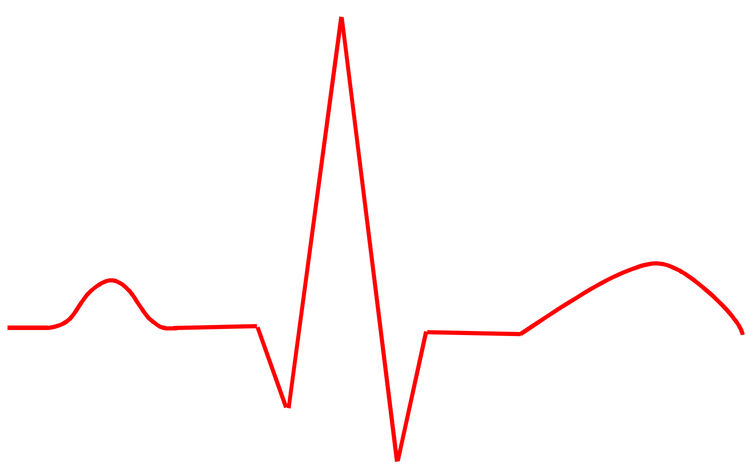
engineeringworldhealth

# ECG Simulator

## Assembly Instructions



# Contents

# Overview

An Electrocardiogram (ECG) Simulator is a device that generates an electrical signal similar to the pattern of the human heart (see description of the heart anatomy and the ECG overview in Appendix 1 and 2). This machine allows a Biomedical Equipment Technician (BMET) to test the performance of cardiac monitors and troubleshoot circuit or cable problems.

The Engineering World Health's ECG Simulator Kit is **an educational tool only and is not to be used for any other purpose, including any medical, diagnostic or other laboratory applications.**

University Chapters may construct Engineering World Health (EWH) ECG Simulator Kits to give students an opportunity to practice hands-on technical skills. The Kit is also suitable for classroom electronic teaching in biosignals.

Kits built by EWH Chapters serve an important role in helping to train BMETs in developing countries. EWH will send completed Kits to students in Rwanda, Cambodia, and Honduras to teach them how to perform electronics troubleshooting and repairs. Even if the boards Chapters build don't work, they can still be used in troubleshooting classes.

We tried to choose low cost components available in poor areas, so that locals can repair their kits if necessary. Nevertheless, chapters are welcome to improve the equipment, for example, adding battery holders, changing switches or building a case,. Thank you for purchasing EWH Kits and for helping EWH's work to improve health care in resource-limited settings.

# Important Guidelines

## 1. Electrostatic discharges

Diodes and the "integrated" circuits (ICs or chips) can be damaged by static electricity if not handled properly. This is a heightened concern in cold, dry climates. Even if you do not live in such an environment, you can prevent electrostatic discharge (ESD) by observing the following precautions:

- Keep components in their antistatic protection bags until you are ready to install them.
- Do not touch pins, leads, or solder connections on the boards with your bare hands, always use proper insulated tools.
- Handle the printed circuit board (PCB) only by its edges.
- If available in your laboratory, wear an ESD strap (Figure 1) connected to a proper ground when handling parts.

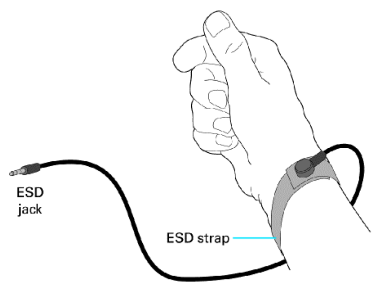



Figure 1 – Electrostatic discharge protection strap.

## 2. Soldering Techniques

Soldering may be dangerous if you do not use the right methods, therefore, follow these safety rules:

- Always wear safety glasses when soldering. The solder (the material heated with the iron) gets very hot. Occasionally an air pocket may form and pop as the solder is heated; sending bits of hot solder flying (beware of skin, clothing, eyes, and work surfaces).
- Never solder a live circuit (one that is energized).
- Solder in a well-ventilated space to prevent the mildly caustic and toxic fumes from building up and causing eye or throat irritation.
- Always put the soldering iron back in its stand when not in use. Be sure the stand is weighted or is attached to the worktable so that it doesn't topple over if someone brushes against the cord.
- To avoid the possibility of a fire, never place a hot soldering iron on the work surface.
- Never try to catch a hot soldering iron if it falls. Let it fall, then buy a new one if it breaks — just do not grab it!
- Give any soldered surface a minute to cool before touching it.
- Never leave flammable items (such as paper or clothing) near the soldering iron.
- Be sure to unplug the soldering iron when finished. Never leave a hot soldering iron unattended.

There are some basic techniques in order to have good joins. Figure 2 shows some soldering problems that result in a bad electronic connection. Insufficient wetting may occur if there is not enough solder applied to the pin/pad. If all metal surfaces are not properly fluxed and brought above the melting temperature of the solder in use, the result will be an unreliable "cold solder joint", which sometimes looks normal, but causes contact issues as well.

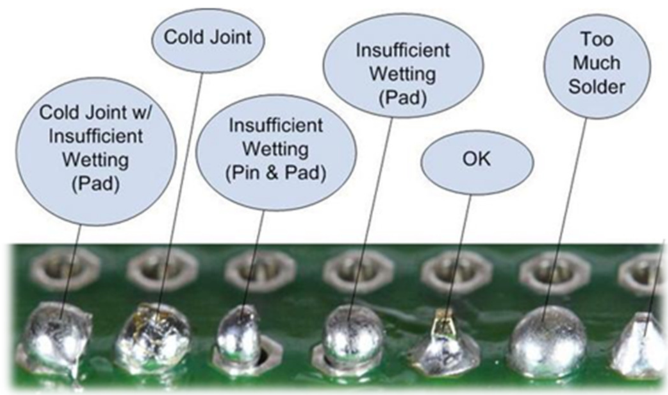



Figure 2 – Common soldering problems and their causes.

The first and most important rule when soldering is to ensure there is a secure mechanical connection to the PCB before soldering the component to the board. The solder is for an electronic connection only and should not be depended upon for mechanical attachment.

The second rule is to heat the electronic connection first, NOT the solder. Once the joint is raised to a sufficient temperature, touch the pin side (opposite to the soldering iron) with the solder, so it will liquefy and flow into the hole (Figure 3).

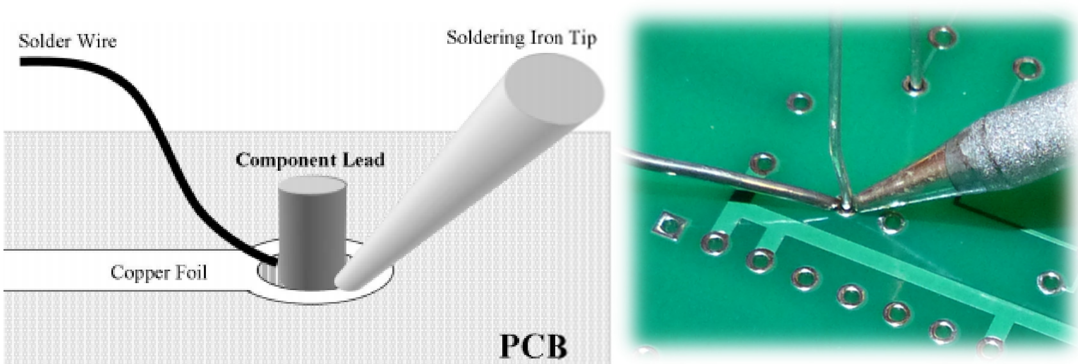



Figure 3 – Correct heating of component lead and hole, touching solder to joint and not the soldering iron.

Then pull the iron and solder away gently to allow this area to cool down. As the temperature lowers, the remaining solder changes from the liquid to the solid state. The resulting shape should be similar to a volcano, as shown in Figure 4.

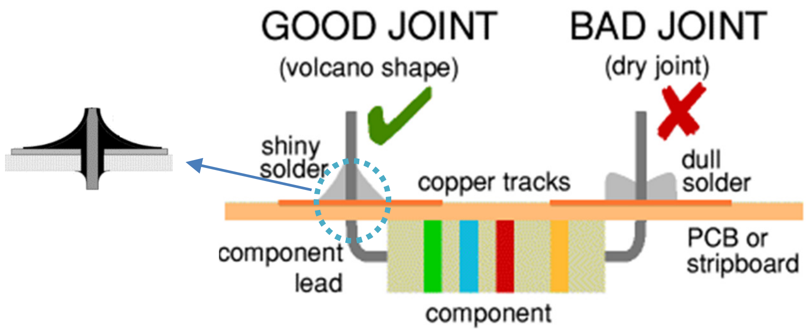



Figure 4 – Cross section view of the PCB in the soldering point.

For a neat appearance in your assembly, solder only one pin per component initially. Then turn the board over and check to see that the component is still mounted flush with the board. If there is a problem, you can carefully reheat the single pin and move the component.

In addition to these instructions, there are many tutorials online that can help improve your soldering technique such as:

- http://www.youtube.com/watch?v=I_NU2ruzyc4
- http://www.youtube.com/watch?v=eU4t0Yko9Uk

## Tools List

To assemble the Kit, you will also need the tools and materials listed in Table 1, these items are not included in the EWH's package and need to be purchased separately.

Table 1 – Tools and materials necessary to assemble the ECG Simulator (NOT included in the Kit package).

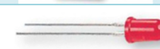
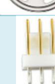
| Description | Image* |
|---|---|
| **Soldering iron** |  |
| **Solder** |  |
| **Cutting pliers** |  |
| **Long nose pliers** |  |
| **Double side tape** |  |
| **9 V battery** |  |

## Parts List

**<u>* Do not remove parts from bags (especially the capacitors). Remove each component from its bag when it is time to install each one individually</u>.**

In addition to the printed circuit board , the EWH ECG Simulator package should contain 19 small bags with the parts listed in Table 2. This parts list is very helpful when assembling your Kit. We suggest printing it out so you can easily reference it as you build the kit.

Table 2 – ECG Simulator Kit part list.

| Description | Value | Quantity | Schematic ID | Schematic Symbol | Image* |
|---|---|---|---|---|---|
| **Printed Circuit Board** | N/A | 1 | N/A | N/A |  |
| **Resistor** | 4.7 kΩ (4700 Ω) | 1 | R1 | |  |
| **Resistor** | 1 MΩ (1,000,000 Ω) | 2 | R2, R8 | |  |
| **Resistor** | 100 KΩ (100,000 Ω) | 7 | R3, R4, R9, R10, R11, R12, R13 | |  |
| **Resistor** | 1 KΩ (1,000 Ω) | 1 | R5 | |  |
| **Resistor** | 470 kΩ (470,000 Ω) | 2 | R6, R7 | |  |
| **Resistor** | 220 Ω | 2 | R14, R15 | |  |
| **Capacitor** | 22 pF ($22.10^{-12}$ F) | 1 | C1 | |  |
| **Capacitor** | 82 pF ($82.10^{-12}$ F) | 1 | C2 | |  |
| **Capacitor** | 0.220 µF ($22.10^{-8}$ F) | 4 | C3, C4, C5, C6 | |  |
| **Diode** | 1N4148 | 3 | D1, D2, D4 | |  |
| **LED** | 3 mm red | 1 | D3 | |  |
| **Integrated Circuit** | 4521 | 1 | IC1 | |  |
| **Integrated Circuit** | 4017 | 1 | IC2 | |  |
| **Crystal** | 4.1943 MHz | 1 | XTAL1 | |  |
| **ECG Connectors Sew-on Snaps** | N/A | 3 | LA, RA, LL | |  |
| **ECG Connector Header Contact** | N/A | 1 | N/A | |  |
| **Switches** | N/A | 2 | S1, S2 | |  |
| **Battery Connector** | N/A | 1 | N/A | N/A |  |
| **PCB Rubber Feet** | N/A | 4 | N/A | N/A |  |

***Component color and shape may change according with supplier availability; images are for illustrative purposes only.**

Figure 5 shows how to identify the components' value in each bag. Do not remove them from the package until you read the "Assembling steps" section. Each bag is carefully labeled for the parts that are inside, and removing them prematurely will make identifying them a challenge. Please contact EWH (+1 919 682 7788 or kits@ewh.org) if there is some part missing.


Figure 5 – Component description in value in the bag label.

# Printed Circuit Board

## 1. Top layer

Figure 6 shows the top of the Printed Circuit Board (PCB), where all parts will be inserted. This PCB is a two-layer through-hole board with plated through vias, which are little holes where the component pins go through. To assist in placing the parts, there are silk-screened symbols and textual information printed in this layer. These references are also found in the schematic diagram and parts list.

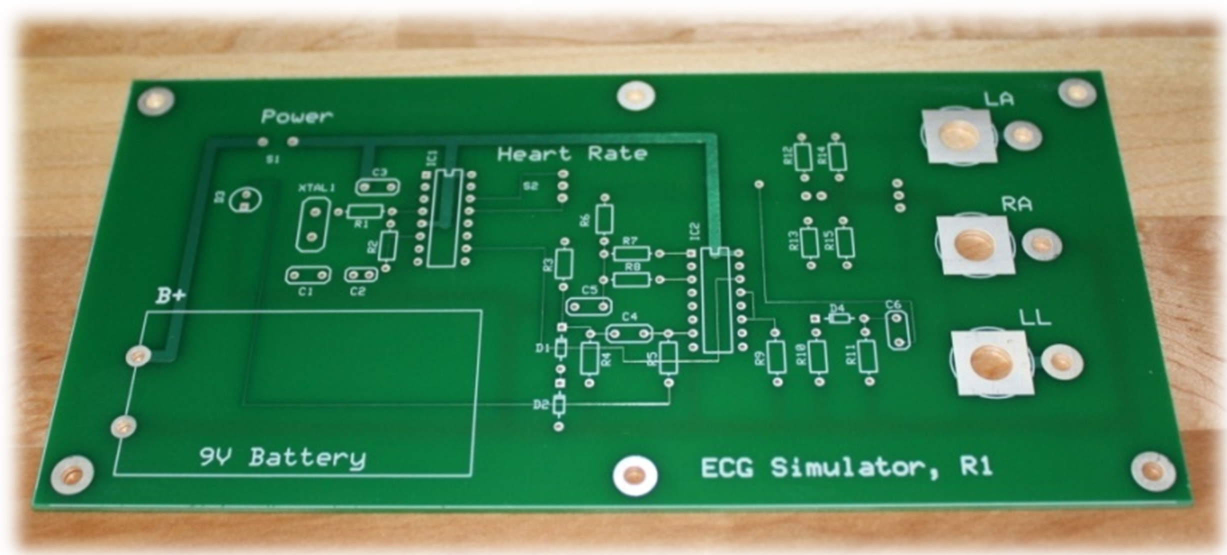



Figure 6 - Top of the bare printed circuit board with silkscreen marks to assist in placement of the electronic parts.

The circuit is powered by a 9 V battery, which can be attached to the left-bottom region of the board with double sided tape. Figure 6 shows the B+ symbol on the left most circuit trace. This via runs from the positive side of the battery to the board power switch (S1). The other battery connector corresponds to the negative polarity, which is the current return path. Although it is sometimes called ground (⏚), in reality, this device has no direct connection to the earth, therefore, it should be named (floating) common (⊥).

The six holes around the board's peripheral edges can be used to fix the PCB into a case. The other six holes, marked as LA (Left Arm), RA (Right Arm), and LL (Left Leg), on the far right side of the top layer, allow two types of output contacts that can connect the simulator to a cardiac monitor.

## 2. Bottom layer

The bottom side of the board, shown in Figure 7, is where the components will be soldered. Note that the thicker via corresponds to the floating common ground track, which is connected to negative contact of the battery.

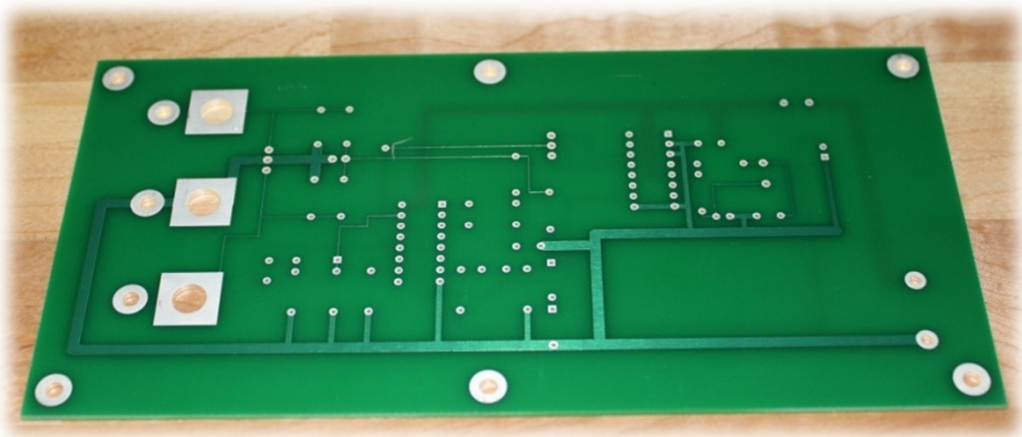
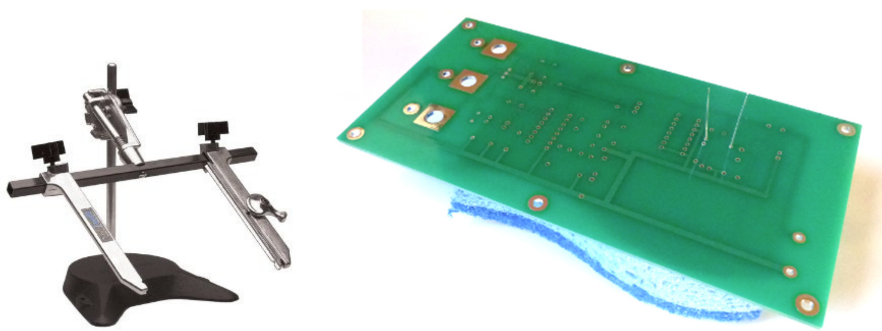


Figure 7 - Bottom layer of the bare PCB; the thicker via corresponds to the floating common, which is connected to the negative contact of the battery.

The physical layout of the PCB often must conform to other mechanical, thermal, electronic, or even electromagnetic requirements. Look carefully at the Kit's bare board, to see that many of the digital signals cross analog signal lines at right angles. This physical layout helps decrease electronic noise coupling.

## 3. Board mechanical support

The clamp in Figure 8 (a) is called a "Panavise." It acts as a third hand to stabilize the board for soldering during assembly. If it is not available, a large, dry kitchen sponge will also give a good support Figure 8 (b). It presses the components flush with the board as their pins are soldered from the other side.



(a) (b)

Figure 8 - Panavise assembly circuit board holder (a) and PCB support on a dry sponge (b).

## Schematic Diagram

Figure 9 shows a diagram of the ECG Simulator with the electronic interconnection of components. Notice that most drawings have identifiers (B1, C1, C2, IC1, D2, etc.) next to them. The letter "C" followed by a number is mostly adopted for capacitors. Next to these designs, you will also see a numeric value such as 22 pF, 82 pF, .22 uF, and so on. These numbers provide the amount of capacitance in this particular element. For instance, C1 22 pF corresponds to the part whose identification is "C1" and has 22 Pico farads of capacitance. All other components are described in the part list section.

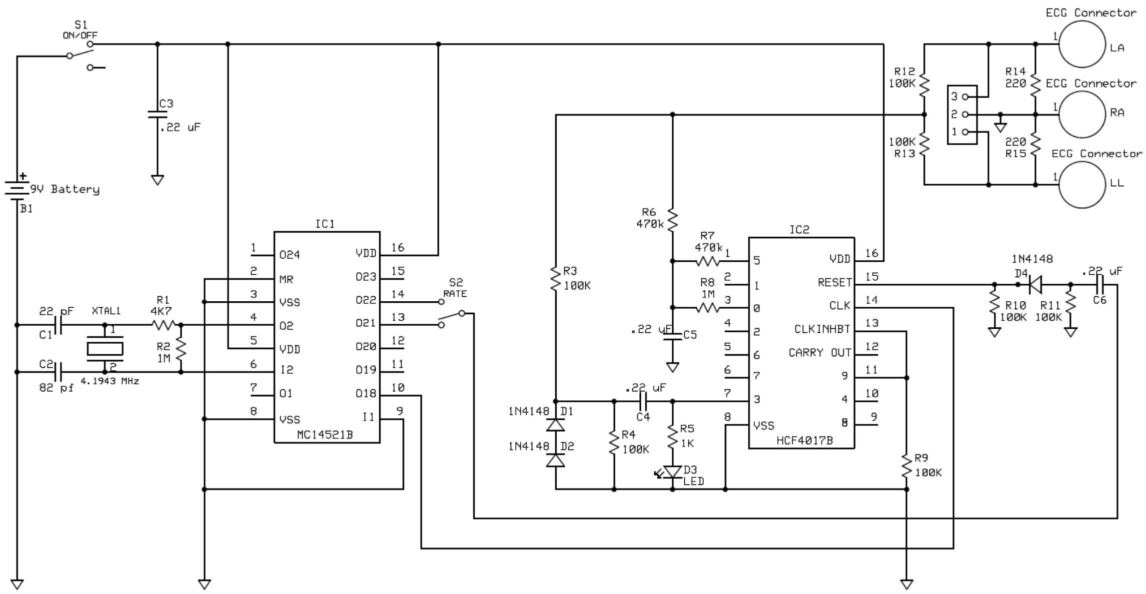



Figure 9 – ECG Simulator electronic schematic diagram. The 9 V battery is NOT included in the Kit!

Electronic elements such as capacitors (C), resistors (R), coils (L), diodes (D) and transistors (Q) are classified as "discrete," for they can perform only one function. On the other hand, there are "integrated" circuits (ICs or chips) that contain many individual parts within them that can perform complex processes. The ECG simulator board has two of these chips: IC1 and IC2.

Frequently on a schematic diagram, supply voltages are on top of the page or component and common or reference returns are on the bottom of the page or component. Signal flow is often left to right across the board's schematic.

Notice: there is a difference between the schematic diagram and the actual physical layout of the PCB itself. For example, on the schematic, the battery is labeled 9V battery and appears in the upper left corner of the figure, near the power switch. On the board, the actual battery connector is in the lower left corner. This practice is common. The schematic is meant to show the logical, electrical, or electronic interconnection of the components to help explain the function of the circuit.

# Assembling Steps

Before beginning to assemble the ECG Simulator, organize your workspace and components. Do not remove parts from bags (especially the capacitors). Remove each part from its bag when it is time to install each one individually.

A physical assembly constraint to think about would normally include the order in which components are soldered to the PCB. With this Kit, there is plenty of room, so probably there will have no issue placing the components, no matter which parts you start with. However, it is still a good idea to have some logical plan and pre-identify all of the parts before installation.

An electronic component may be classified as passive, active, or electromechanic. Electromechanical components can carry out electrical operations by using moving parts or by using electrical connections. Active components, such as diodes and ICs, rely on a source of energy and usually can inject power into a circuit. Passive components cannot introduce net energy into the circuit. They include two-terminal components such as resistors and capacitors and are easier to assemble.

## 1. Passive components

Resistors are a good choice to start with, if the person assembling is practicing soldering for the first time. They are relatively flat and close to the board, easy to identify, and will tolerate a large amount of heat. In case you mixed these parts, you can identify the resistance value through color bands printed around their body, shown in Figure 10.

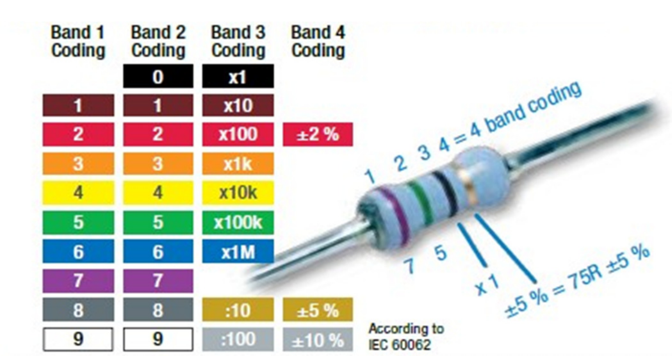


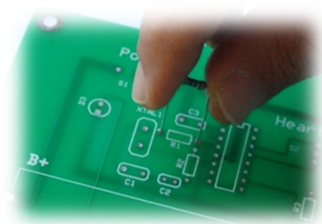
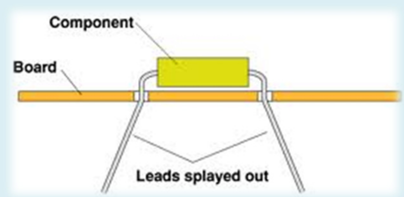
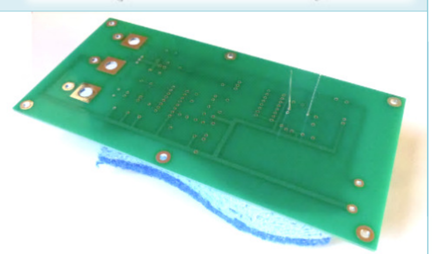
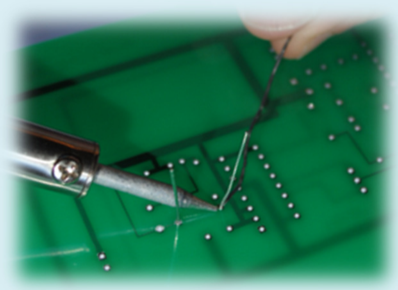

Figure 10 – Resistor color code identification chart.

Note: resistors R3, R4, R12, and R13 are all 100K Ohms (100,000 Ohms resistance). Thus, all will have the same colored bands printed on them.

# ECG Simulator Assembly Instructions

After identifying each component position on the PCB, you can assemble the part following Table 3 instructions.

Table 3 – Assembling steps for ECG Simulator parts.

| Component Assembly Steps | | |
|---|---|---|
| 1 | **Bend the component wires 90º.** |  |
| 2 | **Insert component pins into corresponding holes on circuit board. The resistor must rest on the top, labeled side of the board.** |  |
| 3 | **Gently bend the leads under the board when installing to get a good mechanical connection.** |  |
| 4 | **Turn the PCB over so that the component is face down and the wires are exposed.** |  |
| 5 | **Solder each component leg to the board.** |  |
| 6 | **Using the wire cutters, cut the excess length of resistor wires as close to the board as possible.** |  |

After assembling all the resistor, the next step is the capacitor's placement (Figure 11). Install one component at a time and only open the package immediately before you place it on the board. If different capacitors are mixed, you will need a test instrument (capacitance meter) to tell them apart. Some physically larger capacitors have their values printed on them or use other markings for identification; however, the elements in this Kit do not.

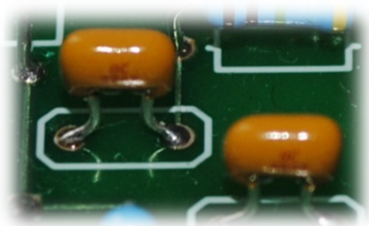
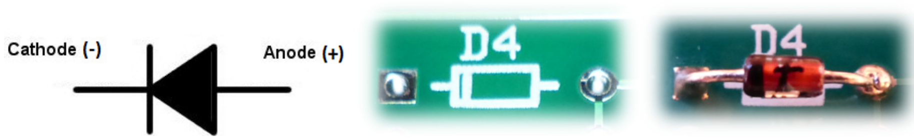


Figure 11 – Ceramic capacitors soldered to the PCB; these kind of capacitors do not have polarization restrictions.

## 2. Active components

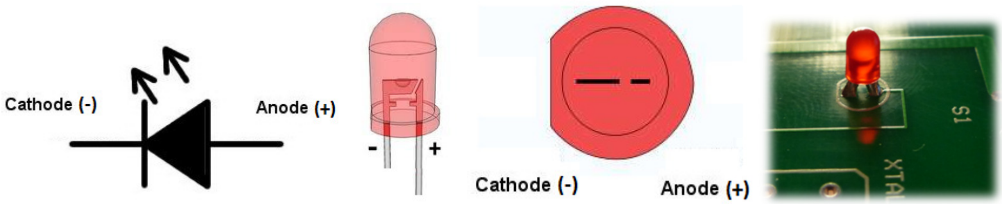
Now install the diodes D1, D2, and D4. They are all the same model (1N4148), which is an industry common part number. The supplier will usually have their own part number on the packaging as well. Look carefully at the PCB top layer to see a small band on the left side of the diode silk screen drawing (Figure 12). This indicates the polarity (cathode) and you should install the diode with the band on the component in the same direction.




(a) (b) (c)

Figure 12 – Diode schematic symbol (a), location on the PCB before (b) and after (c) installation.

The most difficult part to orient is the Light Emitting Diode (LED). Figure 13 shows its symbol, appearance, PCB representation and picture. If an LED is installed with the wrong polarity, it will not turn on or might even burn out. You might test the LED's polarity with a battery and a resistor for current limiting, as shown in Figure 14. Be careful to install this component correctly on the "D3" position of the board. The anode (positive voltage) should be placed towards the upper side of the board and the cathode (negative reference) towards the lower side of the board. The flashing of this LED will be one important indication that the ECG Simulator is working properly.




(a) (b) (c) (d)

Figure 13 – Light emission diode (LED) schematic symbol (a), appearance (b), PCB representation (c) and picture (d).

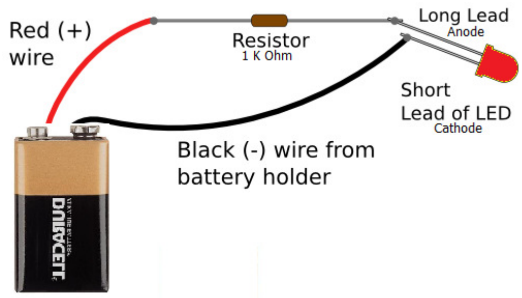
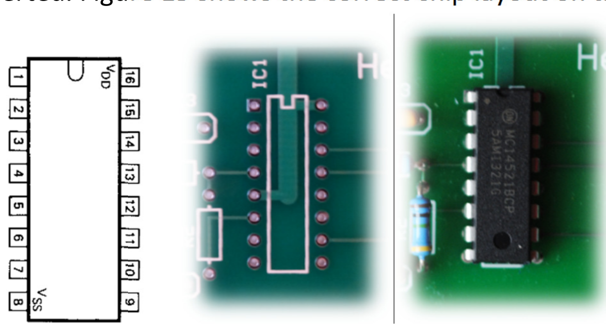



Figure 14 – Basic LED test procedure, the resistor value can change as long as it is higher than 1 kΩ (to avoid burning the diode).

Next, install the ICs on the board; Take care to form the leads by bending them slightly into a more vertical position. The easiest way to do this is to lay the part on its side and "<u>gently</u>" roll with a little pressure. With practice, you can straighten eight IC leads at one time. Pay attention to place these components in the right polarity! The wrong pin layout on the PCB may burn the part since VDD (+ 9 V) and VSS (0 V) would be inverted. Figure 15 shows the correct chip layout on the board.




(a) (b) (c)

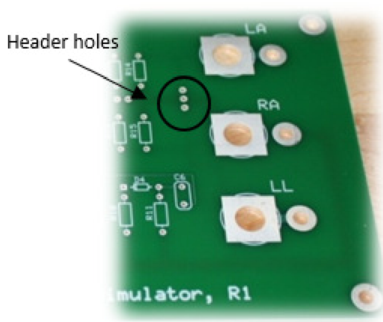
Figure 15 – Integrated Circuit outline drawing (a), silk screen (b) and chip placement (c).

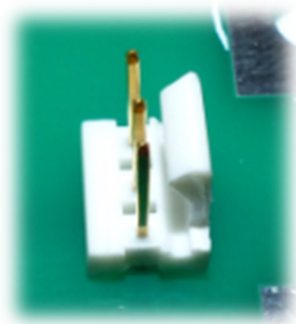
## 3. Electromechanical components

The only parts left to solder are electromechanical. Install the 4.1943 MHz crystal in the "XTAL1" location of Figure 16. This component does not have any polarity restriction.


Figure 16 – Placement of the 4.1943 MHz crystal in the printed circuit board.

The header contact shown in Figure 17 and the switches were designed in case you want to build your own box and connect them with cables to the PCB. There is no silk screen reference for the header contact, neither polarity. This part only needs to be placed if you want to make a box/case for the ECG Simulator.

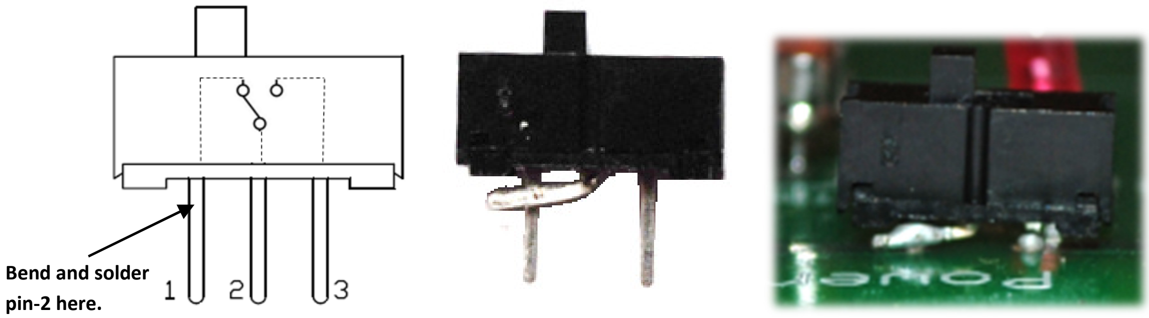


(a) (b)

Figure 17 – Header contact position (a) and picture (b). The header contact allows the ECG signals to be connected to the case (not included in the kit).

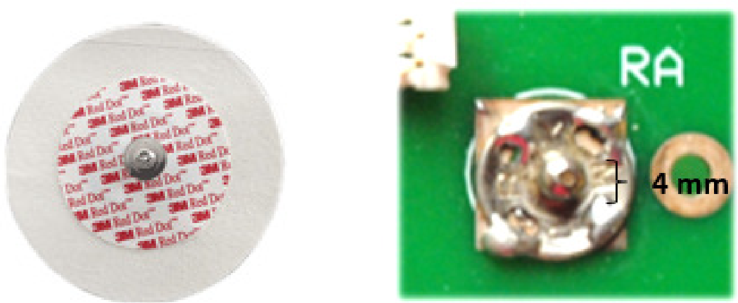
There are two slide switches in the circuit: one is the power function, and the other changes the heart rate (60 bpm or 120 bpm). This frequency switch can be placed directly in the board. However, if you want to solder the power switch directly in the PCB, you need to bend and solder the middle pin, as shown in Figure 18. You can connect either pins 1 and 2 or pins 2 and 3, without worrying about the polarity.




(a) (b) (c)

Figure 18 –Slide switch internal connection (s), pin 1 and 2 soldered (b) and picture of the ON/OFF power position.

Figure 19 (a) shows an adhesive disposable patient electrode with a 4 mm diameter contact. This is the most common type of ECG connector, and a wide variety of parts can be used for the output contact with these dimensions. The Simulator Kit uses clothing snaps (size 3 sew-on), which can be found easily in the developing world. When assembling these snaps, use three or four different soldering spots in the PCB for a good mechanical support, as seen in Figure 19 (b).




(a) (b)

Figure 19 - Disposable patient ECG electrode 4 mm contact (a) and sew-on snap soldered to the Kit board (b).

The final part that needs to be soldered is the 9 V battery connector. The red cable is soldered to the hole next to the silk screen marked as "B+", as shown in the lower left corner of Figure 21. The battery can be fixed to the PCB through a double-sided tape. The kit also includes four rubber feet to be placed underneath the corner holes (if there is no box in which to fix the board) as shown in Figure 20.

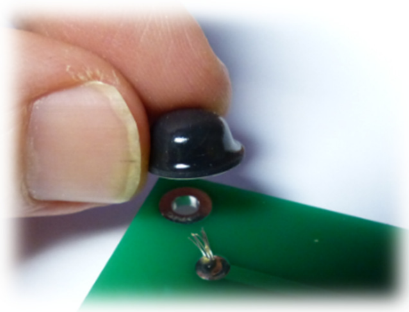


Figure 20 - Rubber feet to be placed underneath the corner holes.

Figure 21 shows the assembled ECG Simulator Kit. The next section shows the steps to follow in testing your circuit.

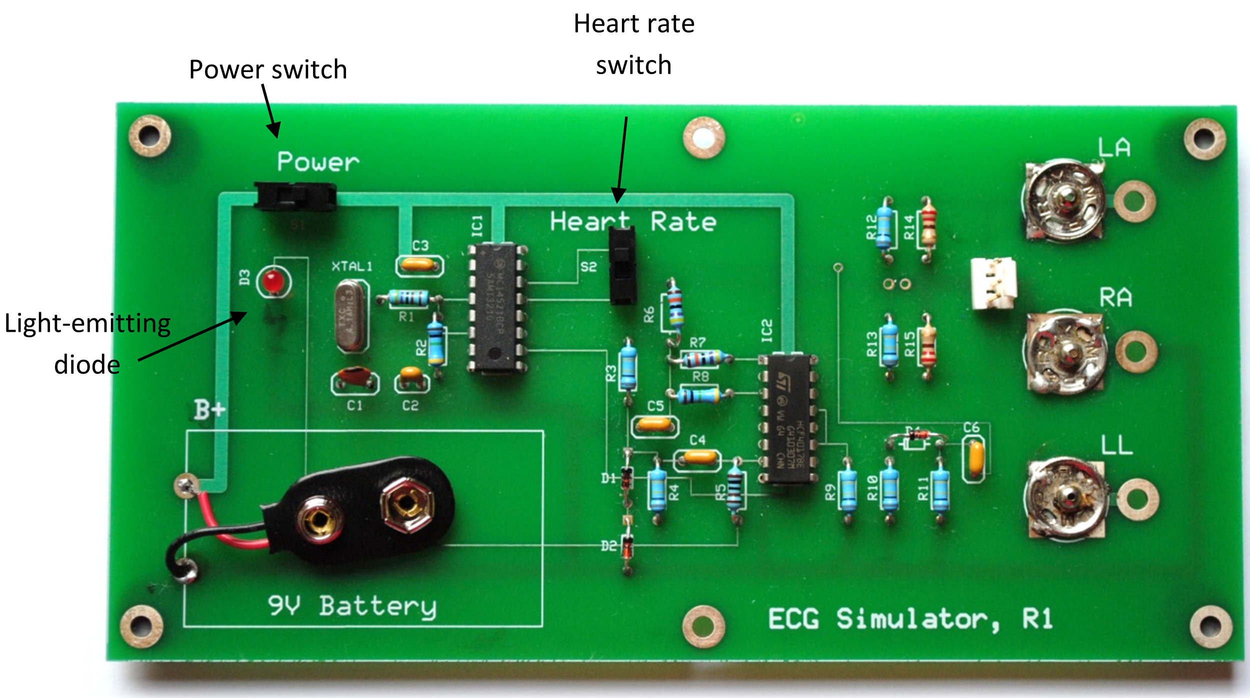



Figure 21 – ECG Simulator Kit after assembly.

# Operation Instructions

## 1. Light-emitting diode indication

The fastest way to verify if the digital circuit works is through the light-emitting diode indicator, shown in Figure 21**Error! Reference source not found.**. After connecting the 9 V battery and turning on the "Power" slide switch, the LED in position "D3" should blink. The frequency can be set either to 1 Hz (60 bpm) or 2 Hz (120 bpm), depending of the "Heart Rate" switch configuration.

## 2. Oscilloscope measurement

The LED light shows that the integrated circuits are working properly; however, it is not enough to determine if there are signals in the pins LA, RA and LL. In addition, it is important to test if the output is within the expected ECG range. Measuring these voltages requires the use of instruments with graphical interfaces such as an oscilloscope, computers with acquisition boards (National Instruments MyDAQ board) and a commercial ECG monitor.

Oscilloscopes are devices that allow observation of constantly varying signal voltages, plotted as a function of time. If you have this equipment available, connect the common of the channel 1 probe to the connector RA of the ECG Simulator, and the outputs LA and LL to channel 1 and 2 inputs, as seen in Figure 22. The common contact from channel 2 does not need to be used, since this cable is connected to the same part in channel 1's probe. Both waveforms should show a similar signal with approximately 5 mV amplitude (1 Hz or 2 Hz). Therefore, the ECG signal can be visualized with a 10 mV Volts/Div scale and 100 ms Time/Div oscilloscope setting.

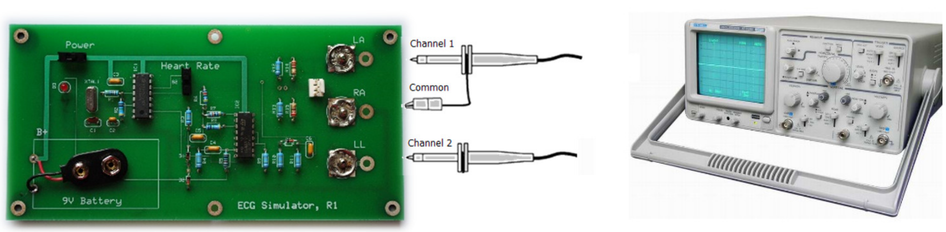



Figure 22 – ECG Simulator output measurement with an oscilloscope. The common contact from channel 2 does not need to be used, since this cable is connected to channel 1's probe.

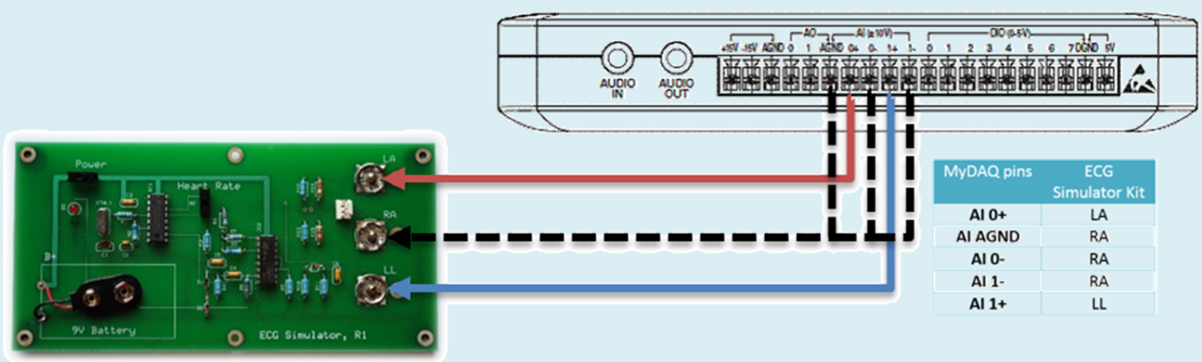
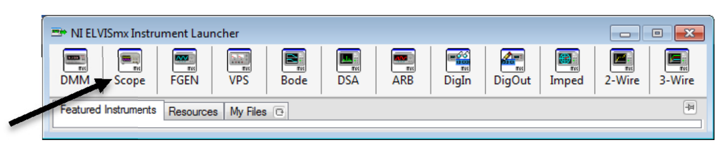
## 3. MyDAQ board measurement

The National Instrument MyDAQ board is a low-cost portable data acquisition (DAQ) device that uses LabVIEW-based software instruments, allowing students to measure and analyze electrical signals. This tool can also be used to quantify the ECG Simulator Kit outputs, as seen in Figure 23.

Figure 23 – ECG Simulator Kit measurement with National Instrument MyDAQ board.

Follow the steps in Table 4 to test your Kit:

Table 4 – Procedures to test the ECG Simulator Kit with MyDAQ.

| MyDAQ Test Procedures | |
|---|---|
| 1 | **Connect the MyDAQ board AI (analog input) circuit to the ECG Simulator, as shown in the image.**   |
| 2 | **Connect the acquisition board to the computer through a USB cable.** |
| 3 | **Open the program "NI ELVISmx Instrument Launcher".** |
| 4 | **Select the "Scope" option.**   |
| 5 | **Enable Channel 1 and Channel 2. Use the same settings as a normal oscilloscope, 10 mV Volts/Div scale and 100 ms Time/Div.** |
| 6 | **Click in the "Run" button.** |

The resulting waveforms should be similar to Figure 24.

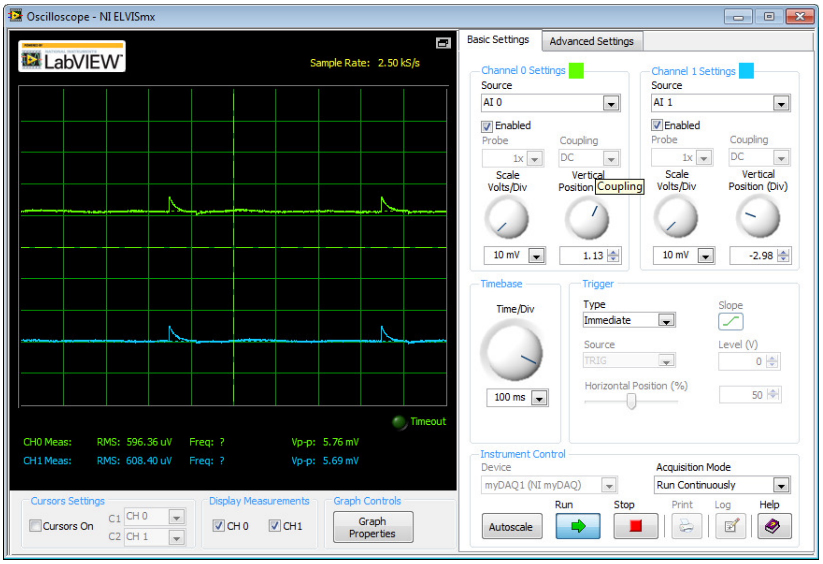



Figure 24 – NI ELVISmx Oscilloscope display and control panel.

## 4. Electrocardiogram test

Figure 25 shows the EWH's simulator Kit connected to a real electrocardiogram monitor. Besides displaying the waveform, the ECG can also measure the heart beat frequency (60 bpm). The connection between the devices is simple, since the measurement cable and the board output have the same nomenclature: LA, RA and LL.

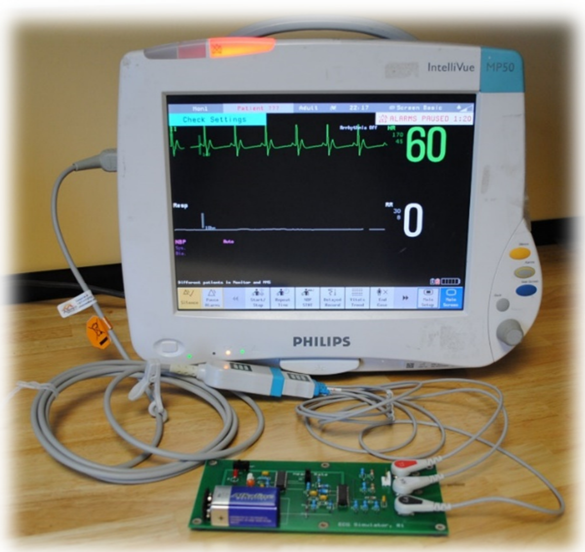



Figure 25 – EWH's Kit connected to a real electrocardiogram machine. The number 60 corresponds to the simulated heart rate.

# Appendix

## 1. Basic Heart Anatomy

The cardiovascular system is responsible for circulating blood throughout the body to supply the tissues with oxygen and nutrients. The heart is the muscle responsible for pumping blood to and through the vessels. It is divided into four chambers: right atrium, right ventricle, left atrium, and left ventricle, as seen in Figure 26. There are valves between each atrium and ventricle and in the ventricle output to prevent backward flow. The average adult cardiac rate is 80 beats per minute; however, this rate increases to 120 bpm in the case of infants. The heart contraction stimulus is caused by an electrical signal that initiates at the Sinoatrial (SA) node, located at the top of the right atrium.

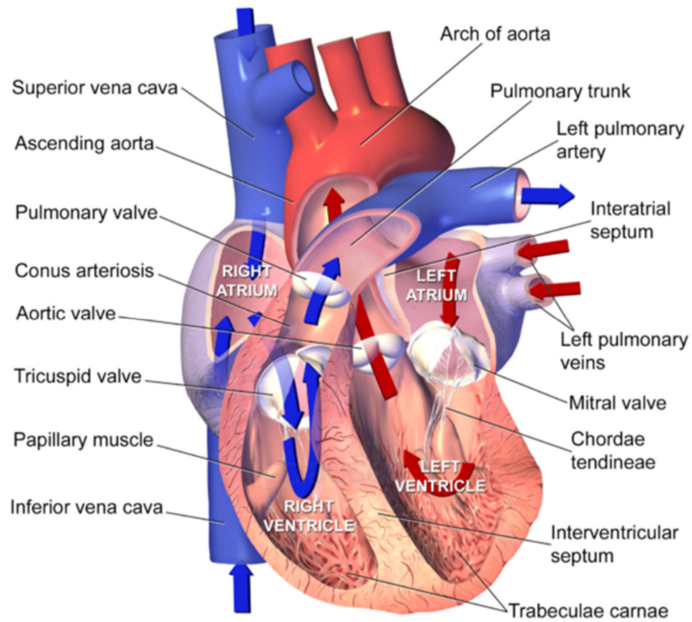



Figure 26 – Sectional anatomy of the heart (Blausen Medical Communications via Wikimedia Commons).

## 2. Principles of Electrocardiography

The small electrical signal (mV) produced in the heart can be measured through a device called electrocardiogram (ECG) monitor, also called electrocardiograph. This instrument allows the physician to obtain the rate and regularity of heartbeats, as well as the size and position of the chambers, the presence of any damage to the heart, and the effects of cardiac drugs or devices. A basic ECG requires at least three connections, which form the Einthoven's triangle in Figure 27.

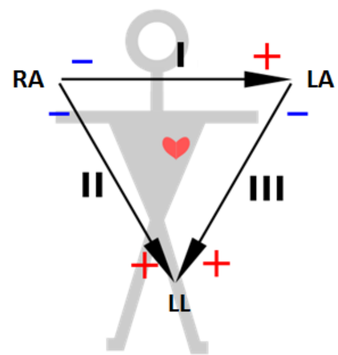



Figure 27 – Einthoven's triangle. Signal II corresponds to the traditional ECG waveform (Kychot via Wikimedia Commons).

Signal I is the voltage between the (positive) left arm (LA) electrode and the right arm (RA) electrode:

$$I = LA - RA$$

Signal II is the voltage between the (positive) left leg (LL) electrode and the right arm (RA) electrode:

$$II = LL - RA$$

Signal III is the voltage between the (positive) left leg (LL) electrode and the left arm (LA) electrode:

$$III = LL – LA$$

The electronic component used for an ECG measurement is called instrumentation amplifier. It has a high gain (multiplies many times the original signal) and requires very low input currents. Inside of this amplifier, there are differential blocks, such as in Figure 28. These circuits are able to measure signals I, II and III directly from the patient’s leads.

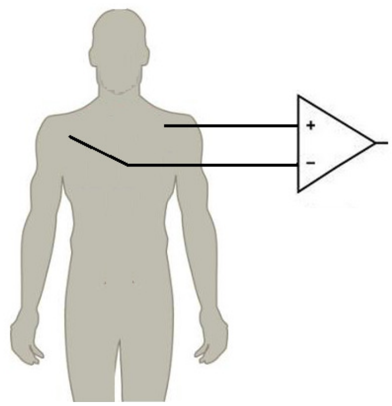


Figure 28 – The ECG measurement circuit uses a differential amplifier to subtract the voltages between the right and left arm (BotMultichill via Wikimedia Commons).

Figure 29 shows a standard ECG wave (II) divided into five parts: P-QRS-T. The P wave represents atrial depolarization, and the QRS represents ventricular depolarization. The T wave reflects the phase of rapid repolarization of the ventricles.

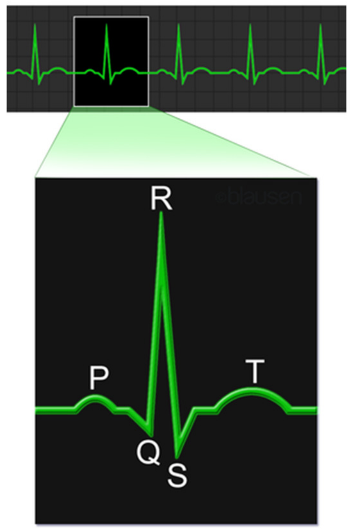



Figure 29 – Normal heart beat electrocardiogram wave signal (Blausen Medical Communications via Wikimedia Commons).