Cardiac Pacemakers
Step by Step

AN ILLUSTRATED GUIDE

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To Jennie
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To Lieve
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The impetus for writing this book came from our observations that many health care professionals and young physicians working in emergency rooms, intensive and coronary care units were unable to interpret simple pacemaker electrocardiograms correctly. Over the years we also heard many complaints from beginners in the field of cardiac pacing that virtually all, if not all, the available books are too complicated and almost impossible to understand. Indeed, the ever-changing progress in electrical stimulation makes cardiac pacing a moving target. Therefore we decided to take up the challenge and write a book for beginners equipped with only a rudimentary knowledge of electrocardiography and no knowledge of cardiac pacing whatsoever. Because many individuals first see the pacemaker patient after implantation, the book contains little about indications for pacing and implantation techniques. The book starts with basic concepts and progressively covers more advanced aspects of cardiac pacing including troubleshooting and follow-up.

As one picture is worth a thousand words, this book tries to avoid unnecessary text and focuses on visual learning. We undertook this project with the premise that learning cardiac pacing should be enjoyable. Cardiac pacing is a logical discipline and should be fun and easy to learn with the carefully crafted illustrations in this book. The artwork is simple for easy comprehension. Many of the plates are self-explanatory and the text in the appendix only intends to provide further details and a comprehensive overview.

Many of the images used to create the illustrations in this book are taken from CorelDraw and Corel Mega Gallery clipart collections.

We are grateful to Charlie Hamlyn of Blackwell Publishing and Tom Fryer of Sparks for their superb work in the production of this book.

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A pacemaker (PM) is an electronic device implanted in the body to regulate the heart beat. A PM is not designed to defibrillate the heart by the delivery of shocks. It consists of a battery and electronic circuits enclosed in a hermetically sealed can. The PM delivers electrical stimuli over leads with electrodes in contact with the heart.
RECORDING PACEMAKER ACTIVITY

* 12-lead ECG during transvenous pacing
* Standard chest electrode positions
* Grid for measuring intervals
* The electrical axis in the frontal plane
* Determination of the mean frontal plane axis 1
* Determination of the mean frontal plane axis 2
* A rule of thumb for the mean frontal plane axis
CONFIGURATION OF 12-LEAD ECG DURING TRANSVENOUS PACING

- **ECG leads**: RA (right arm), LA (left arm), RL (right leg), LL (left leg)
- **Pacing lead through subclavian vein**
- **Pacing anode (skin electrode)**
- **Pacing cathode (inside heart)**
- **Precordial ECG leads V1 to V6**
- **Limb ECG leads**

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The right position of all the electrodes is extremely important !!!

STANDARD CHEST ELECTRODE POSITIONS

- **V1**: 4th intercostal space at right border of sternum
- **V2**: 4th intercostal space at left border of sternum
- **V3**: Midway between positions 2 & 4
- **V4**: 5th intercostal space at left midaxillary line
- **V5**: Same level as pos. 4 in anterior axillary line
- **V6**: Same level as pos. 4 & 5 in midaxillary line
- **V7**: In left posterior axillary line
TIMING INTERVALS VERSUS RATE

This is elementary! Everybody should know that!!!

Calibration

10 mm = 1 mV
25 mm = 1 sec

5 mm = 200 ms

5 mm = 0,5 mV

1 mm = 40 ms

The paper speed is normally 25 mm/s, thus 1 mm on the paper corresponds with 1/25 s = 0.04 s = 40 ms

UNITS OF TIME
1 minute = 60 seconds
or 1 min = 60 s
1 second = 1,000 milliseconds
or 1 s = 1,000 ms
1 minute = 60,000 milliseconds
or 1 min = 60,000 ms

RATE is expressed in beats per minute or bpm

THE CONVERSION

60,000
RATE
INTER-
VAL

RATE (in bpm) = \[
\frac{60,000}{\text{INTERVAL (in ms)}}
\]

The pacemaker rate is the average of several intervals calculated for 1 minute of time

INTERVAL (in ms) = \[
\frac{60,000}{\text{RATE (in bpm)}}
\]

An interval is the time between two consecutive events, e.g. Vp-Vp or Vs-Vs

Abbreviations: min = minute; mm = millimeter; ms = millisecond; mV = millivolt; s = second; Vp = ventricular paced event; Vs = ventricular sensed event
At any time during depolarization, there is a resultant instantaneous vector which represents the electrical activity of the depolarization process of all the ventricular myocardium. As depolarization proceeds, the magnitude and direction of this instantaneous vector varies continuously. The mean frontal plane vector or axis represents the summation of all the instantaneous vectors recorded in the frontal plane that occur during depolarization, and is depicted as a single mean vector.

Why is the frontal plane axis important during pacing?
Because it can help locate the 4 important sites of stimulation which are the RV apex, RV outflow tract, LV and biventricular (i.e. simultaneous RV and LV) pacing.

To determine the mean frontal plane axis, you have to understand the frontal plane diagram and arrangement of the frontal plane ECG leads. You also have to understand the hemisphere concept of the various frontal plane ECG leads. If the mean QRS vector or axis is situated in the positive (+) hemisphere of a particular lead, this ECG lead will show a positive (+) deflection.

Lead aVF will be negative if the mean QRS vector is in this hemisphere.
Lead aVF will be positive if the mean QRS vector is situated in this hemisphere.
Lead I will be positive if the mean QRS vector is situated in this hemisphere.
Lead I will be negative if the mean QRS vector is in this hemisphere.
DETERMINATION OF THE MEAN FRONTAL PLANE AXIS

JUST REMEMBER 3 IMPORTANT QUESTIONS:
* In which quadrant is the QRS vector situated?
* Which of the adjacent leads has the tallest R wave or the deepest S wave?
* Which is the most equiphasic lead (or zero lead)?

STEP 1: LOOK AT LEADS I & aVF TO DETERMINE IN WHICH QUADRANT THE FRONTAL PLANE AXIS IS SITUATED

STEP 2: LOOK IN THE APPROPRIATE QUADRANT FOR THE TALLEST R WAVE OR THE DEEpest S WAVE

The lead nearest to (or parallel along) the QRS axis has the largest positive deflection. If two leads have equal positive deflections, the axis is exactly in the middle between these two leads.
STEP 3: LOOK FOR THE MOST EQUIPHASIC LEAD (where the positive minus the negative deflection is closest to zero)
THIS LEAD IS PERPENDICULAR TO THE QRS AXIS

QRS axis in the frontal plane
QRS axis is along lead II. Note that lead II has the largest positive deflection, confirming the direction of the axis.

SUMMARY: the QRS axes of the heart (not paced)
RULE OF THUMB FOR DETERMINING THE FRONTAL PLANE AXIS
LOOK AT LEADS I AND aVF

1/ If both leads I and aVF are positive (dominant R wave), the axis is normal (yellow area)
2/ If lead I is positive and lead aVF is negative, you must look at lead II
   a. If lead II is equiphasic (positivity is equal to negativity so that the algebraic sum is zero), the axis is directed along lead aVL. This because an equiphasic lead (lead II in this case) is perpendicular to the axis (along lead aVL)
   b. If lead II is more positive than negative, the axis is below -30° and normal (yellow area)
   c. If lead II is more negative than positive, the axis is more negative than -30° and is in the left superior quadrant (red area)
3/ If lead I is negative (down) and aVF is positive (up) the axis is in the right inferior quadrant (green area - right axis deviation)
4/ If leads I and aVF are negative (down), the axis is in the right superior quadrant (blue area). The axis is simply described as being in the right superior quadrant. It is called neither extreme right nor extreme left axis deviation.
**FUNDAMENTALS of ELECTRICITY**

* Ohm’s law
* Water equivalent
* Impedance
* Common units for pacemaker variables
* Battery 1
* Battery 2
* Battery impedance and battery voltage
* Battery capacity
Ohm's Law

This is the most important law of electricity!!!
Everybody should be familiar with these three variables, their relation and their units!

\[ U = \text{voltage (in volt V)} \]
\[ I = \text{current (in ampere A)} \]
\[ R = \text{resistance (in ohm } \Omega \text{)} \]
## THE WATER EQUIVALENT

### WATER
- * waterpump
- * pump pressure
- * quantity of water
  - * liter
- * flow of water
  - * liter per sec
- * water pipe
- * resistance

### ELECTRICITY
- * battery
- * voltage
- * electric charge
  - * ampere.second
- * electric current
  - * ampere
- * wire
- * resistance

---

Note for the electricians:

ampere.second (As) = coulomb (C)

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PACING IMPEDANCE

According to Ohm’s law:

\[ R = \frac{VOLTAGE\ U\ (in\ volt)}{CURRENT\ I\ (in\ ampere)} \]

comprises:
* lead resistance
* tissue impedance

Note for electricians:
The pacing impedance is not purely resistive (the tissue impedance is capacitive) and should be indicated by a Z. In the clinical practice only the absolute value or magnitude of the pacing impedance is considered and since it is expressed in “OHM” according to Ohm’s law, most people simply call it “resistance”

<table>
<thead>
<tr>
<th>INSULATION DEFECT</th>
<th>NORMAL PACING IMPEDANCE</th>
<th>LEAD FRACTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 250Ω</td>
<td>ca. 500Ω</td>
<td>&gt; 1000Ω</td>
</tr>
</tbody>
</table>
**COMMON UNITS FOR PACEMAKERS**

**VOLTAGE**
- Basic unit: **volt** - symbol V
- Sometimes used: **millivolt** - symbol mV
  
  \[ 1 \text{ V} = 1,000 \text{ mV} \quad \text{or} \quad 1 \text{ mV} = \frac{1}{1,000} \text{ V} = 10^{-3} \text{ V} \]

**CURRENT**
- Basic unit: **ampere** - symbol A
- Used stimulus amplitude: **milliampere** - symbol mA
  
  \[ 1 \text{ A} = 1,000 \text{ mA} \quad \text{or} \quad 1 \text{ mA} = \frac{1}{1,000} \text{ A} = 10^{-3} \text{ A} \]
- Used for battery current drain: **microampere** - symbol µA
  
  \[ 1 \text{ A} = 1,000,000 \mu \text{A} \quad \text{or} \quad 1 \mu \text{A} = \frac{1}{1,000,000} \text{ A} = 10^{-6} \text{ A} \]

**RESISTANCE**
- Basic unit: **ohm** - symbol Ω
- Sometimes used: **kilo-ohm** - symbol kΩ
  
  \[ 1 \Omega = \frac{1}{1,000} \text{ k} \Omega \quad \text{or} \quad 1 \text{ k} \Omega = 1,000 \Omega = 10^{3} \Omega \]

Learning how a pacemaker works is overwhelming because I don’t know anything about electricity!

It’s really simple because you only have to understand elementary concepts. You know about the flow of electrons in an electrical circuit? And do you remember Ohm’s law? Just learn Ohm’s law and the units of current, voltage and resistance used in Ohm’s law.

You can forget parameters like energy (joules) and charge (coulombs) because they are not strictly needed in the day-to-day practice of pacemaker follow-up.

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The arrangement of a circuit with a battery and a load is confusing! Is the anode not always positive and the cathode always negative???

* First, you have to know that electric current only flows if the circuit is closed and that the external resistance or load limits the current.
* Second, you have to understand that in a closed circuit the **electrons** flow from the negative pole of the battery, through the load and back to the positive pole of the battery. However, **conventional electric current** flows in the opposite direction from the + pole of the battery via the load to its - pole. That’s a historical convention dating from the time electrons weren’t yet discovered.
* Third, just remember that the battery is the source delivering electricity while the load consumes electricity. If you follow the circuit, you will see that the anode is always the electrode by which the electrons leave (A for anode in “Away”). The cathode on the contrary, is always the electrode into which the electrons enter or come (C for cathode in “Come”). That’s easy isn’t it? This terminology applies to both the battery and the load!
The Lithium - Iodine battery

Battery anode

Oxidation

\[ 2\text{Li} \rightarrow 2\text{Li}^+ + 2e^- \]

Each atom of Li loses one electron

Electrolyte

Solid LiI

Continuously formed by the reaction between Li and I

\[ 2\text{Li} + I_2 = 2\text{LiI} \]

Battery cathode

Reduction

\[ I_2 + 2e^- \rightarrow 2I^- \]

Each molecule of I combines with two electrons

How about the lithium-iodine battery? Someone told me that no electrons can flow through that battery?

Yes, that’s true, but it isn’t difficult to understand. The anode of a lithium-iodine battery is the place where electrons free themselves from lithium atoms to form Li\(^+\) ions. With the electrolyte of the battery serving as an electron barrier and all electrons being negative and repelling each other, the electrons are pushed outside the battery to start their journey through the electrical circuit. Following the electrical conductors, the electrons enter the load via its cathode. Just as a liquid, electricity cannot be compressed. So, an equal amount of electrons is leaving the load via its anode, being attracted by the positive pole of the battery. The electrons enter the battery cathode where they combine with iodine I\(_2\) to form 2I\(^-\) ions.

Inside the battery, the electrical circuit is closed by the flow of the Li\(^+\) and I\(^-\) ions. These ions attract each other and diffuse through the electrolyte. When the two kinds of ions meet each other, they combine to form lithium-iodide LiI. However, the lithium-iodide is not a good electrical conductor and so the buildup of this LiI increases the internal resistance of the battery.
The anode of the battery produces lithium ions, while the cathode is producing iodine ions. These ions are moving to the other pole of the battery and are recombining to lithium iodide (LiI). This discharge product forms a barrier for the further movement of ions and thus an internal battery resistance is built up.

At the BOL the electrolyte barrier is thin with a low normal impedance. However, at the EOL the layer becomes thick and when the cathode material is almost depleted, the internal resistance is very high.

**BOL** = beginning-of-life ; **EOL** = end-of-life
The output current of the pulses to the heart is expressed in mA (1 mA = 1/1,000 A)
The current drain of the battery is expressed in µA (1 µA = 1/1,000,000 A)
1 milliampere (mA) = 1,000 microampere (µA)
VENTRICULAR STIMULATION

* Myocardial refractory period
* Asynchronous ventricular pacing (VOO)
* Ventricular depolarization by pacing
* The output pulse of the pacemaker
* The programmer and telemetry
* Panic button
* Programming amplitude and pulse width
* Determination of pacing threshold with constant pulse width
* Determination of pacing threshold with constant voltage
* Strength-duration curve
* Safety margin for capture
* Autocapture
* Bipolar vs unipolar pacing -
  - stimulus on analog recorder
* Variable stimulus appearance on digital recorder
Always keep in mind! The myocardial refractory period refers to stimulation. In contrast, the pacemaker refractory period refers to the sensing function of the device.

VENTRICULAR MYOCARDIAL REFRACTORY PERIOD

**Ventricular action potential**

**ECG**

- **Absolute refractory period**
  - No stimulus can activate the ventricle

- **Relative refractory period**
  - Only a stronger than normal stimulus can activate the ventricle

- **NORMAL**
  - A normal stimulus activates the ventricular myocardium