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Eugenijus Kaniusas

# Biomedical Signals and Sensors II

## Linking Acoustic and Optic Biosignals and Biomedical Sensors

With 73 Figures

Springer

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# Preface

The present volume set develops a bridge between physiologic mechanisms and diagnostic human engineering. A multitude of biomedical sensors are commonplace in clinical practice today. The registered biomedical signals, which will be referred to as biosignals, reflect vital physiologic phenomena and are relevant not only for diagnosis but also for therapy. In order to adequately apply biomedical sensors and reasonably interpret the corresponding biosignals, a proper and strategic understanding of the physiologic phenomena involved, their specific influence on the registered biosignals, and the technology behind the sensors is critical.

While the *first volume* is focused on the interface between physiologic mechanisms and the resultant biosignals, the second volume is devoted to the interface between biosignals and biomedical sensors. That is, in the first volume, the physiologic mechanisms determining biosignals are described from the basic cellular level—as the place of origin of each and every biosignal—up to their advanced mutual coordination level, e.g., during sleep. It allows a physiologically accurate interpretation and comprehensive analysis of biosignals.

Consequently, this *second volume* considers the genesis of acoustic and optic biosignals and the associated sensing technology from a *strategic point of view*. Unlike other contributions, this book deals differently on the subject of specific engineering aspects pertaining to particular biosignals, since it discusses *heterogeneous biosignals* within a *common frame*. In particular, this frame comprises both the *biosignal formation path* from the biosignal source at the physiological level to biosignal propagation in the body and the *biosignal sensing path* from the biosignal transmission in the sensor applied on the body up to its conversion to a, usually electric, signal.

Some biosignals arise in the course of the body's vital functions while others map these functions that convey physiological data to an observer. It is highly instructive how sound and light beams interact with biological tissues, yielding *acoustic and optic biosignals*, respectively. Discussed phenomena teach a lot about the physics of sound and physics of light (as engineering sciences), and, on the other hand, biology and physiology (as live sciences). This book provides a sort of *common denominator* for acoustic and optic biosignals, i.e., instructive similarities and differences in between, whereas these biosignals—at first glance—are entirely different in their physical nature. Basic and application-related issues are covered in depth; in fact, these issues should remain strong because these stand the test of time and mine knowledge of great value.

This book is directed primarily at graduate and post graduate students in biomedical engineering and biophysics. It is also accessible to those who are interested in physical, engineering, and life sciences, since expected background knowledge is minimal and many basic phenomena are explained in depth within numerous footnotes. Furthermore, the book should serve engineers and practitioners who have an interest in biomedical engineering. Discussed biosignals and sensing technologies substantiate wearable sensor technologies—the hot topic today—which comprise an appealing solution for pervasive (home) monitoring and prompt novel approaches in diagnosis and therapy.

It is important to note that this book was mainly inspired by my lectures entitled "Biomedical Sensors and Signals," "Biomedical Instrumentation," and "Biophysics" which constitute a significant part of a master's degree program "Biomedical Engineering" at the Vienna University of Technology in Austria.

In the end, it is not the spot-like knowledge of biosignals and engineering technologies coming from independent considerations of biosignals that constitute a successful biomedical engineer with profound professional knowledge, but the strategic and global consideration of basically different biosignals and of the corresponding sensing technologies, both integrated in the common frame. The highly interdisciplinary nature of biosignals and biomedical sensors is obviously a challenge. However, it is a rewarding challenge after it has been coped with in a strategic way, as offered here. The book is intended to have the presence to answer intriguing "Aha!" questions.

Vienna, Austria Eugenijus Kaniusas

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# Contents

# Symbols and Abbreviations

*Note:* Variables used within limited contexts are not listed, for they are described within the relevant section. The different types of biosignals are separately listed below.

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| | |
|---|---|
| $A$ | Area |
| $BMI$ | Body mass index |
| $c$ | Constant, specific heat capacity, speed of light (in vacuum) |
| $C$ | Capacitance |
| CSA | Central sleep apnea |
| $d$ | Distance, light probing depth |
| $D$ | Compliance, diffusion length |
| $E$ | Electric field |
| $E_{\mathrm{I}}$ | Incident electric field |
| $E_{\mathrm{R}}$ | Reflected electric field |
| $f$ | (oscillating, resonating) Frequency |
| $f_{\mathrm{C}}$ | Heart rate |
| $f_{\mathrm{F}}$ | Formant frequency |
| $f_{\mathrm{R}}$ | Respiratory rate |
| $f_{\mathrm{R1}}$ | Fundamental harmonic frequency of lung sounds or snoring sounds |
| $g$ | Scattering anisotropy coefficient |
| $G$ | Transfer function |
| $h$ | Planck's constant |
| $H$ | Hematocrit |
| $I$ | Electric current amplitude, sound intensity, light intensity |
| $I_{\mathrm{AC}}$ | Alternating component of light intensity |
| $I_{\mathrm{DC}}$ | Direct component of light intensity |
| $k$ | Index, wavenumber |
| $l$ | Length |
| LED | Light-emitting diode |

| | |
|---|---|
| MSA | Mixed sleep apnea |
| $n$ | Index of refraction |
| OHA | Obstructive sleep hypopnea |
| OSA | Obstructive sleep apnea |
| $p$ | Air pressure, sound pressure, power spectral density, probability density, blood pressure |
| $P$ | Power, acoustic pulsatile pressure amplitude |
| $p_{\mathrm{I}}$ | Incident pressure wave |
| $p_{\mathrm{R}}$ | Reflected pressure wave |
| $p_{\mathrm{S,D}}$ | Systolic–diastolic deflection of the blood pressure |
| $p_{\mathrm{T}}$ | Transmural pressure |
| $q$ | Air flow |
| $Q$ | Electric charge |
| $r$ | Radius, distance |
| $r_{\mathrm{D}}$ | Diastolic artery radius |
| $r_{\mathrm{S}}$ | Systolic artery radius |
| $r_{\mathrm{R}}$ | Source-sink distance in the reflectance mode |
| $r_{\mathrm{T}}$ | Source-sink distance in the transmittance mode |
| $R$ | Reynolds number, (electrical) resistance, red to infrared absorbance ratio |
| $\mathcal{R}$ | Alternating to direct light ratio |
| $s$ | Biosignal, see below |
| $s^{\mathrm{C}}$ | Cardiac component of biosignal |
| $s^{\mathrm{R}}$ | Respiratory component of biosignal |
| $s_{\mathrm{S,D}}$ | Systolic–diastolic deflection of the cardiac component |
| $S$ | Biosignal amplitude, hemoglobin oxygen saturation |
| SPL | Sound pressure level |
| $t$ | Time |
| $u$ | Voltage, air flow velocity, particle velocity |
| $U$ | (complex) Voltage amplitude |
| $v$ | Sound propagation velocity, light propagation velocity, pulse wave velocity |
| $V$ | Volume |
| $W$ | Energy |
| $x$ | Coordinate, distance |
| $X$ | Distance |
| $Z$ | (complex) Electrical impedance, characteristic acoustic impedance |
| $\alpha$ | Sound absorption coefficient, light attenuation coefficient, constant |
| $\Gamma$ | Reflection factor |
| $\varepsilon$ | Dielectric permittivity, step function |
| $\varepsilon_{\mathrm{r}}$ | Relative electric permittivity |
| $\vartheta$ | Temperature |
| $\kappa$ | Module of volume elasticity |
| $\lambda$ | Wavelength |
| $\mu$ | Dynamic viscosity, magnetic permeability |
| $\mu_{\mathrm{A}}$ | Light absorption coefficient |

| | |
|---|---|
| $\mu_r$ | Relative magnetic permeability |
| $\mu_S$ | Light scattering coefficient |
| $\mu_S'$ | Light reduced scattering coefficient |
| $\mu_T$ | Light total absorption coefficient |
| $\rho$ | Density |
| $\sigma$ | Mechanical stress, absorption cross section |
| $\tau$ | Relaxation time constant, time constant |
| $\upsilon$ | Heat conductivity |
| $\varphi$ | Angle |
| $\omega$ | Angular frequency |

# Symbols of Biosignals

The types of biosignals discussed and their short descriptions.

| Symbol | Name | Biosignal class | | Phenomena reflected |
|---|---|---|---|---|
| $s_{ECG}$ | electrocardiogram signal | permanent | electric | electrical excitation of heart muscles |
| $s_{MRG}$ | mechanorespirogram signal | permanent | mechanic | circumference changes of the abdomen or chest during breathing |
| $s_{PCG}$ | phonocardiogram signal | permanent | acoustic | sounds emitted by sources in the inner body |
| $s_{OPG}$ | optoplethysmogram signal | induced | optic | artificial light absorption by pulsatile blood |