Biomedical sensors: Types and Principles

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***Abstract*—Modern healthcare depends on the availability of suitable sensors and transducers of biomedical signals into electrical quantities suitable for processing and visualization by modern computer systems. From measuring temperature and SPO_2 saturation in the blood to determining pulse rate or registering brain activity, various sensors for biomedical signals are used in every stage of healthcare. This article attempts to systematize and describe the most common types of sensors and transducers of biomedical signals. A brief description of their operating principles is also provided.**

***Index Terms*—Sensors, ECG, EMG, PPG, temperature, glucose**

I. Introduction

There are various definitions of the term sensor. In [1] it is said "…a device that is used to record that something is present or that there are changes in something…". Wikipedia [2] states "...In the broadest definition, a sensor is a device, module, machine, or subsystem that detects events or changes in its environment and sends the information to other electronics, frequently a computer processor..." The Britannica Dictionary [3] gives the following definition "...a device that detects or senses heat, light, sound, motion, etc., and then reacts to it in a particular way..." The are many definitions in all over the world which are in most cases are true. In order not to use different terms for each type of sensor and transducer, we will make the following generalized definition - sensor is a device that converts one type of impact quantity into another type of impact quantity. For example, a photo sensor is a device that converts light into electrical signals – voltage, resistance, etc.

Biomedical sensors are at the heart of modern healthcare, providing critical data that underpins diagnosis, monitoring and treatment. From tracking vital signs like heart rate and blood pressure to detecting glucose levels in diabetic patients, these sensors are crucial in everyday medical devices. As technology advances, the role of biomedical sensors continues to expand, offering new ways to improve patient care. As a result of miniaturization in microelectronics and the expanding applications of automated systems and devices for health monitoring, research and development of biomedical sensors are directed towards reducing their size and increasing their precision.

Figure 1 shows a common block diagram of a sensor for a certain quantity. It consists of the following several main elements:

- Sensing element - this is the part of the sensor that registers the quantity under observation;
- Conditioning – this part serves to process the investigated parameter and bring it to a form suitable for further processing.
- Conversion – at this stage, the conversion of the obtained quantity into an electrical signal, mechanical movement, light, etc. is performed, which are used for direct reading of the investigated parameter or for subsequent processing or storage.
- Power supply – in most cases, for the correct operation of the sensors, there is a need for a power supply source – battery, accumulator, electrical network. In some types, there is no such need, i.e. the sensor itself generates voltage (for example - a thermocouple).

Figure 2 shows a simplified block diagram of a system for monitoring a person's health status [4]. It consists of several main components:

- Sensors – their number and type are determined by how comprehensive and detailed the study should be. In some cases, it is necessary to monitor only the work of the heart. In others, the change in temperature. In the third, a combination of several factors is used to achieve a more complete and informative description of changes in the individual's condition.
- Signal conditioning – another main part of the system takes care of normalizing the registered parameters, converting them into an electrical signal and their primary processing. In some cases, comprehensive processing of all registered parameters such as temperature, ECG, SPO_2, body position, movement, etc. is performed.
- Output - the result of the primary or comprehensive processing of the registered parameters is used depending on the necessary needs – it is displayed on a screen in real time, recorded for statistical research, transmitted to other devices for subsequent processing. When registering deviations from the normal values of certain parameters, it

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is possible to generate an alarm to notify, for example, the attending physician.

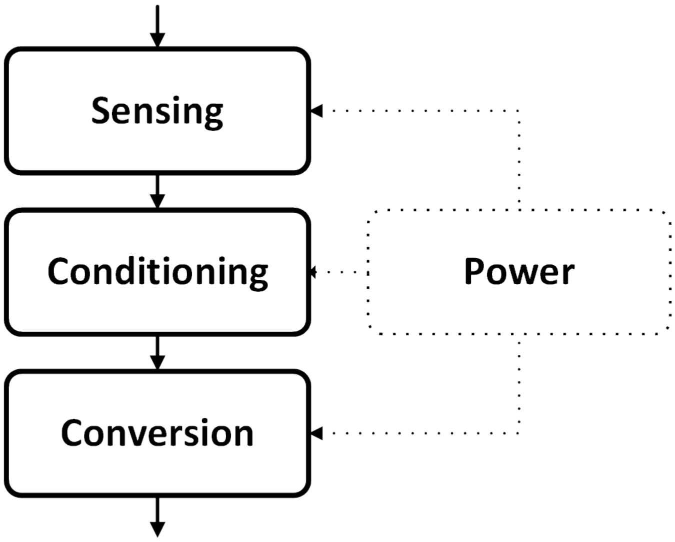

Fig. 1. Sensor block diagram

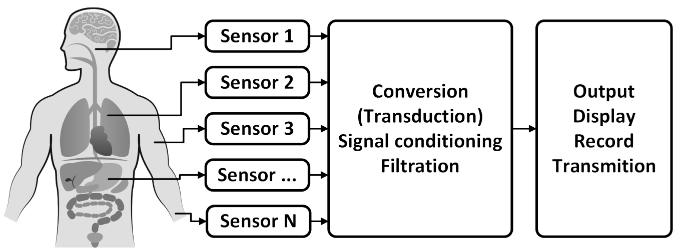

Fig. 2. Complete sensor system

To choose a suitable sensor, various factors must be taken into account. In general, we can say that they are reduced to the following three main categories

- economic - this includes the price of the sensor itself, the possibility of buying it over a long period of time, the possibility of its delivery - the best and highest quality sensor is useless if it cannot be delivered on time.
- characteristic - this category includes all the parameters of the sensor that determine its quality indicators: accuracy, stability, repeatability, linearity, range, etc.
- dependent on the environment - this includes dependencies on environmental changes - temperature, humidity, pressure, overload, energy consumption, self-calibration, etc.

For example, choosing a cheap sensor for single use over time may turn out to be more expensive than using a more expensive sensor that allows multiple use. In another case, using a supersensitive sensor may prove problematic if the data received during reading has large deviations. Similarly, a sensor whose readings are greatly influenced by changes in its environment may be unsuitable, even though it may have ideal other parameters.

II. Biomedical sensors Classification

The biomedical sensors can be classified according to several different characteristics. The first one is a by type of quantity they registered. Yu-Yan Zhuang et al. [5] states that according to the type of quantities that biosensors register, they can be divided into three main groups. We can add to them a few more types:

- Physical quantity sensors - they convert mechanical movements, pressure, speed, fluid movement and volume etc.
- Chemical quantity sensors - they measure the oxygen quantity in the blood, the pH also ions and any other chemical substances and compounds
- Biomedical quantity sensors - they measure
- Temperature sensors - they convert various forms of radiated energy to convenient signals to use
- Biopotential sensors - they measure the electrical voltage generated by physiological processes occurring in the body.

A. *Physical quantity sensors*

Sensors for physical quantities are the same as those used in non-biomedical applications. This class includes sensors for motion, position, pressure, speed, sound, flow, etc. Although the same sensors are used for medical and non-medical applications, some of them have significant differences in their use. For example, sensors for direct measurement of blood pressure and blood flow are placed in a blood vessel, which implies that they must be designed to allow their placement in a blood vessel. Another challenge is their placement itself, which requires that it be done by qualified personnel.

B. *Chemical quantity sensors*

Chemical quantity sensors are used to measure chemical parameters such as the concentration of oxygen and carbon dioxide in human metabolism, as well as the pH, Na^+, K^+, Ca^{2+}, and Cl_+ values in body fluids [6].

C. *Biomedical quantity sensors*

A biosensor uses a living component or product of a living being for measurement or indication. They are characterized by the nature of the interaction that underlies the sensing effect - the very specific chemical reactions typical of biological systems. They used to detect biological parameters like enzymes, DNA, RNA, hormones etc. One of the most important applications of enzymatic biosensors is the monitoring of blood sugar levels in diabetic patients using a glucose sensor. The most commonly used principle is through enzymes that, when reacting with sugar, release hydrogen peroxide + (Gluconolactone - acid). It, in turn, affects an electrode by changing the electric current flowing through it. Depending on the magnitude of this current, the sugar content is determined. To perform the test, the classic method is used by pricking the blood sample and applying it to the sensor. There are also certified minimally invasive methods - a sensor is implanted in the body that reads the glucose content and transmits this information to an external device. Currently, there is no approved and certified non-invasive method for monitoring sugar in the body. There are developments and attempts to use optical technologies to determine sugar content. There are also attempts to use the change in the absorption and reflection of RF energy passing through tissues [7].

D. Energy sensors

1) Temperature sensors: Temperature is one of the most constant variables in the human body. Like any auto-regulation system, here we have a supporting source, executive elements for regulation – muscles, skin, lungs and a control center – the hypothalamus. The absolute value of temperature for a healthy person is about 37°C. The classic method of measuring temperature is by using a mercury thermometer [8]. It is simple and cheap. The main disadvantages include the relatively long time for determination and the difficulty of reading the measured value. Another major disadvantage is the possibility of dangerous environmental pollution when it is broken. The development of microelectronics allows the replacement of mercury thermometers with safer electronic ones. Figure 3 shows a simplified block diagram of an electronic thermometer. It contains a thermally sensitive element usually a thermistor or diode, an analog to digital converter and a display. It is also possible to have memory and communication capability to connect to external systems.

Fig. 3. Contact electronic thermometer

Another method for determining temperature is measuring the intensity of infrared radiation. Figure 4 shows a block diagram of such a thermometer. The energy emitted by the object is focused by a lens or set of lenses. It is then filtered, which achieves measurement only in a narrow region of the spectrum, in order to avoid the influence of side radiation sources. An advantage of the method is that the measurement is non contact, and it is possible to make it from a relatively long distance. Recent developments in infrared thermometers combine pulsed laser technology with single color infrared thermometers to automatically determine the values of the emissivity and accurately correct the measured temperature.

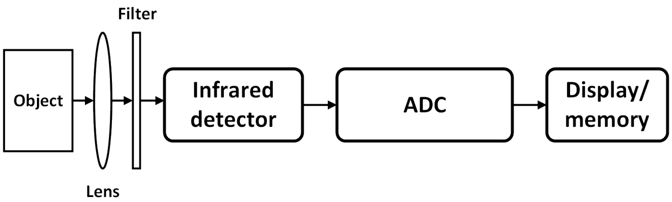

Fig. 4. Contactless electronic thermometer

2) Optical sensors: During the systolic phase, the arteries fill with blood, which leads to their expansion. The path that the light travels also increases and as a result, the absorption of light by the blood increases. At maximum absorption, we have a minimum in the signal graph. Similarly, during the diastolic phase, we have less blood, the blood vessels are more constricted, as a result of which the absorption of light is less and a maximum is obtained in the graph of the photoplethysmographic signal. Figure 5 [9] shows the path of the light and the shape and level of the received signal.

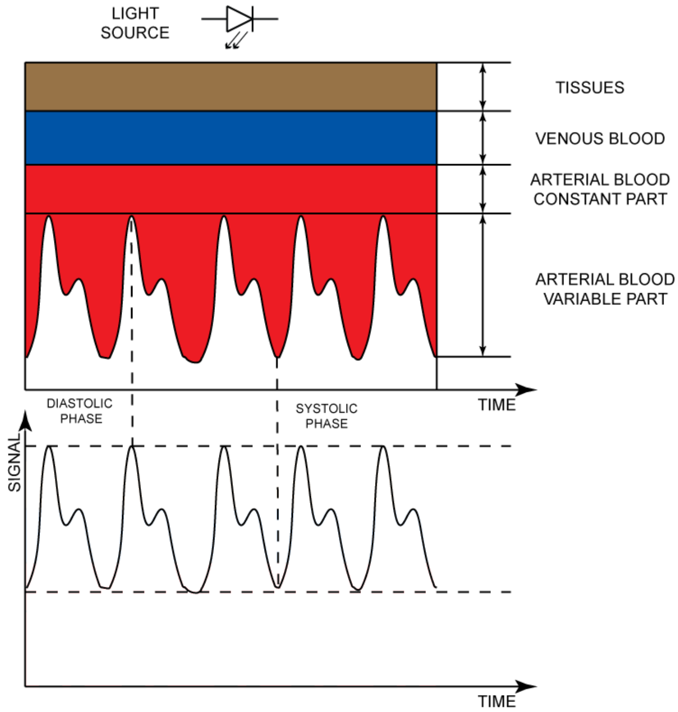

Fig. 5. Photoplethysmographic principle

There are two main methods for measuring the pulse wave using photoplethysmographic technology:

- by measuring the volume of blood when light is reflected from the tissue Figure 6, with the light source and photodetector located on the same side of the study site.
- by measuring the volume of blood as light passes through the tissue Figure 7, with the light source located on one side of the tissue and the photodetector on the other;

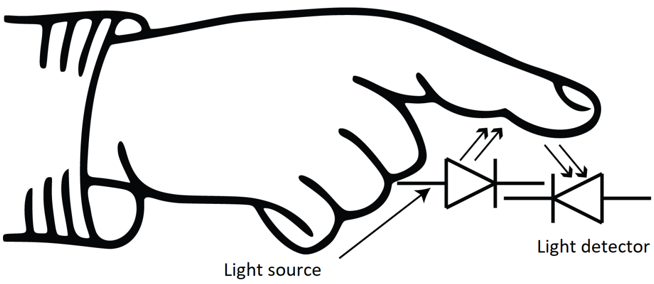

Fig. 6. Photoplethysmographic usage using reflection

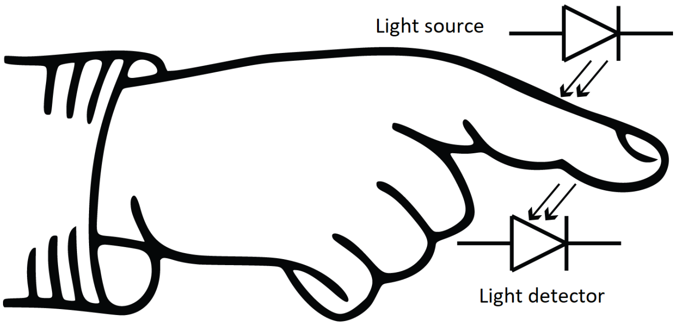

Fig. 7. Photoplethysmographic using pass trough

Figure 8 shows a typical block diagram of a heart rate an SPO_2 device. The signal coming from the photodiode(s) is amplified, then digitized with ADC and then is processed by DSP circuit.

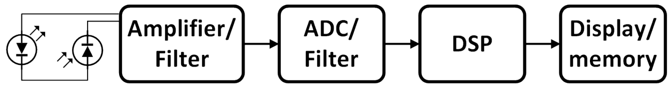

Fig. 8. Photoplethysmographic sensor device diagram

$$A = \epsilon c l \tag{1}$$

where:

A - absorption;

ϵ - molar absorption coefficient;

c - concentration;

l - thickness of the layer through which light passes.

3) X-ray sensor: A typical block diagram of a x-ray sensor is shown on Figure 9. X-rays from the source pass through the object of study and fall on a surface covered with phosphor. As a result light is generated, which falls on a photocathode. There it is converted into an electrical signal. Then the received signal passes through a photomultiplier, where it is amplified and falls again on a surface covered with phosphor. The electrical signal is converted into visible light. After passing through a converge lens, the obtained image is displayed on a monitor for direct observation or is converted by a CCD camera into digital form for recording or subsequent processing.

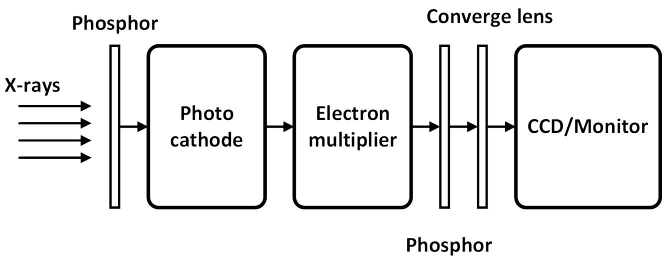

Fig. 9. X-ray sensor simplified block diagram

E. Biopotential sensors

The most commonly used sensors in this group are electrocardiogram, electroencephalogram, and electromyogram. Below we will provide a brief overview of each of them.

1) Electrocardiogram: One of the most commonly used diagnostic tools for assessing the activity of the cardiovascular system is the electrocardiogram (ECG). The electrocardiogram is a time-lapse recording of the electrical activity of the heart [10] and is a reflection of the magnitude of the voltage between specific points on the individual's body.

The main task of recording an electrocardiogram is to detect and monitor the electrical signals coming from the heart. This is done by determining the voltage potential in the heart using two bipolar leads placed on either side of the heart. There are many techniques for obtaining an ECG signal from the body of an individual, and these techniques depend on the way the electrodes are placed. The relative placement of the electrodes determines the area of the heart from which the ECG signal will be obtained. According to Eythoffen, the heart is located approximately in the center of an equilateral triangle, called Einthoven's triangle [11], [12]. Figure 10 [13] shows two of the peaks, which are located on the two shoulders of a person, and the third peak is located in the abdominal region. According to Einthoven, the instantaneous magnitude and direction of the resultant electrical vector of the ECG signal is obtained by measuring the projections of the vector onto the sides of the triangle.

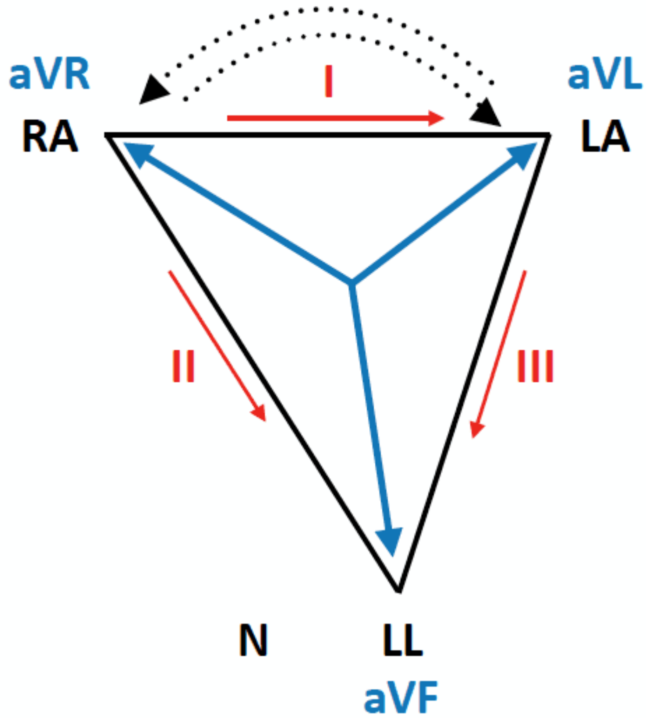

Fig. 10. The Einthoven's triangle

Electrical voltage is measured by electrodes attached to the individual's body at specific locations. Figure 11. [14] shows the arrangement of 6 electrodes for a 12-lead study. For this purpose, 10 electrodes are required, with 4 electrodes placed on the limbs.

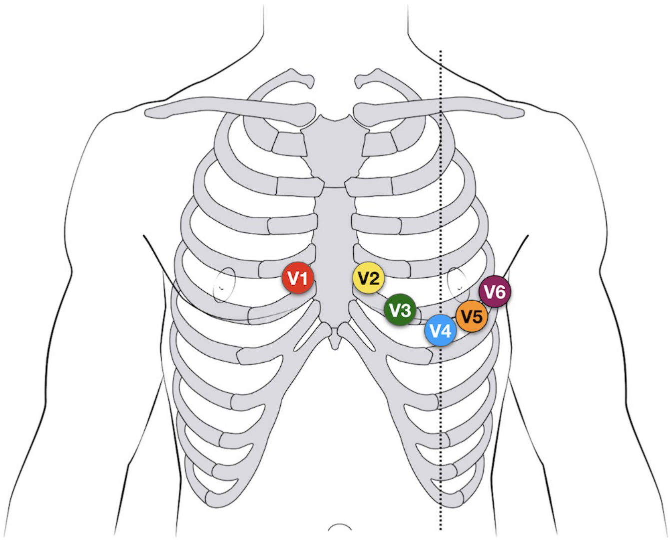

Fig. 11. ECG Electrodes placement

The typical ECG sensor system consists of several main components shown on Figure 12. They are:

- Leads - A standard 12-lead configuration is used to obtain a complete, detailed picture of the heart's condition. When using Holter devices for continuous monitoring, a 3- or 5-lead configuration is used. A single-lead configuration is commonly used in wearable ECG recording devices.
- Processing - In nowadays the processing block consists of input amplifier, input filter, digital processing unit for filtering, removing a base line drift, removing artefacts etc. Most if not all of this processing can be made in one single electronic integrated circuit.
- Display - The results of the study can be recorded for further future research and reference.

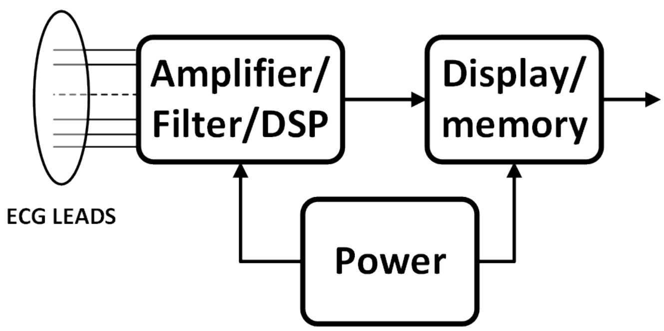

Fig. 12. Typical ECG sensor system

2) Electroencephalogram: Electroencephalogram are recordings of electrical activity of human brain. The electrical potentials produced by brain are small about 300μV range. The electrodes are are placed on scalp in a specific way. Standard clinical EEG uses a 21 electrodes. Figure 13 [15] shows a standard placement on scalp of subject to study.

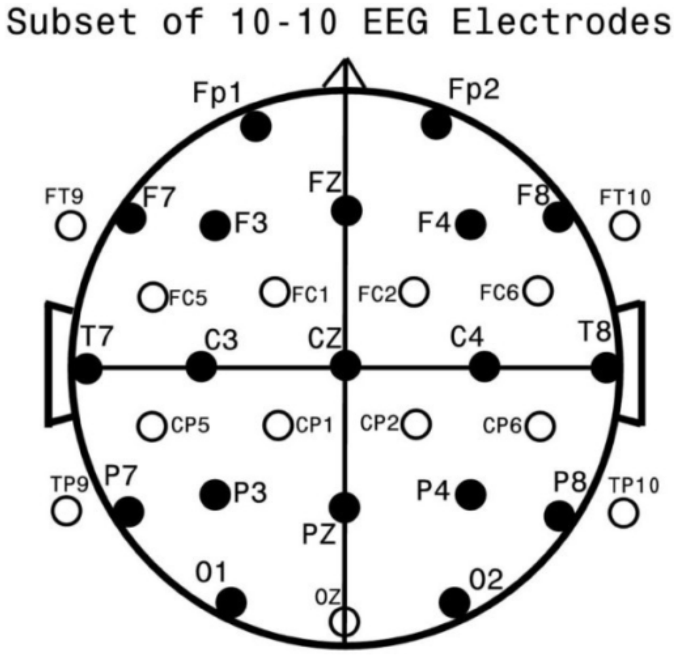

Fig. 13. EEG leads naming and typical placement. Source: National Library of Medicine.

In rare and special cases up to 128 and more electrodes can be used. The acquisition system for registering a EEG activity is similar to that for ECG recording. There is a input amplifiers, filters, digital signal processing, displays, data recording etc. Unlike the characteristic shape of the ECG signal, there are no easily recognizable areas of the graph. The interpretation of the EEG requires the services of experienced electroencephalographers, who can distinguish between normal brain activity and the presence of various abnormalities. Figure 14 shows a sample EEG image [16].

III. Conclusions

This article provides a brief overview of the most commonly used biomedical sensors in modern healthcare. A classification has been made depending on the quantities they register. Their principles of operation are presented. Greater attention is paid to the sensors that are present in modern wearable electronic devices such as electronic bracelets, smart watches, phones and others.

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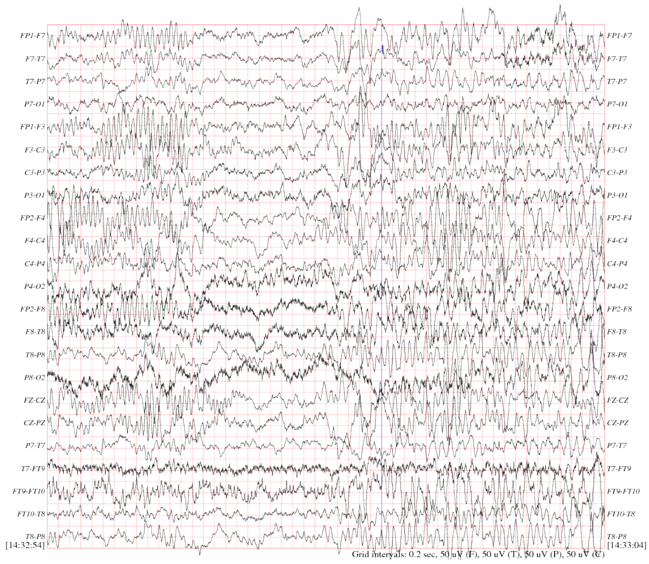

Fig. 14. Sample EEG image

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