

## 2. Electric conduction and potentials

### Ionic conduction and ECG

#### 2.1 Medical reference and goals of the experiment

The basic physics concepts of electricity are needed in various fields of medicine, e.g. during the development and the proper operation of all medical devices and equipment and the fundamental understanding of physiological relations. This experiment is divided into two parts:

**Ionic conduction/Electrolytes:** Conduction mechanisms, integral to the human body, will be studied. The fundamental terms used in the experiment are electric current strength, voltage, and conductance with its associated quantities conductivity and resistivity in particular. All mentioned terms usually need the addition “electric” in front of them, since especially the terms current strength, resistance and conductance also find usage in fluid mechanics (see experiment “Fluid Mechanics / Blood circulation”). In fact, there exists a very extensive analogy in the description of electric circuits and their properties between fluid mechanics and the physics of electricity. In the following, the quantities are used exclusively in the context of electricity, the electric connotation is thus self-evident. The properties of an ohmic resistor and of electrolytes are studied in the first part of the experiment. Because of their physiological relevance, potassium chloride, calcium chloride, and sodium chloride are used as examples. The concentration of these ions greatly influence the conductivity of the intra- and extracellular fluid.

**Electric potentials (ECG):** An important fundamental term of the physics of electricity is the electric potential and thus the distribution of potentials. It forms the basis of the creation of signals in electrocardiograms (ECG) and electroencephalograms (EEG). Since the human body is a conducting medium, the occurrence of potential differences (also called voltage) is thus always connected to electric currents. In the case of the ECG, the excitation expansion (depolarisation) of the heart extends to extracellular currents in the whole body. Due to these currents, a potential distribution in the body and on its surface is created. Potential differences between specific points on the surface of the body can be determined using the ECG-electrodes. Recording the potential differences allows for a reconstruction of the direction, the strength

and the time line of the excitation expansion (depolarisation). These reconstructions and the identification of artefacts in the measurement signal are only possible if the principal relations between the depolarisation of the heart and the measured potential differences are known. As the human body is a three-dimensional, inhomogeneously conducting medium, these relations are very complex. As a simplification, a one-dimensional homogeneously conducting model is initially used in the experiment. On that model, the potential distribution, created by the connection to a current source, and the resulting potential differences (or voltages) can then be analysed.

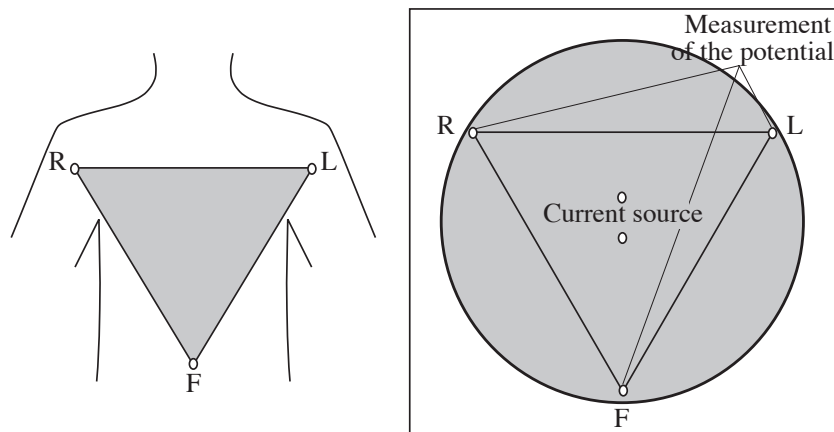


Figure 2.1.1: *Einthoven's EKG-leads and the two-dimensional ECG-model.*

In the next step, a two-dimensional (still) homogeneously conducting model is used, in form of a circular disc (Fig. 2.1.1). The connection of a current source at two points in the center of the circular disc results in a potential distribution in the torso of a human body very similar to that produced by cardiac excitation. The location of the connections for the current source can be compared with the location of the excitation front of the heart. Analogous to Einthoven's arrangement of the ECG-electrodes (R: right arm, L: left arm, F: left foot), the potential differences between three fixed points and their variation in relation to the position of the connections of the current source are to be measured. These potential differences in the context of the ECG are called leads. With these measurements, the formation of ECG-signals can be explained in principle. Additionally, questions, such as why the ECG-electrodes are not connected to the torso – as suggested in Fig. 2.1.1 – but to the limbs and what influence the locations and the contacts of the electrodes have on the measured signal, can also be answered.

The experimental set-up is an electrical circuit. Usually, such circuits are described by a schematic circuit diagram. In these diagrams, the used components are depicted by symbols and their connections (the cables) as lines. The corresponding symbols for the most important components are shown in Fig. 2.1.2.











Component	Symbol	Component	Symbol
Current source		Amperemeter	
Voltage source		Resistance meter	
Crossing without connection		Ohmic resistance	
Crossing with connection		Diode	
Voltmeter		Capacitor	

Figure 2.1.2: Table with symbols of important electric components in a circuit.

## 2.2 Experimental part

**Important!** The grey surface of the plates used in the second part of the experiment is very sensitive. Please do not put anything on the plates, especially not the graphite disc. Thank you!

### 2.2.1 Ionic conduction and electrolytes

#### Electric conductance and resistance

Substances, in which electric charge is transported via charge carriers (electrons or ions), such as metal or electrolytes (e.g. NaCl-solution), are called electric conductors, the process of charge transfer is called (electric) current. It is described by the (electric) current strength  $I$ , meaning the transported charge per unit of time. The consequence of a current is a loss of energy of the charge carriers, expressed in voltage  $U$  (or voltage drop) across the conductor. In the following, you have to study the relation between current strength and the resulting voltage drop. You have at your disposal:

- A current source, providing either direct current or alternating current (switch). For the first part of the experiment, you need direct current exclusively. The charge is thus always transported in the same direction. The current strength can be varied using a turning knob.
- Two digital multimeters with which you can measure the current strength and the voltage. In both cases, the COM-socket needs to be connected. For current strength measurements, the A-socket has also to be connected (use the “2A”- or “mA”-socket). For voltage measurements use the V-socket. Furthermore, you need to adjust the selection switch to the correct unit (Ampere or Volt, direct current) and measurement range.
- An ohmic resistor on pins.
- A pinboard for the circuit set-up.

**Ohmic resistor** In the beginning, you should study the relation between current strength and the resulting voltage drop on a particularly simple electric component, an ohmic resistor. A behaviour similar to the ohmic resistor is exhibited by a large number of (passive) ionic channels as well as – for small currents – the human body as a whole.

- Assemble the circuit depicted in Fig. 2.2.1 on the pinboard and ask the assistant to check it for you.
- Turn on the current source and the amperemeter (direct current (DC) for both) and adjust the current to 5 mA. (If the amperemeter does not show positive values, exchange the connections on the amperemeter).

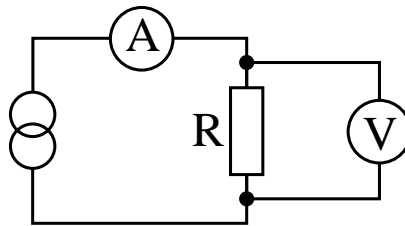
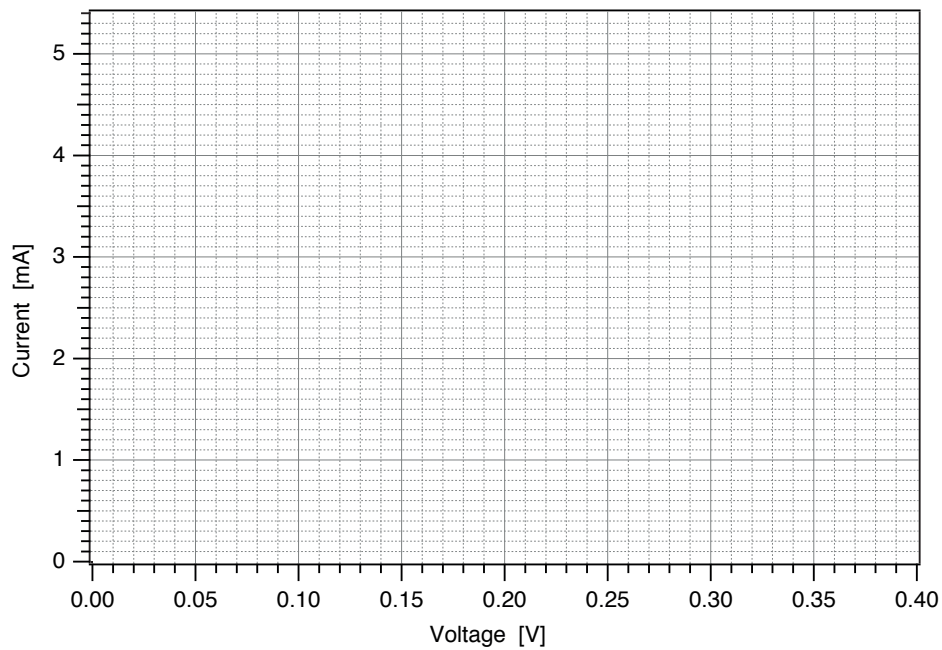


Figure 2.2.1: *Circuit for resistance measurements.*

Now you have a closed circuit, where a current flows from the current source through the resistor and the amperemeter back to the current source. The voltmeter has to be connected in parallel to the resistor. It has to run in direct current mode (DC) and should show positive values (exchange the COM- and V-connection cables if not).

- ◇ Measure the voltage on the ohmic resistor for 4 different current strengths between 0 mA and 5 mA. Write the current strength and the voltage into the table and the following figure. Draw a best-fit curve (or line) through the data points. Such a graphic representation of the electric properties of a component is called its **characteristic curve**.

Measurements on the ohmic resistor				
$I$ [mA]				
$U$ [V]				



- ◇ Which relationship exists between the current strength and the voltage?

From the characteristic curve of a component, the **conductance**  $G$  can be determined for each value of the current strength inside the measured range: The conductance  $G$  of a specific current strength  $I$  is the ratio of current strength and the corresponding voltage, read from the characteristic curve. The unit of the conductance is Siemens (S), where:  $1 \text{ S} = 1 \text{ A/V}$

- ◇ Determine the conductance for two different current strengths from the characteristic curve (the best-fit straight), distributed over the whole measurement range. Consider the units (mA or A)!

Conductance of the ohmic resistor		
$I$ [mA]		
$U$ [V]		
$G$ [S=A/V]		

- ◇ How does the conductance of the ohmic resistor relate to the current strength?
  
- ◇ Usually, as an alternative to the conductance, the **resistance**  $R$  of a component is given. It is defined as the reciprocal value of the conductance, thus the ratio of the voltage to the current strength. The unit of the resistance is Ohm and is abbreviated by the symbol  $\Omega$  with  $1 \Omega = 1 \text{ V/A}$ . What is the value of the resistance here?

$$\text{Resistance } R = \frac{1}{G} =$$

### Conductivity of electrolytes

The intra- and extracellular fluids in the human body are electrolytes, meaning fluids with dissolved positive (such as  $\text{Na}^+$ ,  $\text{K}^+$ , and  $\text{Ca}^{2+}$ ) and negative (such as  $\text{Cl}^-$ ) ions. Through the movement of these ions, electric charge can be transported inside an electrolyte. You will now analyse the conductive properties of an electrolyte that consists of a 0.1-molar NaCl-solution. This means that 0.1 mol NaCl molecules are dissolved in a litre of distilled water in form of  $\text{Na}^+$  and  $\text{Cl}^-$  ions<sup>1</sup>. The ion concentrations are comparable to those of positive or negative ions in the intra- and extracellular fluid; their relationship however is more complex. If a direct current – a current always in the same direction – flows through an electrolyte, the ions are actively separated (electrolysis, see Fig. 2.2.2). In the case of a NaCl-solution, this would mean that the  $\text{Na}^+$  are collected on the cathode creating caustic soda (sodium hydroxide) and hydrochloric acid on the anode with the concentration depending on the current density<sup>2</sup>.

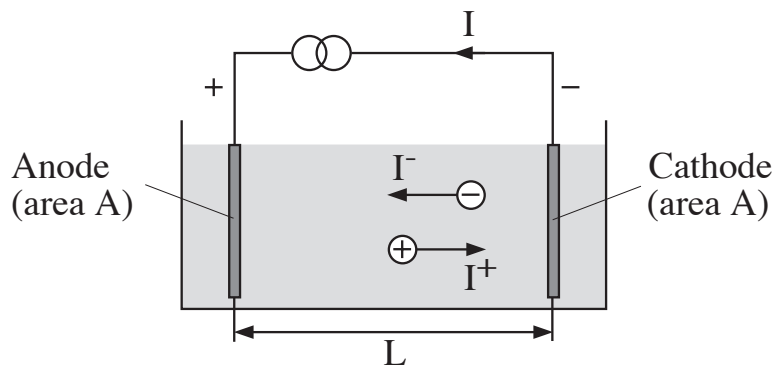


Figure 2.2.2: *Conductivity of an electrolyte (here in the case of direct current).*

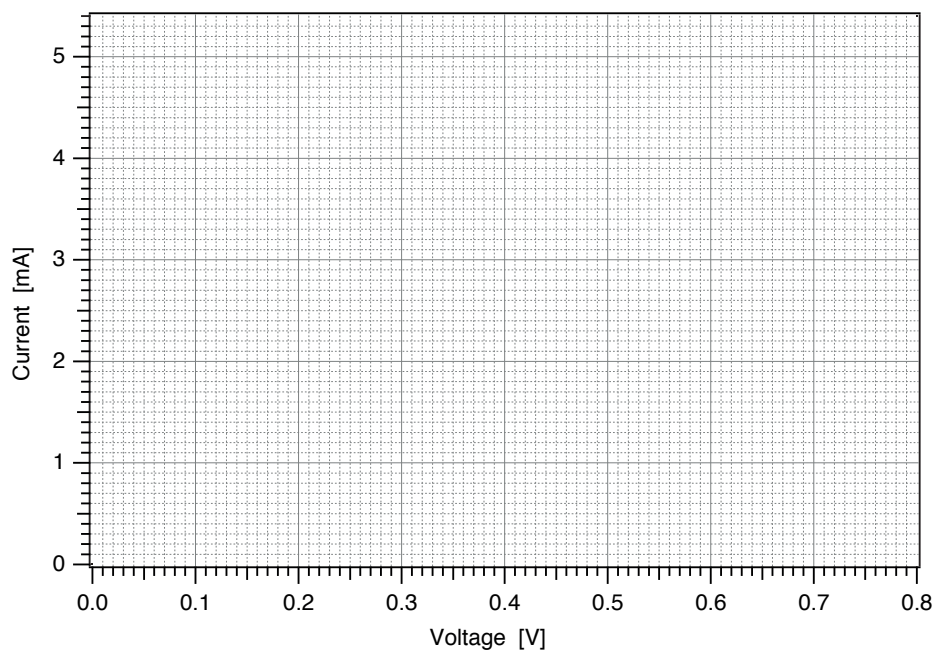
<sup>1</sup>The high dielectric constant of water leads to a strong suppression of the coulomb force and thus the bonding force of the ion molecules. Especially so-called strong electrolytes are thus practically fully disassociated.

<sup>2</sup>This effect would lead to cellular necrosis.

**Dependence of the conductance on the current strength** Check if the electrolyte exhibit an ohmic behaviour, meaning that the conductance is independent of the current strength. For this you need to find the characteristic curve:

- Connect the two metal electrodes with a minimum distance of around 8 cm in the tank. Fill the tank up to the lower mark on the electrodes (immersion depth 1 cm) with the 0.1-molar NaCl-solution.
  - The circuit is in principal the same as sketched in Fig. 2.2.1. Remove the ohmic resistor -from the pinboard and replace it with the contact of the electrodes.
  - You have to use alternating current (AC). Use the alternating current option on the current source. The current thus changes its direction all the time (here around 4000 times per second). The two digital multimeters have to be changed to alternating current and voltage as well.
  - Turn on the current source and adjust it to a current of 5 mA.
- ◇ Vary the current strength between 0 mA and 5 mA and measure the voltage on the electrodes for 5 points on the characteristic curve. Draw in the characteristic curve in the following figure and determine the conductance of the electrolyte.

Measurements on the electrolyte					
$I$ [mA]					
$U$ [V]					



- ◇ (How) does the conductance of the electrolyte depend on the current strength?
  
- ◇ What is the conductance of the electrolyte?  $G =$

### Dependence of the conductance on the geometry of the set-up

The influence of length and cross section of the conductor (electrolyte) on its conductance is the next point of interest. The relationship conductance - cross section becomes important e.g. in the excitation expansion (depolarisation) along the nerve cells. The intracellular conductance depends in the same way on the cell cross section, as it does here, measured in an experiment for a simple geometry.

- ◇ To study the influence of the cross section, fill up the tank to the second mark on the electrodes (the conductor cross section is thereby doubled) and determine the conductance for a chosen current strength.

Conductance for a lower filling height (last part):  $G_1 =$

for a doubled cross section:  $I =$  ,  $U =$   $\rightarrow G_2 =$

- ◇ What relation between the conductance and the conductor cross section do you suspect?

**Conductivity as a geometrically independent quantity** To describe the conduction properties of an electrolyte, a quantity independent of the particular geometry (e.g. the size and form of the cell for intracellular fluid) is needed. This is the so-called **conductivity**  $\sigma$  (say: sigma) of the electrolyte. To calculate the conductivity, the conductance  $G$  (depending on  $L$  and  $A$ ) has to be multiplied with the electrode distance  $L$  and divided by the electrode cross section  $A$ :

$$\sigma = G \cdot \frac{L}{A}$$



- ◇ Determine the values of the electrode distance  $L$  and electrode area  $A$  for the two geometries and therefore, using the measured conductance  $G$ , the conductivity  $\sigma$ . Keep in mind that in the determination of the area, only the immersed area counts! Use therefore the given values for the immersion depth  $H$  of the electrodes from the following table and measure the width  $B$  and the distance  $L$  with the supplied ruler.

Conductivity of a 0.1-molar NaCl-solution						
	$H$ [m]	$B$ [m]	$A = H \cdot B$ [m <sup>2</sup> ]	$L$ [m]	$G$ [S]	$\sigma = G \cdot L/A$ [S/m]
Mark 1	0.01					
Mark 2	0.02					

The result should be independent of the electrode distance and electrode area and thus characteristic for the electrolyte solution.

**Dependence of the conductivity on the properties of the electrolyte** The conductivity of an electrolyte can also be measured directly using a so-called conducting meter. The assistant will demonstrate this in the following for the whole group: With  $K^+$ ,  $Na^+$ ,  $Ca^{2+}$ , and  $Cl^-$ , the ions that are most important for the electric properties of the intra- and extracellular fluid are examined.

- ◇ The electrolytes are in plastic bottles, in which the sensor of the conducting meter can be directly immersed. On the bottles, the individual content and concentration is given. Between measurements, the sensor has to be cleaned with de-mineralised water from a spray bottle. Note down the measured values with the corresponding contents and concentrations  $c$  in the following table (units!).

Conductivity of different electrolytes		
Electrolyte	$c$ [mol/l]	$\sigma$ [mS/cm]
NaCl	0.1	
NaCl	0.2	
KCl	0.1	
CaCl <sub>2</sub>	0.1	

- ◇ Which relationship do you suspect between the conductivity and the concentration of the electrolyte? Can you explain this “theoretically”?
  
  
  
  
  
  
  
  
  
  
- ◇ With the same concentration for the KCl- and CaCl<sub>2</sub> -solution, what role does the valence of the dissolved ions play? Can you explain this?
  
  
  
  
  
  
  
  
  
  
- ◇ Compare this to the conductivity of the NaCl and KCl solution for the same concentration. What qualitative relationship do you suspect between the size of the cation (positive ion) and the conductivity? (Na has the atomic number 11, K has the atomic number 19, both are located in the first main group.)

### 2.2.2 Electric potentials (ECG)

In the first part of the experiment, you have seen that an electric current flow is created by an electric field, which is characterised by its voltage. The term of the electric voltage is equivalent to the one of the potential difference between two given points. The latter is used very often not only in physics, but also in physiology<sup>3</sup>. To understand the term potential better, please read the addendum to the experiment Part 2.3, *Physikalische Grundlagen*. It is enough to know that the value of the potential  $\phi$  (say: phi) at a location  $x$  is equal to the electric voltage between the point  $x$  and an **arbitrarily chosen reference point**. In a further analogy, you can compare the potential with the height of a point on the surface of the earth, which is given by an arbitrarily chosen reference point (sea level). The equipotential lines that you will measure in the experiment, therein correspond to contour lines found on a map.

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<sup>3</sup>Other quantities such as the membrane potential or the action potential in the excitation conduction are in the physical sense no potentials, but voltages or voltage pulses. In physiology however, they are usually called “potentials”.

### Measurement of the potential distribution in the electrolyte (one-dimensional model)

To understand current paths and distributions of potential in complex, three-dimensional bodies, it is helpful to look at the principles on simplified models. To do that, you replace in a first step, the three-dimensional, inhomogeneously conducting human body by a strongly simplified one-dimensional, homogeneously conducting model, as described by the electrolyte in the first part of the experiment.

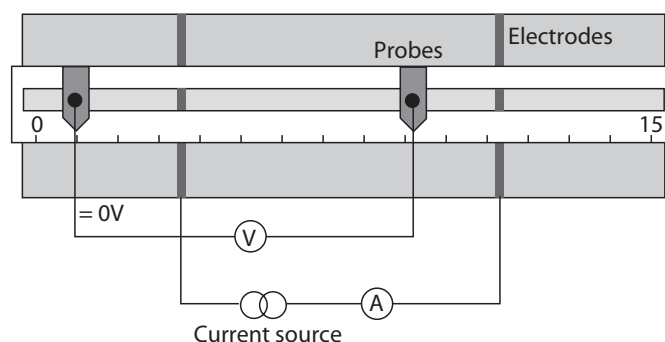


Figure 2.2.3: *Set-up and circuit of the one-dimensional model.*

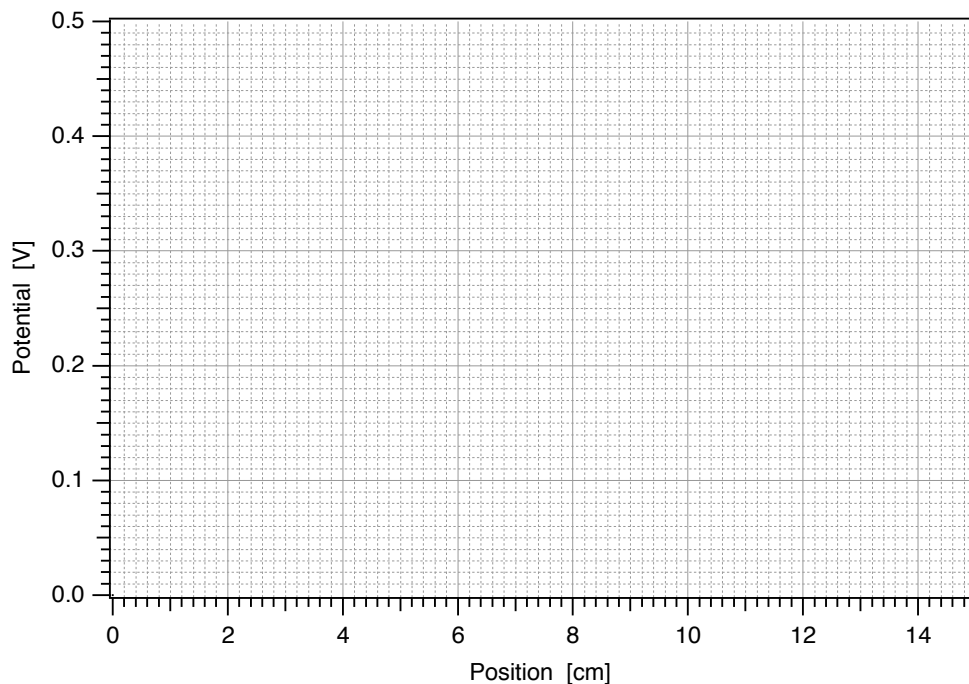
As shown in Fig. 2.2.3, the voltmeter has to be connected to the two rod electrodes, which can be put into the guiding rail. Using these rod electrode, the potential distribution in the electrolyte can be found. The zero point<sup>4</sup> of the potential, meaning the electrode connected to the COM-socket, is to be fixed at 1 cm. Turn on the current source and adjust the current to 5 mA. Connect the second electrode with a cable to the V-socket of the voltmeter. Now you can use this second electrode to measure the potential  $\phi$  at every point in the electrolyte in relation to the chosen zero point (at 1 cm). The potential has the same unit as the voltage: Volt.

- ◇ Conduct a systematic measurement of the potential distribution  $\phi(x)$  at the specified locations (not distances) longitudinal to the electrolyte, where  $x$  is the position of the measuring scale. Note down the values in the following table (units!).

Potential in the electrolyte in relation to $x=1$ cm; $I=5$ mA								
$x$ [cm]	3	4	6	8	10	11	12	14
$\phi(x)$ [V]								

- ◇ Draw in the values in the following figure and mark the positions of the plate electrodes and the reference point. Then connect the measurements points by an appropriate curve.

<sup>4</sup>Since alternating current is used here, the reference point should be located at the edge.



- ◇ What does the potential distribution look like::
  - ... between the current conducting plate electrodes?
  - ... behind the plate electrodes?
- ◇ Why does the potential look like that? Keep in mind that the electrolyte is a conductor and think about where a current flows and where it does not...

### Measurements on the two-dimensional model

In the next step, you will work with the two-dimensional model, which approximates the torso of the human body with a circular disc with the heart in its centre (see ECG-model in Fig. 2.1.1 ). The model consists of a disc, that possesses the same conductivity on the whole area due to its graphite coating. This homogeneous conductivity is another simplification in comparison to the human body, where e.g. in the lung inhomogeneous conductivity leads to a complex potential distribution.

The location of the excitation front (depolarisation) at the heart can be compared to two connections to a current source. The connections to the current source of the disc (the “heart”) are given by 18 socket pairs, they are wired to 9 pairs of light emitting diodes (LEDs) (Fig. 2.2.4). The LED’s

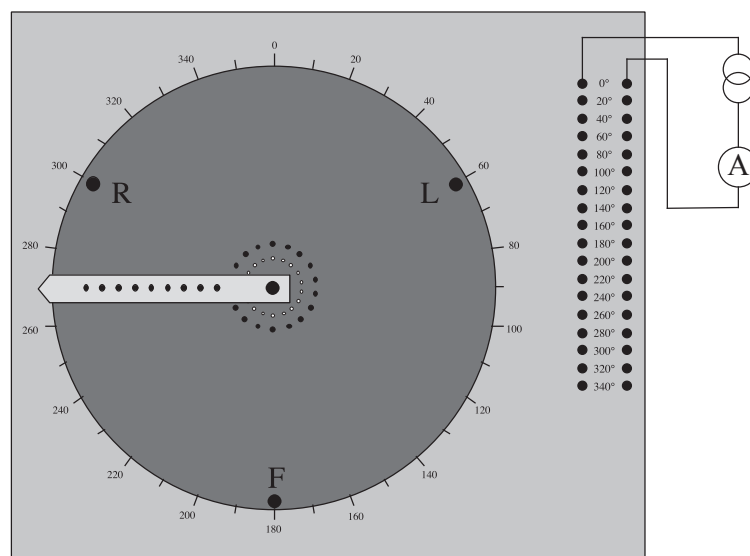


Figure 2.2.4: *Set-up and circuit of the two-dimensional model.*

are in contact with the graphite paper and show you, which socket pair is connected to the current source, including the polarity: the diode lights up red if the corresponding screw is connected to the plus pole and green if it is connected to the minus pole.

- Adjust the current source to *direct current (DC)* and connect it via the amperemeter to the desired socket pair (see Fig. 2.2.4). For clarity, choose the colours of the cables according to the polarisations: Red cables for plus and blue cables for minus.
  - Turn on the current source and adjust the current to 5 mA. This setting should not be changed throughout the entire experiment.
  - Test the operation of the model (and the diodes) by connecting the current source to various socket pairs.
- ◇ What happens if the current source is connected once at  $0^\circ$  and then once at  $180^\circ$ ? Prove your hypothesis by connecting the voltmeter between the sockets R (or L) and F. What do you observe?

The same happens if you exchange the connections to the voltmeters. Due to this, the reference electrode, the one connected to the COM-socket of the voltmeter, is always clearly stated and written down. For Einthoven's leads, it is either (for lead I and II) the electrode R on the right hand or (for lead III) the electrode L on the left hand (Fig. 2.1.1).

### Potential distribution in the two-dimensional model

For the first measurements, only the vertically aligned screw pair (sockets at  $0^\circ$ ) is of interest. Connect the current source now, such that the upper screw is connected to the plus and the lower is

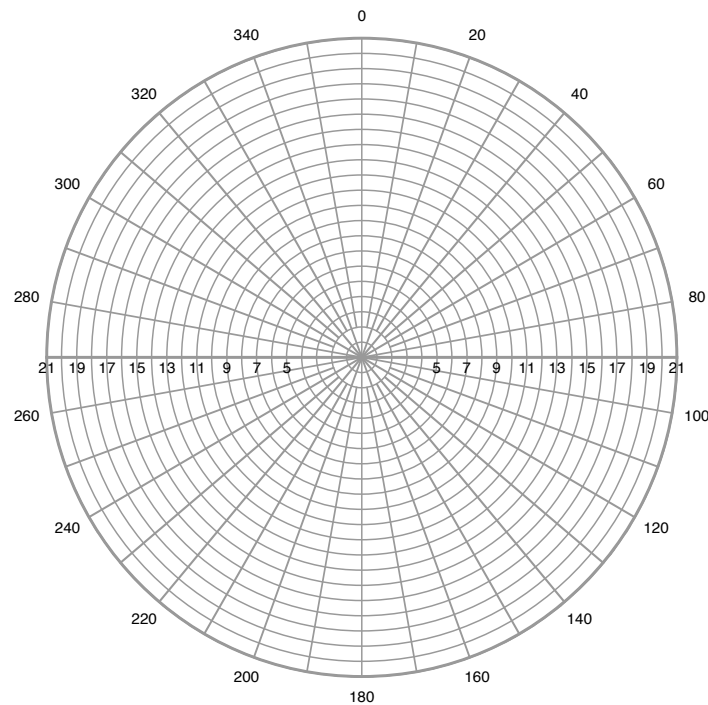
connected to the minus pole. To fully determine the potential distribution, that is thereby created, one would need to scan it with a two-dimensional grid, which is much more complex than in the one-dimensional model. We will thus narrow it down to the measurement of chosen lines. Due to circular symmetry, it is best to choose the zero point of the potential in the socket in the middle of the graphite paper.

### Measurement of the equipotential lines

To characterise the potential distribution, one has to find the equipotential lines – similar to the contour lines in cartography – lines of the same potential. You will now measure these lines in two groups for two different values of potential (0.2 V und 0.4 V) (Division into groups by the assistant).

- Connect the *red electrode touch electrode (spring contact)* to the V-socket of the voltmeter. The COM-socket should still be connected to the socket in the middle of the disc. **Please scan the graphite paper only with this spring contact by gently touching the graphite paper in small, regular distances. Otherwise you damage the graphite paper!**
- ◇ Plug the touch electrode through the innermost hole of the rotor (distance from the centre  $r=5$  cm). Go around in a circle and look for the two angles  $\alpha_1$  and  $\alpha_2$ , for which the voltmeter shows +0.2 V (or +0.4 V depending on your group). Note down the angles in the following table and repeat this for the other distances  $r$ .
- ◇ Draw in the data point of the two equipotential lines with different colours in the following figure by drawing in a cross for each value pair distance/angle on the intersection of the corresponding circle (line of same distance) with the straight of the corresponding angle. This polar representation directly reflects the distribution of the potential on the plate.
- ◇ Where would you expect the 0 V–line, due to symmetry, and draw it in. You can verify this quickly for a few distances.

Measurement of the equipotential lines for 0.2 V					
$r$ [cm]	5	9	13	17	21
$\alpha_1$ [degrees]					
$\alpha_2$ [degrees]					
Measurement of the equipotential lines for 0.4 V					
$r$ [cm]	5	9	13	17	21
$\alpha_1$ [degrees]					
$\alpha_2$ [degrees]					



### Potential distribution along the “extremities”(limbs):

The circular disc possesses on the edge three further sockets, that form an equilateral triangle. These sockets will be the connections for the "ECG-electrodes" for the further measurements. On the human body, electrodes are connected usually on the wrists or ankle joints and not the torso. The influence of the limbs on the measurement itself is negligible, since the flow of current from the torso through the arms and legs and voltmeter back to the torso is very low. On arms and legs, the same potentials can thus be measured in good approximation.

- ◇ Measure now the potentials on the "ECG-electrodes" R, L, and F in relation to the zero point of the potential in the centre of the circular disc.

Socket R (upper left):  $\phi_{\mathbf{R}} =$

Socket L (upper right):  $\phi_{\mathbf{L}} =$

Socket F (lower middle):  $\phi_{\mathbf{F}} =$

### Potential differences in the two-dimensional model

The ECG-leads are not potentials, but potential differences between two given points, e.g. in each case measured between two of the three sockets R, L, and F. Since potential differences are equivalent to electric voltage (both terms describe the same quantity!), they are described with the letter  $U$





