Review of Various Biomedical Signals

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1 Introduction

The present document is mainly based on [Ran02, Chapter 1] and [SL05]. Other references that you might find useful include [NS06], [EBB05],\(^1\) [Bau02].

Our presentation gives only a small selection of biomedical signals with the aim to have a first understanding of what to analyze and to process with discrete-time signal processing methods. The reference [Ran02] is much more comprehensive and additionally introduces action potentials, the electroneurogram, the electromyogram, event-related potentials, the electrogastrogram, the vibromyogram, the vibroarthrogram, and otoacoustic emission signals. The reference [SL05] is likewise much more detailed than our excerpt in its concentration on cardiac and neurological applications.

Databases of various biomedical signals are important for the development as well as for the test of signal processing algorithms. [SL05, pp. 17 ff.] discuss some of them: The MIT-BIH database contains ECG signals; another ECG database is the AHA (American Health Association) database; still another ECG database is the European ST-T and LTST database. Multimodal databases include signals that reflect activities from brain, heart, muscles, blood pressure, respiration, and others together; here there is the MIMIC, the IMPROVE, and the IBIS database. Most databases are publicly available, either at no cost or at a charge, but some remain the private property of those having collected the data. The PhysioNet (www.physionet.org) is a website where various types of biomedical signals are freely available for download.

\(^1\)We note that there is, in the meantime, a newer version of the book, [EB12].
2 Electrocardiogram (ECG) Signals

The Electrocardiogram (ECG)

- ECG: electrical manifestation of heart activity recorded from the body surface
- monitoring of heart rate

The ECG signal can be recorded fairly easily with surface electrodes placed on the limbs and/or the chest, see pages 6–17 below.

We note in passing that ECG signals might also be captured from inside of the esophagus by using electrodes mounted on special catheters. As an active project of a team in our lab—HUCE-microLab, in cooperation with teams at the Bern University Hospital and at the University of Bern ARTORG Center—reveals, such a special signal capturing approach has advantages over surface capturing in that, first, the recordable time might be much longer due to the avoidance of skin irritations, and, second, the obtained signal qualities are better due to the closer proximity of the recording electrodes to the heart, [HNM+12], also see the signal traces on page 18.
We have obtained the data in the above figure from files accompanying [Ran02]; we have applied some post-processing to the obtained raw data. The signal values are not calibrated, but are arbitrarily normalized.

The following waves and time intervals describe some important characteristics of the ECG signal; see, for example, [SL05, pp. 426 ff.]:

**RR-interval.** The RR-interval, measured between two successive R waves, represents the length of a complete cardiac
cycle. It is the fundamental rhythm quantity and is used to characterize different arrhythmias (see below on pages 19–23), as well as to study the variability of the heart rate.

**QRS-complex.** The QRS-complex reflects the contraction of the right and left ventricles. In a normal heart, the QRS-complex lasts for about 70–110 msec and is a sharp bi- or tri-phasic wave. The first negative deflection of the QRS-complex is the Q-wave, and the first positive is the R-wave, while the negative deflection subsequent to the R-wave is the S-wave. Although the QRS-complex might have less than three individual waves, it is nevertheless called QRS-complex. The morphology of the QRS-complex is highly variable and depends on the origin of the heart beat: the duration of the QRS-complex may extend up to 250 msec in an abnormally working heart, and it is sometimes composed of more than three waves.

The QRS-complex has an amplitude sometimes reaching 2–3 mV; it is the largest amplitude of the ECG signal.

Due to the steep slopes, the QRS-complex contains frequencies that are considerably higher than frequencies from other ECG waves. Its frequencies are mostly concentrated in the interval 10–50 Hz.

**P-wave.** The P-wave reflects the sequential contraction of the left and the right atria. Mostly, the P-wave has positive polarity and a smooth monophasic morphology. Its amplitude normally stays below 300 µV, and its duration is less than 120 msec.

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2 Each cardiac cycle is composed of two phases, activation and recovery, which are referred to in mechanical terms as contraction and relaxation, and in electrical terms as de-polarization and re-polarization.

3 Our present statements concern surface ECG signals. We remark that ECG signals captured in the esophagus near the heart show a much more pronounced P-wave.
The spectral characteristic of a normal P-wave is usually considered to be low-frequency, below 10–15 Hz, but certain advanced signal processing techniques\textsuperscript{4} that produce very noise-reduced ECG signals have revealed, that much higher frequency components might exist in a P-wave, especially in some abnormal working-conditions of a heart. Often it is hard to determine the time instants that define the onset and the end of a P-wave because of its low amplitude and smoothness. Consequently, the analysis of individual P-waves is not done in ECG signals having considerable noise.

**T-wave.** The T-wave reflects ventricular relaxation and extends about 300 msec after the QRS-complex. The position of the T-wave strongly depends on the heart rate; it becomes narrower and closer to the QRS-complex at high rates.

The T-wave is smooth and has an amplitude in the range of 100–300 µV. Its frequency content is similar to that of the P-wave, with an even stronger low-frequency content.

**Pq-Interval.** The Pq-interval is the time interval from the onset of atrial activation to the onset of ventricular activation. The length of the Pq-interval is only weakly dependent on the heart rate.

**QT-Interval.** The QT-interval is the time interval from the onset of the ventricular activation to the completion of ventricular recovery. This interval is normally dependent on the heart rate; it becomes shorter at more rapid rates.

\textsuperscript{4}Such signal processing techniques are often based on ensemble averaging, see our document [Goe18a].
ECG-Acquisition: Standard 12-Lead System

- 10 electrodes at standardized positions
  - 4 limb electrodes
  - 6 chest electrodes
- combination of 3 different lead configurations
  - bipolar limb leads: $I$, $II$, $III$
  - augmented unipolar limb leads: $aVR$, $aVL$, $aVF$
  - unipolar pre-cordial (chest)leads: $V_1$, $V_2$, ..., $V_6$

- note: a number of lead systems exist today
  ~ standard 12-lead system is the best known

Together with the presently discussed 12-lead system, the orthogonal lead system producing a vector-cardiogram (VCR) are the two that have received the most attention; see, for example [SL05, Section 6.2].
ECG-Acquisition: Limb Electrodes

- 4 limb electrodes
- 1 reference electrode, three signal electrodes

With the limb electrodes on the right arm, the left arm, and the left leg one measures the so-called limb-lead signals, see pages 10 and 11 below. The electrode on the right leg serves as reference electrode.
ECG-Acquisition: Chest Electrodes

We have copied the above figure from [Ran02, p. 24].

With the chest electrodes $V_1$, $V_2$, $\ldots$, $V_6$ one measures the precordial-lead signals, see page 13 below.


**ECG-Acquisition: Leads**

**lead:** difference voltage between a pair of electrodes

**unipolar lead:** voltage variation of a single electrode
  - measured in relation to a reference electrode
  - reference electrode positioned such that the voltage remains almost constant during cardiac cycle
  - reference commonly called “central terminal”

**bipolar lead:** voltage difference between two electrodes
  - example: difference between left and right arm

Today, there exist various lead systems using standardized electrode positions. The standard lead system presently discussed is just the maybe best-known; as already mentioned, the orthogonal lead system producing a *vector-cardiogram* (VCR) is also quite common.

We note that it is often possible to synthesize one lead system from another. In practice, the preferred lead system is usually selected based on clinical issues and practical considerations; to maximize the information content is not necessarily the basis for the selection of a specific lead-system.
ECG-Acquisition: Bipolar Limb Leads

\[ I = V_{LA} - V_{RA} \]
\[ II = V_{LL} - V_{RA} \]
\[ III = V_{LL} - V_{LA} \]

- LA $\triangleq$ left arm
- RA $\triangleq$ right arm
- LL $\triangleq$ left leg

The three electrodes at the right arm, the left arm, and the left leg can be viewed as the corners of an equiangular triangle, see below the “Einthoven’s triangle” on page 12, with the heart at its center. With the heart at the center, the limb leads \( I \), \( II \), and \( III \) describe the cardiac electrical activity in three different directions of the frontal plane. Each of these directions is separated by an angle of 60 degrees.

Note that it is not necessary to measure all of the three limb leads, because we have, for example,

\[
III = II - I = (V_{LL} - V_{RA}) - (V_{LA} - V_{RA}) = V_{LL} - V_{LA}.
\]
ECG-Acquisition: Augmented Limb Leads

\[ aVR \triangleq V_{RA} - \frac{V_{LA} + V_{LL}}{2} \]
\[ aVL \triangleq V_{LA} - \frac{V_{RA} + V_{LL}}{2} \]
\[ aVF \triangleq V_{LL} - \frac{V_{LA} + V_{RA}}{2} \]

\( \sim \) to fill the 60 degree gaps in the directions of the bipolar limb leads

The augmented unipolar limb leads use the same electrodes as the bipolar limb leads lead I, lead II, and lead III. They are defined as voltage differences between one corner of the triangle and the average of the two remaining corners. The augmented limb leads are considered to be unipolar, because one electrode is exploring while the other two serve as reference.

The augmented limb leads describe directions that are shifted by 30° from those of the bipolar limb leads:

<table>
<thead>
<tr>
<th>gap between</th>
<th>directions</th>
<th>filled by</th>
</tr>
</thead>
<tbody>
<tr>
<td>lead I and lead II</td>
<td>( \sim )</td>
<td>( aVR )</td>
</tr>
<tr>
<td>lead II and lead III</td>
<td>( \triangledown )</td>
<td>( aVF )</td>
</tr>
<tr>
<td>lead III and lead I</td>
<td>( \triangledown )</td>
<td>( aVL )</td>
</tr>
</tbody>
</table>
We finally note that the augmented limb leads need not to be recorded but, instead, they may be computed from the leads lead I and lead II.

**ECG-Signal Acquisition: Einthoven’s Triangle**

- Einthoven’s triangle
- shows
- axis of six ECG-leads
- formed by using
- four limb electrodes

![Einthoven’s Triangle Diagram]
Precordial Leads

- chest electrodes: electrodes positioned in succession on the front and the left side of the chest
- provide a more detailed view of the heart activity than the limb leads can do
- six leads $V_1, V_2, \ldots, V_6$
- are unipolar leads and related to the central terminal
  \[ V_{\text{WCT}} = \frac{V_{\text{LA}} + V_{\text{RA}} + V_{\text{LL}}}{3} \]

- Wilson’s central terminal is the average of the voltages measured on the right arm, the left arm, and the left leg

Referring to the figure on page 8 giving the positions of the chest electrodes, and referring to an image of the heart, such as in [SL05, Figure 6.1, page 413] or in [Ran02, Figure 1.11, page 18], one may state that

- $V_1$ and $V_2$ primarily reflect the activity of the right ventricle,
- $V_3$ and $V_4$ primarily view the front of the left ventricle,
- and $V_5$ and $V_6$ primarily view the side (lateral wall) of the left ventricle.
Concerning ECG-signal acquisition, we may state the following generalities:

- The six limb leads lead I, lead II, and lead III; and lead aVR, lead aVL, and lead aVF give waveforms with relatively low amplitudes which are more noisy than the waveforms of the precordial leads V₁, V₂, …, V₆. This is because the electrodes at the extremities have a much larger distance from the heart than the chest electrodes have. So the signal-to-noise ratio of limb leads is normally lower than that of the precordial leads.

- The recording equipment must use differential amplifiers with high gain and large dynamic range. Although individual ECG-waveforms have a maximum of only a few millivolts (but might be as small as a few microvolts), a wandering baseline due to variations in the electrode-skin impedance may reach up to 1 V. The amplifier bandwidth must extend from 0.05 Hz to 100–500 Hz, where the upper limit depends on the application. Obviously, safety is important: everything on the side of the patient is battery powered.

- ECG signals are normally filtered to the bandwidth from 0.05 Hz to 100 Hz. The recommended sampling rate then is 500 Hz for diagnostic purposes. High-resolution ECG-signal acquisition uses a band of 0.05 Hz–500 Hz; obviously, the sampling rate must then be at least 1 kHz.⁵ ECG-signal acquisition for heart-rate monitoring only might use a reduced bandwidth of 0.05 Hz–50 Hz with a correspondingly lower sampling rate.

- Captured ECG signals are contaminated by the following perturbations and artifacts:

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⁵This 1 kHz sampling rate is in the present situation just the limit given by Shannon’s sampling theorem, see our document [Goe18b]; in practice, one should have some margin.
- Electrical power-line perturbations are narrow-band at 16.6 Hz, at 50 Hz, and at 60 Hz, depending on the situation and location; the bandwidth is about ±2 Hz. They are continuous in time, that is, they persist.

- The already mentioned baseline wander is likewise narrow-band and below approximately 0.5 Hz. This artifact might be transient but also continuous in time.

- There is muscle noise, which is approximately white (broad-band); it is transient.

- Electrical interferences additional to power-line interferences are above approximately 100 Hz and narrow-band; these interferences might be transient but also continuous.

- Electrode pop artifacts are narrow-band (1 to 10 Hz) and transient (0.1 to 1 sec). They result from an instantaneous change of the DC contact potential at the interface between electrode and skin, which in turn leads, if the used amplifiers are AC-coupled, to a sudden change of the measured amplitude with a subsequent exponential decay.

- Measurement noise is a perturbation always present; it is broadband and continuous in time and can be white as well as colored (for example, it might have a 1/f-like spectrum).

- Finally we have, in the case of digital signal processing, the quantization noise of the analog-to-digital conversion process; it is usually (assumed) to be white and Gaussian and it persists.
We have copied the above figure from [Ran02, p. 26]; there, the author writes “Courtesy of E. Gedamu and L. B. Mitchell, Foothills Hospital, Calgary.”

Whereas the upper panel shows the six limb leads, the lower panel shows the six precordial (chest) leads. The used acquisition system records three channels at the time: The three bipolar limb leads lead I, lead II, and lead III are simultaneously recorded; the augmented limb leads aVR, aVL, and aVF, are simultaneously recorded; the first three chest leads V₁, V₂, and V₃ are simultaneously recorded; and finally, the last three chest leads V₄, V₅, and V₆ are simultaneously recorded.
Observe that the limb leads are smaller in amplitude than the chest leads. The limb leads usually come with a rectangular calibration pulse of 1 mV height and 200 msec duration; distortions in this calibration pulse may indicate improper filter settings (anti-aliasing filters) or an otherwise poor signal acquisition system.

From the six limb leads, a well-trained cardiologist is able to deduce the three-dimensional orientation of the cardiac electrical vector.

Cardiac defects may be localized by analyzing the wave-shapes of the six chest leads.
Ecg-Traces from Captures in the Esophagus

We remark that the blue (last) signal in the above picture has been recorded by an E2CORDER-prototype engineered at the microLab. The red trace of channel 1 shows a standard surface Ecg, and the green and blue traces of channels 2 and 4 represent signals captured inside of the esophagus. We note then that the P-wave is much more pronounced in the esophageal Ecgs than in the surface Ecg. This improved signal quality in the vicinity of the P-wave results because the electrodes sit inside of the esophagus and capture signals from a location as close as possible to the atrium of the heart.
ECG: **Heart Arrhythmias**

- normal heart rhythm (sinus rhythm)
  - controlled by electrical impulse formed in SA node
  - impulse propagates through the conduction system of the heart
  - 50 – 100 beats per minute

- arrhythmias: disturbances in regular heart rhythm
  - respiratory sinus arrhythmia (is normal)
  - irregular firing patterns of SA node
  - abnormal or additional pacing activity from other pacemaker cells than SA node
  - conduction of electrical pulse is altered

The SA node is a mass of pacemaker cells with the ability to spontaneously fire an electrical impulse. These cells, collectively referred to as the sinoatrial (SA) node, are situated in the upper part of the right atrium. The conduction of the initially generated electrical impulse goes through specialized muscle cells, which are connected into a network, and reaches with corresponding delays the lower regions of the heart.

Although the SA node is the natural pacemaker of the heart, under certain conditions another mass of cells than the SA node—referred to as ectopic focus—may take precedence of the SA node impulse generation. This irregularity will alter the formation of the electrical impulse. As a result, there might be premature beats—beats that occur before the expected time. The ectopic focus producing such a premature beat might be located in any...
part of the heart other than the SA node; *atrial arrhythmias*—with ectopic foci in the atria; and *ventricular arrhythmias*—with ectopic foci in the ventricles.

Arrhythmias may also be caused by problems in conducting the electrical impulse: the propagation of the impulse can be disturbed by a block along the normal conduction pathways.
ECG: **Signal Abnormalities**

- many diseases cause specific changes in the ECG-signal waveshapes
- QRS-complex widening (and/or jagging)
  - due to impulse-conduction blocking
  - due to ventricular hypertrophy
  - due to arrhythmias
- P-waves: might be masked by T-wave or even by QRS-complex of previous cycle due to arrhythmias
- ST-segment
  - normally flat and in line with PQ-segment
  - may be elevated or depressed

ST-segment depression or elevation might indicate a reduced blood-supply to a part of the heart muscle due to a block. It might also be caused by an infarct (dead myocardial tissues that are incapable to contract).
ECG: **Arrhythmic Traces due PVC**

3rd and 6th beats are premature ventricular contractions (PVC)

We have copied the above figure from [Ran02, p. 21]; there, the author writes “Data courtesy of G. Groves and J. Tyberg, Department of Physiology and Biophysics, University of Calgary.”

The first PVC has blocked the normal beat that would have arrived at about the same time instant as the PVC has arrived; the second PVC has not blocked any normal beat, but is additionally present.
**ECG: Arrhythmic Traces due RBBB**

RBBB ≡ right bundle-branch block, hypertrophy

We have copied the above figure from [Ran02, p. 22]; male patient of age 3 months.

The disease of right bundle-branch block and hypertrophy (enlarged ventricles) manifest themselves by a QRS-complex that is wider than normal and which shows an abnormal (jagged) waveform due to de-synchronized ventricular contraction.
3 Phonocardiogram (PCG) Signals

The Phonocardiogram (PCG)

- stethoscope: ear-trumpet
- PCG:
  - vibration signals
  - sound signals
  - related to contractile activity of cardiohemic system (heart & blood)
  - recording of heart-sound signal
- measurement:
  - transducer to convert vibration or sound into electrical signal
  - microphones or pressure transducers placed on chest
- diagnosis: cardiovascular diseases
The Pcg signal in top, Ecg in middle, and Cp in bottom panel

We have copied the above figure from [Ran02, p. 35]; normal adult male.

A normal cardiac cycle contains two major sounds: The first heart sound (S1) and the second heart sound (S2). The above figure shows the Pcg signal in relation to, first, the Ecg signal and, second, to the carotid pulse (Cp) signal (which we discuss below on pages 28 ff.).
Genesis of Heart Sound

We have copied the above figure from [Ran02, p. 36]; there, the author writes “Reproduced with permission from R. F. Rushmer, *Cardiovascular Dynamics*, ©W. B. Saunders, Philadelphia, PA, 1976.”

The above figure only shows the left portion of the heart which is the main source of heart sound; the corresponding events in right portion of the heart also contribute, but to a lesser extent.

**Sound S1:** The initial vibrations occur when the first contractions in the ventricles move blood; the second component in
S1 begins with abrupt closure of valves, decelerating the blood flow; the third component is caused by blood oscillations; and the fourth component is caused by blood ejection.

**Sound S2:** The second sound follows the systolic pause in a normal cardiac cycle. S2 has two components, the first caused by the closure of the aortic valve, and the second caused by the closure of the pulmonary valve.

In some cases a third sound might be heard; it stems from a sudden termination of the ventricular rapid filling phase.

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**Heart Murmurs**

- intervals between S1 and S2, and S2 and S1 of next cycle are normally silent

- murmurs occur in these intervals due to certain cardiovascular defects and diseases

- are high frequency, noise-like sounds that arise when the velocity of blood becomes high as it flows through an irregularity

- are caused by turbulence in blood flow
  - valvular stenosis
  - insufficiency
4 Carotid Pulse (Cp) Signals

The Carotid Pulse (Cp)

- pressure signal recorded over the carotid artery
  - near the surface of the body at the neck
- indicates variations in arterial blood pressure and volume with each heart beat
- closely resembles the morphology of the pressure signal at the root of the aorta
  - however, cannot be used to measure absolute pressure
- is useful together with the Pcg ~ identification of S2 and its components
**CP Signals**

P: percussion wave; T: tidal wave; D: dicrotic notch; DW: dicrotic wave

We have copied the above figure from [Ran02, p. 35]; normal adult male.
5 Signals from Catheter-Tip Sensors

Catheter-Tip Signals

for specific and close monitoring of cardiac function

• sensors placed on catheter tips are inserted into cardiac chambers

• to acquire signals such as
  – left ventricular pressure (Lv)
  – right ventricular pressure (Rv)
  – aortic pressure (Ao)
  – atrial pressures
  – intracardiac sounds

• but: an invasive procedure
Intracardiac Pressure Signals and Normal ECG

AO: aortic; LV: left ventricle; RV: right ventricle

We have copied the above figure from [Ran02, p. 41]; there, the author writes “Data courtesy of R. Sas and J. Tyberg, Department of Physiology and Biophysics, University of Calgary.”

The above figure shows a multi-channel recording of aortic (AO) pressure, left ventricular (LV) pressure, and right ventricular (RV) pressure signals from a dog using catheter-tip sensors. Observe that the LV- and the RV pressures increase exactly at the time instants of the QRS-complexes in the ECG signal. The AO pressure reaches its peak slightly after the increase in the LV pressure signal; the notch in the AO pressure signal indicates the closure of the aortic valve.
Observe that the Lv pressure is much stronger than the Rv pressure (10–100 mm of Hg for the Lv pressure as compared to 5–25 mm of Hg for the Rv pressure).

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**Intracardiac Pressure Signals and Abnormal Ecg**

Ao: aortic; Lv: left ventricle; Rv: right ventricle

We have copied the above figure from [Ran02, p. 42]; there, the author writes “Data courtesy of R. Sas and J. Tyberg, Department of Physiology and Biophysics, University of Calgary.”

The signals in the above figure show effects of premature ventricular contractions (Pvc) in Ao pressure, Lv pressure, and Rv pressure signals as well as in the corresponding Ecg signal. The Pvc appear just after 2 sec and 3 sec; they arise from different ectopic foci, as is evident from their very different waveforms.
6 Electroencephalogram (EEG) Signals

The Electroencephalogram (EEG)

- electrical activity of the brain
- cortical potentials \(\rightarrow\) generate signals due to
  - physiological control processes
  - thought processes
  - external stimuli (generate signals in corresponding parts of the brain)

- measurement:
  - on the scalp using surface electrodes (scalp EEG)
  - special EEG-recording techniques

- uses of EEG:
  - studying nervous system
  - monitoring sleep stages
  - biofeedback and control (BCI \(\triangleq\) brain-computer interface)
  - diagnoses of diseases such as epilepsy

The mentioned special EEG-recoding techniques include the use of needle electrodes; the use of naso-pharyngeal electrodes;
the recording of the electrocorticogram (ECoG) from an exposed part of the cortex; and the use of intra-cerebral electrodes.

Often, evocative techniques are used to record the EEG. These techniques include initial recording at rest (eyes open, eyes closed); hyperventilation (recording after breathing at 20 respirations per minute for 2–4 minutes); photic stimulation (with 1–50 flashes of light per second); auditory stimulation (with loud clicks); sleep (different stages); pharmaceutical and drug influence.

**EEG-Signal Measurement: Scalp-Electrode Placement**

We have copied the above figure from [Ran02, p. 29]; its author has taken it from: R. Cooper, J. W. Osselton, and J. C. Shaw. *EEG Technology*, 1980. ©Butterworth Heinemann Publishers,
a division of Reed Educational & Professional Publishing Ltd., Oxford, UK. The shown electrode placement is a recommendation of the *International Federation of Societies of Electroencephalography and Clinical Neurophysiology*.

An EEG recorded using the 10–20 system of scalp electrodes shows an average of brain activities of many small zones of the cortical surface beneath the electrodes. The acquisition instrument settings include a lowpass filtering to frequencies below 75 Hz. The recording time is often 10–20 minutes on 8–16 simultaneous channels.

The name “10–20 system” of electrode placement indicates that the electrodes are at the shown positions oz, pz, cz, fz, and fpz are placed at 10%, 20%, 20%, 20%, 20%, 10% of the total distance; the remaining series of electrodes are placed at corresponding fractional distances of the corresponding reference pathways.

EEG signals contain several patterns of periodic or rhythmic activities with signal frequencies in distinguishable frequency bands. The traces in the figure on page 36 below show

(a) The delta (δ) rhythm is a signal with frequencies in the range $0.5 \text{ Hz} \leq f < 4 \text{ Hz}$.

(b) The theta (θ) rhythm is a signal with frequencies in the range $4 \text{ Hz} \leq f < 8 \text{ Hz}$.

(c) The alpha (α) rhythm is a signal with frequencies in the range $8 \text{ Hz} \leq f \leq 13 \text{ Hz}$.

(d) The beta (β) rhythm is a signal with frequencies above $13 \text{ Hz}$, $13 \text{ Hz} < f$.

Note that the notion “rhythm” stands for different phenomena and events in the branch of EEG signals and the branch of ECG signals.
(e) This trace shows the blocking of the \( \alpha \) rhythm by opening of the eyes: Auditory and mental-arithmetic tasks lead to strong \( \alpha \)-waves if the eyes are closed; if the eyes are opened, the \( \alpha \)-waves are suppressed (blocked).

**EEG-Signal Waves**

(a) \( \delta \)-, (b) \( \theta \)-, (c) \( \alpha \)-, (d) \( \beta \)-rhythm, (e) blocking

We have copied the above figure from [Ran02, p. 31]; there, the author writes “Reproduced with permission from R. Cooper, J. W. Osselton, and J. C. Shaw. *EEG Technology*, 1980. ©Butterworth Heinemann Publishers, a division of Reed Educational & Professional Publishing Ltd., Oxford, UK.”
Example of 8-Channel EEG-Signal Traces

We have copied the above figure from [Ran02, p. 32]; there, the author writes "Data courtesy of Y. Mizuno-Matsumoto, Osaka University Medical School, Osaka, Japan."

The above figure shows an eight channel EEG obtained with measurement electrodes placed at the places indicated by the labels for each trace, compare the 10–20 system of electrode placement shown in the figure on page 34. The EEG traces clearly display the α rhythm.
7 Speech Signals

The Speech Sound

- produced by transmitting puffs of air from the lungs through the vocal (& nasal) tract
- vocal tract acts as a dynamic filter that modulates the spectral characteristics of the input puffs of air
- sound units classified as
  - voiced sounds (vowels; quasi-periodic pulses)
  - unvoiced sounds (appears as random noise)
  - plosive sounds (stops; complete closure of vocal tract, followed by abrupt release of built-up pressure)

We note that speech signals are more commonly considered as communication signals than as biomedical signals. Nevertheless, speech signals also serve as diagnostic signals to investigate speech and vocal-tract disorders. Therefore, to consider speech signals also as biomedical signals is appropriate.
Speech Sound Example: The Word “safety”

We have copied the above figure from [Ran02, p. 44].

Note that the above figure indicates approximate time intervals of the various phonemes appearing in the word “safety.” These intervals are as follows: the /S/ extends from 0.2–0.35 sec; the /E/ extends from 0.4–0.7 sec; the /F/ extends from 0.75–0.95 sec; the /T/ is a transient at 1.1 sec; and the /I/ extends from 1.1–1.2 sec.

Also note that quite a bit of background noise is present in the signal; it seems even that we see the resolution of the used AD converter.
Speech Sound Example: The “a” and the “s”

We have copied the above figure from [Ran02, p. 45].

Segments of the word “safety” from the figure on page 39 on an extended time-scale: We see the quasi-periodic nature of the voiced sound /E/ in the upper panel, and the noise-like nature of the fricative /S/ in the lower panel.
References


