Chapter 1
Fundamentals of Biosignals

If you sharpen your electrical sense to generators in the body,
If you listen to body sounds emerging from depths of the body,
If you look through a fragment of the body,
If you feel the skin pulsation of the body,
You are to gain a valuable knowledge of the body's well-being…

Sensing technologies in physiology gain a lot of importance for the assessment of the human functional state. The registered biomedical signals—referred to as *biosignals* here—are important not only for timeless classical applications concerning medical diagnosis and subsequent therapy, but also for future applications such as daily driver monitoring.

Thus, this chapter starts by giving a definition of biosignals and its very *general model*, considering biosignal generation, propagation, and its conversion for application-specific analysis. This model offers a solid basis for each type of biosignal, which will accompany us throughout the book. Then the very beginning steps of biosignal registration, the *history of biosignal* assessment, are discussed. The problems encountered (at that time) are described, as well as applied methods to solve them, with some of these methods having outlasted many centuries and are in use even today. Possible *classifications* of commonly used biosignals (state of the art biosignals) are introduced in this chapter to perceive a nearly unlimited diversity of biosignals. Lastly, a few *ubiquitous applications* of biosignal assessment are given, followed by *future trends* in biosignal monitoring.

1.1 Definition and Model of Biosignals

Within the scope of biomedical signals and sensors, a *biosignal* can be defined *as a description of a physiological phenomenon*, irrespective of the nature of this description. Since there is a nearly unlimited number of physiological mechanisms

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of interest, the number of possible biosignals is very large. In the broadest sense, the variety of biosignals extends from a visual inspection of the patient (Sect. 1.2) up to signals recorded from the human body using sensors, e.g., electrocardiography, compare Fig. 1.1. The huge diversity of biosignals can be best demonstrated by the fact that there are numerous kinds of biosignal classification, as discussed later in Sect. 1.3.

To give an *example of a biosignal* from its generation up to its registration, Fig. 1.2 depicts the formation of *acoustic biosignals* which are used, for instance, for the assessment of cardiorespiratory pathologies. The corresponding biosignal *source* in the heart is given by the periodic closure of heart valves, which yields

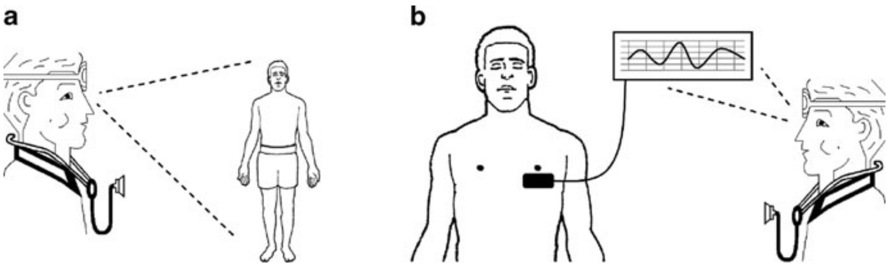

Fig. 1.1 Basic procedures for biosignal assessment from (**a**) visual appraisal of patient by a physician to (**b**) application of a biomedical sensor on the patient

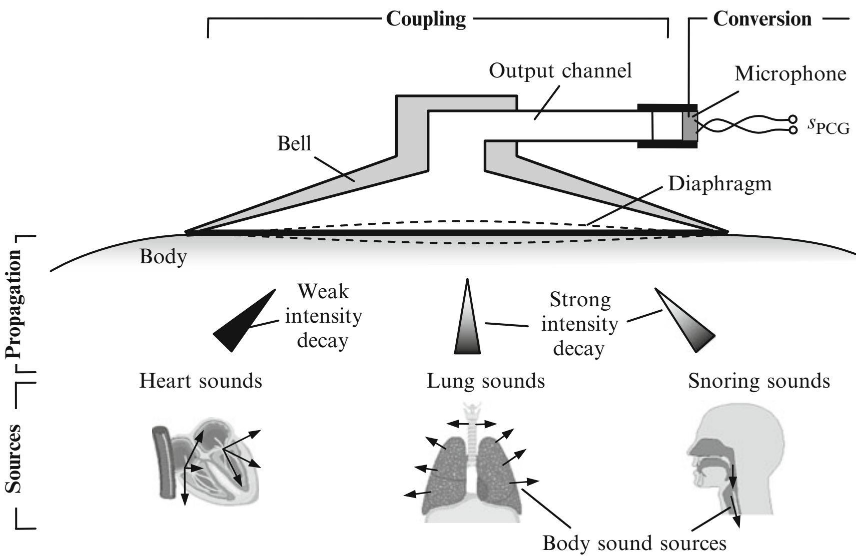

Fig. 1.2 The biomedical sensor on the chest for the registration of body sounds. The generation phenomena of the acoustic biosignals are depicted, along biosignal's propagation, coupling, and registration

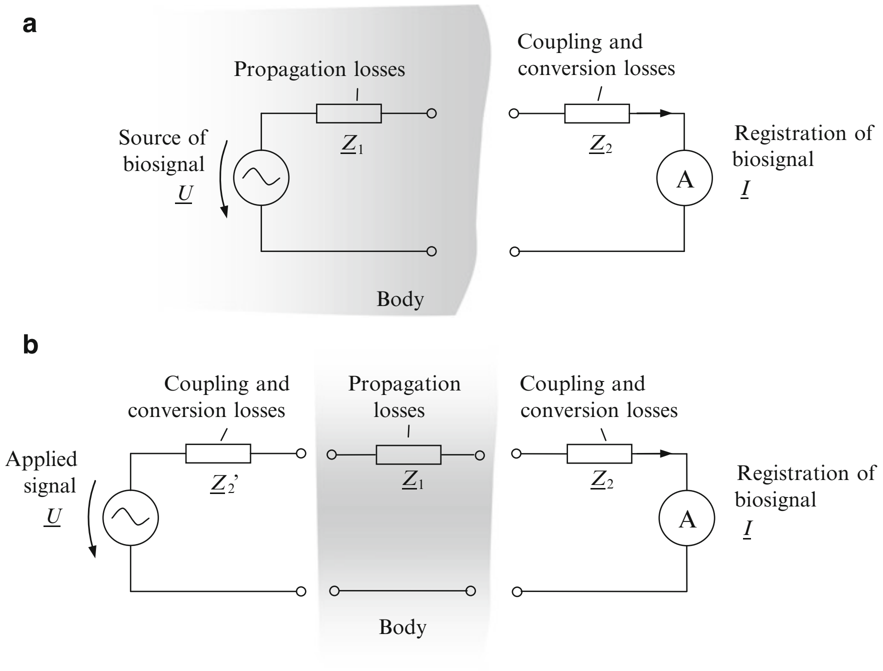

Fig. 1.3 Model of biosignal generation, propagation, coupling, and registration. (**a**) Permanent biosignal. (**b**) Induced biosignal

heart sounds. In addition, the lung sounds are generated by air turbulences in the branching airways of the lung, whereas the snoring sounds arise in the upper airways due to elastic oscillation of the pharyngeal walls. The sounds *propagate* throughout the tissue and undergo attenuation due to increasing distance from the source and damping by the medium itself. As indicated in Fig. 1.2 by intensity decay, the attenuation is different for different sounds, since their spectral components differ. In particular, the attenuation is less for the heart sounds than for the lung and snoring sounds, since the latter sounds exhibit more high-frequency components facing a stronger damping. The *coupling* (and amplification) of sounds is performed by a stethoscope chestpiece with an oscillating diaphragm and a resonating volume. Lastly, the *conversion* of the acoustical pressure vibrations into an electric signal is carried out by an electroacoustic transducer, a microphone.

Thus, the principle behavior in the formation of an arbitrary biosignal can be *modeled as an equivalent circuit* according to Fig. 1.3a. That is the *source of the biosignal* is represented by a sinusoidal[1] voltage source $u(t) = U \cdot \cos(\omega t + \varphi_{\mathrm{U}})$

[1] Usually the source of the biosignal exhibits nonsinusoidal behavior. However, the *nonsinusoidal* waveform can be represented as a sum of *sinusoidal* functions (according to Footnote 150), thus the equivalent circuit from Fig. 1.3a is also applicable here.

with complex amplitude

$$\underline{U} = U \cdot \mathrm{e}^{\mathrm{j}\varphi_{\mathrm{U}}}, \tag{1.1}$$

magnitude U, angular frequency ω ($= 2\pi \cdot f$ with f as oscillating frequency), and phase φ_{U}, satisfying $u(t) = \mathrm{Re}[\underline{U} \cdot \mathrm{e}^{\mathrm{j}\omega t}]$. The *propagation losses* are represented by a series impedance

$$\underline{Z_1} = Z_1 \cdot \mathrm{e}^{\mathrm{j}\varphi_1}, \tag{1.2}$$

the *coupling and conversion losses* by another series impedance

$$\underline{Z_2} = Z_2 \cdot \mathrm{e}^{\mathrm{j}\varphi_2}, \tag{1.3}$$

and the *registered biosignal* by the resulting current $i(t) = I \cdot \cos(\omega t + \varphi_{\mathrm{I}})$ with complex amplitude

$$\underline{I} = I \cdot \mathrm{e}^{\mathrm{j}\varphi_{\mathrm{I}}}, \tag{1.4}$$

satisfying $i(t) = \mathrm{Re}[\underline{I} \cdot \mathrm{e}^{\mathrm{j}\omega t}]$. According to Ohm's law,[2]

$$\underline{I} = \frac{\underline{U}}{\underline{Z}_1 + \underline{Z}_2}. \tag{1.5}$$

In other words, the higher the losses, e.g., the magnitudes $Z_1(\neq 0)$ and $Z_2(\neq 0)$ of usually capacitive-ohmic losses, the weaker the registered biosignal will be, i.e., the magnitude I. In general, $\varphi_{\mathrm{I}} \neq \varphi_{\mathrm{U}}$ provided that $\varphi_1 \neq 0$ or $\varphi_2 \neq 0$; likewise, if all losses can be modeled by real resistances then $\varphi_{\mathrm{I}} = \varphi_{\mathrm{U}}$ and $I = U/(Z_1 + Z_2)$. It should be noted that *physiological phenomena of interest are hidden* not only in $\underline{U}$ but also in $\underline{Z}_1$, for the propagation may influence the resulting $\underline{I}$ in a significant and even advantageous way (Sect. 5).

If the *acoustic biosignal* (Fig. 1.2) is considered in the light of the above *model* (Fig. 1.3a), the temporal behavior of an acoustical source can be described by $u(t)$ and its intensity by U. The strength of the propagation losses of the body sounds can be given as Z_1 (1.2) while the capacitive behavior of the propagating

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[2]Georg Simon Ohm (1789–1854) was a German physicist after which *Ohm's law* was named. The law states that the strength of electric current I through a conductor is directly proportional to the voltage U across the conductor divided by the impedance Z of the conductor, if a constant Z is given, e.g., over conductor temperature or oscillation frequency of the current. For complex values, it can be written as

$$\underline{I} = \frac{\underline{U}}{\underline{Z}}.$$

For the continuum form of Ohm's law see Footnote 45.

medium can be described by the corresponding phase angle $\varphi_1 (\neq 0)$. Alternatively, the strength of the coupling and conversion losses in the acoustical sensor can be defined as Z_2, whereas the corresponding $\varphi_2 (\neq 0)$ can describe the time delay in the chestpiece and the conversion delay in the microphone (1.3). The output $s_{\mathrm{PCG}}(t)$ of the microphone—as schematically shown later in Fig. 1.15c—corresponds then to $i(t)$ [compare (1.5)].

While the model from Fig. 1.3a applies to permanent biosignals with their source already inside the body, Fig. 1.3b depicts a *model of an induced biosignal* (Sect. 1.3). Here, the biosignal is generated outside the body with an artificial signal source with its complex amplitude $\underline{U}$. After coupling and conversion losses $\underline{Z'}_2$ on the input side, the induced signal undergoes propagating losses $\underline{Z}_1$ in the body, which are *modulated by a physiologic phenomena* of interest. On the output side, the coupling and conversion losses $\underline{Z}_2$ co-determine the resulting induced biosignal $\underline{I}$ according to

$$\underline{I} = \frac{\underline{U}}{\underline{Z}_1 + \underline{Z}_2 + \underline{Z}'_2}. \tag{1.6}$$

To give an example, $\underline{U}$ could characterize an incident *artificial light* beam coupled into a finger, whereas $\underline{Z}_1$ varies by the changing light absorption due to pulsating blood volume (Sect. 6). Since blood pulsations carry cardiac and respiratory information, the transmitted light characterized by $\underline{I}$ reflects cardio-respiratory activity, as depicted later in Fig. 1.15c, which can be used advantageously in clinical applications.

In accordance with the origin of the biosignals, the biosignals are used in both diagnosis and therapy. While the *diagnosis*[3] is concerned with an assessment of health status based on biosignals (Fig. 1.3), the *therapy*[4] utilizes the biosignals as an objective feedback for selecting appropriate therapeutic measures, continuously monitoring their impact, and improving their efficiency, as depicted in Fig. 1.4. In the latter case, the biosignal registered by a diagnostic device and represented by $\underline{I}$ controls a therapeutic device by adjusting its stimulus given by $\underline{U}$.

From a practical point of view, the aforementioned acoustic biosignals (Fig. 1.2) could serve as an example for the *diagnostic application of biosignals*, as will be discussed in Sect. 5 in detail. The *therapeutic application of biosignals* could be demonstrated by functional muscle stimulation (e.g., on the leg) or functional nerve stimulation (e.g., on the ear auricle). While the stimulation (i.e., therapy) is performed by the use of electric impulses in both cases—compare Fig. 1.4—the respective feedback is given, for instance, by electromyography or force/torque measurement to assess the muscle response in the former case and by heart rate

[3]Generally, the *diagnostic area* of biomedical technologies can be *classified* into functional evaluation of the physiological state, clinical evaluation, and bioimaging (Turchetti et al. 2010); compare Footnote 4.

[4]The *therapeutic area* of biomedical technologies can be *classified* into noninvasive treatments, invasive treatments (minimally invasive and surgical), artificial organs and prosthesis, and rehabilitation (Turchetti et al. 2010); compare Footnote 3.

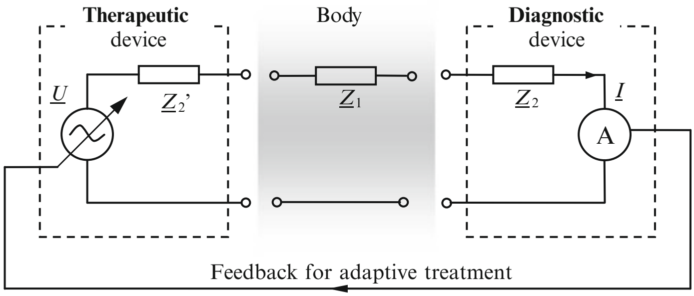


Fig. 1.4 Diagnostic application of biosignals (compare to Fig. 1.2b)

variability to assess the response of the autonomic nervous system (Sect. 3.1.1) in the latter case.

1.2 Historical Aspects

The registration of human biosignals underwent a long-lasting development over many centuries. It began with visual inspections without the use of any instruments, moved to the application of technical tools for signal registration, and is now in an implementation stage of pervasive, almost imperceptible, monitoring. Obviously this development has been driven by patient and physician needs as well as by problems that were encountered, interestingly not always relevant from a pure diagnostic point of view. As was recognized centuries ago concerning biosignal analysis in Mahomed (1872): "…surely it must be to our advantage to appreciate fully all it tells us, and to draw from it all that it is capable of imparting…."

1.2.1 The Very First Biosignals

The very first diagnoses were made on the patient's verbal account of his illness with the unaided senses. Forthcoming investigations yielded the first biosignals which were used for the diagnostic purposes only. The methods applied here encompassed mainly inspection, palpation, percussion, and auscultation (Fig. 1.5):

- *Inspection* (latin *inspectio* scrutiny) is the thorough visualization of the patient by the use of the naked eye. The physician may judge, for instance, body features, nutritional state, or skin color (Fig. 1.1a).
- *Palpation* (latin *palpare* feeling by touch) involves feeling the surface of the body with the hands to determine the size, shape, stiffness, or location of the organs beneath the skin (Fig. 1.5a). Often, applying a small amount of pressure to the surface of the skin or superficial artery to partially constrict it facilitates an easy observation of mechanical changes.

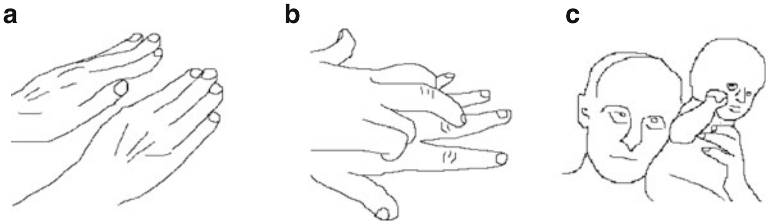


Fig. 1.5 Primary diagnosis methods besides inspection from Fig. 1.1a. (**a**) Palpation. (**b**) Percussion. (**c**) Auscultation

- *Percussion* (latin *percussio* striking) is a procedure that involves striking the body directly or indirectly with short, sharp taps of a finger or a hammer (Fig. 1.5b). The sounds produced display a resonant or dull character, indicating the presence of a solid mass or hollow, air-containing structures, respectively. The sounds are helpful in determining the size and position of various internal organs, in localizing fluid or air in the chest and abdomen, and in aiding in the diagnosis of certain lung disorders.
- *Auscultation* (latin *ausculto* hear attentively) describes a diagnostic procedure in which the physician listens to inner body sounds to detect pathologies or the state of health (Fig. 1.5c). The body sounds may be comprised of heart sounds due to closure of the heart valves or lung sounds due to air turbulences in the branching airways.

Hippocrates of Cos (around 460 BC–377 BC), ancient Greek physician regarded as the father of medicine, emphasized a simple *visual inspection*: "It is necessary to begin with the most important things and those most easily recognized. It is necessary to study all that one can see, feel, and hear, everything that one can recognize and use" (Castiglioni 1941). For instance, he noted that good humor, quiet sleep, clear mind, and mobility were descriptive of a favorable prognosis. By contrast, lying with the mouth and eyes open with legs spread apart, insomnia, and intense movements, indicated an unfavorable prognosis (Marinella 2008).

Palpation was also used by Hippocrates as a method for clinical examination, as demonstrated in Fig. 1.6. For instance, in his work "Diseases of Women" he writes "...And if you then palpate the uterus...." In particular, palpation of the *arterial pulse* has been recognized from antiquity as the most fundamental sign of life,[5] a periodic expansion of an artery (e.g., radial artery on the wrist) is felt in response to a periodic rise in blood pressure. Galen of Pergamum (around 129–200), Greek physician and philosopher, was one of the first great authorities on the pulse,

[5]Erasistratus (about 310 BC–250 BC), Greek physician, regarded by some as the "father of physiology," already used the pulse in clinical diagnosis. As a curiosity, the lover's pulse or love-sickness became a well-documented clinical entity and an integral part of pulse lore through the centuries. The love-sickness was described as pulse quickening in the presence of a beloved person (Hajar 1999).

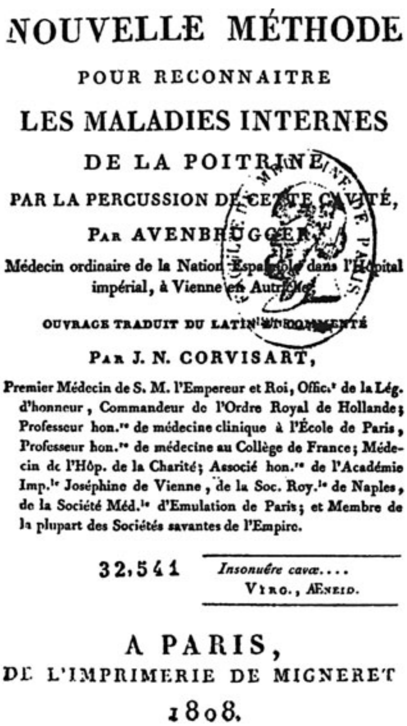
Fig. 1.6 Hippocrates is pictured palpating a young patient (painting from Christian Medical College 2008)

admired by his patron, the emperor Marcus Aurelius. He described the pulsation as "The feeling of the artery striking against the fingers" and characterized it in many details as "the worm-like pulse, feeble and beating quickly; the ant-like pulse that has sunk to extreme limits of feebleness" (Hajar 1999).

Centuries later, Dr. Leopold Auenbrugger (1722–1809), Austrian physician, introduced the *percussion* technique as a diagnostic tool in medicine in 1761 in Vienna, Austria. Percussion was described as "a slow tapping with the fingers, brought close together and extended, on the fingers of the other hand laid on the chest" (Auenbrugger 1761). However, this technique was widely disseminated only decades later by Dr. Jean-Nicolas Corvisart (1755–1821), French physician and primary physician of Napoleon Bonaparte, who translated Auenbrugger's book into French (Auenbrugger and Corvisart 1808) in 1808, as illustrated in Fig. 1.7.

The *direct auscultation* of body sounds (Fig. 1.8) was also already employed more than twenty centuries ago, as suggested in Hippocrates work "de Morbis": "If you listen by applying the ear to the chest…" (Rappaport and Sprague 1941). However, only at the beginning of the nineteenth century did the body sounds gain adequate relevance and recognition among physicians.

A few decades later, after the wide acceptance of the percussion, which also involves an auscultation of artificially produced sounds, the *auscultation* technique was *fundamentally improved* by Dr. Rene Theophile Hyacinthe Laennec (1781–1826). The French internist and a student of Dr. Corvisart made in 1816 an epoch making observation with a wooden cylinder, which was primarily sought to avoid embarrassment. "I was consulted," says Laennec, "by a young women who presented some general symptoms of disease of heart, in whose case the application of the hand and percussion gave but slight indications, on account of her corpulency. On account of the age and sex of the patient, the common modes of exploration (i.e., immediate application of the ear) being inapplicable, I was led to recollect a well



NOUVELLE MÉTHODE
POUR RECONNAITRE
LES MALADIES INTERNES
DE LA POITRINE,
PAR LA PERCUSSION DE CETTE CAVITÉ,
PAR AVENBRUGGER,
Médecin ordinaire de la Nation Espagnole dans l'Hôpital impérial, à Vienne en Autriche.
OUVRAGE TRADUIT DU LATIN ET COMMENTÉ
PAR J. N. CORVISART,
Premier Médecin de S. M. l'Empereur et Roi, Offic.r de la Lég. d'honneur, Commandeur de l'Ordre Royal de Hollande; Professeur hon.re de médecine clinique à l'École de Paris, Professeur hon.re de médecine au Collège de France; Médecin de l'Hôp. de la Charité; Associé hon.re de l'Académie Imp.le Joséphine de Vienne, de la Soc. Roy.le de Naples, de la Société Méd.le d'Emulation de Paris; et Membre de la plupart des Sociétés savantes de l'Empire.
32,541
Insonuêre cavæ....
VIRG., ÆNEID.
A PARIS,
DE L'IMPRIMERIE DE MIGNERET
1808.

Fig. 1.7 Title page of Corvisart translation about percussion as a diagnostic tool (Auenbrugger and Corvisart 1808)

known acoustic phenomenon… I took a quire of paper which I rolled together as closely as possible, and applied one end to the precordial region; by placing my ear at the other end, I was agreeably surprised at hearing the pulsation of the heart much more clearly and distinctly than I had ever been able to do by the immediate application of the ear" (Rappaport and Sprague 1941; Abdulla 2001).

A *precursor of the stethoscope* (greek *stetos* chest and *skopein* explore) was born—as shown in Fig. 1.9—viewed by many as the very symbol of medicine, for conduction of the sounds generated inside the body between the body surface and the ears, as depicted in Fig. 1.10. An oil painting is shown in Fig. 1.11 with Laennec among students holding his stethoscope in the hand, while applying his ear to the chest of a patient.

Later, in 1894, A. Bianchi introduced a rigid diaphragm over the part of the (wooden) cylinder, i.e., the chestpiece, that was applied to the chest (Hollins 1971; Rappaport and Sprague 1941), compare Fig. 1.2. The *modern stethoscope* consists of a bell-type chestpiece for sound amplification (Welsby et al. 2003; Abdulla et al. 1992), rubber tube for sound transmission, and earpieces for conducting the sound into ears (Ertel et al. 1971).

Fig. 1.8 Direct auscultation of body sounds

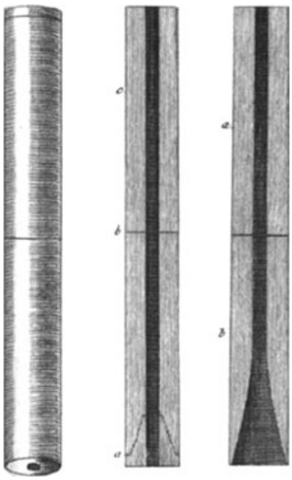


Fig. 1.9 Drawings of the original Laennec's stethoscpe (Laennec 1819)

Fig. 1.10 Indirect auscultation of body sounds with Laennec's stethoscope (Thom 1954)

At the end of the nineteenth century, Laennec's stethoscope was still not used on a regular basis. The introduction of the stethoscope *forced physicians* to undergo a *cardinal reorientation*, for the stethoscope altered both the physician's perception of disease and his relation to the patient. Despite the clear superiority of the instrument in the sound auscultation, it was accepted with some *antagonism* even by prominent chest physicians. Among others, the amusing critics concluded that "The stethoscope is a largely decorative instrument insofar as its value in diagnosis... Nevertheless, it occupies an important place in the art of medicine. Apprehensive patients with functional complaints are often relieved as soon as they feel the chestpiece on their pectoral muscles..." or physicians complained that "they heard too much" (Loudon and Murphy 1984).

1.2.2 Problems and Solutions

The main *problems faced* by the original biosignal acquisition methods—inspection, palpation, percussion, and auscultation (Sect. 1.2.1)—were related to an *objective evaluation* of the diagnostic results. In particular,

- *Proof* of biosignals
- *Analysis* of biosignals
- *Comparison* of biosignals
- *Circulation* of biosignals

Fig. 1.11 Laennec, inventor of the stethoscope, applies his ear to the chest of a patient (Chartran 1849–1907)

were impossible due to the subjective nature of the diagnosis. In other words, *reproducibility* of the biosignal observation was not possible because of the observer's variability and no means for the biosignal's archival storage, as is self-evident for today's applications. *Analysis* of the biosignals was restricted to an instantaneous impression by the physician, with the impression being strongly affected by the physician's personal experience. The classification of biosignals was impeded by nomenclature difficulties. The *comparison* of two biosignals was hardly possible, as they were restricted to a single physician and recent impressions. *Circulating* the accumulated biosignal data was also impossible because of the lack of archives.

Obviously the above problems and limitations were recognized early, with an attempt to circumvent them in a contemporary manner. The most notable

Table 1.1 Approaches to objectify the biosignals from a historical point of view

Description	Subjective impact	Quality
Verbal	Strong	Qualitative
Musical notes	Weak	Qualitative and quantitative
Technical	No	Quantitative

approaches to objectify and characterize the attained biosignals, given roughly in chronological order, were

- *Verbal* descriptions
- *Musical* notes
- *Technical* tools

As summarized in Table 1.1, the *verbal descriptions* had the most subjective impact from the author of the description, since it is purely *qualitative*. A variety of qualifying adjectives were used as well as vague subjective terms. Avicenna (980–1037), Muslim polymath and Islam's "Prince of Physicians," ingeniously compares more than 50 identifiable pulses with natural objects and human actions: "irregular pulse as the flight of a gazelle; stone bullet shot out of a crossbow; scattered leaves" (Hajar 1999). In order to accommodate the difficulties in describing lung sounds, familiar sound descriptions (at that time) were chosen to clarify the distinguishing characteristics (Loudon and Murphy 1984). Descriptive and illustrative sounds were used such as "crepitation of salts in a heated dish," "noise emitted by healthy lung when compressed in the hand," "bass note of a musical instrument," "wet, dry, crackling sound," or even "cooing of wood pigeon." As another example, percussion sounds were described as being sonorous, morbid, or dull (Murray and Neilson 1975). The *difficulties in the verbal description* could be best viewed in terms of Laennec's observation that the sounds heard with this "cylinder" were *easier to distinguish than to describe* (Loudon and Murphy 1984), yielding a need for better methodologies.

The proposed use of *musical notes* obviously reduced the subjectivity and provided—for the first time—a quantitative means to objectify biosignals (Table 1.1). While the height of the note could be used for a *qualitative* coding of biosignals, the rhythm of the successive notes could be used for a *quantitative* coding. A very nice example is given by notable attempts to *objectively* describe the pulsatile behavior of the blood pressure with music rhythm. The flute teacher Francois Nicolas Marquet(1687–1759) made pulse to a natural metronome (Marquet 1769), as demonstrated in Fig. 1.12. Up to 30 different pulses were documented by music notes.

The last and clearly most successful approach implements the use of *technical tools* (Table 1.1). Historical progress in technical tools is shortly but conclusively summarized in Geddes and Roeder (2009). They eliminate subjective influence from the observer, since the approach is intrinsically based on quantitative data. With each new advance in these novel techniques, new vistas with previously *unforeseen opportunities* became exposed. Since there is an *enormous diversity* of technical

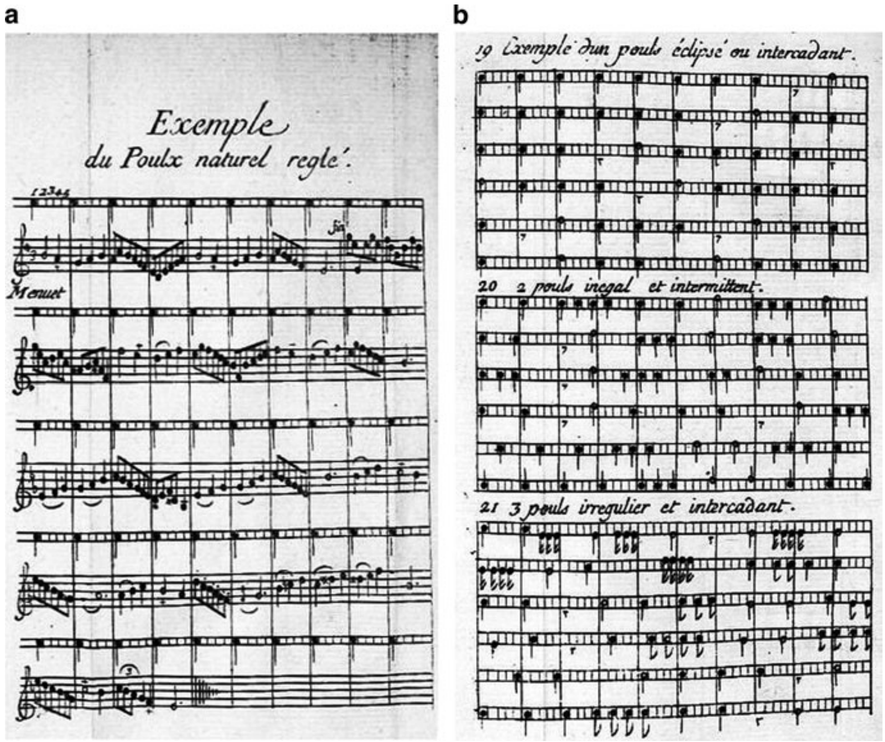


Fig. 1.12 Coding of heart pulses with musical notes (Marquet 1769). (**a**) Natural regulated pulse. (**b**) Three different abnormal pulses including, from *top* to *bottom*, discontinuous pulse, irregular intermittent pulse, and irregular pulse arising in between normal pulses

tools being introduced, only two historically relevant developments will be shortly mentioned.

Representative of tools applied in *clinical* praxis, Fig. 1.13 demonstrates an ancestor of a sphygmomanometer (greek *sphygmos* pulse, *manometer* pressure measuring device) used for recording *pulse* and blood pressure on, e.g., radial artery. The device stems from developments in the nineteenth century and is acknowledged as the *first diagnostic instrument* introduced for artificial palpation of the pulse if the thermometer and stethoscope are regarded as clinical aids only. It used cuff-based recording, the methodology that is still nearly unrivaled up to current times, see Sect. 3.1.3.1.

The *advent of portable* technical tools for diagnosis is demonstrated by a sphygmograph (greek *sphygmos* pulse, *grapho* write), as shown in Fig. 1.14. This instrument was devised by Dr. Robert Ellis Dudgeon (1820 – 1904) for graphically recording features of the radial pressure pulse, which was beautifully compact and found its way into medical practice around the world. It consists of a lever with an elastic spring placed on the radial artery. The other end of the lever carries a stylus for recording of the pulse on a moving smoked paper.

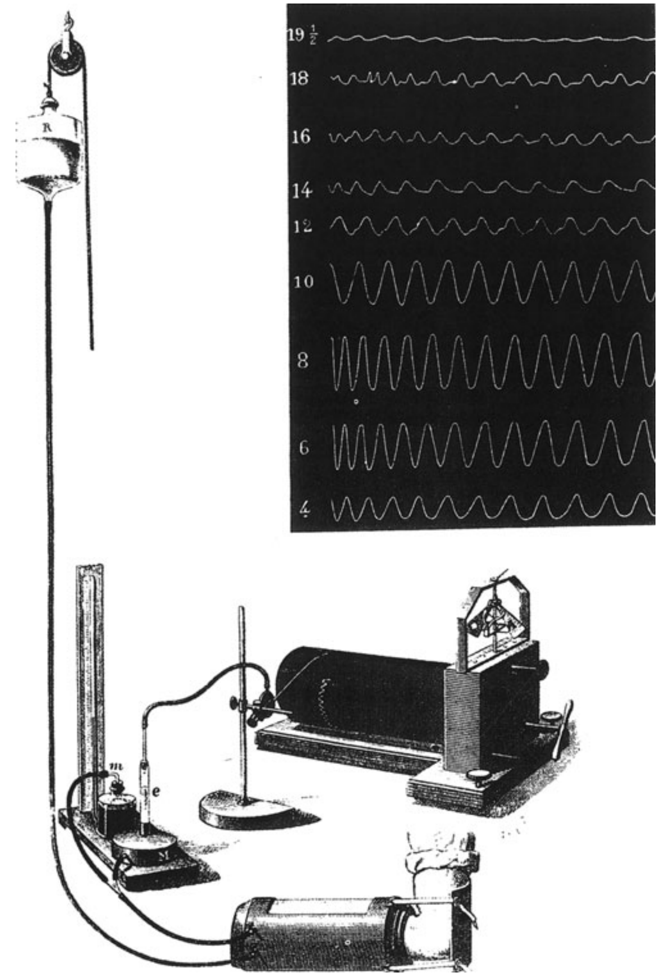


Fig. 1.13 The ancestor of the sphygmomanometer for clinical applications (Marey 1858)

1.3 Classification of Biosignals

The variety of biosignals is nearly unlimited, as shown in Sects. 1.1 and 1.2. This circumstance makes a unique classification of biosignals impossible. However, there are at least three ways of defining their (overlapping) strategic classification, as demonstrated in Fig. 1.15 and described below.

As a first classification method, the *existence of biosignals* could be taken as a basis for their classification. In particular,

- Permanent biosignals
- Induced biosignals

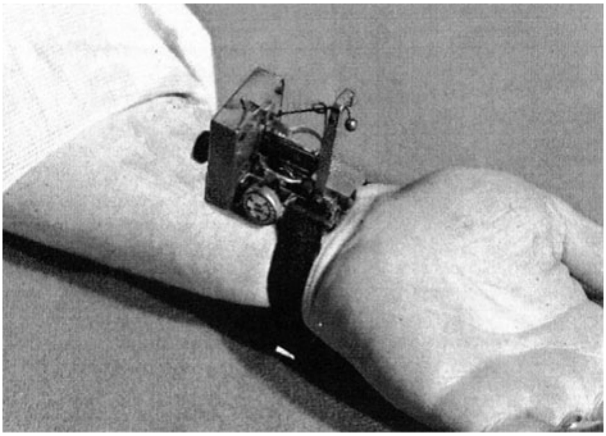


Fig. 1.14 A sphygmograph according to Dr. Dudgeon for portable application (Dudgeon 1882)

would comprise the corresponding classification groups. *Permanent biosignals* exist without any artificial impact, trigger, or excitation from outside the body and are available at any time (compare Fig. 1.3a). The source of the biosignal is already inside the body. To give some examples, an *electrocardiographic* signal (=electrocardiogram) induced by electrical heart muscle excitation (Sect. 4) with the typical peaks P–Q–R–S–T (Fig. 1.15a) and the aforementioned *acoustic* biosignal (= phonocardiogram) induced by the consecutive heart valve closures (Sect. 5) with the typical first and second heart sounds (Fig. 1.15c) belong to the group of permanent biosignals.

The group of *induced biosignals* considers biosignals that are artificially triggered, excited, or induced (compare Fig. 1.3b). In contrast to permanent biosignals, induced biosignals exist roughly for the duration of the excitation. That is, as soon as the artificial impact is over, the induced biosignal decays with a certain time constant determined by the body properties. The interaction of the tissue with the induced stimulus, irrespective of the stimulus nature, is then recorded as an induced biosignal. A corresponding example could be given by *electric plethysmography*, in which an artificial current is induced in the tissue and a voltage along the current path reflects tissue impedance changes (Sect. 4). The voltage is then registered as an induced biosignal (=electroplethysmogram) with discernible cardiac and respiratory components (Fig. 1.15a). Alternatively, *optical oximetry* uses artificially induced light while the transmitted light intensity is mainly governed by light absorption through local pulsatile blood volume (Sect. 6). The transmitted light is detected as an induced biosignal, showing a steep systolic increase and a slow diastolic decrease (Fig. 1.15c). In general, the origin of the induced stimulus, e.g., magnetic field from coils above the head for magnetic stimulation, may be different from that of the registered biosignal, e.g., generated electric potentials from electrodes on the head.

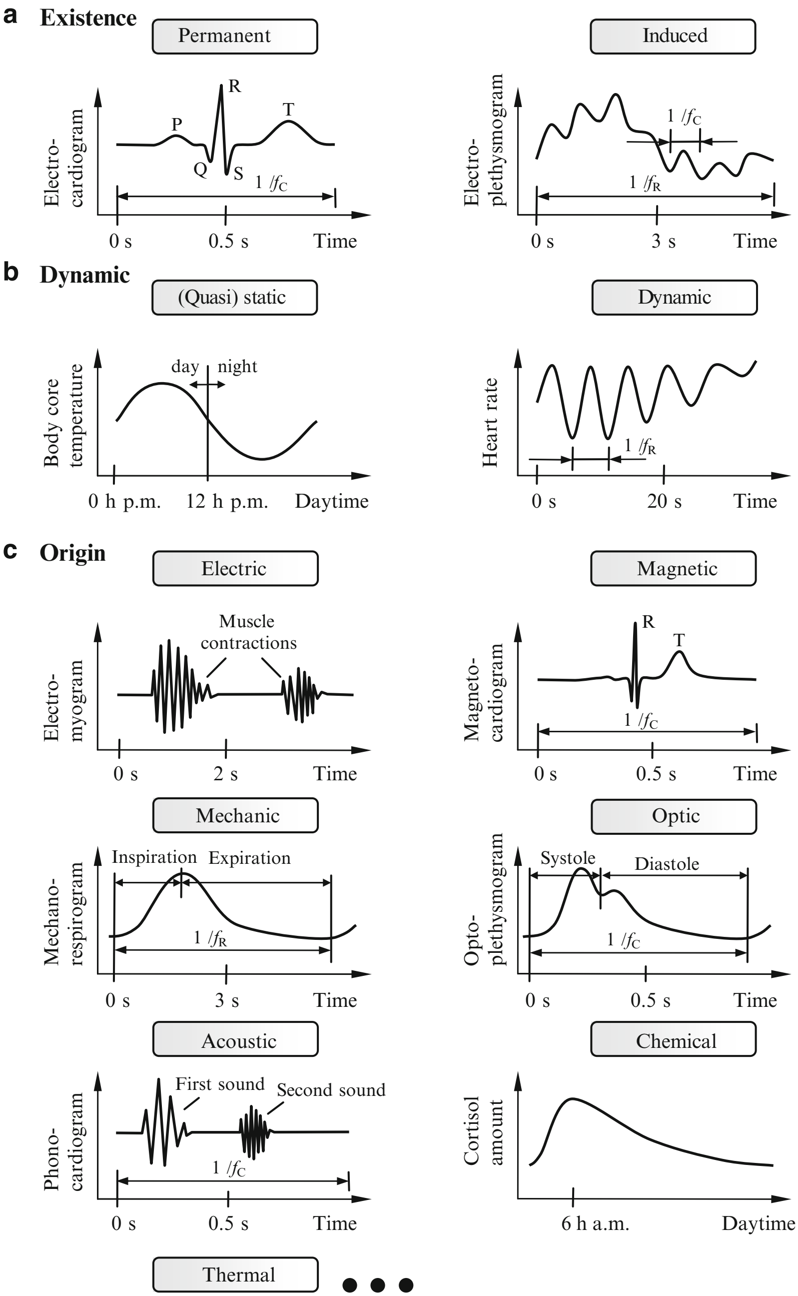


Fig. 1.15 The possible classifications of biosignals according to their (**a**) existence, (**b**) dynamic, and (**c**) origin, with indicated heart rate f_C, respiratory rate f_R, and additional information

The second classification method considers the *dynamic nature of biosignals*. Accordingly,

- (Quasi) Static biosignals
- Dynamic biosignals

can be differentiated. A *(quasi) static biosignal* carries information in its steady-state level which may exhibit relatively slow changes over time. By contrast, *dynamic biosignals* yield extensive changes in the time domain, with dynamic processes conveying the physiological information of interest. For instance, the *core body temperature* would be a (quasi) static biosignal, exhibiting relatively slow circadian changes over 24 h (Sect. 3.1.5). As shown in Fig. 1.15b, it increases during the morning hours and decreases before the onset of sleep (Sect. 3.2.4). On the other hand, the instantaneous *beat-to-beat changes of the heart rate* would constitute a highly dynamic biosignal (Sect. 3.1.1). The course of the heart rate (Fig. 1.15b) reveals respiratory related oscillation, i.e., an increase during inspiration and a corresponding decrease during expiration.

The third classification method uses the *origin of biosignals* as a basis for their classification. The most prominent origins encompass

- Electric biosignals
- Magnetic biosignals
- Mechanic biosignals
- Optic biosignals
- Acoustic biosignals
- Chemical biosignals
- Thermal biosignals
- Other biosignals

Correspondingly, *electric biosignals* comprise, for instance, the aforementioned *electrocardiogram* (Fig. 1.15a), *electroencephalogram*, which reflects electrical activity of neurons in the brain, or *electromyogram*, which reflects electrical activation of muscles. Figure 1.15c schematically depicts an electromyogram which shows bursts of electrical impulses yielding muscle contractions of different strengths. *Magnetic biosignals* reflect a magnetic field induced by usually nonstationary currents which convey physiological information. As an example, Fig. 1.15c shows a *magnetocardiogram* reading of magnetic fields emitted by currents during electrical heart excitation (compare peaks in electrocardiogram and magnetocardiogram in Fig. 1.15).

Mechanic biosignals reflect, for instance, body deformations or local body skin vibrations unveiling physiological data. An example is given in Fig. 1.15c by a *mechanorespirogram*, showing a respiratory cycle from abdominal circumference changes. *Optic biosignals* benefit from light absorption and scattering, which are related to propagation volume and medium, both changing in a physiologically relevant way. Here, an artificial light is used within the scope of induced biosignals, as already described. As demonstrated in Fig. 1.15c, cardiac pulsations with a clinically relevant time course can be clearly recognized in an *optoplethysmogram*.

Acoustic biosignals remain for the assessment of diverse body sounds, ranging from cardiac sounds to snoring sounds to swallowing sounds. A *phonocardiogram*, as shown in Fig. 1.15c and discussed earlier in Sect. 1.1, mirrors cardiac activity. It is comprised of two discernable heart sounds corresponding to two consecutive heart valve closures. The oscillation amplitude and frequency indicate the closure strength and the valve's stiffness, respectively. *Chemical biosignals* reflect chemical composition and its temporal changes in body solids, liquids, and gases. To demonstrate their relevance, Fig. 1.15c shows a typical course of *cortisol* (= stress hormone) over 24 h in humans, with a peak during the morning hours in order to prepare the body for awakening. Lastly, *thermal biosignals* usually assess highly heterogeneous mechanisms of heat loss and heat absorption in the body. For instance, the aforementioned body core temperature in Fig. 1.15b constitutes a thermal biosignal. For the sake of completeness, it should be mentioned that the above list of biosignals—classified according to their origin—is obviously not complete.

1.4 Trends in Biosignals Monitoring

Biosignals were first employed more than twenty centuries ago, as exemplified in Sect. 1.2.1, and became even more prominent in the twenty-first century. Though having been used since time immemorial, a further advancement of their acquisition, interpretation, and use in the diagnostic approaches was still never out of question. Their *developmental history is marked with revolutions* rather than continuous improvements, with revolutions usually followed by antagonism.[6] Even today, their proper assessment and analysis are the focal point of many research groups worldwide. The obvious reason for these *never ending improvements* in biosignal monitoring is that the biosignals reflect human health and wellbeing. Biosignals are essential for mankind and not just for increased comfort. In particular, biosignals detail vital physiological phenomena and are relevant not only for the pre-screening of the human functional state and diagnosis of illness but also for subsequent therapy, follow-up treatment, and appraisal of its efficiency.

Future trends in biosignal monitoring could be partly deduced from the *history* of biosignals and the current *state-of-the-art* technology, as aimed at in Fig. 1.16. From a technical point of view, a qualitative relation exists between the comfort of the sensor system, approximated as the number of applied sensors (horizontal axis),

[6]For instance, Kurt Karl Stephan Semm (1927–2003), German gynecologist, who performed the first appendicectomy in 1980 in a *laparoscopic way*, was heavily criticized by his colleagues and public. Later it was recognized that it not only helps patients recover faster and with less pain, but also prevents deaths in the operating room. Another example would be Ignaz Semmelweiss (1818–1865), Hungarian physician, who was largely ignored or ridiculed when in 1847 he suggested that childbed fever could be drastically reduced if doctors *sterilized their hands*.

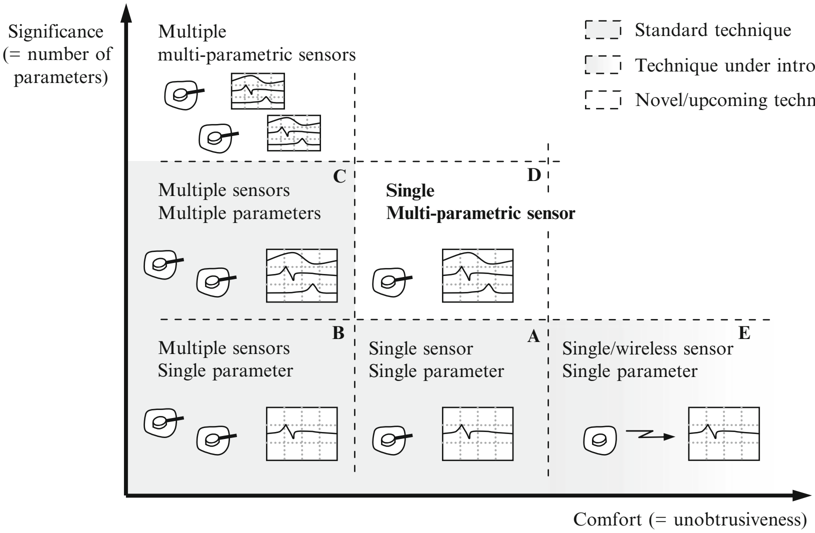


Fig. 1.16 Future vision of physiologic monitoring including standard and novel techniques. Qualitative relationship is given between the significance and comfort of the different monitoring systems, i.e., number of physiological parameters attained versus number of sensors needed, including novel multiparametric sensors. *Bold* letters refer to cases discussed in the text

and the significance of attained biosignals, the latter quantified as the total number of physiologic parameters available to derive (vertical axis).

Obviously the oldest and most commonly used systems follow the rule that a *single physiological parameter* is attained per *single sensor* (case A in Fig. 1.16). For instance, respiratory rate is usually assessed by a respiratory belt around the thorax, which monitors circumference changes related to breathing. In many cases, a single sensor may not be sufficient to determine a *single parameter*; thus, *two or more sensors* might be needed (= multisite recording), as depicted in case B. Here, the common arterial blood pressure recording could be an example, in which decreasing cuff pressure on the upper arm is recorded in parallel to sounds (= Korotkoff sounds) recorded by a microphone over the brachial artery; audible sounds arise due to blood flow turbulences at cuff pressure values corresponding to systolic and diastolic blood pressure. In comparison with case A, case B shows reduced comfort but the same significance because the assessed number of physiologic parameters is the same.

If two or *more single-parameter sensors* (from case A) are applied, then obviously *multiple parameters* are provided (case C). For instance, sleep monitoring in sleep labs includes the monitoring of a large number of brain, cardiac, and respiratory parameters with the use of the corresponding single-parameter sensors. Numerous parameters are needed here for a comprehensive sleep assessment, e.g., for sleep staging.

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