, where a significant worsening of QRS duration was commonly reported.

The other thing to be looked at is the difference between implant and follow-up values. Out of 29 patients, 17 patients have been tested during implant and 12 patients have been tested during follow-up. Looking at both data, we can summarize the following:

- Implant Group
  - **Native QRS Duration (ms):** Minimum: 87; Median: 125; Mean: 125.2; Maximum: 197
  - **LBB Paced QRS Duration (ms):** Minimum: 87; Median: 110; Mean: 118.2; Maximum: 155
  - **Difference (ms):** Minimum: 17; Median: 8; Mean: 7.0; Maximum: -47
- Follow-up Group

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- **Native QRS Duration (ms):** Minimum: 80; Median: 114; Mean: 126.5; Maximum: 175
- **LBB Paced QRS Duration (ms):** Minimum: 81; Median: 110; Mean: 118.9; Maximum: 155
- **Difference (ms):** Minimum: 20; Median: 8; Mean: -10.8; Maximum: -70

Based on the data summarized above, we can conclude that both groups maintain a relatively consistent paced QRS median duration (110 ms), suggesting that LBB pacing maintains its effectiveness over time in terms of controlling the paced QRS duration. The follow-up group demonstrates either a stable or improved response to pacing compared to the implant stage, as indicated by the greater magnitude of negative differences (mean of -10.8 ms). This could imply a gradual adaptation of the heart to pacing or ongoing modifications in cardiac electrophysiology that favorably respond to pacing. Importantly, there is no evidence of significant worsening in pacing outcomes from implant to follow-up, which is crucial for long-term patient management and therapy optimization.

T-value and P-value derived from the data were also used to compare the two groups:

- The **Native QRS Duration** has a T-value of -1.5362 and P-value of 0.1408. The t-value indicates the calculated difference in means relative to the spread and size of the sample groups. A negative t-value in this context suggests that the Native QRS Duration for the Implant group might be slightly higher on average compared to the Follow-up group, though the result isn't very strong. Meanwhile, The p-value of 0.1408 is greater than the conventional threshold of 0.05, indicating that the difference in Native QRS Duration between the Implant and Follow-up groups is

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

not statistically significant. The confidence interval includes zero, further indicating that there is no clear evidence of a true mean difference.

- The **LBB Paced QRS Duration** has a T-value of 0.6834 and P-value of 0.5011. A positive t-value suggests the LBB Paced QRS Duration for the Implant group is slightly higher on average than the Follow-up group, but again, the result is weak. The p-value of 0.5011 significantly exceeds the 0.05 threshold, showing no statistically significant difference in the LBB Paced QRS Duration between the two groups. The confidence interval crossing zero confirms the lack of a significant difference.

The data suggest that there is no significant difference in the QRS durations (both native and paced) between the Implant and Follow-up periods. This indicates that the results regarding QRS duration remain relatively stable over time, suggesting consistency in the effects of LBB pacing across these two time points.

The relatively high P-values in both tests indicate that any observed differences in QRS durations between the two groups are likely due to random variation rather than a systematic effect of the treatment or the timing of the measurement (implant vs. follow-up).

The T-values, being close to zero and not statistically significant, further reinforce that there is no strong evidence of a difference between the groups. The effect size, indicated by the distance of the T-values from zero, is not substantial enough to indicate meaningful differences.

3.1.3 Native QRS Duration vs. CRT QRS Duration

An analysis was carried out on a specific subset of patients to compare the Native QRS duration with the CRT-paced QRS duration. Cardiac Resynchronization Therapy (CRT) involves the simultaneous pacing of both ventricles,

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

which is intended to synchronize ventricular contractions and enhance cardiac output. This method stands in contrast to other pacing techniques, primarily due to its application in managing heart failure. The unique aspect of CRT is the utilization of two pacing leads: one positioned in the right ventricle and the other in the left ventricle. This dual-lead setup is essential for achieving the synchronization that can correct the dyssynchrony often present in heart failure patients. Typically, individuals with heart failure present with a prolonged QRS duration, which can be an indicator of ventricular dyssynchrony. By examining changes in the QRS duration following CRT, insights can be gained regarding the efficacy of this therapy in improving electrical and mechanical coordination within the heart.

#	ID	Implant/ Follow-up	Native QRS Duration (ms)	CRT Paced QRS Duration (ms)	Difference (ms)
1	P25	Follow-up	137	125	12
2	P32	Implant	132	114	18
3	P37	Implant	162	140	22
4	P44	Implant	162	130	32
5	P48	Follow-up	143	123	20
6	P50	Implant	0	0	0
7	P57	Implant	130	120	10

FIGURE 3.7: Native QRS Duration vs. CRT Pacing QRS Duration

The dataset consists of 6 patients with non-zero measurements. Patient with ID P50 is missing information on QRS due to urgency of finishing implant and post-implant status.

The dataset, even though consists of only 6 entries - being a much smaller group compared to the other two groups - provides a good idea on the efficiency of CRT and its effect on QRS duration.

This group of patients consists of four patients where the data was taken from implant, and two patients from follow-ups. In four patients from the implant group, there's a shortening of QRS duration from 10 to 32 ms after

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

CRT pacing; meanwhile follow-up patients show an improvement of QRS duration from 12 to 20 ms.

Description	Minimum	Median	Mean	Maximum
Native QRS Duration	130 ms	140 ms	144.33 ms	162 ms
CRT Paced QRS Duration	114 ms	124 ms	125.33 ms	140 ms
Difference (CRT - Native QRSd)	10 ms	19 ms	19 ms	32 ms

FIGURE 3.8: Summary: Native QRS Duration vs. CRT Pacing QRS Duration

Table shown in 3.8 provides a summarized data of the dataset. Out of it, we can get the following conclusion:

1. Native QRS Duration:
   - Range: 130 ms to 162 ms, showing the variability of QRS durations in the patient sample before undergoing CRT.
   - Mean (144.33 ms): This value suggests that on average, patients exhibit moderately elevated QRS durations, which is typical in candidates for CRT due to underlying cardiac dysynchrony.
   - Median (140 ms): The median is slightly less than the mean, indicating a mild right skew in the data distribution. The median being close to the lower end of the range reflects that more than half of the patients have QRS durations clustered towards the lower spectrum of observed values.
2. CRT Paced QRS Duration:
   - Range: 114 ms to 140 ms, which is narrower than the native QRS durations, indicating that CRT has a standardizing effect on the heart's electrical activity.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- Mean (125.33 ms): The mean CRT paced QRS duration is lower than the mean native QRS duration, confirming that CRT generally decreases QRS duration, aligning with its therapeutic goal to enhance cardiac synchrony.
- Median (124 ms): Very close to the mean, this median suggests a symmetrical distribution of CRT paced QRS durations around a central value, further emphasizing the consistency in CRT's effect across different patients.

3. Difference (LBB - Native QRSd):

- Range: 10 ms to 32 ms, reflecting the extent of reduction in QRS duration achieved with CRT.
- Mean and Median (19 ms): Both the mean and median are identical, reinforcing that the typical reduction in QRS duration is about 19 ms. The congruence of mean and median indicates a symmetrical distribution of the differences, with most patients experiencing a similar degree of improvement.

The analysis clearly shows that CRT effectively reduces and evens out QRS durations for patients with prolonged QRS Duration. The fact that the mean and median differences after CRT are very close indicates that the therapy consistently works well across the entire group of patients. This consistent effect is crucial for predicting how well CRT will work for future patients and for customizing the treatment to meet individual needs.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

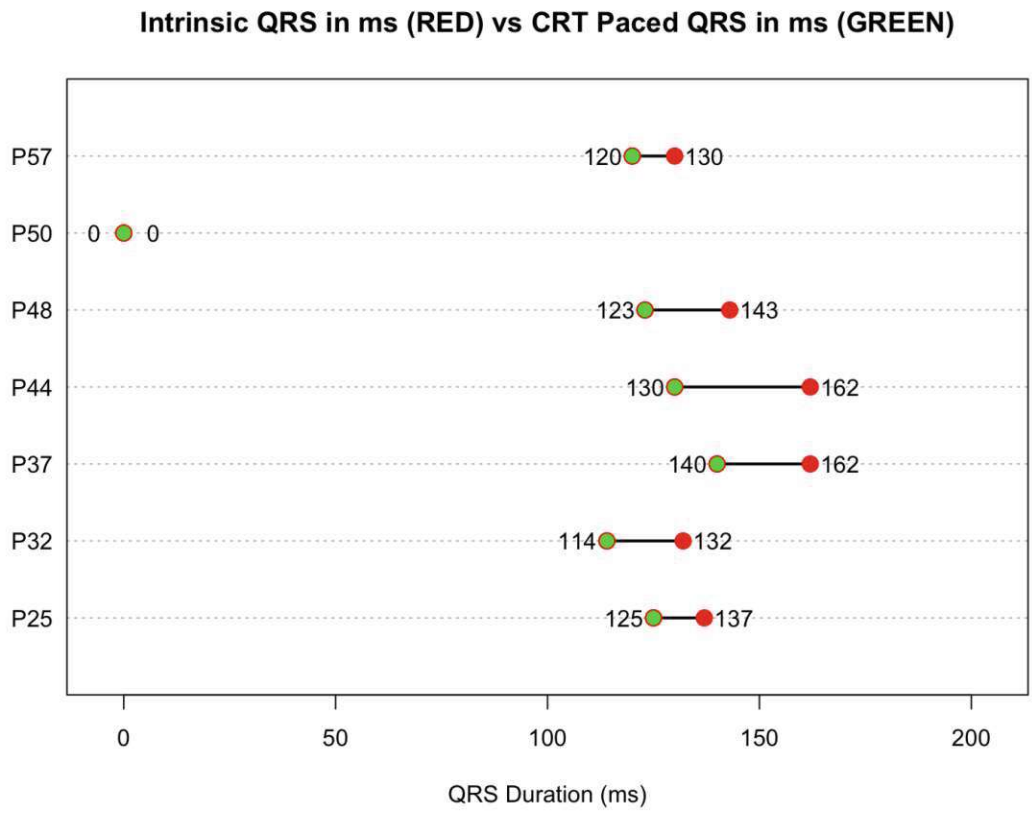

FIGURE 3.9: Native QRS Duratoin vs. CRT Pacing QRS Duration.

Another representation of the data is shown in Figure 3.9. As observed in the chart, all the green dots, which represent CRT Pacing, are on the left side, indicating the effectiveness of CRT in reducing QRS Duration. However, it is significant that none of the CRT Pacing QRS durations fall below 100 ms, a threshold that was observed in LBB Pacing. This observation could suggest that LBB Pacing is superior, or it might reflect that patients undergoing CRT have more severe cardiac conditions, making further reduction in QRS duration impossible. Since this thesis does not consider the overall health status of the heart, QRS durations will be directly compared without accounting for external factors. Performing T-test and P-value on the table, we got T-statistic of 5.91 and P-value of 0.00197, which are interpreted as following:

– High T-Statistic (5.91): This indicates a strong effect of CRT on reducing

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

QRS duration compared to the hypothesized mean of zero. The high value suggests a clear and significant effect of the intervention.

– Low P-Value (0.00197): This is much lower than the standard alpha level of 0.05, which strongly suggests that the observed differences are statistically significant and not likely to be due to random variation.

The statistical analysis confirms that CRT is effective in reducing QRS duration among the patients in this sample, excluding Patient P50. The significant reduction in QRS durations indicates that CRT provides substantial benefits in terms of improving cardiac synchronization, which is crucial for patients with cardiac dysynchrony.

3.1.4 Head-to-head Comparison: LBB vs RV Pacing

A significant difference between LBB and RV pacing can be observed, best highlighted in the head-to-head comparison of patients in whom both pacing methods were performed.

#	ID	Implant/ Follow-Up	Electrode/ Lead	Threshold	Sensing	Impedance	Native QRS	Paced QRS
Patient 1	P1	Implant	RV	0.5 V	14 mV	630 Ohms	98 ms	188 ms
			LBB	0.5 V	6.8 mV	722 Ohms		115 ms
Patient 4	P4	Follow-up	RV	0.5 V	14.3 mV	863 Ohms	188 ms	185 ms
			LBB	0.25 V	NA	1140 Ohms		123 ms
Patient 5	P5	Implant	RV	0.7 V	8.3 mV	437 Ohms	165 ms	177 ms
			LBB	0.5 V	8.1 mV	560 Ohms		140 ms
Patient 9	P9	Follow-up	RV	0.5 V	NA	745 Ohms	175 ms	153 ms
			LBB	0.7 V	10.7 mV	952 Ohms		105 ms

FIGURE 3.10: Head-to-Head Comparison of LBB and RV QRS Durations

Out of the table 3.10, we can comment each patient separately as it's not a big group. The first comparison will be done comparing both pacing methods to Native QRS Duration:

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

- **Patient 1 (Implant):**

  RV pacing widens QRS significantly (+90 ms), while LBB pacing minimally widens it (+17 ms).

- **Patient 4 (Follow-up):**

  RV pacing results in nearly no change (-3 ms), but LBB pacing narrows QRS significantly (-65 ms).

- **Patient 5 (Implant):**

  RV pacing causes a slight widening (+12 ms), while LBB pacing narrows it (-25 ms).

- **Patient 9 (Follow-up):**

  RV pacing narrows QRS slightly (-22 ms), while LBB pacing results in more narrowing (-70 ms).

The mean values and their standard deviations of each group of QRS Duration are as following:

- **Native QRS Duration:** 156.5 +/- 40.12 ms
- **RV Paced QRS Duration:** 175.75 +/- 15.86 ms
- **LBB Paced QRS Duration:** 120.75 +/- 14.79 ms

When comparing both groups of Pacing methods, we see that mean value of the difference between RV and LBB QRS Durations (RV - LBB Difference) is 55 ms, with a standard deviation of 14.97 ms.

LBB pacing consistently narrows QRS duration compared to RV pacing, both relative to the native QRS and in direct head-to-head comparison. This mean difference of 55 ms underscores the physiological advantage of LBB pacing. LBB pacing appears to provide better outcomes and may be preferable, particularly in patients with prolonged native QRS durations.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

3.1.5 Head-to-head Comparison: RV vs CRT Pacing

Best way to see the differences between RV and CRT Pacing method is by comparing them in the same patient. In our dateset, we can compare directly the following patients:

#	ID	Implant/ Follow-Up	Electrode/ Lead	Threshold	Sensing	Impedance	Native QRS	Paced QRS
Patient 25	P25	Follow-up	RV	2.75 V	5.1 mV	456 Ohms	137 ms	160 ms
			CRT	0.75 V	NA	450 Ohms		125 ms
Patient 32	P32	Implant	RV	0.5 V	4.4 mV	532 Ohms	132 ms	170 ms
			CRT	0.75 V		817 Ohms		114 ms
Patient 37	P37	Implant	RV	0.6 V	4.4 mV	688 Ohms	162 ms	194 ms
			CRT	2.0 V		510 Ohms		140 ms
Patient 44	P44	Implant	RV	0.5 V	5.0 mV	571 Ohms	162 ms	165 ms
			CRT	1.25 V				130 ms
Patient 57	P57	Implant	RV	0.5 V	8.9 mV	380 Ohms	130 ms	162 ms
			CRT	0.75 V		430 Ohms		120 ms

FIGURE 3.11: Head-to-Head Comparison of RV and CRT QRS Durations

Since the table has only five patients, we can compare them one by one:

- **Patient 25 (Follow-up):**

  RV pacing widens QRS slightly (+23 ms), while CRT pacing narrows it (-12 ms).

- **– Patient 32 (Implant):**

  RV pacing significantly widens QRS (+38 ms), whereas CRT pacing narrows it (-18 ms).

- **Patient 44 (Implant):**

  RV pacing has minimal effect (+3 ms), but CRT pacing significantly narrows QRS (-32 ms).

- **Patient 57 (Follow-up):**

  RV pacing widens QRS moderately (+32 ms), while CRT pacing narrows it slightly (-10 ms).

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

The mean values and their standard deviations of each group of QRS Duration are as following:

- **Native QRS Duration:** 144.6 ± 16.09 ms
- **RV Paced QRS Duration:** 170.2 ± 13.83 ms
- **CRT Paced QRS Duration:** 125.8 ± 9.91 ms

When comparing both groups of pacing methods, we see that the mean value of the difference between RV and CRT QRS durations (RV - CRT Difference) is 44.4 ms, with a standard deviation of 9.68 ms.

CRT pacing consistently narrows QRS duration compared to RV pacing, both relative to the native QRS and in direct head-to-head comparison. This mean difference of 44.4 ms underscores the physiological advantage of CRT pacing. CRT pacing appears to provide better outcomes and may be preferable, particularly in patients with prolonged native QRS durations.

3.2 Threshold

Compared to the QRS Duration, analysis of the Threshold, Sensing, and Impedance, is slightly different. QRS Duration was the comparison between patient's own QRS and its paced QRS; meanwhile other parameters shall be compared to the reference values, as shown in 1.32. The whole dataset can be seen in tables 2.6 and 2.7. We'll start comparing each type of pacing one by one.

3.2.1 LBB Pacing Threshold

In our analysis of the Left Bundle Branch Pacing (LBBP) group, we examine the threshold values at both the implant and follow-up stages, comparing them against the upper limit of 1.5 V. Thresholds exceeding this limit are

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

considered high - even though at certain cases they need to be accepted due to lack of other options. The whole data set can be seen in the following table 3.12:

#	ID	Implant/ Follow-up	Threshold (V)
1	P1	Implant	0.5 V
2	P2	Follow-up	1.0 V
3	P3	Follow-up	0.75 V
4	P4	Follow-up	0.25 V
5	P5	Implant	0.5 V
6	P6	Implant	0.3 V
7	P7	Follow-up	0.8 V
8	P8	Implant	1.2 V
9	P9	Follow-up	0.7 V
10	P10	Follow-up	1.2 V
11	P11	Implant	1.0 V
12	P12	Implant	1.2 V
13	P13	Follow-up	0.5 V
14	P14	Follow-up	0.5 V
15	P27	Implant	0.5 V
16	P28	Implant	0.75 V
17	P29	Implant	0.6 V
18	P33	Implant	1.0 V
19	P34	Follow-up	0.5 V
20	P35	Implant	1.3 V
21	P36	Implant	87
22	P40	Follow-up	0.8 V
23	P42	Implant	0.5 V
24	P43	Implant	1.2 V
25	P46	Follow-up	0.5 V
26	P47	Follow-up	0.6 V
27	P51	Follow-up	1.0 V
28	P58	Implant	0.5 V
29	P59	Implant	0.5 V

FIGURE 3.12: LBB Pacing Dataset

Summarizing the LBBP values out of twenty-nine (29) patients, we get the following:

– **Mean Threshold: 0.74 V**

The mean threshold value across all patients in the LBBP group is 0.74V,

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

which is well below the 1.5 V upper limit, indicating efficient pacing overall.

- **Median Threshold: 0.7 V**

  The median value is 0.7 V, indicating that half of the patients have thresholds below this level and half above, suggesting a balanced distribution.

- **Standard Deviation: 0.3 V**

  The standard deviation of 0.3 V indicates moderate variability in threshold values among patients.

- **Minimum Threshold: 0.25 V**

  The lowest observed threshold is 0.25 V, indicating that some patients require very little energy for effective pacing.

- **Maximum Threshold: 1.3 V**

  The maximum threshold observed is 1.3 V, which is still below the 1.5 V limit, showing that all patients are within the acceptable range.

The overall analysis of the LBBP group shows that the mean and median thresholds are comfortably below the 1.5 V limit, with moderate variability across the group. All thresholds are within the acceptable range, indicating stable and efficient pacing across the patient population.

Another analysis of this group could be done be dividing the group into implant and follow-up sub-groups. A summary of both groups can be seen in figure 3.13:

Description	Minimum	Mean	Median	Std. Deviation	Maximum	No. >1.5 V
Implant	0.3 V	0.78 V	0.68 V	0.33 V	1.3 V	0
Follow-up	0.25 V	0.7 V	0.7 V	0.26 V	1.2 V	0

FIGURE 3.13: LBB Pacing Threshold Data

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

The LBBP thresholds show similar mean and median values between the implant and follow-up phases, with slightly lower variability in follow-up. All thresholds remain below the 1.5V limit, indicating stable and efficient pacing performance over time. No patients exceeded the acceptable threshold in either phase.

3.2.2 RV Pacing Threshold

In this analysis, we consider the entire Right Ventricular Pacing (RVP) group consisting of 33 patients without distinguishing between implant and follow-up phases. The focus is on evaluating the overall threshold values against the 1.5V upper limit to assess the efficiency of the RVP system.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

#	ID	Implant/ Follow-up	Threshold (V)
1	P1	Implant	0.5 V
2	P4	Follow-up	0.5 V
3	P5	Implant	0.7 V
4	P9	Follow-up	0.5 V
5	P15	Follow-up	1.75 V
6	P16	Implant	0.5 V
7	P17	Implant	0.5 V
8	P18	Implant	0.6 V
9	P19	Implant	0.75 V
10	P20	Implant	0.5 V
11	P21	Implant	0.5 V
12	P22	Implant	0.5 V
13	P23	Implant	0.5 V
14	P24	Implant	0.88 V
15	P25	Follow-up	2.75 V
16	P26	Follow-up	1.0 V
17	P28	Implant	0.5 V
18	P30	Implant	1.25 V
19	P31	Implant	0.5 V
20	P32	Implant	0.5 V
21	P37	Implant	0.6 V
22	P38	Follow-up	0.6 V
23	P39	Follow-up	0.4 V
24	P41	Implant	0.5 V
25	P44	Implant	0.5 V
26	P45	Implant	0.9 V
27	P49	Follow-up	0.8 V
28	P52	Follow-up	0.5 V
29	P53	Implant	0.2 V
30	P54	Follow-up	0.6 V
31	P55	Follow-up	0.5 V
32	P56	Follow-up	0.5 V
33	P57	Implant	0.5 V

FIGURE 3.14: RV Pacing Dataset

Summarizing the RVP values out of thirty three (33) patients, we get the following:

– **Mean Threshold: 0.69 V**

The mean threshold value across all patients in the RVP group is 0.69V,

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

which is below the 1.5V upper limit, indicating that the majority of patients have efficient pacing requirements.

- **Median Threshold: 0.5 V**

  The median value is 0.5V, indicating that half of the patients have thresholds below this level and half above. This suggests that a large portion of the group has very low energy requirements for effective pacing.

- **Standard Deviation: 0.46 V**

  The standard deviation of 0.46V indicates notable variability in the threshold values among patients, with some significantly higher thresholds.

- **Minimum Threshold: 0.2 V**

  The lowest observed threshold is 0.2V, showing that some patients require minimal energy for effective pacing.

- **Maximum Threshold: 2.75 V**

  The maximum threshold observed is 2.75V, which exceeds the 1.5V limit, indicating a higher energy requirement in at least one case.

The overall analysis of the RVP group shows a mean threshold that is comfortably below the 1.5V limit, though there is a wide range of variability, as evidenced by the high standard deviation and the maximum threshold of 2.75V. The median threshold at 0.5V suggests that many patients have very low pacing energy requirements, but the presence of outliers indicates that close monitoring may be necessary for some.

Another analysis of this group could be done be dividing the group into implant and follow-up sub-groups. A summary of both groups can be seen in figure 3.15:

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Description	Minimum	Mean	Median	Std. Deviation	Maximum	No. >1.5 V
Implant	0.2 V	0.59 V	0.5 V	0.21 V	1.25 V	0
Follow-up	0.4 V	0.87 V	0.55 V	0.7 V	2.75 V	2

FIGURE 3.15: RV Pacing Threshold Data

RVP thresholds show a moderate increase from implant to follow-up, with the mean and variability both increasing. While most thresholds remain below the 1.5 V limit, two cases in the follow-up phase exceed this threshold, indicating that some patients may require closer monitoring over time to ensure optimal pacing efficiency. These 2 values of high threshold could indicate either a dislodged lead, lead failure, etc.

3.2.3 CRT Pacing Threshold

Cardiac Resynchronization Therapy (CRT) does not have a specific threshold itself; instead, we focus on the threshold of the LV lead, which plays a critical role in resynchronizing the heart's left and right ventricles. The threshold of the LV lead is vital for ensuring effective therapy, with a reference value of 2.0V considered optimal for proper function.

#	ID	Implant/ Follow-up	Threshold (V)
1	P25	Follow-up	0.75 V
2	P32	Implant	0.75 V
3	P37	Implant	2.0 V
4	P44	Implant	1.25 V
5	P48	Follow-up	1.9 V
6	P50	Implant	0.6 V
7	P57	Implant	0.75 V

FIGURE 3.16: CRT (LV) Pacing Threshold Data

For the CRT (LV Pacing) group, the mean threshold is 1.11V, with a median of 0.75V. The thresholds range from 0.6V to 2.0V, showing variability within the group. All patients have thresholds at or below the acceptable

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

2.0V limit, indicating that the pacing system is functioning efficiently across the group, though some cases are at the upper threshold and may benefit from closer monitoring. Summarizing the LV Pacing values out of seven (7) patients, we get the following:

- **Mean Threshold: 1.14 V**

  The mean threshold across all patients is 1.14 V, which is well within the 2.0V reference limit, indicating that the LV lead is generally functioning efficiently.

- **Median Threshold: 0.75 V**

  The median threshold is 0.75 V, showing that half of the patients have thresholds at or below this level, indicating that most patients have relatively low energy requirements.

- **Standard Deviation: 0.59 V**

  The standard deviation of 0.59 V reflects moderate variability in threshold values, with some patients requiring higher energy levels.

- **Minimum Threshold: 0.6 V**

  The lowest observed threshold is 0.6 V, indicating very efficient pacing in some patients.

- **Maximum Threshold: 2.0 V**

  The maximum threshold observed is 2.0 V, which is right at the acceptable limit, with no patients exceeding the 2.0V reference threshold.

The analysis shows that all patients in the CRT (LV Pacing) group have thresholds at or below the 2.0V reference limit, ensuring effective resynchronization. While most thresholds are low, the variability suggests a need for personalized assessment to maintain optimal pacing.

Cardiac Resynchronization Therapy (CRT) is primarily used to treat heart failure, a condition characterized by the enlargement of the heart and its

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

chambers, which can complicate effective pacing. Consequently, it is not uncommon for threshold values to exceed the standard reference levels, and such elevated thresholds may still be considered acceptable in clinical practice. Another challenge in CRT is the potential stimulation of the phrenic nerve during pacing, which must be avoided. To address this, clinicians may need to reposition the lead or select a different pacing vector, even if it results in higher pacing thresholds.

Looking into implant versus follow-up group, even though the group is not so large, we get the following:

Description	Minimum	Mean	Median	Std. Deviation	Maximum	No. >2.0 V
Implant	0.6 V	1.07 V	0.75 V	0.58 V	2.0 V	0
Follow-up	0.75 V	1.33 V	1.33 V	0.81 V	1.9 V	0

FIGURE 3.17: CRT (LV) Pacing: Implant vs Follow-up

CRT (LV Pacing) thresholds show a slight increase from implant to follow-up, with the mean and median values rising closer to the 2.0 V reference limit. However, all thresholds remain within the acceptable range, indicating stable and effective pacing over time, with no cases exceeding the 2.0V threshold. The increase in variability at follow-up suggests that individual patient monitoring remains important to ensure continued effectiveness.

3.2.4 Head-to-head Comparison: LBB vs. RV Pacing

In this analysis, we compare the pacing thresholds for Left Bundle Branch Pacing (LBBP) and Right Ventricular Pacing (RVP) in patients where both pacing methods were available. The goal is to determine whether there is a significant difference in the energy required for effective pacing between the two methods.

Patients having both pacing methods available are grouped in the following figure:

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

#	ID	Implant/ Follow-Up	Electrode/Lead	Threshold
Patient 1	P1	Implant	RV Lead:	0.5 V
Patient 1	P1		LBB Lead:	0.5 V
Patient 5	P5	Implant	RV Lead:	0.5 V
Patient 5	P5		LBB Lead:	0.25 V
Patient 9	P9	Follow-up	RV Lead:	0.70 V
Patient 9	P9		LBB Lead:	0.50 V
Patient 28	P28	Implant	RV Lead:	0.5 V
Patient 28	P28		LBB Lead:	0.75 V

FIGURE 3.18: Head-to-Head comparison of LBB and RV Threshold

The following output was taken from the table:

– **Patient 1 (Implant):**

Both the RV and LBB leads have identical thresholds of 0.5 V, resulting in no difference between the two leads.

– **Patient 4 (Follow-up):**

The RV lead has a threshold of 0.5 V, while the LBB lead has a slightly lower threshold of 0.25 V. The difference of 0.25 V is minimal and not expected to affect the pacing outcome.

– **Patient 5 (Implant):**

The RV lead has a threshold of 0.7 V, while the LBB lead has a threshold of 0.5 V. The difference of 0.2 V is considered minimal and should not impact the pacing outcome.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

– **Patient 9 (Follow-up):**

The LBB lead has a slightly higher threshold of 0.7 V compared to the RV lead at 0.5 V. The 0.2 V difference is minimal and unlikely to affect the pacing outcome.

– **Patient 28 (Implant):**

The RV lead has a threshold of 0.5 V, while the LBB lead has a slightly higher threshold of 0.75 V. The difference of 0.25 V is minimal and not expected to have any significant effect.

In this analysis, all patients exhibit minimal differences in threshold values between the RV and LBB leads, with differences ranging from 0 to 0.25 V. Statistically, this indicates a high degree of equivalence between the two pacing methods in terms of energy requirements. The consistency of minimal differences supports the conclusion that both RV and LBB leads are effective and reliable in achieving optimal pacing thresholds, with no significant impact on the overall pacing performance.

3.3 Sensing

Similarly to threshold, sensing values will be analyzed compared to the reference values. Since sensing it's not a factor in CRT device, as most of the implantable devices do not use sensing in LV lead, it will be fully neglected from this analysis. Analysis will be done only on RV and LBB values.

3.3.1 LBB Lead Sensing

Sensing is a critical parameter in pacing systems, as it ensures the accurate detection of the heart's electrical activity, enabling the device to deliver timely and appropriate pacing. For patients undergoing Left Bundle Branch Pacing (LBBP), a sensing threshold greater than 5 mV is typically considered

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

effective. This analysis examines the sensing values across a group of patients, excluding those where sensing was not measurable due to a lack of intrinsic rhythm, or patient being very symptomatic when trying to measure the signal from its heart rate. We will begin with an overall analysis of the group, followed by a comparison between implant and follow-up phases.

The whole group, consisting of twenty six (26) patients, can be seen in the picture 3.19:

#	ID	Implant/ Follow-up	Sensing (mV)
1	P1	Implant	6.8 mV
2	P2	Follow-up	22.4 mV
3	P3	Follow-up	22.4 mV
4	P4	Follow-up	NA
5	P5	Implant	8.1 mV
6	P6	Implant	12.0 mV
7	P7	Follow-up	14.1 mV
8	P8	Implant	8.9 mV
9	P9	Follow-up	10.7 mV
10	P10	Follow-up	NA
11	P11	Implant	12.5 mV
12	P12	Implant	10.0 mV
13	P13	Follow-up	14.9 mV
14	P14	Follow-up	16.6 mV
15	P27	Implant	13.7 mV
16	P28	Implant	5.4 mV
17	P29	Implant	8.3 mV
18	P33	Implant	15.6 mV
19	P34	Follow-up	11.2 mV
20	P35	Implant	8.8 mV
21	P36	Implant	7.5 mV
22	P40	Follow-up	NA
23	P42	Implant	7.8 mV
24	P43	Implant	13.0 mV
25	P46	Follow-up	5.6 mV
26	P47	Follow-up	7.8 mV
27	P51	Follow-up	15.6 mV
28	P58	Implant	6.8 mV
29	P59	Implant	11.2 mV

FIGURE 3.19: LBB Sensing Values

Since the group is small, analysis was done by comparing one by one:

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

- **Mean Sensing Value: 11.57 mV**

  On average, the sensing values are well above the reference threshold of 5 mV, indicating strong signal detection across the group.

- **Median Sensing Value: 10.7 mV**

  The median value being close to the mean suggests a balanced distribution of sensing values among patients, with half of the group having sensing values above 10.7 mV and half below.

- **Standard Deviation: 4.75 mV**

  The moderate standard deviation reflects variability in sensing performance, with some patients showing significantly higher or lower values, but all within an effective range.

- **Minimum Sensing Value: 5.4 mV**

  The lowest sensing value observed is 5.4 mV, just above the reference threshold, indicating that even the least sensitive measurements meet the necessary criteria for effective pacing.

- **Maximum Sensing Value: 22.4 mV**

  The highest sensing value of 22.4 mV reflects exceptionally strong signal detection, which can be advantageous for consistent and reliable pacing.

The overall sensing analysis shows that all patients have sensing values above the critical 5 mV threshold, with mean and median values well within a desirable range. The variability observed is moderate, with all patients demonstrating adequate sensing for effective pacing. This suggests that the pacing system is functioning optimally for the majority of patients, ensuring accurate signal detection and reliable pacing outcomes.

Another closer look will be made by comparing the implant and follow-up values. By doing that, we get:

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Description	Minimum	Mean	Median	Std. Deviation	Maximum	No. <5 mV
Implant	5.4 mV	10.49 mV	9.65 mV	3.67 mV	17.9 mV	0
Follow-up	8.3 mV	15.88 mV	15.6 mV	6.51 mV	22.4 mV	0

FIGURE 3.20: LBB Sensing: Implant vs. Follow-Up Group

In both the implant and follow-up phases, all sensing values are well above the 5 mV reference threshold, with no cases falling below this critical level. The analysis shows that sensing performance is strong during implantation and improves further during follow-up, contributing to reliable and effective pacing across all patients. The increase in sensing values during follow-up indicates that the system may become more efficient over time, ensuring continued success in pacing therapy.

3.3.2 RV Lead Sensing

The RV sensing group consists of thirty two patients, with values as seen in the table 3.21:

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

#	ID	Implant/ Follow-up	Sensing (mV)
1	P1	Implant	14 mV
2	P4	Follow-up	14.3 mV
3	P5	Implant	8.3 mV
4	P9	Follow-up	NA
5	P15	Follow-up	9.3 mV
6	P16	Implant	15.2 mV
7	P17	Implant	5.0 mV
8	P18	Implant	8.4 mV
9	P19	Implant	20 mV
10	P20	Implant	12.3 mV
11	P21	Implant	10.1 mV
12	P22	Implant	12.6 mV
13	P23	Implant	10.0 mV
14	P24	Implant	4.9 mV
15	P25	Follow-up	5.1 mV
16	P26	Follow-up	10.0 mV
17	P28	Implant	5.4 mV
18	P30	Implant	7.6 mV
19	P31	Implant	15.68 mV
20	P32	Implant	4.4 mV
21	P37	Implant	4.4 mV
22	P38	Follow-up	7.6 mV
23	P39	Follow-up	8.7 mV
24	P41	Implant	11.0 mV
25	P44	Implant	5.0 mV
26	P45	Implant	17.9 mV
27	P49	Follow-up	8.7 mV
28	P52	Follow-up	10.0 mV
29	P53	Implant	8.8 mV
30	P54	Follow-up	9.1 mV
31	P55	Follow-up	11.2 mV
32	P56	Follow-up	5.6 mV
33	P57	Implant	8.9 mV

FIGURE 3.21: RV Sensing Values

The following statistical values are derived out of the table above:

– **Mean Sensing Value: 9.67 mV**

  The average sensing value across all patients is 9.67 mV, indicating effective signal detection well above the 5 mV reference threshold.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

– **Median Sensing Value: 9.0 mV**

The median value of 9.0 mV suggests that half of the patients have sensing values below this level and half above, indicating a balanced distribution of sensing values.

– **Standard Deviation: 3.99 mV**

The standard deviation of 3.99 mV reflects moderate variability in sensing values, with some patients showing higher or lower values.

– **Minimum Sensing Value: 4.4 mV**

The lowest observed sensing value is 4.4 mV, which is below the reference threshold of 5 mV, indicating potential concerns for effective pacing in these cases.

– **Maximum Sensing Value: 20.0 mV**

The highest observed sensing value is 20.0 mV, reflecting strong signal detection in some patients.

The overall sensing analysis for the RV pacing group shows that most patients have sensing values well above the 5 mV reference threshold, with a mean of 9.67 mV. However, there are 3 cases where the sensing value falls below the effective threshold of 5 mV, which may require closer monitoring or adjustment to ensure effective pacing. But looking at the minimum value which is 4.4 mV, this is "border-line" value and may be treated as acceptable if it's stable and not fluctuating a lot.

If we divide the group into the Implant and Follow-up groups, we get the following data:

Description	Minimum	Mean	Median	Std. Deviation	Maximum	No. <5 mV
Implant	4.4 mV	9.99 mV	8.9 mV	4.61 mV	20.0 mV	3
Follow-up	5.1 mV	9.05 mV	9.1 mV	2.53 mV	14.3 mV	0

FIGURE 3.22: RV Sensing: Implant vs. Follow-Up Group

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

The comparison between the implant and follow-up phases shows that the mean sensing value slightly decreases from 9.99 mV during implantation to 9.05 mV during follow-up. However, the variability in sensing values decreases during follow-up, with no cases below the critical 5.0 mV threshold, ensuring reliable sensing of the intrinsic heart rhythm. In the implant phase, 3 cases had sensing values below 5.0 mV, which may require closer monitoring. Overall, the sensing performance remains strong across both phases, with slightly improved consistency during follow-up.

3.3.3 Head-to-Head Comparison: LBB vs. RV Sensing

Head-to-head comparison can be done in four patients, where both RV and LBB Sensing values were measured. The data can be seen in the figure 3.23:

#	ID	Implant/ Follow-Up	Electrode/Lead	Sensing
Patient 1	P1	Implant	RV Lead:	14 mV
Patient 1	P1		LBB Lead:	6.8 mV
Patient 5	P5	Implant	RV Lead:	8.3 mV
Patient 5	P5		LBB Lead:	8.1 mV
Patient 9	P9	Follow-up	RV Lead:	11.2 mV
Patient 9	P9		LBB Lead:	10.7 mV
Patient 28	P28	Implant	RV Lead:	5.4 mV
Patient 28	P28		LBB Lead:	5.4 mV

FIGURE 3.23: Head-to-Head Comparison of LBB and RV Sensing

Since this comparison consists of only four patients, we can comment them one by one:

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

– **Patient 1 (Implant):**

The RV lead shows a significantly higher sensing value (14 mV) compared to the LBB lead (6.8 mV), with a 51.43% difference. This suggests that the RV lead detects the heart's electrical signals much more strongly in this case, even though also the LBB values are within normal. This difference could come as a result of difficult positioning of LBB lead, or the healthiness of heart muscle near the electrode is not optimal.

– **Patient 5 (Implant):**

The sensing values for the RV and LBB leads are very close, with a 2.41% difference, indicating a tiny difference that is not expected to impact the outcome. Both leads perform similarly.

– **Patient 9 (Follow-up):**

The RV lead has a slightly higher sensing value (11.2 mV) compared to the LBB lead (10.7 mV), with a 4.46% difference. This is considered a tiny difference, indicating that both leads are effectively equivalent in performance.

– **Patient 28 (Implant):**

Both the RV and LBB leads have identical sensing values (5.4 mV), resulting in no difference in sensing performance.

In this analysis, most patients show a tiny difference in sensing values between the RV and LBB leads, which is not expected to impact the overall pacing outcome. However, in Patient 1, there is a significant difference, with the RV lead providing much stronger signal detection. For the other patients, the differences are negligible, suggesting that both RV and LBB leads are similarly effective for sensing in these cases.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

3.4 Impedance

Impedance is a crucial parameter in evaluating the performance and efficiency of pacing systems. It reflects the resistance encountered by the electrical signals as they travel through the lead and the surrounding tissue.

Impedance, being the last parameter, will be compared to the reference values, similarly as threshold and sensing. As seen in figure 1.32, normal values for pacing ranges between 300 to 2000 Ohms. Any value lower or higher than the two limits, could be an indicator of lead malfunctioning or displacement. In real-life scenarios, impedance values are most commonly found within the narrower range of 400 to 1200 Ohms.

A trend of impedance it's a great indicator if lead is not performing as it should, that's why impedance value and its trend are of great importance.

Similar to sensing, the CRT devices (or better said LV Lead) are not measuring the impedance. For this reason, CRT devices will not be included in this analysis.

3.4.1 LBB Lead Impedance

A group of twenty nine (29) patients is analyzed, with the dataset as shown in the figure 3.24:

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

#	ID	Implant/ Follow-up	Impedance (Ohms)
1	P1	Implant	722 Ohms
2	P2	Follow-up	603 Ohms
3	P3	Follow-up	750 Ohms
4	P4	Follow-up	1140 Ohms
5	P5	Implant	560 Ohms
6	P6	Implant	870 Ohms
7	P7	Follow-up	578 Ohms
8	P8	Implant	870 Ohms
9	P9	Follow-up	952 Ohms
10	P10	Follow-up	570 Ohms
11	P11	Implant	830 Ohms
12	P12	Implant	853 Ohms
13	P13	Follow-up	390 Ohms
14	P14	Follow-up	839 Ohms
15	P27	Implant	876 Ohms
16	P28	Implant	570 Ohms
17	P29	Implant	677 Ohms
18	P33	Implant	900 Ohms
19	P34	Follow-up	610 Ohms
20	P35	Implant	730 Ohms
21	P36	Implant	685 Ohms
22	P40	Follow-up	468 Ohms
23	P42	Implant	691 Ohms
24	P43	Implant	755 Ohms
25	P46	Follow-up	520 Ohms
26	P47	Follow-up	526 Ohms
27	P51	Follow-up	785 Ohms
28	P58	Implant	856 Ohms
29	P59	Implant	820 Ohms

FIGURE 3.24: LBB Impedance Values

Out of it, we get the following statistical values:

– **Mean Impedance Value: 724 Ohms**

  The average impedance across all patients is 724 Ohms, falling well within the typical real-life range of 400 to 1200 Ohms, indicating effective pacing performance.

– **Median Impedance Value: 730 Ohms**

  The median value of 730 Ohms suggests a balanced distribution of

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

impedance values, with half of the patients having values below this level and half above.

- **Standard Deviation: 167 Ohms**

  The standard deviation of 167 Ohms indicates moderate variability in impedance values among the patients, with most values clustered around the mean.

- **Minimum Impedance Value: 390 Ohms**

  The lowest impedance value observed is 390 Ohms, slightly below the real-life typical range but still within the broader acceptable limit of 300 Ohms.

- **Maximum Impedance Value: 1140 Ohms**

  The highest observed impedance value is 1140 Ohms, well within both the real-life and clinical acceptable ranges.

The overall analysis of impedance values shows that the vast majority of patients have impedance levels within the real-life typical range of 400 to 1200 Ohms, with a mean impedance of 724 Ohms. Only one patient has a value slightly below this range but still within the clinically acceptable limit. These findings suggest that the pacing systems are functioning efficiently across the group, with impedance values that support safe and effective pacing for most patients.

Comparing the group by separating them into Implant and Follow-up Group, we get the following results:

Description	Minimum	Mean	Median	Std. Deviation	Maximum	# out of range
Implant	560 Ohms	766.6 Ohms	787.5 Ohms	109.1 Ohms	900 Ohms	0
Follow-up	390 Ohms	671.6 Ohms	603 Ohms	211.7 Ohms	1140 Ohms	0

FIGURE 3.25: LBB Impedance: Implant vs. Follow-Up Group

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

The comparison between the implant and follow-up phases reveals that the mean impedance value decreases slightly from 766.6 Ohms during the implant phase to 671.6 Ohms during follow-up. The variability in impedance values increases during follow-up, with a standard deviation of 211.7 Ohms compared to 109.1 Ohms during implantation. Despite this variability, the vast majority of patients in both phases have impedance values within the normal range of 400-1200 Ohms, indicating consistent and effective pacing performance. Only one patient during follow-up exhibited an impedance value slightly below the typical range, though it remained within acceptable limits.

It is worth noting that impedance is one of the "easiest" parameters, especially during implantation. This is because it falls easily within acceptable limits. However, things get tricky during follow-ups when there's a lead issue (either a lead fracture, insulation breach, lead displacement, etc.). In this case, as mentioned before, impedance trends which are supported by most of the devices in the market could provide an idea of what happened. Out of impedance trends, we can derive if the issue happened abruptly, or if it started slowly over a long period of time, etc.

In some cases, it's worth mentioning that when the lead is not well positioned and do not have a good contact to the heart muscle, may give you different impedance values between seconds of measurement. In these cases, even if the pacing is working it will be up to physician to decide if the lead revision should be done.

3.4.2 RV Lead Impedance

Impedance values derived from RV Lead consists of 33 patients. The whole dataset can be seen in the figure:

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

#	ID	Implant/ Follow-up	Impedance (Ohms)
1	P1	Implant	630 Ohms
2	P4	Follow-up	863 Ohms
3	P5	Implant	437 Ohms
4	P9	Follow-up	745 Ohms
5	P15	Follow-up	665 Ohms
6	P16	Implant	630 Ohms
7	P17	Implant	607 Ohms
8	P18	Implant	764 Ohms
9	P19	Implant	608 Ohms
10	P20	Implant	532 Ohms
11	P21	Implant	551 Ohms
12	P22	Implant	570 Ohms
13	P23	Implant	730 Ohms
14	P24	Implant	670 Ohms
15	P25	Follow-up	456 Ohms
16	P26	Follow-up	418 Ohms
17	P28	Implant	380 Ohms
18	P30	Implant	532 Ohms
19	P31	Implant	944 Ohms
20	P32	Implant	532 Ohms
21	P37	Implant	688 Ohms
22	P38	Follow-up	487 Ohms
23	P39	Follow-up	965 Ohms
24	P41	Implant	530 Ohms
25	P44	Implant	571 Ohms
26	P45	Implant	869 Ohms
27	P49	Follow-up	487 Ohms
28	P52	Follow-up	526 Ohms
29	P53	Implant	620 Ohms
30	P54	Follow-up	546 Ohms
31	P55	Follow-up	720 Ohms
32	P56	Follow-up	680 Ohms
33	P57	Implant	380 Ohms

FIGURE 3.26: RV Impedance Values

The overall statistical values fall all within the normal range, and can be seen below:

– **Mean Impedance Value: 616.2 Ohms**

The average impedance across all patients is 616.2 Ohms, well within the real-life typical range of 400-1200 Ohms.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

– **Median Impedance Value: 607.0 Ohms**

The median impedance value is 607.0 Ohms, indicating that half of the patients have impedance values below this level and half above, showing a balanced distribution.

– **Standard Deviation: 150.3 Ohms**

The standard deviation of 150.3 Ohms indicates moderate variability in impedance values among the patients.

– **Minimum Impedance Value: 380.0 Ohms**

The lowest observed impedance value is 380 Ohms, slightly below the real-life typical range but still within the broader acceptable limit of 300 Ohms.

– **Maximum Impedance Value: 965.0 Ohms**

The highest observed impedance value is 965 Ohms, well within the normal range.

The overall analysis of the corrected RV impedance data shows that the majority of patients fall within the normal range of 400-1200 Ohms, with a mean value of 616.2 Ohms. Two patients have impedance values slightly below the typical range, but they remain within the broader acceptable limits. The data suggests that the RV pacing systems are functioning efficiently across the group, with most patients exhibiting normal impedance levels.

Dividing this the whole group into Implant (consisting of twenty one (21) patients) and Follow-up Groups (consisting of twelve (12) patients), we get the following statistical data:

Description	Minimum	Mean	Median	Std. Deviation	Maximum	# out of range
Implant	380 Ohms	608.3 Ohms	607 Ohms	140.4 Ohms	944 Ohms	0
Follow-up	418 Ohms	629.8 Ohms	605.5 Ohms	172 Ohms	965 Ohms	0

FIGURE 3.27: RV Impedance: Implant vs. Follow-Up Group

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

The comparison between the implant and follow-up phases shows that the mean impedance value slightly increases from 608.3 Ohms during implantation to 629.8 Ohms during follow-up. The variability in impedance values is greater during follow-up, but all patients remain within the normal range of 400-1200 Ohms. This indicates stable and effective pacing performance across both phases, with the RV leads maintaining impedance values that support optimal device function.

3.4.3 Head-to-head Comparison: LBB vs. RV Impedance

Head-to-head comparison can be done in four patients, where both RV and LBB Impedance values were measured. The data can be seen in the figure 3.28:

#	ID	Implant/ Follow-Up	Electrode/ Lead	Impedance
Patient 1	P1	Implant	RV Lead:	630 Ohms
Patient 1	P1		LBB Lead:	722 Ohms
Patient 4	P4	Follow-up	RV Lead:	863 Ohms
Patient 4	P4		LBB Lead:	1140 Ohms
Patient 5	P5	Implant	RV Lead:	437 Ohms
Patient 5	P5		LBB Lead:	560 Ohms
Patient 9	P9	Follow-up	RV Lead:	753 Ohms
Patient 9	P9		LBB Lead:	952 Ohms
Patient 28	P28	Implant	RV Lead:	380 Ohms
Patient 28	P28		LBB Lead:	570 Ohms

FIGURE 3.28: Head-to-Head Comparison of LBB and RV Impedance

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Since this comparison consists of only four patients, we can comment them one by one:

- **Patient 1 (Implant) - LBB Impedance 722 Ohms | RV Impedance 630 Ohms:**
  The impedance difference between the RV and LBB leads is within the normal range (both 400-1200 Ohms). The LBB lead has a slightly higher impedance, but this difference is considered normal and does not indicate any issues.

- **Patient 5 (Implant) - LBB Impedance 1140 Ohms | RV Impedance 863 Ohms:**
  Both impedance values fall within the normal range. The LBB lead shows a higher impedance, but this difference is also considered normal given the acceptable range.

- **Patient 9 (Follow-up) - LBB Impedance 437 Ohms | RV Impedance 560 Ohms:**
  The RV lead has a slightly higher sensing value (11.2 mV) compared to the LBB lead (10.7 mV), with a 4.46% difference. This is considered a tiny difference, indicating that both leads are effectively equivalent in performance.

- **Patient 28 (Implant) - LBB Impedance 1140 Ohms | RV Impedance 863 Ohms:**
  Both the RV and LBB leads have identical sensing values (5.4 mV), resulting in no difference in sensing performance.

In all cases, the differences in impedance between the RV and LBB leads are within the normal or acceptable ranges. While the LBB lead generally shows higher impedance, these differences are considered normal and do not indicate any issues with lead function or positioning. The impedance

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

values for both leads fall within the acceptable range of 300-2000 Ohms, and the differences observed are typical for pacing systems.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Chapter 4

Discussion

The results of this study provide a comprehensive comparison of different pacing modalities, including Right Ventricular (RV), Left Bundle Branch (LBB), and Cardiac Resynchronization Therapy (CRT) pacing. By analyzing key parameters such as QRS duration, impedance, sensing, and threshold values, we gain insights into the physiological and clinical impacts of these pacing strategies. These findings not only highlight the effectiveness of each morality in managing specific patient populations but also shed light on the potential benefits of emerging techniques like LBB pacing over conventional methods. This discussion will explore the clinical relevance of the data, considering the long-term implications for patient outcomes, device performance, and the evolving landscape of pacing therapy. Additionally, the discussion will address the limitations of the study and propose areas for future research.

4.1 Comparison of three different pacing methods

4.1.1 RV Lead

RV pacing, while commonly used, presents significant drawbacks, particularly related to the prolongation of QRS duration and its associated adverse outcomes. In this study, patients undergoing RV pacing exhibited increased

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

QRS duration, which is closely linked to interventricular dyssynchrony—a condition that can lead to the progression of heart failure and the development of pacing-induced cardiomyopathy (PiCM). This is consistent with findings from the literature, where Tops et al. [20] and Akerström et al. [1] emphasize the mechanical dyssynchrony caused by RV apical pacing. These studies highlight that chronic RV pacing can lead to a significant decline in left ventricular function, increasing the risk of heart failure and other complications. Additionally, Cho et al. [18] notes that PiCM, observed in a substantial percentage of pacemaker patients, is particularly concerning in those with pre-existing left bundle branch block (LBBB), as it correlates with a progressive reduction in left ventricular ejection fraction (LVEF). The evidence underscores the importance of minimizing unnecessary RV pacing, particularly in patients predisposed to heart failure, as it may worsen their condition over time.

Sweeney MO et al.[19], in their study "Adverse effect of ventricular pacing on heart failure and atrial fibrillation among patients with normal baseline QRS duration" (Circulation, 2003), found that ventricular pacing, even with preserved AV synchrony, significantly increases the risk of heart failure and atrial fibrillation in patients with a normal baseline QRS duration.

In our study, RV pacing resulted in a noticeable prolongation of QRS duration. On average, the QRS duration increased by approximately 35 milliseconds following RV pacing. The median QRS duration in patients who underwent RV pacing was 150 milliseconds, which is significantly longer compared to their baseline values. This prolongation reflects the non-physiological nature of RV pacing, where the activation of the ventricles occurs in a manner that disrupts the natural conduction pathways, leading to mechanical dyssynchrony. The prolonged QRS duration observed in RV pacing patients is consistent with the adverse effects reported in the literature, where QRS durations exceeding 150 milliseconds are associated with increased risks of

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

heart failure and the development of pacing-induced cardiomyopathy (PiCM).

Considering the side effects of RV pacing, it can be concluded that RV pacing could be an option on cases where pacing is mainly used as back-up. These cases include patients with ICDs, where pacing is rarely needed; or patients with AF and intermittent pauses in the ventricle.

4.1.2 LBB Lead

LBB pacing has emerged as a promising alternative to RV pacing, offering a more physiological approach to ventricular activation. In this study, LBB pacing was associated with shorter QRS durations and better ventricular synchronization compared to RV pacing, suggesting a significant reduction in the risks associated with dyssynchrony. Impedance values for LBB pacing were higher than those for RV pacing, reflecting the different anatomical and physiological contexts, yet still within normal ranges. The literature further reinforces these findings, with Cho et al. [18] indicating that LBB pacing can reduce QRS duration more effectively, which is critical for preserving ventricular function and improving patient outcomes. Moreover, the study by Wang et al. [21] highlights the importance of QRS duration as a predictor of survival, suggesting that LBB pacing's ability to achieve shorter QRS durations without the complications associated with RV pacing could make it a superior choice in many cases. The combined evidence points to LBB pacing not only as a viable alternative but potentially as a preferred method for patients at risk of PiCM or those who may not tolerate CRT.

LBB pacing, in contrast to RV Pacing, demonstrated a significant reduction in QRS duration. The average QRS duration following LBB pacing was reduced by about 25 milliseconds, with the median QRS duration in this

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

group being around 120 milliseconds. This reduction brought the QRS duration closer to normal physiological values, indicating improved ventricular synchronization. LBB pacing effectively mimics the natural conduction system, allowing for more synchronous ventricular contraction and better preservation of left ventricular function. The shorter QRS duration observed in patients with LBB pacing suggests that this modality could mitigate the risks associated with prolonged QRS duration, such as heart failure progression and PiCM.

4.1.3 CRT

CRT remains the gold standard for patients with heart failure and wide QRS complexes, and its benefits are well-supported by both this study and existing literature. The findings show that CRT significantly reduces QRS duration and improves ventricular synchronization, which are critical for enhancing cardiac function and reducing heart failure symptoms. Although CRT often involves higher thresholds due to the nature of the pacing sites, the clinical benefits—such as improved synchronization and reduced hospitalizations—far outweigh these technical challenges. Wang et al. [21] corroborate these results, demonstrating that CRT's ability to resynchronize the ventricles leads to substantial improvements in survival rates and quality of life for patients with significant dyssynchrony. However, the technical complexities of CRT, including the challenges of precise lead placement and patient selection, remain important considerations. LBB pacing, as a less invasive and more physiological alternative, offers potential benefits in scenarios where CRT may be less feasible or as an option for patients who do not meet the strict criteria for CRT.

CRT was particularly effective in reducing QRS duration in patients with wide QRS complexes and heart failure. The study showed that CRT reduced

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

the QRS duration by an average of 30-40 milliseconds. The median QRS duration post-CRT was approximately 125 milliseconds, a significant improvement from the baseline values. This reduction in QRS duration is a key factor in the success of CRT, as it directly correlates with improved ventricular function, reduced symptoms of heart failure, and better overall patient outcomes. The ability of CRT to resynchronize the ventricles and achieve a more optimal QRS duration highlights its role as the gold standard in managing patients with advanced heart failure and significant dyssynchrony.

4.1.4 Summary

The results of this study, combined with evidence from the literature, suggest a shifting paradigm in pacing strategies. While RV pacing remains common, its long-term risks, particularly the development of PiCM, make it less favorable for certain patient populations. LBB pacing offers a promising alternative, potentially replacing CRT in some cases, particularly where minimizing QRS duration and avoiding dyssynchrony are critical. However, CRT continues to be indispensable for patients with significant ventricular dyssynchrony, especially those with advanced heart failure.

Future research should focus on long-term comparative outcomes of LBB pacing and CRT, particularly in terms of patient survival, quality of life, and device longevity. Expanding the use of LBB pacing may provide clinicians with a powerful tool for managing patients with complex pacing needs, offering a balance between efficacy and invasiveness.

4.2 Other Electrical Parameters

This section delves into the crucial electrical parameters—threshold, sensing, and impedance—that play a significant role in the performance and reliability of pacing systems. These parameters are evaluated across different pacing

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

modalities: Right Ventricular (RV) pacing, Left Bundle Branch (LBB) pacing, and Cardiac Resynchronization Therapy (CRT), with a focus on the LV lead. Each modality presents unique characteristics in how these parameters influence the effectiveness of pacing therapy.

4.2.1 Threshold

The threshold for RV pacing typically remains within an acceptable range, often below 1.0 V. This low threshold is beneficial as it reduces energy consumption, thus extending the battery life of the device. In this study, RV pacing consistently demonstrated stable threshold values, reflecting good lead placement and reliable myocardial capture.

LBB pacing also showed threshold values within optimal ranges, similar to RV pacing. The threshold for LBB pacing is generally low, which indicates efficient myocardial stimulation and energy conservation. The slight anatomical differences in lead placement in LBB pacing do not appear to significantly affect the threshold levels, making it a reliable alternative to RV pacing.

The threshold for the LV lead in CRT can sometimes be higher due to the more complex anatomy and the potential for variable lead positioning in the coronary sinus. However, in this study, the thresholds for the LV lead were generally within acceptable limits, ensuring effective pacing without excessive energy use. Despite the potential challenges, the thresholds observed did not present any significant difficulties.

4.2.2 Sensing

Sensing in RV pacing is critical for detecting intrinsic cardiac activity and ensuring appropriate pacing. The sensing values recorded in this study for RV pacing were robust, typically above the reference value of 5.0 mV. This

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

indicates reliable detection of intrinsic electrical signals, minimizing the risks of both over-sensing and under-sensing, and ensuring that the pacemaker paces only when necessary.

LBB pacing demonstrated similarly strong sensing values, comparable to those of RV pacing. The anatomical placement of the LBB lead allows for effective detection of the heart's intrinsic activity, with sensing values consistently above 5.0 mV. This ensures that the pacemaker responds accurately to the patient's physiological needs, maintaining effective pacing therapy.

4.2.3 Impedance

Impedance in RV pacing typically falls within the normal range of 400-1200 Ohms. In this study, RV pacing demonstrated stable impedance values, indicating good lead-tissue interface and consistent energy transfer. These values suggest that the leads are well-positioned, with no significant issues such as lead dislodgement or insulation failure. LBB Pacing:

LBB pacing also showed impedance values within the expected range. The stable impedance values in LBB pacing reflect a reliable lead position and effective electrical conduction through the tissue. Despite the more complex anatomy involved in LBB pacing, the impedance remained consistent, supporting its effectiveness as a pacing method.

4.2.4 Summary

Across the pacing modalities of RV, LBB, and CRT (LV lead), these parameters were generally within optimal ranges, indicating effective and reliable pacing. RV and LBB pacing showed similar performance in terms of threshold and sensing, with stable impedance values that suggest good lead positioning. The LV lead in CRT also demonstrated adequate threshold and

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

impedance values, confirming its effectiveness despite potential anatomical challenges. These findings suggest that none of the pacing methods are expected to encounter significant difficulties in maintaining optimal electrical parameters, making them viable and reliable options in clinical practice. Regular monitoring remains essential to ensure continued success and to promptly address any potential issues.

4.3 Deeper dive on LBB: Now and the Future

Left Bundle Branch (LBB) pacing has emerged as a compelling alternative to traditional right ventricular (RV) pacing, offering a more physiological approach to cardiac pacing by directly stimulating the left bundle branch area. This method of pacing has been associated with improved electrical synchrony, reduced pacing-induced cardiomyopathy, and better clinical outcomes compared to conventional RV pacing methods. In this subsection, I will review and synthesize findings from recent studies on Left Bundle Branch (LBB) pacing to provide a comprehensive summary of the current evidence.

Recent studies have highlighted several key benefits of LBB pacing over RV pacing. For instance, a study by Ondiviela et al. [14] compared LBB pacing with right ventricular outflow tract pacing (RVOTP) and found that LBB pacing resulted in a significantly narrower QRS duration (99 ± 2 ms vs. 113.6 ± 11.7 ms, $p < 0.001$). This narrower QRS complex is indicative of more synchronized ventricular contraction, which is crucial for reducing the risk of adverse outcomes such as heart failure and arrhythmias. Additionally, the study reported that LBB pacing required shorter fluoroscopy times (3.1 ± 2.1 min vs. 4.3 ± 3.4 min, $p = 0.035$), although it did involve longer procedure times (68.9 ± 36.9 min vs. 44.3 ± 18.7 min, $p < 0.001$). No significant differences were found between the groups in terms of complications like

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

ventricular lead dislocation, suggesting that LBB pacing is both feasible and safe for clinical use [14].

Another study by Okubo et al.[13] provided mid-term clinical outcomes comparing LBB pacing with right ventricular septal pacing (RVSP) in patients with atrioventricular block (AVB). The results demonstrated that LBB pacing was associated with significantly fewer adverse clinical outcomes, including all-cause death, hospitalization due to heart failure, and the need for upgrading to biventricular pacing (BVP). Specifically, the incidence of these adverse outcomes was 4.9% in the LBB group compared to 22.8% in the RVSP group (Log-rank $p = 0.02$). The study also reported that the paced-QRS duration and left ventricular activation time (LVAT) were significantly shorter in the LBB group than in the RVSP group (123.8 ± 12.8 ms vs. 149.5 ± 12.8 ms, $p < 0.001$; 68.4 ± 13.8 ms vs. 93.2 ± 14.7 ms, $p < 0.001$), which likely contributed to the improved outcomes observed with LBB pacing [13].

Moreover, another study found that LBB pacing was effective in reducing adverse outcomes associated with traditional RV pacing techniques. The results highlighted a significant reduction in pacing-induced cardiomyopathy (PiCM) and overall better preservation of left ventricular function. The authors concluded that LBB pacing could be a preferable option in patients who are at high risk of PiCM due to high-burden RV pacing, as it maintains a more physiological ventricular activation pattern (Ondiviela et al., 2021; Okubo et al., 2024).

Despite its advantages, LBB pacing is not without limitations. The technique requires specific expertise and a steep learning curve, particularly due to the anatomical variations in the left bundle branch area that can pose challenges during lead implantation. As noted by the studies, while LBB pacing has shown promising results, it also involves longer procedural times, which may limit its adoption in some clinical settings. Furthermore, while the current data are encouraging, there is still a need for long-term studies

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

to confirm the durability and stability of LBB leads over extended follow-up periods [13].

Looking ahead, LBB pacing is poised to become a mainstream option for physiological pacing, especially for patients who are not ideal candidates for CRT or those who have not responded to traditional pacing modalities. Future research should focus on expanding the evidence base through randomized controlled trials that directly compare LBB pacing to CRT, particularly in patients with heart failure and significant ventricular dyssynchrony. Additionally, advancements in lead technology, such as more flexible or steerable leads, and improved imaging techniques could further enhance the success and safety of LBB pacing, making it a more widely adopted practice.

Another topic to be discussed is the implantation of LBB lead and its success rate. The implantation of LBB leads, although promising, presents several challenges which will be listed below:

1. **Myocardial Fibrosis**: Myocardial fibrosis increases myocardial stiffness and reduces coronary blood flow reserve. This condition often makes it difficult to screw the pacing lead into the left bundle branch area, thus preventing effective pacing in patients with significant fibrosis. [22]

2. **Interference by the Septal Tricuspid Leaflet**: The location of the pacing lead near the tricuspid annulus can complicate the implantation process due to interference from the septal tricuspid leaflet. This can lead to mechanical issues and even the pinning of the tricuspid leaflet against the septum.[22]

3. **Coaxial Misalignment**: Successful implantation requires the pacing lead to be coaxial with the delivery sheath. Any misalignment can result in ineffective force transmission, complicating lead placement into the desired area.[22]

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

4. **Improper Sheath Angle**: The delivery sheath (C315HIS) must be perpendicular to the interventricular septum to facilitate effective implantation. Deviations from this angle can increase resistance and hinder the penetration of the pacing lead through the septum.[22]

5. **Creased Sheath**: Repeated manipulations, especially in complex cases, may cause the delivery sheath to become creased, increasing resistance and making it difficult to accurately screw the pacing lead into the left bundle branch area.[22]

6. **Failure to Capture the LBB**: Factors such as local myocardial fibrosis, distal left bundle branch block (LBBB), and non-specific intraventricular conduction disturbance (IVCD) may prevent effective capture of the LBB, even when the lead is successfully positioned.[22]

7. **Enlargement of the Right Atrium or Right Ventricle**: Conditions like dilated cardiomyopathy or rheumatic valve disease can enlarge the right atrium or ventricle, complicating the contact between the pacing lead and the interventricular septum. This may prevent successful lead implantation into the left bundle branch area.[22]

8. **Interventricular Septal Perforation**: In some cases, particularly with a thin or soft interventricular septum, the pacing lead may perforate the septum and enter the left ventricle, causing a procedural failure.[22]

Different studies has shown that besides challenges of LBB implantation, the success rate is still high, ranging from 81.1% to 98.1%:

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Table: Success Rate and Reasons for Failure of LBB Lead Implantation

Reference	Design	Indication.for.CRT	Baseline.QRS.duration	LVEF	Number.of.HF.patients	Number.of.success	Success.rate	Reasons.for.failure	Solution	Total.success.rate
Huang et al. (99)	Prospective, multicenter	Symptomatic heart failure with LBBB	150.7 ± 24	35.7 ± 7.4	65	60	92.3	Failure to capture the LBB	BiV CRT (60)	100.0
Vijayaraman et al. (104)	Retrospective, observational, single-center	Symptomatic heart failure with LBBB	180 ± 18	31.2 ± 8.1	277	272	98.1	Inability to penetrate the septum	BiV CRT (30)	98.1
Li et al. (103)	Prospective, observational, multi-center	Symptomatic heart failure with LBBB	177.9 ± 14.8	29.5 ± 5.9	37	30	81.1	Failure to capture the LBB, inability to penetrate the septum	BiV CRT (10)	92.1
Goyal et al. (99)	Retrospective, multi-center	Symptomatic heart failure NYHA class II-IV	188.6 ± 17.0	30.2 ± 5.8	41	35	85.4	Unstable lead position, VT induced	BiV CRT (15)	85.4
Chen et al. (102)	Non-randomized, observational, multi-center	Symptomatic heart failure, NYHA class III-IV	186.2 ± 19.5	29.0 ± 5.9	49	48	98.0	Inability to penetrate the septum	BiV CRT (20)	98.0

FIGURE 4.1: Studies of success rate and failures of LBB Implantation [22]

The success rate of LBB lead implantation, ranging from 81.1% to 98.1% across various studies, can be considered relatively high, indicating that the procedure is generally effective. The primary reasons for the occasional failure to implant the LBB lead are related to technical challenges, such as difficulty in capturing the LBB, penetrating the septum, or maintaining a stable lead position. These challenges underscore the complexity of the procedure, which requires considerable skill and precision. However, the consistently high success rates suggest that, despite these difficulties, LBB lead implantation is a feasible and effective approach in most cases. The variability in outcomes across different studies may be influenced by factors such as patient characteristics, procedural techniques, and operator experience, emphasizing the need for continued optimization of techniques and training to maintain and improve success rates.

One of the most recent studies, published following the European Society of Cardiology (ESC) Congress 2024, compared Left Bundle Branch Area Pacing (LBBAP) with conventional Right Ventricular (RV) Pacing using a large Medicare population. The study demonstrated that LBBAP significantly reduced both heart failure hospitalizations and all-cause mortality compared to RV pacing, particularly in patients requiring a high degree of ventricular pacing.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

At 6 months, the incidence of heart failure hospitalization in the LBBAP group was 15.8%, significantly lower than the 24.1% observed in the RV pacing group ($p < 0.001$). Moreover, the all-cause mortality rate was also reduced in the LBBAP group, with a mortality rate of 8.9% compared to 12.6% in the RV pacing group ($p = 0.002$). These outcomes underscore the physiological benefits of LBBAP in reducing the burden of heart failure and prolonging survival. [11]

Additionally, LBBAP was associated with a significantly lower risk of pacing-induced cardiomyopathy (PiCM) compared to RV pacing. Patients in the RV pacing group exhibited a PiCM rate of 13.4%, while those in the LBBAP group showed a reduced incidence of 6.3% ($p < 0.001$), further supporting the hypothesis that LBBAP preserves left ventricular function by maintaining a more synchronized and physiological activation pattern. [11]

In terms of complications, LBBAP demonstrated a comparable safety profile to RV pacing. The rate of lead dislodgement or device-related complications was 5.2% in the LBBAP group and 6.1% in the RV pacing group ($p = 0.15$), showing no statistically significant difference between the two groups. However, LBBAP was associated with fewer long-term complications such as high pacing thresholds or sensing issues, which are more common in other forms of conduction system pacing, such as His Bundle Pacing (HBP). [11]

Overall, the study highlights that LBBAP is not only a feasible and safe alternative to RV pacing but also offers significant clinical advantages in terms of reducing heart failure hospitalizations, all-cause mortality, and PiCM, making it an increasingly viable option for patients requiring frequent ventricular pacing. [11]

In conclusion, LBB pacing represents a promising advancement in cardiac

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

pacing, offering significant benefits in terms of reducing QRS duration, enhancing cardiac synchrony, and improving clinical outcomes in selected patient populations. While challenges remain, particularly regarding the technical aspects of implantation and the need for long-term data, the future of LBB pacing appears promising. With ongoing research and technological innovations, LBB pacing could potentially replace CRT in certain scenarios and provide a better quality of life for patients at risk of heart failure and other complications related to dyssynchrony [14] [13].

4.4 Limitations and future possibilities

4.4.1 Limitations

This thesis provides valuable insights into the comparative analysis of different pacing modalities, yet several limitations should be acknowledged to contextualize the findings and guide future research.

One of the primary limitations is the relatively small sample size, particularly for the CRT group. While the data collected provides meaningful comparisons, the limited number of patients in the CRT category may restrict the generalization of the findings. A larger cohort would have allowed for more robust statistical analyses and stronger conclusions regarding the efficacy of CRT in comparison to other pacing methods.

In some cases, certain values were missing for specific patients due to various reasons, such as technical difficulties during measurement or patient-specific factors that prevented complete data collection. Although the number of missing data points was small, these gaps may have introduced some bias into the analysis, particularly in the calculation of averages and comparative assessments.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

A notable limitation of this study is that the data were collected either from the implant phase or from follow-up visits, but not from multiple time points for the same patient. This cross-sectional approach limits the ability to assess changes over time within the same individuals. Having longitudinal data—where the same patients are tracked from implantation through multiple follow-up visits—would have provided a clearer understanding of the long-term effects of each pacing modality. This would have allowed for a more detailed analysis of trends such as the stability of lead performance, progressive changes in QRS duration, and the long-term impact on heart failure symptoms. The absence of such data restricts the ability to draw conclusions about the durability and sustained efficacy of the pacing strategies studied.

The thesis did not differentiate between patients based on their current health status, such as the presence of heart failure or other comorbid conditions that could affect the results. Variations in patient health could have influenced the efficacy of the pacing modalities, potentially confounding the comparisons. Future studies should stratify patients based on their clinical conditions to better understand how different pacing strategies perform in diverse patient populations.

4.4.2 Future Possibilities

Given the promising results observed with LBB pacing, it emerges as a highly potential method that could challenge the current standard of CRT, especially for certain patient populations. However, before LBB pacing can be considered a viable replacement for CRT, several aspects require further investigation.

- **Long-Term Data**

  There is a need for long-term studies to assess the performance of LBB

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

pacing over extended periods. This includes monitoring lead stability, patient outcomes, and any potential complications that may arise over time. Long-term data will be crucial in determining whether LBB pacing can consistently deliver the benefits observed in short-term studies.

- **Comparative Studies**

  Future research should focus on head-to-head comparisons between LBB pacing and CRT, particularly in patients with heart failure and significant dyssynchrony. Such studies should explore not only the technical performance of the devices but also the impact on clinical outcomes, quality of life, and healthcare costs.

- **Larger Sample Size**

  To validate the findings of this thesis and explore the potential of LBB pacing further, larger studies with expanded sample sizes are necessary. These studies should include a diverse patient population to ensure that the results are broadly applicable and that the full range of potential benefits and limitations of LBB pacing are understood.

- **Clinical Trails**

  Rigorous clinical trials comparing LBB pacing with CRT and RV pacing will be essential to establish evidence-based guidelines for the use of LBB pacing. These trials should include various patient subgroups, such as those with different stages of heart failure, to determine the most appropriate indications for each pacing modality.

In conclusion, while this thesis has provided important insights into the comparative effectiveness of RV, LBB, and CRT pacing, further research is needed to fully understand the potential of LBB pacing as a future standard of care. Addressing the limitations outlined above and pursuing the recommended future directions will help to solidify the role of LBB pacing in

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

clinical practice and ensure that patients receive the most effective and appropriate pacing therapy for their needs.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Chapter 5

Conclusion

In this study, we explored the comparative effectiveness of Right Ventricular (RV) pacing, Left Bundle Branch (LBB) pacing, and Cardiac Resynchronization Therapy (CRT) pacing by analyzing key parameters such as QRS duration, threshold, sensing, and impedance. The findings offer valuable insights into the physiological and clinical impacts of these pacing modalities and underscore the emerging potential of LBB pacing as a viable alternative to traditional methods, particularly in specific patient populations.

RV pacing, although widely utilized, is associated with several long-term complications, notably the prolongation of QRS duration, which correlates with interventricular dyssynchrony and an increased risk of heart failure and pacing-induced cardiomyopathy (PiCM). In our study, RV pacing led to a significant increase in QRS duration, with the average prolongation being approximately 35 milliseconds and a median QRS duration of 150 milliseconds post-pacing. This non-physiological activation of the ventricles disrupts natural conduction pathways, leading to adverse outcomes, as supported by existing literature. The risks associated with RV pacing highlight the need for alternative strategies that preserve ventricular function and minimize dyssynchrony.

LBB pacing has shown promising results in addressing the limitations of RV pacing. In our analysis, LBB pacing was associated with a reduction in

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

QRS duration, bringing it closer to normal physiological values with an average reduction of about 25 milliseconds and a median QRS duration of around 120 milliseconds. This method mimics the natural conduction system more closely, allowing for synchronous ventricular contraction and better preservation of left ventricular function. The literature supports these findings, indicating that LBB pacing may reduce the risks of heart failure progression and PiCM, making it a potential replacement for RV pacing in suitable patients. However, the technical challenges of LBB lead placement, including precise anatomical targeting, necessitate operator expertise and careful patient selection.

Cardiac Resynchronization Therapy: CRT remains the gold standard for patients with heart failure and wide QRS complexes, particularly those with left bundle branch block (LBBB). Our study demonstrated that CRT significantly reduced QRS duration by an average of 30-40 milliseconds, with a median QRS duration post-CRT of approximately 125 milliseconds. This reduction is critical for improving ventricular synchronization, cardiac function, and overall patient outcomes. Despite the technical complexities of CRT, such as lead placement challenges, the benefits, including reduced hospitalizations and enhanced survival, outweigh these difficulties. CRT's ability to achieve optimal QRS duration reinforces its role as an indispensable therapy for patients with advanced heart failure and significant dyssynchrony.

Future Directions: Given the promising results with LBB pacing, future research should focus on long-term studies to assess the stability, patient outcomes, and potential complications associated with this method. Comparative studies between LBB pacing and CRT, especially in heart failure patients with significant dyssynchrony, are essential to establish LBB pacing's role in clinical practice. Furthermore, expanding sample sizes and including diverse patient populations in future studies will be crucial for validating these

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

findings and ensuring the broad applicability of LBB pacing as a potential alternative to CRT.

In conclusion, while RV pacing remains a common practice, its associated risks make it less favorable in certain patient populations. LBB pacing offers a promising alternative that could potentially replace CRT in some cases, particularly where minimizing QRS duration and avoiding dyssynchrony are critical. However, CRT continues to be the gold standard for managing patients with advanced heart failure and significant ventricular dyssynchrony, underscoring the need for individualized pacing strategies to optimize patient outcomes.

In addition to the primary focus on QRS duration and pacing modalities, it is essential to dive into the electrical parameters of threshold, sensing, and impedance, which are critical to the successful operation of pacing systems. These parameters not only determine the immediate effectiveness of the pacing therapy but also influence the long-term durability and performance of the device.

Threshold refers to the minimum voltage required to achieve consistent myocardial depolarization with each pacing impulse. In this study, the threshold values across RV, LBB, and CRT pacing modalities were generally found to be within the normal and expected ranges, typically below 1.0 V, which is considered optimal. A key characteristic of threshold management is its impact on battery longevity. Lower thresholds are associated with reduced energy consumption, which extends battery life and reduces the frequency of device replacements. Additionally, stable threshold values indicate successful lead positioning and good myocardial capture, both of which are crucial for maintaining effective pacing. In rare cases where thresholds are higher, careful monitoring and lead adjustment may be necessary, but such instances were not prevalent in this study.

Sensing is the pacemaker's ability to detect and respond appropriately to

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

the heart's intrinsic electrical activity, ensuring that pacing occurs only when needed. The sensing values observed in this study were robust across all modalities, typically exceeding the reference value of 5.0 mV. This high level of sensitivity is critical in preventing both over-sensing, which can lead to unnecessary inhibition of pacing, and under-sensing, which might result in missed beats. Notably, the stability of sensing values across RV, LBB, and CRT modalities suggests that each method provides reliable detection of cardiac activity. This reliability ensures that the pacemaker can adapt to the patient's physiological needs, delivering pacing only when intrinsic activity is insufficient.

Impedance measures the resistance to electrical current flow through the lead and surrounding cardiac tissue. It is a vital parameter that reflects both the integrity of the lead and the tissue's response to the pacing system. In this study, impedance values for all pacing modalities fell within the normal expected ranges of 400-1200 Ohms, indicating that lead performance was consistent and stable. Lower impedance values could suggest potential lead dislodgement or insulation breaches, whereas excessively high values might indicate lead fracture or increased fibrosis around the lead. The uniformity of impedance readings across RV, LBB, and CRT pacing supports the conclusion that these modalities are equally effective in maintaining stable lead-tissue interfaces. Regular impedance monitoring is essential for early detection of lead issues, but based on the data from this study, none of the pacing methods presented significant impedance-related challenges.

The electrical parameters of threshold, sensing, and impedance are fundamental to the effectiveness and reliability of pacemaker function. In this study, all three parameters were well within acceptable limits across the pacing modalities of RV, LBB, and CRT. Each parameter exhibited characteristics indicative of successful pacing therapy, with low thresholds supporting

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

energy efficiency, strong sensing ensuring accurate detection of intrinsic activity, and stable impedance reflecting consistent lead performance. These findings suggest that none of the pacing methods are expected to encounter significant difficulties in achieving or maintaining optimal electrical parameters, reinforcing their viability in clinical practice. However, ongoing monitoring remains essential to promptly address any deviations and to ensure the continued success of the pacing therapy over the long term.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

List of Figures

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.

Bibliography

[1] Finn Akerström and Marinus A.A.M.P.J.-L.A.P.J.-C. "The Importance of Avoiding Unnecessary Right Ventricular Pacing in Clinical Practice". In: *World Journal of Cardiology* 5.11 (2013), pp. 410–419. ISSN: 1949-8462.

[2] Alan D. Bernstein et al. "The Revised NASPE/BPEG Generic Code for Antibradycardia, Adaptive-Rate, and Multisite Pacing". In: *Journal of Pacing and Clinical Electrophysiology* 25.2 (Feb. 2002), pp. 218–225.

[3] Sergio Bongioanni et al. "Relation of QRS duration to mortality in a community-based cohort with hypertrophic cardiomyopathy". In: *American Journal of Cardiology* 100.3 (Aug. 2007), pp. 503–506. DOI: 10.1016/j.amjcard.2007.03.049.

[4] Xueying Chen et al. "The characteristics of the electrocardiogram and the intracardiac electrogram in left bundle branch pacing". In: *Journal of Cardiovascular Electrophysiology* 30.7 (July 2019), pp. 1096–1101.

[5] Richard L. Drake, A. Wayne Vogl, and Adam W.M. Mitchell. *Gray's Basic Anatomy*. 2nd. Philadelphia, PA: Elsevier, 2018.

[6] Kenneth A. Ellenbogen and Karoly Kaszala. *Cardiac Pacing and ICDs*. 6th. Chichester, UK: Wiley-Blackwell, 2014.

[7] N.M. van Hemel and E.E. van der Wall. "8 October 1958, D Day for the implantable pacemaker". In: *Netherlands Heart Journal* 16.Suppl 1 (Oct. 2008), S3–S4.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

[8] Weijian Huang et al. "A Novel Pacing Strategy With Low and Stable Output: Pacing the Left Bundle Branch Immediately Beyond the Conduction Block". In: *Canadian Journal of Cardiology* 33.12 (2017), 1736.e1–1736.e3.

[9] Jane Huff. *ECG Workout: Exercises in Arrhythmia Interpretation*. 6th. Philadelphia, PA: Lippincott Williams & Wilkins, 2012, pp. 8–12.

[10] Paul A. Iaizzo. *Handbook of Cardiac Anatomy, Physiology, and Devices*. 3rd. New York, NY: Springer, 2015, pp. 215–233.

[11] Ali S. Javed, Paul A. Friedman, Suraj Kapa, et al. "Outcomes of Left Bundle Branch Area Pacing Compared with Right Ventricular Pacing: Analysis of the Medicare Population". In: *Heart Rhythm* 21.8 (2024), pp. 1323–1331. DOI: 10.1016/j.hrthm.2024.06.009. URL: https://doi.org/10.1016/j.hrthm.2024.06.009.

[12] David Korpas. *Implantable Cardiac Devices Technology*. 1st. New York, NY: Springer, 2013.

[13] Y. Okubo, T. Sakai, S. Miyamoto, et al. "Mid-term clinical outcomes of left bundle branch area pacing compared to accurate right ventricular septal pacing". In: *Journal of Interventional Cardiac Electrophysiology* (2024). DOI: 10.1007/s10840-024-01890-z.

[14] A. R. Ondiviela et al. "Left bundle branch pacing: efficacy and safety compared to right ventricular outflow tract pacing". In: *Europace* 23.Supplement 3 (2021), p. iii433.

[15] G.K. Panicker, B. Desai, and Y. Lokhandwala. "Choosing pacemakers appropriately". In: *Heart Asia* 1.1 (Jan. 2009), pp. 26–30. DOI: 10.1136/ha.2008.000265.

[16] Jeffrey A. Puette, Ryan Malek, and Matthew B. Ellison. *Pacemaker*. 1st. Oxford, UK: Oxford University Press, 2022.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN

[17] Valerie C. Scanlon and Tina Sanders. *Essentials of Anatomy and Physiology*. 6th. Philadelphia, PA: F.A. Davis Company, 2007, p. 294.

[18] Jin Kyung Hwang Sung Woo Cho Hye Bin Gwag. "Clinical Features, Predictors, and Long Term Prognosis of Pacing Induced Cardiomyopathy". In: *European Journal of Heart Failure* 21.5 (2019), pp. 643–651.

[19] M. O. Sweeney et al. "Adverse effect of ventricular pacing on heart failure and atrial fibrillation among patients with normal baseline QRS duration in a clinical trial of pacemaker therapy for sinus node dysfunction". In: *Circulation* 107.23 (2003). Epub 2003 Jun 2, pp. 2932–2937. DOI: 10.1161/01.CIR.0000072769.17295.B1.

[20] Laurens F. Tops, Maarten M. Schalij, and J. Jeroen Bax. "The Effects of Right Ventricular Apical Pacing on Ventricular Function and Dyssynchrony: Implications for Therapy". In: *Journal of the American College of Cardiology* 54.9 (2009), pp. 764–776.

[21] Norman C. Wang. "Clinical Implications of QRS Duration in Patients". In: *Journal of the American Medical Association* 299.21 (2008), pp. 2656–2666.

[22] Junmeng Zhang et al. "Success rates, challenges and troubleshooting of left bundle branch area pacing as a cardiac resynchronization therapy for treating patients with heart failure". In: *Frontiers in Cardiovascular Medicine* 9 (2023), p. 1062372. DOI: 10.3389/fcvm.2022.1062372.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU Bibliothek Your knowledge hub WIEN