BIOMEDICAL SIGNAL ANALYSIS

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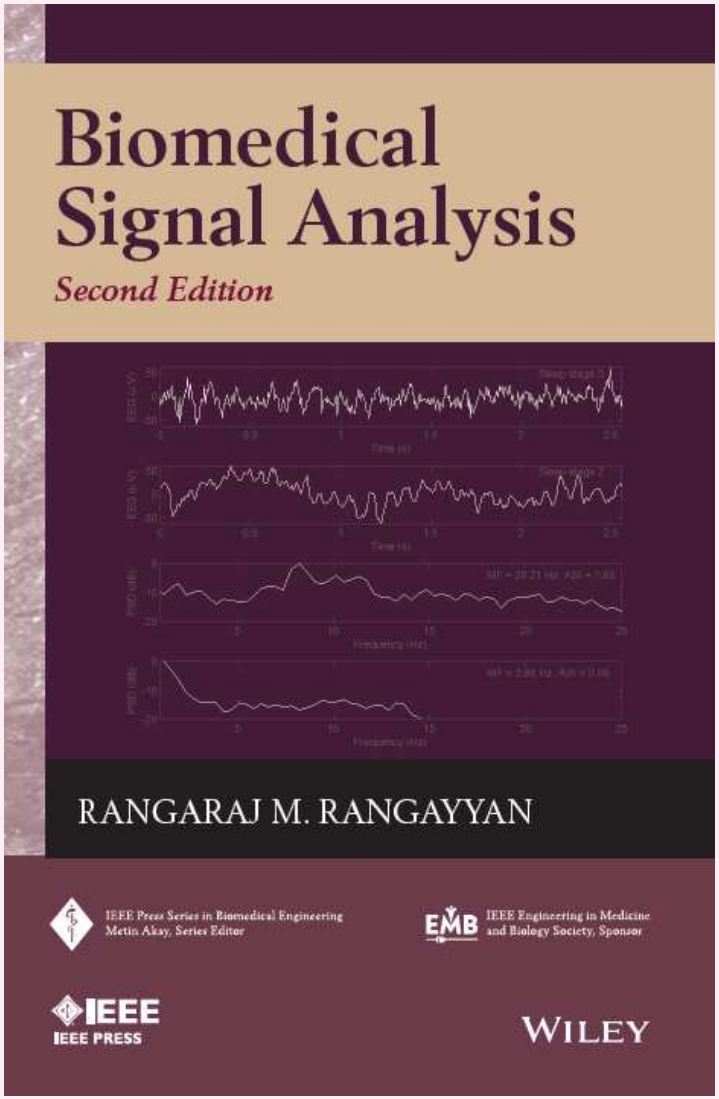

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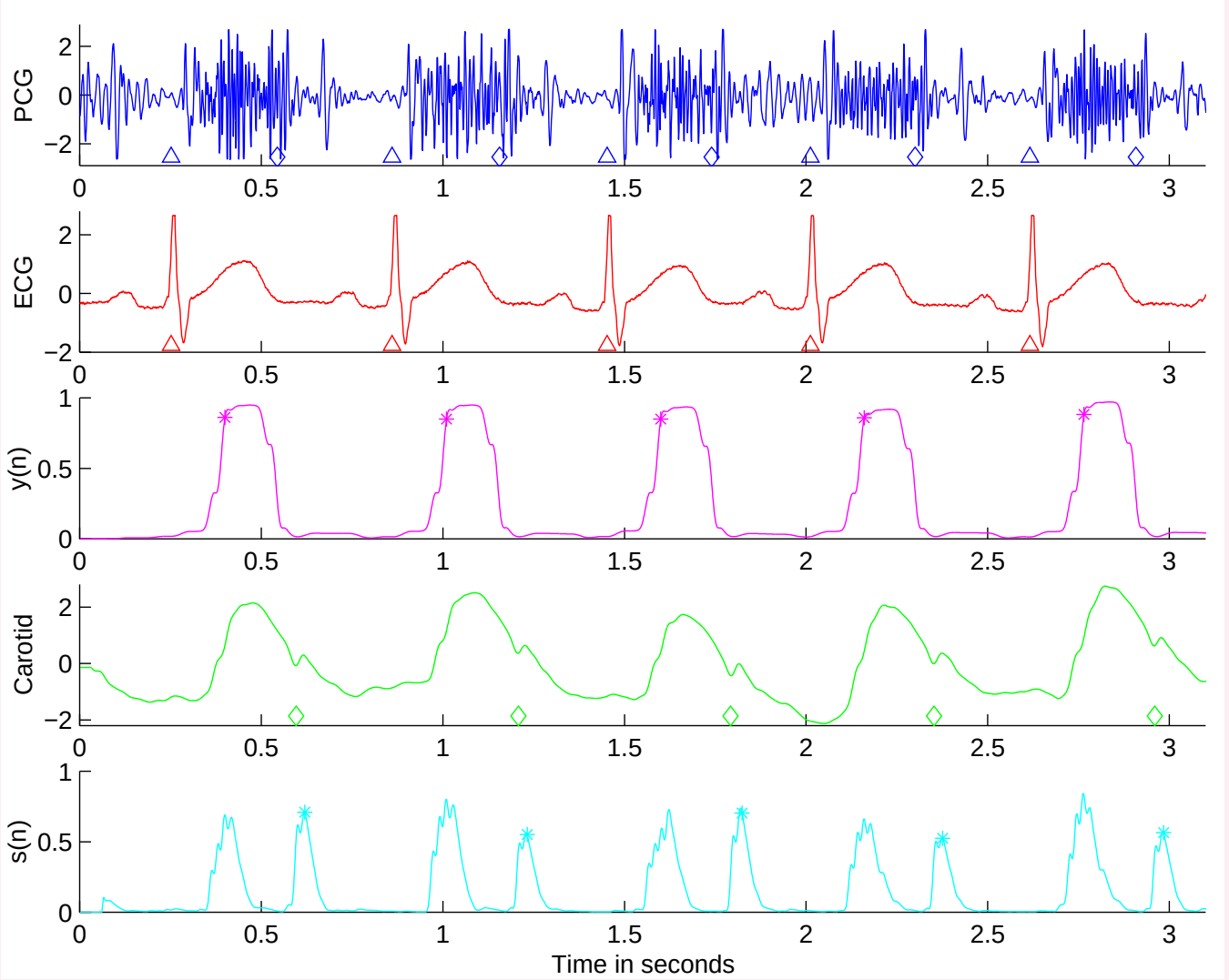
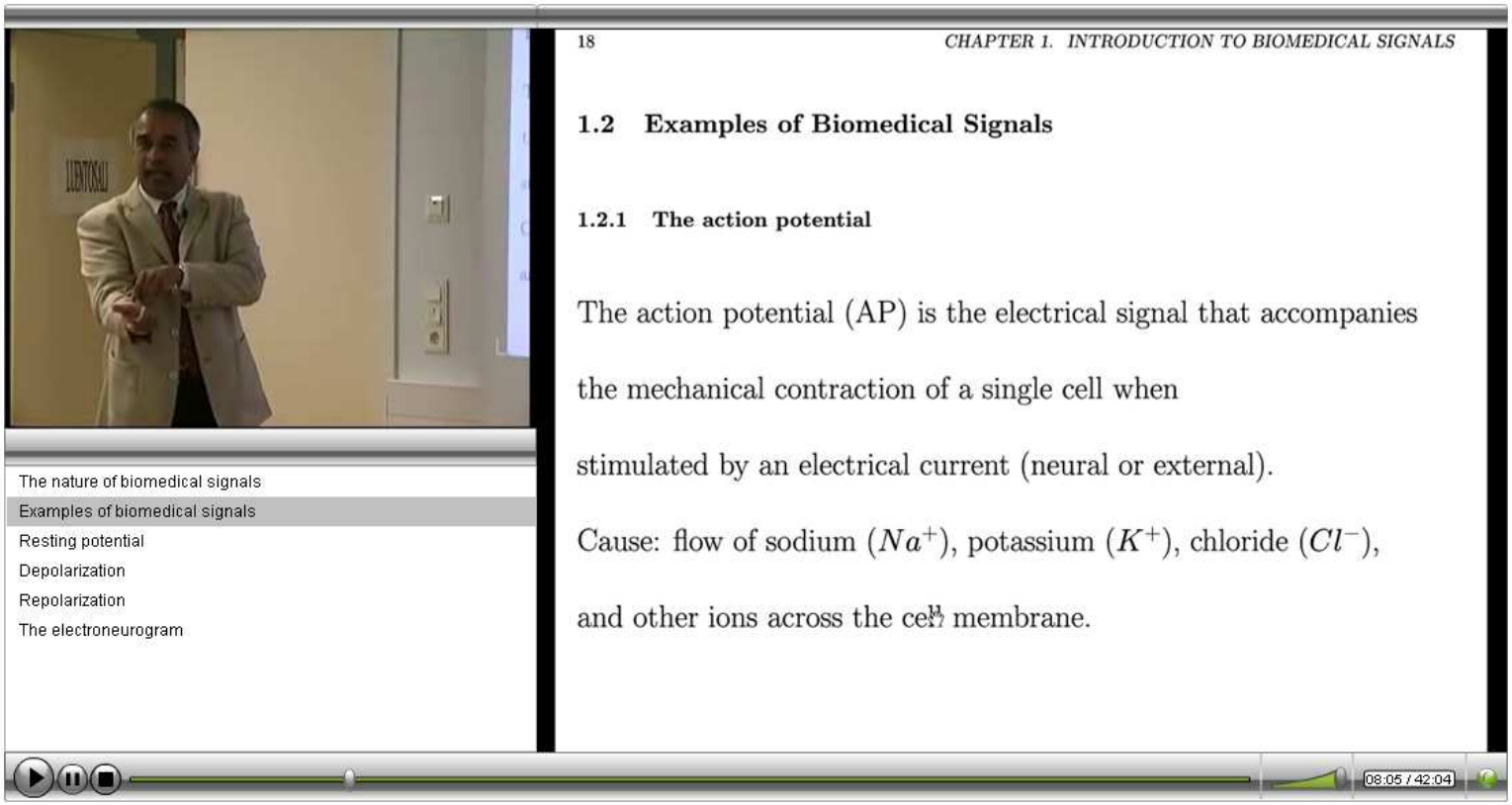


Illustration of various stages of biomedical signal processing and analysis



Video of course given at
Ragnar Granit Institute of Biomedical Engineering
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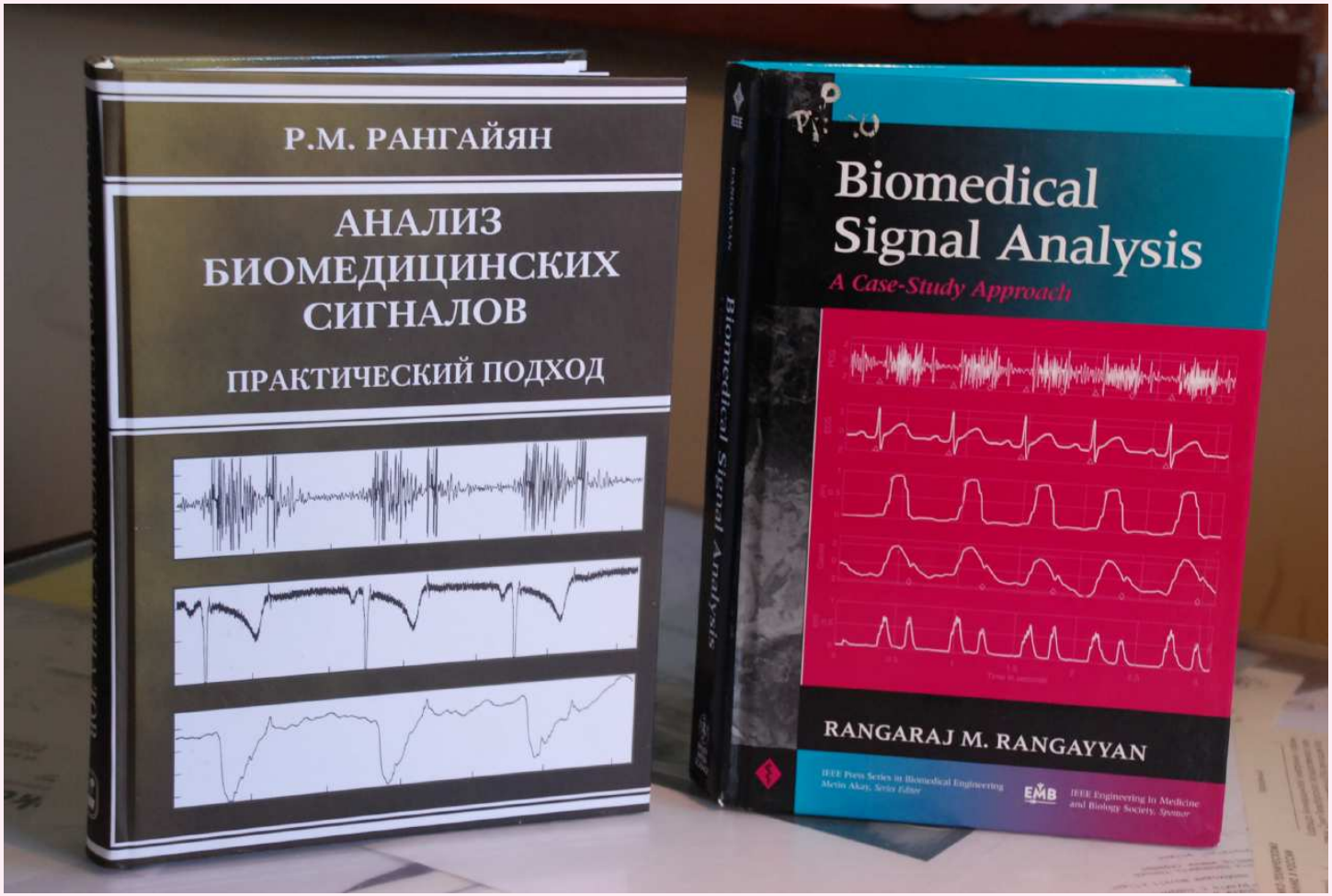


Russian translation of 1st Edition by A. Kalinichenko, 2007
Physmathlit, Moscow, Russia

1

Introduction to Biomedical Signals

1.1 The Nature of Biomedical Signals

Living organisms are made up of many component *systems:*

the human body includes several systems.

For example:

- the nervous system,
- the cardiovascular system,
- the musculoskeletal system.

Each system is made up of several subsystems that carry on many *physiological processes.*

Cardiac system: rhythmic pumping of blood throughout the body to facilitate the delivery of nutrients, and

pumping blood through the pulmonary system for oxygenation of blood.

Physiological processes are complex phenomena, including

- nervous or hormonal stimulation and control;
- inputs and outputs that could be in the form of physical material, neurotransmitters, or information; and
- action that could be mechanical, electrical, or biochemical.

Most physiological processes are accompanied by *signals* of several types that reflect their nature and activities:

- biochemical, in the form of hormones and neurotransmitters,
- electrical, in the form of potential or current, and
- physical, in the form of pressure or temperature.

Diseases or defects in a biological system cause alterations in its normal physiological processes,

leading to *pathological processes* that affect

the performance, health, and well-being of the system.

A pathological process is typically associated with signals that are different in some respects from the corresponding normal signals.

We need a good understanding of a system of interest to observe the related signals and assess the state of the system.

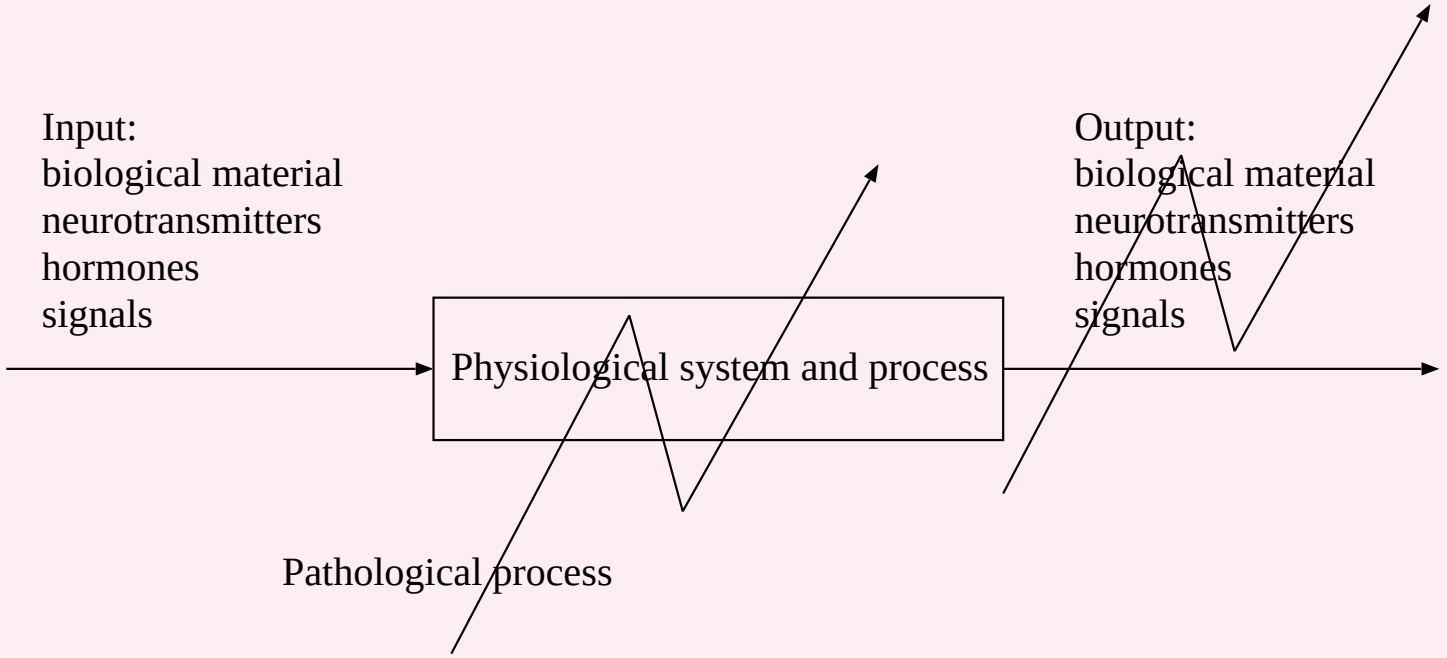


Figure 1.1: Schematic representation of a generic physiological system with various types of possible inputs and outputs. The effect of a pathological process is depicted by the zigzag line across the system and the list of possible outputs.

Most infections cause a rise in the temperature of the body:

this can be sensed easily in a relative and *qualitative* manner via the palm of one's hand.

Objective or *quantitative* measurement of temperature

requires an instrument, such as a thermometer.

A single measurement x of temperature is a *scalar:*

represents the thermal state of the body at a

particular or single instant of time t

and a particular position.

If we record the temperature continuously,

we obtain a *signal as a function of time:*

expressed in *continuous-time* or *analog* form as $x(t)$.

When the temperature is measured at *discrete* points of time,

it may be expressed in *discrete-time* form as $x(nT)$ or $x(n)$,

n: index or measurement sample number of the array of values,

T: uniform interval between the time instants of measurement.

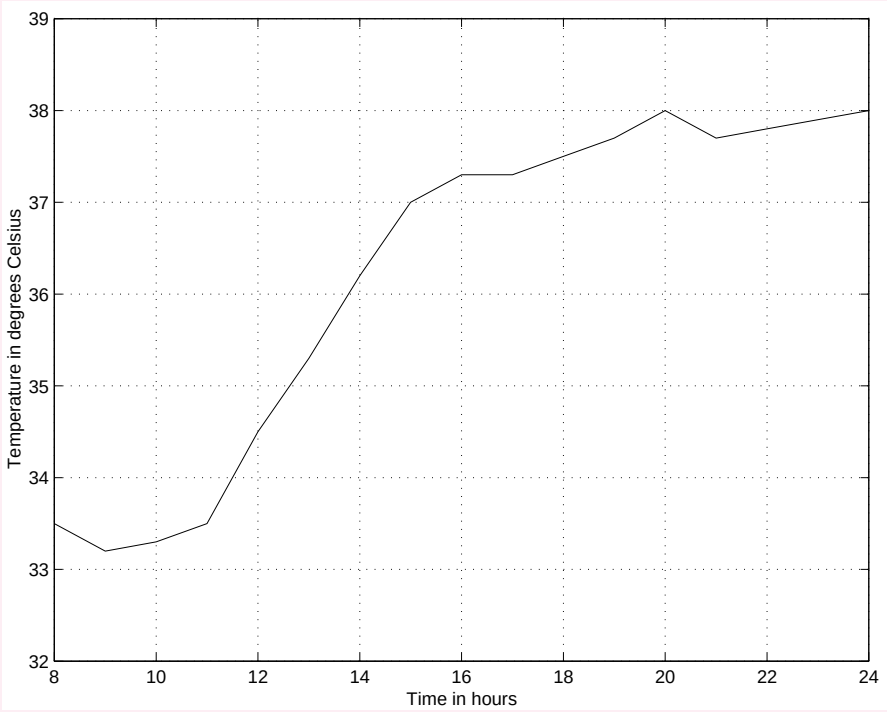
A discrete-time signal that can take amplitude values only from a limited list of *quantized* levels is called a *digital* signal.

$$x = 33.5\ ^\circ C$$

(a)

Time (h)	08:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00	24:00
$x(n)$ $(^\circ C)$	33.5	33.3	34.5	36.2	37.3	37.5	38.0	37.8	38.0

(b)



(c)

Figure 1.2: Measurements of the temperature of a patient presented as (a) a scalar with one temperature measurement x at an unspecified instant of time, (b) an array $x(n)$ made up of several measurements at different instants of time, and (c) a plot of the signal $x(n)$ or $x(t)$. The horizontal axis of the plot represents time in *hours*; the vertical axis gives temperature in *degrees Celsius*. Data courtesy of Foothills Hospital, Calgary.

Another basic measurement in health care and monitoring:

blood pressure (BP).

Each measurement consists of two values —

the systolic pressure and the diastolic pressure.

Units: millimeters of mercury ($mm\ of\ Hg$)

in clinical practice,

although the international standard unit for pressure

is the *Pascal* ($1\ Pa = 0.0075\ mm\ of\ Hg$).

A single BP measurement:

a *vector* $\mathbf{x} = [x_1, x_2]^T$ with two components:

x_1 indicating the systolic pressure and

x_2 indicating the diastolic pressure.

When BP is measured at a few instants of time:

an array of vectorial values $\mathbf{x}(n)$

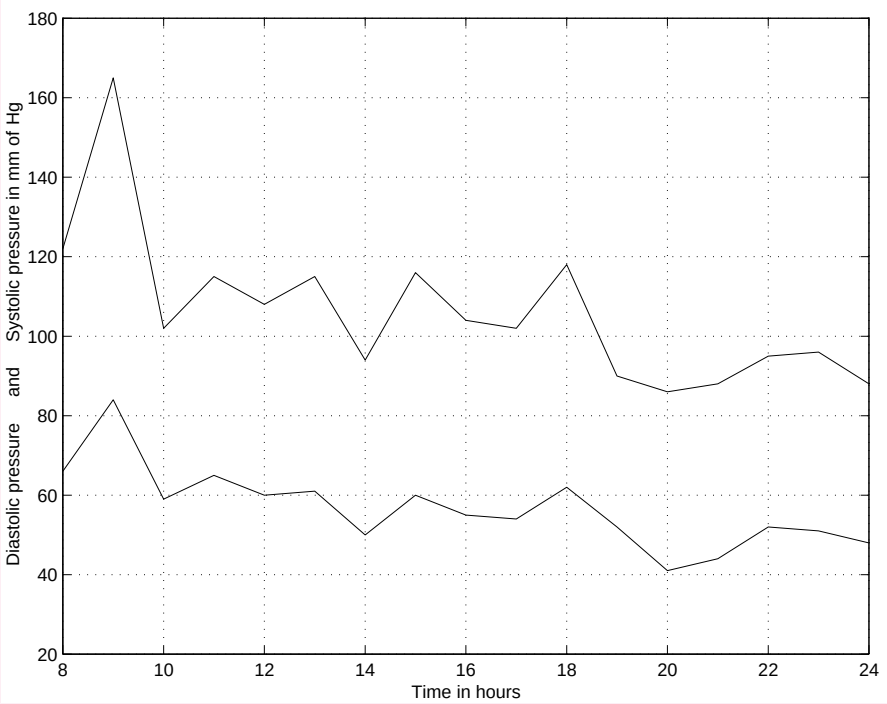
or a function of time $\mathbf{x}(t)$.

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} Systolic \\ Diastolic \end{bmatrix} = \begin{bmatrix} 122 \\ 66 \end{bmatrix}$$

(a)

Time (h)	08:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00	24:00
Systolic	122	102	108	94	104	118	86	95	88
Diastolic	66	59	60	50	55	62	41	52	48

(b)



(c)

Figure 1.3: Measurements of the BP of a patient presented as (a) a single pair or vector of systolic and diastolic measurements $\mathbf{x}$ in *mm of Hg* at an unspecified instant of time, (b) an array $\mathbf{x}(n)$ made up of several measurements at different instants of time, and (c) a signal $\mathbf{x}(t)$ or $\mathbf{x}(n)$. Note the use of boldface $\mathbf{x}$ to indicate that each measurement is a vector with two components. The horizontal axis of the plot represents time in *hours*; the vertical axis gives the systolic pressure (upper trace) and the diastolic pressure (lower trace) in *mm of Hg*. Data courtesy of Foothills Hospital, Calgary.

1.2 Examples of Biomedical Signals

1.2.1 The action potential

Action potential: electrical signal that accompanies the mechanical contraction of a single cell when stimulated by an electrical current (neural or external).

Cause: flow of sodium (Na^+), potassium (K^+), chloride (Cl^-), and other ions across the cell membrane.

Action potentials are also associated with signals and messages transmitted in the nervous system with no accompanying contraction.

Hodgkin and Huxley conducted pioneering work on recording action potentials from a nerve fiber.

Action potential:

Basic component of all bioelectrical signals.

Provides information on the nature of physiological activity at the single-cell level.

Recording an action potential requires the isolation of a single cell,

and microelectrodes with tips of the order of a few micrometers

to stimulate the cell and record the response.

Resting potential:

Nerve and muscle cells are encased in a

semipermeable membrane:

permits selected substances to pass through; others kept out.

Body fluids surrounding cells are conductive solutions

containing charged atoms known as ions.

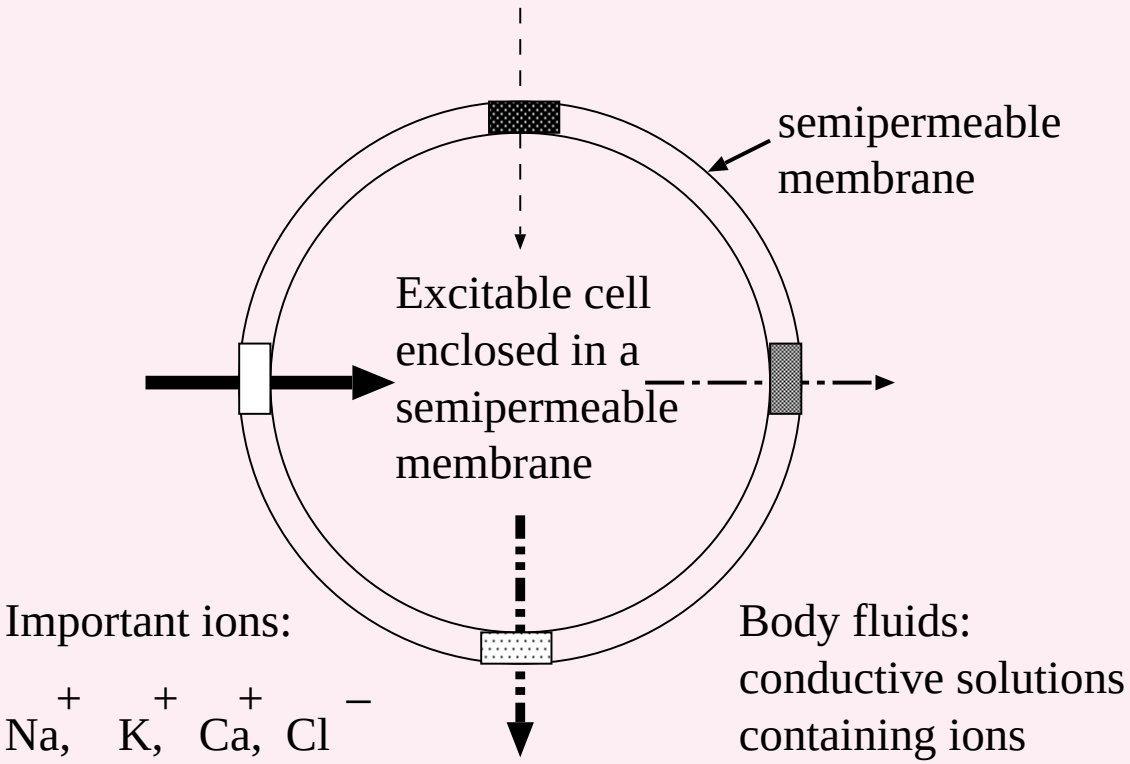
Resting state: membranes of excitable cells

permit entry of K^+ and Cl^-, but block Na^+ ions —

permeability for K^+ is 50–100 times that for Na^+.

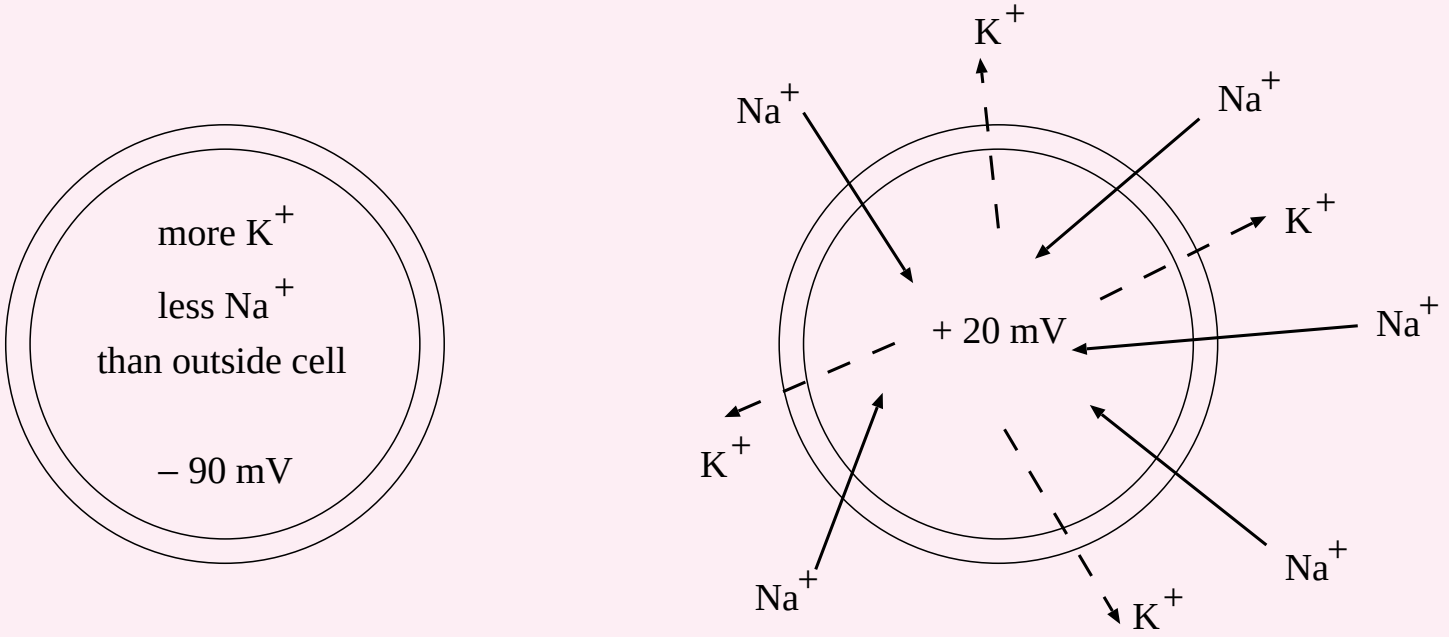
Various ions seek to establish inside vs outside balance

according to charge and concentration.



Selective permeability: some ions can move in and out of the cell easily, whereas others cannot, depending upon the state of the cell and the voltage-gated ion channels.

Figure 1.4: Schematic representation of a cell and its characteristics. The parts of the cell membrane with different shades and the corresponding arrows of different types and thickness represent, in a schematic manner, the variable permeability of the membrane to different ions.



At rest: permeability for K^+ 50 to 100 times that for Na^+. The cell is polarized.

Depolarization: triggered by a stimulus; fast Na^+ channels open

Figure 1.5: Schematic representation of a cell in its resting or polarized state (left) and the process of depolarization of the cell due to a stimulus (right).

Results of the inability of Na^+ to penetrate a cell membrane:

- Na^+ concentration inside is far less than that outside.
- The outside of the cell is more positive than the inside.
- To balance the charge, additional K^+ ions enter the cell, causing higher K^+ concentration inside than outside.
- Charge balance cannot be reached due to differences in membrane permeability for various ions.
- State of equilibrium established with a potential difference:

  inside of the cell negative with respect to the outside.

A cell in its resting state is said to be *polarized.*

Most cells maintain a *resting potential* of the order of

-60 to $-100\ mV$

until some disturbance or stimulus upsets the equilibrium.

Depolarization:

When a cell is excited by ionic currents or an external stimulus, the membrane changes its characteristics and begins to allow Na^+ ions to enter the cell.

This movement of Na^+ ions constitutes an ionic current, which further reduces the membrane barrier to Na^+ ions.

Avalanche effect: Na^+ ions rush into the cell.

K^+ ions try to leave the cell

as they were in higher concentration inside the cell

in the preceding resting state,

but cannot move as fast as the Na^+ ions.

Net result: the inside of the cell becomes positive

with respect to the outside due to an imbalance of K^+.

New state of equilibrium reached

after the rush of Na^+ ions stops.

This represents the beginning of the *action potential*,

with a peak value of about $+20\ mV$ for most cells.

An excited cell displaying an action potential

is said to be *depolarized;*

the process is called *depolarization.*

Repolarization:

After a certain period of being in the depolarized state

the cell becomes polarized again and

returns to its resting potential

via a process known as *repolarization.*

Principal ion involved in repolarization: K^+.

Voltage-dependent K^+ channels:

predominant membrane permeability for K^+.

K^+ concentration is much higher inside the cell:

net efflux of K^+ from the cell,

the inside becomes more negative,

repolarization back to the resting potential.

Nerve and muscle cells repolarize rapidly:

action potential duration of about $1\ ms$.

Heart muscle cells repolarize slowly:

action potential duration of $150 - 300\ ms$.

The action potential is always the same for a given cell,

regardless of the method of excitation or

the intensity of the stimulus beyond a threshold:

all-or-none or *all-or-nothing* phenomenon.

After an action potential, there is a period during which

a cell cannot respond to any new stimulus:

absolute refractory period — about $1\ ms$ in nerve cells.

This is followed by a *relative refractory period:*

another action potential may be triggered by a

much stronger stimulus than in the normal situation.

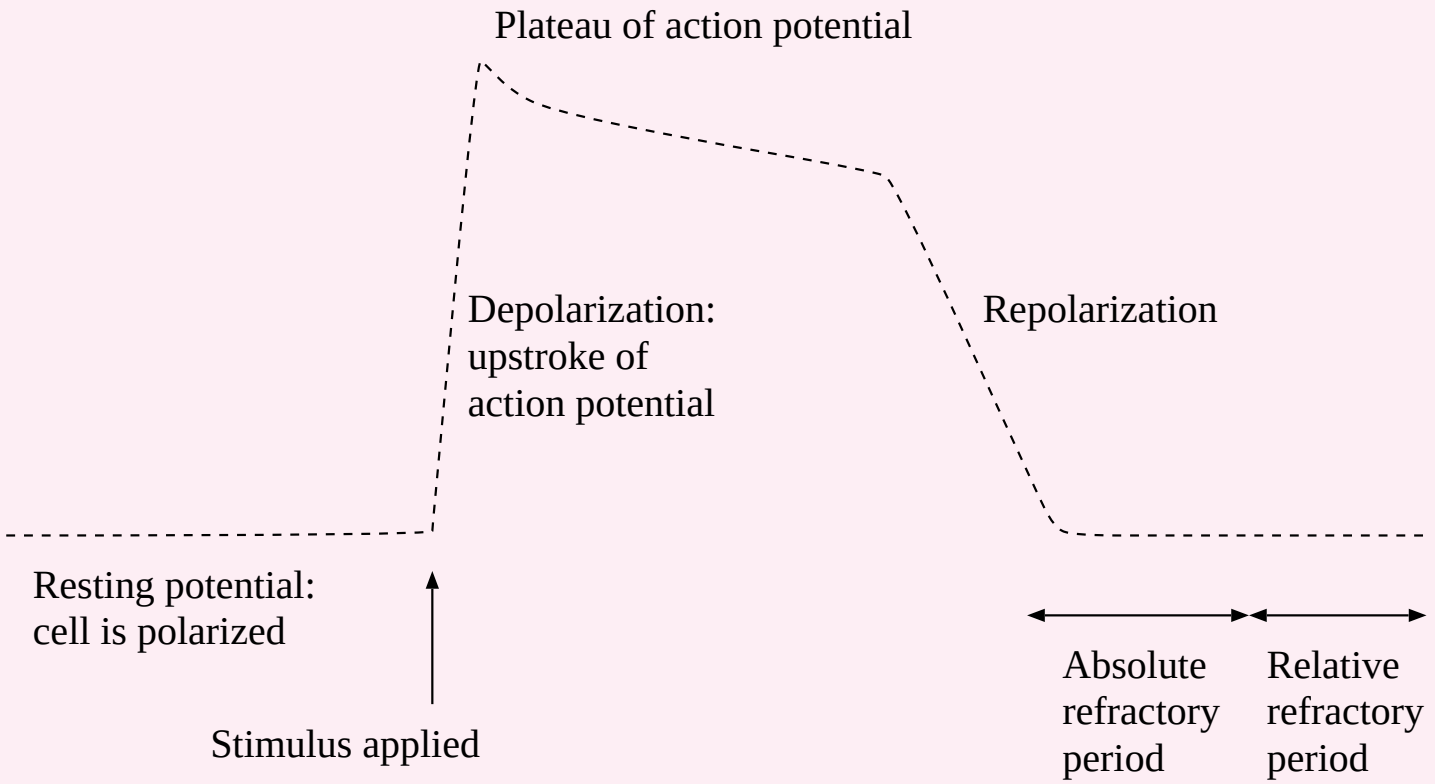


Figure 1.6: Illustration of the various phases or intervals of an action potential. Some specifications of the absolute refractory period include the duration of the action potential itself.

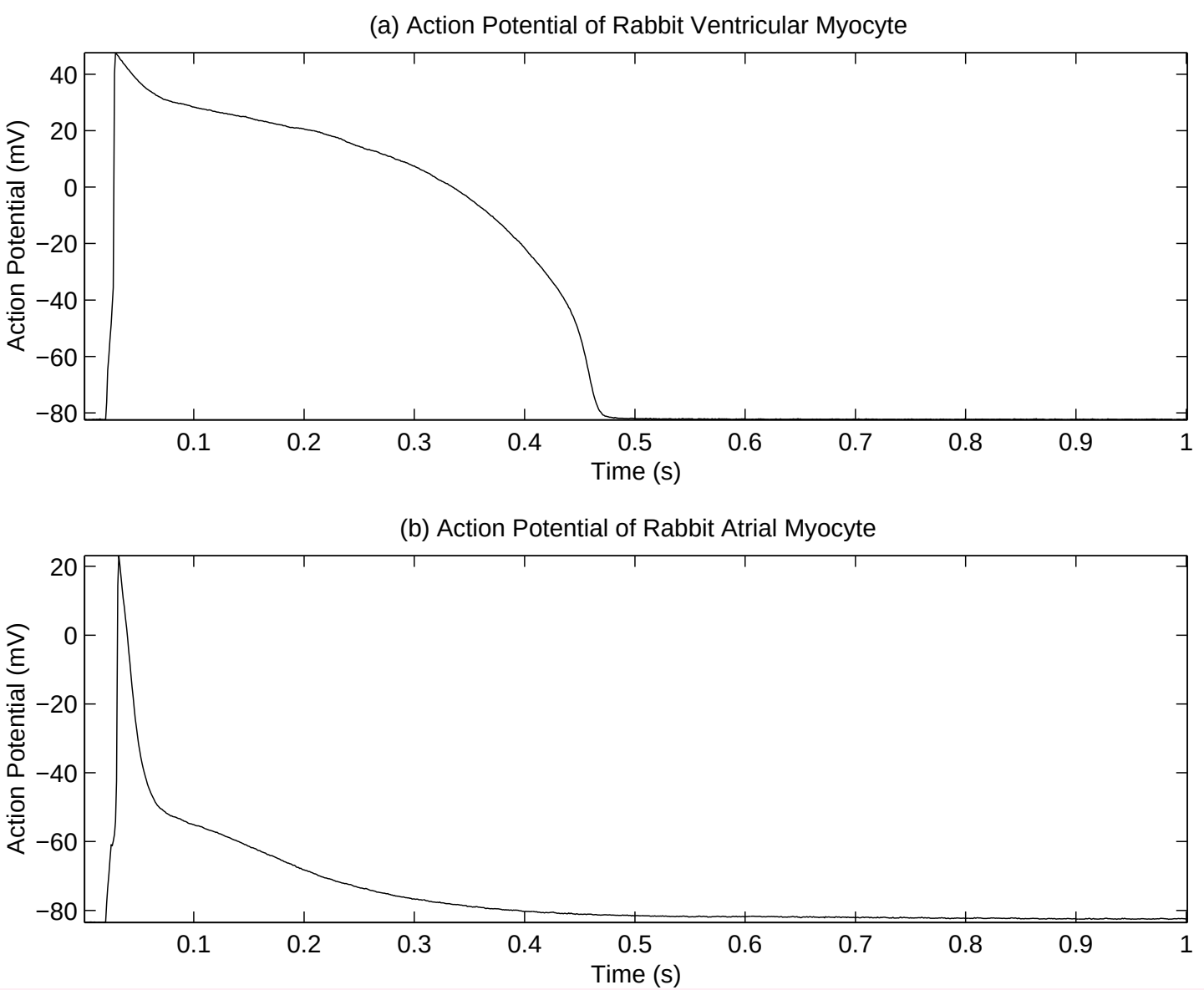
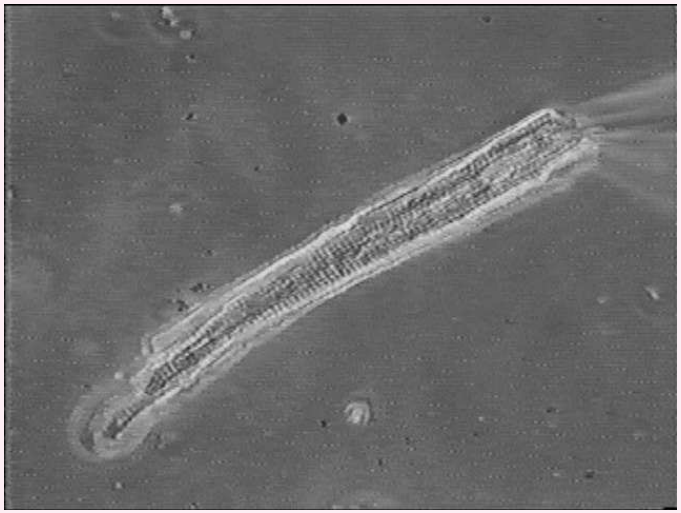
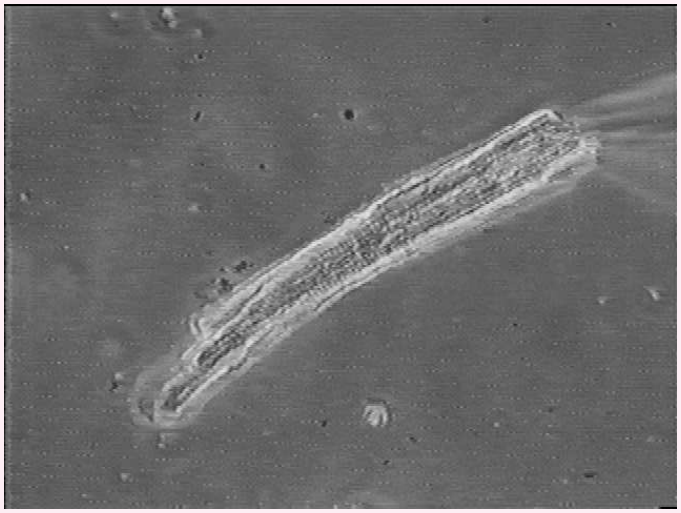


Figure 1.7: Action potentials of rabbit ventricular and atrial myocytes. Data courtesy of R. Clark, Department of Physiology and Biophysics, University of Calgary.



(a)



(b)

Figure 1.8: A single ventricular myocyte (of a rabbit) in its (a) relaxed and (b) fully contracted states. The length of the myocyte is approximately 25 μm. The tip of the glass pipette, faintly visible at the upper-right end of the myocyte, is approximately 2 μm wide. A square pulse of current, 3 ms in duration and 1 nA in amplitude, was passed through the recording electrode and across the cell membrane causing the cell to depolarize rapidly. Images courtesy of R. Clark, Department of Physiology and Biophysics, University of Calgary.

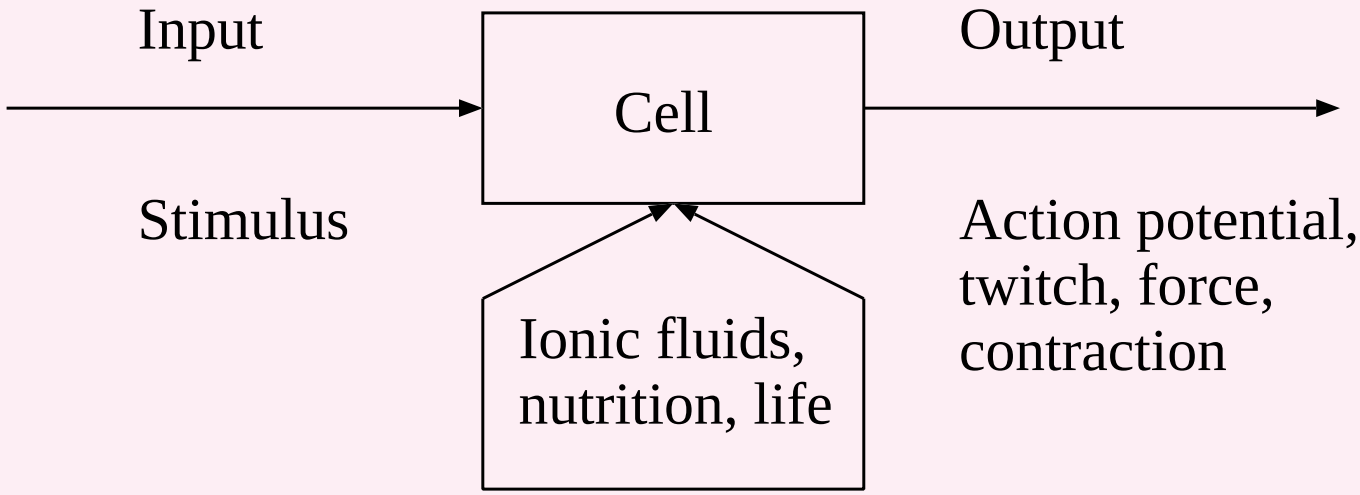


Figure 1.9: Schematic representation of a cell as a system. Upon receiving an input of a stimulus, the cell provides a response that could cause an action potential, a twitch, contraction, or force.

1.2.2 The action potential of a neuron

In studies of the central nervous system (CNS),

it is desirable to record the action potentials

of isolated neurons *in situ*.

Hodgkin and Huxley conducted pioneering studies on

recording action potentials from the giant axon of the squid;

they proposed mathematical and electrical circuit models

for the generation of action potentials.

Drake et al. described the design and performance of a multisite microprobe system to record isolated and interrelated neuronal activity *in vivo*.

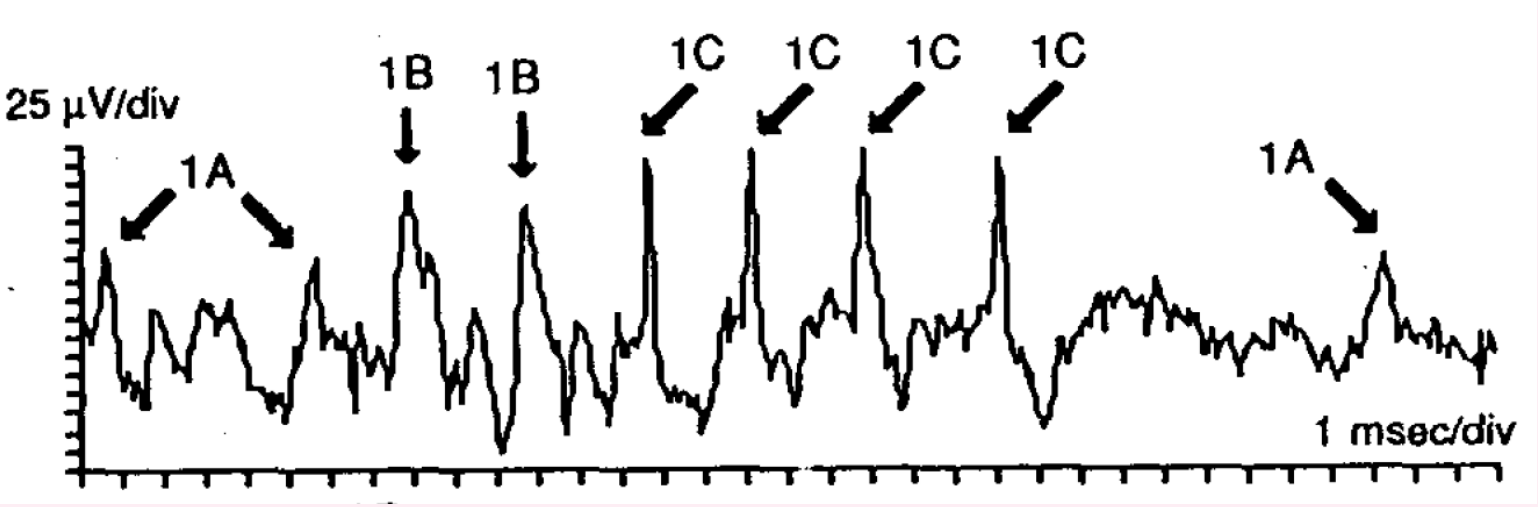


Figure 1.10: Neuronal action potentials recorded from a rat's brain using a multisite microprobe system. The action potentials marked 1A have low amplitude, just above the baseline neural noise level. The action potentials marked 1B possess broader waveforms and could possibly be composed of two superimposed action potentials. The action potentials marked 1C are clearly isolated, have the same amplitude, and are likely from the same cell. Reproduced with permission from K.L. Drake, K.D. Wise, J. Farraye, D.J. Anderson, and S.L. BeMent, Performance of planar multisite microprobes in recording extracellular single-unit intracortical activity, *IEEE Transactions on Biomedical Engineering*, 35(9):719–732, 1988. ©IEEE.

An action potential propagates along a muscle fiber or an unmyelinated nerve fiber as follows:

Once initiated by a stimulus, the action potential propagates along the whole length of a fiber without decrease in amplitude by progressive depolarization of the membrane.

Current flows from a depolarized region through the intracellular fluid to adjacent inactive regions, thereby depolarizing them.

Current also flows through the extracellular fluids, through the depolarized membrane, and back into the intracellular space, completing the local circuit.

The energy to maintain conduction is supplied by the fiber.

Myelinated nerve fibers are covered by an insulating sheath of *myelin*, interrupted every few millimeters by spaces known as the *nodes of Ranvier*, where the fiber is exposed to the interstitial fluid. Sites of excitation and changes of membrane permeability exist only at the nodes: current flows by jumping from one node to the next in a process known as *saltatory conduction*.

1.2.3 The electroneurogram (ENG)

The ENG is an electrical signal observed as a stimulus and the associated nerve action potential propagate over the length of a nerve.

ENGs used to measure the velocity of propagation

or conduction velocity of a stimulus or action potential.

ENGs may be recorded using concentric needle electrodes

or $Ag - AgCl$ electrodes at the surface of the body.

Conduction velocity in a peripheral nerve measured by

stimulating a motor nerve

and measuring the related activity at two points

at known distances along its course.

Stimulus: $100\ V$, $100 - 300\ \mu s$.

ENG amplitude: $10\ \mu V$;

Amplifier gain: $2,000$; Bandwidth $10 - 10,000\ Hz$.

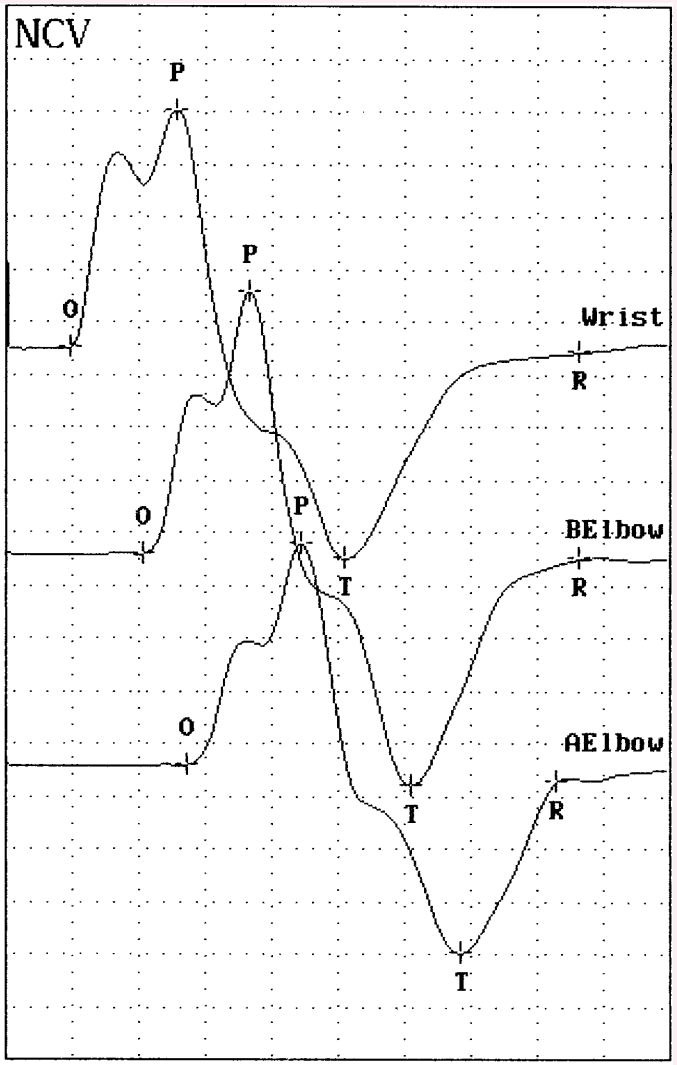


Figure 1.11: Nerve conduction velocity measurement via electrical stimulation of the ulnar nerve. The grid boxes represent 3 ms in width and 2 μV in height. AElbow: above the elbow. BElbow: below the elbow. O: onset. P: Peak. T: trough. R: recovery of base-line. Courtesy of M. Wilson and C. Adams, Alberta Children's Hospital, Calgary.

The responses shown in the figure are normal.

BElbow – Wrist latency 3.23 ms. Nerve conduction velocity 64.9 m/s.

Typical nerve conduction velocity:

- $45 - 70\ m/s$ in nerve fibers;
- $0.2 - 0.4\ m/s$ in heart muscle;
- $0.03 - 0.05\ m/s$ in time-delay fibers between the atria and ventricles.

Neural diseases may cause a decrease in conduction velocity.

1.2.4 The electromyogram (EMG)

Skeletal muscle fibers are twitch fibers:

produce a mechanical twitch response for a single stimulus

and generate a propagated action potential.

Skeletal muscles made up of collections of

motor units (MUs),

each of which consists of an anterior horn cell,

or motoneuron or motor neuron,

its axon, and all muscle fibers innervated by that axon.

Motor unit: smallest muscle unit

that can be activated by volitional effort.

Constituent fibers of an MU activated synchronously.

Component fibers of an MU extend lengthwise

in loose bundles along the muscle.

Fibers of an MU interspersed with the fibers of other MUs.

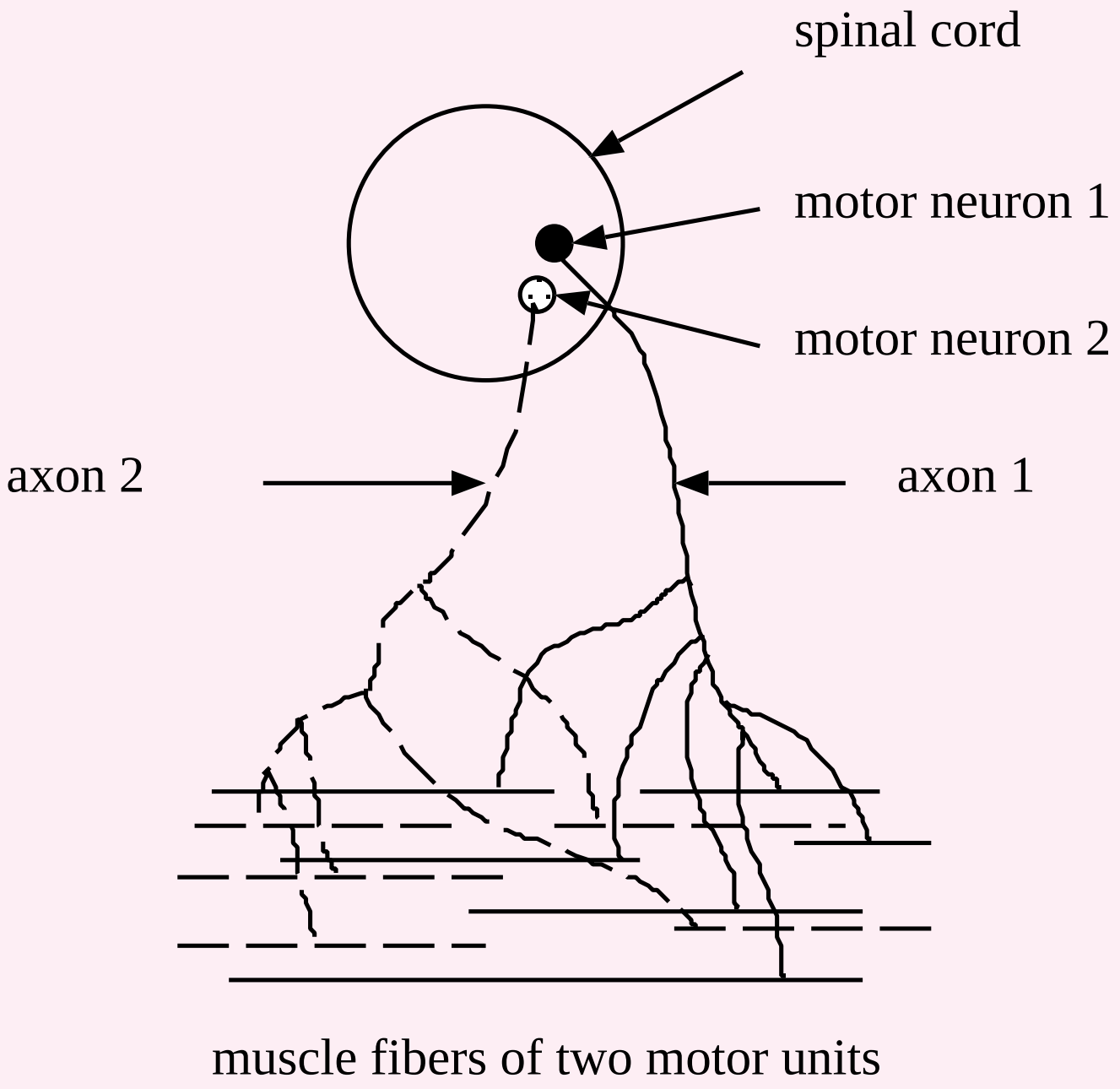


Figure 1.12: Schematic representation of two motor units, one in solid line and the other in dashed line.

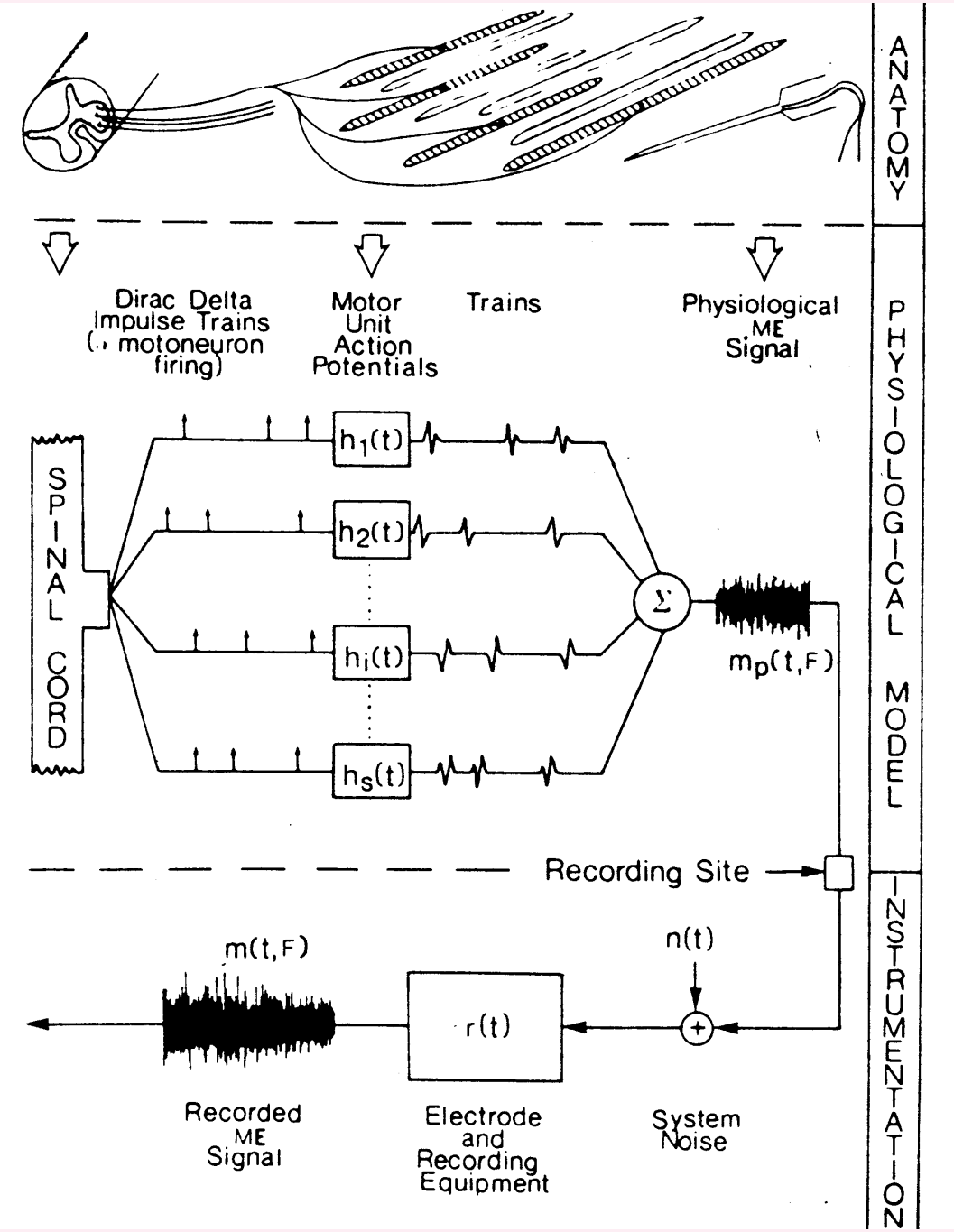


Figure 1.13: Schematic representation of a motor unit and model for the generation of EMG signals. Top panel: A motor unit includes an anterior horn cell or motor neuron (illustrated in a cross-section of the spinal cord), an axon, and several connected muscle fibers. The hatched fibers belong to one motor unit; the non-hatched fibers belong to other motor units. A needle electrode is also illustrated. Middle panel: The firing pattern of each motor neuron is represented by an impulse train. Each system $h_i(t)$ shown represents a motor unit that is activated and generates a train of SMUAPs. The net EMG is the sum of several SMUAP trains. Bottom panel: Effects of instrumentation on the EMG signal acquired. The observed EMG is a function of time t and muscular force produced F. Reproduced with permission from C.J. de Luca, Physiology and mathematics of myoelectric signals, *IEEE Transactions on Biomedical Engineering,* 26:313–325, 1979. ©IEEE.

Muscles for gross movement have 100s of fibers/MU;

muscles for precise movement have fewer fibers per MU.

Number of muscle fibers per motor nerve fiber:

innervation ratio.

Mechanical output (contraction) of a muscle = net result of stimulation and contraction of several of its MUs.

The platysma, a large sheet-like muscle spanning parts of the pectoral muscle, deltoid, clavicle, and neck, has

$1,826$ large nerve fibers controlling

$27,100$ muscle fibers in

$1,096$ MUs:

~ 25 muscle fibers per MU.

The first dorsal interosseus (FDI) muscle

on the back of the palm of the hand and the index finger has

199 large nerve fibers and

$40,500$ muscle fibers in

119 MUs:

~ 340 muscle fibers per MU.

The medial gastrocnemius (calf muscle of the leg) has

965 large nerve fibers and

$1,120,000$ muscle fibers in

579 MUs:

$\sim 1,934$ muscle fibers per MU.

Laryngeal muscles have been estimated to have only $2 - 3$ muscle fibers per MU.

Brown and Harvey studied the muscles of cats' eyes and noted that not more than 10 muscle fibers are supplied by a single nerve fiber in the extrinsic ocular muscles.

Gath and Stålberg used a multielectrode probe for *in situ* measurement of the innervation ratios of human muscles.

Estimated the number of muscle fibers per MU:

72 in the brachial biceps,

70 in the deltoid, and

124 in the tibialis anterior.

When stimulated by a neural signal, each MU contracts and causes an electrical signal that is the summation of the action potentials of all of its constituent cells: this is known as the *single-motor-unit action potential*.

SMUAP or MUAP recorded using needle electrodes.

Normal SMUAPs usually biphasic or triphasic;

$3 - 15\ ms$ in duration, $100 - 300\ \mu V$ in amplitude, appear with frequency of $6 - 30/s$.

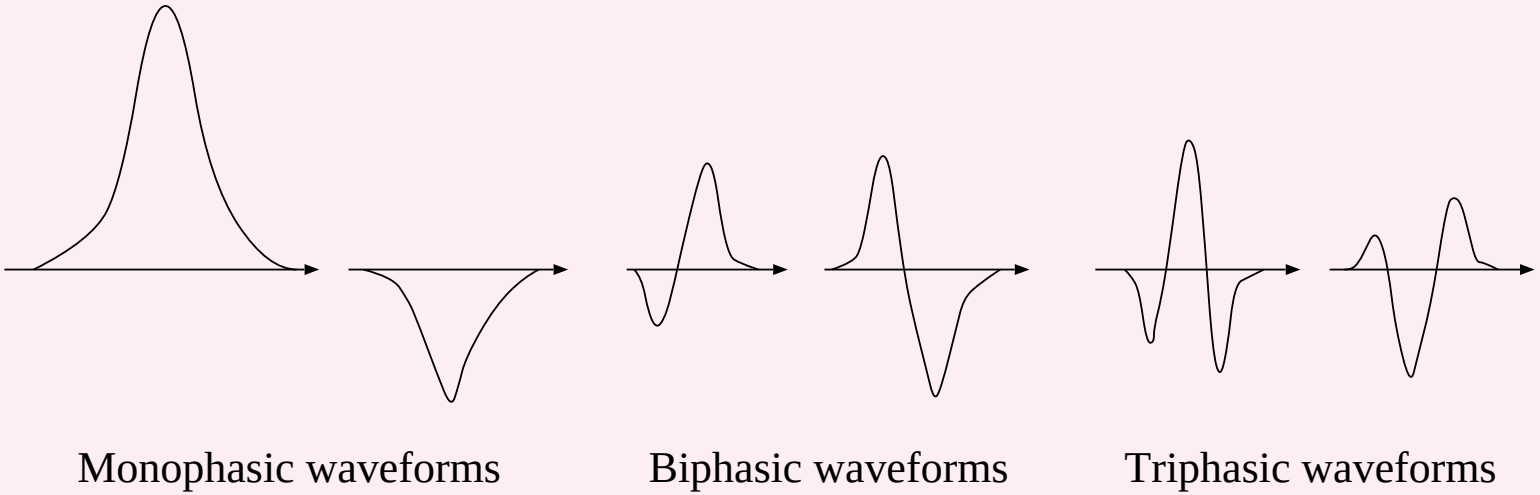


Figure 1.14: Schematic representations of monophasic, biphasic, and triphasic waveforms.

The shape of a recorded SMUAP depends upon

the type of the needle electrode used,

its position with respect to the active MU,

and the projection of the electrical field of the activity

on to the electrodes.

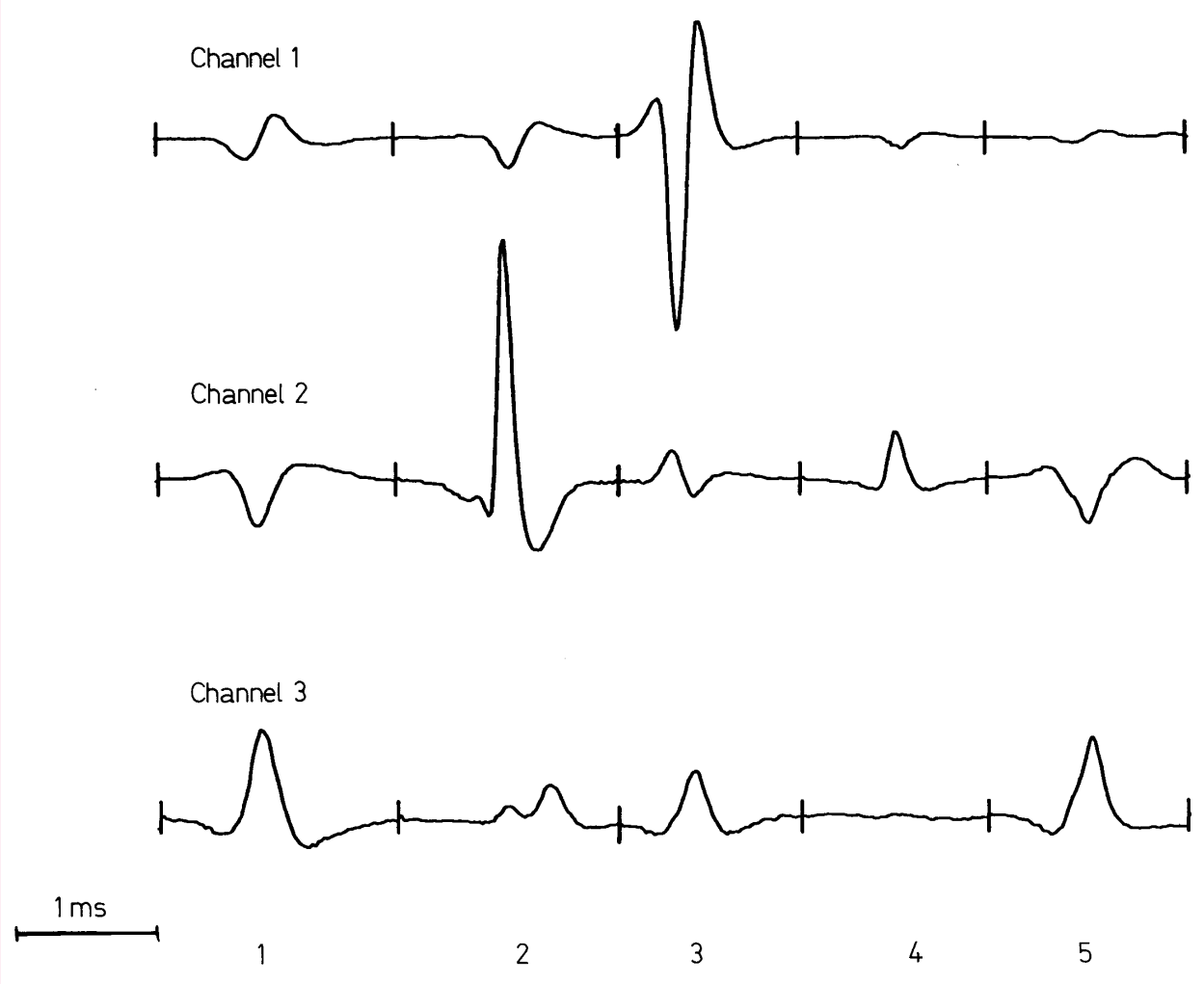


Figure 1.15: SMUAP trains recorded simultaneously from three channels of needle electrodes. Observe the different shapes of the same SMUAPs projected on to the axes of the three channels. Three different motor units are active over the duration of the signals illustrated. Reproduced with permission from B. Mambrito and C.J. de Luca, Acquisition and decomposition of the EMG signal, in *Progress in Clinical Neurophysiology*, Volume 10: Computer-aided Electromyography, Editor: J.E. Desmedt, pp 52–72, 1983. ©S. Karger AG, Basel, Switzerland.

The shape of SMUAPs is affected by disease.

Neuropathy: slow conduction,

desynchronized activation of fibers,

polyphasic SMUAP with an amplitude larger than normal.

The same MU may fire at higher rates than normal

before more MUs are recruited.

Myopathy: loss of muscle fibers in MUs,

with the neurons presumably intact.

Splintering of SMUAPs occurs due to

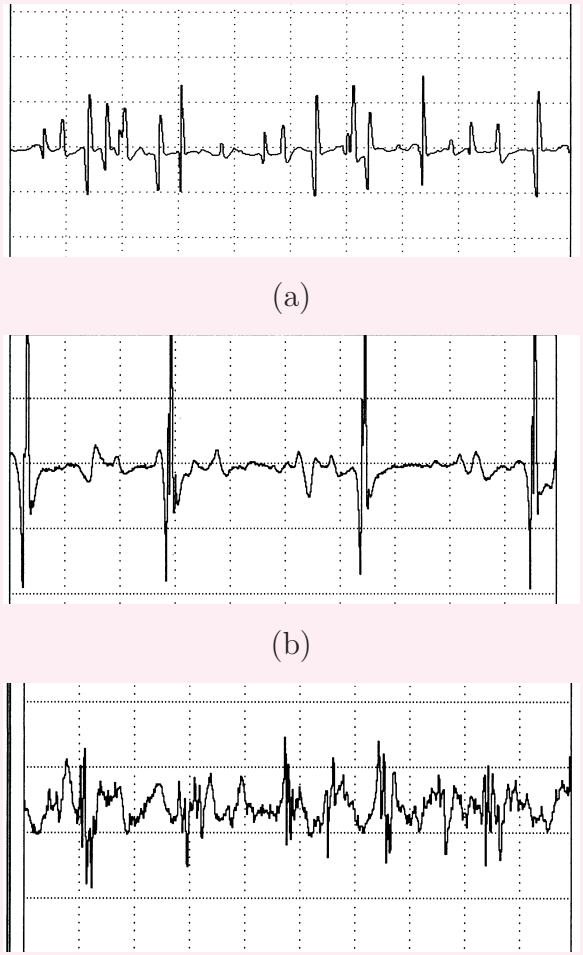
asynchrony in activation

as a result of patchy destruction of fibers

(muscular dystrophy),

leading to splintered SMUAPs.

More MUs recruited at low levels of effort.



(a)

(b)

(c)

Figure 1.16: Examples of SMUAP trains. (a) From the right deltoid of a normal subject, male, 11 years; the SMUAPs are mostly biphasic, with duration in the range $3-5$ ms. (b) From the deltoid of a six-month-old male patient with brachial plexus injury (neuropathy); the SMUAPs are polyphasic and large in amplitude (800 μV), and the same motor unit is firing at a relatively high rate at low-to-medium levels of effort. (c) From the right biceps of a 17-year-old male patient with myopathy; the SMUAPs are polyphasic and indicate early recruitment of more motor units at a low level of effort. The signals were recorded with gauge 20 needle electrodes. The width of each grid box represents a duration of 20 ms; its height represents an amplitude of 200 μV. Courtesy of M. Wilson and C. Adams, Alberta Children's Hospital, Calgary.

Gradation of muscular contraction:

Muscular contraction levels are controlled in two ways:

- *Spatial recruitment* — activating new MUs, and
- *Temporal recruitment* — increasing the frequency of discharge or firing rate of each MU,

with increasing effort.

MUs activated at different times and at different frequencies:

asynchronous contraction.

The twitches of individual MUs sum and fuse to form

tetanic contraction and increased force.

Weak volitional effort: MUs fire at about $5 - 15\ pps$.

As greater tension is developed, an *interference pattern*

EMG is obtained, with the active MUs firing at $25 - 50\ pps$.

Spatiotemporal summation of the MUAPs of all active MUs gives rise to the EMG of the muscle.

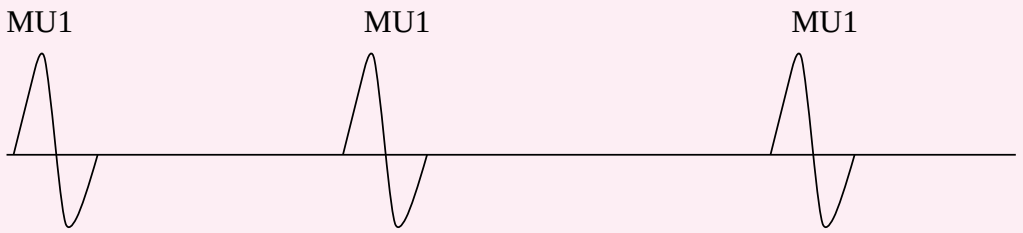
EMG signals recorded using surface electrodes:

complex signals including interference patterns

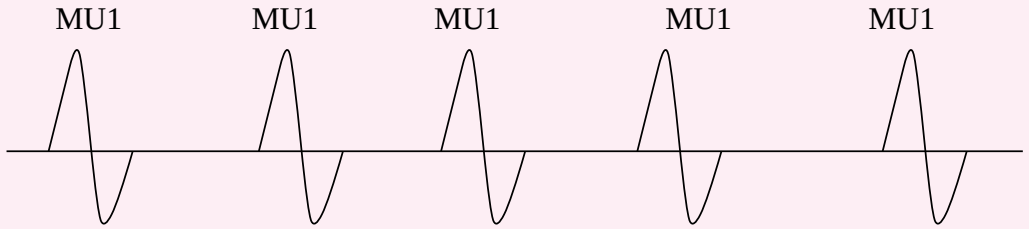
of several MUAP trains — difficult to analyze.

EMG may be used to diagnose neuromuscular diseases

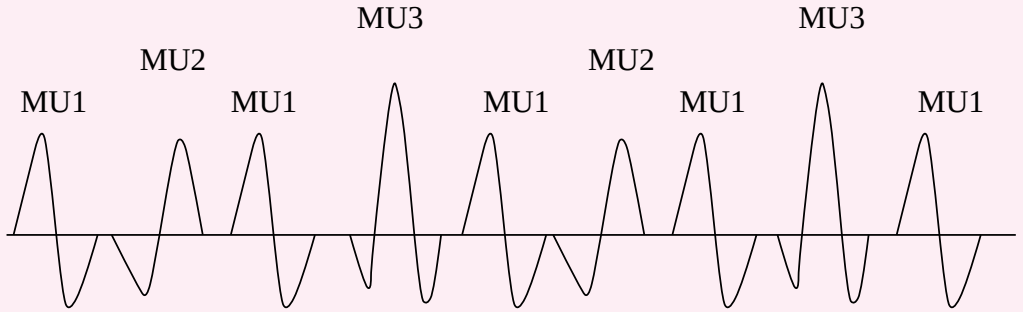
such as neuropathy and myopathy.



(a) At the beginning with low effort, only motor unit MU1 is firing at a low rate.



(b) At a slightly higher level of effort, with temporal recruitment, the firing rate of MU1 is increased. No other motor unit has been recruited yet.



(c) At an even higher level of effort, with spatial recruitment, new motor units MU2 and MU3 have been brought into action. MU1 continues to fire at the same rate as in (b).

Figure 1.17: Schematic representation of spatiotemporal recruitment of motor units and the resulting EMG signals. To keep the illustration simple, it is assumed that the MUAPs do not overlap.

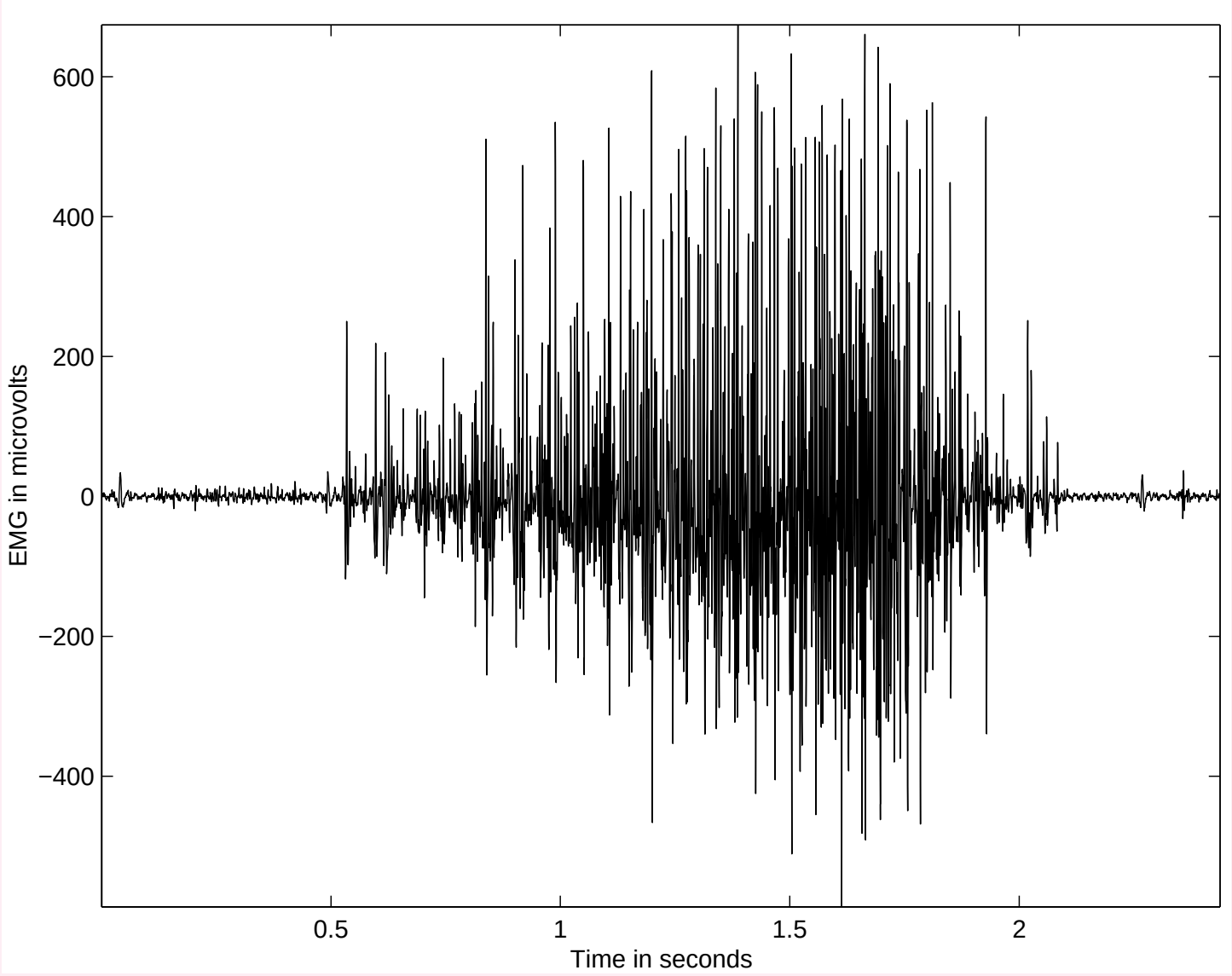


Figure 1.18: EMG signal recorded from the crural diaphragm muscle of a dog using implanted fine-wire electrodes. Data courtesy of R.S. Platt and P.A. Easton, Department of Clinical Neurosciences, University of Calgary.

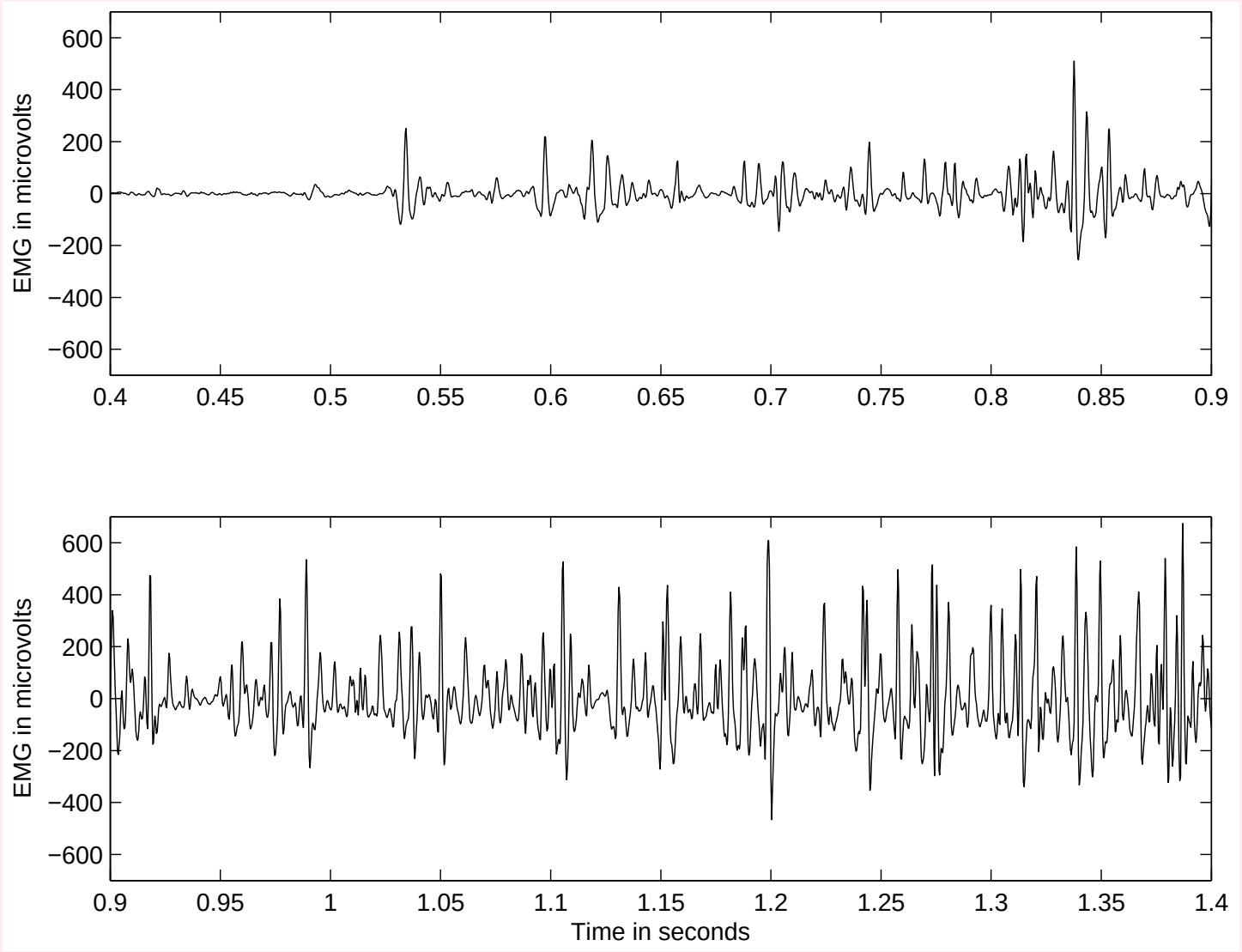


Figure 1.19: The initial part of the EMG signal in Figure 1.18 shown on an expanded time scale. Observe the SMUAPs at the initial stages of contraction, followed by increasingly complex interference patterns of several MUAPs. Data courtesy of R.S. Platt and P.A. Easton, Department of Clinical Neurosciences, University of Calgary.

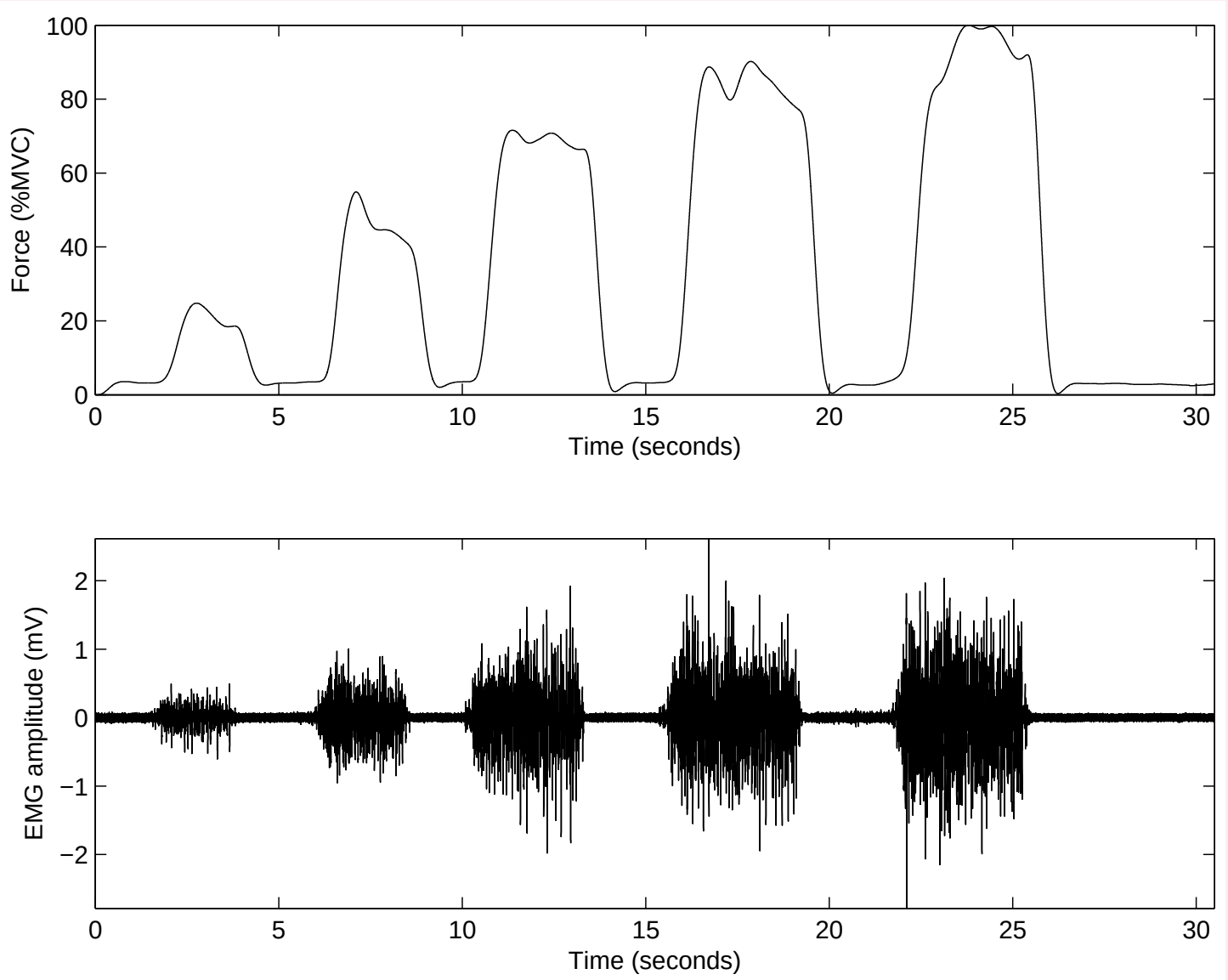


Figure 1.20: Force signal (upper plot) and the EMG signal (lower plot) recorded from the forearm muscle of a subject using surface electrodes; see also Figure 1.21. Data courtesy of Shantanu Banik. MVC: maximal voluntary contraction.

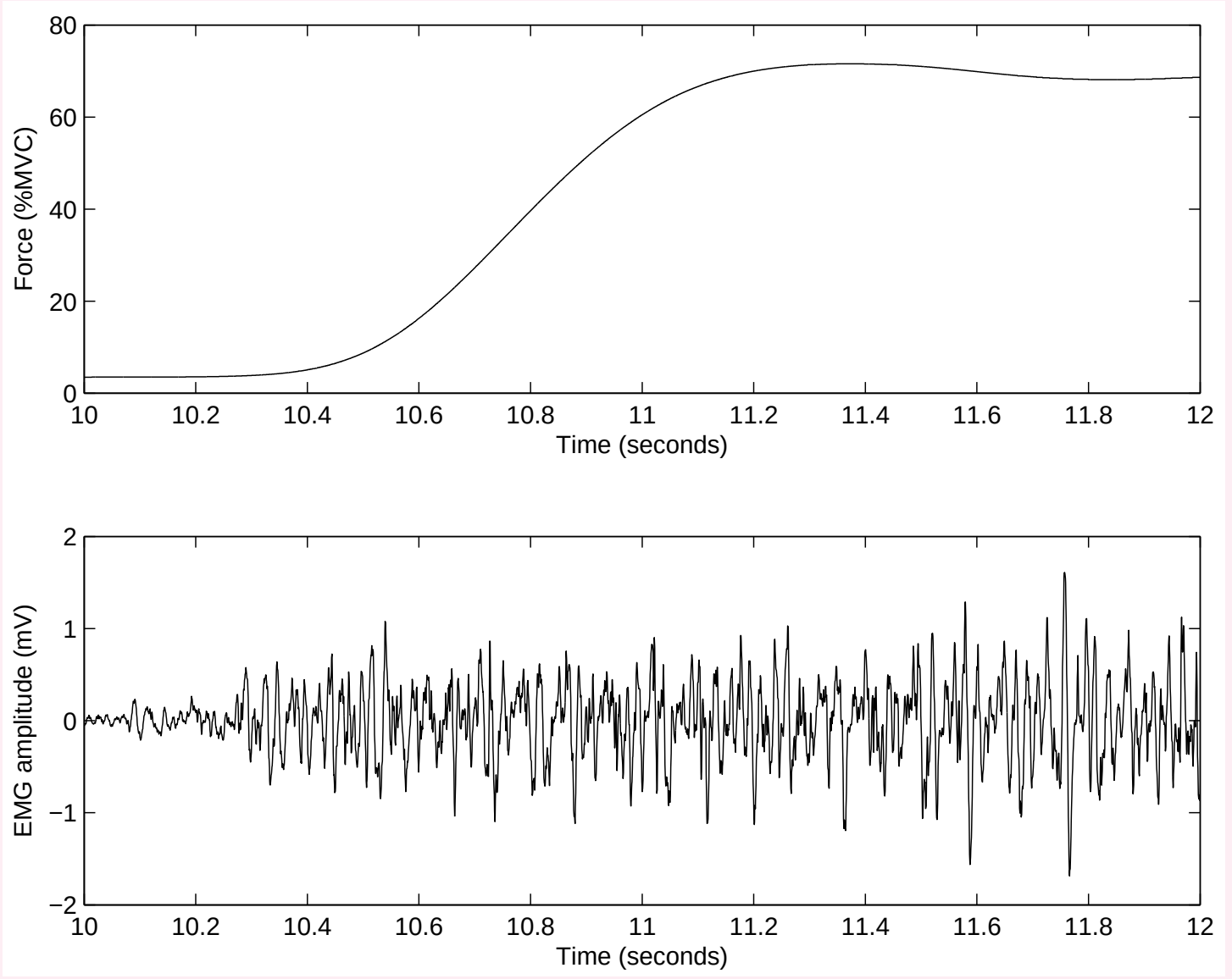


Figure 1.21: Expanded view of the part of the EMG (lower plot) and force signals (upper plot) in Figure 1.20 over the period $10 - 12$ s. Observe the increasing levels of the range and power of the EMG signal at the initial stages of contraction. Data courtesy of Shantanu Banik.

1.2.5 The electrocardiogram (ECG)

ECG: electrical manifestation of the

contractile activity of the heart.

Recorded with surface electrodes on the limbs or chest.

ECG: most commonly known & used biomedical signal.

The rhythm of the heart in terms of beats per minute (*bpm*)

may be estimated by counting the readily identifiable waves.

ECG waveshape is altered by cardiovascular diseases and abnormalities: myocardial ischemia and infarction, ventricular hypertrophy, and conduction problems.

The heart:

A four-chambered pump with

two atria for collection of blood

and two ventricles for pumping out of blood.

Resting or filling phase of a cardiac chamber: *diastole;*

contracting or pumping phase: *systole.*

Right atrium (or auricle, RA): collects deoxygenated blood from the superior and inferior vena cavae.

Atrial contraction: blood is passed from the right atrium to the right ventricle (RV) through the tricuspid valve.

Ventricular systole: blood in the right ventricle pumped out through the pulmonary valve to the lungs for oxygenation.

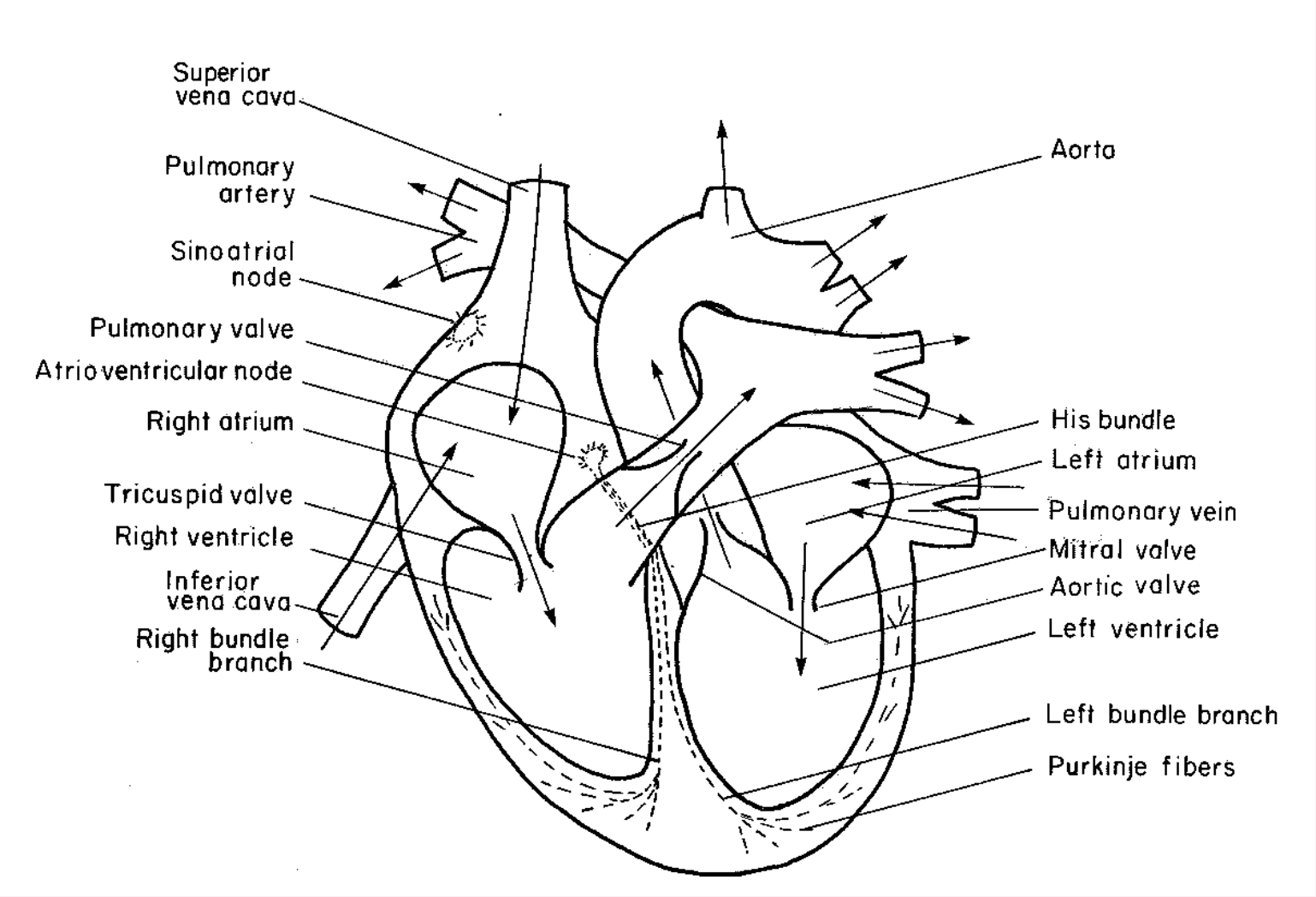


Figure 1.22: Schematic representation of the chambers, valves, vessels, and conduction system of the heart.

Left atrium (LA) receives oxygenated blood from the lungs.

Atrial contraction: blood passed to the

left ventricle (LV) via the mitral valve.

Left ventricle: largest and most important cardiac chamber.

Left ventricle: strongest contraction among the cardiac chambers to pump oxygenated blood through the aortic valve and the aorta against the pressure of the rest of the vascular system of the body.

The terms systole and diastole are applied to the ventricles by default.

Heart rate (HR) or cardiac rhythm controlled by

specialized pacemaker cells in the sinoatrial (SA) node.

Firing rate of SA node controlled by impulses from

the autonomous and central nervous systems

leading to the delivery of the neurotransmitters:

acetylcholine for vagal stimulation — reduced HR;

epinephrine for sympathetic stimulation — increased HR.

Normal, resting heart rate: $70\ bpm$.

Abnormally low $HR < 60\ bpm$ during activity:

bradycardia.

High resting HR due to illness or cardiac abnormalities:

tachycardia.

The electrical system of the heart:

Coordinated electrical events and a specialized

conduction system intrinsic and unique to the heart:

rhythmic contractile activity.

SA node: basic, natural cardiac pacemaker —

triggers its own train of action potentials.

SA node's action potential propagates through the heart

causing a particular pattern of excitation and contraction.

Sequence of events and waves in a cardiac cycle:

1. The SA node fires.
2. Electrical activity propagates through atrial musculature at comparatively low rates, causing slow-moving depolarization or contraction of the atria:
   P wave in the ECG.
   Due to slow contraction and small size of the atria,
   the P wave is a slow, low-amplitude wave:
   $0.1 - 0.2\ mV$, $60 - 80\ ms$.

3. Propagation delay at the atrioventricular (AV) node.
   Normally isoelectric segment of $60 - 80\ ms$
   after the P wave in the ECG — PQ segment.
   Transfer of blood from the atria to the ventricles.
4. The AV node fires.
5. The His bundle, the bundle branches, and the
   Purkinje system of specialized conduction fibers
   propagate the stimulus to the ventricles at a high rate.

6. The wave of stimulus spreads rapidly from the apex of the heart upwards, causing rapid depolarization or contraction of the ventricles:
   QRS wave — sharp biphasic or triphasic wave
   $1\ mV$ amplitude and $80\ ms$ duration.

7. Ventricular muscle cells possess a relatively long action potential duration of $300 - 350\ ms$.
   The plateau portion of the action potential causes a normally isoelectric segment of about $100 - 120\ ms$ after the QRS: the ST segment.
8. Repolarization or relaxation of the ventricles causes the slow T wave, with amplitude of $0.1 - 0.3\ mV$ and duration of $120 - 160\ ms$.

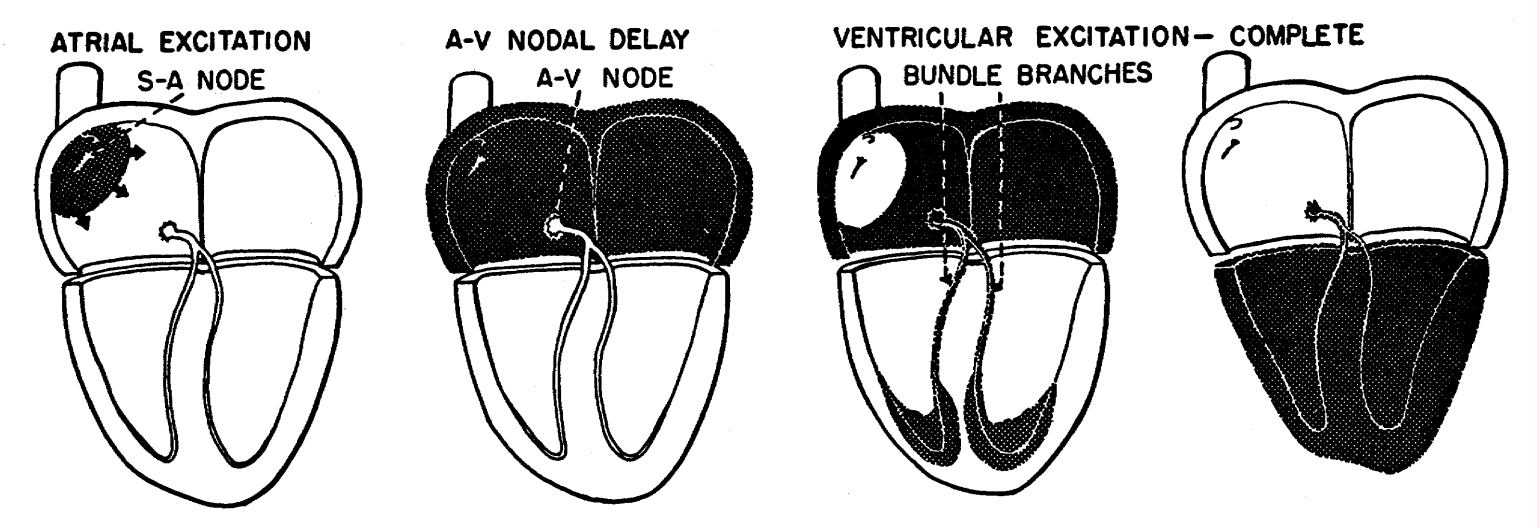


Figure 1.23: Propagation of the excitation pulse through the heart. Reproduced with permission from R.F. Rushmer, *Cardiovascular Dynamics*, 4th edition, ©W.B. Saunders, Philadelphia, PA, 1976.

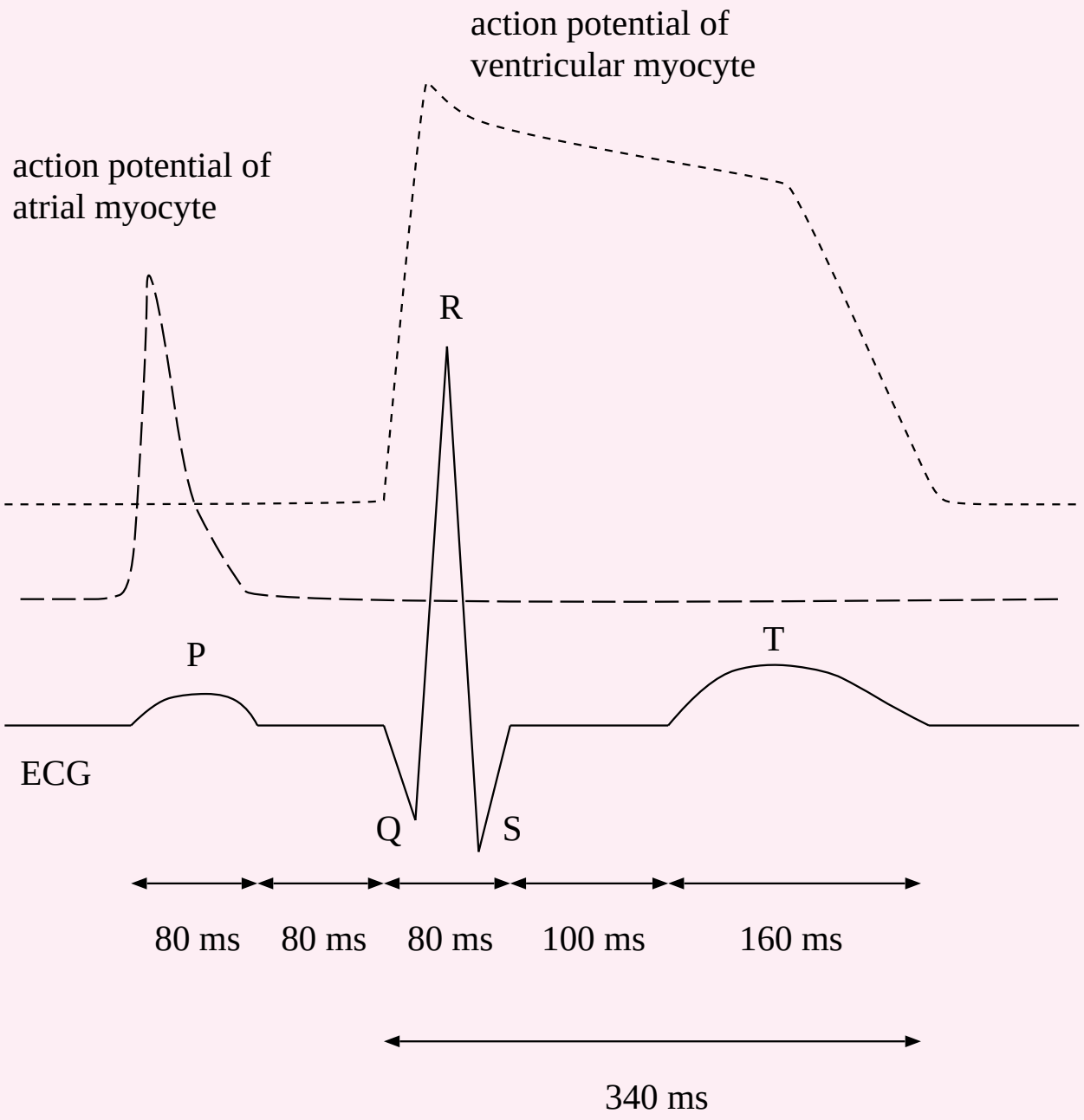


Figure 1.24: Schematic representations of an ECG signal and the action potentials of atrial and ventricular myocytes. See also Figure 1.7.

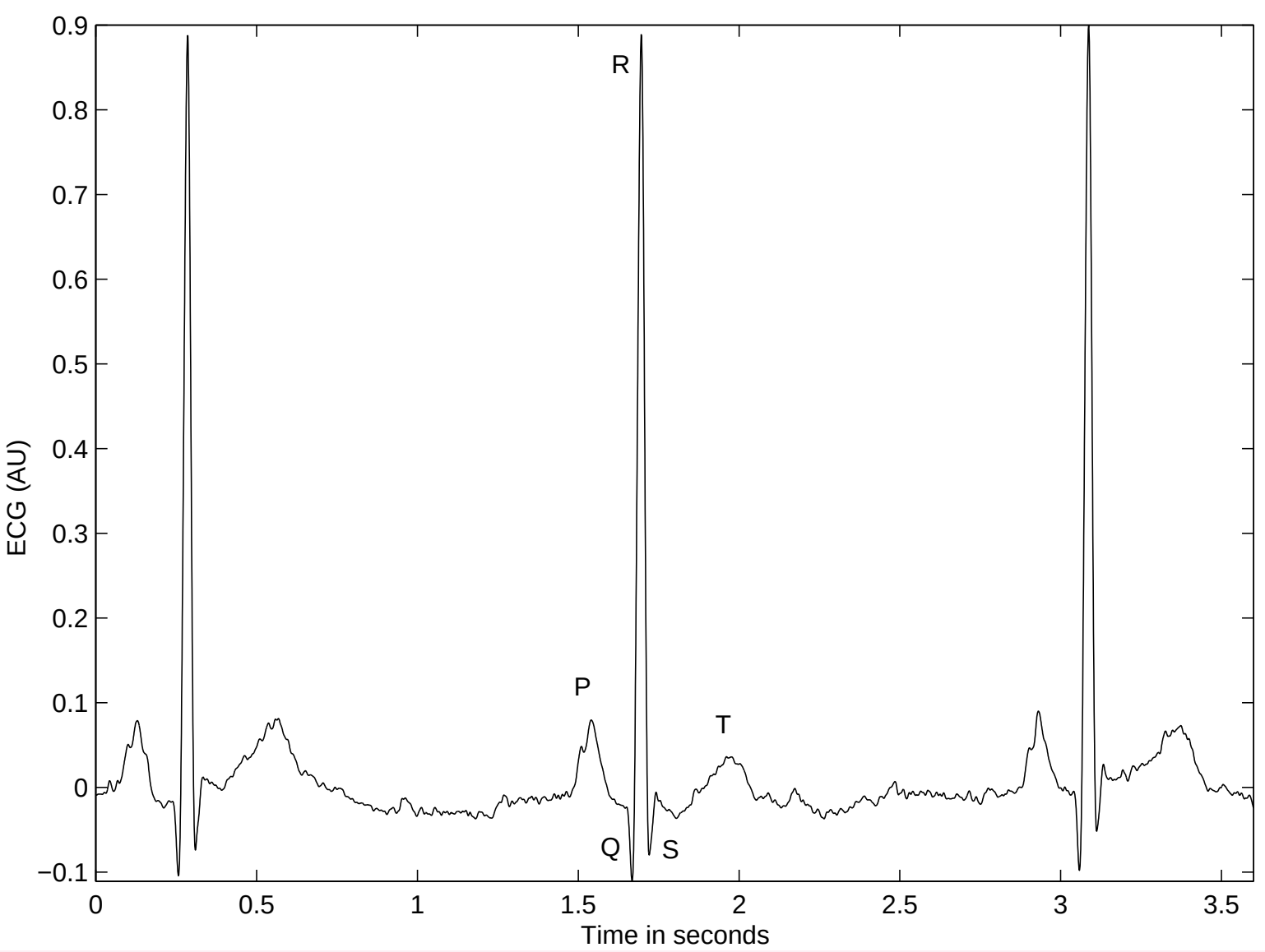


Figure 1.25: A typical ECG signal (male subject of age 24 years). (*Note:* Signal values are not calibrated, that is, specified in physical units, in many applications. As is the case in this plot, signal values in plots in this book are in arbitrary or normalized units unless specified.)

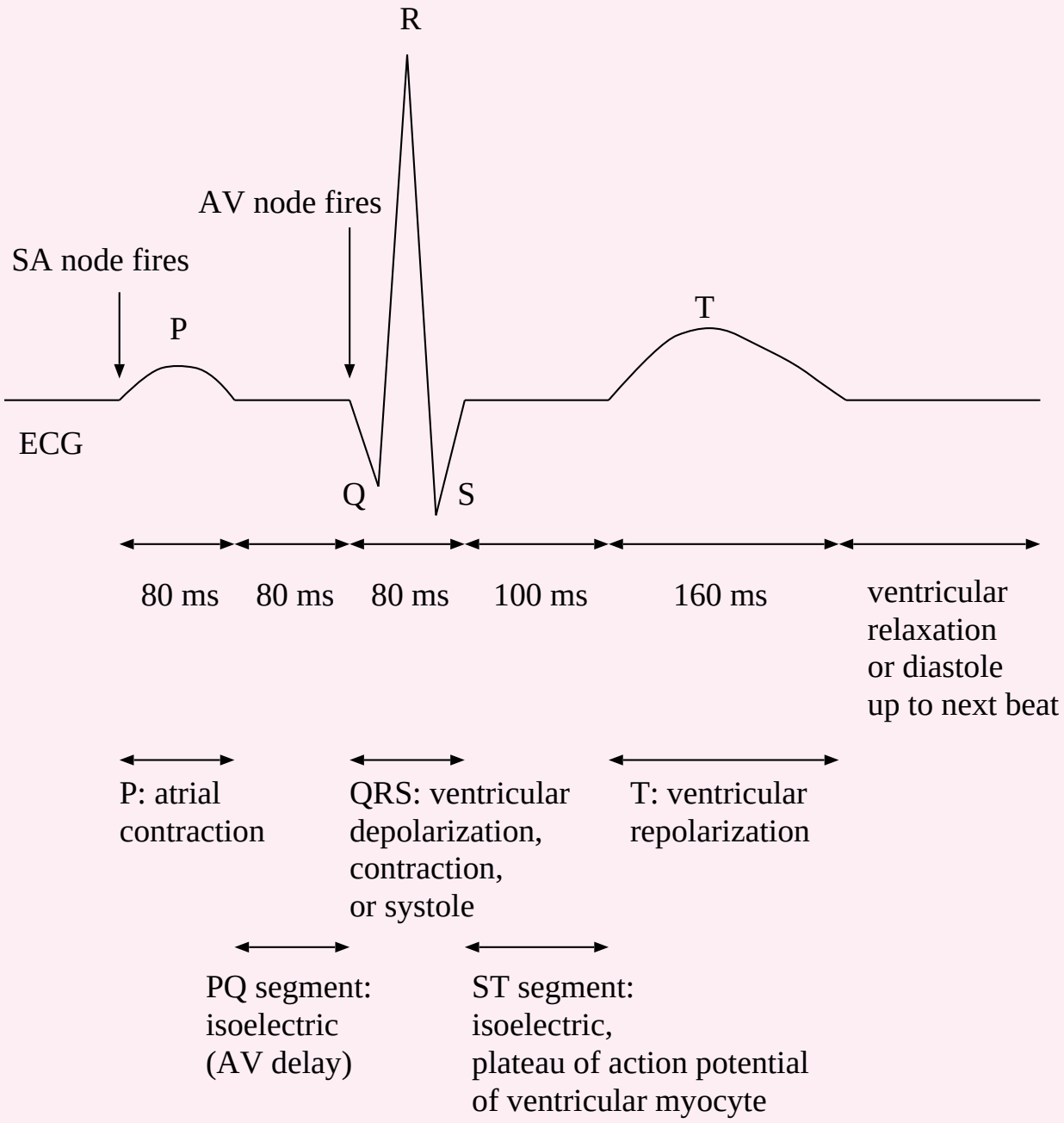


Figure 1.26: Summary of the parts and waves of a cardiac cycle as seen in an ECG signal.

Disturbance in the regular rhythmic activity of the heart:

arrhythmia.

Cardiac arrhythmia may be caused by:

irregular firing patterns from the SA node,

abnormal and additional pacing activity

from other parts of the heart.

Many parts of the heart possess inherent rhythmicity

and pacemaker properties:

SA node, AV node, Purkinje fibers,

atrial tissue, and ventricular tissue.

If the SA node is depressed or inactive, any one of the above

may take over the role of the pacemaker

or introduce *ectopic* beats.

Different types of abnormal rhythm (arrhythmia) result from variations in the site and frequency of impulse formation.

Premature ventricular contractions (PVCs):

caused by ectopic foci on the ventricles.

May lead to ventricular dissociation and fibrillation —

a state of disorganized contraction of the

ventricles independent of the atria.

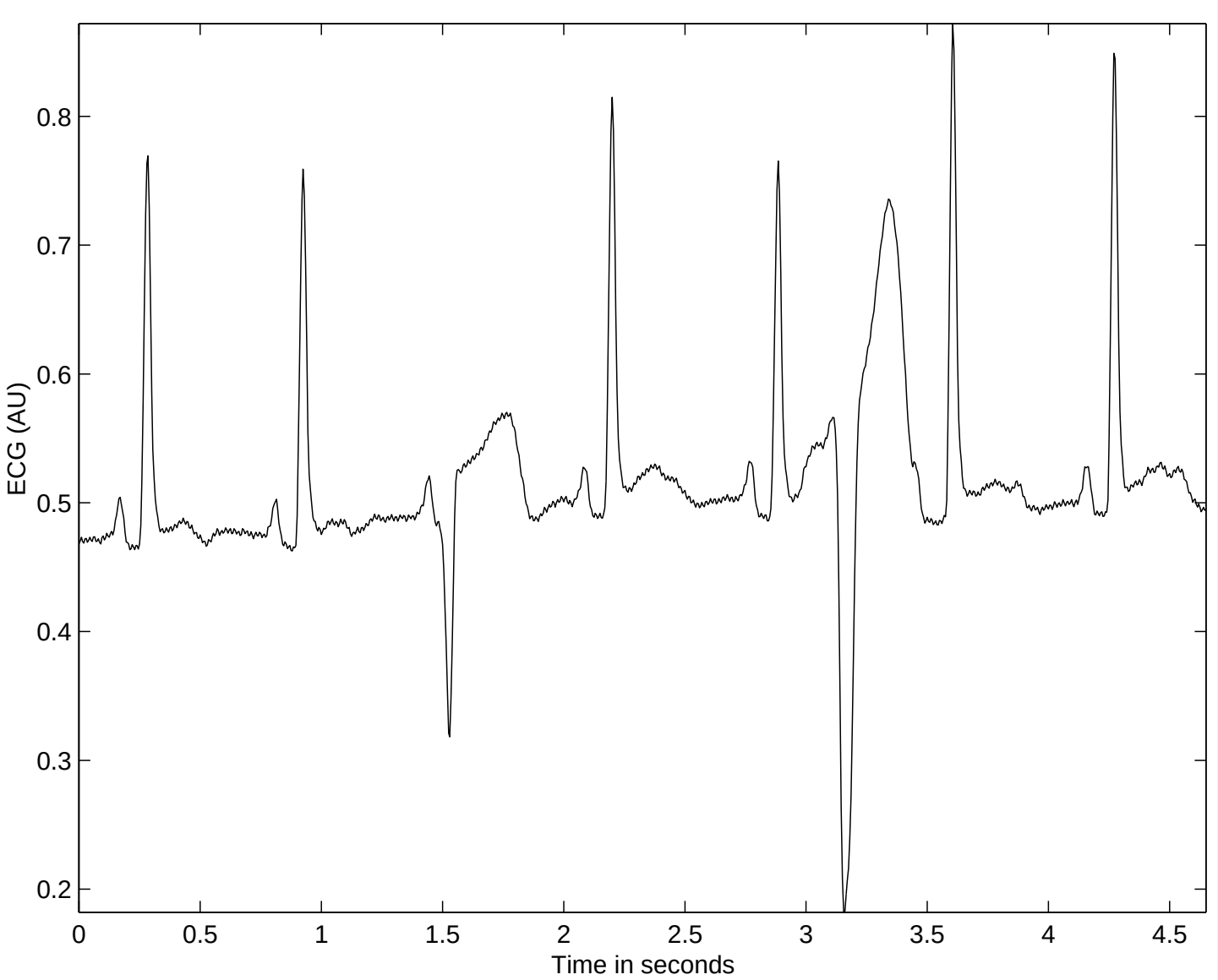
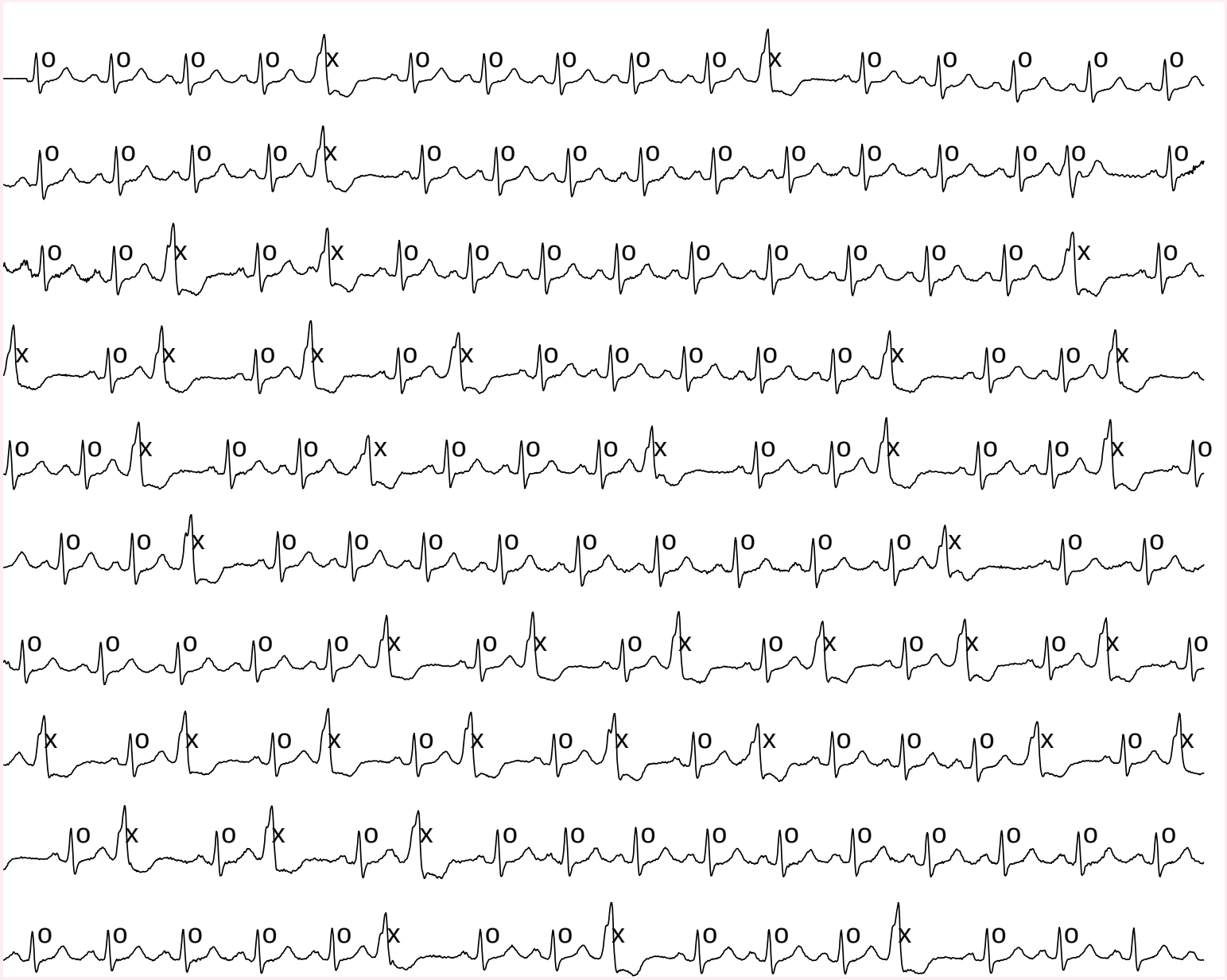


Figure 1.27: ECG signal with PVCs. The third and sixth beats are PVCs. The first PVC has blocked the normal beat that would have appeared at about the same time instant, but the second PVC has not blocked any normal beat triggered by the SA node. Data courtesy of G. Groves and J. Tyberg, Department of Physiology and Biophysics, University of Calgary.



The ECG signal of a patient (male, 65 years) with PVCs. Each strip is of duration 10 s; the signal continues from top to bottom. The second half of the seventh strip and the first half of the eighth strip illustrate an episode of bigeminy.

QRS waveshape affected by conduction disorders:

bundle-branch block causes a widened and jagged QRS.

Ventricular hypertrophy or enlargement: wide QRS.

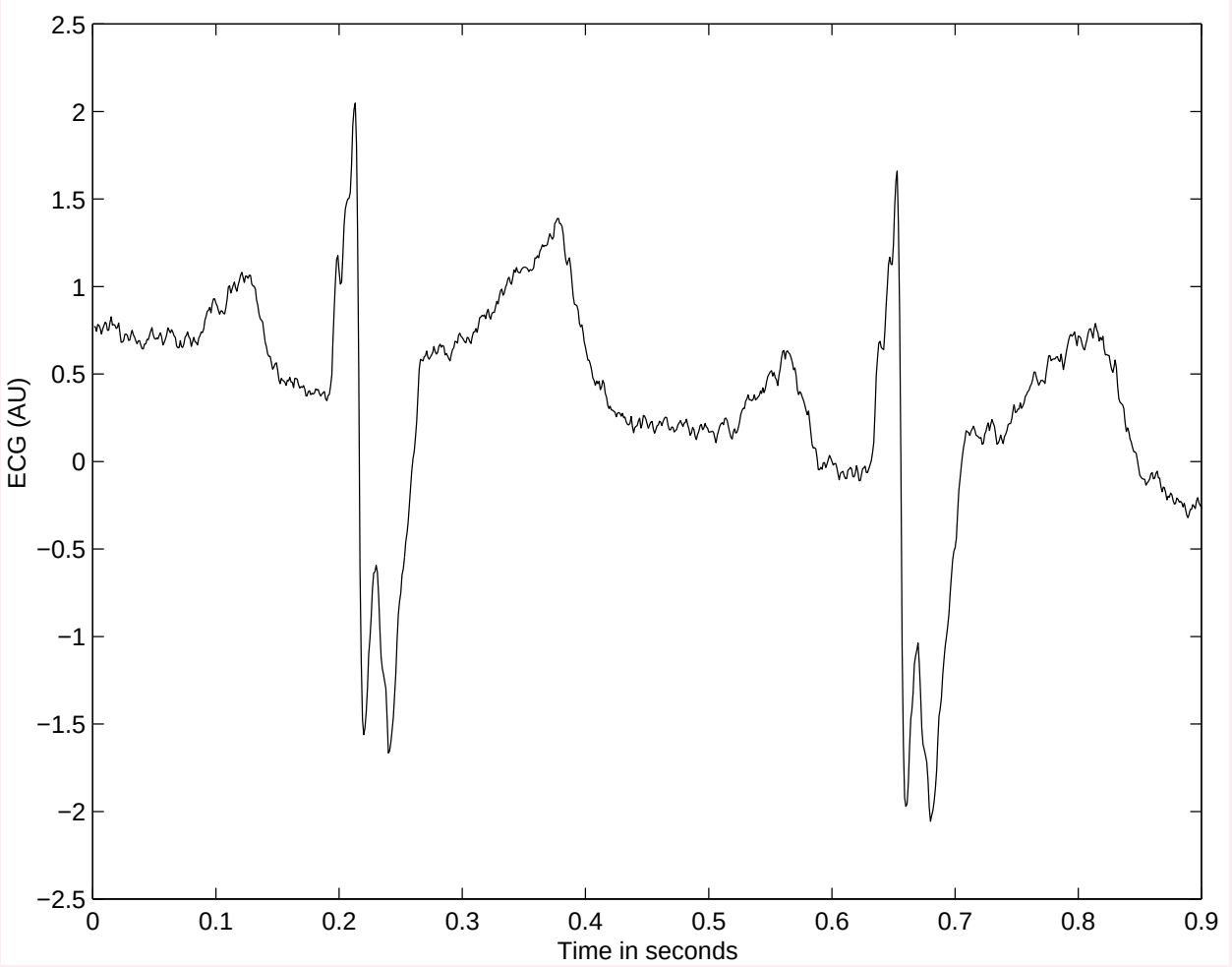


Figure 1.28: ECG signal of a patient with right bundle-branch block and hypertrophy (male patient of age 3 months). The QRS complex is wider than normal, and displays an abnormal, jagged waveform due to desynchronized contraction of the ventricles. (The signal also has a base-line drift, which has not been corrected for.)

ST segment: normally isoelectric —

flat and in line with the PQ segment.

May be elevated or depressed due to myocardial ischemia —

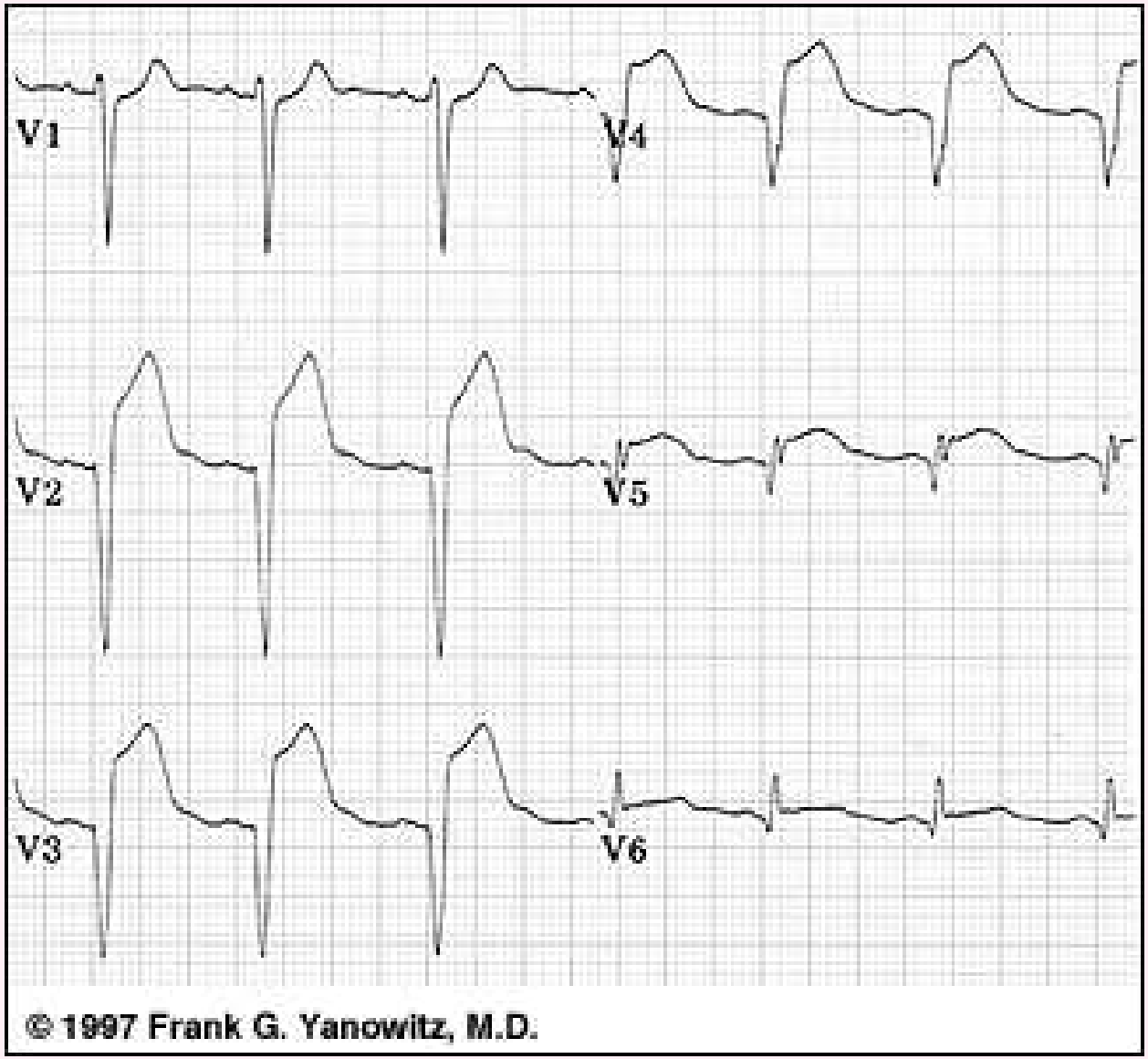
reduced blood supply to a part of the heart muscles

due to a block in the coronary arteries,

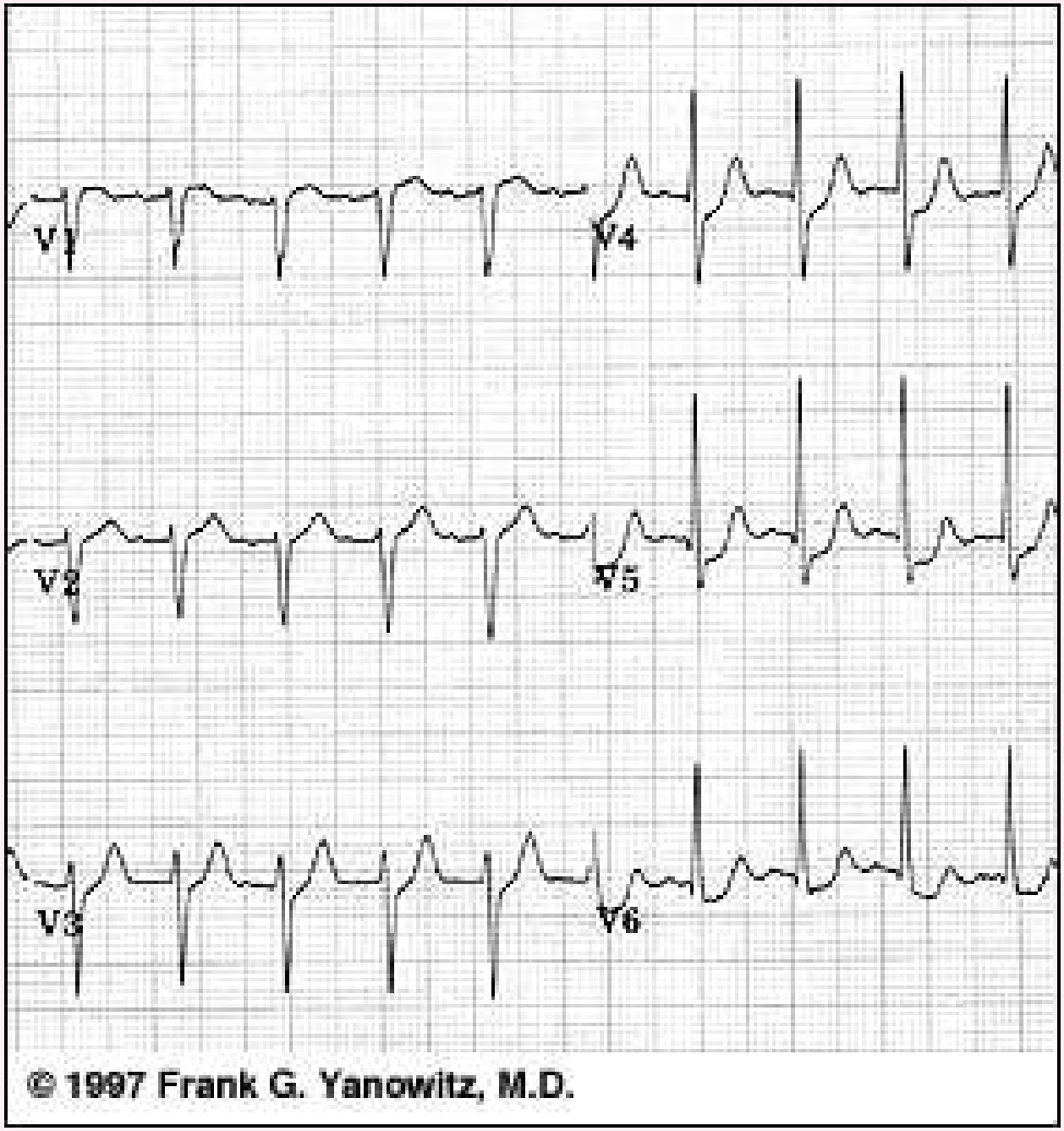
or due to myocardial infarction —

dead myocardial tissue incapable of contraction

due to total lack of blood supply.



ST elevation: Ischemic Heart Disease: Acute transmural injury, acute anterior MI.
http://library.med.utah.edu/kw/ecg/ecg_outline/Lesson10/index.html



ST depression: Subendocardial ischemia: exercise induced or during angina attack.
http://library.med.utah.edu/kw/ecg/ecg_outline/Lesson10/index.html

ECG signal acquisition:

Clinical practice: standard 12-channel ECG

obtained using four limb leads

and chest leads in six positions.

Right leg: reference electrode (ground).

Left arm, right arm, left leg: leads I, II, and III.

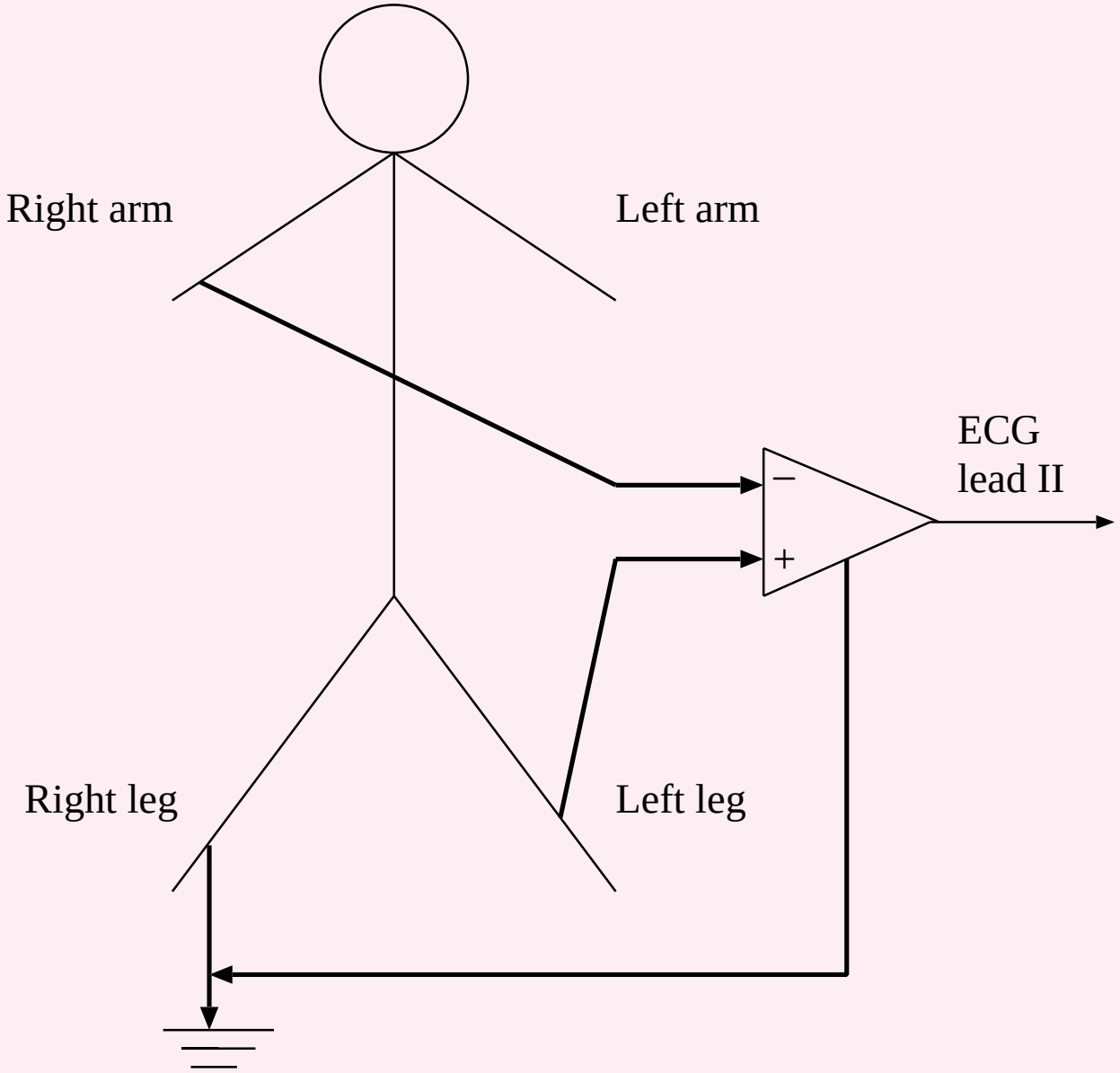


Figure 1.29: Limb leads used to acquire the commonly used lead II ECG. *Note:* The labeling of the left or right side refers to the corresponding side of the patient or subject, as in medical convention, and not the side of the reader.

Wilson's central terminal: combining left arm,

right arm, and left leg leads; reference for chest leads.

Augmented limb leads known as aVR, aVL, and aVF —

aV for augmented lead, R for right arm,

L for left arm, and F for left foot —

obtained by using the exploring electrode on the limb

indicated by the lead name, with the reference being

Wilson's central terminal without the exploring limb lead.

Hypothetical equilateral triangle formed by

leads I, II, and III: *Einthoven's triangle.*

Center of the triangle: Wilson's central terminal.

Schematically, the heart is at the center of the triangle.

The six leads measure projections of the 3D cardiac electrical vector on to the axes of the leads.

Six axes: sample the $0^\circ - 180^\circ$ range in steps of $\sim 30^\circ$.

Facilitate viewing and analysis of the electrical activity of the heart from different perspectives in the frontal plane.

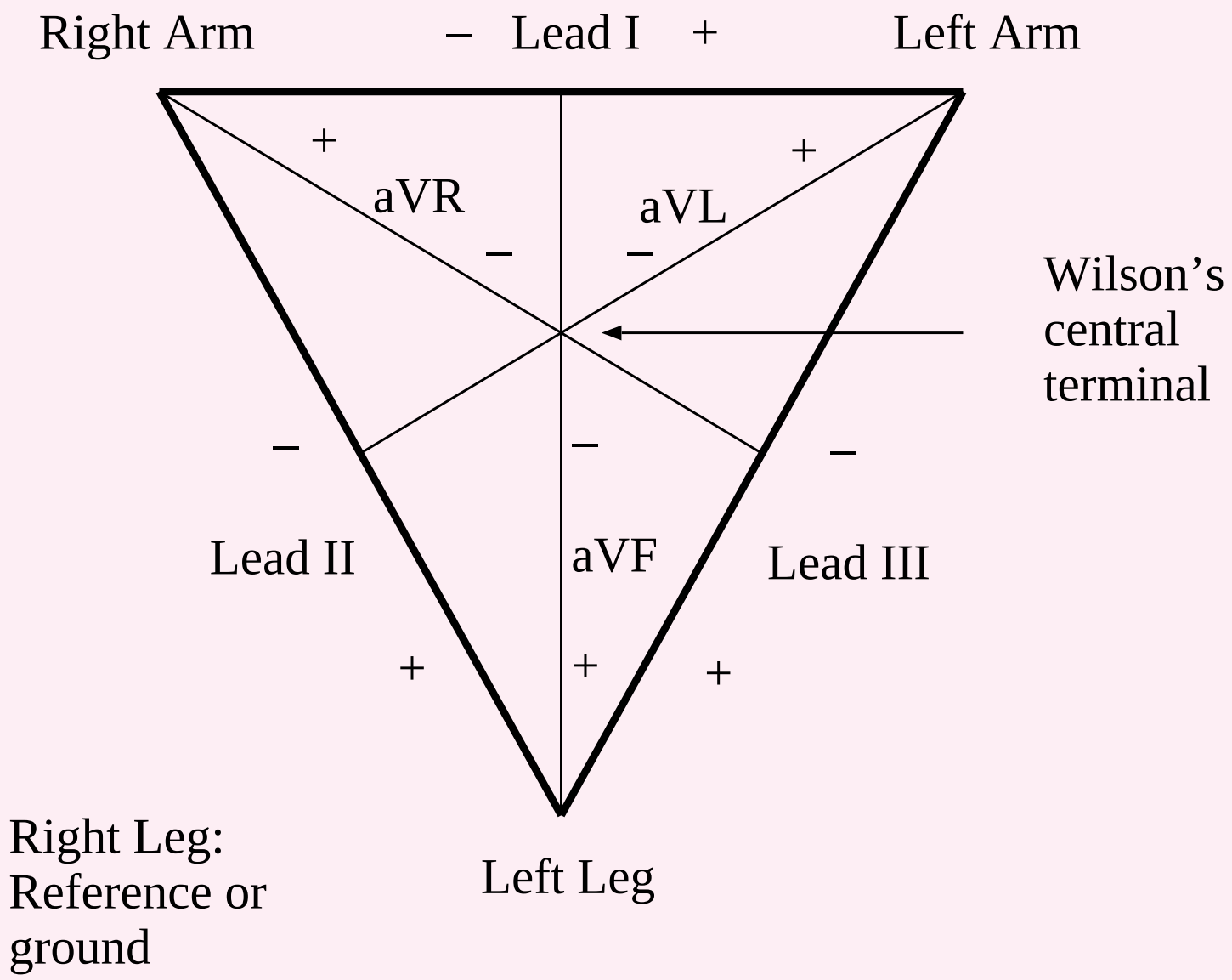


Figure 1.30: Einthoven's triangle and the axes of the six ECG leads formed by using four limb leads.

Six chest leads (V1 – V6) obtained from

six standardized positions on the chest

with Wilson's central terminal as the reference.

V1 and V2 leads placed at the fourth intercostal space

just to the right and left of the sternum, respectively.

V4: fifth intercostal space at the left midclavicular line.

The six chest leads permit viewing

the cardiac electrical vector from

different orientations in a cross-sectional plane:

V5 and V6 most sensitive to left ventricular activity;

V3 and V4 depict septal activity best;

V1 and V2 reflect activity in the right-half of the heart.

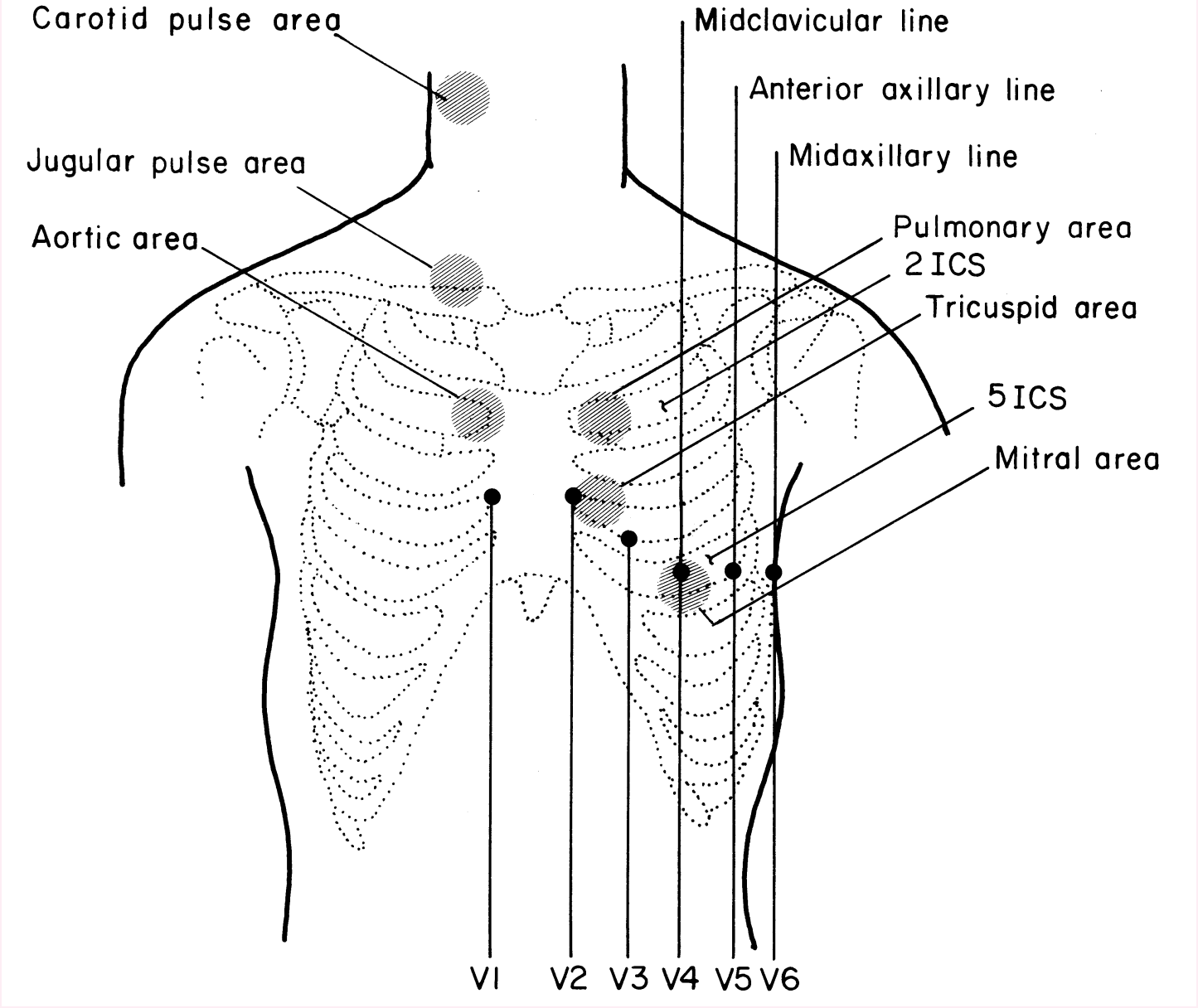


Figure 1.31: Positions for placement of the precordial (chest) leads V1 – V6 for ECG, auscultation areas for heart sounds, and pulse transducer positions for the carotid and jugular pulse signals. ICS: intercostal space.

In spite of being redundant, the 12-lead system serves as the basis of the standard clinical ECG.

Clinical ECG interpretation is mainly empirical, based on experimental knowledge.

Some of the lead interrelationships are:

- II = I + III
- aVL = (I - III) / 2.

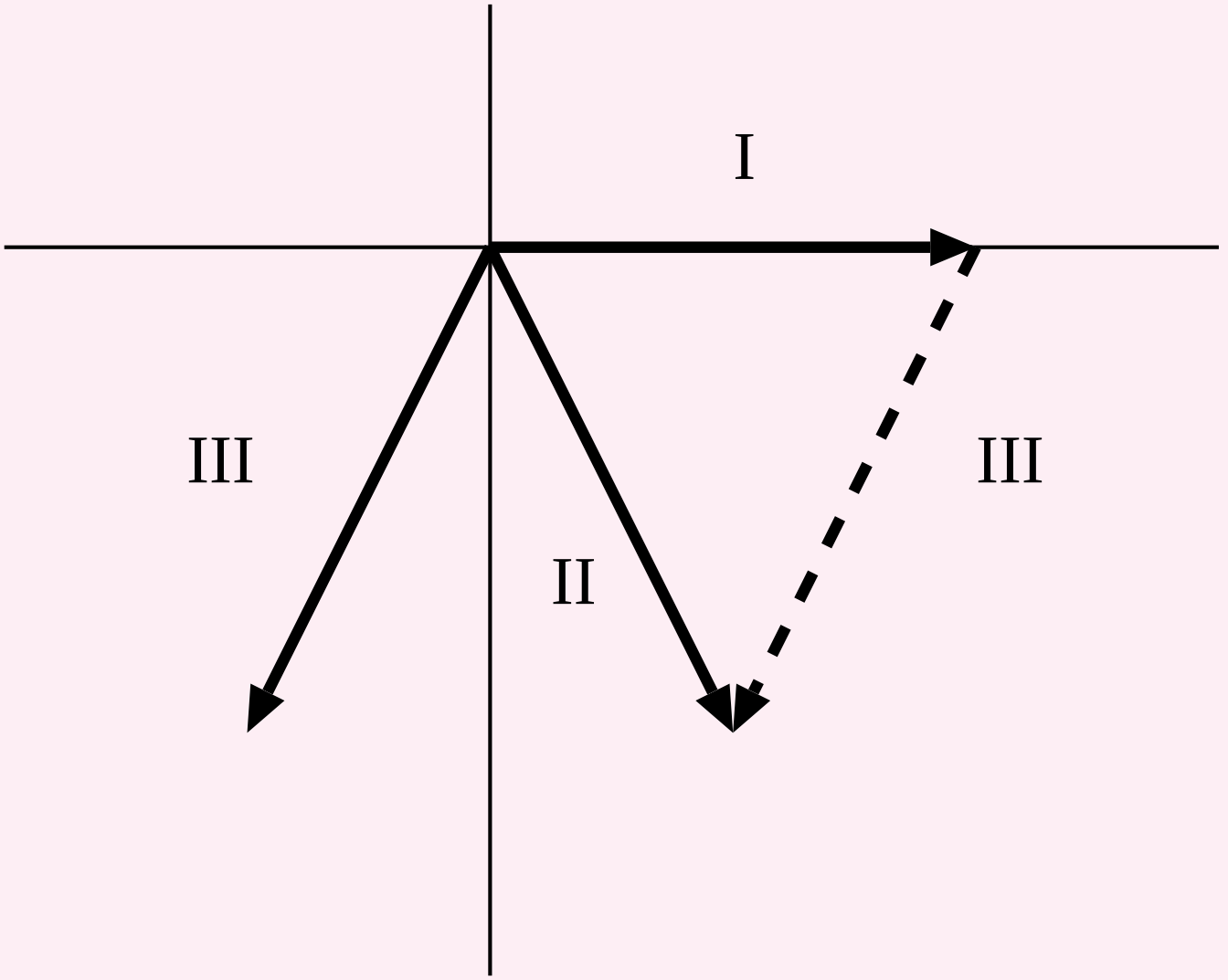


Figure 1.32: Vectorial relations between ECG leads I, II, and III. See also Figure 1.30.

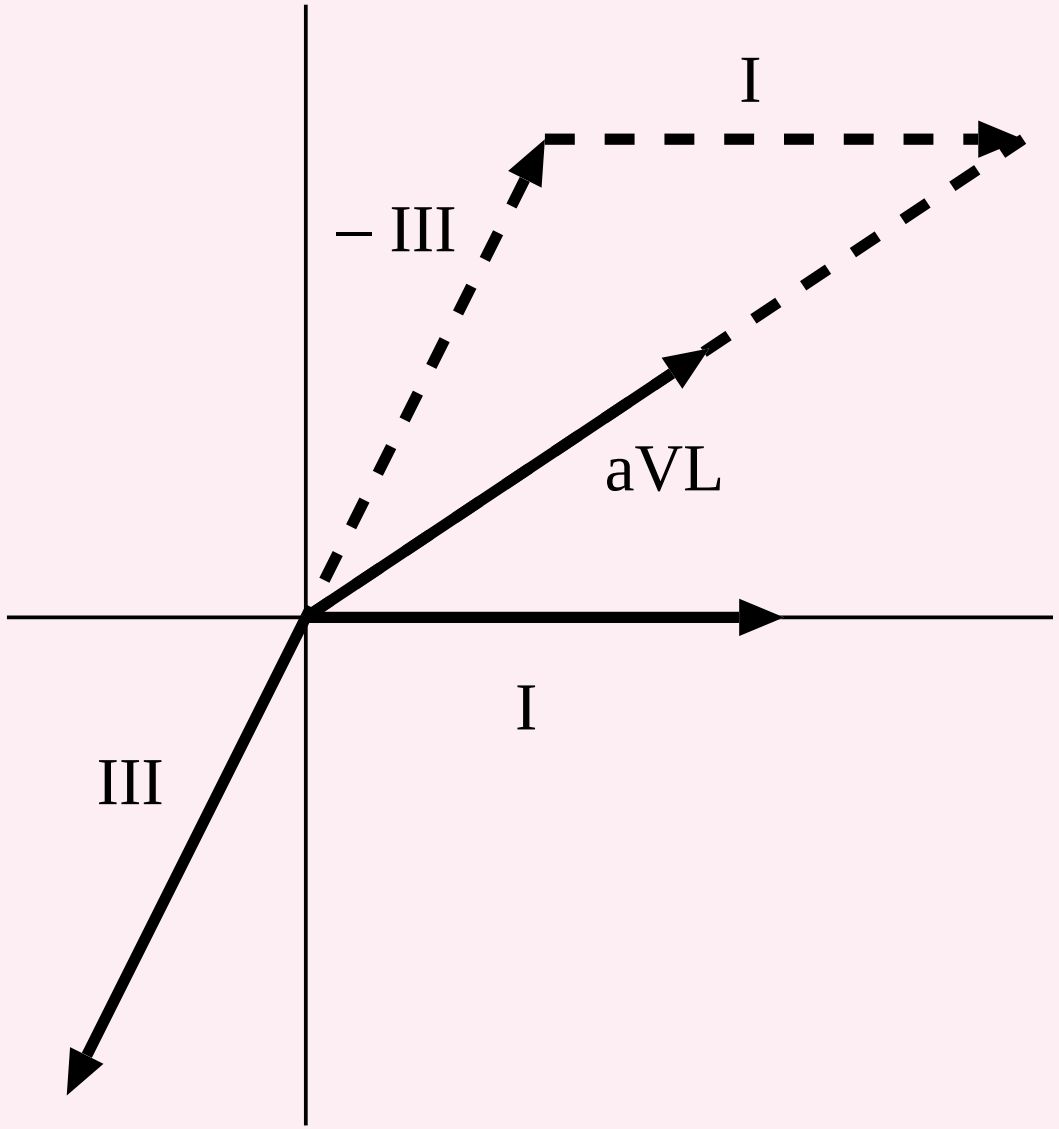


Figure 1.33: Vectorial relations between ECG leads I, II, and III. See also Figure 1.30.

Important features of standard clinical ECG:

- Rectangular calibration pulse, $1\ mV$ and $200\ ms$: pulse of $1\ cm$ height on the paper plot.
- Speed $25\ mm/s$: $0.04\ s/mm$ or $40\ ms/mm$. Calibration pulse width: $5\ mm$.
- ECG signal peak value normally about $1\ mV$.
- Amplifier gain: 1,000.

- Clinical ECG: filtered to $0.05 - 100\ Hz$ bandwidth.

  Recommended sampling rate:
  $500\ Hz$ for diagnostic ECG.

  Distortions in the shape of the calibration pulse

  may indicate improper filter settings or a

  poor signal acquisition system.

- ECG for heart-rate monitoring: reduced bandwidth
  $0.5 - 50\ Hz$.

- High-resolution ECG: greater bandwidth of
  $0.05 - 500\ Hz$.

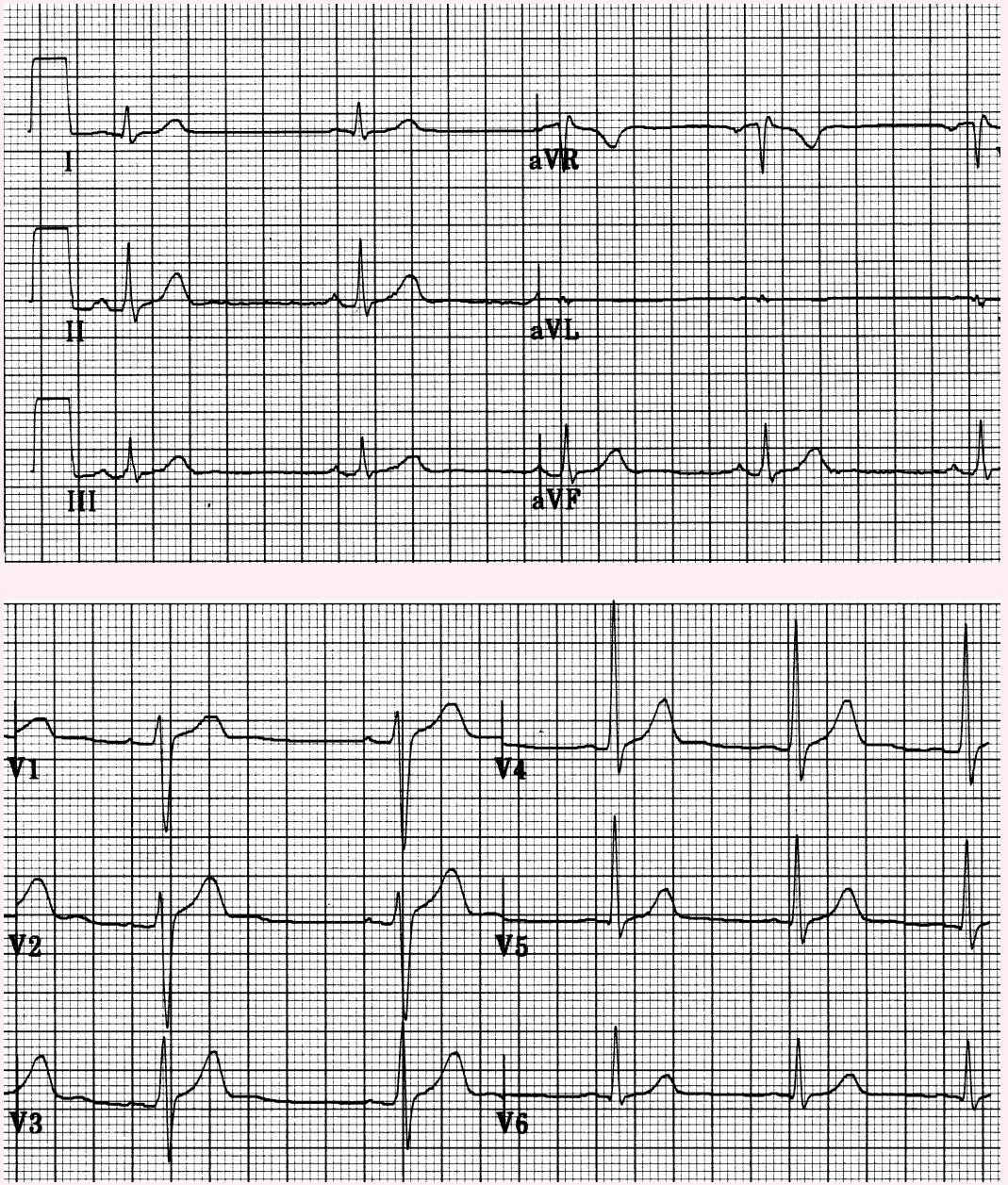


Figure 1.34: Standard 12-lead ECG of a normal male adult. Courtesy of E. Gedamu and L.B. Mitchell, Foothills Hospital, Calgary.

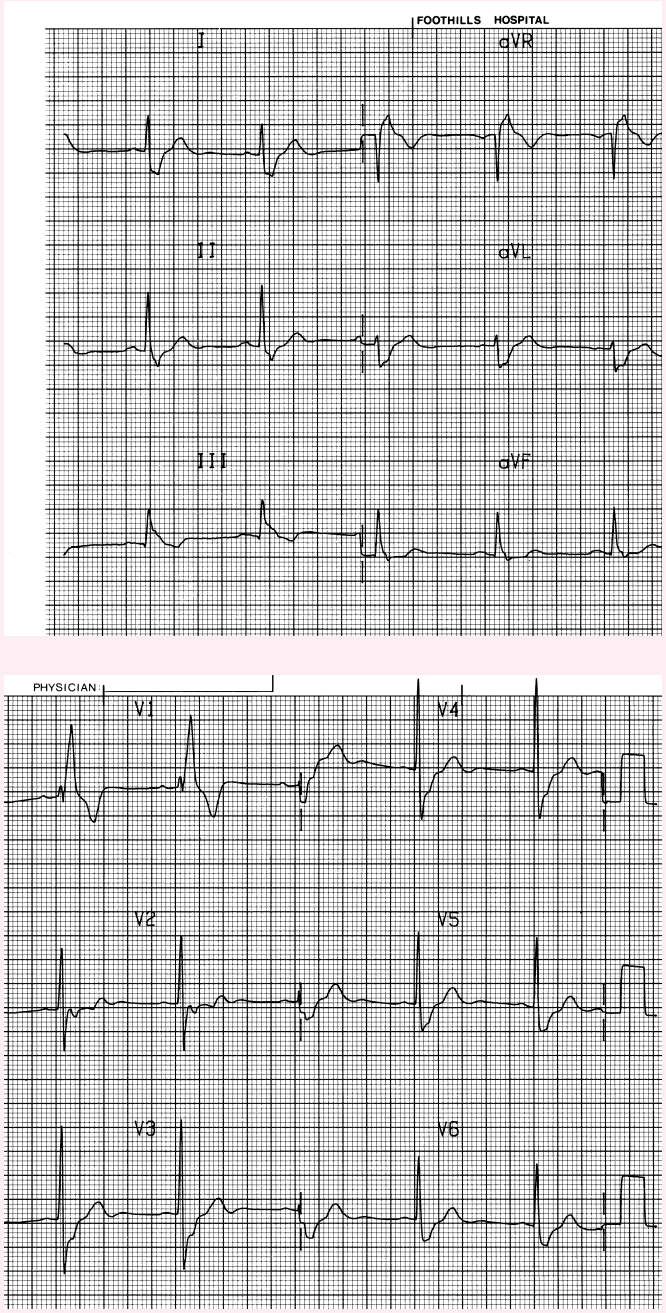


Figure 1.35: Standard 12-lead ECG of a patient with right bundle-branch block. Courtesy of L.B. Mitchell, Foothills Hospital, Calgary.

1.2.6 The electroencephalogram (EEG)

EEG or *brain waves:* electrical activity of the brain.

Main parts of the brain: cerebrum, cerebellum,

brain stem (midbrain, pons medulla, reticular formation),

thalamus (between the midbrain and the hemispheres).

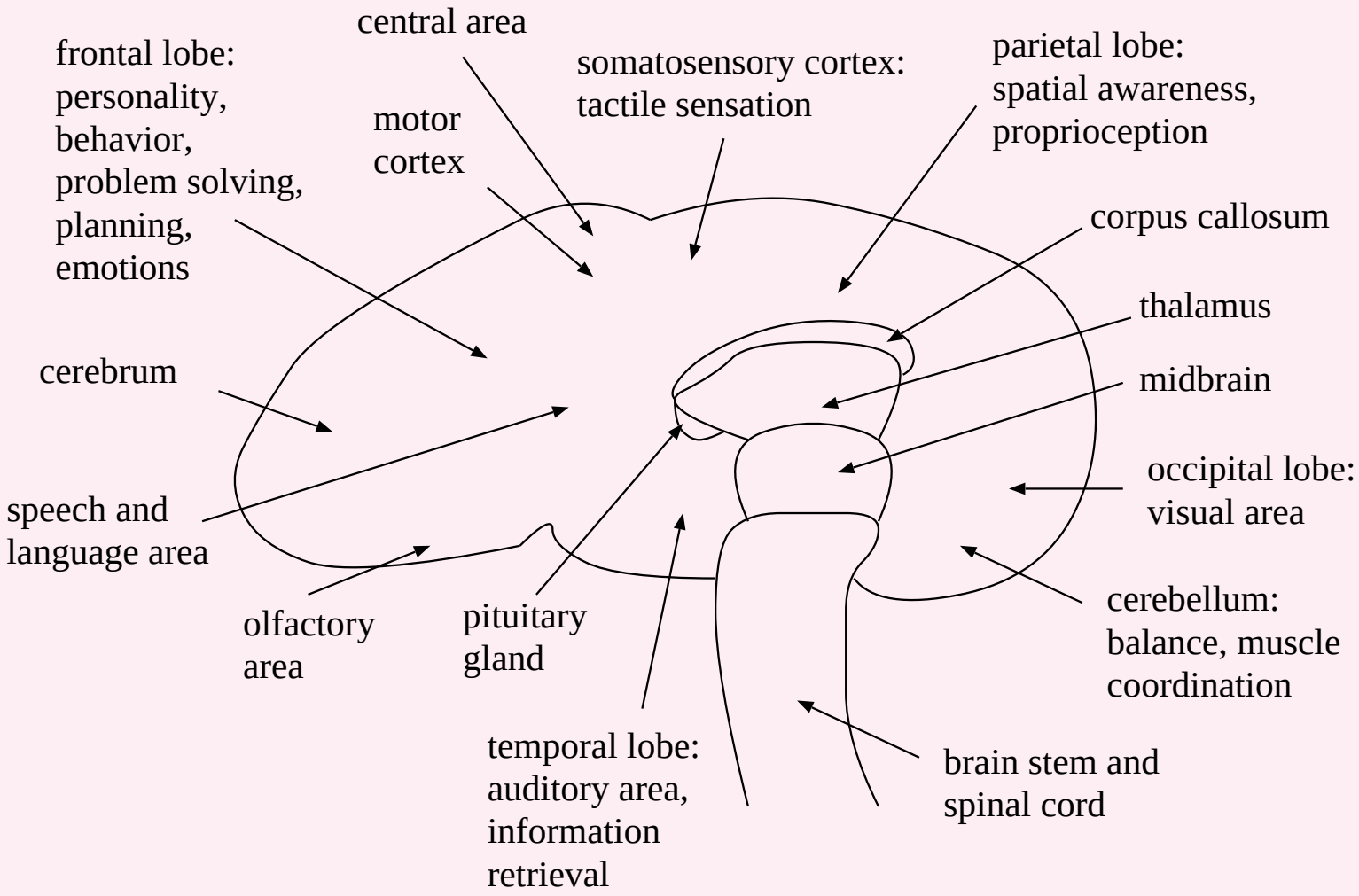


Figure 1.36: Schematic diagram showing the various parts and functional areas of the human brain.

Cerebrum divided into two hemispheres,

separated by a longitudinal fissure with a large

connective band of fibers: corpus callosum.

Outer surface of the cerebral hemispheres (cerebral cortex)

composed of neurons (grey matter) in convoluted patterns,

separated into regions by fissures (sulci).

Beneath the cortex lie nerve fibers that lead to

other parts of the brain and the body (white matter).

Cortical potentials generated due to excitatory and inhibitory postsynaptic potentials developed by cell bodies and dendrites of pyramidal neurons. Physiological control processes, thought processes, and external stimuli generate signals in the corresponding parts of the brain.

Scalp EEG: average of activities of many small zones of the cortex beneath the surface electrode.

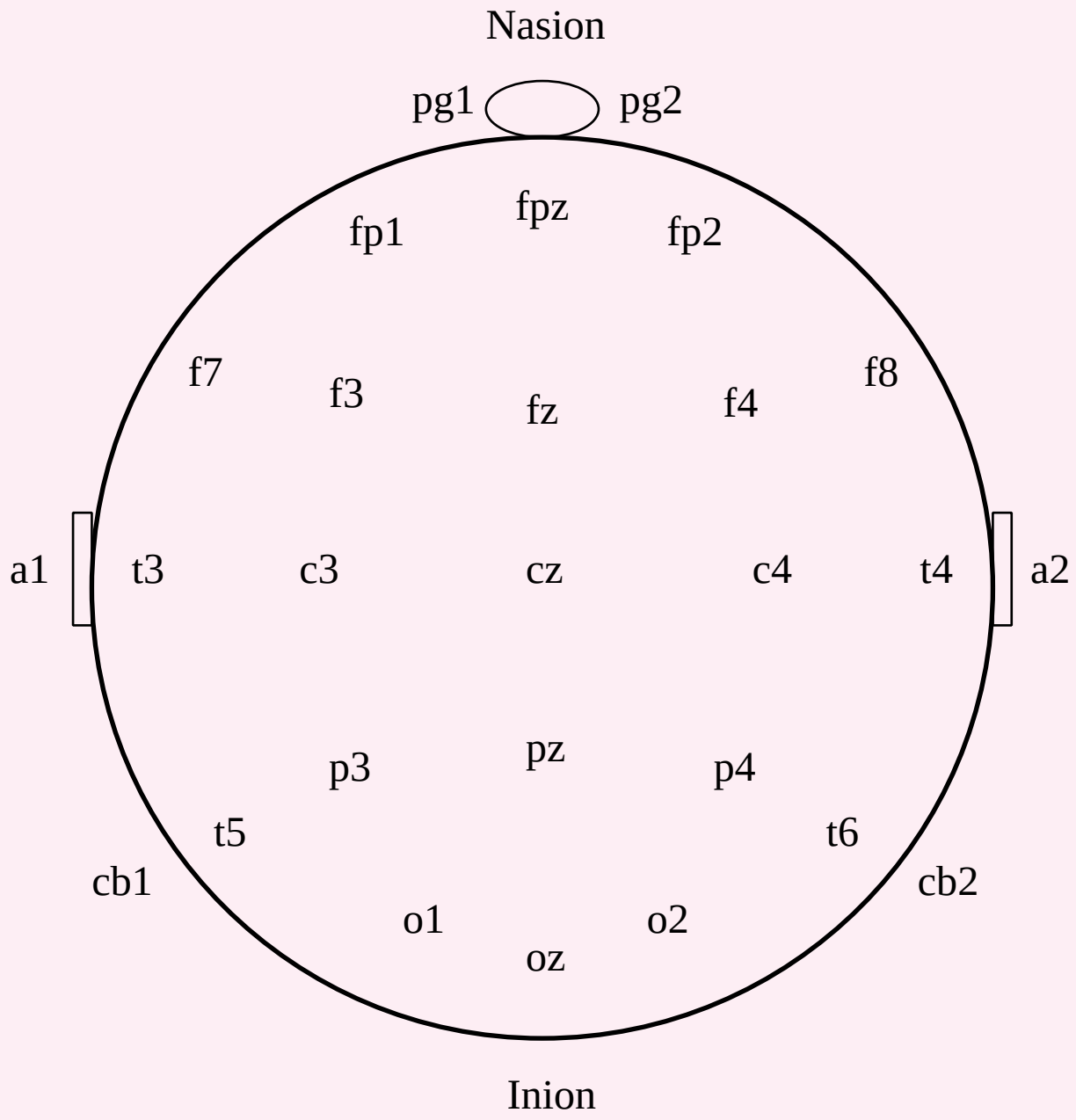


Figure 1.37: The $10-20$ system of electrode placement for EEG recording. Notes regarding channel labels: pg– naso-pharyngeal, a– auricular (ear lobes), fp– pre-frontal, f– frontal, p– pareital, c– central, o– occipital, t– temporal, cb– cerebellar, z– midline, odd numbers on the left, even numbers on the right of the subject.

EEG instrumentation settings:

lowpass filtering at $75\ Hz$,

(paper recording at $100\ \mu V/cm, 30\ mm/s$)

for $10 - 20$ minutes over $8 - 16$ simultaneous channels.

Monitoring of sleep EEG and

detection of transients related to epileptic seizures:

multichannel EEG acquisition over several hours.

Special EEG techniques:

needle electrodes,

nasopharyngeal electrodes,

electrocorticogram (ECoG) from exposed cortex,

intracerebral electrodes.

Evocative techniques for recording the EEG:

initial recording at rest (eyes open, eyes closed),

hyperventilation (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), and pharmaceuticals or drugs.

EEG rhythms or frequency bands:

- Delta (δ): $0.5 \leq f < 4\ Hz$;
- Theta (θ): $4 \leq f < 8\ Hz$;
- Alpha (α): $8 \leq f \leq 13\ Hz$; and
- Beta (β): $f > 13\ Hz$.

EEG rhythms:

associated with physiological and mental processes.

Alpha: principal resting rhythm of the brain:

common in wakeful, resting adults,

especially in the occipital area with bilateral synchrony.

Auditory and mental arithmetic tasks with the

eyes closed lead to strong alpha waves:

suppressed when the eyes are opened.

Alpha wave replaced by

slower rhythms at various stages of sleep.

Theta waves: beginning stages of sleep.

Delta waves: deep-sleep stages.

High-frequency beta waves:

background activity in tense and anxious subjects.

Spikes and sharp waves: epileptogenic regions.

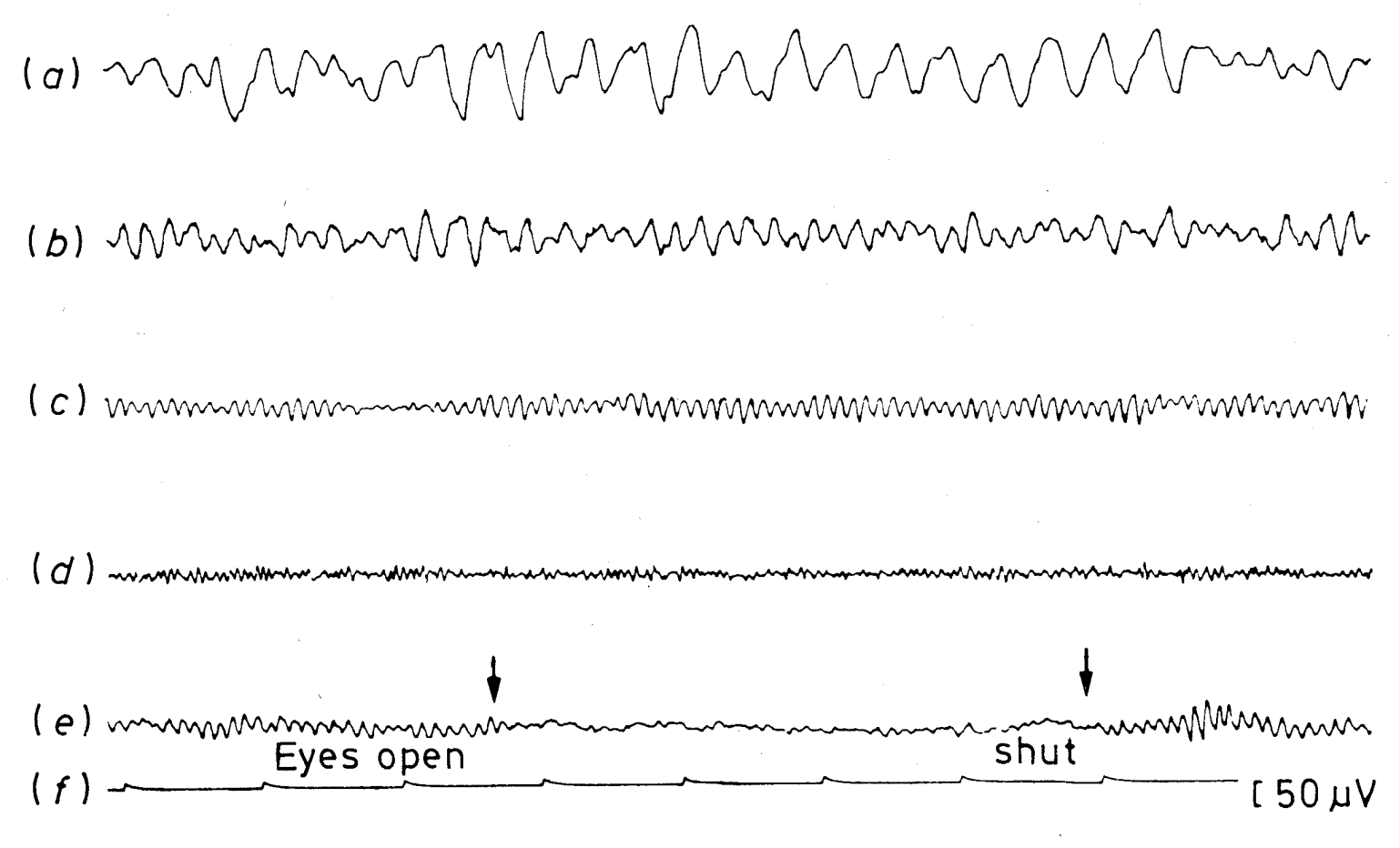


Figure 1.38: From top to bottom: (a) delta rhythm; (b) theta rhythm; (c) alpha rhythm; (d) beta rhythm; (e) blocking of the alpha rhythm by eye opening; (f) 1 s time markers and 50 μV marker. Reproduced with permission from R. Cooper, J.W. Osselton, and J.C. Shaw, *EEG Technology*, 3rd Edition, 1980. ©Butterworth Heinemann Publishers, a division of Reed Educational & Professional Publishing Ltd., Oxford, UK.

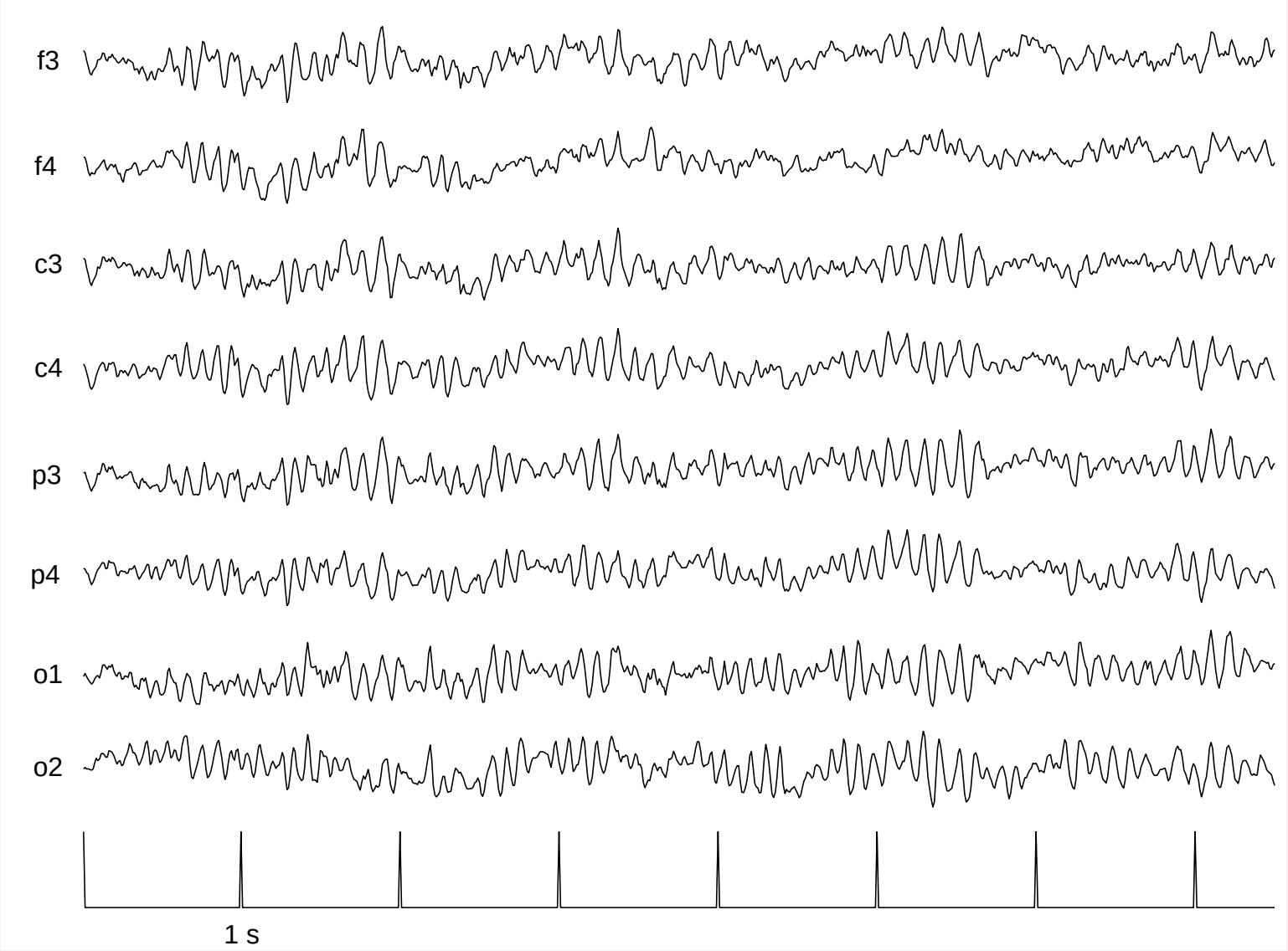


Figure 1.39: Eight channels of the EEG of a subject displaying alpha rhythm. See Figure 1.37 for details regarding channel labels. Data courtesy of Y. Mizuno-Matsumoto, Osaka University Medical School, Osaka, Japan.

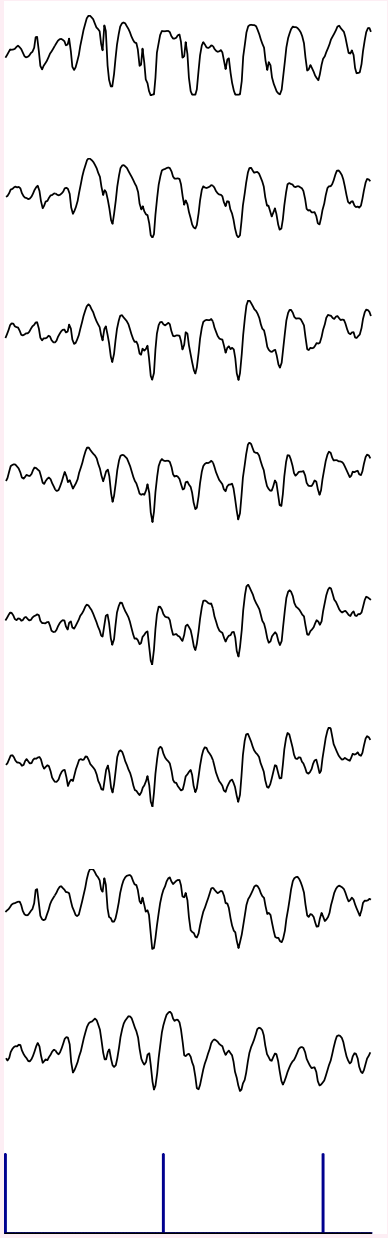


Figure 1.40: Ten channels of the EEG of a subject displaying spike-and-wave complexes. The channels shown are, from top to bottom: c3, c4, p3, p4, o1, o2, t3, t4, and time (1 s per mark). See Figure 1.37 for details regarding channel labels. Data courtesy of Y. Mizuno-Matsumoto, Osaka University Medical School, Osaka, Japan.

Gamma rhythm: EEG activity in the range $30 - 80\ Hz$

related to responses induced by various sensory stimuli,

active sensory processes involving attention, and

short-term memory processes.

EEG signals also include spikes, transients, and other waves and patterns associated with various disorders of the nervous system (see Figure 4.1 and Section 4.2.4).

Figure 1.41 shows a 21-channel record of a patient with a seizure starting at about the 50-s mark.

The signal is characterized by a recruiting theta rhythm at about $5\ Hz$ in the channels T2, F8, T4, and T6.

Artifacts are evident due to muscle activity (in T3, C3, and C4) and blinking of the eye (in Fp1 and Fp2).

Increased amounts of high-frequency activity are seen in several channels after the 50-s mark related to the seizure.

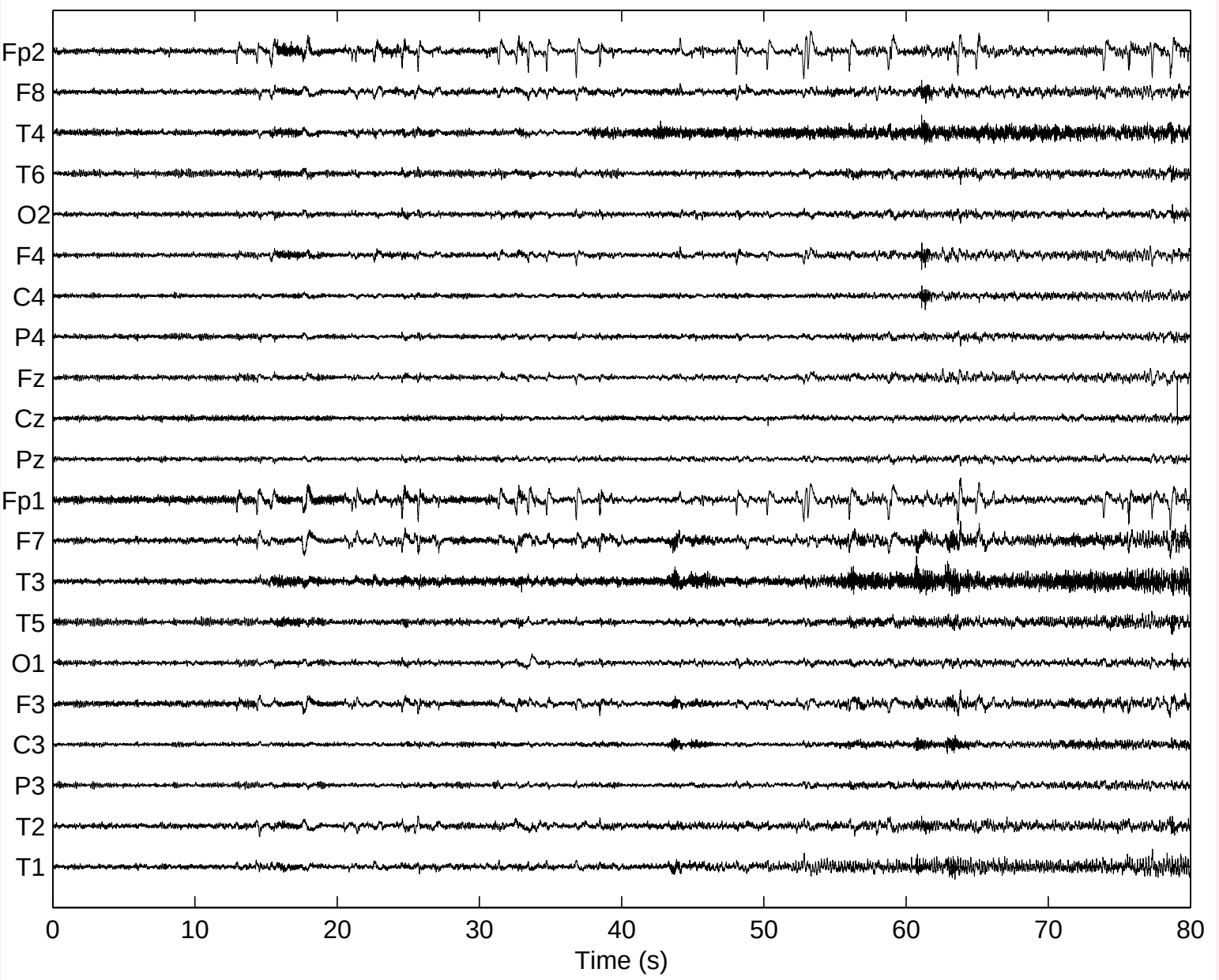


Figure 1.41: 21 channels of the EEG of a subject displaying seizure activity. Data courtesy of M. De Vos, Katholieke Universiteit Leuven, Leuven, Belgium. T1 and T2 are sphenoidal electrodes.

1.2.7 Event-related potentials (ERPs)

The term *event-related potential*

is more general than and preferred to

the term *evoked potential:*

includes the ENG or the EEG in response to

light, sound, electrical, or other external stimuli.

Short-latency ERPs: dependent upon the

physical characteristics of the stimulus.

Longer-latency ERPs: influenced by the

conditions of presentation of the stimuli.

Somatosensory evoked potentials:

useful for noninvasive evaluation of the nervous system

from a peripheral receptor to the cerebral cortex.

Median nerve short-latency SEPs:

obtained by placing stimulating electrodes

$2 - 3\ cm$ apart over the median nerve at the wrist

with electrical stimulation at $5 - 10\ pps$,

each stimulus pulse less than $0.5\ ms$, about $100\ V$

(producing a visible thumb twitch).

SEPs recorded from the surface of the scalp.

Latency, duration, and amplitude of the response measured.

ERPs and SEPs are weak signals:

buried in ongoing activity of associated systems.

SNR improvement: synchronized averaging and filtering.

1.2.8 The electrogastrogram (EGG)

Electrical activity of the stomach:

rhythmic waves of depolarization and repolarization

of smooth muscle cells.

Surface EGG: overall electrical activity of the stomach.

Gastric dysrhythmia or arrhythmia may be detected

with the EGG.

1.2.9 The phonocardiogram (PCG)

PCG: vibration or sound signal related to the contractile activity of the cardiohemic system (heart and blood).

Recording the PCG requires a transducer to convert the vibration or sound signal into an electronic signal: microphones, pressure transducers, or accelerometers.

Cardiovascular diseases and defects cause changes or additional sounds and murmurs: useful in diagnosis.

The genesis of heart sounds:

Heart sounds not caused by valve leaflet movements *per se,*

but by vibrations of the whole cardiovascular system

triggered by pressure gradients.

Secondary sources on the chest related to the well-known

auscultatory areas: mitral, aortic, pulmonary, tricuspid.

A normal cardiac cycle contains two major sounds —

the first heart sound (S1) and

the second heart sound (S2).

S1 occurs at the onset of ventricular contraction:

corresponds in timing to the QRS in the ECG.

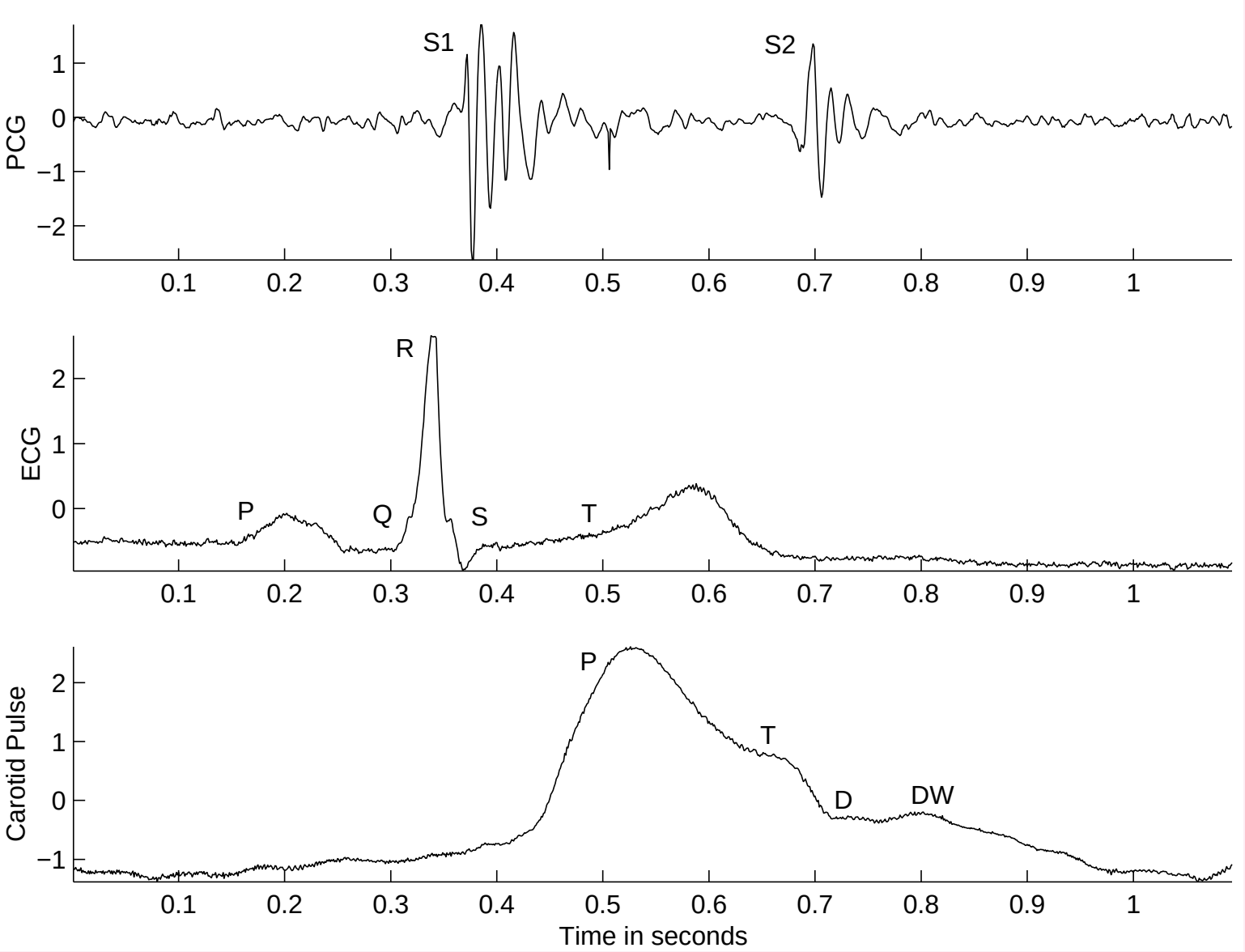


Figure 1.42: Three-channel simultaneous record of the PCG, ECG, and carotid pulse signals of a normal male adult.

Initial vibrations in S1: first myocardial contractions

in the ventricles move blood toward the atria,

sealing the AV (mitral and tricuspid) valves.

Second component of S1: abrupt tension of the

closed AV valves, decelerating the blood.

Next, the semilunar (aortic and pulmonary) valves open:

blood is ejected out of the ventricles.

Third component of S1: caused by oscillation of blood between the root of the aorta and the ventricular walls.

Fourth component of S1: vibrations caused by turbulence in the ejected blood flowing rapidly through the ascending aorta and the pulmonary artery.

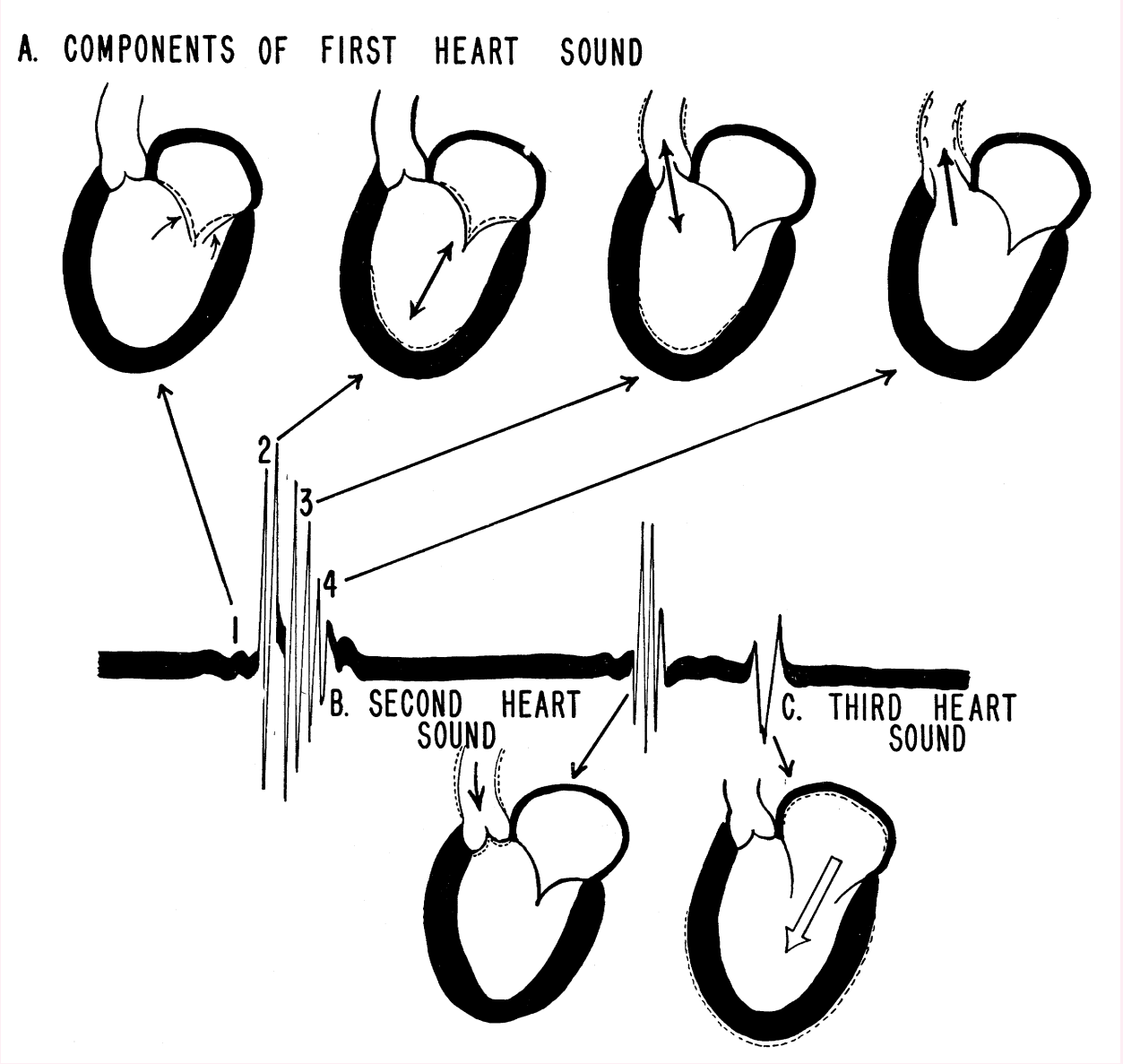


Figure 1.43: Schematic representation of the genesis of heart sounds. Only the left portion of the heart is illustrated as it is the major source of the heart sounds. The corresponding events in the right portion also contribute to the sounds. The atria do not contribute much to the heart sounds. Reproduced with permission from R.F. Rushmer, *Cardiovascular Dynamics*, 4th edition, ©W.B. Saunders, Philadelphia, PA, 1976.

Following the systolic pause in a normal cardiac cycle,

second sound S2 caused by the

closure of the semilunar valves.

Primary vibrations occur in the arteries due to

deceleration of blood;

the ventricles and atria also vibrate, due to transmission

of vibrations through the blood, valves, and the valve rings.

S2 has two components:

one due to closure of the aortic valve (A2) and

another due to closure of the pulmonary valve (P2).

The aortic valve normally closes before the

pulmonary valve; A2 precedes P2 by a few milliseconds.

Pathologic conditions could cause this gap to widen,

or may also reverse the order of occurrence of A2 and P2.

A2 – P2 gap also widened during normal inspiration.

Other sounds:

S3: sudden termination of the ventricular rapid-filling phase.

S4: atrial contractions displacing blood into the

distended ventricles.

Valvular clicks and snaps.

Murmurs.

Heart murmurs:

S1 – S2 and S2 – S1 intervals normally silent:

corresponding to ventricular systole and diastole.

Murmurs caused by cardiovascular defects and diseases

may occur in these intervals.

Murmurs are high-frequency, noise-like sounds:

arise when the velocity of blood becomes high

as it flows through an irregularity (constriction, baffle).

Conditions that cause turbulence in blood flow:

valvular stenosis and insufficiency.

Valve stenosed due to the deposition of calcium:

valve leaflets stiffened and do not open completely —

obstruction or baffle in the path of the blood being ejected.

Valve insufficient when it cannot close effectively:

reverse leakage or regurgitation of blood through

a narrow opening.

Systolic murmurs caused by

ventricular septal defect —

hole in the wall between the left and right ventricles;

aortic stenosis, pulmonary stenosis,

mitral insufficiency, and tricuspid insufficiency.

Semilunar valvular stenosis:

obstruction in the path of blood being ejected during systole.

AV valvular insufficiency:

regurgitation of blood to the atria during

ventricular contraction.

Diastolic murmurs caused by

aortic or pulmonary insufficiency,

mitral or tricuspid stenosis,

atrial septal defect.

Features of heart sounds and murmurs:

intensity, frequency content, and timing

affected by physical and physiological factors such as

recording site on thorax, intervening thoracic structures,

left ventricular contractility,

position of the cardiac valves at the onset of systole,

the degree of the defect present,

the heart rate, and blood velocity.

S1 is loud and delayed in mitral stenosis;

right bundle-branch block causes wide splitting of S2;

left bundle-branch block results in reversed splitting of S2;

acute myocardial infarction causes a pathologic S3;

severe mitral regurgitation leads to an increased S4.

Although murmurs are noise-like events, their features aid in distinguishing between different causes.

Aortic stenosis causes a diamond-shaped midsystolic murmur.

Mitral stenosis causes a decrescendo – crescendo type diastolic – presystolic murmur.

Recording PCG signals:

Piezoelectric contact sensors sensitive to displacement

or acceleration at the skin surface.

HP21050A: bandwidth $0.05 - 1,000\ Hz$.

PCG recording performed in a quiet room;

patient in supine position, head resting on a pillow.

PCG transducer placed firmly at the desired position

on the chest using a suction ring and/or a rubber strap.

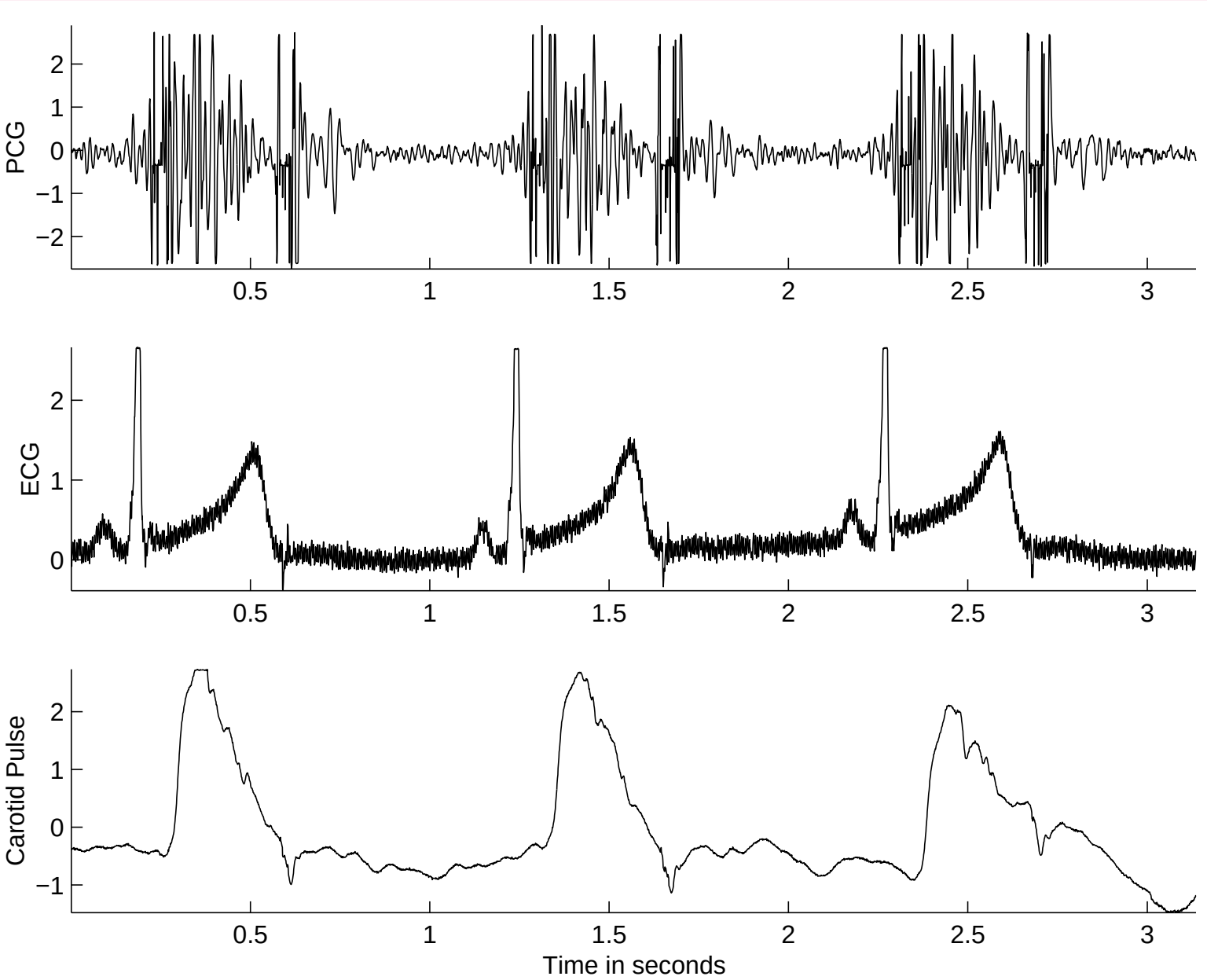


Figure 1.44: Three-channel simultaneous record of the PCG, ECG, and carotid pulse signals of a patient (female, 11 years) with aortic stenosis. Note the presence of the typical diamond-shaped systolic murmur and the split nature of S2 in the PCG.

1.2.10 The carotid pulse

Pressure signal recorded over the carotid artery

as it passes near the surface of the body at the neck.

Pulse signal indicating the variations in arterial

blood pressure and volume with each heart beat.

Resembles the pressure signal at the root of the aorta.

HP21281A pulse transducer: bandwidth of $0 - 100\ Hz$.

Carotid pulse: rises abruptly with the ejection of blood

from the left ventricle to the aorta.

Peak: percussion wave (P).

Plateau or secondary wave: tidal wave (T):

caused by reflected pulse returning from the upper body.

Closure of the aortic valve: dicrotic notch.

Dicrotic wave (DW): reflected pulse from the lower body.

1.2.11 Signals from catheter-tip sensors

Sensors placed on catheter tips inserted into the cardiac chambers:

left ventricular pressure, right atrial pressure,

aortic pressure, and intracardiac sounds.

Invasive procedures associated with certain risks.

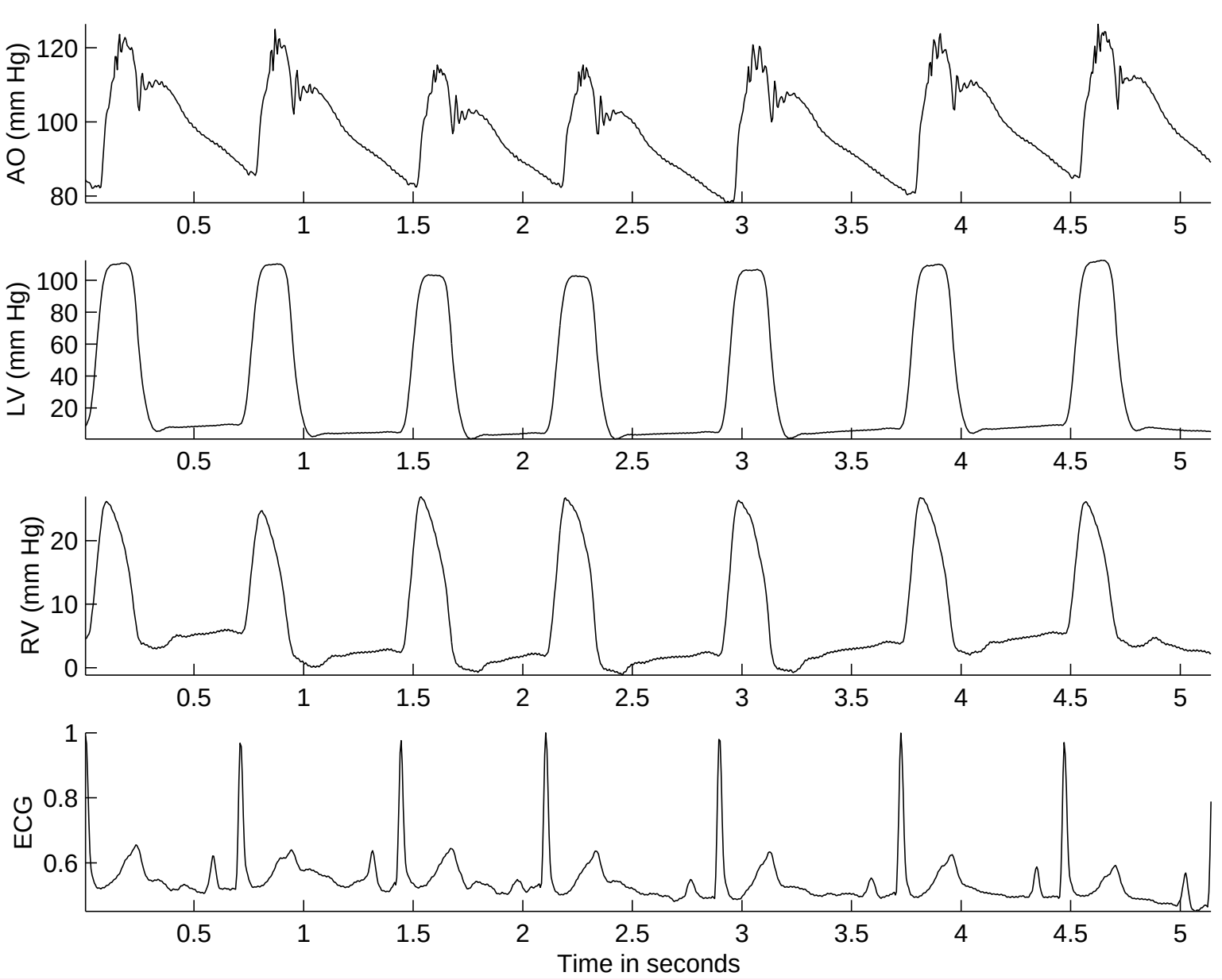


Figure 1.45: Normal ECG and intracardiac pressure signals from a dog. AO represents aortic pressure near the aortic valve. Data courtesy of R. Sas and J. Tyberg, Department of Physiology and Biophysics, University of Calgary.

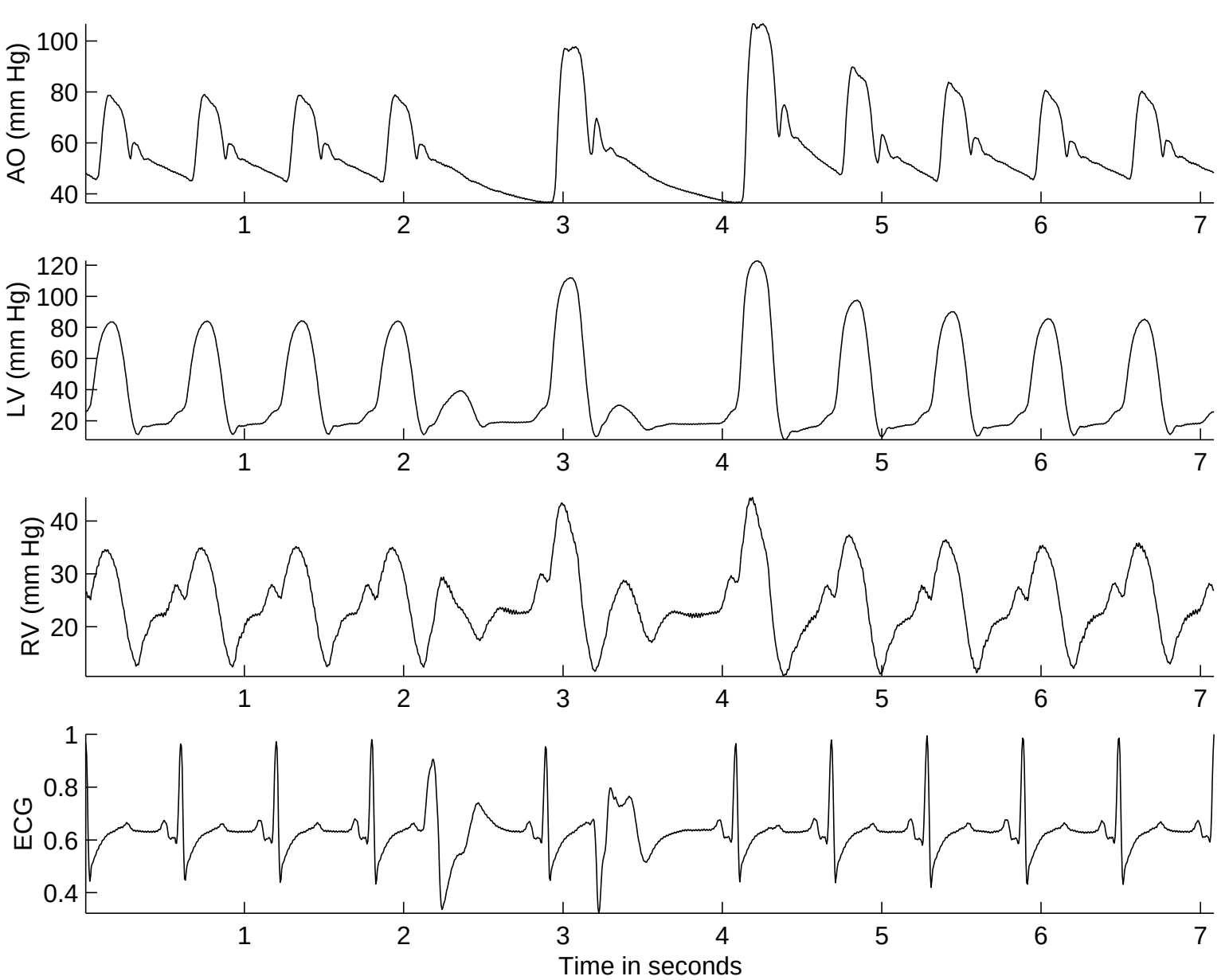


Figure 1.46: ECG and intracardiac pressure signals from a dog with PVCs. Data courtesy of R. Sas and J. Tyberg, Department of Physiology and Biophysics, University of Calgary.

1.2.12 The speech signal

Speech produced by transmitting puffs of air from the lungs through the vocal tract as well as the nasal tract.

Vocal tract: starts at the vocal cords or glottis in the throat and ends at the lips and the nostrils.

Shape of vocal tract varied to produce different types of sound units or *phonemes* which form speech.

The vocal tract acts as a filter that modulates the spectral characteristics of the input puffs of air.

The system is dynamic: the filter and the speech signal have time-varying characteristics — they are nonstationary.

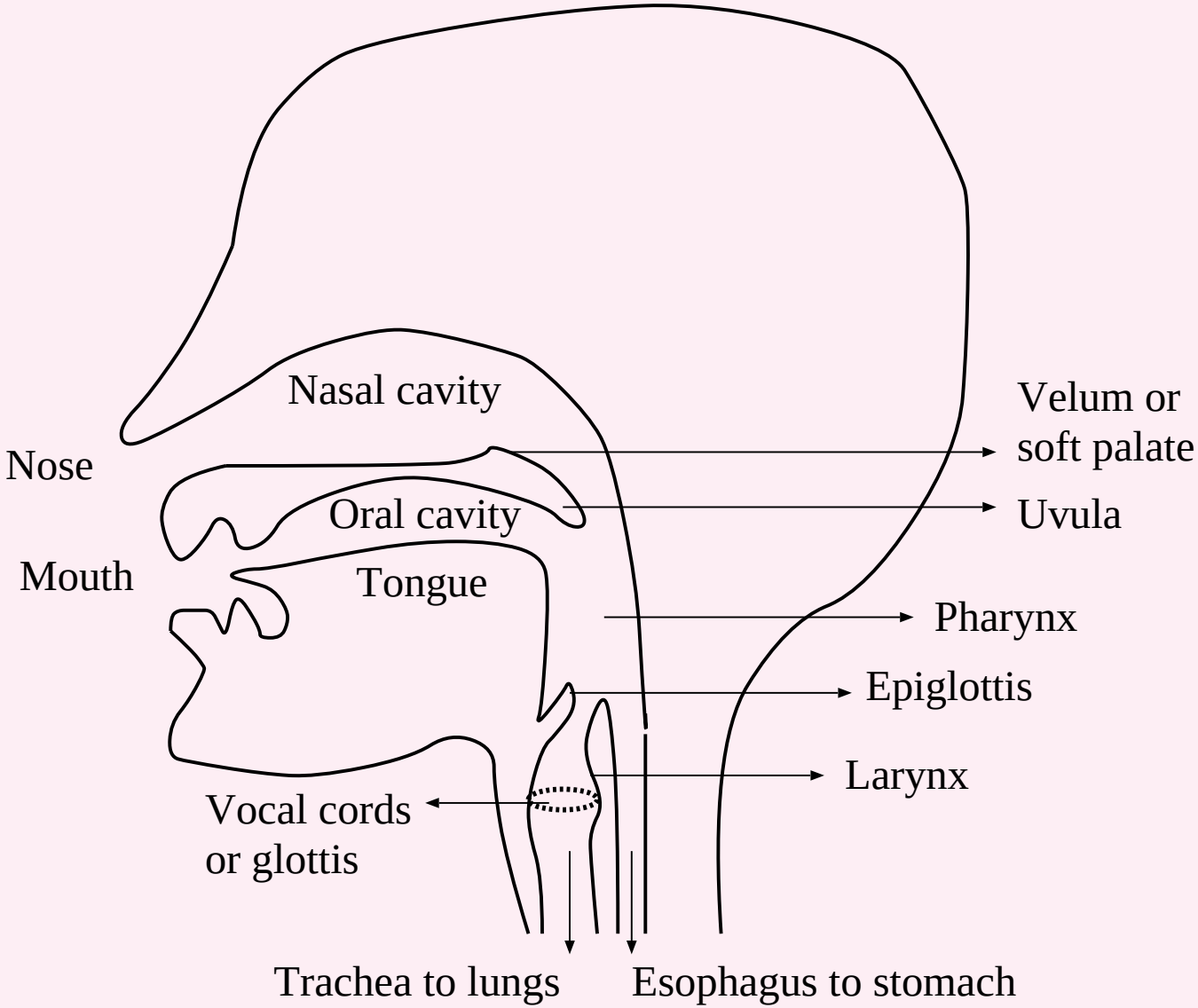


Figure 1.47: Schematic diagram of anatomy of the vocal tract.

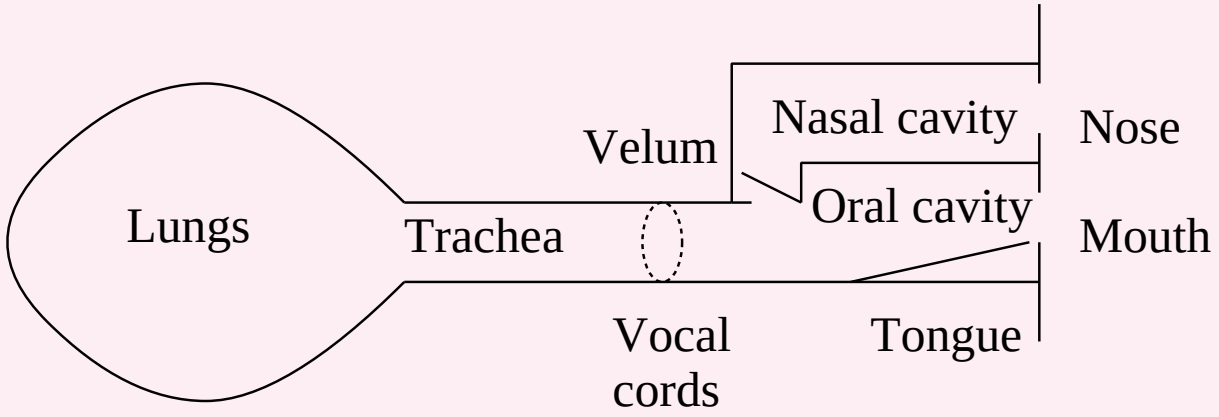


Figure 1.48: Schematic representation of the speech production system.

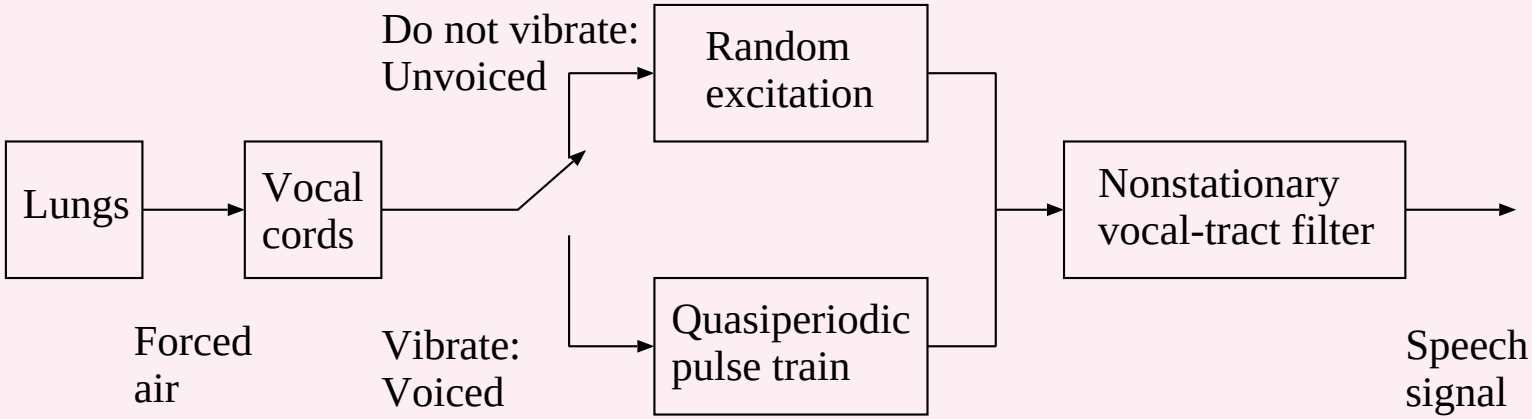


Figure 1.49: Schematic representation of the production of voiced and unvoiced speech.

Speech sounds classified mainly as

voiced, unvoiced, and plosive sounds.

Voiced sounds involve participation of the glottis:

air forced through vocal cords held at a certain tension.

The result is a series of quasiperiodic pulses of air

which is passed through and filtered by the vocal tract.

The input to the vocal tract may be treated as an impulse train that is almost periodic.

Upon convolution with the impulse response of the vocal tract, held at a certain configuration for the duration of the voiced sound desired,

a quasiperiodic signal is produced

with a characteristic waveshape that is repeated.

Vowels are voiced sounds.

Features of interest in voiced signals are the pitch and

resonance or formant frequencies of the vocal-tract system.

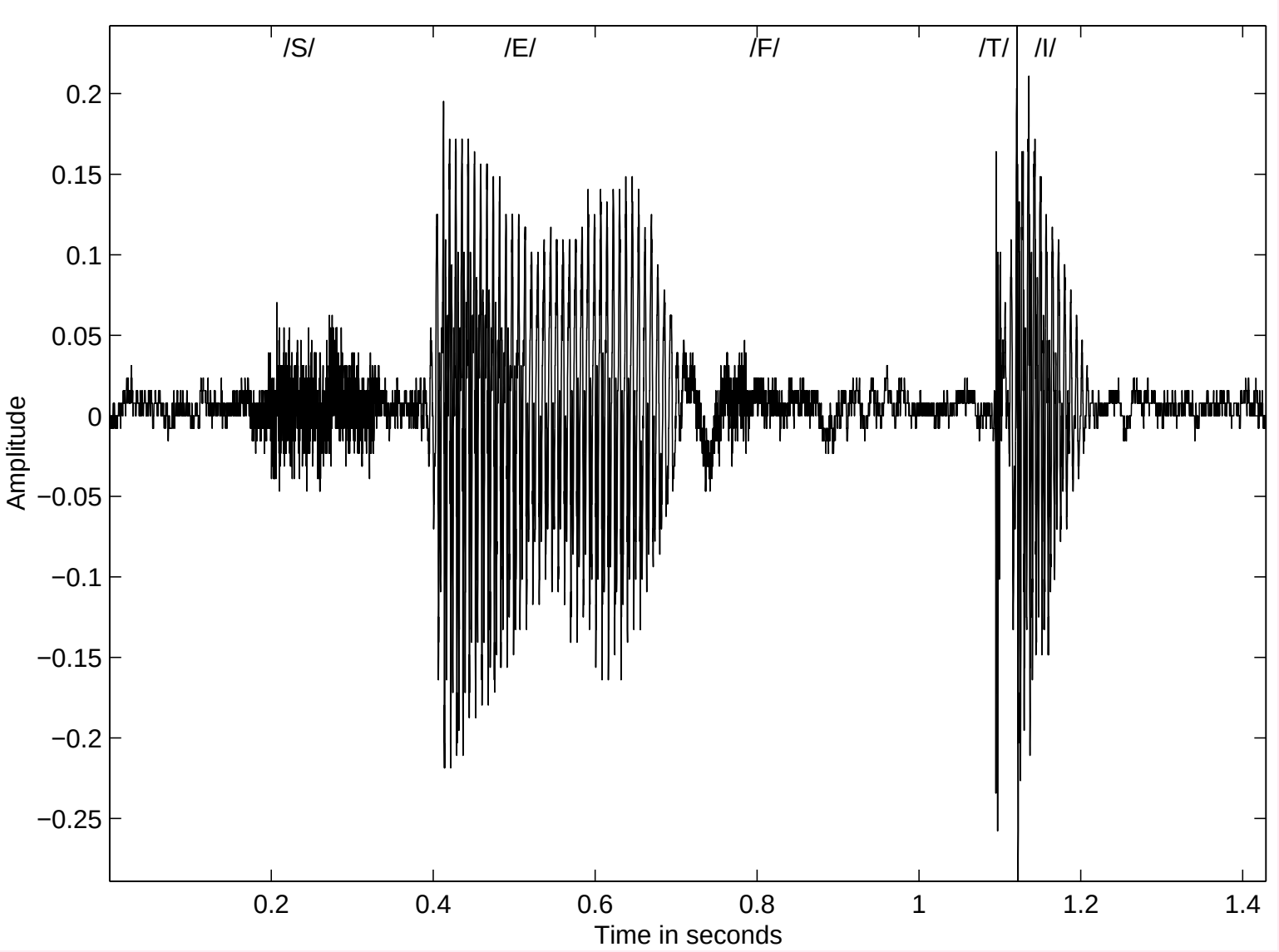


Figure 1.50: Speech signal of the word "safety" uttered by a male speaker. Approximate time intervals of the various phonemes in the word are /S/: $0.2 - 0.35\ s$; /E/: $0.4 - 0.7\ s$; /F/: $0.75 - 0.95\ s$; /T/: transient at $1.1\ s$; /I/: $1.1 - 1.2\ s$. Background noise is also seen in the signal before the beginning and after the termination of the speech, as well as during the stop interval before the plosive /T/.

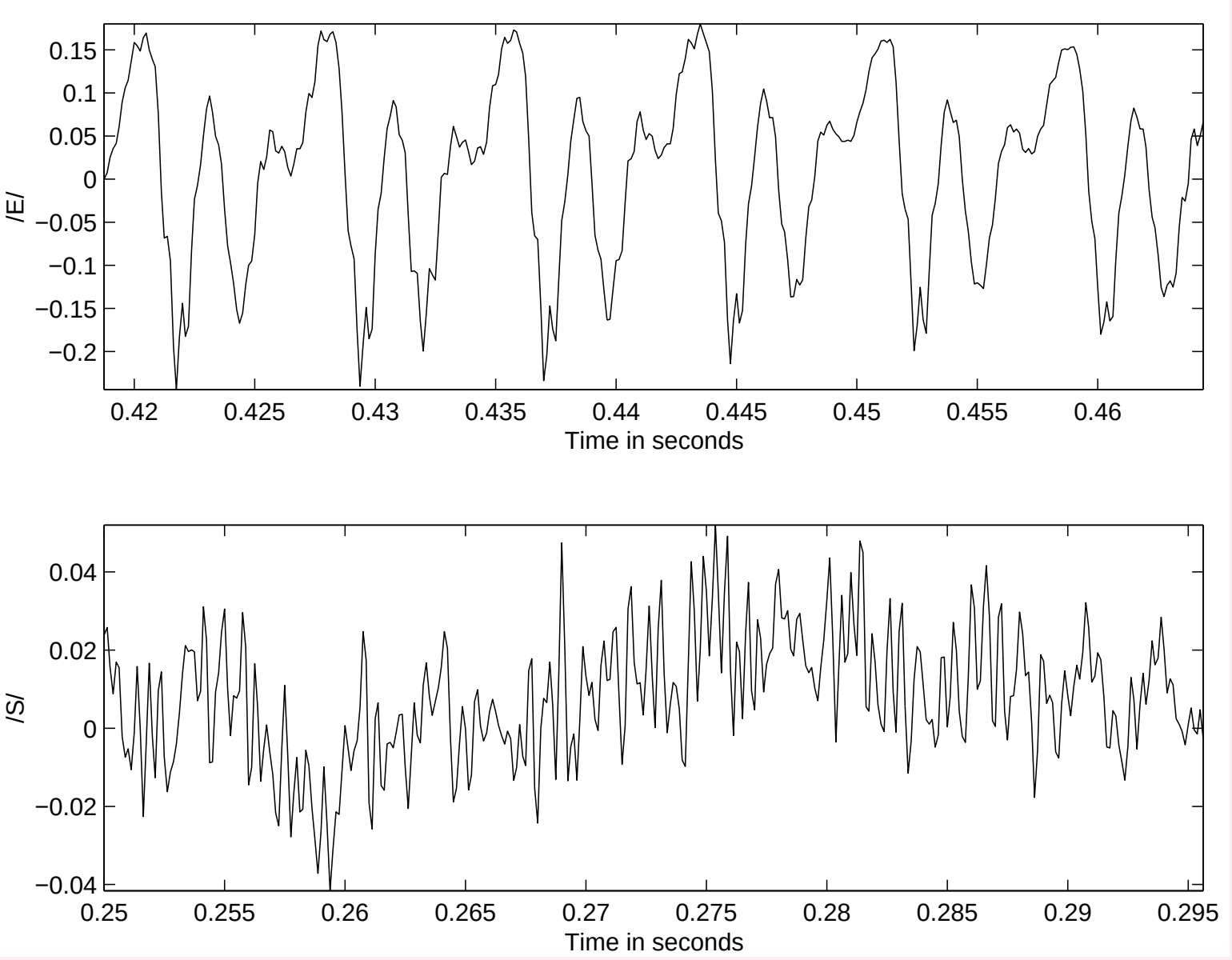


Figure 1.51: Segments of the signal in Figure 1.50 on an expanded scale to illustrate the quasiperiodic nature of the voiced sound /E/ in the upper trace, and the almost-random nature of the fricative /S/ in the lower trace.

An unvoiced sound (fricative) is produced by

forcing a steady stream of air through

a narrow opening or constriction formed

at a specific position along the vocal tract:

turbulent signal that appears like random noise.

The input to the vocal tract is a broadband random signal;

filtered by the vocal tract to yield the desired sound.

Fricatives are unvoiced sounds:

do not involve any activity (vibration) of the vocal cords.

Fricatives: /S/, /SH/, /Z/, /F/.

Plosives (stops): complete closure of the vocal tract,

followed by an abrupt release of built-up pressure.

Plosives: /P/, /T/, /K/, /D/.

1.2.13 The vibromyogram (VMG)

VMG: mechanical manifestation of contraction of skeletal muscle;

vibration signal that accompanies the EMG.

Muscle sounds or vibrations related to the change in dimensions (contraction) of the constituent muscle fibers.

Recorded using contact microphones or accelerometers.

VMG frequency and intensity vary in proportion to contraction level.

VMG and EMG useful in studies on neuromuscular control, muscle contraction, athletic training, and biofeedback.

1.2.14 The vibroarthrogram (VAG)

The knee joint: the largest articulation in the human body formed between the femur, the patella, and the tibia.

0° extension to 135° flexion;

20° to 30° rotation of the flexed leg on the femoral condyles.

The joint has four important features:

joint cavity,

articular cartilage,

synovial membrane, and

fibrous capsule.

The knee joint is a synovial joint: contains a

lubricating substance called the synovial fluid.

The patella (knee cap), a sesamoid bone, protects the joint:

precisely aligned to slide in the groove (trochlea)

of the femur during leg movement.

Knee joint is made up of three compartments:

the patellofemoral,

the lateral tibiofemoral, and

the medial tibiofemoral compartments.

Patellofemoral compartment: synovial gliding joint;

tibiofemoral: synovial hinge joint.

The anterior and posterior cruciate ligaments

as well as the lateral and medial ligaments

bind the femur and tibia together,

give support to the knee joint, and

limit movement of the joint.

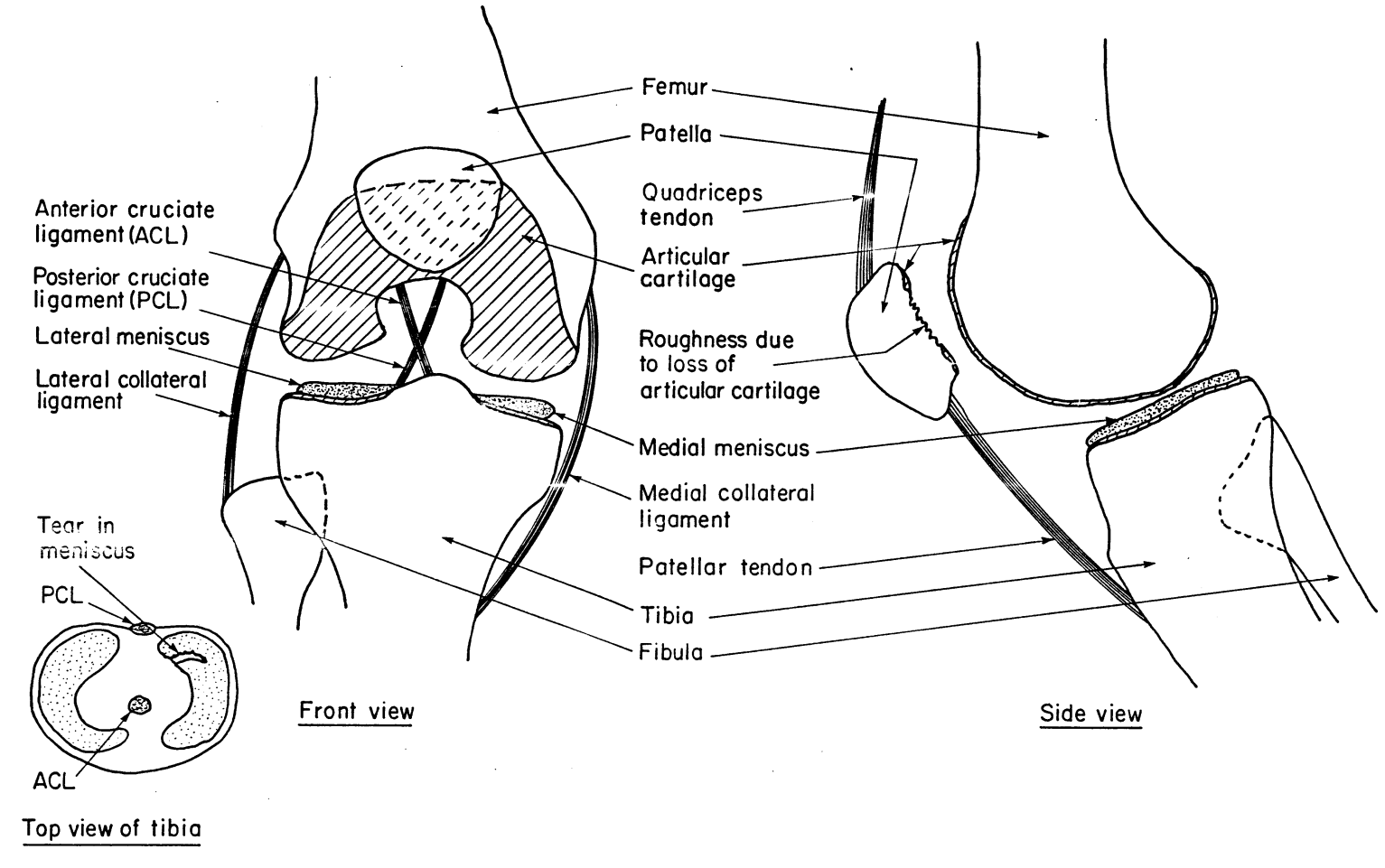


Figure 1.52: Front and side views of the knee joint (the two views are not mutually orthogonal). The inset shows the top view of the tibia with the menisci.

Two types of cartilage in the knee joint:

the *articular cartilage* covers the ends of bones;

the wedge-shaped fibrocartilaginous structure called the

menisci, located between the femur and the tibia.

Cartilage is vital to joint function:

protects the underlying bone during movement.

Loss of cartilage function leads to pain, decreased mobility, deformity, and instability.

Chondromalacia patella: articular cartilage softens, fibrillates, and sheds off the undersurface of the patella.

Meniscal fibrocartilage can soften: degenerative tears.

Noise associated with degeneration of knee-joint surfaces.

VAG: vibration during movement or articulation of the joint.

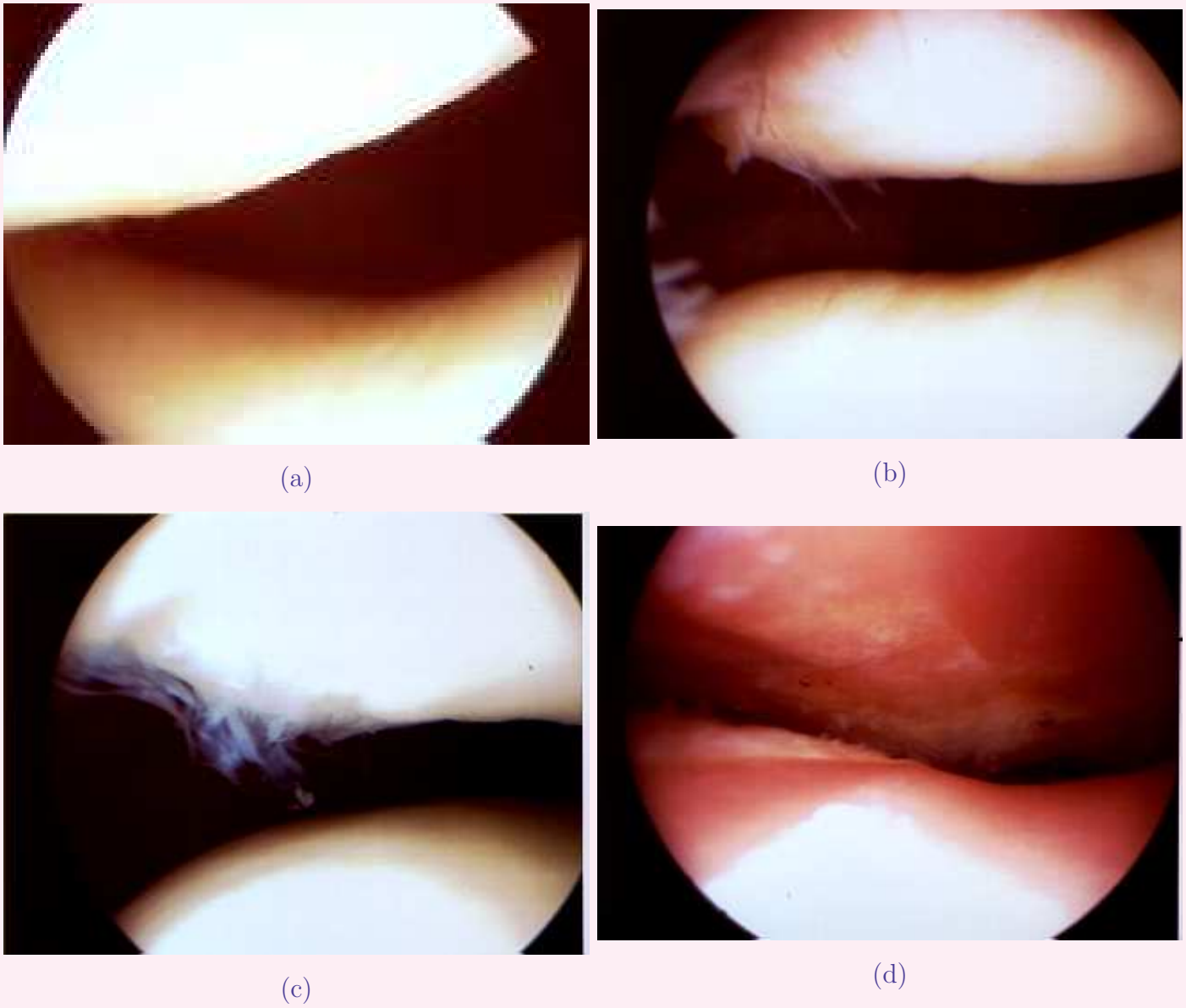
Normal joint surfaces: smooth, produce little or no sound.

Joints affected by osteoarthritis and degenerative diseases:

cartilage loss leads to grinding sounds.

Analysis of VAG signals could help avoid exploratory

surgery and aid in diagnosis of knee-joint problems.



(a) (b) (c) (d)

Arthroscopic views of the patellofemoral joint. (a) Normal cartilage surfaces. (b) Chondromalacia Grade II at the patella. (c) Chondromalacia Grade III at the patella. (d) Chondromalacia Grade IV at the patella and the femur; the bones are exposed. The under-surface of patella is at the top and the femoral condyle is at the bottom. Figure courtesy: G.D. Bell, Sport Medicine Centre, University of Calgary.

1.2.15 Otoacoustic emission (OAE) signals

OAE: acoustic energy emitted by the cochlea

either spontaneously or in response to an acoustic stimulus.

May assist in screening of hearing function and

diagnosis of hearing impairment.

1.2.16 Bioacoustic signals

Several systems and parts of the human body produce sounds and vibrations in various bands of frequencies under normal physiological and pathological conditions: PCG, VMG, VAG, OAE signals; snoring; crying of infants; breathing, tracheal, lung, and chest sounds; bowel sounds; sounds of the shoulder, temporomandibular, and hip joints.

1.3 Objectives of Biomedical Signal Analysis

- *Information gathering* — measurement of phenomena to interpret a system.
- *Diagnosis* — detection of malfunction, pathology, or abnormality.
- *Monitoring* — obtaining continuous or periodic information about a system.

- *Therapy and control* — modification of the behavior of a system based upon the outcome of the activities listed above to ensure a specific result.
- *Evaluation* — objective analysis to determine the ability to meet functional requirements, obtain proof of performance, perform quality control, or quantify the effect of treatment.

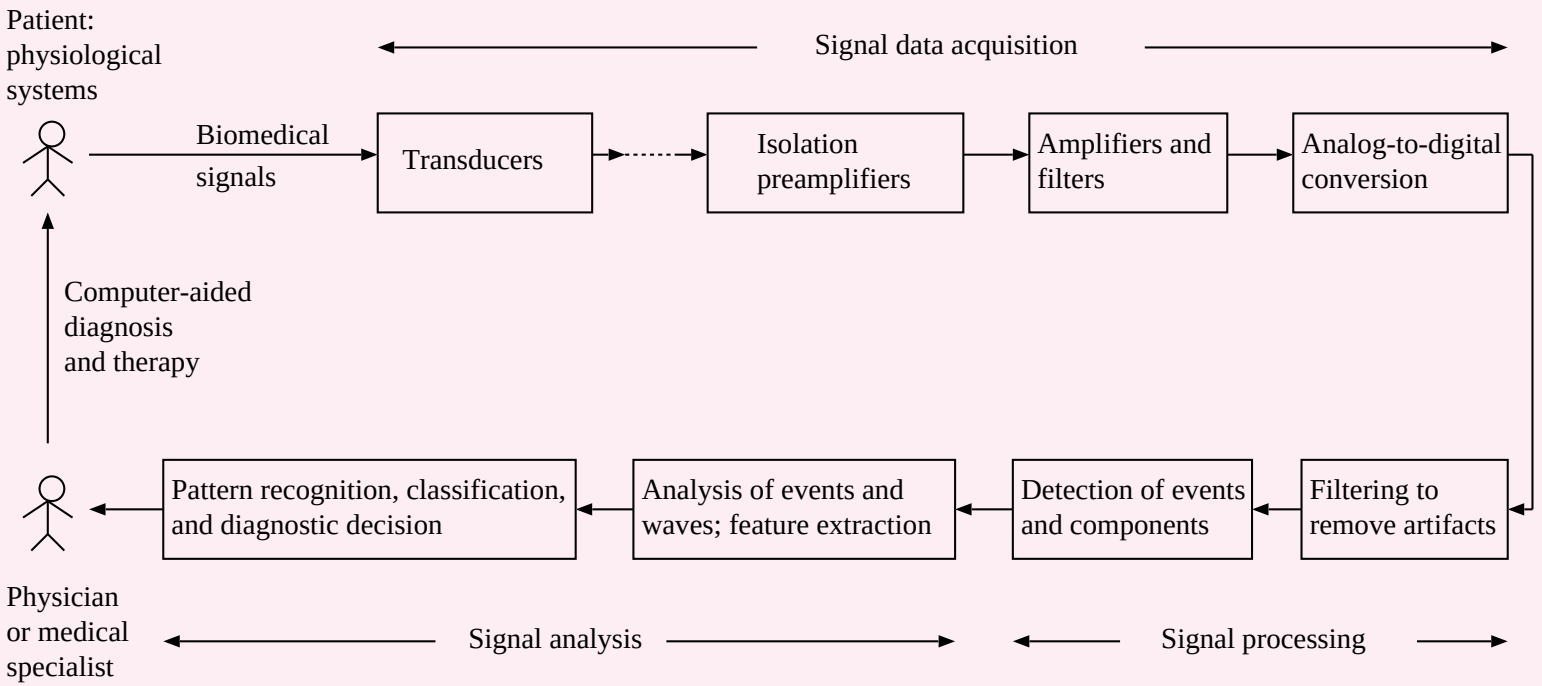


Figure 1.53: Computer-aided diagnosis and therapy based upon biomedical signal analysis.

Signal acquisition procedures may be categorized as

invasive or noninvasive, active or passive.

Risk – benefit analysis.

Be prepared to manage adverse reactions.

Ethical approval by specialized committees required

for experimental procedures involving

human or animal subjects:

minimize the risk and discomfort to the subject,

maximize benefits to the subjects and the investigator.

The human – instrument system:

- *The subject or patient.*
- *Stimulus or procedure of activity.*
- *Transducers.*
- *Signal-conditioning equipment.*
- *Display equipment.*
- *Recording, data processing, and transmission equipment.*
- *Control devices.*

1.4 Difficulties Encountered in Biomedical Signal Acquisition and Analysis

Accessibility of the variables to measurement.

Variability of the signal source.

Interactions among physiological systems.

Effects of the instrumentation or procedure on the system.

Physiological artifacts and interference.

Energy limitations. Patient safety.

1.5 Computer-aided Diagnosis: CAD

- Humans are highly skilled and fast in the analysis of visual patterns but slow in arithmetic operations.
- Humans could be affected by fatigue, boredom, and environmental factors: susceptible to committing errors.
- Computers are inanimate but accurate and consistent machines: can be designed to perform specific and repetitive tasks.
- Analysis by humans is usually subjective and qualitative.

- Analysis by humans is subject to interobserver as well as intraobserver variations over time.
- *On-line, real-time* analysis of biomedical signals is feasible with computers.
- *Quantitative analysis* becomes possible by the application of computers to biomedical signals.
- The logic of clinical diagnosis via signal analysis can be *objectively* encoded and *consistently* applied in routine or repetitive tasks using computers.

- End-goal of biomedical signal analysis: computer-*aided* diagnosis and not automated diagnosis.
- Results of signal analysis need to be integrated with clinical signs, symptoms, and information by a physician.
- The *intuition* of the specialist plays an important role in arriving at the final diagnosis.
- Quantitative and objective analysis facilitated by the application of computers to biomedical signal analysis: *improved diagnostic decision by the physician.*

On the importance of quantitative analysis:

"When you can measure what you are speaking about,
and express it in numbers,
you know something about it;
but when you cannot measure it,
when you cannot express it in numbers,
your knowledge is of a meager and
unsatisfactory kind:
it may be the beginning of knowledge,
but you have scarcely, in your thoughts,
advanced to the stage of *science*."

— *Lord Kelvin (William Thomson, 1824 – 1907)*

On assumptions made in quantitative analysis:

"Things do not in general run around
with their measure stamped on them
like the capacity of a freight car;
it requires a certain amount of investigation
to discover what their measures are ...
What most experimenters take for granted
before they begin their experiments
is infinitely more interesting
than any results to which their experiments lead."

— *Norbert Wiener (1894 – 1964)*

2

Analysis of Concurrent, Coupled, and Correlated Processes

The human body is a complex integration of a number of biological systems with several ongoing physiological, functional, and pathological processes.

Most biological processes within a body are

not independent of one another;

they are mutually correlated and bound together

by physical or physiological control and

communication phenomena.

2.1 Problem Statement

Determine the correspondences, correlation, and interrelationships present between concurrent signals related to a common underlying physiological system or process, and identify their potential applications.

2.2 Illustration of the Problem with Case Studies

2.2.1 The electrocardiogram and the phonocardiogram

Problem: *Identify the beginning of S1 in a PCG signal and extract the heart sound signal over one cardiac cycle.*

Solution: Use the QRS wave in the ECG as

reference or trigger.

2.2.2 The phonocardiogram and the carotid pulse

Problem: *Identify the beginning of S2 in a PCG signal.*

Solution: Use the dicrotic notch in the carotid pulse.

2.2.3 The ECG and the atrial electrogram

Problem: *Obtain an indicator of atrial contraction to measure the PR interval.*

Solution: Jenkins et al. developed a pill electrode

to obtain a strong and clear signal of atrial activity.

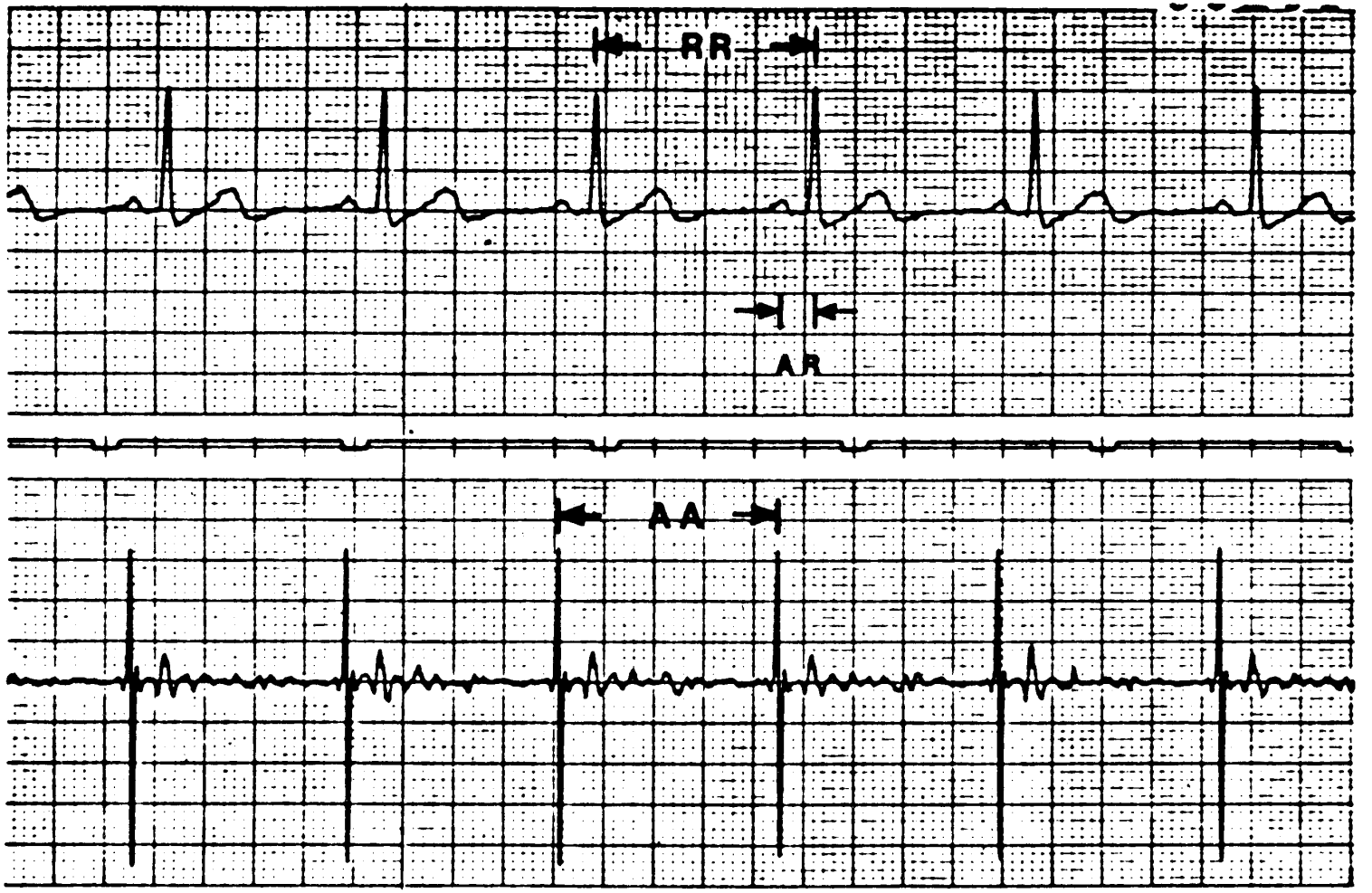


Figure 2.1: Pill-electrode recording of the atrial electrogram (lower tracing) and the external ECG (upper tracing) of a normal subject. The pulse train between the two signals indicates intervals of 1 s. Reproduced with permission from J.M. Jenkins, D. Wu, and R. Arzbaecher, Computer diagnosis of abnormal cardiac rhythms employing a new P-wave detector for interval measurement, *Computers and Biomedical Research*, 11:17–33, 1978. ©Academic Press.

Jenkins et al. developed a four-digit code for each beat.

The first digit was coded as

0: abnormal waveshape, or

1: normal waveshape,

determined by a correlation coefficient between

the beat being processed and a normal template.

The remaining three digits encoded the nature of the

RR, AR, and AA intervals.

0: short,

1: normal, or

2: long.

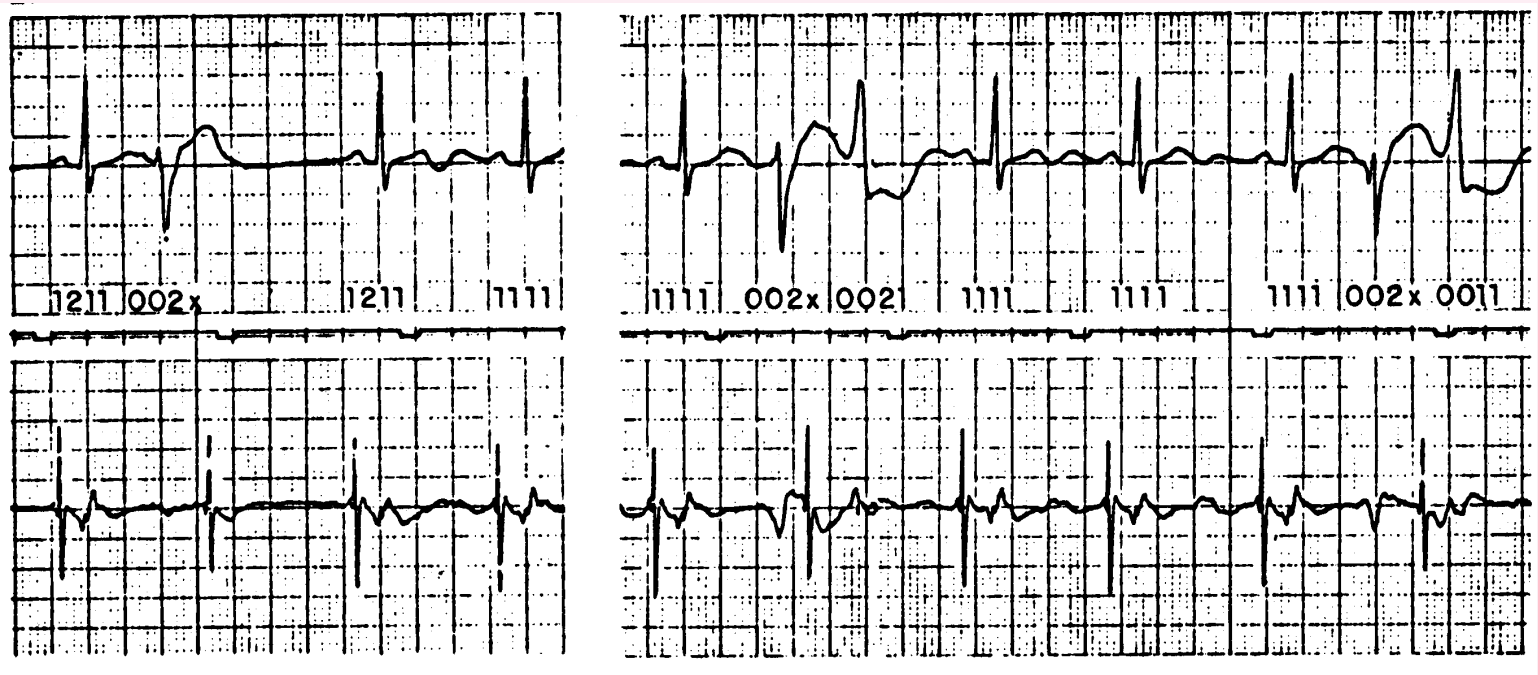


Figure 2.2: Atrial electrogram (lower tracing) and the external ECG (upper tracing) of a subject with ectopic beats. The pulse train between the two signals indicates intervals of 1 s. Reproduced with permission from J.M. Jenkins, D. Wu, and R. Arzbaecher, Computer diagnosis of abnormal cardiac rhythms employing a new P-wave detector for interval measurement, *Computers and Biomedical Research*, 11:17–33, 1978. ©Academic Press.

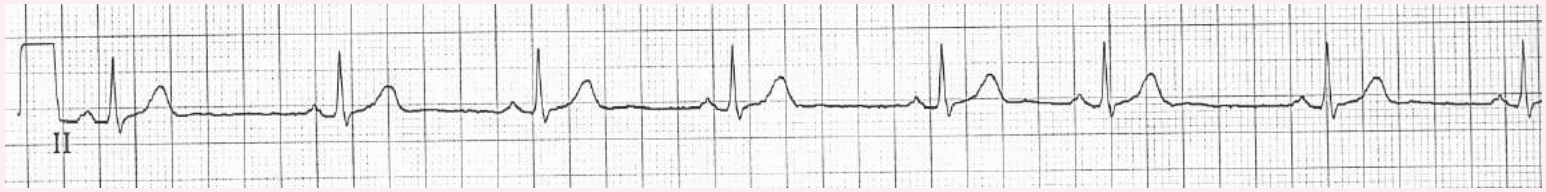
2.2.4 Cardiorespiratory interaction

The heart rate is affected by breathing due to coupling and interaction between the cardiac and respiratory systems: baroreceptors in the aorta and carotid artery.

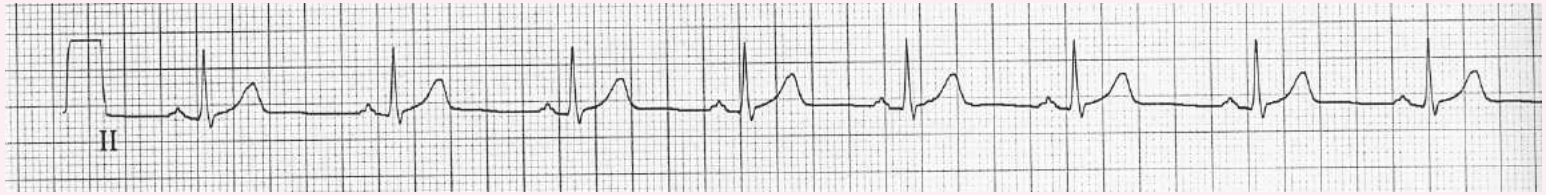
Vagus nerve activity impeded when we inhale:

The heart rate increases.

Breathing also affects the transmission of the heart sounds from the cardiac chambers to the chest surface.



(a)



(b)

Figure 2.3: ECG signal of a subject (a) with the subject breathing normally, and (b) with the subject holding breath. Signal courtesy of E. Gedamu and L.B. Mitchell, Foothills Hospital, Calgary.

2.2.5 The importance of HRV

Even under resting and apparently steady conditions, the RR interval and the heart rate are not constant.

Variability of the RR interval and heart rate is a normal and healthy physiological phenomenon.

Reduced HRV in patients following acute myocardial infarction has been observed to be related to poor prognosis.

HRV is an important predictor of patients at high risk of sudden death and ventricular arrhythmia.

2.2.6 The EMG and VMG

Problem: *Obtain a mechanical signal that is a direct indicator of muscle-fiber or motor unit activity to study muscle contraction and force development.*

Solution: Use the VMG —

direct manifestation of the contraction of muscle fibers.

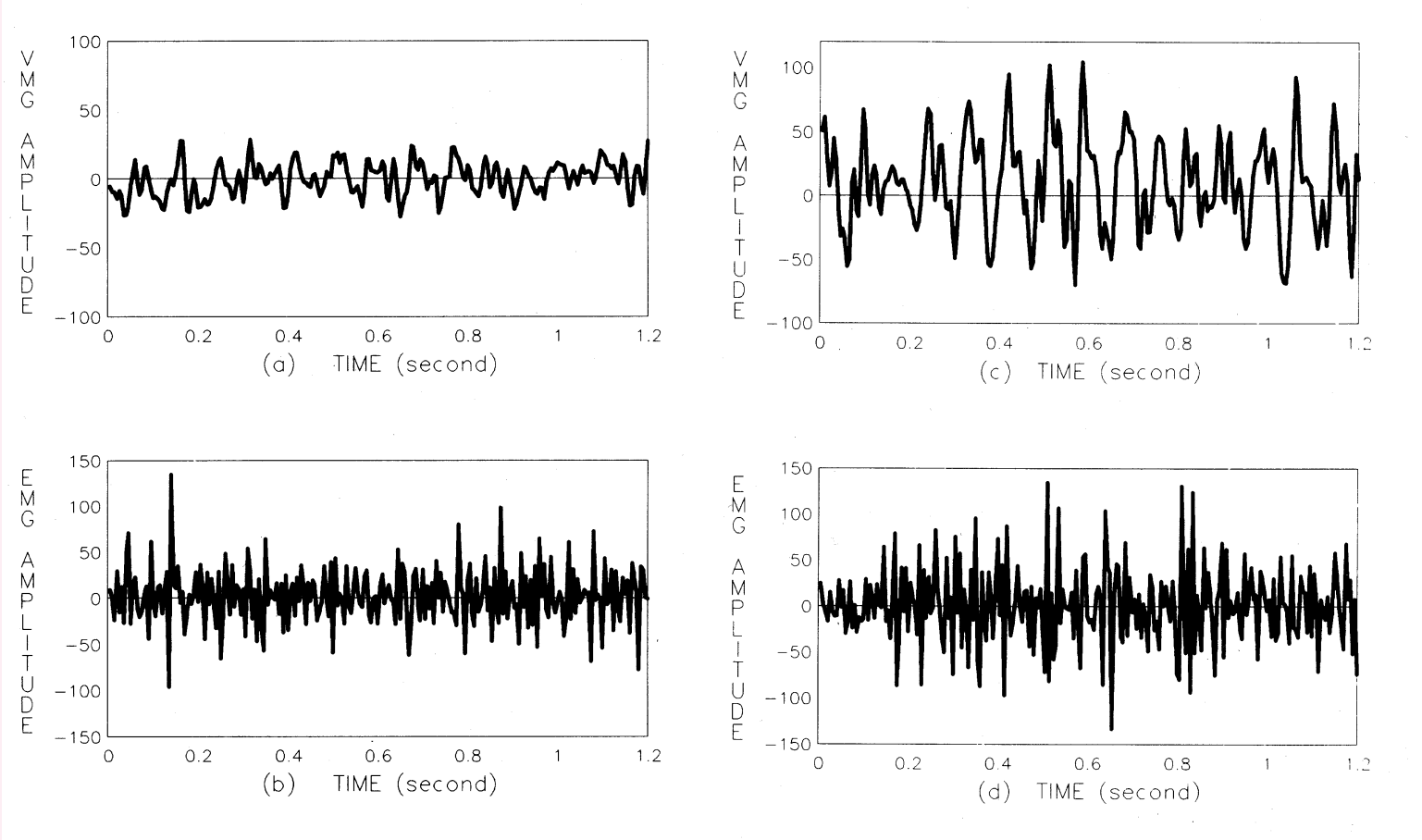


Figure 2.4: Simultaneous EMG – VMG records at two levels of contraction of the rectus femoris muscle. (a) VMG at 40% of the maximal voluntary contraction (MVC) level. (b) EMG at 40% MVC. (c) VMG at 60% MVC. (d) EMG at 60% MVC. Reproduced with permission from Y.T. Zhang, C.B. Frank, R.M. Rangayyan, and G.D. Bell, Relationships of the vibromyogram to the surface electromyogram of the human rectus femoris muscle during voluntary isometric contraction, *Journal of Rehabilitation Research and Development*, 33(4): 395–403, 1996. ©Department of Veterans Affairs.

2.2.7 The knee-joint and muscle vibration signals

VMG associated with the rectus femoris muscle

that must necessarily be active during extension of the leg

appears as an interference and corrupts the VAG signal.

Problem: *Suggest an approach to remove the*

muscle-contraction interference from the

knee-joint vibration signal.

Solution:

The rectus femoris muscle and the knee-joint systems are coupled dynamic systems with vibration characteristics that vary with activity level and time: *nonstationary.*

Record the VMG signal at the rectus femoris at the same time as the VAG signal is acquired from the patella.

Apply adaptive filtering and noise cancellation techniques.

2.3 Application: Segmentation of the PCG into Systolic and Diastolic Parts

Problem: *Show how the ECG and carotid pulse signals may be used to break a PCG signal into its systolic and diastolic parts.*

Solution: QRS in ECG $\Longleftrightarrow$ S1 in PCG.

Dicrotic notch in carotid pulse $\Longleftrightarrow$ S2 in PCG.

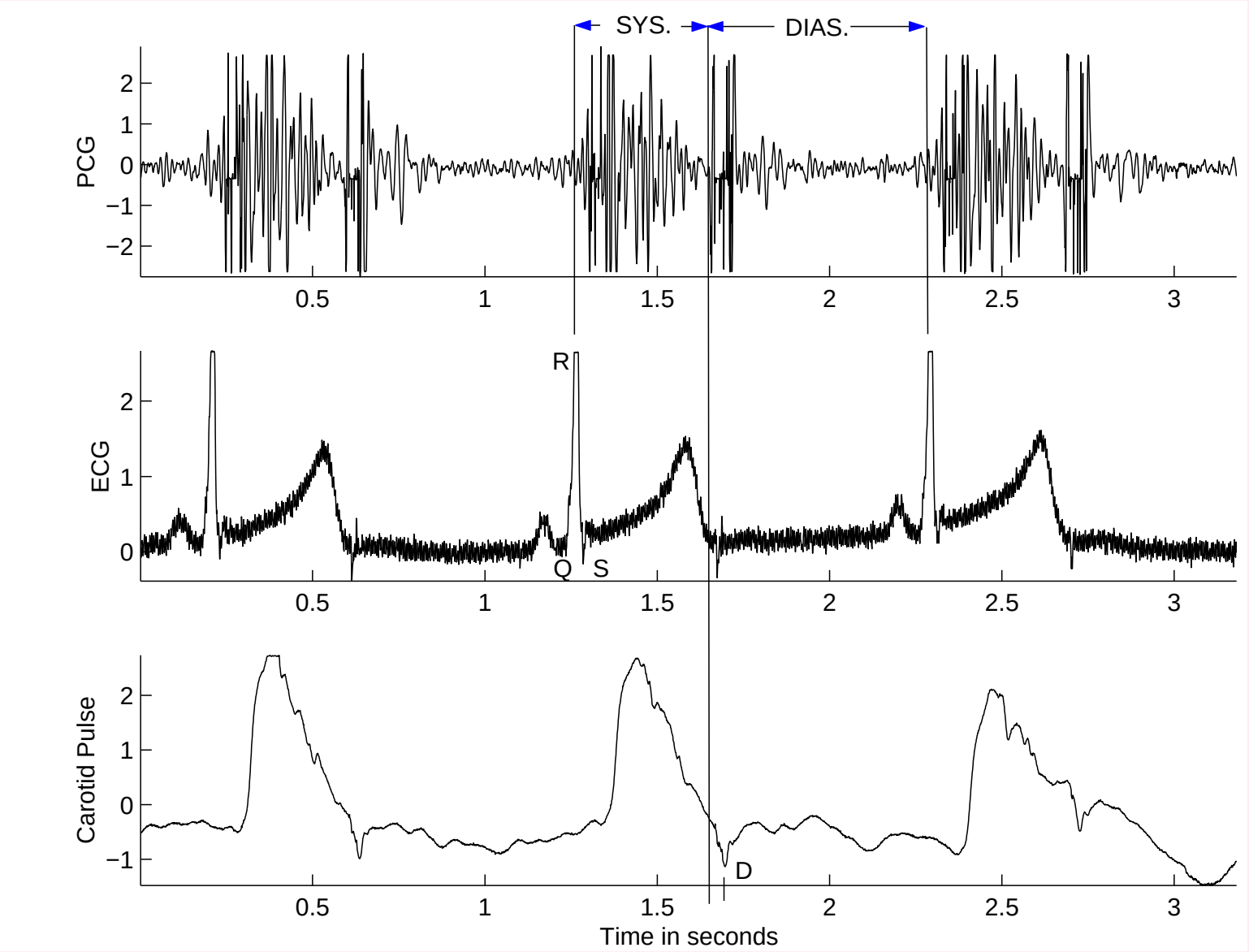


Figure 2.5: Demarcation of the systolic (SYS.) and diastolic (DIAS.) parts of the PCG signal in Figure 1.44 by using the ECG and carotid pulse as reference signals. The QRS complex and the dicrotic notch D are marked on the ECG and carotid pulse signals, respectively.

2.4 Application: Diagnosis and Monitoring of Sleep Apnea

Problem: *Propose approaches based on biomedical signal analysis to detect sleep apnea. Analyze the problem taking into consideration the various physiological systems that are either part of the problem or are affected by the resulting condition.*

Solution: "Apnea" is a condition in which one stops breathing for several seconds, usually during sleep.

"Hypopnea" is a condition when airflow is diminished.

The total number of episodes of apnea and hypopnea per hour of sleep is defined as the apnea–hypopnea index (AHI).

A patient affected by sleep apnea may stop breathing $10 - 100$ times/hour in episodes of duration $10 - 30\ s$ each.

Diagnosis of sleep apnea is typically based on an AHI threshold of 10 to 15.

Causes of sleep apnea:

lack of neural input from the CNS to the diaphragm to cause contraction and breathing — central sleep apnea (CSA),

collapse of the upper airway — obstructive sleep apnea (OSA).

A common symptom of OSA is snoring.

Sleep apnea leads to decreased oxyhemoglobin in the blood.

The absorption of different wavelengths of light by hemoglobin changes when it is bound to oxygen:

oxyhemoglobin — red

deoxyhemoglobin — blue.

A finger-tip sensor with a light emitting diode (LED) and a photo sensor, known as a finger-tip pulse oximeter, or a

CO-oximeter is used to estimate the level of oxyhemoglobin.

2.4.1 Monitoring of sleep apnea by polysomnography

Polysomnography (PSG) involves multichannel recording of several biomedical signals and parameters:

current standard for the evaluation of sleep-related problems, including sleep apnea.

Some of the signals and parameters measured are respiratory effort, airflow, oxygenation, sleep state, EMG of the submental muscle (beneath the chin), EMG of the legs, the electrooculogram (EOG), EEG, ECG, and snoring sound.

PSG requires the subject to sleep overnight in a laboratory.

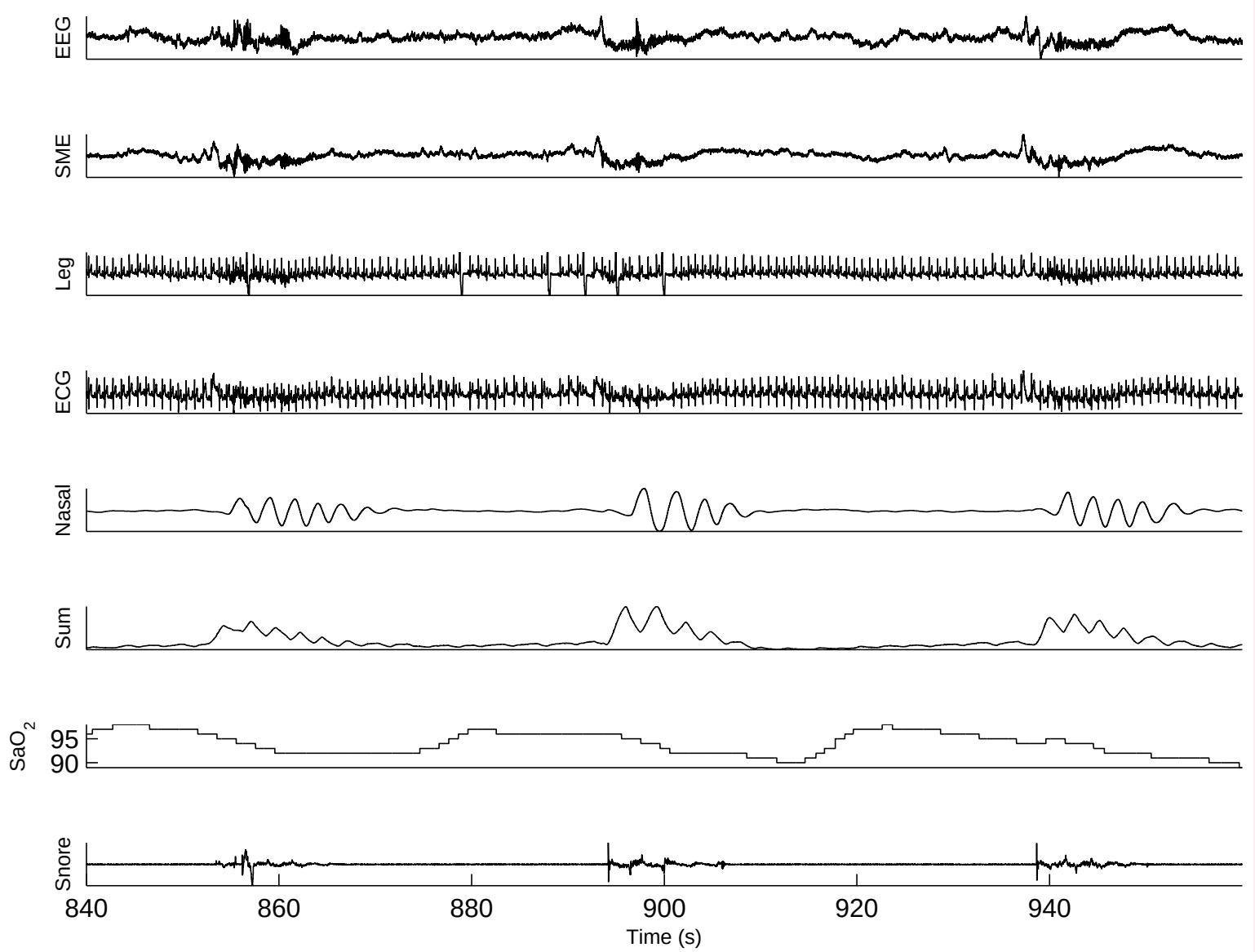


Figure 2.6: Top to bottom: EEG (F4), submental EMG (SME), leg EMG, ECG, airflow (nasal pressure cannula), sum of thoracic and abdominal activity (sum, from respiratory inductance plethysmography), SaO_2 %, and snoring sound signals selected from a 14-channel PSG record of a patient with OSA. Amplitude information has been removed from all channels except SaO_2 % to reduce clutter. Data obtained from Hisham Alshaer and T. Douglas Bradley, Sleep Research Laboratory of the University Health Network Toronto Rehabilitation Institute, Toronto, Ontario, Canada, with permission.

2.4.2 Home monitoring of sleep apnea

PSG is a comprehensive and accurate method for diagnosing sleep apnea; however, it is expensive, inconvenient, and often not available.

Practical home-monitoring systems have been developed and are commercially available for the diagnosis and follow-up of sleep apnea.

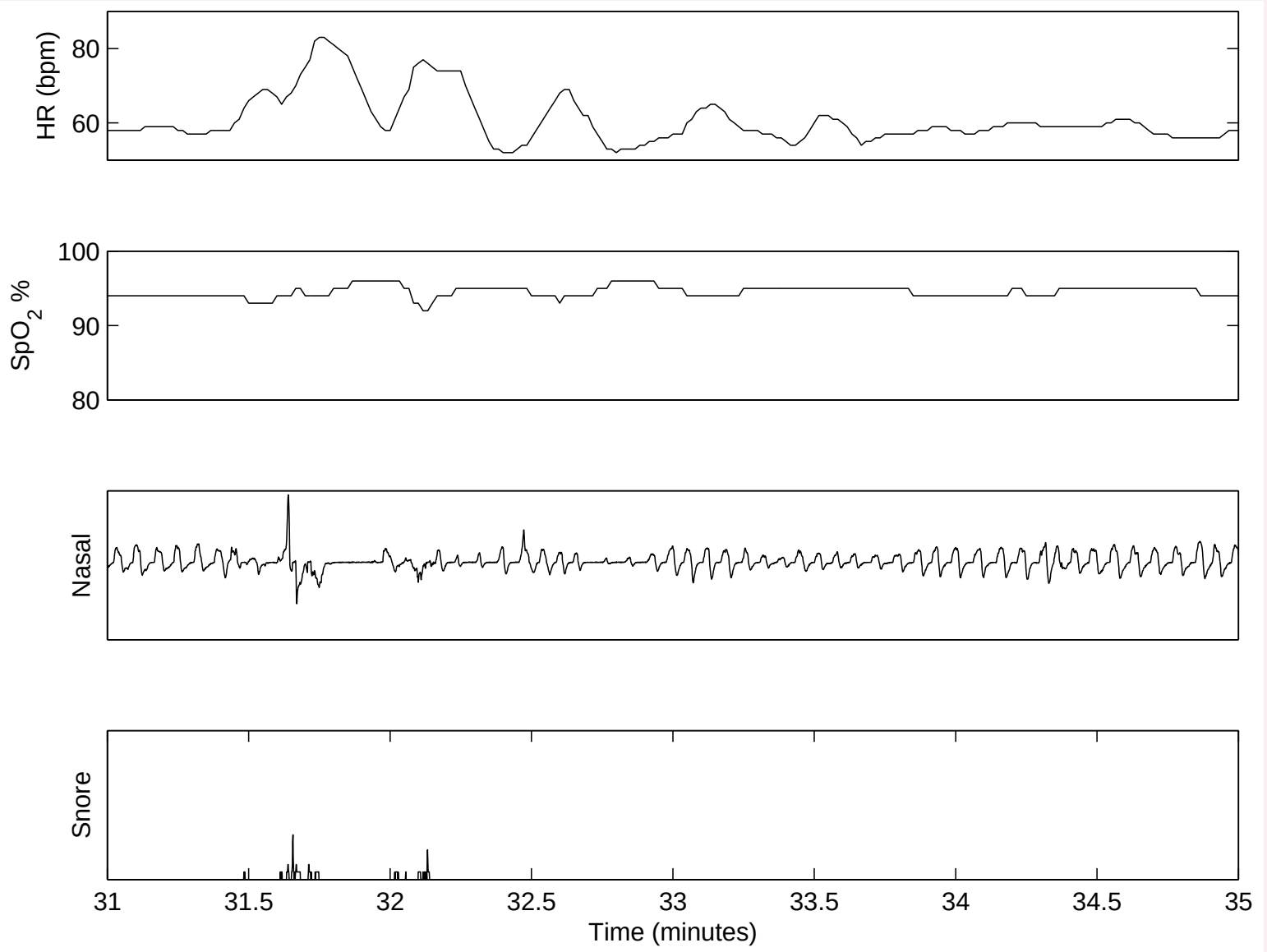


Figure 2.7: Top to bottom: Heart rate, SpO_2, nasal pressure, and snoring sound signals from a home apnea monitoring record of a moderately symptomatic subject. Amplitude information has been removed from the nasal pressure and snoring sound channels to reduce clutter. Data courtesy of R. Platt, SagaTech Electronics Inc., Calgary, Alberta, Canada, sagatech.ca.

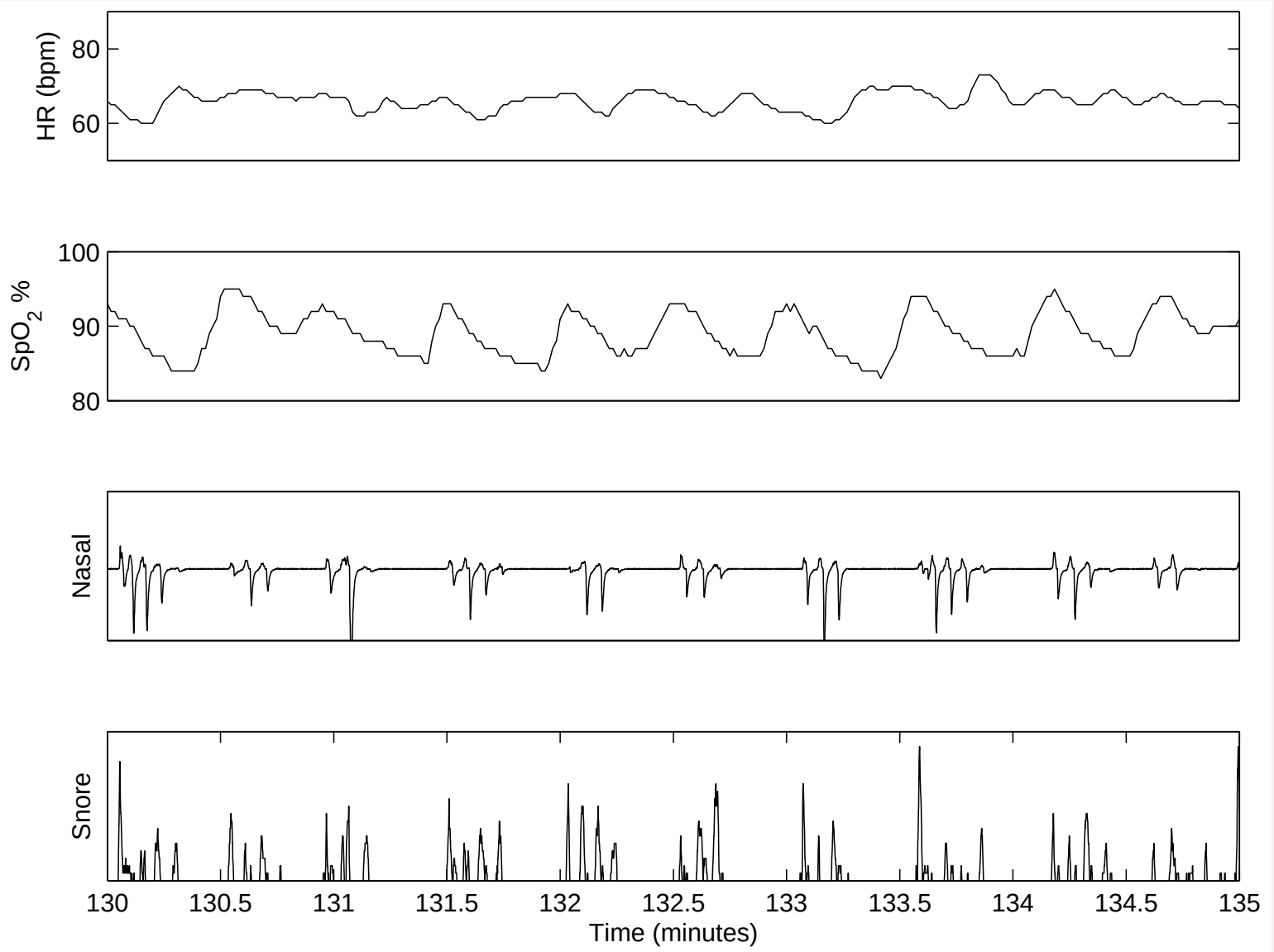


Figure 2.8: Top to bottom: Heart rate, SpO_2, nasal pressure, and snoring sound signals from a home apnea monitoring record of a subject with severe sleep apnea. Amplitude information has been removed from the nasal pressure and snoring sound channels to reduce clutter. Data courtesy of R. Platt, SagaTech Electronics Inc., Calgary, Alberta, Canada, sagatech.ca.

2.4.3 Multivariate and multiorgan analysis

Bianchi et al. proposed a multivariate and multiorgan approach for the analysis of cardiorespiratory variability.

Application: analysis of sleep and sleep-related disorders.

This approach emphasizes that the ANS influences several organs and systems, including the cardiovascular, respiratory, and endocrine-metabolic systems;

it also indicates a direct connection to the central and peripheral nervous systems.

Cerutti proposed an integrated approach for analysis of signals from coupled and correlated systems.

Figure 2.9 shows the EEG, EMG from the tibia, RR intervals, and respiration from a patient with myoclonus (involuntary twitching or jerking of a muscle) during sleep.

Repeated jerking of the leg, known as the restless leg syndrome, is associated with sleep disruption and apnea.

Figure 2.9 shows synchronization between arousal events in the EEG, spikes of activity related to myoclonus in the tibial EMG, increased heart rate (diminished RR intervals), and decreased respiratory activity.

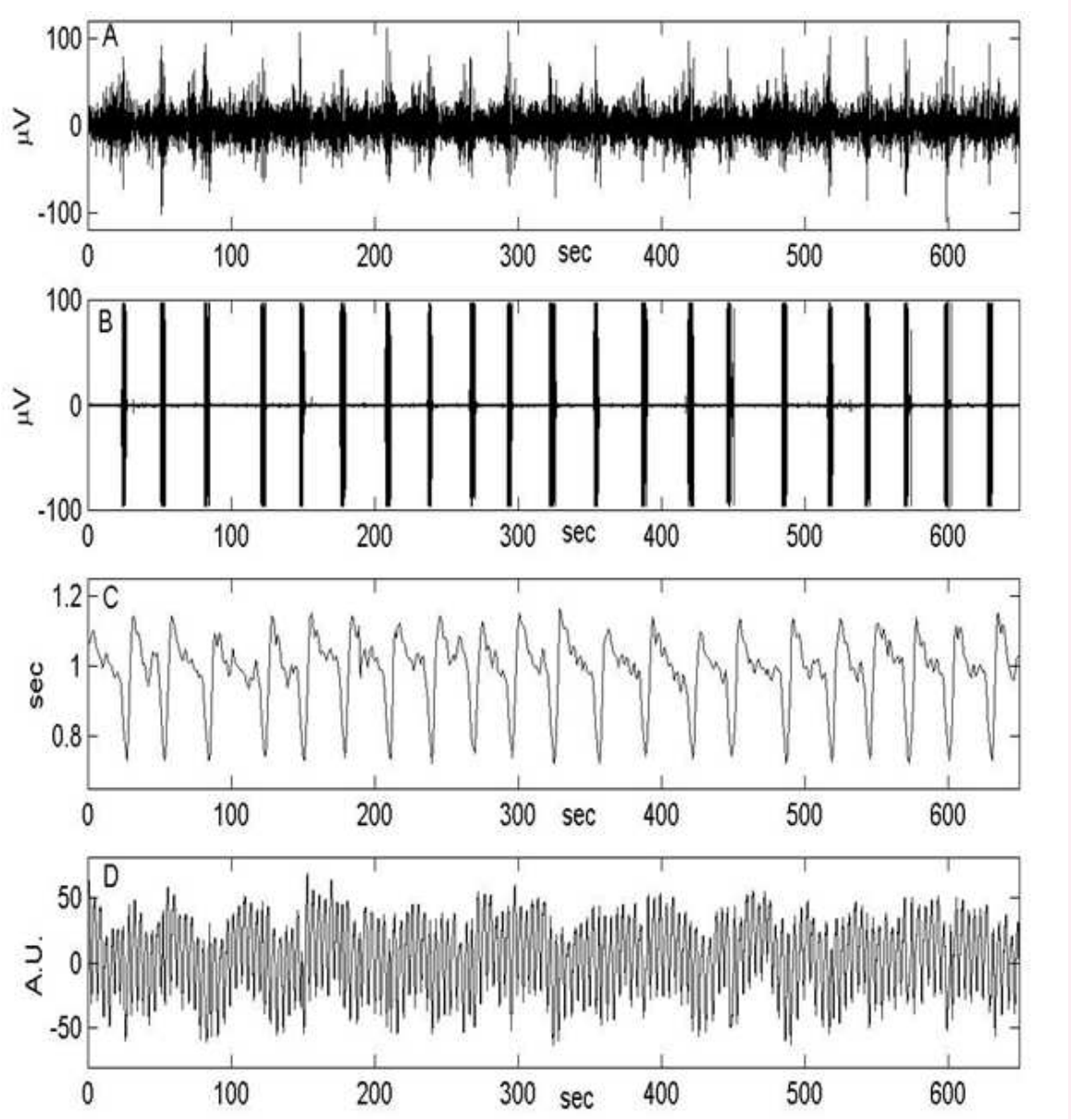


Figure 2.9: Top to bottom: EEG, EMG from the tibia, RR intervals, and respiration signal from a patient with myoclonus (involuntary twitching or jerking of a muscle) during sleep. Reproduced with permission from S. Cerutti, "Methods of biomedical signal processing: multiparametric and multidisciplinary integration toward a better comprehension of pathophysiological mechanisms," pp 3–31, Chapter 1 in *Advanced Methods of Biomedical Signal Processing,* Edited by S. Cerutti and C. Marchesi, IEEE and Wiley, New York, NY, 2011. ©IEEE.