Review of Some Biomedical Signals

Hamidreza Abooei Mehrizi
Student ID: 9733002
dept. of Biomedical Engineering
Amirkabir University of technology
Tehran, Iran
Hamidreza.abooei@aut.ac.ir

Mohammad Hassan Moradi
dept. of Biomedical Engineering
Amirkabir University of technology
Tehran, Iran
mhmoradi@aut.ac.ir

Abstract—A signal is a phenomenon that conveys information. Biomedical signals are signals, used in biomedical fields, mainly for extracting information on a biologic system under investigation. The complete process of information extraction may be as simple as a physician estimating the patient's mean heart rate by feeling, with the fingertips, the blood pressure pulse or as complex as analyzing the structure of internal soft tissues by means of a complex CT machine. [1] In this review, we will take a look at some of these signals.

Index Terms—Biomedical Signal, introduction, bio signals ,bioelectric signals, acquisition, signal specifications

I. Introduction

This document is the answer of a class exercise about finding some unpopular human signals (biomedical signal) at BSP class, presented by Dr. MH Moradi.
Biomedical signals originate from a variety of sources including: Bioelectric signals, Bioimpedance signals, Bioacoustic signals, Biomagnetic signals, Biomechanical signals, Biochemical signals, Biooptical signals. [1]

II. Bioelectric signals

It is generated by nerve cells and muscle cells. Its source is the membrane potential, which under certain conditions may be excited to generate an action potential. [1]

A. ENG (Electroneurogram)

Clinically, the ENG is used to measure the conduction velocities and latencies in peripheral nerves by stimulating a nerve at different points along the nerve. [4] Conduction velocity in a peripheral nerve is measured by stimulating a motor nerve at two points a known distance apart along its course. Subtraction of the shorter latency from the longer latency Fig.1 gives the conduction time along the segment of nerve between the stimulating electrodes. Knowing the separation distance, we can determine the conduction velocity of the nerve, which has potential clinical value since, e.g., conduction velocity in a regen-erating nerve fiber is slowed following nerve injury [4]. Needle electrodes used in order to signal acquisition. frequency range of this signal is $(100, 1k)Hz$ and its dynamic range is $(5\mu, 5m)V$.

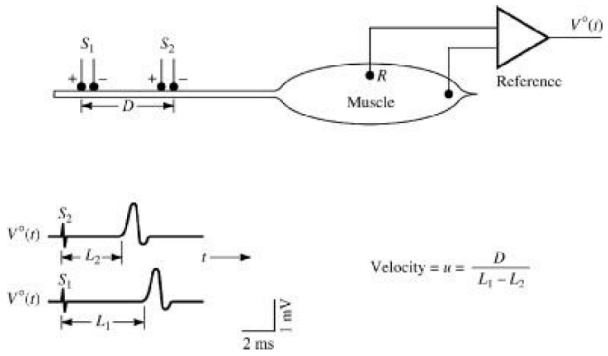

Fig. 1. Measurement of neural conduction velocity via measurement of latency of evoked electrical response in muscle. The nerve was stimulated at two different sites a known distance D apart. [2]

B. ERG (Electroretinogram)

1) Anatomy of vision: The normal eye is an approximately spherical organ about 24 mm in diameter Fig.2. The retina, located at the back of the eye, is the sensory portion of the eye. [2]

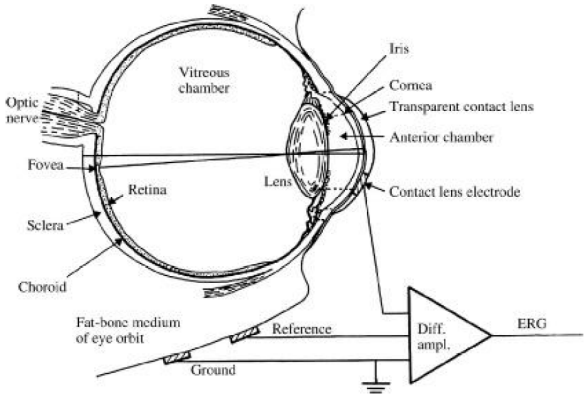

Fig. 2. The transparent contact lens contains one electrode, shown here on horizontal section of the right eye. Reference electrode is placed on the right temple. [2]

When the retina is stimulated with a brief flash of light, a characteristic temporal sequence of changes in potential can be recorded between an exploring electrode—placed either on the inner surface of the retina or on the cornea—

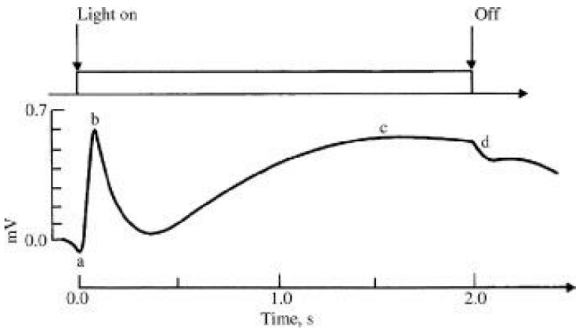

Fig. 3. Vertebrate ERG [2]

and an indifferent electrode placed elsewhere on the body (usually the temple, forehead, or earlobe). These potential changes are collectively known as the electroretinogram (ERG), and they are clinically recorded with the aid of an Ag/Ago electrode embedded in a special contact lens used as the exploring electrode. The saline-filled contact lens is in good contact with the cornea, which is very thin and in intimate contact with the aqueous humor and passive fluid medium of the inner eye. The contact lens is usually well tolerated by the subject and permits long examinations without discomfort. By considering the eye as a fluid-filled sphere and the retina as a thin sheetlike bioelectric source attached to the posterior pole of the sphere (Fig.2), we can easily visualize the volume-conductor problem in electroretinography. Fig.3 shows a typical vertebrate ERG waveform in response to a 2 s light flash. The four most commonly identified components of the ERG waveform (the a, b, c, and d waves) are common to most vertebrates, including humans. The first part of the response to a brief light flash is the early-receptor potential (ERP) generated by the initial light-induced changes in the photo-pigment molecules. It appears almost instantaneously with the onset of the light stimulus. The second component, with a latency of I to 5 ms, is the late-receptor potential (LRP), which has been found to be maximal near the synaptic endings of the photoreceptors and therefore reflects the outputs of the receptors. Normally the ERP and LRP sum to form the leading edge of the a wave. The b wave is generated by activity of the bipolar and ganglion cells of the inner layers of the retina. This is best seen in laboratory experiments under conditions where the retinal artery supplying the inner layers of the retina is occluded, and the b wave is abolished. This experimental technique is useful since in the absence of the b wave, the entire time course of the early photoreceptor response (ERP LRP) can be studied. The ERP is linear with light intensity; the LRP is already markedly nonlinear, varying approximately logarithmically with intensity. The c wave is not generated by the retina itself, but rather by the pigment epithelial layer in which the tips of the external segments are embedded. This is shown experimentally by chemically ablating the pigment epithelium or using an isolated retina preparation. The d wave is the off-response of the retina to the light stimulus. [2]

C. EOG (Electrooculography)

These types of signals are produced by the electric potential that is generated by the cornea and the retinal activity during eye movement. A typical EOG records the electrical field that is produced by the difference between the cornea's positive potential and the retina's negative potential, i.e., the corneoretinal potential, with an amplitude from 0.4 to 1 mV [9]. EOG has been used as a method for removing ocular artifacts in other biosignals, such as EEG [10], as well as for studying the eye movement in humanecomputer interaction systems [11]. Other relevant procedures include the electronystagmography [12] that records the eye movement during nystagmus. [1]

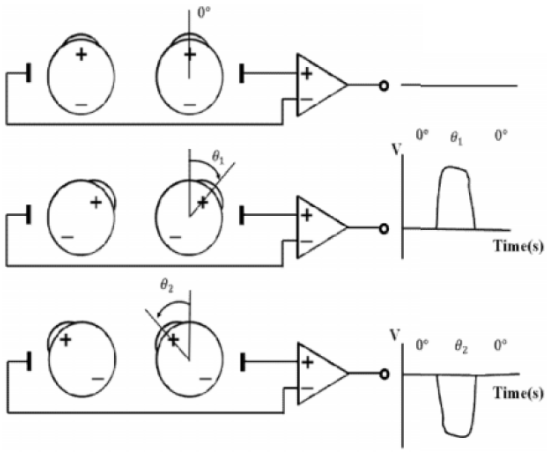

Fig. 4. Output signal of comparator; no signal when eyeball are centered (top), positive pulse with movement to the right (middle) and negative pulse with movement to the left (bottom) [13]

In addition to the transient potential recorded as the ERG, there is a steady corneal—retinal potential. This steady dipole may be used to measure eye position by placing surface electrodes to the left and right of the eye (e.g., on the nose and the temple). When the gaze is straight ahead, the steady dipole is symmetrically placed between the two electrodes, and the EOG output is zero. When the gaze is shifted to the left, the positive cornea becomes closer to the left electrode, which becomes more positive. There is an almost linear relationship between horizontal angle of gaze and EOG output up to approximately $\pm 30°$ of arc. Electrodes may also be placed above and below the eye to record vertical eye movements.

The EOG, unlike other bipotentials, requires a dc amplifier. The signal is in the microvolt range, so recessed Ag/AgC1 electrodes are required to prevent drift. It is necessary to abrade the skin to short out changes in the potential that exists between the inside and the outside of the skin. A noise is present that is compounded of effects from EEG, EMG, and the recording equipment;

it is equivalent to approximately 1° of eye movement. Thus EOG data suffer from a lack of accuracy at the extremes. Specifically eye movements of less than 1° or 2° are difficult to record, whereas large eye movements (for example, greater than 30° of arc) do not produce bioelectric amplitudes that are strictly proportional to eye position. For an analysis of the accuracy and precision of electro-oculographic recordings, consult North (1965).

The EOG is frequently the method of choice for recording eye movements in sleep and dream research, in recording eye movements from infants and children, and in evaluating reading ability and visual fatigue. For a practical clinical EOG setup, see Niedermeyer and Lopes Da Silva (1999).

D. EP (Evoked potentials)

Evoked potentials are the signals recorded from the brain in response to external stimulation.Evoked responses can be elicited by electrical stimulation (somatosensory evoked response), visual stimulation (visual evoked response), or auditory stimulation (brainstem auditory evoked response). Usually the signals are small, while the background noise, mostly the background EEG activity, is quite large. The low signal-to-noise ratio (SNR) necessitates use of ensemble averaging, sometimes signal averaging as many as a thousand responses. [20]

1) VEP (Visual Evoked potentials): Visual evoked potentials (VEPs) have been used in the clinical environment as a diagnostic tool for many decades. Stochastic analysis of experimental recordings of VEPs may yield useful information that is not well understood in its original form. Such information may provide a good diagnostic criterion in differentiating normal subjects from subjects with neurological diseases as well as provide an index of the progress of diseases. [1]

E. EGG (Electrogastrography)

Electrogastrography (EGG) is the name given to the recording of gastric electrical activity from cutaneous electrodes. (In analogy with terms like electrocardiography and electroencephalography, it seems wise to reserve the term EGG for cutaneous recording and to renounce its use for intraluminal and serosal recording of gastric potentials.) Since 1922 [25] a limited number of investigators have published studies on EGG, mostly in man. Agreement exists on the sinusoidal configuration of the EGG signal and on its frequency in man, about 3 cycles per minute (0.05 Hz). The gastric origin of the signal was proven or claimed to be proven by several authors [25]–[30], but convincing evidence was provided only recently by Brown et al. [31] and Smallwood [32].

A question of major importance, which has not yet been answered satisfactorily, concerns what exactly is measured in EGG. Most earlier investigators concluded or assumed that the electrogastrogram reflects the phasic contractile activity of the stomach. Due to a lack of knowledge of gastric myoelectric activity, the mechanism by which this reflection is achieved could not be elucidated. It has been suggested that contraction-induced changes in the electrical impedance of the abdomen play a role in the generation of the electrogastrogram [33].

Studies made during the past 15 years yielded much information about the electrical activity of gastric smooth muscle. It is now known that in the extracellular signal derived with serosal electrodes two kinds of electrical activity can be distinguished. The first kind, often referred to as electrical control activity (ECA), is an omnipresent periodic activity that is not indicative of contractile activity. The second kind, the so-called electrical response activity (ERA), is time-locked to the ECA, but only occurs in connection with phasic contractile activity.

Brown et al [33] concluded from their experiments in man that gastric ECA is the only source of the electrogastrographic signal. This conclusion is in contrast with the assumption that in electrogastrography phasic contractile activity is measured. The possibility that gastric ERA contributes to the surface signal has not yet been suggested as such in literature.

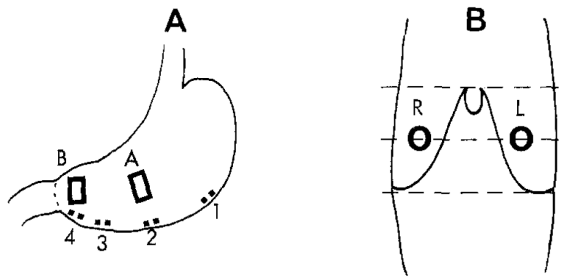

Fig. 5. Positions of serosal and cutaneous electrodes and force transducers. (A) Bipolar serosal electrodes 1, 2, 3, and 4 placed along the greater curvature at 12, 7, 4, and 2 cm from the pylorus respectively. Force transducers A and B opposite electrodes 2 and 4. (B) Abdominal surface electrodes R and L were placed 8 cm apart on a transverse line midway between the lower end of the body of the sternum and the lowest point of the costal arch. [24]

The finding that the gastric frequency can be derived from the skin in the absence of phasic contractile activity is in accordance with the results of Brown et al [31], who concluded from their experiments in man that in EGG the basic electrical rhythm (ie, ECA) of the stomach is measured. However, this study shows that not only ECA, but also ERA is reflected in the electrogastrogram. [24]

F. SFEMG (Single-fiber Electromyography)

Single-fiber electromyography (SFEMG) is a selective recording technique in which a needle electrode with a small recording surface in the side is used to identify action potentials from individual muscle fibers. The SFEMG parameters of greatest clinical use are fiber density (FD) and neuromuscular jitter. FD reflects the local organization of muscle fibers within the motor unit; jitter reflects the safety factor of neuromuscular transmission

at individual neuromuscular junctions. SFEMG can be of great value in demonstrating or excluding abnormalities in mild or questionable disease of nerve, muscle, or the neuromuscular junction. The neuromuscular jitter may be measured during nerve stimulation, which is particularly useful in uncooperative patients or when it is desirable to control the firing rate precisely, or during voluntary muscle activation, which is less subject to technical artifact. The SFEMG findings may not be specific to a particular diseases, but they frequently increase understanding of the disease process by demonstrating abnormal neuromuscular transmission or rearrangement of muscle fibers within the motor unit, which complements information from more conventional EMG examinations. [23]

G. MUAP (Motor unit action potential)

A model of the motor unit action potential was developed to investigate the amplitude and frequency spectrum contributions of motor units, located at various depths within muscle, to the surface detected electromyographic (EMG) signal. A dipole representation of the transmembrane current in a three-dimensional muscle volume was used to estimate detected individual muscle fiber action potentials. [21]

H. SEMG (Surface EMG)

THE SURFACE ELECTROMYOGRAM (EMG) comprises the sum of the electrical contributions made by the active motor units (MUs) as detected by electrodes placed on the skin overlying the muscle. The information extracted from the surface EMG is often considered a global measure of MU activity, because of the inability of the traditional (2 electrode) recording configuration to detect activity at the level of single MUs. The global characteristics of the surface EMG, such as its amplitude and power spectrum, depend on the membrane properties of the muscle fibers as well as on the timing of the MU action potentials. Thus the surface EMG reflects both peripheral and central properties of the neuromuscular system. Two approaches are available to study the relations between the surface EMG and the properties of the neuromuscular system: one forward and the other inverse. The forward approach, such as can be accomplished with modeling, allows us to predict the effect of various physiological processes on features of the surface EMG. The inverse approach uses the EMG to identify the underlying physiology. The inverse approach, however, requires simplifications to reduce the number of parameters and multiple solutions that influence the association. [22]

I. PCG (Phonocardiography)

A phonocardiogram is a recording of the heart sounds and murmurs (Vermarien, 2006). It eliminates the subjective interpretation of these sounds and also makes possible an evaluation of the heart sounds and murmurs with respect to the electric and mechanical events in the cardiac cycle. In the clinical evaluation of a patient, a number of other heart-related variables may be recorded simultaneously with the phonocardiogram. These include the ECG, carotid arterial pulse, jugular venous pulse, and apexcardiogram. The indirect carotid, jugular, and apexcardiogram pulses are recorded by using a micro-phone system with a frequency response from 0.1 to 100 Hz. The cardiologist evaluates the results of a phonocardiograph on the basis of changes in wave-shape and in a number of timing parameters. [2]

These types of acoustic signals record the sounds that are produced by the heart's beat and the blood flow (murmurs) between the heart valves [14]. PCGs have the same origins as ECGs, and they have been used to study abnormalities on heart sound for the detection of heart defects (e.g., cardiomyopathy) [15], as well as for biometric identification [16].

J. ECoG (Electrocorticography)

Electroencephalography (EEG) is used to non-invasively monitor electric potentials of the brain through scalp electrodes. It collects signals from the entire brain, but the sensitivity can be low due to interference from the dura, skull, and scalp. When the electrode leads are placed directly over surgically-exposed cortical surface, this monitoring technique is called electrocorticography (ECoG). This technique was pioneered by Penfield and Jasper at the Montreal Neurological Institute in the early 1950s with the aim to more precisely identify seizure foci and facilitate epilepsy surgery (Penfield and Jasper, 1954). The monitoring can be performed in the operating room for a relatively short duration at the time of surgery; intraoperative ECoG (acute), or can be performed outside the operating room (after surgical electrode implantation) for a longer time (chronic) to capture abnormal electric signals from the brain. ECoG monitoring was found in a survey in 1992 to be used by over 80% of epilepsy surgeons around the world (Engel, 1993). [2]

These types of signals can directly capture the extracellular currents that are produced by the electrical activity of the brain cells within the cerebral cortex [17]. ECoG signals have been widely used to localize epileptic zones before epileptic surgery with very high precision [18] and for the localization of activated brain regions using motor- or somatosensoryevoked potentials through a procedure that is known as electrical cortical stimulation [19]. ECoG signals yield high temporal resolutions, and their invasive nature, however, involves surgical operation procedures, a fact that makes it difficult to obtain with the exception of heavy medical conditions.

III. Bioimpedance signals

The impedance of the tissue contains important information concerning its composition, blood volume, blood distribution, endocrine activity, automatic nervous system

activity, and more. The bioimpedance signal is usually generated by injecting into the tissue under test sinusoidal currents (frequency range of 50 kHz–1 MHz, with low current densities of the order of 20–20 mA). The frequency range is chosen to minimize electrode polarization problems, and the low current densities are chosen to avoid tissue damage mainly due to heating effects. Bioimpedance measurements are usually performed with four electrodes. Two source electrodes are connected to a current source and are used to inject the current into the tissue. The two measurement electrodes are placed on the tissue under investigation and are used to measure the voltage drop generated by the current and the tissue impedance. [1]

A. Electrodermal measurement

The electrodermal response (EDR) is a phenomenon which is very connected with sweat gland response nowadays [37]. Two main EDR measurements have traditionally involved resistance or conductance [38] (exosomatic) and voltage detection [39] (endosomatic). These measurements can also be tonic (depth-L) or phasic (variable response-R). Table I shows the abbreviations used for types of measurement.

TABLE I
Abbreviations used to distinguish the type of electrodermal measurement [36]

Abbreviation	Significance
EDA	Electrodermal Activity
EDL	Electrodermal level
EDR	Electrodermal response
SCL	Skin conductance level
SCR	Skin conductance response
SRL	Skin resistance level
SRR	Skin resistance response
SPL	Skin potential level

Measurement is usually done with electrodes on the palm; when an electrode is reversible, polarisation and slanted potentials become minimised. The recorded signals are characterised because they present slow recovery around 40s, phase amplitude for conductivity around 2 S, and 10-20 mV potency (depending on the electrode area [40].

Fowles (1974) developed a global EDR model (Fig. 6) which is a useful qualitatively. The top of the model represents the skin surface and the bottom the interface between hypodermis and dermis. R1 and R2 represent, respectively, resistance to current flow in epidermis and dermis, E1 and R4 represent access to the dermis and E2 and R3 access to the epidermis. Transduction potentials E1 and E2 emerge as a result of the inequality of ion concentration through the ducts. R5 is surface resistance and E3 is the potential.

The skin's potential is located between the external surface of skin and the internal body' s environment which can be considered as skin potential response (SPR) to a stimulus or skin potential level (SPL). SPR can

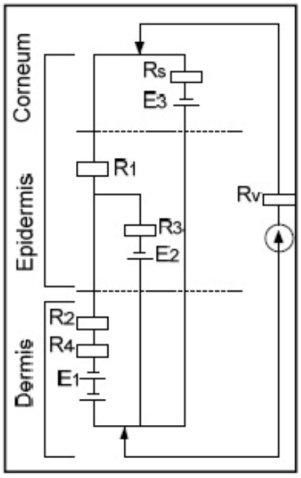

Fig. 6. A simplified equivalent circuit describing the electrodermal sys-tem. Components are identified in the text [37]

be monophasic, biphasic or occasionally triphasic and is mainly attributed to sweat gland activity [41]. SPL is usually negative on the surface [42] and involves more epidermal mechanisms than SPR. Edelberg has suggested that skin electrical measurements can reflect sweat gland activity level, the local blood vessels' state and the state of one or more living cell layers. [36]

B. GSR (Galvanic Skin Response,)

Galvanic Skin Response, (GSR), is a measure of conductivity of human skin, and can provide an indication of changes in human sympathetic nervous system (SNS). Research and empirical data have long linked GSR variation to stress and SNS arousal [47]. As a person becomes more or less stressed, the GSR increases or decreases respectively. Early work that investigated possibility of using GSR as a function of stress and cognitive activity can be found in [46]. More recent research has also linked GSR readings to cognitive activity [44] and established credible correlation between stress and cognitive functions [45]. All these works provides us with a theoretical basis for the use of GSR to measure cognitive load and its variations. [43] , Fig.7 shows a GSR data set for one multimodal task. We observe a combination of several large peaks (there are four in Figure 5) and several small peaks. GSR peaks usually indicate user frustration or stressful events. Despite the peaks, the GSR values decrease over time. After cross-examining this GSR data set with video recording of the subject performing the task and with multimodal annotation results, we can make some observations.

IV. Bioacoustic signals

Many biomedical phenomena create acoustic noise. The measurement of this acoustic noise provides information about the underlying phenomenon. The flow of blood in the heart, through the heart's valves, or through

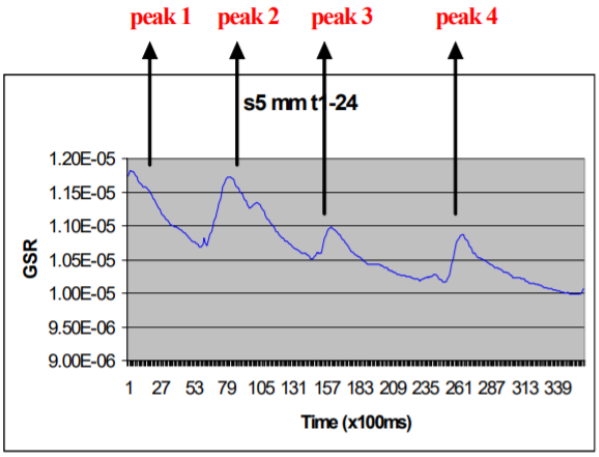

Fig. 7. Typical GSR for a task [43]

blood vessels generates typical acoustic noise. The flow of air through the upper and lower airways and in the lungs creates acoustic sounds. These sounds, known as coughs, snores, and chest and lung sounds, are used extensively in medicine. Sounds are also generated in the digestive tract and in the joints. It also has been observed that the contracting muscle produces an acoustic noise (muscle noise). Since the acoustic energy propagates through the biologic medium, the bioacoustic signal may be conveniently acquired on the surface, using acoustic transducers (microphones or accelerometers). [1]

V. Biomagnetic signals

Various organs, such as the brain, heart, and lungs, produce extremely weak magnetic fields. The measurements of these fields provides information not included in other biosignals (such as bioelectric signals). Due to the lowlevel of the magnetic fields to be measured, biomagnetic signals are usually of very low signal-to-noise ratio. Extreme caution must be taken in designing the acquisition system of these signals. [1]

A. MEG (magnetoencephalography)

MEG signals: these types of signals are produced by the magnetic fields that are generated by the electrical activity of the brain cells. The electrical activity that is generated by the neuronal triggering produces an extremely weak magnetic field (as a result of intracellular current flow) that can be only recorded by powerful magnetometers, known as superconducting quantum interference devices (SQUIDs) [5] SQUIDs are usually placed in liquid helium and are able to capture the extremely small alterations in the brain's magnetic field (10^{-15} T), when the Earth's magnetic field varies between 10^{-4} and 10^{-5} T [6]. For this reason, the MEG examination is performed inside magnetically shielded rooms to shield out the inference of outside magnetic fields [5]. The main advantage of MEG against EEG is that the former is not affected by the electrical field's distortion during its propagation through the skull, scalp, and cerebrospinal fluid. Thus, the MEG yields both higher spatial and temporal resolution [5]. However, the MEG equipment is very expensive due to its superconducting technology and is often subject to high noise levels. MEG has been used for the examination of neocortical epilepsy regions due to its high spatial resolution [7], amnesia [8], etc. [3]

B. MCG (magnetocardiography)

Magnetocardiography is a noninvasive contactless method to measure the magnetic field generated by the same ionic currents that create the electrocardiogram. The time course of magnetocardiographic and electrocardiographic signals are similar. However, compared with surface potential recordings, multichannel magnetocardiographic mapping (MMCG) is a faster and contactless method for 3D imaging and localization of cardiac electrophysiologic phenomena with higher spatial and temporal resolution. For more than a decade, MMCG has been mostly confined to magnetically shielded rooms and considered to be at most an interesting matter for research activity. [34] New developments in instrumentation, in clinical application, as well as in data analysis and

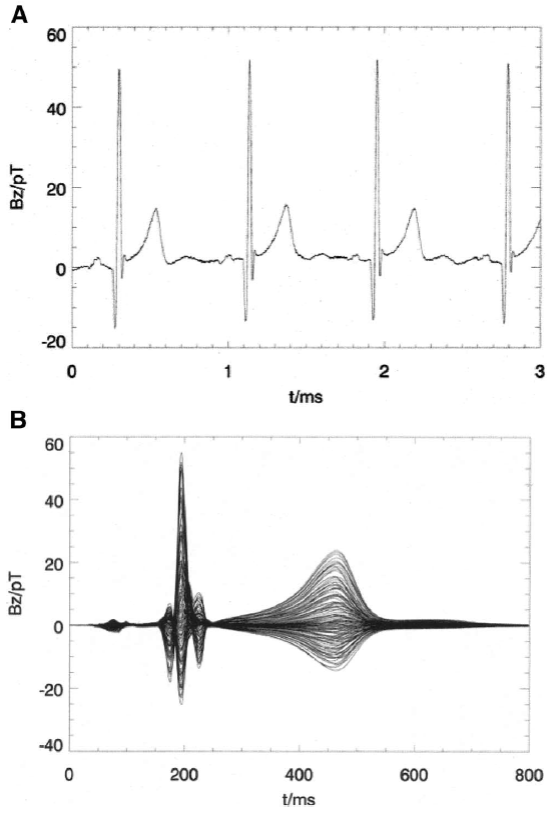

Fig. 8. (A) High-quality unavaraged MCG-signal of a single channel (Bz-component), (B) "Butterfly"-plot of MCGsignals from 199 positions in a hexagonal grid with 3 cm sensor-to-sensor distance app. 4 cm over the torso. [35]

visualization have provided new momentum to magnetocardiography (MCG). On one hand robust, easy to use and budget-priced MCG-systems entered the market and are applied to a multi-centred clinical study. On the other hand highly sophisticated vectormagnetometer systems with >300 SQUID sensors are opening new perspectives in electrocardiology research. Several parameters have recently been introduced to evaluate MCG-signals in order to support diagnosis, therapy follow-up and risk stratification. Particularly interesting is the renaissance of the Hosaka-Cohen-transformation which allows to visualize so-called pseudo current density (PCD) maps. [35]

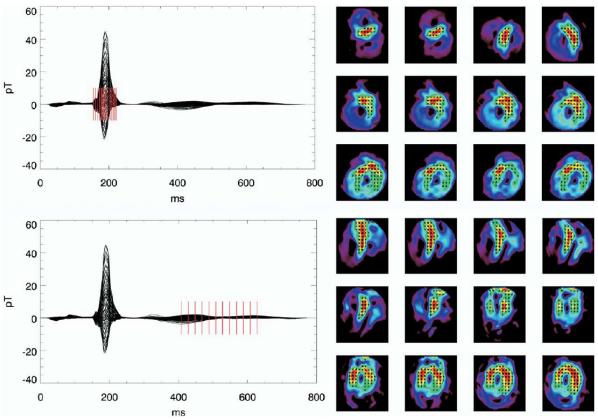

Fig. 9. Sequences of pseudo current density maps: top left: MCG with cursors during QRS marking the time instants of the frames shown in the three top rows on the right side; bottom left: MCG with cursors during T- and U-wave marking the time instants of the frames shown in the three bottom rows on the right side. [35]

VI. Biomechanical signals

The term biomechanical signals includes all signals used in the biomedicine fields that originate from some mechanical function of the biologic system. These signals include motion and displacement signals, pressure and tension and flow signals, and others. The measurement of biomechanical signals requires a variety of transducers, not always simple and inexpensive. The mechanical phenomenon does not propagate, as do the electric, magnetic, and acoustic fields. The measurement therefore usually has to be performed at the exact site. This very often complicates the measurement and forces it to be an invasive one. [1]

VII. Biochemical signals

Biochemical signals are the result of chemical measurements from the living tissue or from samples analyzed in the clinical laboratory. Measuring the concentration of various ions inside and in the vicinity of a cell by means of specific ion electrodes is an example of such a signal. Partial pressures of oxygen (pO2) and carbon dioxide (pCO2) in the blood or respiratory systemare other examples. Biochemical signals are most often very low frequency signals. Most biochemical signals are actually dc signals. [1]

VIII. Biooptical signals

Biooptical signals are the result of optical functions of the biologic system, occurring naturally or induced by the measurement. Blood oxygenation may be estimated by measuring the transmitted and backscattered light from a tissue (in vivo and in vitro) in several wavelengths. Important information about the fetus may be acquired by measuring fluorescence characteristics of the amniotic fluid. Estimation of the heart output may be performed by the dye dilution method, which requires the monitoring of the appearance of recirculated dye in the bloodstream. The development of fiberoptic technology has opened vast applications of biooptical signals. [1]

IX. Conclusion

In this article, different types of biomedical signals introduced. To conclude, frequency and dynamic range of some signals are illustrated in the Fig.10 To access the code and change the parameters and add some, you can visit: Google Colab or Github.

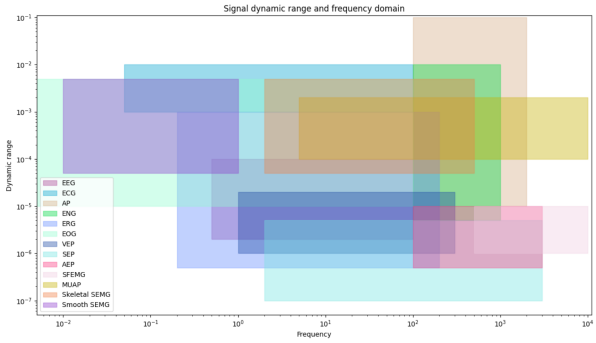

Fig. 10. Illustration of some biomedical signals as their frequency and dynamic range.

References

[1] Bronzino, Joseph D. Biomedical Engineering Handbook 2. Vol. 2. Springer Science & Business Media, 2000.

[2] Webster, John G., ed. Medical instrumentation: application and design. John Wiley & Sons, 2009.

[3] Pezoulas, Vasileios, Themis Exarchos, and Dimitrios I. Fotiadis. Medical Data Sharing, Harmonization and Analytics. Academic Press, 2020. Chapter 2

[4] Sinkjær, Thomas, et al. "Electroneurography." Encyclopedia of Medical Devices and Instrumentation (2006).

[5] Hari R, Salmelin R. Magnetoencephalography: from SQUIDs to neuroscience: neuroimage 20th anniversary special edition. Neuroimage 2012;61(2):386e96.

[6] Proudfoot M, Woolrich MW, Nobre AC, Turner MR. Magnetoencephalography. Pract Neurol 2014;14(5):336e43.

[7] Proudfoot M, Woolrich MW, Nobre AC, Turner MR. Magnetoencephalography. Pract Neurol 2014;14(5):336e43.

[8] Kharkar S, Knowlton R. Magnetoencephalography in the presurgical evaluation of epilepsy. Epilepsy Behav 2015;46:19e26.

[9] Usakli AB, Gurkan S, Aloise F, Vecchiato G, Babiloni F. On the use of electrooculogram for efficient human computer interfaces. Comput Intell Neurosci 2010;2010:1

[10] Hsu WY, Lin CH, Hsu HJ, Chen PH, Chen IR. Wavelet-based envelope features with automatic EOG artifact removal: application to single-trial EEG data. Expert Syst Appl 2012;39(3):2743e9

[11] Deng LY, Hsu CL, Lin TC, Tuan JS, Chang SM. EOG-based Human-Computer Interface system development. Expert Syst Appl 2010;37(4):3337e43.

[12] Szirmai A, Keller B. Electronystagmographic analysis of caloric test parameters in vestibular disorders. Eur Arch Oto-Rhino-Laryngol 2013;270(1):87e91.

[13] Kim, Myoung Ro, and Gilwon Yoon. "Control signal from EOG analysis and its application." World Academy of Science, Engineering and Technology, International Journal of Electrical, Electronic Science and Engineering 7.10 (2013): 830-834.

[14] Emmanuel BS. A review of signal processing techniques for heart sound analysis in clinical diagnosis. J Med Eng Technol 2012;36(6):303e7.

[15] Konishi E, Kawasaki T, Shiraishi H, Yamano M, Kamitani T. Additional heart sounds during early diastole in a patient with hypertrophic cardiomyopathy and atrioventricular block. J Cardiol Cases 2015;11(6):171e4.

[16] Kumar SBB, Jagannath M. Analysis of phonocardiogram signal for biometric identification system. In: Proceedings of the 2015 IEEE International Conference on Pervasive Computing (ICPC); 2015. p. 1e4.

[17] Hill NJ, Gupta D, Brunner P, Gunduz A, Adamo MA, Ritaccio A, et al. Recording human electrocorticographic (ECoG) signals for neuroscientific research and real-time functional cortical mapping. J Vis Exp 2012;64.

[18] Tripathi M, Garg A, Gaikwad S, Bal CS, Chitra S, Prasad K, et al. Intra-operative electrocorticography in lesional epilepsy. Epilepsy Res 2010;89(1):133e41.

[19] Picht T, Schmidt S, Brandt S, Frey D, Hannula H, Neuvonen T, et al. Preoperative functional mapping for rolandic brain tumor surgery: comparison of navigated transcranial magnetic stimulation to direct cortical stimulation. Neurosurgery 2011;69(3):581e9.

[20] Aunon, Jorge I., Clare D. McGillem, and Donald G. Childers. "Signal processing in evoked potential research: averaging and modeling." Critical reviews in bioengineering 5.4 (1981): 323-367.

[21] Fuglevand, Andrew J., et al. "Detection of motor unit action potentials with surface electrodes: influence of electrode size and spacing." Biological cybernetics 67.2 (1992): 143-153.

[22] Farina, Dario, Roberto Merletti, and Roger M. Enoka. "The extraction of neural strategies from the surface EMG." Journal of applied physiology 96.4 (2004): 1486-1495.

[23] Sanders, Donald B., and Erik V. Stålberg. "AAEM minimonograph # 25: Single-fiber electromyography." Muscle & Nerve: Official Journal of the American Association of Electrodiagnostic Medicine 19.9 (1996): 1069-1083.

[24] Smout, A. J. P. M., E. J. Van der Schee, and J. L. Grashuis. "What is measured in electrogastrography?." Digestive diseases and sciences 25.3 (1980): 179-187.

[25] Alvarez WC: The electrogastrogram and what it shows. J Am Med Assoc 78:1116-1119, 1922

[26] Davis RC, Garafolo L, Gault FP: An exploration of abdominal potentials. J Comp Physiol Psychol 52:519-523, 1957

[27] Nelsen TS, Kohatsu S: Clinical electrogastrography and its relation to gastric surgery. Am J Surg 116:215-221, 1968

[28] Martin A, Moline J. Thouvenot J: Potentiels 61ectriques drrivrs la surface de l'abdomen en relation avec l'activit6 antropylorique chez l'animal et chez l'homme. CR Soc Biol (Paris) 163:1423-1425, 1969

[29] Drieux C, Garnier D, Martin A, Moline J: Corrrlation entre l'activit6 61ectrique de l'antre gastrique et l'61ectrogastroentrrogramme du Cobaye. J Physiol (Paris) 73:A20, 1977

[30] Tonkovic S, Thouvenot J, Penaud J: Electrosplanchnographical exploration of the digestive tract diseases. Digest l lth International Conference on Medical and Biological Engineering, Ottawa, 1976

[31] Brown BH, Smallwood RH, Duthie HL, Stoddard CJ: Intestinal smooth muscle electrical potentials recorded from surface electrodes. Med Biol Eng 13:97-103, 1975

[32] Smallwood RH: Gastrointestinal electrical activity from surface electrodes. Thesis, Sheffield, 1976

[33] Thouvenot J, Penaud J, Morelle O: Sur les phrnom nes 6-lectrophysiologiques des viscrres: leur traduction la surface cutan e. J Physiol (Paris) 65:A170-171, 1972

[34] Fenici, Riccardo, Donatella Brisinda, and Anna Maria Meloni. "Clinical application of magnetocardiography." Expert review of molecular diagnostics 5.3 (2005): 291-313.

[35] Koch, Hans. "Recent advances in magnetocardiography." Journal of electrocardiology 37 (2004): 117-122.

[36] Moncada, María Elena, and Jorge de la Cruz. "Electrodermal activity-a review." Ingeniería e Investigación 31.2 (2011): 143-151.

[37] Fowles, D.C., The ecrine system and electrodermal activity in Psychophysiology., ed. MGH Coles, E Donchin, SW Porges. Guilford Press, New York, 1986, pp. 51-96.

[38] Féré, C., Note sur les modifications de la resistance electrique sous l'influence des excitations sensorielles et des emotions., C.R. Soc. Biol., 5, 1888, pp. 217-9.

[39] Tarchanoff, J. "Décharges électriques dans la peau de l'homme sous l'influence de l'excitation des organes des sens et de différentes formes d'activité psychique." Comptes Rendus des Séances de la Société de Biologie (Paris) 41 (1889): 447-451.

[40] Venables, P.H., Christie, M.J., Techniques in Psychophysiology., Ed. I Martin, 1980, pp. 3-67.

[41] Fowles, D.C., Mechanisms of electrodermal activity: Methods in Physiological Psychology., Bioelectric Recording Techniques, Vol. 1, Ed. RF Thompson, MM Patterson. Academic Press, New York, 1974, pp. 231-71.

[42] Christie, M., Electrodermal activity in the 1980's- A review., J Royal Soc Med., 74, 1981, pp. 616-622.

[43] Shi, Yu, et al. "Galvanic skin response (GSR) as an index of cognitive load." CHI'07 extended abstracts on Human factors in computing systems. 2007.

[44] Boucsein, W. (1992). Electrodermal Activity. New York: Plenum Press.

[45] McEwen, B.S, Sapolsky, R.M. Stress and cognitive function. Journal of Current Opinion in Neurobiology, 1995.

[46] Miller, L.H, Shmavonian B.M. Replicability of two GSR indices as a function of stress and cognitive activity. Journal of Personality and Social Psychology. 1965 Nov;2(5):753-6.

[47] Seyle, H. (1956). The stress of life. New York: McGraw-Hill.