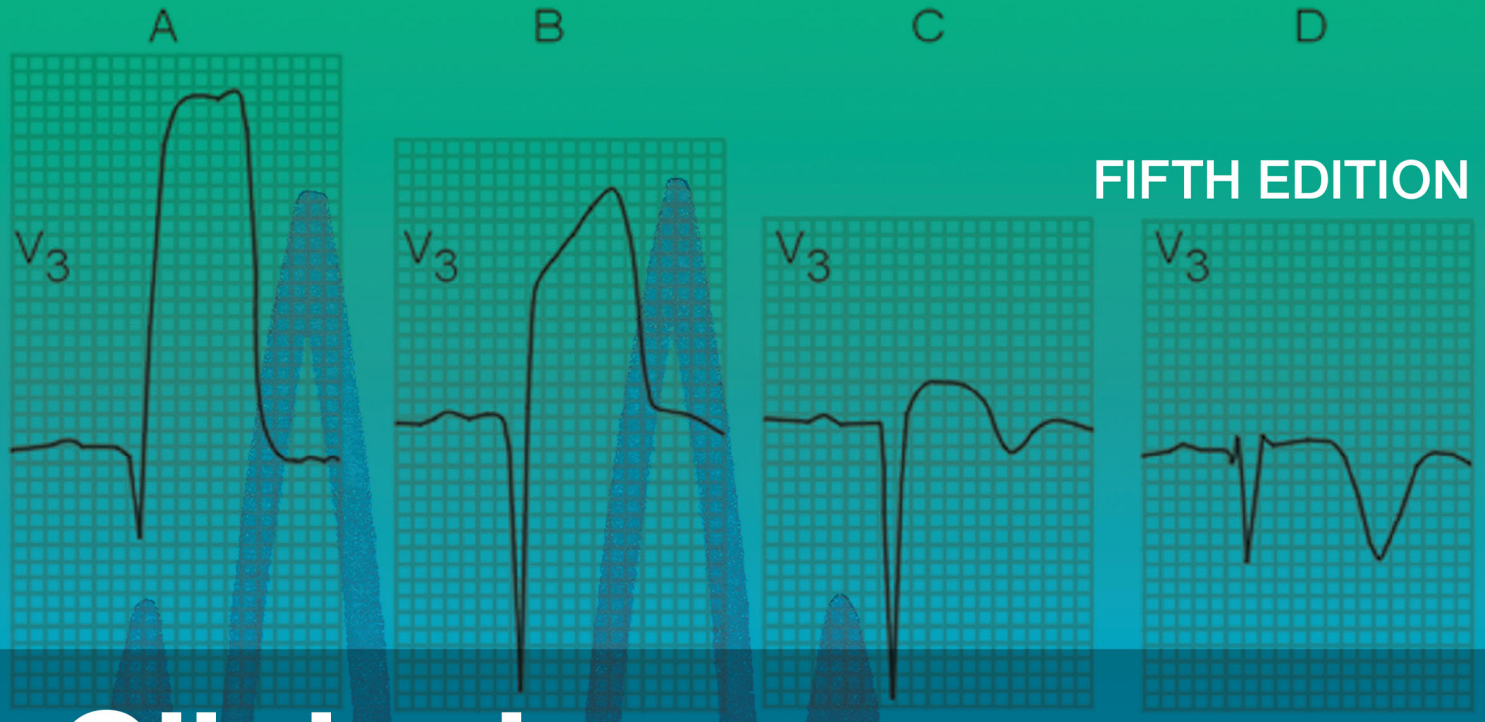
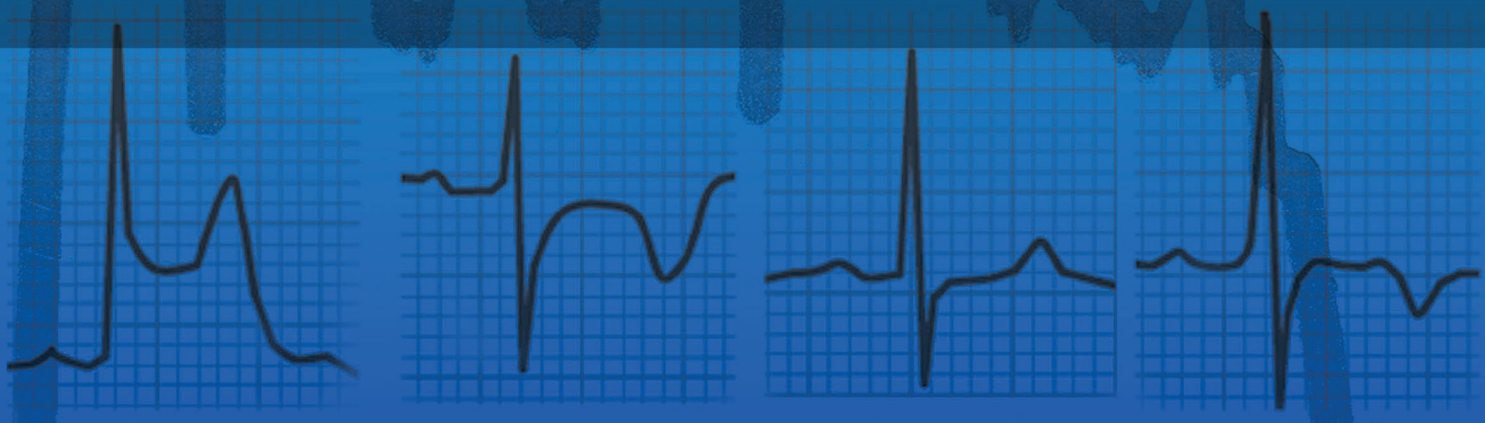


FIFTH EDITION

Clinical Electrocardiography

A TEXTBOOK

Antoni Bayés de Luna, Miquel Fiol-Sala,
Antoni Bayés-Genís, and Adrián Baranchuk



The Bayés de Luna ECG Collection

WILEY Blackwell

Clinical Electrocardiography

Clinical Electrocardiography

A Textbook

FIFTH EDITION

ANTONI BAYÉS DE LUNA
Autonomous University of Barcelona, Hospital de la Santa Creu i Sant Pau, Barcelona, Spain

MIQUEL FIOL-SALA
Illes Balears Health Research Institut (IdISBa), and Hospital Son Espases, Palma, Spain

ANTONI BAYÉS-GENÍS
Heart Institute, Hospital Universitari Germans Trias i Pujol, Badalona, Spain

ADRIÁN BARANCHUK
Division of Cardiology, Kingston Health Sciences Center, Kingston, Ontario, Canada

With contributions from:
ROBERTO ELOSUA
Hospital del Mar Medical Research Institute (IMIM), Barcelona, Catalonia, Spain

MANUEL MARTÍNEZ-SELLÉS
Department of Cardiology, Hospital General Universitario Gregorio Marañón, Madrid, Spain

WILEY Blackwell

This edition first published 2022

Edition History
Fourth edition published 2012 by John Wiley & Sons Ltd

Registered Offices
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial Office
9600 Garsington Road, Oxford, OX4 2DQ, UK

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Library of Congress Cataloging-in-Publication Data

Names: Baye´s de Luna, Antoni, 1936- author. | Fiol-Sala, M. (Miquel), author. | Genis, A. Baye´s, author. | Baranchuk, Adrian, author.
Title: Clinical electrocardiography : a textbook / Antoni Baye´s de Luna, Miquel Fiol-Sala, Antoni Baye´s-Geni´s, Adria´n Baranchuk ; with contributions from Roberto Elosua, Manuel Marti´nez-Selle´s.
Description: Fifth edition. | Hoboken, NJ : Wiley, 2022. | Includes bibliographical references and index.
Identifiers: LCCN 2021025949 (print) | LCCN 2021025950 (ebook) | ISBN 9781119536451 (cloth) | ISBN 9781119536468 (Adobe PDF) | ISBN 9781119536437 (epub)
Subjects: MESH: Electrocardiography–methods | Arrhythmias, Cardiac–diagnosis | Heart Diseases–diagnosis
Classification: LCC RC683.5.E5 (print) | LCC RC683.5.E5 (ebook) | NLM WG 140 | DDC 616.1/207547–dc23
LC record available at https://lccn.loc.gov/2021025949
LC ebook record available at https://lccn.loc.gov/2021025950

Cover Design: Wiley
Cover Image: © Courtesy of Antoni Bayés de Luna

Set in 9.25/12pt Palatino LT Std by Straive, Pondicherry, India

10 9 8 7 6 5 4 3 2 1

Contents

Preface

by Prof. Antoni Bayés de Luna

I am very pleased to present the 5th Edition of the book "Clinical Electrocardiography," for which in its four previous editions (1987, 1993, 1998, 2012) I was the sole author and responsible for it.

Given my age, and foreseeing the book continuity in the future, three expert cardiologists—Adrián Baranchuk, Antoni Bayés-Genís, and Miquel Fiol-Sala—accompany me in the present edition as co-authors. All three have worked for many years with me in the field of clinical electrocardiography, and together we have selected and included in the book what we considered more interesting from the work published in the last 10 years. It is therefore not a book that has four cardiologists acting as editors of the work performed by many co-authors, but a book of clinical electrocardiology in which four cardiologists become joint authors of the entire work.

I am satisfied and happy with the choice. Adrián Baranchuk has achieved success in Canada, far from his country, Argentina, and has turned his center, Queen's University, into a benchmark in arrhythmology, not only in all of America but also worldwide. Toni Bayés-Genís, my son, is a worldwide expert in heart failure who has positioned his center, Hospital Germans Trias de Badalona, as one of the best in Europe in its specialty. And finally, Miquel Fiol, the oldest of my dear collaborators for more than 40 years, is a great expert in ECG and has made original and very valuable contributions from his Hospital in Mallorca, especially in the field of ischemic heart disease.

I have been fortunate that all three have accepted this challenge. All of them have exceptional qualities that make them the best collaborators, so that this book continues to be a "work of the author" thanks to their contributions.

Nevertheless, we have had the collaboration of other experts in specific aspects. For this edition, Dr Roberto Elosua is the sole author of Chapter 8—Epidemiology, and Dr Manuel Martínez-Sellés has reviewed Chapters 22 and 23. Also I would like to thank Iwona Cygankiewicz, Wojciech Zareba, Xavier Viñolas, Ramón Brugada, Javier García-Niebla, Juan Lacalzada-Almeida, José Nunes de Alencar, Delicia Lorente Gentille, José Guerra, Gemma Vilahur, Guiomar Mendieta, Luis Alberto Escobar-Robledo, and many others, for the help they have offered me regarding specific aspects and in previous editions, and my collaborators for many years, especially Andrés Carrillo, Jaume Riba, Josep Guindo, Josep Massó, Ignasi Duran, and Diego Goldwasser. Finally, I also am very grateful to my previous secretary Montse Sauri and currently Esther Gregoris for her excellent secretarial work and help throughout the entire process of this edition.

Also, I am glad to express my gratitude to Fundación Jesús Serra-Catalana Occidente for the great support given to us in the last nearly 25 years.

Finally, our very special gratitude to Professors Hein Wellens, Paul Puech, Eugene Braunwald, and Marcelo Elizari, authors of the forewords in previous editions. I am deeply grateful to Professors Pedro Brugada and Marcelo Elizari for the excellent prologues they have written for this edition.

I want to conclude by stating that electrocardiology continues to be a key piece in cardiological diagnosis, and its contribution is irreplaceable for the benefit of the patient to correctly focus the diagnosis and treatment of our patients. We trust that this book will help to achieve this goal.

I now leave the other authors to give their opinion on it.

Antoni Bayés de Luna
December 2020

Preface

by Drs Miquel Fiol-Sala, Antoni Bayés-Genís, and Adrián Baranchuk

This 5th edition of Clinical Electrocardiography is very special. Antoni has decided to invite some of his closest collaborators as co-authors of the book.

Working with Prof. Bayés de Luna is a privilege. Each one of us that have had the opportunity to share his vision, his vast knowledge, his deep understanding of electrocardiology, and more importantly, his view about humanity, the world and the reason for our existence, has felt at some point, the immensity of his Universe.

Antoni teaches to teach, teaches how to approach any conflict, concern, or disparity, with an open mind, without prejudices, exercising tolerance to overdrive frustration and in a calm manner that calls to understanding.

He has taught generations of cardiologists around the globe, he has traveled five continents and his voice has been heard in all academic environments. In addition, his lessons, books and papers, were replicated in each corner of the planet. His books were translated to more than 10 languages, and his way to understand human electricity, has helped millions of health care providers, from students and ECG techs to professors of medicine.

What makes Antoni unique?

Maybe his capacity of "giving" without "taking." Antoni never asks for a return on what he gives. It is natural for him to keep giving and giving: knowledge, opportunities, collaborations, money. . . All these co-authors have personally experienced what is being said here. Antoni would share his grants and honorariums with his stuff and collaborators, and several times we have questioned that he is not taking his share. Money, glory, or fame is not important to Prof. Bayés' de Luna. He would not ask anything in return; however, to work with him, you have to feel the same passion.

Antoni walks at a fast pace. This is not a metaphor. Antoni literally walks at a faster pace than any of us. In order to walk at his pace and to be at his side during a conversation through the corridors of Sant Pau Hospital, you have to almost run.

This is a reflection on what it takes to collaborate with him: at the same time, we would complete a registry, write 2–3 papers, an editorial, supervise students and fellows, create slides for presentations, interact with editorial groups and much more. You want to be at his side, you have to run.

And when you think you had enough, Antoni will tell you to stop and enjoy life, family, friends, and a good glass of wine. He will not like to know that you are missing a birthday, a celebration, or an important date, because you are working too hard. If it is difficult to explain, please imagine how difficult it is to keep his pace. . .

Clinical Electrocardiography 5th edition would not be possible without the amazing collaboration and commitment from Wiley and its staff. We learnt to communicate fluently, frequently, and to design strategies that are mutually convenient. All the editors of this book are grateful to Wiley for their decision to go ahead with this new edition.

In this book, the reader will find what we call the "Bayés' spirit." We have updated some chapters and references, but we have followed the way Antoni teaches. This is the "magic" of this book. Chapter after chapter, you will immerse into the Universe of a unique man and scientist. You will understand his approach to "active" and "passive" arrhythmias, you will enjoy his definitions, repetitions, and perspective of multiple aspects of human cardiac electricity.

We welcome you to the opportunity to dig deep in the mind of this amazing colleague. Here it is, all his knowledge condensed in a book for you to enjoy.

Open the book, and enjoy this trip to knowledge, page by page, like a slow train arriving to a desired destination.

This group of co-authors is pleased to bring you the 5th edition of Clinical Electrocardiography. For all of us, a dream comes true.

Sit down, and enjoy this unique ECG book!

Adrián Baranchuk, Antoni Bayés-Genís, and Miquel Fiol-Sala
December 2020

Foreword

by Dr Marcelo V. Elizari

Again, Professor Antoni Bayés de Luna has honored me with his invitation to write the foreword to the 5th edition of "Clinical Electrocardiography: A Text Book." I believe the main reason for this invitation lies in the old and unbreakable friendship that has bonded us since our first meeting in the Symposium "Recent Advances in Ventricular Conduction," organized by Mario Cerqueira Gomes in Oporto in 1973.

While the four previous editions that preced this issue were written by Prof. Bayés de Luna as the sole author, this textbook is co-authored by renowned experts in the field of electrocardiography and arrhythmias, such as Miquel Fiol-Sala, Antonio Bayés-Genís, and Adrián Baranchuk. Prof. Bayés de Luna's strong genetic influence, for his joy, has been transmitted to his son Antoni, who has followed the path of spirituality traced by his father.

More than a hundred years ago, Wilhelm Einthoven introduced the electrocardiogram. Some years later, Thomas Lewis, his successor and Wilson's teacher, made his invaluable contribution to the understanding of the mechanisms and diagnosis of rhythm disorders, causing a profound impact in the development of electrocardiography. And afterward, the introduction of the unipolar leads by Frank Norman Wilson continued drawing the virtuous circle, marking the dawning of a new era of great progress for the interpretation of morphologic changes in intraventricular bundle branch blocks and cardiovascular diseases. In 1949, Silvio Weidmann and Edouard Coraboeuf recorded the first intracellular cardiac action potential and in the 1960s, Benjamin Scherlag developed the technique for His bundle recording.

Both advances and the advent of newer diagnostic and therapeutic tools gave rise to a new discipline: clinical cardiac electrophysiology. Besides, the deep knowledge about molecular biology has fostered the recognition and management of different familial cardiomyopathies. Thus, invasive and non-invasive diagnoses have allowed the correlation of the electrocardiographic imaging with subyacent physiopathologic mechanisms. Bayés de Luna honors in this book those pioneers and researchers that are not only part of history but also of the present and future.

The usual question is what is the reason for a new book on already so extensively discussed topics. And the answer is straightforward: there is always a place for a good book and, particularly in cardiology, a specialty that has developed in an unpredictable fashion. The publication of a medical book always marks the crystalization of a noble objective: provide medical education by mentors, whose deep knowledge and vast experience contribute to the management of patients.

Bayés de Luna and collaborators have distilled their extraordinary medical knowledge in the field of electrocardiology based on their own experience and research and always appealing to a profuse and well-selected bibliography. Since current technological advances have dramatically changed the approach to the clinical significance of any morphologic or rhythm disorder, this textbook frames the fundamental concepts covering all the possibilities for the correct interpretation of an electrocardiogram.

The 5th edition of Clinical Electrocardiography is a well-structured and well-planned medical work for advanced students, internists, trainees in cardiology, clinicians and physicians in the emergency room to find in the electrocardiogram a diagnostic resource to broadly interpret the value of images more simply and easily. However, a detailed and thoughtful history and a meticulous physical examination are essential to reach an accurate diagnosis since a normal electrocardiogram does not rule out in any way the existence of a potentially malignant cardiomyopathy. Thus, the authors alert the reader about the limitations of this diagnostic method but also, about its sensitivity and specificity as determinants of its clinical usefulness.

Every chapter deals in detail with the anatomical basis, the underlying physiopathology of the electrocardiographic and vectorcardiographic manifestations, clinical implications and differential diagnosis of every electrocardiographic pattern or rhythm disorder. A perfect logic and a rigorous plan allow the reader to easily follow the

steps to diagnosis, even if unfamiliar with the diagnostic methods of electrophysiologic and clinical exploration. An asset of this edition is the systematic description of each electrocardiographic phenomenon profusely illustrated with figures, sketches, and diagrams and the bringing together of the interrelated resources for a more comprehensive analysis. In this way, the readers are presented with a remarkable teatrise that highlights the surface electrocardiogram as the "gold standard" in clinical practice and, at the same time, pays tribute and glorifies the Spanish electrocardiology and cardiology.

Antoni has always been an inspiring leader in the field of electrocardiography and arrhythmias because his intellect, clinical sagacity, and pursuit of new horizons have led him to transcendent contributions of international impact that will remain in the history of cardiology. As a prestigious scientist and mentor, he has gained the recognition of the world scientific community and has achieved top national and international positions as a cardiologist through his prestige as a scientist and teacher. The academic training in cardiology at Sant Pau Hospital, under Antoni's genuine vocation for medical education, has become the seedbed for renowned cardiologists and electrocardiologists in the world.

Lastly, I feel genuinely happy and grateful to Antoni because Pedro Brugada, another giant in the world of electrocardiology, has also been invited to write more introductory words to this book. I am sure Pedro will agree with me that this 5th edition is worth the hightest merit because the reader will learn not only clinical electrocardiography but also to interpert and apply it on a scientific basis. Certainly, this 5th edition by Bayés de Luna and his well-known collaborators will become a "must" in all medical libraries for health carers in cardiology.

Prof. Marcelo V. Elizari
February 2021

Foreword

by Dr Pedro Brugada

In November 1982, almost 40 years ago, I presented my doctoral thesis at the University of Maastricht, The Netherlands. The topic was "New Observations on the Role of the AV Junction in tachycardias in Man." The promotor was the late Hein Wellens. As co-promotors, I had no less than the Physiologist Mauritz Allessie, and the Electrophysiologists Jeronimo Farre and the late Mark E. Josephson. It was a real dream becoming true. In the eighties, I do not believe any doctoral candidate had ever had such an exquisite panel. The doctoral thesis had been written in just two years and contained no less than nine original articles already published or accepted for publication in the most outstanding cardiology journals of the time.

Four years before, I had written almost two-hundred letters to any existing organization or foundation supposed to support education and research. By the time my cardiology training at the University of Barcelona was about to finish, I had discussed with my mentor, the late Paco Navarro-Lopez, the possibility of expending some time abroad before deciding upon my future career. The idea was to learn some clinical cardiac electrophysiology at a good laboratory. Electrophysiology was a new cardiology subspecialty. Only a few centers in the world were starting to perform electrophysiological investigations in man by means of electrode catheters placed within the heart via a venous access. Scherlag had performed the first recordings of electrical activity of the His bundle in man, in vivo, and Coumel in Paris and Durrer in Amsterdam started to provoke and stop cardiac arrhythmias in the in situ human heart using the same technology. At the other side of the Atlantic, a few centers were also exploring the value and limitations of these new techniques. Among them, Kenneth Rosen in Chicago was the closest follower of the European steps. The University of Maastricht was about to open its doors in 1977 and Hein Wellens, by that time an associate of Durrer, moved from Amsterdam to Maastricht (via Liege by the way) to become the first Professor of Cardiology of the new University. Together with Durrer, he had just published the proceedings of one of the first grand meetings in electrophysiology. The book was titled: "The conduction system of the heart." I had bought that book, did my best, but I finished by not understanding a single chapter. That was the reason I wanted to go abroad and understand that book. It could not be that I just finished my cardiology training and could not understand a word about cardiac electrophysiology.

Obtaining a position as a visitor, fellow, or whatever name you may give it, was not an easy task. I was accepted both by Rosen in Chicago and Wellens in Maastricht, but the problem was how to finance my trip—initially planned for six months. The 200 letters became 200 hours of telephonic calls, appointments at institutions and foundations. Even I visited the president of the football club Barcelona to see whether they could help finance my stay abroad. The 200 letters and answers are a genuine piece of the black history of Spain in the immediate post-Franco time. The President of the Fundacion Pablo Iglesias wrote by hand a letter to me excusing himself, not for not having a grant for me, but for the letter "because they do not even had money to pay for a secretary and a typewriter."

When all hope was almost gone, something unusual was going to happen, something that justifies explaining all of this to you in this foreword. A young but mature cardiologist of the Hospital de San Pau in Barcelona had become the new President of the Arrhythmia Section of the Spanish Society of Cardiology. The first thing this new president did was to take care of the program for trainees, residents and fellows. He wanted electrocardiography and rhythmology to become an important domain in the knowledge of the future cardiologists. As president, he created also a grant for trainees to visit other centers than the one where they were being trained. I applied for the grant and obtained it. It was presented to me by the president, who was nobody else than Antoni Bayés de Luna. The grant was 25 000 pesetas, the equivalent to €400 nowadays. When I explained the reason for me requesting the grant, Antonio put his hands on his head and said: "We must do something, with this amount you cannot expend 6 months in Maastricht." He decided to immediately double the amount of the grant.

The €800 were spent immediately with my first trip to Maastricht to introduce myself to Hein Wellens and with

the second trip to move to Maastricht for the six months. Literally, I had received from Antonio the only thing that I needed: an injection of moral support. The amount of money was now irrelevant, I had accepted it, he had doubled it, and now I was committed, there was no way back. Three months after my arrival, I was offered a position as research fellow at the new university and moved rapidly the next years to present my doctoral thesis, and to become assistant, associate, and full professor in cardiology. The "primum movens" behind all this was that exceptional man Antoni Bayés de Luna.

There has been a mutual respect between us since, however, as one of the key factors in my life, I kept a respectful subordinate relation with him. As a matter of fact, he was for me the hand of the destiny that pulled me to my future and to what I appreciate as a very privileged life for my family and myself. It is with the passage of time that my respect for him started to change into something else. His support for us went beyond the explainable and then I understood that Antoni was much more than a supporting colleague, he actually had become my "oldest brother."

This is my story with Antoni Bayés de Luna. Hundreds of fellows, residents, students and thousands of colleagues could tell each a similar special relation with this very special human being.

I thought it would have been too arrogant from my side to try to explain to you how good this excellent book by Antoni and his coworkers is.

Pedro Brugada
Lede, Valentine's Day
February 2021

Recommended Reading

Baranchuk A. *Interatrial Block & Supraventricular Arrhythmias: Clinical Implications of Bayés' Syndrome*. Cardiotext, 2017.

Baranchuk A. *Brugada Phenocopy: The Art of recognizing the Brugada ECG pattern*. Elsevier, 2018.

Bayés de Luna A. The morphology of the electrocardiogram. In Camm AJ, Lüscher TF, Serruys PW (eds). *The ESC Textbook of Cardiovascular Medicine*, 3rd edn. Oxford University Press, 2019.

Bayés de Luna A, Cosín J (eds). *Cardiac Arrhythmias*. Pergamon Press, 1978.

Bayés de Luna A, Baranchuk A. *Clinical Arrhythmology*, 2nd edn. Willey-Blackwell, 2017.

Bayés de Luna A, Goldwasser D, Fiol M, Bayés-Genis A. Chapter 12: Surface electrocardiography. In Valentin Fuster, Robert A. Harrington, Jagat Narula, Zubin J. Eapen (eds). *Hurst's The Heart*, 14th edn. McGraw-Hill, 2017.

Bonow RO, Mann DL, Zipes, DP, Libby P. *Braunwald's. Heart diseases. A textbook of Cardiovascular Medicine*, 9th edn. Elsevier Saunders Pu, 2012.

Camm AJ, Lüscher TF, Serruys PW (eds). *The ESC Textbook of Cardiovascular Medicine*. Blackwell Publishing, 2006.

Cooksey JD, Dunn M, Marrie E. *Clinical Vectorcardiography and Electrocardiography*. Year Book Medical Publishers, 1977.

Fiol-Sala M, Birnbaum Y, Nikus K, Bayés de Luna A. *Electrocardiography in Ischemic Heart Disease. Clinical and Imaging Correlations and Prognostic Implications*, 2nd edn. Willey-Blackwell, 2020.

Fisch C, Knoebel S. *Electrocardiography of Clinical Arrhythmias*. Futura, 2000.

Friedman HH. *Diagnostic Electrocardiography and Vectorcardiography*, 3rd edn. McGraw-Hill, 1985.

Fuster V, Walsh RA, Harrington RA (eds). *Hurst's The Heart*, 13th edn. McGraw-Hill, 2010.

Gerstch M. *The ECG: A Two Step Approach for Diagnosis*. Springer, 2004.

Grant RP. *Clinical Electrocardiography: The Spatial Vector Approach*. McGraw-Hill, 1957.

Kligfield P, Gettes L, Wagner G, *et al*. *Guidelines of AHA/ACC/HRS*. Circulation 2007; 115 (10): 1306–1324. Doi:10.1161/CIRCULATIONAHA.106.180200.

Lipman BS, Marrie E., Kleiger RE. *Clinical Scalar Electrocardiography*, 6th edn. Year Book Medical Publishers, 1972.

Macfarlane PW, van Oosterom A, Pahlm O, Kligfield P, Janse M, Camm J. *Comprehensive Electrocardiology*, 2nd edn. Springer-Verlag, London, 2010.

Nadeau-Ruthier C, Baranchuk A. *Electrocardiography in Practice: What to do?* iTunes USA, 2016. https://itunes.apple.com/ca/book/electrocardiography-in-practice/id1120119530?mt=13

Piccolo E. *Elettrocardiografia e vettocardigorafia*. Piccin Editore, 1981.

Restrepo Molina G, Wyss F, Sosa Liprandi A, Barbosa M, Baranchuk A. *Texto de Cardiologia de la Sociedad Interamericana de Cardiologia*. Distribuna, 2019.

Rosenbaum M, Elizari M, Lazzari J. *Los hemibloqueos*. Editorial Paidos, 1968.

Sodi Pallares D, Bisteni A, Medrano G. *Electrocardiografía y vectorcardiografia deductiva*. La Prensa Médica Mexicana, 1967.

Surawicz B, Knilans TK. *Chou's Electrocardiography in Clinical Practice*, 6th edn. WB Saunders Company, 2009.

Tranchesi J. *Electrocardiograma normal y patológico*. La Medica, 1968.

Wagner GS. *Marriott's Practical Electrocardiography*, 10th edn. Lippincott Williams & Wilkins, 2001.

Zipes D, Jalife J. *Cardiac Electrophysiology. From Cell to Bedside*. WB Saunders, Philadelphia, 2004.

Part 1
Introductory Aspects

Chapter 1
The Electrical Activity of the Heart

Basic concepts

The heart is a pump that sends blood to every organ in the human body. This is carried out through an electrical stimulus that originates in the sinus node and is transmitted through the specific conduction system (SCS) to contractile cells.

During the rest period, myocardial cells present an equilibrium between the positive electrical charges outside and the negative charges inside. When they receive the stimulus propagated from the sinus node, the activation process of these cells starts. **The activation** of myocardial cells is an electro-ionic mechanism (as explained in detail in Chapter 5) that involves two successive processes: **depolarization**, or loss of external positive charges that are substituted by negative ones, and **repolarization**, which represents the recovery of external positive charges.

The process of depolarization in a contractile myocardial cell starts with the formation of a **depolarization dipole** comprising a pair of charges (−+) that advance through the surface cell like a wave in the sea, leaving behind a wave of negativity (Figure 1.1A). When the entire cell is depolarized (externally negative), a new dipole starting in the same place is formed. This is known as a **dipole of repolarization** (+−). **The process of repolarization**, whereby the entire cell surface is supplied with positive charges, is then initiated (Figure 1.1B).

The expression of the dipoles is a vector that has its head in the positive charge and the tail in the negative one. An electrode facing the head of the vector records positivity (+), whereas when it faces the tail, it records negativity (−) (Figures 1.1–1.3; see also Figures 5.24, 5.25, and 5.28). The deflection originating with the depolarization process is quicker because the process of depolarization is an active one (abrupt entry of Na ions, and later Ca) and the process of repolarization is much slower (exit of K) (see Chapter 5, Section "Transmembrane action potential").

If what happens in one contractile cell is extrapolated to the left ventricle as the expression of all myocardium, we will see that the **repolarization process in this case starts in the opposite place to that of depolarization**. This explains why the repolarization of a single contractile cell is represented by a negative wave, whereas the repolarization of the left ventricle expressing the human electrocardiogram (ECG) is represented by a positive wave because the repolarization process of all left ventricles starts in the zone less ischemic, the subepicardium compared with the subendocardium that is the more ischemic zone (Figure 5.28) (see Chapter 5, Section "From cellular electrogram to human ECG").

How can we record the electrical activity of the heart?

There are various methods used to record the electrical activity of the heart. The best known method, the one we examine in this book, is **electrocardiography**. **An alternative method**, rarely used in clinical practice today but **very useful in understanding ECG curves and therefore helpful in learning about ECGs, is vectorcardiography**.

The latter and other methods will be briefly discussed in Chapter 25. These include, among others, body mapping, late potentials, and esophageal and intracavitary electrocardiography. In addition, normal ECGs can be recorded during exercise and in long recordings (ECG monitoring, Holter technology, telemetry, etc.) (Braunwald et al. 2012; Camm et al. 2006; Fuster et al 2010). For more information about different techniques, consult our books *Clinical Arrhythmology* (Bayés de Luna and Baranchuk 2017) and *Electrocardiography in Ischemic Heart Disease* (Fiol-Sala *et al*. 2020), and other ECG reference books (Macfarlane and Lawrie 1989; Wagner 2001; Gertsch 2004; Surawicz *et al*. 2008) (see "Recommended Reading").

Clinical Electrocardiography: A Textbook, Fifth Edition. Antoni Bayés de Luna, Miquel Fiol-Sala, Antoni Bayés-Genís, and Adrián Baranchuk.

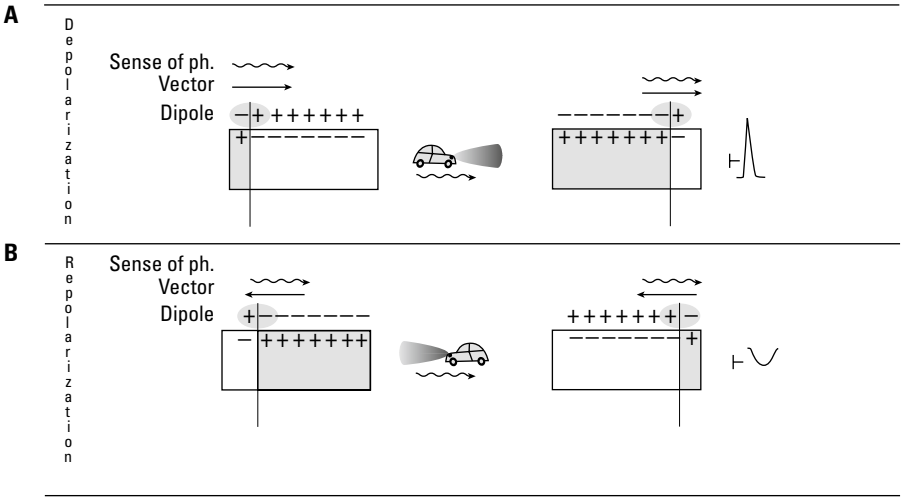


Figure 1.1 Depolarization (A) and repolarization (B) of the dipole in an isolated myocardium cell. We see the onset and end of the depolarization and repolarization processes and how this accounts for the positivity and negativity of corresponding waves (see text and Chapter 5).

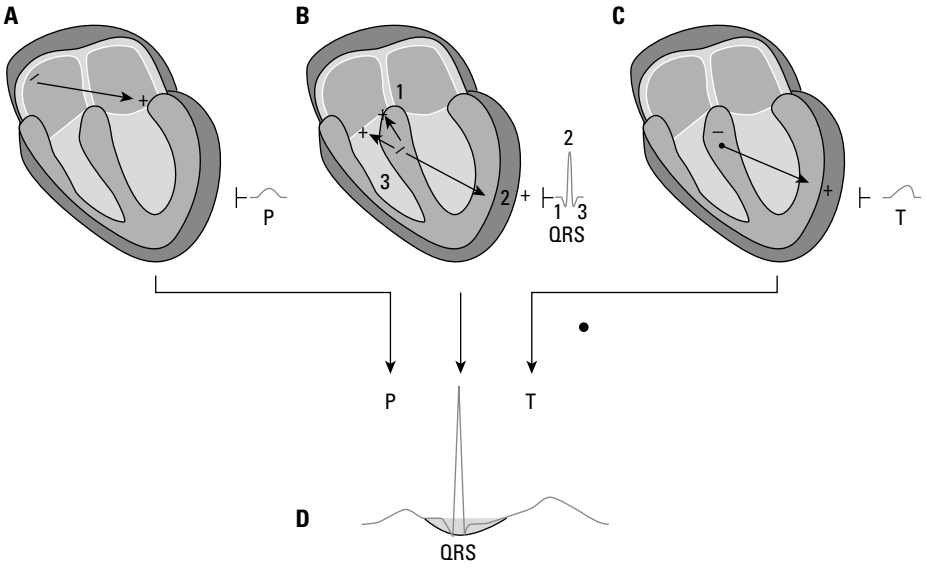


Figure 1.2 The origin of P, QRS, and T deflections (A, B and C). When van electrode located in some zone of LV faces the head (+) of a vector of depolarization (P, QRS) or repolarization (T), it records positivity. When an electrode faces the tail of a vector (−), it records negativity. Atrial repolarization is hidden in the QRS (shadow area) (see text and Chapter 5).

What is the surface ECG?

The ECG is the standard technique used for recording the electrical activity of the heart. **We can record the process of depolarization and repolarization** through recording electrodes (leads) located in various places.

The depolarization process of the heart, atria, and ventricles (see Chapter 5 and Figures 5.16 and 5.18) starts with the formation of a dipole of depolarization (−+), which has a vectorial expression (⟶) that advances through the surface of the myocardium and seeds the entire surface of the myocardial cells with negative charges. A recording electrode facing the head of the vector records positivity (Figure 1.2). Later, **the repolarization process starts** with the formation of a **repolarization dipole** (+−), which also has a vectorial expression. During this process, the positive charges of the outside surface of the cells are restored.

These two processes relate to specific characteristics of the atria and ventricles (Figure 1.2). **The process of atrial depolarization**, when recorded on the surface of the body in an area close to the left ventricle (Figure 1.2), presents as a small positive wave called the P wave (⌒). This is the expression of the atrial depolarization dipole (vector). **The process of ventricular depolarization**, which occurs later when the stimulus arrives at the ventricles, usually presents as three deflections (⩚), known as the QRS complex, caused by the formation of three consecutive dipoles (vectors). The first vector appears as a small and negative deflection because it represents the depolarization of a small area in the septum the first part of LV to be depolarized, and is usually directed upward and to

the right and therefore, recorded from the left ventricle as a small negative deflection ("q wave"). Next, a second important and positive vector is formed, representing the R wave. This is the expression of depolarization in most of the left ventricular mass. The head of this vector faces the recording electrode. Finally, there is a third small vector of ventricular depolarization that depolarizes the upper part of the septum and right ventricle. It is directed upward and to the right and is recorded by the recording electrode in the left ventricle zone as a small negative wave ("s wave") (Figure 1.2).

After depolarization of the atria and ventricles, the **process of repolarization starts**. The repolarization of the atria is usually a smooth curve that remains hidden within the QRS complex. The ventricular repolarization curve appears after the QRS as an isoelectric ST segment and a T wave. This T wave is recorded as a positive wave from the left ventricle electrode because the process of ventricular repolarization, as already mentioned and later explained in detail (see Chapter 5, Section "From cellular electrogram to the human ECG" and Figures 5.24 and 5.25), appears very differently from what happens in an isolated contractile cell (see Figure 5.9). Repolarization starts on the opposite side to that of depolarization, because it starts in the zone less ischemic of LV that is the subepicardium. Thus, the recording electrode faces the positive part of the dipole, or head of the vector, and will record a positive deflection, even though the dipole moves away from it (Figure 1.2C; see also Figures 5.24 and 5.25). Therefore, repolarization of the left ventricle in a human ECG (the T wave) is recorded as a positive wave, just as occurs with the depolarization complex (QRS) in leads placed close to the left ventricle surface ( ).

The successive recording of the ECG is linear and the distance from one P–QRS–T to another can be measured in time. The frequency of this sequence is related to heart rate.

The heart is a three-dimensional organ. In order to see its electrical activity on a two-dimensional piece of paper or screen, it must be projected from at least two planes, the frontal plane (FP) and the horizontal plane (HP) (Figure 1.3).

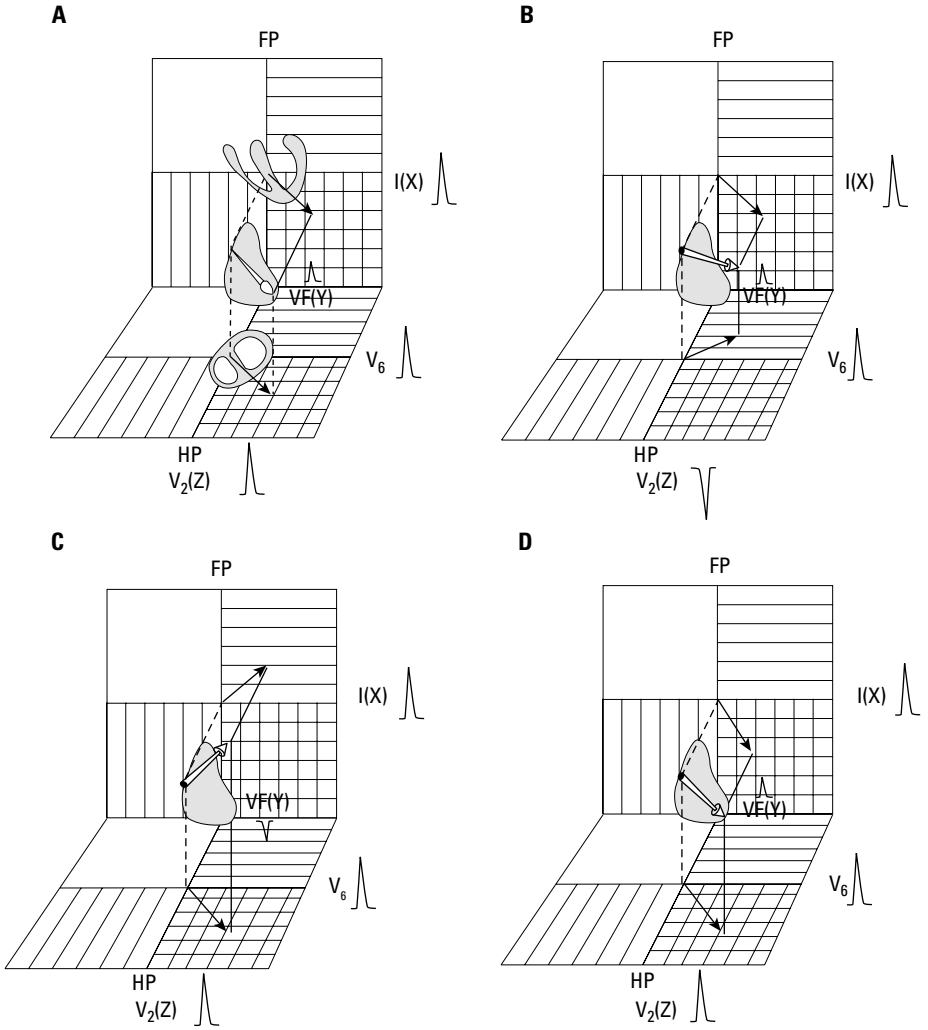


Figure 1.3 Four locations of a vector and their projection in frontal (FP) and horizontal planes (HP). **A** and **B** have the same projection in FP but not in HP. **C** and **D** have the same projection in HP but not in FP. Different positive and negative morphologies appear according to these projections. The locations of the orthogonal leads X, Y, and Z perpendicular to each other are similar to I, aVF, and V2 leads. Vertical lines correspond to the positive hemifields of aVF and V2, and horizontal lines correspond to the positive hemifields of leads I and V6. FP lead I (X) = 0°; VF (Y) = +90°; HP V2 (Z) = +90°; V6 = 0°.

The shape of the ECG varies according to the location (lead) from which the electrical activity is recorded. In general, the electrical activity of the heart is recorded using 12 different leads: six on the FP (I, II, III, aVR, aVL, aVF), located from +120° (III) to −30° (aVL). The aVR is usually recorded in the positive part of the lead that is located in −150° (see Figures 6.10 and 6.11), and six on the HP (V1–V6) located from +120° to 0° (see Chapter 6, Section "Leads" and Figures 6.10 and 6.13).

Each lead has a line that begins where the lead is placed, 0° for lead I or +90° for lead aVF in the FP and 0° for lead V6 and +90° for lead V2 in the HP, for example (see Figure 6.10), and ends at the opposite side of the body, passing through the center of the heart. **By tracing each perpendicular line that passes through the center of the heart, we may divide the electrical field of the body into two hemifields for each lead, one positive and one negative** (Figure 1.3). A vector that falls into the positive hemifield records positivity, while one that falls into the negative hemifield records negativity. When a vector falls on the line of separation between hemifields, an isodiphasic curve is recorded that is +− or −+ according to the sense of rotation of the curve (loop) (see later) (see Figures 6.14 and 6.16).

The different vectors are recorded as positive or negative depending on whether they are projected onto positive or negative hemifields of different leads (Figures 1.3 and 1.5). This is a key concept for understanding the morphology of ECG curves in different leads and is explained in Chapter 6 in more detail (Figure 6.14).

The ECG and its different morphologies can be explained using the following sequence:
Dipole → Spatial vectors → Projection in frontal (FP) and horizontal (HP) planes

What is vectorcardiography? (See Chapter 25 for more extensive information)

The vectorcardiogram (VCG) is the closed curve or loop that records the entire pathway of an electrical stimulus from the depolarization of the atria (P loop) and ventricles (QRS loop) to the repolarization of the ventricles (T loop). These loops are recorded in FP and HP, as well as in the sagittal plane. The VCG is the result of the joined heads of the multiple vectors that are formed during the consecutive processes of depolarization and repolarization of the heart (Figure **1.4**). VCG loops are obtained from three orthogonal (perpendicular to each other) leads, X, Y, and Z, which are placed in positions similar to those of leads I, aVF, and V2, respectively (see Figure **1.4** and Chapter 25).

The VCG curve is a plot of voltage against voltage of the different waves generated by the heart (P, QRS, T loops), and therefore in the VCG loops, it is not possible to measure the time between the beginning of the P loop and the beginning of the QRS loop (PR interval), or the beginning of QRS and the end of the T loop (QT interval). However, we can interrupt the loops of P, QRS, and T by

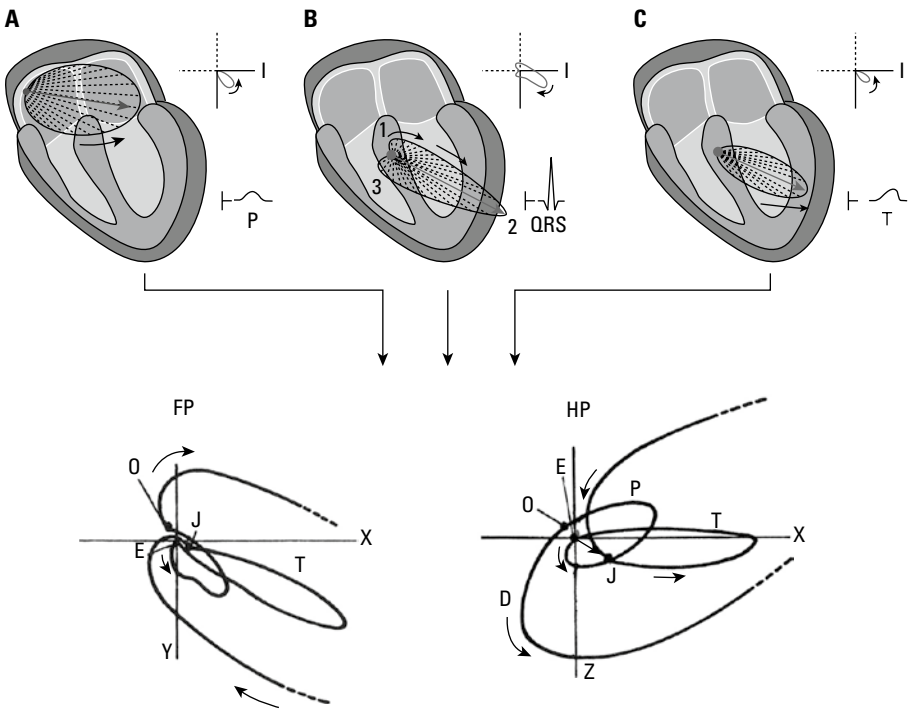


Figure 1.4 The origin of P, QRS, and T loops (A, B and C). The vectorcardiographic curve (D) is the union of the heads of multiple vectors that form during the consecutive processes of depolarization and repolarization (see text and Figure 5.23).

cutting the tracing every 2.5 ms, which allows the duration of each loop to be measured (see Figures 10.6–10.10 and 10.22–10.25).

One advantage of the VCG is that the different rotations of the loop can be visualized. It is important to know if the stimulus follows a clockwise or counterclockwise rotation when one complex or wave is biphasic. Figure 1.5B shows how the mean vector of a loop directed to +0° that falls within the limit between the positive or negative hemifields in lead "Y" (aVF) may present a +− (⩘) or a −+ (⩗) deflection. The direction of the mean vector of the loop does not solve one important problem: a +− deflection is normal, but a −+ deflection may be the expression of myocardial infarction (MI). The correct morphology will be shown, however, by the direction of loop rotation (Figure 1.5). In addition, the mean vector of the QRS loop, which expresses the sum of all vectors of depolarization, does not indicate the direction of the small initial and final forces when these forces are opposed to a mean vector (Figure 1.5). However, the small part of the loop (beginning and end) that falls in the opposite hemifield of the main vector can explain the complete ECG morphology with initial (q) and final small (s) deflections (Figures 1.5 and 1.6; see also Figures 7.10 and 7.11).

The VCG can be described using the following sequence:
The head of multiple vectors → Spatial loops → Projection in FP and HP

ECG–VCG correlation

Bearing in mind the abovementioned information, it is clear that **to better understand the morphology of an ECG, we must consider the stimulus pathway through the heart (VCG loop) in different normal and pathological conditions and identify the projection of these loops in FP and HP**. It is important to understand how the different parts of the loop that fall into the positive or negative hemifields of each lead correspond to the different deflections of an ECG curve (Figures 1.5 and 1.6; see also Figure 5.23) (ECG–VCG correlation). **This allows the ECG curves to be drawn from the VCG loops and vice versa.**

The key concepts around how ECG curves can be obtained from the VCG loops and vice versa (ECG–VCG correlation) are defined using the following sequence:
Dipole → Vector → Loop → Projection in different hemifields → ECG patterns

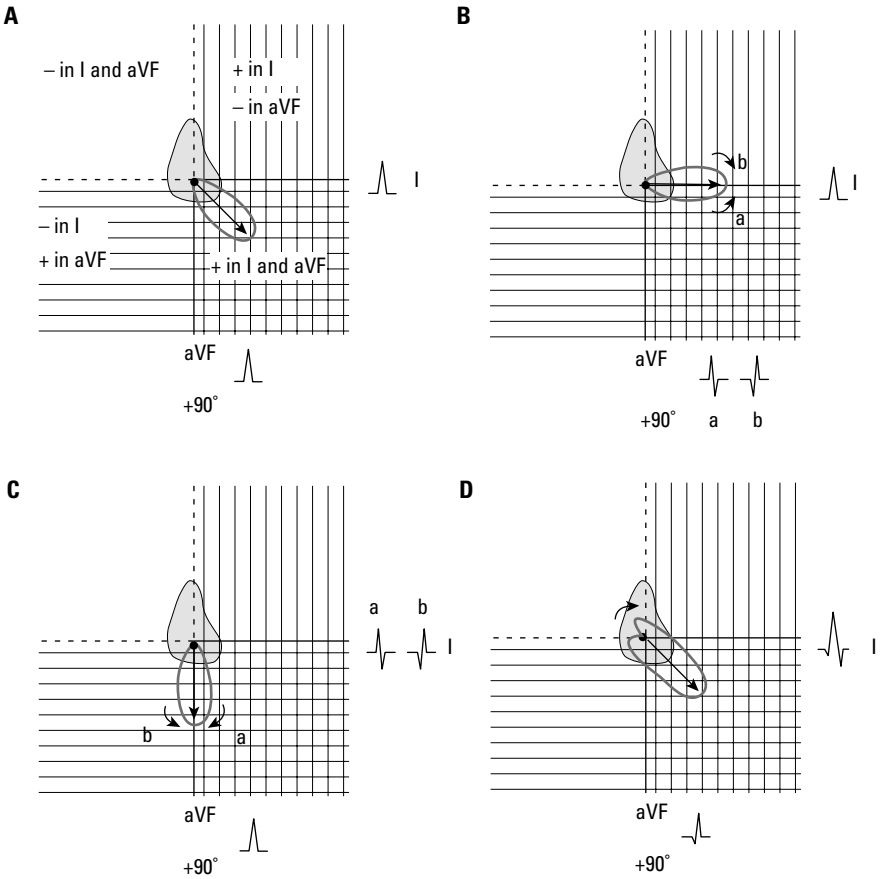


Figure 1.5 The concept of the hemifield. We see how a morphology may be +− or −+ with the same vector but a different loop rotation (B and C) (A and B). The recording of the initial and terminal deflections of qRs are well understood with the correlation of the loop and hemifields in D (see I and aVF).

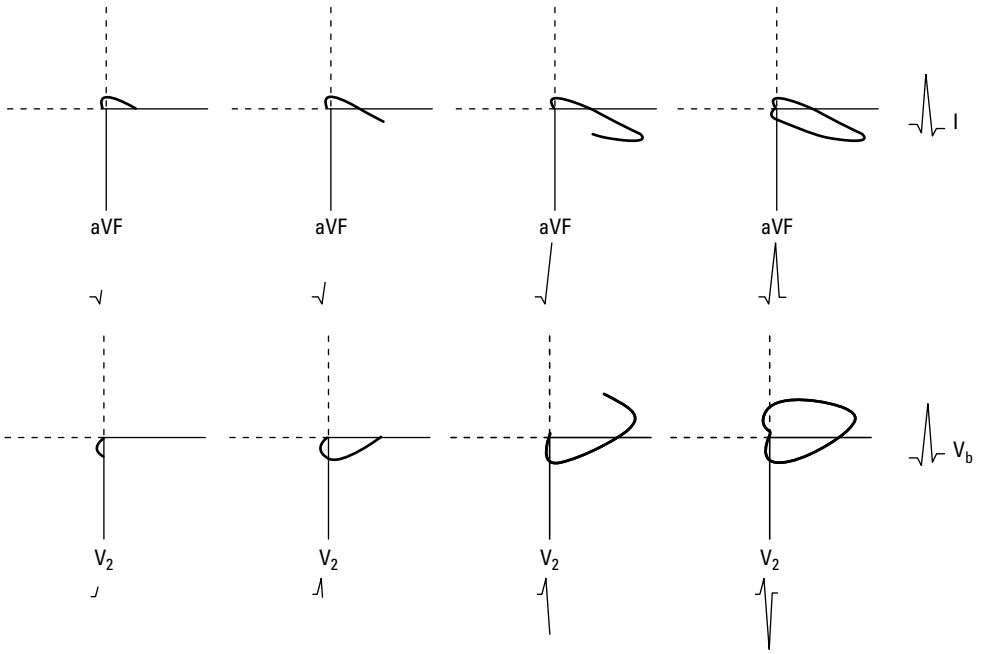


Figure 1.6 Correlation of a vectorcardiographic loop with an electrocardiographic morphology in aVF and V2.

Why do we record ECG curves and not VCG loops?

Although ECG–VCG correlation is used in this book to explain how the different ECG patterns appear, the recording of vectorcardiographic loops for diagnostic purposes is rarely used in clinical practice at present. **There are many reasons for the superiority of ECG curves over VCG loops, the main ones being as follows**:

- **The established diagnostic criteria of ECG in different pathologies are more defined and agreed-upon, compared with the VCG criteria**. They are also easier to apply. Furthermore, it has not been clearly demonstrated by experts in ECG/VCG interpretation that VCG criteria provide more diagnostic information than that taken from ECGs, even in an era when VCG criteria were most used (Simonson *et al*. 1967; Rautaharju 1988; Van Bemmel *et al*. 1992) (see later).
- **VCG loops do not show an appreciation of time (PR and QT interval)**, as previously mentioned.
- **The ECG curves–VCG loop correlation gives us all the detailed information obtainable from VCG loops**. In fact, if the origin of the ECG curve interpretation based on the projection of VCG loops in the positive and negative hemifields of different leads (ECG–VCG correlation) is understood and used, we are able to derive the same information that VCGs provide by just looking at the ECG. For example, it has been reported (Benchimol *et al*. 1972) that VCGs are essential for the diagnosis of superoanterior fascicular block (hemiblock) associated with inferior MI. However, as discussed in Chapter 13, the same information can be obtained from the ECG if we recognize the exact pathway of the stimulus in both cases (inferior MI alone or associated with hemiblock) and we make a good ECG–VCG correlation (see Figure 13.99). Furthermore, many details provided by amplified VCG loops (the degree of ST shifts, onset of pre-excitation, characteristics of the P wave, etc.) can also be obtained from surface ECGs through amplification of the ECG waves, if necessary (see Figure 13.24) (Fiol-Sala *et al*. 2020).
- **The VCG is not useful in the diagnosis of arrhythmias**. Even information about the ectopic P wave may be correctly obtained from ECG curves. However, the recording of P loops may help to know better how is the way of stimulus in situations such as the presence of advanced interatrial block (Bayés de Luna *et al*. 2012).
- **Computerization of ECG data and not of VCG has become dominant** and, despite current limitations, it has a great future. However, as we see later on (Chapter 3, Section "Limitations"), it is necessary to improve the results of ECG computerization with better technology and the inclusion of new data (clinical setting, different scores, etc.), and we hope that in the near future become a substitute of individualized interpretations.
- **The ECG is used more than the VCG** for estimating the size of an MI (Selvester QRS scoring system) (Selvester *et al*. 1972; Wagner *et al*. 1982). However, in the era of ECG-imaging correlations, it is necessary to improve the methodology of QRS score measurement to obtain a better correlation with contrast-enhanced cardiovascular magnetic resonance measurements (see later and Chapter 3, Section "Limitations").

• **ECG and not VCG patterns have already been correlated with imaging techniques**, especially coronarography and contrast-enhanced cardiovascular magnetic resonance (CE-CMR). The correlation of ECG patterns with coronarography has allowed us to better locate the occlusion and determine the severity of ischemia in different types of acute coronary syndromes (leads with different ST shifts) (Sclarovsky 1999; Wellens *et al*. 2004; Fiol-Sala *et al*. 2020). It is also possible to obtain better classification and location of Q-wave MI (leads with abnormal Q or R waves as mirror image) using CE-CMR-ECG correlation (Bayés de Luna *et al*. 2006a, 2006b; Cino *et al*. 2006; Bayés de Luna 2007; Rovai *et al*. 2007; Van der Weg *et al*. 2009; Fiol-Sala *et al*. 2020). Similar correlations have not been done with VCG loops. Currently, a good estimation of infarction size using CE-CMR has been obtained (Kim *et al*. 1999; Moon *et al*. 2004). However, the correlation of infarct size measurement performed by surface ECG (QRS scoring system) (Selvester *et al*. 1972) with CE-CMR is not very consistent, and the CE-CMR shows larger values than the QRS score estimation (Weir *et al*. 2010). We hope that in the future it will be possible to improve these results with new equations (see Chapter 3, Section "The future"). Good results have also recently been shown by Montant *et al*. (2010) using a contrast-enhanced three-dimensional echocardiography compared with CE-CMR to identify and quantify myocardial scars (positive and negative predictive value (PV) > 90%).

• **Young physicians should realize that ECG–VCG correlation is a basis for better understanding ECG curves.** This does not mean that they need to know specific VCG criteria, such as the number of milliseconds the loop is going up and down, because these data obtained from the VCG does not add too much diagnostic information. Therefore, a recorded VCG loop is not clinically necessary. However, **it is important to remember that the ECG–VCG correlation is a key point for better understanding of how ECG curves are originated** (see below).

• Currently, **there are very few devices that still correctly record VCG curves**. At the Electrocardiology Congress held in 2009, titled with the subheading "VCG symposium," it was decided that this subheading should be suppressed (Macfarlane 2009). "Signum temporis" stated the first organizers (Sobieszczańska and Jagielski 2010). The number of VCG papers published in Medline in the 1970s and 1980s reached more than 800 per decade; today, in the first decade of this century, there are fewer than 60 and in the last decade the number is probably still lower.

• It appears that the VCG loops taken from the orthogonal leads do not give much more information of clinical interest than a conventional 12-lead surface ECG. They are also time consuming and need special devices. Although we consider that VCG is not very useful for diagnosis, we are sure that the VCG loops are very useful for teaching and research purposes (Kors *et al*. 1990, 1998; Rautaharju *et al*. 2007; Pérez Riera 2009; Lazzara 2010). It may be that incorporating VCG loops synthesized directly from 12-lead surface ECG recordings would be an interesting option (see Chapter 3).

Why do we use ECG–VCG correlations to understand ECG patterns?

Electrocardiography and vectorcardiography are two methods for recording the electrical activity of the heart. As explained above, the **ECG is a linear curve** based on the positive and negative deflections recorded when an electrode faces the head or the tail of a depolarization and repolarization dipole, the expression of which is a vector, from leads placed in frontal and horizontal planes. The **VCG is a loop** that represents the outline of the joining of multiple dipoles (vectors) formed along the electrical stimulus pathway through the heart. The projection of these loops in frontal and horizontal planes is a closed curve that is different in morphology from the linear curves of an ECG. Both ECG curves and VCG loops, however, are completely connected so that the **ECG curve may be easily deduced from the VCG loop, and vice versa** (see ECG–VCG correlation, Figures 1.5 and 1.6). As already mentioned, this approach is considered to be the best way to understand both the normal ECG and all the morphological changes that different pathologies introduce to the ECG.

The correlation between VCG loops and projection of this on different hemifields to understand the ECG pattern (**dipole → vector → loop → hemifield sequence**) will no doubt remain a cornerstone of the teaching of the ECG (Grant and Estes 1952; Sodi-Pallares and Calder 1956; Cooksey *et al*. 1957; Cabrera 1958; Gertsch 2004).

1. **The deduction of the ECG from the VCG loops is crucial** to better recognizing how both normal ECG curves and the many ECG changes found in different heart diseases and under special circumstances originate.
2. Although the deductive method for teaching electrocardiography is fundamentally based on the correlation that exists between ECG curves and VCG loops, VCG criteria are not used for diagnosis.
3. **In the majority of diagrams** used to show the usefulness of **VCG** loop–ECG wave correlations, the pathway of the electrical stimulus is represented as a curve with a **continuous line**. When we **record original VCG tracings**, however, dashes every 2.5 ms in the VCG loops are shown. Examples of this may be seen throughout this book (see, for example, Figures 11.25, 11.36, and 11.40).

References

Bayés de Luna A. New heart wall terminology and new electrocardiographic classification of Q-wave myocardial infarction based on correlations with magnetic resonance imaging. *Rev Esp Cardiol* 2007;60:683.

Bayés de Luna A., Baranchuk A. *Clinical Arrhythmology*, 2nd edn. Willey-Blackwell, 2017.

Bayés de Luna A, Wagner G, Birnbaum Y, *et al*. A new terminology for left ventricular walls and location of myocardial infarcts that present Q wave based on the standard of cardiac magnetic resonance imaging: a statement for healthcare professionals from a committee appointed by the International Society for Holter and Noninvasive Electrocardiography. *Circulation* 2006a;114:1755.

Bayés de Luna A, Cino JM, Pujadas S, *et al*. Concordance of electrocardiographic patterns and healed myocardial infarction location detected by cardiovascular magnetic resonance. *Am J Cardiol* 2006b;987:443.

Bayés de Luna A, Platonov P, García-Cosio F, *et al*. Interatrial blocks. A separate entity from left atrial enlargement: a consensus report. *J of Electrocardiol* 2012; 45: 445–451.

Benchimol A, Desser KB, Schumacher J. Value of the vectorcardiogram for distinguishing left anterior hemiblock from inferior infarction with left axis deviation. *Chest* 1972;61:74.

Braunwald E, Bonow RO, Mann DL, Zippes D, Libby P. *Heart Disease*, 11th edn. Elsevier Saunders, 2012.

Cabrera E. *Teoría y práctica de la Electrocardiografía*. Edic INC México, La Prensa Médica Mexicana, 1958.

Camm J, Luscher TF, Serruys PW (eds). *The ESC Textbook of Cardiovascular Medicine*. Blackwell, 2006.

Cino J, Pons-Lladó G, Bayés de Luna A, *et al*. Utility of contrast-enhanced cardiovascular magnetic resonance (CE-CMR) to assess how likely is an infarct to produce a typical ECG pattern. *J Cardiovasc Magn Reson* 2006;8:335.

Cooksey J, Dunn M, Massie E. *Clinical Vectorcardiography and Electrocardiography*, 2nd edn. YearBook MP, 1957.

Fiol-Sala M, Birnbaum Y, Nikus K, Bayés de Luna A. *Electrocardiography in Ischemic Heart Disease. Clinical and Imaging Correlations and Prognostic Implications*, 2nd edn. Willey-Blackwell, 2020.

Fuster V, Walsh RA, Harrington RA (eds). *Heart's*, 13th edn. McGraw-Hill, 2010.

Gertsch M. *The ECG: A Two Step Approach for Diagnosis*. Springer, 2004.

Grant R, Estes EH. *Spatial Vector Electrocardiography*. Blakston Co, 1952.

Kim RJ, Fieno D, Parrish T, *et al*. Relationship of CE-CMR to irreversible injury, infarct age and contractile function. *Circulation* 1999;100:1992.

Kors JA, Van Herpen G, Sitting AG, *et al*. Reconstruction of the Frank VCG from the standard ECG leads. *Eur Heart J* 1990;11:1083.

Kors JA, De Bruyne MC, Hoes AW. T axis as an independent indicator of risk of cardiac events in elderly people. *The Lancet* 1998;352:361.

Lazzara R. Spatial vectorcardiogram to predict risk for sudden arrhythmic death: Phoenix risen from the ashes. *Heart Rhythm* 2010;7:1614.

Macfarlane PW. Interview with Peter W Macfarlane by Ljuba Bacharova. *J Electrocardiol* 2009;42:223.

Macfarlane PW, Lawrie TDV (eds). *Comprehensive Electrocardiography*. Pergamon Press, 1989.

Montant P, Chenot F, Gaffinet C, *et al*. Detection and quantification of myocardial scars using CE-3D-echocardiography. *Circulation CV Imag* 2010;3:415.

Moon JC, De Arenaza DP, Elkington AG, *et al*. The pathologic basis of Q-wave and non-Q-wave myocardial infarction: a cardiovascular magnetic resonance study. *J Am Coll Cardiol* 2004;44:554.

Pérez Riera A. *Learning Easily Frank Vectorcardiogram*. Editora Mosteiro, Sao Paulo, 2009.

Rautaharju PM. A hundred years of progress in electrocardiography. 2: The rise and decline of vectorcardiography. *Can J Cardiol* 1988;4:60.

Rautaharju P, Prineas R, Zhang Z-M. A simple procedure for estimation of the spatial QRS/T angle from the standard 12-lead ECG. *J Electrocardiol* 2007;40:300.

Rovai D, Di Bella G, Rossi G, *et al*. Q-wave prediction of myocardial infarct location, size and transmural extent at magnetic resonance imaging. *Coronary Artery Dis* 2007;18:381.

Sclarovsky S. *Electrocardiography of Acute Myocardial Ischaemic Syndromes*. Martin Dunitz, 1999.

Selvester RH, Wagner JO, Rubin HB. Quantitation of myocardial infarct size and location by electrocardiogram and vectorcardiogram. In Snelin HA (ed.) *Boerhave Course in Quantitation in Cardiology*. Leyden University Press, 1972, p. 31.

Simonson E, Tune N, Okamoto N, *et al*. Vectorcardiographic criteria with high diagnostic accuracy. *Z Kreislaufforsch* 1967;56:1243.

Sodi-Pallares D, Calder R. *New Bases of Electrocardiography*. Mosby, 1956.

Sobieszczańska M, Jagielski J. The International Society of Electrocardiology: a 50 year history originated in Poland. *J Electrocardiol* 2010;43:187.

Surawicz B, Knilans TK, Te-Chuan Chou. *Chou's Electrocardiography in Clinical Practice*, 6th edn. Saunders, 2008.

Van Bemmel JH, Kors JA, van Herpen G. Combination of diagnostic classifications from ECG and VCG computer interpretations. *J Electrocardiol* 1992;25(suppl):126.

Van der Weg K, Bekkers S, Gorgels A, *et al*. The R in V1 in nonanterior wall infarction indicates lateral rather than posterior involvement. Results from ECG/MRI correlations. *Eur Heart J* 2009;30(suppl):P2981.

Wagner GS (ed.) *Marriott's Practical Electrocardiography*, 10th edn. Lippincott Williams & Wilkins, 2001.

Wagner G, Freye C, Palmer ST, *et al*. Evaluation of QRS scoring system for estimating myocardial infarction size. *Circulation* 1982;65:347.

Weir R, Martin T, Wagner G. Comparison of infarct size and LVEF by CE-CMR and ECG scoring in reperfused anterior STEMI. *J Electrocardiol* 2010;43:230.

Wellens H, Doevedans P, Gorgels A. *The ECG in Acute Myocardial Infarction and Unstable Angina*. Kluwer Academic, 2004.

Chapter 2
The History of Electrocardiography

Electrical phenomena have been observed by humans for more than 2500 years. **Thales of Miletus** in Greece (sixth century BCE) noted that amber rubbed with wool attracts light objects. In fact, the ancient Greek name for amber is *elektron*. As early as the end of the sixteenth century, the English physician William Gilbert postulated the relationship between electricity and magnetism. He was followed by Benjamin Franklin, who discovered the lightning rod in about 1750. At the end of the eighteenth century, the Italian **Luigi Galvani** discovered that electricity in animals is generated via "an electric fluid." Galvani believed that electrical stimulus preceded muscle contraction. He would become the world's first electrophysiologist (Rosen 2002; Rosen and Janse 2006).

The electrical activity of the heart was first recorded in the late nineteenth century by **Augustus D Waller** (Figure 2.1), who in 1887 recorded the curves of electrical activity of the human heart using saline-filled tube electrodes and the capillary electrometer developed by Gabriel Lippmann (Figure 2.2A,B). The first human ECG was taken to Thomas Goswell, a technician in his laboratory. Initially, he used his dog Jimmy to perform ECG recordings, but was accused of cruelty to animals because of the belts used and the practice of putting the dog's extremities in saline water. Although Waller was credited with being the first to record the electrical activity of the heart, he did not have much faith in the usefulness of electrocardiography, stating "I do not imagine the electrocardiography is likely to find any very extensive use . . . just occasionally to record some rare anomaly of cardiac action" (Burch and DePasquale 1964).

In the last years of the nineteenth century, **Willem Einthoven** (1860–1927) (Figure 2.3) (Einthoven 1912; Snellen 1977; Moukabary 2007; Kligfield 2010) began to study animal action potentials using the capillary electrometer. Because he was dissatisfied with the records obtained, he made several modifications that greatly improved the tracing quality by using differential equations to correct the poor frequency response of the original design (Figure 2.2A). With these modifications, he was able to predict the correct form of the human ECG

Figure 2.1 Dr AD Waller recorded many ECG tracings using his dog Jimmy, resulting in accusations of animal cruelty (Portrait of A.D. Waller Wellcome M0012782, https://commons.wikimedia.org/wiki/File:Portrait_of_A.D._Waller_Wellcome_M0012782.jpg. CC-BY-4.0).

Clinical Electrocardiography: A Textbook, Fifth Edition. Antoni Bayés de Luna, Miquel Fiol-Sala, Antoni Bayés-Genís, and Adrián Baranchuk.

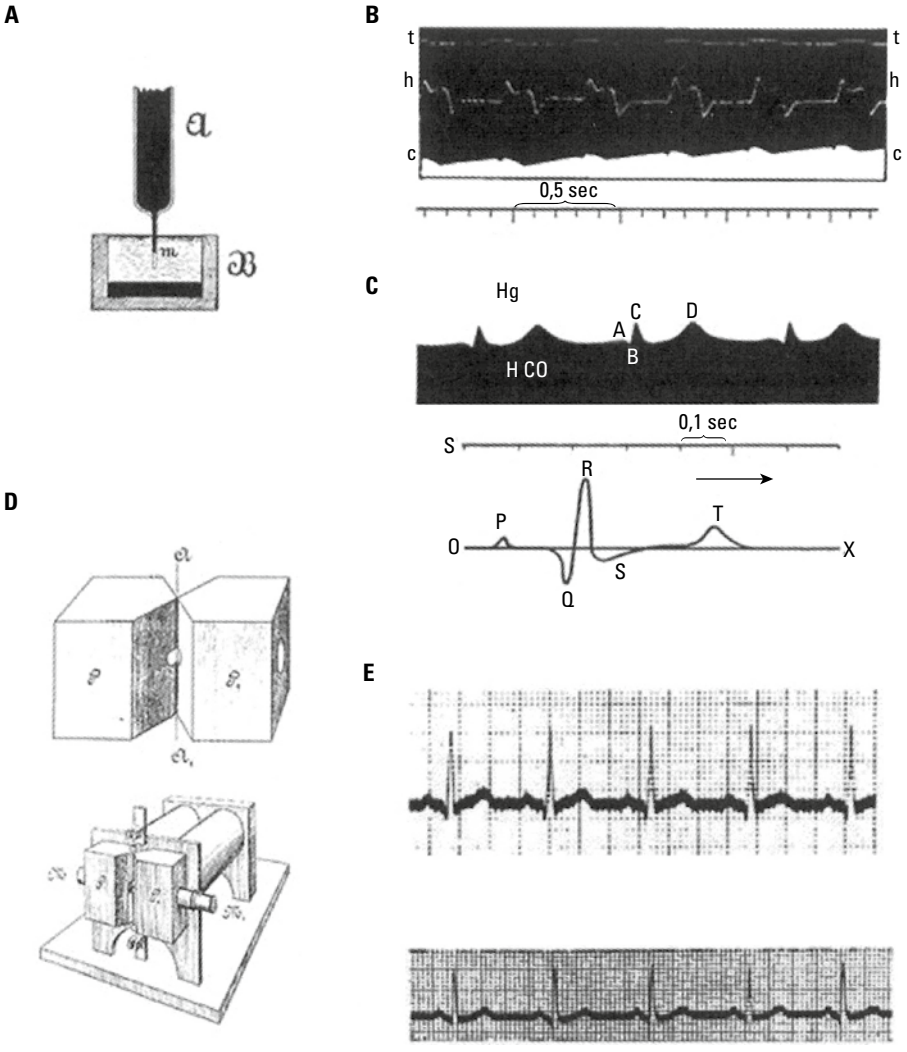
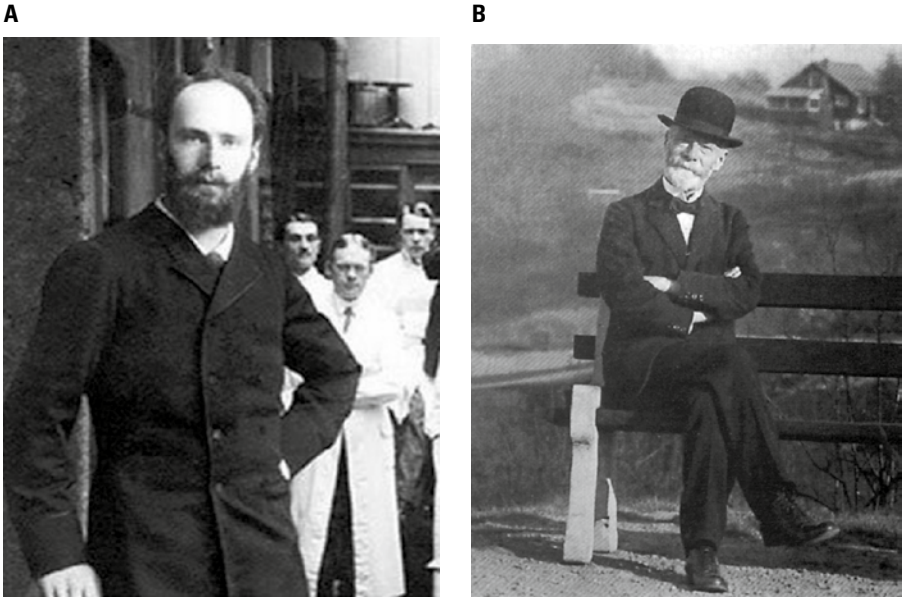


Figure 2.2 (A) Lippmann's capillary electrometer consisted of a mercury reservoir ending in a glass capillary with the upper half filled with mercury and the lower half and reservoir filled with sulfuric acid. (B) Waller's cardiogram recorded using a capillary electrometer. *t* = time; *h* = external pulsation from heart beat; *c* = electrical activity of heart. (C) Einthoven's recording using a capillary electrometer. Upper: A, B, C, and D waves; lower: mathematically corrected waves, now designated PQRST. (D) A string galvanometer. Upper: Poles *P* and P_1 of electromagnet and aperture for string. Note holes for viewing via microscopes. Lower: electromagnet with string in place and two microscopes. (E) Einthoven's ECG recordings.



Willem Einthoven (1860–1927)

Figure 2.3 Dr Willem Einthoven in his laboratory early in his career (A) and years later (B) while visiting Frank N Wilson in Ann Arbor, Michigan.

(Figure 2.2C) and he proved his findings using a string galvanometer developed in 1902.

Einthoven's **string galvanometer** (Figure 2.2D) consisted of a silver-coated quartz filament suspended between the two poles of an electromagnet. The fixed magnetic field created by the electromagnet established a strong constant force moving from one pole to the other. Currents from the heart registered from the surface of the body were conducted through the quartz string, thereby creating a varying magnetic field of force around the long axis of the string. The interaction between the two magnetic fields, one between the poles of the electromagnet and the other depending on the magnitude of the current that flowed through the string, resulted in movements of the string that were recorded as sharp deflections.

The first electrocardiogram recorded using the string galvanometer was published in 1902. The quality of the tracings was undoubtedly very good and similar to today's tracings (Figure 2.2E). It is interesting to note that because Einthoven's laboratory was more than a mile from the academic hospital in Leyden, he developed a method for recording the ECG from a distance, which he called "Telecardiogramme."

Unlike Waller, Einthoven intuited the great potential of electrocardiography, stating that **"A new chapter has been opened in the study of heart diseases . . . by which suffering mankind is helped."** In fact, by 1906, **he had already published his first paper presenting normal and abnormal ECGs** (Einthoven 1912). With this new technique, the recording of ECG curves had a high fidelity and sensitivity and represented an undistorted, directly readable graphic record of the electrical activity of the heart. Einthoven labeled the detailed wave deflections "PQRST," instead of using the "ABCD" notations used for the waves taken with the capillary electrometer (Figure 2.2C). This avoided confusion between uncorrected and corrected records and allowed the addition of further letters if other earlier or later wave forms should be discovered. Starting with "P" to describe the first wave avoided the use of the letters "N" and "O," which were already in use for other mathematical/geometrical conventions.

The diagnostic technique introduced by Einthoven more than 110 years ago was soon manufactured by the Cambridge Scientific Instrument Company, founded by Horace Darwin, younger son of the great biologist Charles Darwin and the first to officially commercialize ECG machines. The first manufactured ECG machine was supplied to EA Schafer in Edinburgh in 1908 (Figure 2.4A). The second model, the table model, was manufactured in 1911. Figure 2.4B shows how the recording of tracings with this huge machine was performed. One of the three first complete electrocardiographs was delivered to Sir Thomas Lewis.

Today's ECG tracings no better in quality from a morphological point of view (Figure 2.2E), although now the

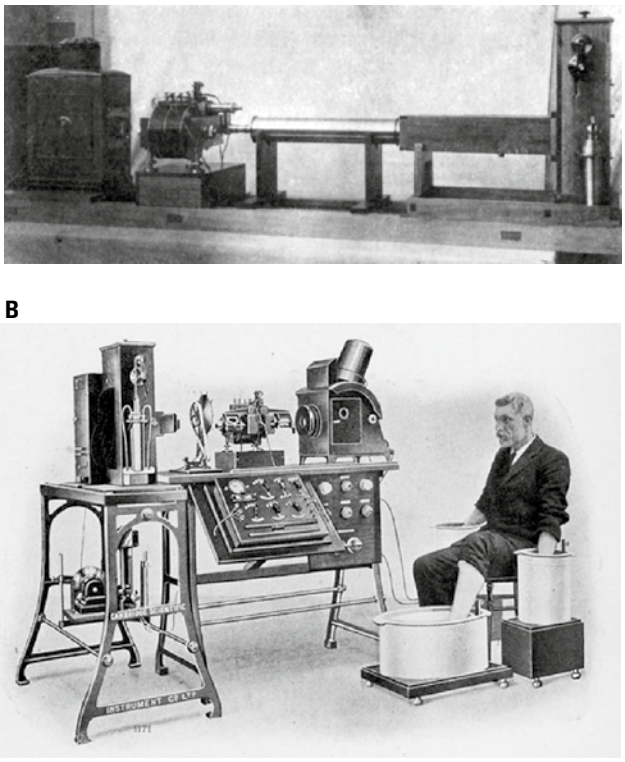


Figure 2.4 (A) The first manufactured ECG machine. (B) The second model (table model manufactured by Cambridge Scientific Instrument Company in 1911) (see text) (https://commons.wikimedia.org/wiki/File:Willem_Einthoven_ECG.jpg).

ECG is usually recorded digitally, and the devices are much smaller, and even may be recorded by a mobile phone or the ECG information may be given with the use of a watch holding the device between two hands (see Chapters 6 and 26, Figure 6.19). Even with a watch, may be recorded the ECG just pushing a bottom, what is especially useful. In any case, the ECG remains, presumably forever, the "gold standard" technique most used in everyday practice in cardiology, and possibly general medicine, throughout the world.

In hindsight, it is clear that **the Nobel Prize Einthoven received in 1924 was very well deserved**. He had a fascinating and creative personality added to his genius. He only looked for the truth. He once stated **"What you or I think is not important. What is important is the truth"** (Burch and De Pasquale 1964).

Prior to the discovery of the ECG, the diagnosis of heart rhythm disorders had been performed by clinical examination and polygraphic recordings of arterial and venous pulsations. The most important studies in this field were performed by the physicians Sir James Mackenzie and Karel F Wenckebach in the late nineteenth century. In the early days of electrocardiography, they were naturally suspicious of this new technique, probably because they thought that it might interfere with careful observation

and the physical diagnosis of heart diseases. However, Wenckebach in particular became convinced of its importance. The ECG made the identification of many of the great concepts discovered by these pioneers much easier and more accurate. In fact, Wenckebach was able to discover with polygraphic recordings different types of second-degree atrioventricular block. The influence of both cardiologists on the evolution of the ECG, especially in the field of heart rhythm disorders, is very significant.

From a historical point of view, the two most important pioneers of clinical electrocardiography, Sir Thomas Lewis and Frank N Wilson, must be mentioned. **Sir Thomas Lewis** (1881–1945) (Figure 2.5) accomplished the daunting task of demonstrating the importance of Einthoven's discovery, especially in the field of heart rhythm disorders. He also demonstrated interesting aspects of changes in wave morphology, such as the significance of the mirror pattern in acute ischemia, and wrote the first ECG books describing the clinical usefulness of the technique (Lewis 1913, 1949). He did not, however, correctly interpret the ECG morphology in bundle branch block; this was accomplished later by other pioneer such as George Fahr (Figure 2.6). Lewis believed that there was nothing left to discover in the field of electrocardiography after 1920, and turned to peripheral circulation. **Frank N Wilson** (1890–1952) (Figure 2.6) was the father of chest leads and the central terminal that allows us to record the so-called "unipolar leads" in the frontal plane (aVR, aVL, aVF) and the horizontal plane (precordial leads) using limb leads as a reference (Wilson *et al*. 1931, 1944). He also performed important studies on ventricular blocks and other aspects of electrocardiography.

Figure 2.5 Dr Willem Einthoven, left, with Sir Thomas Lewis, right (Museum Boerhaave, Leiden).

Figure 2.6 Twelve pioneers of electrocardiology (see text).