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The Origin of Bioelectric Signals

Lecture Notes for BSP, Chapter 2

Master Program Data Engineering

2 The Origin of Bioelectric Signals

The source of bioelectric signals is the activity of single *excitable* neural or muscular cell. Indeed, the collective electrical activity of a large group of active cells in vicinity changes the properties of the electric field which propagates in the *volume conductor* consisting of the various tissues of the body. The changes in this electrical field is then indirectly monitored and measured by electrodes placed on the skin. In clinical practice, two electrode and multiple electrode recording configurations are commonly used. Multiple electrode configuration provides a spatial description of bioelectric phenomena whereas the two electrode setup is useful to study the time course of the electrical source. However, in both measurement configurations, the activity of neural or muscular cell (in unknown locations) transmitted through an inhomogeneous medium is monitored from a distance. Therefore, it is difficult to analyze the noninvasively collected information and to characterize the electrical source. In spite of these difficulties, analyzing the electric signals, recorded on the skin surface, plays a crucial role in clinical decision- making.

In this chapter, the basic bioelectric phenomena at cellular level in neural and muscular cells and volume conductor is introduced and examples of bioelectrical signals are presented.

The main reference for this chapter is:

[1] Plonsey, Robert, and Roger C. Barr. Bioelectricity: a quantitative approach. Springer Science & Business Media, 2007.

[2] Cohen, Arnon. Biomedical Signal Processing: Time and frequency domains analysis, Volume I. CRC-Press, 1986.

2.1 The Nerve Cell

Neural network is the most important information processing mechanism in living biological systems. Nerve cells (also known as neurons) are the basic processing units in this system. They receive, process and transfer the neural information through electrical and chemical signals. There are different types of specialized neurons: *sensory neurons* receive the sensory information from the cells of the sensory organs and transduce a particular type of stimuli (e.g., pressure, light, temperature, etc.) into electrical and chemical signals. *Motor neurons* receive signals from the

brain and spinal cord and control the muscles contraction. A group of neurons known as *Interneurons* create neural circuits enabling information transfer from neurons to another neurons within the same regions of the brain or spinal cord. Though there exist various types of neurons specialized for particular tasks, they all operate more or less in the same way: an external stimulation can trigger continuous exchange of chemical ions across the membrane of the nerve cell through which an electrical pulse can be produced. To be clearer, the structure of a nerve cell is depicted in Figure 2-1. Each neuron has three major parts: soma (cell body), dendrites and axon. The cell body consists of intracellular fluids and contains the cell nucleus. It is connected to the dendrites, the root-like structures at one end of the cell through which the information is brought into the neuron. On the other side, cell body is connected to the axon through which the information propagates and is sent to other neurons. Through a junction, called synapse, the information is introduced into the neuron from other neurons. Synapses are mostly located on the dendrites or on the soma. Changes in chemical and electrical properties of extracellular fluids in synaptic cleft can increase or decrease the voltage across the membrane. The cell function is based on the integrative (in time and space) effects of these potential changes.

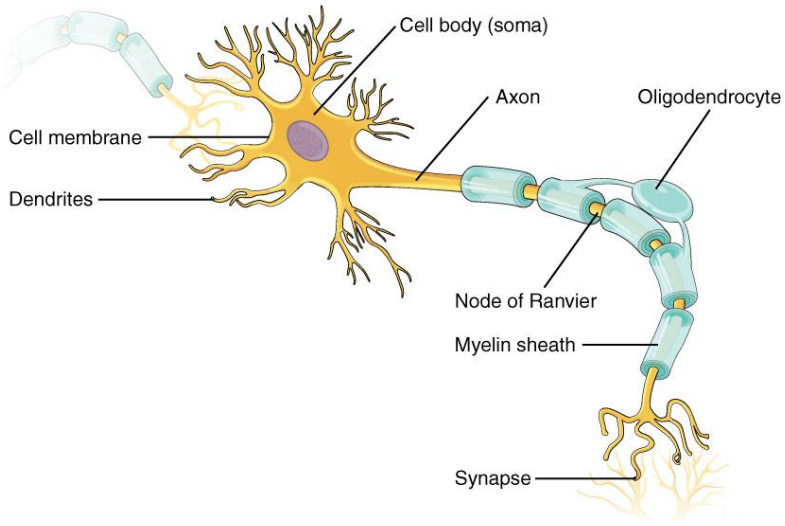

Figure 2-1: The structure of a nerve cell [http://oerpub.github.io/epubjs-demo-book/content/m46509.xhtml].

The lipidic cell membrane divides the extracellular and intracellular fluids with different ionic concentrations. Since there exist a combination of passive ionic channels and active pumps over the membrane, the membrane is not equally permeable to various ions in the solution. For simplicity, let's assume there exist only three main ions, namely potassium, $[K^+]$, sodium, $[Na^+]$

and chloride, $[Cl^-]$ in solutions at either side of the membrane. With respect to the concentrations of the ions, we can calculate the membrane potential, E_m, from the Nernst Equation:

$$E_m = \frac{RT}{F}\ln\left(\frac{P_{K^+}[K^+]_{out} + P_{Na^+}[Na^+]_{out} + P_{Cl^-}[Cl^-]_{in}}{P_{K^+}[K^+]_{in} + P_{Na^+}[Na^+]_{in} + P_{Cl^-}[Cl^-]_{out}}\right)$$

where R, T, and F are the universal gas constant, the absolute temperature, and the Faraday constant, respectively. P_X denotes the permeability of the resting membrane to the ion X, and $[X]_{out}$ and $[X]_{in}$ are the concentrations of the ion X in the extracellular and intracellular fluids. When the neuron is at rest, ionic channels are closed and the pumps are active such that the resultant concentration difference causes the cross-membrane potential ($v_m = v_{in} - v_{out}$) to be approximately $-70\ mV$ (i.e., the inside of the neuron is negative with respect to the outside).

When the membrane of an excitable cell is excited by means of chemical, mechanical or electrical stimulus, some changes in permeability of the membrane to ionic transfer causes the membrane potential to become positive for a short period of time. Then, when the membrane repolarizes, the membrane potential returns to its resting potential. As it is shown in Figure 2-2, time course of the potential change (also known as *action potential*) undergoes three phases of activity: depolarization, repolarization and refractory period. At depolarization phase, increase in sodium influx results in less negative charge inside the cell and increases the membrane potential. If the stimulus exceeds a threshold (about 20 mv), the action potential is produced. Repolarization occurs when the potassium channels open and outward potassium flux changes the polarity between the outside of the cell and the inside. Following the action potential initiation, there is a certain period of time (of the order of 1 to 3 ms) in which no new action potential can be initiated. This period is called refractory period. The generation and propagation of action potential is the underlying mechanism through which the heart muscle contracts and the neural information is transmitted.

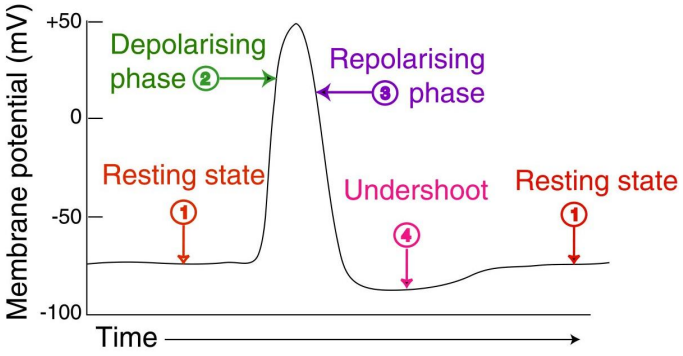

Figure 2-2: The time course of an action potential [https://fuzzyscience.wikispaces.com/Action+Potential].

The shape and time duration of the action potentials differ in various cells. The repolarization phase of a cardiac cell is much longer than repolarization phase of a nerve cell and lasts for 200 to 300 ms. Figure 2-3 shows the action potentials for nerve cells, the skeletal muscle and the heart cell.

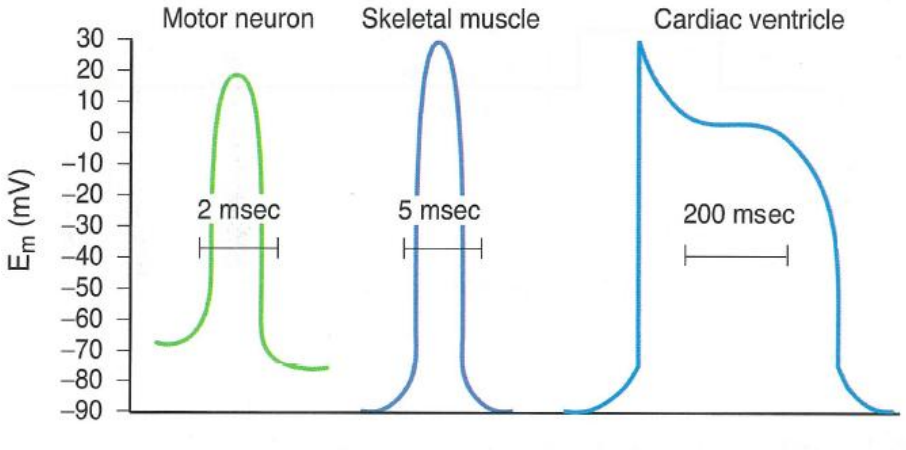

Figure 2-3: Schematic representation of action potentials ranging from spike like waveform observed in nerve cells to waveform with a wide plateau recorded from a cardiac cell [http://i.imgur.com/xX73Lvs.png].

Action potential generation and propagation in excitable cells exhibit certain behaviors:

- It is all-or- none. A neuron either fires an action potential or not. There is no fuzzy state in between.
- Since the action potential is regenerated as it propagates along the axon, its amplitude remains unchanged over the length.
- The information carried by the neuron is coded in the inter-spike intervals, not in the shape of the action potential.
- The firing rate of the neuron is correlated with the stimulation such that a neuron can be modeled as a stimulation to frequency convertor.

It is worth mentioning that in most signal processing applications, single action potentials are not being monitored and the field generated by a trunk of fibers is being measured. Therefore, both amplitude and frequency contents of the recorded signal relate to the neural activity.

When an action potential produced in pre-synaptic neuron arrives at the presynaptic region in axon, the membrane characteristics change to let certain chemical substances (called neurotransmitter) diffuse from the presynaptic region into the cleft. The released neurotransmitters are then captured by receptors in the postsynaptic neuron and cause its membrane potential change. The change may be excitatory or inhibitory depending on the type of transmitter released.

2.2 The Muscle

Both skeletal and cardiac muscles consist of excitable cells. Though the membrane of these cells are similar to the neuron's membrane, their function is not information transfer or process. They generate tension. A whole muscle is composed of many separate bundles and each bundle consists of many individual fibers. The fiber is the basic functional unit made up of many fibrils; Fibrils are divisible into individual filaments, each of which, in turn, is composed of contractile proteins, mainly *myosin* and *actin* (see Figure 2-4).

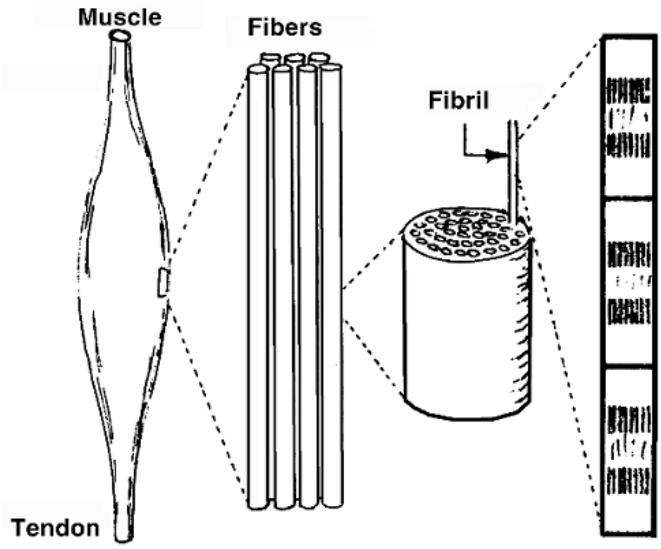

Figure 2-4: Structure of a muscle and its components [1].

According to the *sliding filament* theory, these filaments are arranged in parallel interlacing layers such that by sliding past one another shortening of the muscle length and producing the contraction is possible.

Each muscle fiber is connected to a single nerve terminal (to receive the signals from motor neurons) through which the fiber membrane can be excited. Propagation of action potential along the surface membrane of the fiber triggers some chemical reactions which eventually result in fiber contraction. When a muscle contracts, the action potentials produce an electric field that can be measured by means of electrodes located on the body surface. This field arise from contribution of many fibers (motor units) at different times with different rates. Therefore, the electromyography (EMG) signals recorded in this way will be a random signal with statistical properties that depend on the anatomical and physiological properties of muscles as well as neuromuscular activities. In addition, due to travelling through different tissues, the acquired signal is highly noisy and advanced methods are needed for EMG signal detection.

2.3 The Volume Conductor

So far, we have seen that action potential generated by single neurons and muscle fibers is the source of bioelectric signals. During the action potential generation and propagation along the cell, due the electro-chemical activity of the membrane the current density in the surrounding medium accordingly undergoes some variations. These variations later are monitored by means of surface electrodes. The surrounding tissue through which the electric (and magnetic) fields are transmitted is called volume conductor. In order to better understand the biological source of bioelectric signals from measured surface fields, therefore, the electrical conduction properties of volume conductor have to be modeled. To do this, in *source analysis* studies, an *inverse problem* is solved to reconstruct the impressed primary current distribution from measured surface fields. This is, however, a complex task when inhomogeneity and finite dimension of volume conductor are needed to be taken into account. Nevertheless, various mathematical models of current flow field in volume conductors have been so far developed. More details on this topic and the brief review of existing models is available here for interested readers.

2.4 Bioelectric Signals

In this course we will study the algorithms for processing the vital signals that describe the activity of the heart and the brain. Some of these signals are responses to an external stimulation, while others arise from spontaneous, ongoing activities. Depend on the source and properties of these signals different processing techniques might be applied; in some applications an individual signal may be directly correlated with a clinical diagnosis, while in other signals, the multiple waveforms must be analyzed before a meaningful interpretation can be conducted.

Here are examples of vital signals with significant clinical applications:

- Electroencephalogram (EEG)

  The recording of the spontaneous electrical activity of the brain over a period of time is known as electroencephalography (EEG). It is mostly recorded by means of surface electrodes located on the scalp and is widely used for clinical and research purposes. In diagnostic applications either event-related potentials are detected or the spectral content of EEG is interpreted. Event-related fluctuations in acquired potentials are investigated at certain events; detecting the onset of stimulation or the moment when a button is pressed are examples. In spectral analysis, the brain waves are studied in the frequency domain. In chapter 4 and 5, more details on EEG applications and processing techniques are provided.

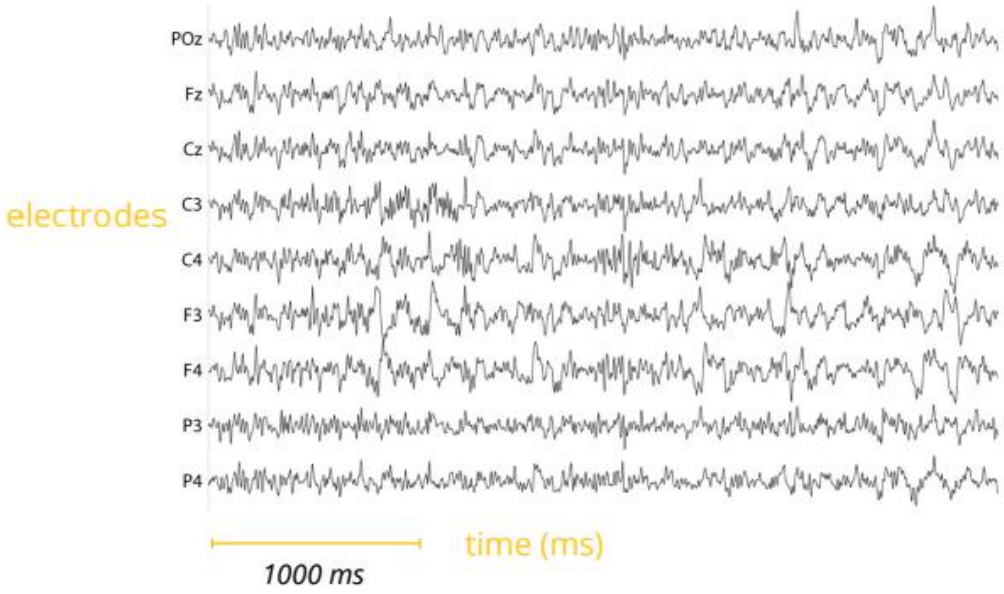

Figure 2-5: A sample of EEG recordings [https://imotions.com/blog/eeg/].

- Electrooculogram (EOG)

  The EOG is the recording of the steady corneal-retinal potential. This potential has been used to measure eye position, either for research purposes (sleep research) or for clinical decision making. The signal is measured by pairs of surface electrodes placed to the left and right of the eyes and above and below the eyes. The amplitude of EOG is in the range of $10\,\mu V$ to $5\,mV$. The signal contains the frequency components in range of DC to $100\,Hz$.

- Electroretinogram (ERG)

  The ERG is the potential generated by retina. Evoked ERG which is the potential generated in response to a flash of light is mostly used. It is recorded mainly in ophthalmological research and clinical diagnoses. The voltage levels of the ERG are in the range of $0.5\,\mu V$ to $1\,mV$ in clinical applications. The bandwidth required for the processing of the ERG is about 0.2 to $200\,Hz$.

- Electroneurogram (ENG)

  The field generated by neuron in central or peripheral nervous system can be directly measured without penetrating the membrane of a single cell. The monitored voltage reflects the contribution of several action potential transmitted through the volume conductor. If it is measured by means of surface electrodes, the range of the recorded amplitude is about $5\,\mu V$ to $10\,mV$ and its bandwidth is about $1\,kHz$. In clinical applications, ENG is recorded to calculate the nerve conduction velocity to detect nerve fiber damage.

- Sensory Evoked Potentials

  Evoked potentials (EP) or Evoked Responses (ER) are the electrical activity of the brain evoked by a sensory stimulation. Visual EP (VEP), Somatosensory EP (SEP, SSEP) and Auditory EP (AEP) are recorded over occipital lobe, sensory cortex and vertex, respectively. In clinical routines, VEP is used for diagnosis of multiple sclerosis and also

to check color blindness and visual acuity. The amplitude of recordings ranges from 1 to 20 μV, its bandwidth is of 1 to 300 Hz and its duration is in order of 200 ms.

- Electromyography (EMG)

  EMG is the recording of the electrical potential generated by the skeletal muscles. In clinical assessments, EMG is used as a diagnostics tool for diagnosis of neuromuscular or motor control pathological conditions. Depends on the muscle from which the signal is recorded, the amplitude of EMG potentials range between less than 50 μV to 30 mV and its bandwidth is about 7– 20 Hz.

- Electrocardiography (ECG)

  The ECG is the recording of the electrical activity of the heart. Since the mechanical activity of the heart function is linked with its electrical activity, the ECG is an important diagnostic tool for assessing cardiac function. Samples of ECG signals in normal and pathological conditions are shown in Figure 2-6. More details on ECG applications and processing methods are provided in chapter 6 and 7.

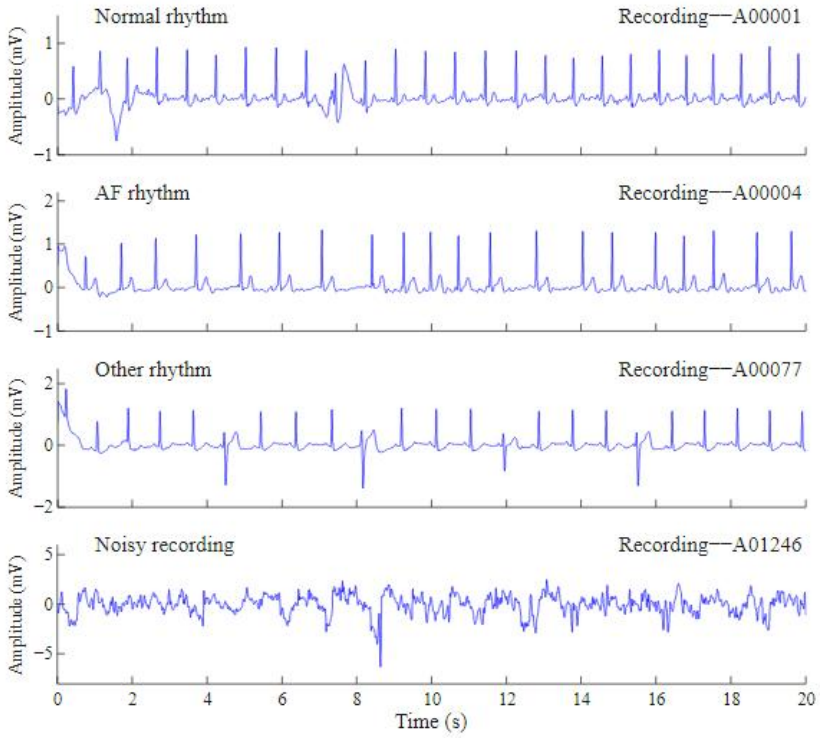

Figure 2-6: Samples of pure and noisy ECG signals in normal and pathological conditions [https://physionet.org].

- Fetal electrocardiography (FECG)

  The non-invasive detection of fetal ECG by means of abdominal surface electrodes is used in clinical practice to assess the fetal life, development and maturity. It is also useful to determine the existence of fetal distress or congenital heart disease. The crucial problem in the processing of FECG is the large interferences from maternal ECG and from other muscles.

- Electrogastrography (EGG)

  The EGG records the cyclic electrical potentials that are transmitted through the smooth stomach muscle fibers and control muscle contractions causing a slow rhythmic (of the order of 0.05 Hz) mechanical motion. This motion is responsible for mixing, grinding, and propelling the absorbed food. Electrical potential changes arise from the wave-like contractions of the stomach can be picked up by means of surface electrodes. The signal has a dominant frequency equal to the frequency of the gastric electric control activity which is about $0.05\ Hz$. The frequency bandwidth of the signal is about 0.01 to $0.5\ Hz$.