Chapter 1

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Biomedical Signal Processing

- Human body functions are often reflected through **electrical, chemical, or acoustic signals**, which contain **hidden information** related to physiological conditions.
- This information must be **decoded or extracted** to make the signals **clinically meaningful**, sometimes through **simple methods** (e.g., visual inspection), but often requiring **complex analysis**.
- The field of **biomedical signal processing** is essential for extracting significant information from such complex signals.
- It is an **interdisciplinary field**, requiring knowledge of:
- **Physiology** (to avoid losing important data during analysis),
- **Anatomy, linear algebra, calculus, statistics**, and **circuit design**.
- Earlier, the aim was to create **fully automated diagnostic systems**, but this has shifted due to:
- The **difficulty of automation**, and
- The importance of keeping the **physician responsible** for diagnoses.
- Current focus is on developing **computer-aided diagnostic tools**, where biomedical signal processing plays a **crucial role**.
- Historically, research has focused on **unimodal signal analysis** (one signal type at a time), but there is **growing interest in multimodal analysis**, which:
- Explores **interactions between different physiological subsystems** (e.g., **blood pressure and heart rate**).
- Allows for **richer diagnostic insight** by analyzing **mutual information** across signals.
- Poses **algorithmic challenges**, which are being addressed through **advances in computer technology** and **increased processing speeds**.

Objectives and Applications of Biomedical Signal Processing

- **Reducing Subjectivity in Measurement**:
- Traditional manual methods (e.g., ruler-based, visual inspection) are prone to **inconsistency and poor concordance**.
- A key goal is to implement **computer-based methods** for **objective and reproducible** signal quantification.
- **Feature Extraction**:
- Methods are developed to **characterize signals** and **reveal information** not visible through the human eye.
- Example: **Small variations in heart rate** may hold valuable clinical insight, detectable only via processing (see Chapter 8).
- While intuitive features are preferred, **non-intuitive features** may offer better **clinical performance**.
- **Noise Reduction**:
- Signals often contain **interference** from sources like:
- Other physiological processes (e.g., **ocular activity**),
- Poor electrode contact,
- External noise (e.g., **50/60 Hz powerline**).
- Biomedical signal processing helps to **separate desired signals from noise**, especially in low-amplitude or transient signals like:
- **Evoked potentials** (brain),
- **Late potentials** (heart).
- **Handling Long-Term Recordings**:
- Diagnostic needs may require **multi-day recordings** for:
- **Sleep disorders**,
- **Intermittent arrhythmias**.

- These recordings generate **large data volumes**, demanding:
- **Efficient data compression**, particularly tailored for biomedical signals.
- Compression also refers to **condensing clinically relevant data** into a more manageable form.
- **Signal Modeling and Simulation**:
- Mathematical models are used to:
- **Simulate signals** (e.g., from cellular level or body surface),
- **Understand physiological relationships**.
- Examples:
- **Head/brain models** for neural source localization,
- **Thorax/heart models** for simulating cardiac rhythms.
- Integral to **model-based signal processing**:
- Algorithms optimize a **performance criterion** by adjusting model parameters to match observed signals.
- Despite its rigor, **heuristic (ad hoc) techniques** may sometimes yield equal or better performance.
- Many **commercial medical devices** utilize such **practical, non-systematic solutions**.

Signal Model Complexity

- The **complexity of a signal model** is determined by the **specific problem** it aims to solve.
- In most cases, it is **not necessary** to include **detailed biological mechanisms** (e.g., cellular activity, current propagation in tissue).
- Instead, a **phenomenological model**—which focuses only on the **relevant observable phenomena**—is usually **sufficient** for effective signal processing.

Clinical Contexts of Biomedical Signal Processing

Biomedical signal processing algorithms are primarily developed for three major **clinical contexts**:

- **Diagnosis**:
- Involves identifying **medical conditions** by analyzing signal data from organs like the **brain** or **heart**, combined with other symptoms and signs.
- Signals are typically acquired through **noninvasive** and **cost-effective** procedures, making them suitable for **global use**, including **low-resource settings**.
- Diagnostic analysis is generally **not time-critical**, allowing for **off-line processing** on personal computers, possibly enhanced with **DSP boards**.
- Algorithms may range from **basic filtering** to more **complex decision-support** tools.
- **Therapy**:
- Refers to the **treatment of disease**, including **drug therapy** and **surgical interventions**.
- In signal processing, therapy implies using algorithms to **actively alter physiological processes**, as seen in **pacemakers** or **defibrillators**.
- Algorithms are often embedded in **implantable devices**, which require:
- **Real-time, on-line analysis**,
- **Minimal time delay** before response,
- **Low algorithmic complexity**,
- **Low power consumption** for **long battery life** (e.g., up to ten years),
- Suitability for **strict resource constraints** due to physical and medical limitations.

Monitoring Context in Biomedical Signal Processing

- Algorithms are integral to **real-time monitoring systems** for patients with **life-threatening conditions**.
- Common applications include detecting changes in **cardiac** and **neurological function**, especially in **intensive care units (ICUs)**.
- The goal is to **predict patient outcomes** and **enable early intervention** to potentially prevent **irreversible damage**.
- **Sequential (causal) processing** is essential:
- **Past samples** are the primary basis for decision-making.

- Only a few **future samples** may be included, unlike in diagnostic contexts, where the **entire signal** is available for **noncausal analysis**.
- This approach reflects the urgency and need for **immediate response**.
- Algorithm design must meet strict constraints:
- **Minimal delay time** to notify ICU staff **within seconds** of a critical event.
- **High reliability** is crucial:
- **Missed events** can lead to **clinical harm**,
- **False alarms** can result in **unnecessary alerts** and **wasted resources**.

1.2 Basics of Bioelectrical Signals

- The textbook primarily focuses on **signal processing of electrical signals recorded on the body surface**.
- However, understanding the **cellular origin** of bioelectrical signals provides useful context.
- **Bioelectrical signals** originate from **ionic processes** resulting from the **electrochemical activity** of **excitable cells**.
- These mechanisms are **fundamentally similar** across various tissues such as the **brain**, **heart**, and **muscles**.
- The **electrical force of attraction** plays a key role in:
- **Information transmission** in the **nervous system**,
- **Mechanical function** of the **heart and muscles**.
- While only a brief overview of the origin of these voltages is provided here, readers are referred to:
- **Human physiology textbooks** for cellular mechanisms [1, 2],
- **Mathematical modeling concepts** of bioelectrical phenomena [3],
- **Comprehensive texts** on bioelectrical activity [4–6].

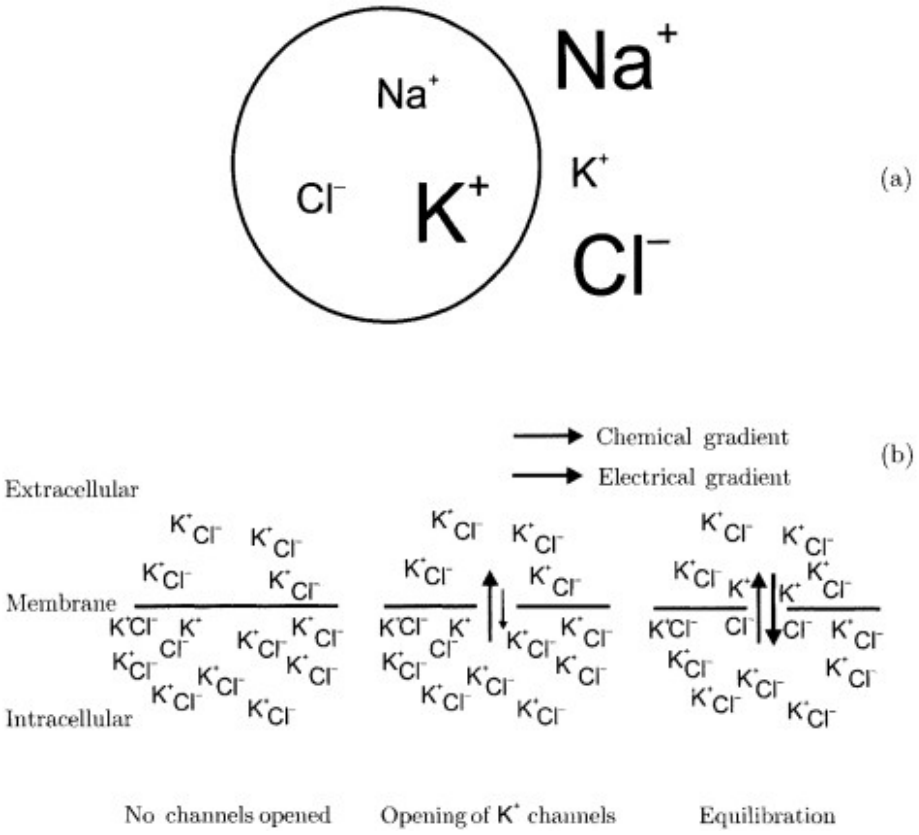
1.2 Basics of Bioelectrical Signals (continued)

- A **cell is surrounded by a plasma membrane** composed of **lipid layers**, which are **poor electrical conductors**.
- The membrane has **selective permeability**, allowing **certain substances** to pass via **fluid-defined channels**, while others are **blocked**.
- **Intracellular and extracellular fluids**:
- Made mostly of **water** (electrically neutral),
- Contain **ions** that render the fluids **electrically conductive**.
- Dominant ions in neurons:
- **Sodium (Na^+)**,
- **Potassium (K^+)**,
- **Chloride (Cl^-)**,
- **Calcium (Ca^{2+})** (more important in **heart cells** than neurons).
- **Resting transmembrane potential**:
- The **inside of the cell** is **negatively charged** relative to the outside.
- This potential arises from:
- A **higher concentration of negative ions** inside the cell,
- A **higher concentration of positive ions** outside.
- Also influenced by **membrane permeability** to different ions.
- **Ion diffusion and potential generation**:
- When **membrane channels open**, ions **diffuse across** the membrane.
- Example:
- With **K^+ inside** and **Na^+ outside**, and **initial potential = 0**:
- Opening **K^+ channels** causes K^+ to leave the cell,
- **Outside becomes more positive**, **inside more negative**,
- This creates an **electrical potential** that opposes further K^+ movement.
- **Equilibrium is reached** when **concentration force** balances the **electrical force**.
- **Equilibrium potentials**:

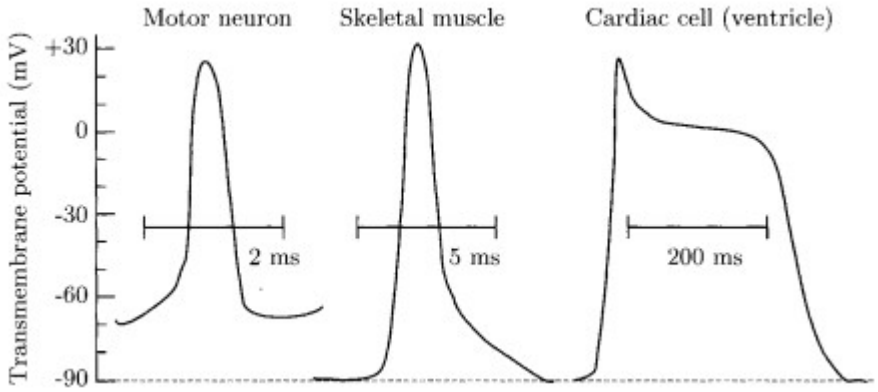
- For **potassium**: approx. **–90 mV**,
- For **sodium**: approx. **+60 mV**,
- **Resting potential**: between **–60 mV and –100 mV**, depending on the **cell type**.
- This resting potential is a **weighted result** of all individual ion equilibrium potentials.

Action Potentials and Signal Propagation

- **Action potential**: A **rapid change in membrane potential** caused by **altered ion permeability**, triggered when a **stimulus current** exceeds a **threshold**.
- Below threshold → **no response**.
- Above threshold → **standardized response** (all-or-nothing principle).
- **Two main phases** of an action potential:
- **Depolarization**:
- Membrane potential moves toward **zero**, then **reverses polarity**.
- Triggered by **sodium channels opening**, allowing **Na^+ to rush in**.
- Simultaneously, **K^+ attempts to exit**, increasing **positive charge** inside.
- **Peak amplitude** occurs near the **Na^+ equilibrium potential**.
- **Repolarization**:
- **Sodium channels close**, **potassium channels open**.
- **K^+ exits**, restoring the **resting negative membrane potential**.
- **Signal propagation**:
- **Action potentials propagate** signals across **neurons** and trigger **heart muscle contractions**.
- **Waveform characteristics** (Figure 1.2):
- **Cardiac cells**: Action potential includes a **plateau phase** due to **staggered ion channel activity**, lasting **200–300 ms**.
- **Neurons**: Action potentials are much shorter (**~1 ms total**), with **balanced depolarization and repolarization** phases.
- **Skeletal muscle**: Intermediate in duration.
- **Refractory period**:
- After an action potential, the cell enters a **temporary unresponsive state**.
- Caused by shifts in **Na^+ and K^+ permeability**.
- This period limits the **maximum frequency** of:
- **Nerve signal transmission**, and
- **Heartbeats**.



- **Figure 1.1**: Illustrates the **activity of a potassium channel** during repolarization.

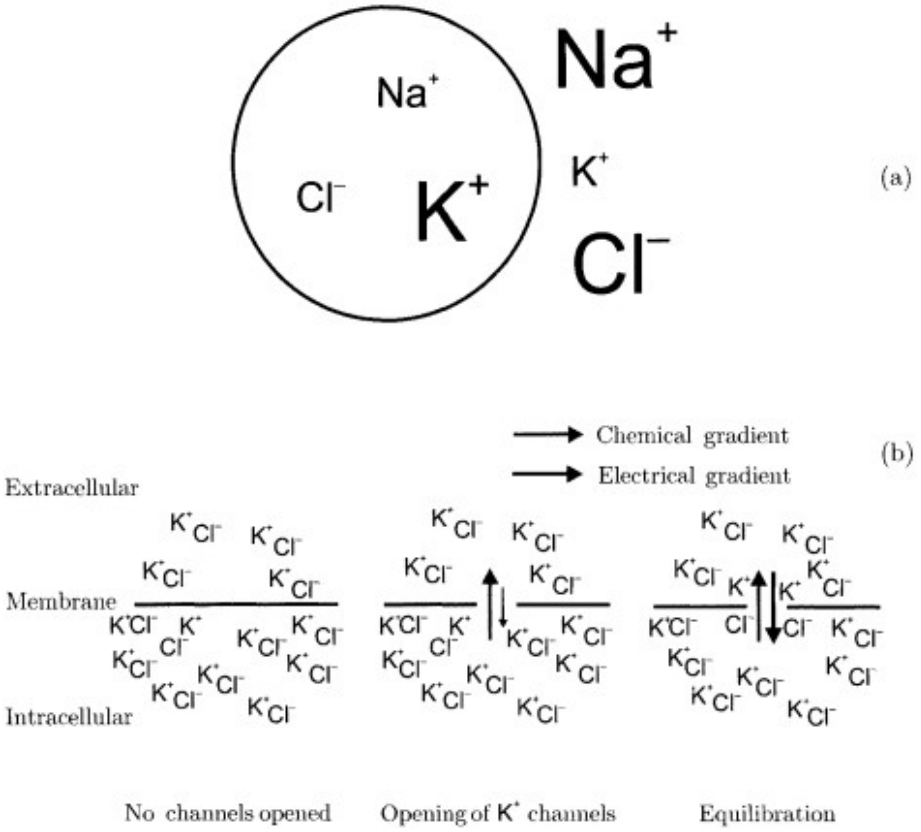


- **Figure 1.2**: Compares **action potentials** in a **motor neuron**, **skeletal muscle cell**, and **cardiac cell**, showing:
- **Short duration** in neurons,
- **Longer, plateaued profile** in cardiac cells.

Propagation of Action Potentials

- **Action potentials do not physically move** along the membrane.
- Instead, they propagate by **sequential triggering**:
- **Depolarization at one membrane location** creates a current,
- This **stimulates adjacent regions**, causing a **new action potential** to occur,

- The cycle **continues** until the signal reaches the **end of the membrane**.
- The **final action potential** is **identical to the initial one**, maintaining signal consistency.
- **Refractory period** ensures **unidirectional propagation**:
- Recently excited membrane regions **cannot be re-stimulated** immediately,
- The signal only travels **forward** to areas with sufficient voltage for excitation.



- **Figure 1.1**: Illustrates **cellular potassium channel activity**.
- (a) Shows **ion concentration distributions** for **K^+, Na^+, and Cl^-** inside and outside the cell.
- (b) Depicts the relationship between **chemical and electrical gradients** for **K^+ ions**:
- **No channels opened** → stable condition,
- **Opening of K^+ channels** → ion movement begins,
- **Equilibration** → gradients balance and ion flow stops.

Measurement and Modeling of Bioelectrical Signals

- **Excitable cell membranes** generate **currents** in surrounding **conductive tissue**, known as a **volume conductor**.
- The **collective electrical activity** of many cells can be **measured noninvasively** on the **body surface**.
- **Recording setup**:
- Requires at least **two surface electrodes**:
- **Exploring electrode**: placed near the electrical source,
- **Indifferent electrode**: placed elsewhere on the body.
- **Multiple electrode configurations** are used to provide a **spatial description** of bioelectrical activity.
- **Limitations of surface recordings**:
- Electrodes view cell activity **from a distance**, across various tissues (e.g., **blood, muscle, fat, bone**),
- This makes it **impossible to resolve fine cellular or propagation details** noninvasively.
- Despite this, **clinical practice** has gained **empirical value** from body surface signals, which are essential

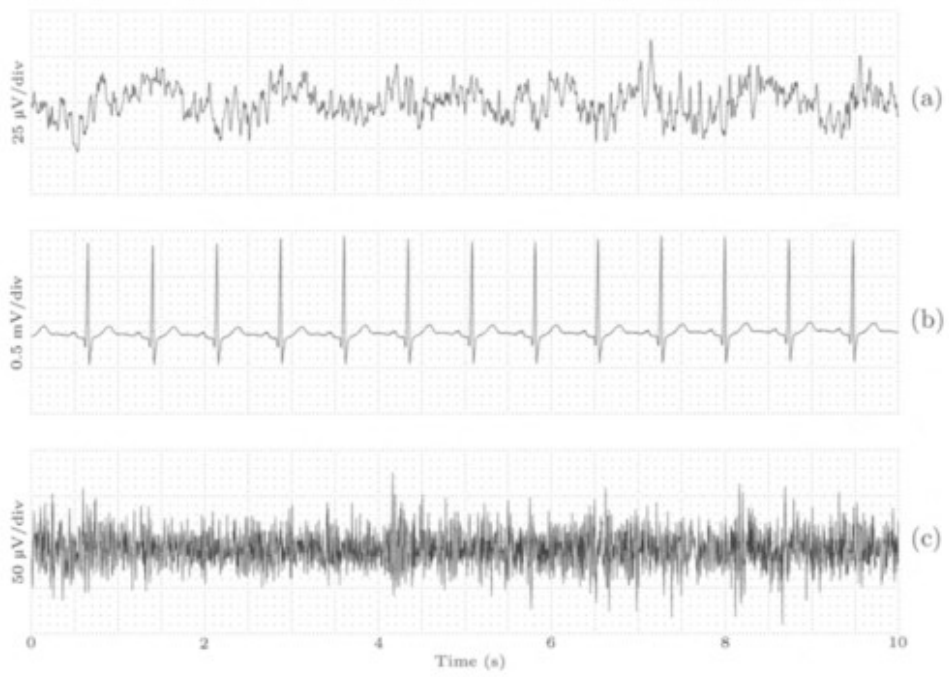
for **diagnostic decision-making**.

- **Modeling approaches**:
- Electrical sources are modeled as **volume sources**:
- E.g., **fixed dipole**, **multiple dipoles**, or other configurations.
- The **volume conductor** is modeled to reflect **human body geometry** and **resistivity**.
- The **inverse problem**:
- Refers to **determining the electrical source** from **body surface measurements**,
- Requires prior knowledge of the **volume conductor's geometry and electrical properties**,
- Solving it has major **clinical relevance** and has been the subject of **extensive research**.
- **Figure 1.2**: Shows action potentials of:
- **Motor neuron**: sharp spike waveform (~5 ms),
- **Skeletal muscle**: intermediate shape,
- **Cardiac cell**: broad waveform with a **plateau phase** (~200 ms).
- Recorded via **microelectrodes inside and outside the cell**.
- **Time scales vary** across waveforms.

Types of Bioelectrical Signals and Their Clinical Relevance

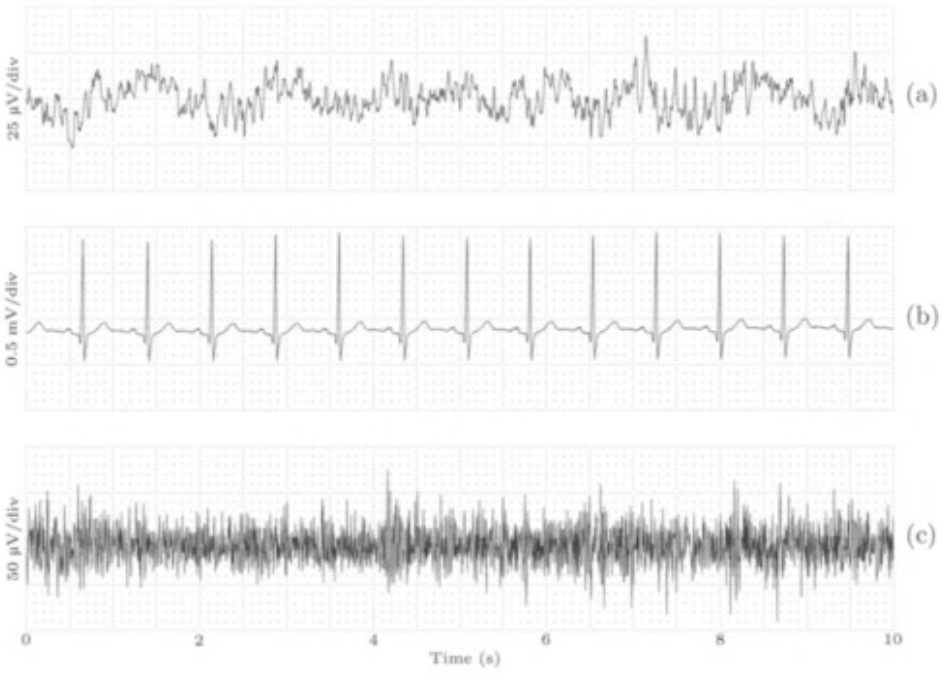
- The textbook focuses on processing **electrical signals from the brain, heart, and muscles**.
- These signals can reflect either:
- **Spontaneous, ongoing activity**, or
- **Stimulus-evoked activity**.
- Signal characteristics vary:
- Some allow **diagnosis from a single waveform**,
- Others require analysis of **multiple waveforms** for clinical interpretation.

- **Electroencephalogram (EEG)**:



- Records **brain activity** using **electrodes on the scalp** (Figure 1.3(a)).
- Used in diagnosing:
- **Epileptic seizures** (type/location of activity),

- **Sleep disorders**.
- **Invasive alternative**: **Electrocorticogram (ECoG)**—electrodes placed directly on the **brain surface** during surgery.
- EEG background: **Chapter 2**; signal processing techniques: **Chapter 3**.
- **Evoked Potentials (EPs)**:
- Also called **event-related potentials**.
- Triggered by **sensory stimuli** (e.g., **visual or auditory**).
- Help diagnose:
- Disorders of **visual pathways**,
- Disorders of the **brainstem**.
- EPs are **transient and low in amplitude**, typically **invisible in background EEG** (see Figure 1.4(a)).
- Recorded similarly to EEG.
- EP methods and waveform analysis: **Chapter 4**.
- **Electrocardiogram (ECG)**:
- Measures **electrical activity of the heart** via electrodes on **chest, arms, and legs** (Figure 1.3(b)).
- Used to evaluate:
- **Heart rhythm and rate**,
- **Myocardial infarction** and other heart diseases.
- **Electrogram (EG)**:
- An **intracardiac** recording,
- Electrodes placed **inside the heart**,
- Used in **implantable devices** like **pacemakers and defibrillators**.
- ECG background: **Chapter 6**; processing techniques: **Chapters 7 and 8**.

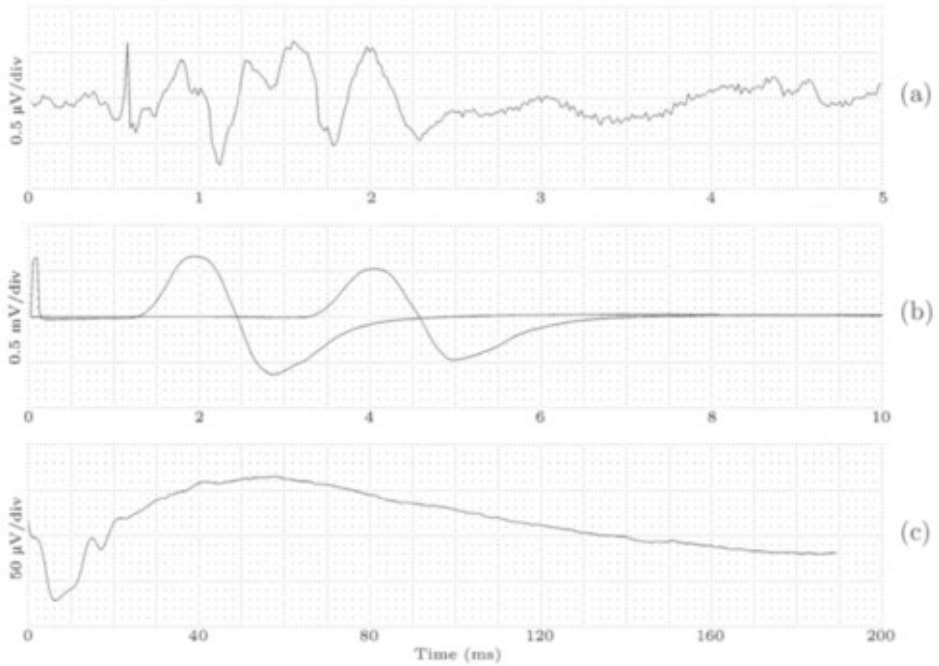


- **Figure 1.3**: Examples of major bioelectrical signals:
- (a) **EEG** with alpha activity,
- (b) **ECG** during sinus rhythm,
- (c) **EMG** from the chin during waking state,
- All obtained from **healthy individuals**.

Electromyogram (EMG) and Other Bioelectrical Signals

- **Electromyogram (EMG)**:
- Records **electrical activity of skeletal muscles**, typically **proportional to muscle activity level** (see Figure 1.3(c)).
- Used to detect abnormalities related to:
- **Muscular dystrophy**,
- **Muscle inflammation**,
- **Nerve injuries** in the limbs.
- **Recording methods**:
- **Surface EMG**: electrodes placed on **skin** over the muscle,
- **Intramuscular EMG**: **needle electrodes** inserted **into the muscle**.
- EMG signal processing is discussed in **Chapter 5**.

- **Other Bioelectrical Signals** (not covered in detail in this textbook):
- **Electroneurogram (ENG)**:
- Measures nerve response to **electrical stimulation** of a **peripheral nerve**.
- Commonly recorded with **needle electrodes**.
- Used to assess **nerve conduction velocity** for diagnosing **nerve damage**.
- Velocity is calculated by stimulating at **two known distances** and measuring **signal delay** (see Figure 1.4(b)).
- Can be recorded **invasively or noninvasively**.
- **Electroretinogram (ERG)**:
- Captures retinal response to **light stimulation**.
- Example shown in **Figure 1.4(c)**.

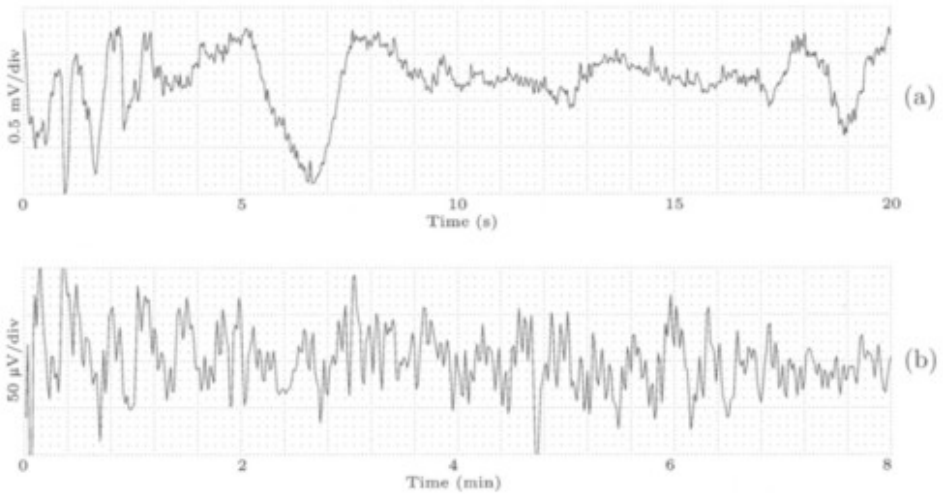


- **Figure 1.4**: Examples of stimulation-evoked bioelectrical signals:
- (a) **Evoked Potential (EP)**: from **auditory stimulation**, shown after **averaging** to reduce noise (see Section 4.3).
- (b) **ENG**: recordings at two locations used to **calculate conduction velocity**.
- (c) **ERG**: response from the **retina** to a **light flash**.

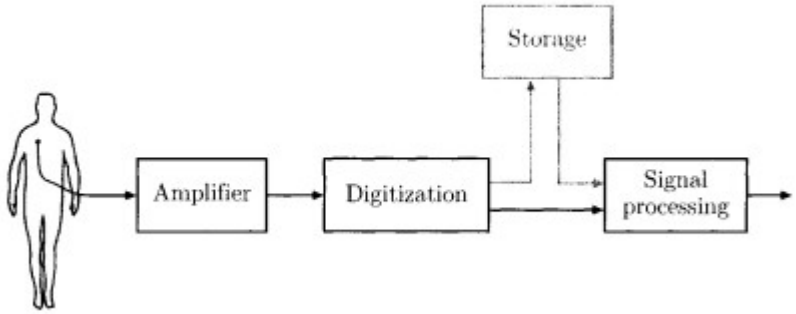
Electroretinogram (ERG), Electrooculogram (EOG), and Electrogastrogram (EGG)

- **Electroretinogram (ERG)**:
- Measures **electrical potentials from the retina** during **light stimulation** (see Figure 1.4(c)).
- Recorded using an **exploring electrode embedded in a contact lens**, placed on the **cornea**.
- Useful for assessing function of **rods and cones** (retinal visual cells).
- **Normal ERG**: response increases with light intensity.
- **Abnormal ERG**: observed in conditions like **retinal arteriosclerosis** and **retinal detachment**.
- **EP signal processing techniques** (Chapter 4) are largely applicable to **ERG analysis**.

- **Electrooculogram (EOG)**:
- Captures **steady corneal-retinal potential**, correlating with **eye movement** direction (see Figure 1.5(a)).
- Used to **objectively track gaze** direction (vertical and horizontal).
- Clinical and applied uses:
- **REM sleep detection** (for sleep disorder diagnosis),
- **Nystagmus evaluation** (involuntary eye oscillations due to vertigo/dizziness),
- **Eye-tracking** in **virtual reality** environments.
- Briefly discussed in **Chapter 3** in relation to **EEG processing**, as **eye movement artifacts** often interfere with EEG signals and need to be cancelled.



- **Electrogastrogram (EGG)**:
- Records **muscle impulses in the stomach** that control **contractions** (see Figure 1.5(b)).
- Used to assess abnormalities in **gastric motility** or **nerve control**, especially when **food emptying is delayed**.
- Recording setup: **multiple electrodes** on the **stomach area**, during **fasting and post-meal** periods.
- **Normal signal**:
- **Rhythmic**,
- **Amplitude increases after eating**,
- Frequency ≈ **3 cycles/minute**.
- **Abnormal signal**:
- **Irregular rhythm**,
- May **lack post-meal amplitude increase**.
- Related technical studies found in references **[12–16]**.

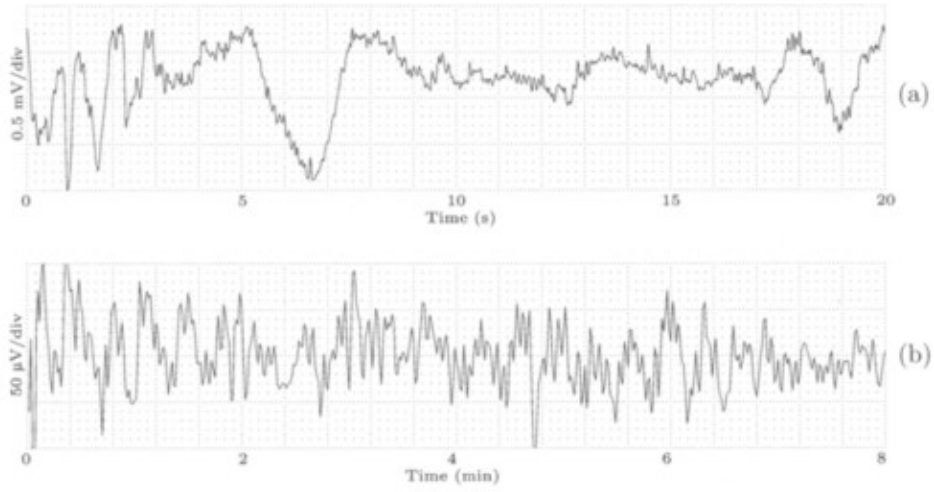


1.3 Signal Acquisition and Analysis

- **Bioelectrical signals** are now commonly acquired using **low-cost equipment** that:
- **Amplifies** and **digitizes** the signal,
- Enables **widespread use** in hospitals for clinical procedures.
- **PC-based systems** are effective for **signal analysis**, offering:
- Cost-efficiency,
- Availability of **data acquisition expansion cards**.
- A typical system includes:
- One or more **sensors**,
- **External hardware** for **patient insulation** and **amplification**,
- **Acquisition card** with **analog-to-digital (A/D) conversion**,
- **Software** for signal processing (**see Figure 1.6**).
- **Implantable devices** require extra design considerations:
- Use of **application-specific integrated circuits (ASICs)**,
- Selection of suitable **battery technology**.

- **Digitization details**:
- **12–14 bits** are sufficient for **amplitude quantization**,
- Assumes **DC drift** is removed beforehand **without altering physiological content**,
- Signal amplitudes range:
- From **0.1 µV** (in noise-reduced EPs),
- To **several millivolts** (ENG, ECG, EOG).
- **Frequency content and sampling**:
- Surface-recorded signals mostly lie **below 1 kHz**,
- **Sampling rates** rarely exceed a few **kHz**,
- **Invasive recordings** (e.g., action potentials) can have **much higher frequency content** due to less **low-pass filtering** by tissues.

- **Analysis setup**:
- Can be done using:
- The PC's **internal CPU**, or
- A **DSP expansion card**.
- Signal may be:
- **Processed in real-time** during acquisition,
- **Stored locally** or on a **web server** for later processing (**Figure 1.6**).
- **Web-based analysis**:
- Enables **remote processing** using **client/server models**,
- Advantageous when the **server** offers greater **computational resources**,
- Signal data typically stored in a **centralized database**.



- **Figure 1.5**:
- (a) **Electrooculogram (EOG)** of the right eye,
- (b) **Electrogastrogram (EGG)** with a different time scale from (a).
- **Figure 1.6**: Block diagram of **biomedical signal analysis steps**:
- Signal acquisition → amplification → digitization → storage/processing (local or remote).

1.4 Performance Evaluation

- **Performance evaluation** is **essential and challenging** in biomedical signal processing, especially before **clinical implementation**.
- Unlike traditional engineering contexts, **bioelectrical signals lack known ground truth**:
- The **message source** is **unknown** and must be **manually uncovered** to allow evaluation.
- Example:
- **Heartbeat detection** is **easy to evaluate**, as physicians can clearly identify beat timings.
- Performance is based on **agreement** between the algorithm's output and **manual annotations**.
- **More complex tasks**, like **disease classification**, are harder to evaluate:
- The **"truth"** (i.e., disease presence or absence) **cannot be directly retrieved** from the signal.
- Instead, evaluation is based on how well the algorithm **discriminates between healthy and diseased subjects**.

- **Common performance measures** for classification tasks (see **Table 1.1**):

Performance Measure	Definition	Interpretation
Sensitivity	NTP / (NTP + NFN)	Probability of a **positive result** for **diseased subjects**
Specificity	NTN / (NFP + NTN)	Probability of a **negative result** for **healthy subjects**
Positive Predictive Value	NTP / (NTP + NFP)	Probability of **disease** when the result is **positive**
Negative Predictive Value	NTN / (NFN + NTN)	Probability of **health** when the result is **negative**

- **NTP** = True Positives (diseased subjects correctly identified)
- **NTN** = True Negatives (healthy subjects correctly identified)
- **NFN** = False Negatives (diseased subjects missed)
- **NFP** = False Positives (healthy subjects incorrectly identified as diseased)

- **Key insight**:
- New algorithms may seem **promising at first**, but **systematic evaluation often reveals limitations** [19].
- Therefore, **substantial development and testing** are necessary to ensure **reliable clinical performance**.

Signal Databases for Algorithm Development and Evaluation

- **Signal databases** are **crucial** for both the **development** and **performance evaluation** of biomedical signal processing algorithms.
- Due to the **high variability** in **waveform patterns across individuals**, algorithms must be tested on **large databases** to ensure they are **clinically reliable**.
- To avoid **overfitting** or **data leakage**, the database is divided into:
- A **development set** (for algorithm design), and
- An **evaluation set** (for independent performance testing).

- **Definition of "database"**:
- A **collection of signals** recorded using a **standard protocol** from **well-selected groups** of:
- **Healthy subjects**, and
- **Patients**.
- May include:
- A **single signal type** (e.g., **EEG**, **ECG**), or
- **Multiple types** of concurrently recorded signals.
- **Annotations**:
- Mark **specific time events** (e.g., **heartbeats**, **epileptic seizures**),
- May also flag:
- **Complex signal characteristics**,
- **Nonphysiological artifacts**, such as:
- **Noise episodes**,
- **Technical issues** (e.g., poor electrode contact) — see **Figure 1.7**.
- Typically **manually added by physicians**, requiring:
- Careful **signal inspection**,
- Sometimes **multiple annotators** for **higher reliability**.
- **Discrepancies** between annotators are resolved via **consensus**, making the process **labor-intensive**.

- **Additional subject information** in databases may include:
- **Demographic data**: gender, age, race, weight,
- **Medical data**: medications, clinical procedure results,
- This metadata is valuable for **comprehensive performance evaluation**.

Biomedical Signal Databases

- Over the years, **many signal databases** have been assembled to tackle **various clinical issues**.

- **Popular ECG Databases**:
- **MIT-BIH Arrhythmia Database**:
- Most **widely used** in biomedical signal processing,
- Contains **ECG signals recorded under ambulatory conditions** (e.g., while **working** or **eating**),
- Used to evaluate algorithms for **cardiac rhythm abnormality detection** [21, 22].
- **AHA Database**:
- Developed to test detectors for **ventricular arrhythmias** [23].
- **European ST-T and LTST Databases**:
- Designed for studying **myocardial ischemia** (insufficient blood supply to the heart) [20, 24].

- **MIT-BIH Noise Stress Test Database**:
- Provides **ECG signals with calibrated noise** added to clean recordings,
- Used to test the **noise robustness** of algorithms [25].

- **Multimodal Databases**:
- Contain a **combination of signal types**, such as:
- **Brain activity (EEG)**,
- **Heart activity (ECG)**,
- **Muscle activity (EMG)**,
- **Blood pressure**, **respiration**, and more (see **Figure 1.8**).
- Notable examples:
- **MIMIC Database** [26],
- **IMPROVE Database** [27],
- **IBIS Database** [28, 29].
- These databases provide **continuously recorded, multi-signal datasets** for advanced analysis.

- **Figure 1.7**:
- Shows a **two-channel ECG** with **manual annotations** from a patient with **myocardial ischemia**.
- Includes:
- **Short vertical bars**: heartbeat timings,
- Labels: `"N"` for **normal beats**, `"V"` for **ventricular beats**,
- **Long vertical bars**: indicate rhythm changes, e.g.,
- `"VT"` = ventricular tachycardia,
- `"N"` = sinus rhythm,
- `"ASTI-300"` = ST depression of **–300 µV**.
- Data sourced from the **European ST-T database** [20].

Database Access and Considerations in Biomedical Signal Processing

- **Databases from intensive care monitoring** and **sleep disorder studies** [30, 31] are available, expanding the variety of clinically relevant data for research.
- Many databases are:
- **Publicly available** (free or paid),
- A few remain **private property** of original collectors.
- Databases benefit both:
- **Researchers**, by enabling development and validation,
- **Instrument manufacturers**, for testing device performance.

- **Convenience of modern access**:
- Widespread online availability **simplifies algorithm development**,
- Removes the need for **manual, time-consuming signal collection**.
- **PhysioNet (www.physionet.org)**:
- A major **online resource** for biomedical signals [32],
- Offers:
- **Freely downloadable** physiological signal databases,
- **Multiple classes of data**, ranging from:
- **Well-annotated and validated datasets**, to
- **Unannotated or incomplete recordings**.

- **Figure 1.8**:
- Shows **multimodal signals recorded concurrently** from the **MIT-BIH polysomnographic database** [30]:

1. ECG
2. Blood pressure
3. EEG
4. Nasal respiration
5. Abdominal respiration
6. Electrogastrogram (EGG)
7. Electromyogram (EMG)

- Used in the **study of sleep disorders** (see Section 2.4.2).

- **Risks and cautions with database use**:
- **Reduced clinical involvement** due to off-site work may lead to:
- **Lack of expert oversight**,
- Potential introduction of **clinically unacceptable distortions**.
- Importance of **collaboration** between **engineers and physicians** is emphasized.
- **Misuse of databases**:
- Adapting data to answer **questions outside the original clinical scope** can lead to **invalid results**.
- **When no suitable database exists**:
- Researchers must:
- Design a **recording protocol**,
- Perform their own **signal acquisition**,
- Handle the full **data collection process**.
- **Key advice**:
- Use of public databases is encouraged, **but not a substitute** for understanding **signal collection** and **clinical context**.

Simulation and Signal Modeling in Performance Evaluation

- **Simulations** use **mathematical equations** to **quantitatively describe physiological behavior**, replicating signals generated by the body.
- **Advantages of simulation**:
- Enables study of **conditions difficult to reproduce experimentally**,
- Allows **precise control** over **signal properties** via adjustable parameters,
- Facilitates **quantitative performance evaluation** of algorithms by comparing:
- Known "**true**" parameters of the simulated signal, and
- Parameters **estimated** by the algorithm.
- **Performance measures** vary based on context:
- **Detection problems**: rates of **missed events** and **false events**,
- **Estimation problems**: **bias** and **variance** of the estimated parameters.

- **Link between modeling and simulation**:
- **Simulation relies on an existing model** of the signal,
- **Realistic signal models** tend to be **complex** and may not be suitable for **parameter estimation**,
- **Simpler models**, though less complete, are still **valuable for algorithm development**.
- In biomedical signal processing:
- Models often include both:
- The **desired physiological (clean) signal**, and
- Models of **noise sources**, including:
- Other **physiological activities** not under study,
- Any **interfering components**.

- This approach allows generation of signals with **variable signal-to-noise ratios (SNRs)**.

- **Performance evaluation aspects**:
- **Accuracy**: how close the algorithm's output is to the **true value**,
- **Reproducibility**: the algorithm's ability to produce **consistent results** across repeated measurements under **identical signal conditions**.
- Though best studied by **repeating real experiments** on the same patient, reproducibility can be **effectively tested using simulated signals**:
- Add **different noise realizations** to the same clean signal,
- Use the algorithm to process each version,
- Analyze the **consistency of results** across trials.

Simulated Signals with Real-World Noise and Final Notes on Evaluation

- **Hybrid simulation approaches** can enhance performance evaluation:
- Use **simulated signals** with added **real-world noise**, offering **more realistic testing conditions**.
- Alternatively, use **real-world signals** combined with **simulated noise** to assess algorithm behavior under **controlled interference**.

- **Key conclusion**:
- **Simulations** are a **valuable tool** in the **early stages** of algorithm development,
- Their effectiveness **depends on the adequacy** of the underlying **signal model**.
- However, **real signal databases** must be the **primary resource** for evaluating an algorithm's **clinical utility**:
- Ensure results are **relevant**, **robust**, and **applicable** to **real-world medical conditions**.