

WAKE-SLEEP TRANSITION



Reference Scientific Contributions:

- Scientific Papers:

- [002] - E. Fujita, Y. Ogura, N. Ochiai, T. Miao, T. Shimizu, T. Kamei, K. Murata, Y. Ueno, and S. Kaneko, “Development of the measurement method of the prediction of sleep by finger plethysmogram data” *The Japanese Journal of Ergonomics*, vol. 41, no. 4, pp. 203–212, Aug. 2005, [doi: 10.5100/jje.41.203](https://doi.org/10.5100/jje.41.203), in Japanese
- [003] - E. Fujita, K. Murata, T. Kamei, Y. Ogura, N. Ochiai, and S. Kaneko, “Evaluation of fatigue by fluctuation of the finger plethysmogram” *Hirō to Kyūyō no Kagaku (Science of Fatigue and Rest)*, vol. 20, no. 1, pp. 71–84, Mar. 2008, in Japanese
- [005] - S. Kojima, S. Maeda, R. Uchikawa, Y. Nobuhiro, K. Aoi, Y. Ogura, E. Fujita, K. Murata, T. Kamei, T. Tsuji, M. Yoshizumi, and S. Kaneko, “Development of a simple system to sense vital signs from the back” *J. Jpn. Soc. Des. Eng.*, vol. 50, no. 2, pp. 78–88, Feb. 2015, in Japanese
- [006] - E. Fujita, M. Horikawa, Y. Nobuhiro, S. Maeda, S. Kojima, Y. Ogura, K. Murata, T. Kisaka, K. Taoda, S. Kaneko, and M. Yoshizumi, “Extraction of apex beat waveform from acoustic pulse wave by sound sensing system using stochastic resonance” *Sci. Rep.*, vol. 11, Art. no. 13711, Jul. 2021, [doi: 10.1038/s41598-021-92983-6](https://doi.org/10.1038/s41598-021-92983-6)
- [008] - N. Hagiyaama, H. Hirano, A. Mito, Z. Soh, E. Fujita, Y. Ogura, S. Kaneko, R. Nakamura, N. Saeaki, M. Kawamoto, M. Yoshizumi, and T. Tsuji, “Unconstrained vital sign monitoring system using an aortic pulse wave sensor” *Sci. Rep.*, vol. 9, Art. no. 17475, Nov. 2019, [doi: 10.1038/s41598-019-53808-9](https://doi.org/10.1038/s41598-019-53808-9)

- Conference Proceedings / Conference Papers:

- [011] - N. Ochiai, S. Maeda, Y. Ogura, Y. Enoki, E. Fujita, K. Murata, T. Kamei, Y. Ueno, and S. Kaneko, “Experimental study on prediction of sleep in sleep-wake state” in *Proc. 37th Annu. Conf. Chugoku-Shikoku Branch, Japan Ergonomics Society*, Hiroshima, Japan, Nov. 27, 2004, pp. 26–27, in Japanese
- [019] - T. Nishiura, A. Sasaki, E. Fujita, and K. Fujikawa, “脳波と脈波のゆらぎ解析による覚醒度の簡易評価方法の開発 [Development of simplified appraisal method of awakening degree by fluctuation analysis via brain wave and finger plethysmogram]” *人間工学 (The Japanese Journal of Ergonomics)*, vol. 41, suppl., pp. 122–123, Jun. 2005 (in Japanese), [doi: 10.5100/jje.41.Supplement_122](https://doi.org/10.5100/jje.41.Supplement_122)
- [024] - N. Ochiai, Y. Ogura, E. Fujita, Y. Ueno, and S. Kaneko, “A study on the sleep predictor signals using the noninvasive biological signal sensing seat” *The Japanese Journal of Ergonomics*, vol. 42, suppl., pp. 224–225, Jun. 2006, [doi: 10.5100/jje.42.Supplement_224](https://doi.org/10.5100/jje.42.Supplement_224) (in Japanese)
- [025] - N. Ochiai, Y. Ogura, E. Fujita, K. Murata, T. Kamei, Y. Ueno, and S. Kaneko, “The application to fatigue and sleep prediction of the signal of biological fluctuation measured from a noninvasive sensor” in *Proc. 39th Annual Meeting of the Chugoku-Shikoku Branch, Japan Ergonomics Society*, Higashihiroshima, Japan, Nov. 25, 2006, pp. 34–35 (in Japanese)

- [031] - K. Murata, S. Kojima, N. Ochiai, T. Kamei, and E. Fujita, “末梢循環系の変化に関連した生理指標と入眠予兆現象の関連性についての検討 [A study on the peripheral circulation system and physiological index to predict the phenomenon of falling asleep]” *人間工学(The Japanese Journal of Ergonomics)*, vol. 43, no. 2Supplement, pp. 196–197, Jun. 2007 (in Japanese), [doi: 10.5100/jje.43.2Supplement_196](https://doi.org/10.5100/jje.43.2Supplement_196)
- [036] - S. Maeda, E. Fujita, Y. Ogura, S. Kojima, S. Kaneko, T. Miao, S. Higashida, K. Murata, T. Kamei, and M. Enokizono, “覚醒レベルと居眠り検知システムの開発 [Development of detection system of sleep and wakefulness level]” in *Proc. Dynamics & Design Conf. 2008*, paper 303, pp. 303-1–303-4, Sep. 2008, [doi: 10.1299/jsmedmc.2008.303-1](https://doi.org/10.1299/jsmedmc.2008.303-1) (in Japanese)
- [040] - S. Maeda, S. Kojima, Y. Ogura, E. Fujita, S. Kaneko, K. Murata, and T. Kamei, “Development of Sleep Detection Sensor System” in *Proc. 2008 Annual Conference of the Chugoku-Shikoku Branch of the Japan Ergonomics Society*, pp. 62–63, 2008.
- [043] - S. Maeda, S. Kojima, Y. Ogura, E. Fujita, K. Murata, T. Kamei, S. Kaneko, and M. Yoshizumi, “入眠予兆センシングシステムの開発 [Development of sleep prediction sensing system]” in *Proc. 2009 JSAE Annual Congress (Spring)*, Yokohama, Japan, no. 3-09, paper 14-20095292, pp. 5–8, May 2009 (in Japanese)
- [046] - S. Maeda, S. Kojima, Y. Ogura, E. Fujita, K. Murata, T. Kamei, S. Kaneko, and M. Yoshizumi, “Development of State Estimation Technology for Driver by Sensor of Unconstrained Type” *Proceedings of the 11th Symposium on Motion and Vibration Control (MoViC 2009)*, no. 09-30, pp. 403–407, Sep. 2009, [doi: 10.1299/jsmemovic.2009.11.403](https://doi.org/10.1299/jsmemovic.2009.11.403)
- [047] - N. Ochiai *et al.*, “脈波時系列解析による睡眠現象解析アルゴリズムの開発 [Development of the sleep state analysis algorithm by the pulse wave time series analysis]” in *Proc. 11th Symposium on Motion and Vibration Control (MoViC 2009)*, Fukuoka, Japan, Sep. 2–4, 2009, paper A37, pp. 420–423, [doi: 10.1299/jsmemovic.2009.11.420](https://doi.org/10.1299/jsmemovic.2009.11.420) (in Japanese)
- [049] - Y. Nobuhiro *et al.*, “エアパックセンサを用いた疲労判定アルゴリズムの開発 [Development of fatigue evaluation algorithm using an air-pressure sensor]” in *Proc. 42nd Chugoku-Shikoku Branch Conf. Japan Ergonomics Society*, Okayama, Japan, Nov. 28, 2009, pp. 88–89 (in Japanese)
- [060] - N. Ochiai *et al.*, “心・循環系指標を用いた長距離運転者のための居眠り警告・疲労検知システムの開発 [Development of the system for warning of drowsy driving and detection of fatigue for over-the-road driver by cardiocirculatory index]” in *Proc. 43rd Annu. Conf. Chugoku-Shikoku Branch, Japan Ergonomics Society*, Hiroshima, Japan, pp. 26–27, 2010 (in Japanese)
- [068] - Y. Nobuhiro *et al.*, “自律神経系の反応を用いた睡眠状態への遷移現象の同定 [Identification of transitional phenomena to sleep state by autonomic nervous system responses]” in *Proc. Joint 44th Annual Conf. Chugoku-Shikoku Branch and 32nd Annual Conf. Kyushu-Okinawa Branch, Japan Ergonomics Society*, Shimonoseki, Japan, Nov. 26, 2011, pp. 130–131 (in Japanese)
- [072] - M. Horikawa, R. Uchikawa, K. Yamamoto, Y. Ogura, E. Fujita, and M. Yoshizumi, “体表脈波から得た周波数変動を用いた覚醒、睡眠状態の推定 [Estimation for wakefulness or sleeping using frequency fluctuation of Aortic Pulse Wave]” in *Proc. 45th Annual Conference of the Chugoku-Shikoku Branch of the Japan Ergonomics Society*, Kurashiki, Japan, Dec. 15, 2012, paper 111 (in Japanese)

- **[073]** - R. Uchikawa *et al.*, “APW（体表脈波）の超低周波成分を用いた運転中の自覚眠気検出に関する研究 [A study of detection of drowsiness while driving with the use of Aortic Pulse Wave ultralow frequency]” in *Proc. 45th Annu. Conf. Chugoku-Shikoku Branch, Japan Ergonomics Society*, Kurashiki, Japan, Dec. 15, 2012, paper 112, pp. 73–74 (in Japanese)
- **[085]** - K. Yamamoto *et al.*, “体表脈波の時系列波形を用いた覚醒状態と睡眠状態の判別法 [Discriminant method of sleep state and awake state using time-series waveform of APW]” in *Proc. 46th Annu. Conf. Chugoku-Shikoku Branch, Japan Ergonomics Society*, Hiroshima, Japan, Dec. 8, 2013, paper 310, pp. 80–81 (in Japanese)
- **[088]** - K. Nakashima *et al.*, “体表脈波を用いた睡眠時無呼吸症候群患者の生体リズムに関する解析事例 [Case study of biological rhythm in sleep apnea syndrome using the aortic pulse wave]” in *Proc. 2014 Joint Conf. of the Chugoku-Shikoku and Kansai Branches of the Japan Ergonomics Society*, Soja, Okayama, Japan, Dec. 13, 2014, paper C302 (in Japanese)
- **[089]** - K. Yamamoto *et al.*, “体表脈波を用いたあくびの捕捉法に関する研究 [Study on the acquisition method of yawn with APW]” in *Proc. 2014 Joint Conf. of the Chugoku-Shikoku and Kansai Branches of the Japan Ergonomics Society*, Soja, Okayama, Japan, Dec. 13, 2014, paper C303 (in Japanese)
- **[090]** - Y. Nobuhiro *et al.*, “覚醒状態と睡眠状態における生体信号のリズムの比較検討 [Comparison of rhythm in biological signals during wakefulness and sleep]” unpublished manuscript, n.d. (in Japanese)
- **[094]** - M. Horikawa *et al.*, “体表脈波を用いた自覚なき疲労の簡易推定法 [Simple method for estimating unconscious fatigue using aortic pulse wave]” in *Proc. 49th Annu. Meeting of the Chugoku-Shikoku Branch, Japan Ergonomics Society*, Takamatsu, Japan, Dec. 10, 2016, paper 102, pp. 16–17 (in Japanese)
- **[095]** - R. Uchikawa *et al.*, “運転技能と運転中の疲労の進行度合に関する研究 [A study on correlation of driving skill and degree of progress of fatigue during driving]” in *Proc. 49th Annu. Meeting of the Chugoku-Shikoku Branch, Japan Ergonomics Society*, Takamatsu, Japan, Dec. 10, 2016, paper 103, pp. 18–19 (in Japanese)
- **[099]** - Y. Nobuhiro, E. Fujita, Y. Ogura, M. Yoshizumi, and S. Kaneko, “カオス解析を用いた疲労度合いの推定（ストレスの程度が人に与える影響について） [Estimation of fatigue degree using chaos analysis (effects of degree of stress on human)]” in *Proc. 2018 Autumn Conf., Japan Society for Design Engineering*, Tottori, Japan, Sep. 29, 2018, paper B04, pp. 55–58 (in Japanese)
- **[104]** - D. Baba *et al.*, “頸動脈波計測用APWセンサの構造と計測データの解釈 [Structure of APW sensor for carotid pulse wave measurement and interpretation of acquired data],” in *Proc. Japan Society for Design Engineering, Chugoku Branch Conf.*, no. 41, Hiroshima, Japan, Jun. 7, 2025, pp. 46–50 (in Japanese)
- **[105]** - Y. Nobuhiro, A. Savio, D. Baba, A. Nishida, Y. Ogura, and E. Fujita, “頭部体表脈波による入眠予兆現象計測 [Measurement of hypnagogic phenomenon using scalp surface pulse waves]” in *Proc. Japan Society for Design Engineering, Chugoku Branch Conf.*, no. 42, Hiroshima, Japan, Jun. 6, 2026, pp. 40–44 (in Japanese)

Note: Copies of the cited publications for which no DOI is available may be requested from Delta Tooling by contacting angelo.savio@deltakogyo.co.jp

From Sleep Onset Prediction to the Establishment of the Superficial Aortic Pulse as a Physiological Signal Source

The focus is no longer on identifying the precise moment at which the transition occurs, but on the physiological process that makes it possible. Sleep is no longer interpreted as an abrupt phenomenon; instead, it is described as the final stage of a continuous transformation that begins long before the loss of conscious wakefulness and progressively involves the organism's entire regulatory system. Within this framework, the scientific challenge is no longer to recognize an already established state, but to reconstruct the dynamics through which that state is formed^[002].

It is assumed that the homeostatic and circadian processes preparing the organism for sleep produce gradual changes in cardiovascular regulation, making them observable even before the electroencephalogram exhibits the conventional criteria of sleep onset. Consequently, photoplethysmography is no longer employed merely as a measure of heart rate or pulse amplitude, but as a source of information on the slow evolution of physiological regulation.

To make this evolution observable, the signal undergoes a sequence of mathematical transformations that fundamentally alter its interpretation. Pulse power and the maximum Lyapunov exponent cease to represent simple signal characteristics and instead become dynamic variables whose evolution is reconstructed through gradient time series obtained using moving temporal windows. Physiological information is therefore no longer sought in the individual heartbeat, but in the direction, rate, and coherence with which the system progressively modifies its behaviour^[002].

The transition into the initial stage of sleep does not coincide with the sudden appearance of a new physiological state, but is preceded by the progressive reorganization of the relationships among different regulatory processes. The phase-opposition configuration established between the dynamics of pulse power and those of the maximum Lyapunov exponent represents the observable expression of this reorganization. Physiology thus acquires a predictive dimension: the present already contains the information required to describe the organism's imminent evolution^[002].

This new ability to anticipate sleep onset naturally raises a broader question. If sleep is preceded by a prolonged period of physiological preparation, what process accompanies the organism during the hours leading up to this transition? The answer emerges through the extension of the same methodology to the dynamics of fatigue. Fatigue is no longer interpreted merely as a consequence of sustained activity or as a subjective perception, but as the physiological process through which the organism progressively modifies its regulatory equilibrium during prolonged wakefulness. The transition towards sleep is thus placed within a much broader biological continuum, in which activity, fatigue, drowsiness, and rest represent different configurations of the same evolving regulatory process^[003].

Once again, the focus is directed not to the instantaneous values of the signal, but to its history. Variations in the photoplethysmographic signal are transformed into a sequence of gradients and subsequently converted into their absolute values. This operation removes the sign of the oscillations without eliminating their physiological significance, since every variation indicates that the system is modifying its regulatory state. The progressive integration of these variations generates a cumulative curve that does not merely describe the level of fatigue, but preserves

the memory of the organism's entire evolutionary trajectory. This transformation introduces one of the most innovative principles of the entire research programme. Physiological state depends not only on the current configuration of the system, but also on the sequence of regulatory adjustments that preceded it. The organism therefore exhibits a genuine physiological memory, in which every adaptation contributes to the construction of the subsequent configuration. Physiology is no longer described as a succession of independent snapshots, but as a continuous history of biological regulation^[003].

Analysis of the cumulative curve further demonstrates that fatigue does not increase linearly. The organism progresses through an initial phase dominated by the mechanisms required to sustain activity, an intermediate phase characterized by the coexistence of excitation and inhibition, and a final phase in which recovery-oriented processes progressively become predominant. Drowsiness is therefore not an isolated event, but rather the final expression of a prolonged regulatory evolution in which the autonomic nervous system continuously modifies its equilibrium in order to maintain wakefulness until its compensatory capacity is progressively exhausted^[003].

This interpretation fundamentally changes the meaning attributed to the Very Low Frequency (VLF) and Ultra Low Frequency (ULF) oscillations. They cease to represent simple spectral components and are instead interpreted as temporal manifestations of different phases of homeostatic regulation. The slowest oscillations no longer describe merely the presence of fatigue or drowsiness, but document the physiological pathway through which these conditions develop. Physiology thus acquires a continuous temporal structure in which every configuration naturally evolves from the preceding one^{[002],[003]}.

Once it has been recognised that physiological regulation evolves over timescales far longer than those typically observed in laboratory experiments, a new challenge emerges. Understanding these processes requires prolonged recordings capable of following the organism throughout the normal alternation of activity, rest, and sleep. Traditional experimental procedures based on sensors attached directly to the body therefore become progressively inadequate for representing dynamics that unfold over many hours. It thus becomes necessary to develop a new observational approach capable of accompanying the organism's physiology naturally throughout everyday life^[005].

This requirement gives rise to a new acquisition methodology based on the dorsal aortic pulse. The objective is not simply to relocate the measurement site, but to determine whether the mechanical vibrations propagating through the trunk can provide a reliable source of information on cardiovascular regulation. Attention therefore shifts from the peripheral photoplethysmographic signal to the propagation of the pulse wave throughout the body, opening a new perspective for the continuous observation of the organism^[005].

The system is designed as a mechanical structure composed of materials with different elastic properties, in which a three-dimensional mesh, a deformable layer, a resonance chamber, and a highly sensitive microphone work together to select and amplify the vibrations generated by cardiovascular activity. The supporting surface is no longer merely a support for the sensor, but becomes an integral part of the measurement process, directly contributing to the transmission, filtering, and amplification of physiological information^[005].

The analysis further demonstrates that the signal acquired from the back consists of several distinct mechanical components. Through appropriate signal processing, it becomes possible

to separate thoracic movements associated with respiration, heart sounds, and the superficial aortic pulse, identifying the latter as the principal source of cardiovascular information. Comparison with electrocardiography, phonocardiography, and photoplethysmography confirms that the temporal intervals derived from the dorsal pulse closely correspond to those obtained using conventional techniques, demonstrating that the dorsal surface preserves sufficient information to characterise the dynamics of the cardiac cycle^[005].

This finding has significance that extends well beyond the development of the sensor itself. For the first time, the superficial aortic pulse is demonstrated to constitute an independent physiological signal source, distinct from both peripheral photoplethysmography and electrocardiography, yet capable of continuously representing cardiovascular regulation through a completely unconstrained measurement approach. This establishes the experimental foundation for extending the study of the wake-to-sleep transition beyond the limitations imposed by conventional acquisition systems^[005].

Having demonstrated the physiological validity of the dorsal pulse as a novel acquisition source, attention shifts from signal quality to the possibility of using it for the continuous monitoring of the organism under normal living conditions. The objective of the research is no longer to demonstrate that such measurements are feasible, but to make them applicable during everyday activities and rest without requiring any cooperation from the observed individual^[008].

This requirement gives rise to a new concept of the measurement system. The sensor is no longer attached directly to the subject, but is incorporated into the environment with which the individual interacts during everyday life. The surface of a seat or a bed becomes an integral part of the acquisition process, transforming from a simple mechanical support into an active measurement element. Through the elastic properties of the material and an appropriate mechanical amplification system, the aortic pulse wave can be detected without requiring any direct contact between the device and the person's body. This transformation has implications that extend far beyond technological innovation. Physiological observation progressively becomes invisible. The organism is no longer studied by modifying its behaviour through instruments attached directly to the body, but is instead observed while naturally performing its everyday activities. Measurement progressively loses its character as an experimental procedure and becomes an integral part of the environment in which physiology is naturally expressed^[008].

Acquisition of the aortic pulse wave also makes it possible to reconstruct heart rate, respiration, heart rate variability indices, and autonomic nervous system balance simultaneously. This demonstrates that different aspects of biological regulation can be traced back to a common measurement source. Physiology is therefore represented through a multiparametric framework in which the heart, respiration, and the autonomic nervous system are no longer regarded as independent phenomena, but as different manifestations of a single regulatory organisation^[008]. Application of the system during rest, seated conditions, and everyday activities confirms that this acquisition approach is sufficiently accurate to continuously follow the evolution of physiological state without significantly altering the subject's natural behaviour. The principles of predictability, physiological memory, and dynamic reconstruction developed in the preceding studies can now be applied under real-life conditions, making it possible to observe biological regulation throughout the entire cycle of everyday life^[008].

Having demonstrated that the superficial aortic pulse can be continuously acquired under normal living conditions, the research addresses a new challenge. The availability of a stable and continuously measurable signal is not, by itself, sufficient to understand physiological regulation unless the different biological components constituting that signal can be distinguished. It therefore becomes necessary to transform the superficial aortic pulse from a simple acquisition source into a structured source of physiological information, in which the different manifestations of cardiac activity can be identified, separated, and interpreted^[006].

The acquired waveform is no longer regarded as a single vibration generated by the heart, but rather as the result of the superposition of different mechanical phenomena. A new signal-processing procedure introduces a separation frequency, termed the Boundary Frequency (BF), which automatically partitions the signal into two physiologically distinct components. The lower-frequency component represents the mechanical pulsation of the heart (Cardiac Apex Beat, CAB), whereas the higher-frequency component primarily describes the cardiac sounds (Cardiac Acoustic Sound, CAS). For the first time, the measurement is no longer limited to detecting the presence of the pulse, but reconstructs its internal organisation by assigning a precise physiological meaning to the different frequency bands^[006].

The identification of the Boundary Frequency also introduces a new descriptive variable of cardiovascular regulation. Experimental analysis demonstrates that this frequency is not constant, but varies systematically with heart rate according to a nonlinear relationship that can be described by a quadratic function. The separation between the mechanical pulse and the acoustic components therefore becomes adaptive: the frequency threshold distinguishing the two components changes spontaneously in accordance with the evolution of the organism's physiological state. Consequently, the spectral structure of the pulse is no longer interpreted as a fixed characteristic of the sensor, but rather as a dynamic property of cardiovascular regulation itself^[006].

This observation also modifies the interpretation of heart rate variability. The analysis demonstrates that the Boundary Frequency follows the evolution of heart rate while simultaneously reflecting the fractal characteristics of heart rate variability. Under resting conditions, the relationship between BF and heart rate exhibits a particularly stable configuration at heart rates of approximately 70–80 beats per minute, where heart rate variability displays a characteristic 1/f behaviour. The spectral structure of the pulse is thus directly linked to the organisation of physiological regulation, reinforcing the interpretation that the complexity of the cardiovascular signal represents an intrinsic property of homeostatic processes rather than a simple consequence of their activity^[006].

The separation between CAB and CAS also makes it possible to analyse the morphology of the cardiac pulse independently of the sounds generated by the heart valves. The mechanical waves associated with ventricular contraction can be reconstructed with sufficient accuracy to permit a morphological classification of the different observed configurations. These different pulse morphologies are no longer regarded as simple geometric variations of the temporal waveform, but as distinct modes through which the mechanical dynamics of the heart are manifested at the body surface. Signal morphology therefore acquires a new descriptive value, complementing the information already provided by heart rate, heart rate variability, and spectral analysis^[006].

This methodological evolution assumes a broader significance. The objective is no longer confined to the continuous, unconstrained observation of physiological regulation, but extends to the progressive reconstruction of its internal organisation. The superficial aortic pulse is interpreted as a structured information system composed of multiple descriptive levels, in which the mechanical component, the acoustic component, the spectral distribution, pulse morphology, and the properties of heart rate variability jointly contribute to the representation of physiological state^[006].

This development naturally prepares the next stage of the research. Once it has been demonstrated that the superficial aortic pulse can be continuously acquired, separated into its fundamental components, and described through physiologically interpretable variables, these descriptors can be used not only to observe cardiovascular regulation, but also to reconstruct the functional relationships linking the different regulatory mechanisms of the organism. The pulse definitively ceases to be regarded as merely a biological signal and instead becomes a privileged gateway through which the dynamic organisation of physiological regulation as a whole can be described^[006].

The organism is no longer represented as a succession of discrete states identified through individual parameters, but as a dynamic system whose organisation evolves continuously over time. Sleep onset represents only one of the configurations emerging along this trajectory; fatigue corresponds to the progressive accumulation of the regulatory adjustments required to sustain wakefulness; and continuous monitoring becomes the means through which this evolution can be observed without altering the individual's natural behaviour. The representation of the wake-to-sleep transition therefore develops through five closely interconnected advances. The first demonstrates that the evolution of physiological state is already encoded in the dynamics of the present. The second shows that these dynamics preserve the memory of the regulatory adjustments accumulated during prolonged wakefulness. The third identifies the superficial aortic pulse as a novel physiological signal source that can be observed in a completely unconstrained manner. The fourth enables the continuous monitoring of this signal source under normal living conditions. The fifth demonstrates that the superficial aortic pulse is not a single physiological manifestation, but rather an organised structure composed of distinct mechanical, acoustic, and spectral components, each carrying specific information about cardiovascular function. Physiology is thus described as a continuous process that can be observed without interrupting the organism's normal activity and represented through a measurement source capable not only of acquiring the pulse, but also of progressively revealing its internal organisation. On this foundation, it becomes possible to address the next challenge: understanding how the different components of the pulse jointly contribute to the representation of physiological regulation throughout the entire wake-to-sleep transition^{[002],[003],[005],[008],[006]}.

From Sleep Onset Prediction to the Construction of a Dynamic Representation of Physiological Regulation

The study of the wake–sleep transition arose from the need to overcome a fundamental limitation of conventional methodologies. Although electroencephalography enables the precise identification of the different stages of sleep, it characterizes a physiological condition that has already been established and provides no information about the regulatory changes that precede it. The objective of this research therefore became the identification of physiological signals capable of representing the evolution of the organism's regulatory processes before sleep onset^[011].

Simultaneous acquisition of the peripheral pulse wave, dorsal pulse wave, respiration, skin temperature, and electroencephalographic activity demonstrates that, several minutes before the disappearance of α activity, the organism passes through a well-defined physiological configuration characterized by a reduction in heart rate and respiratory rate, an increase in skin temperature, and a coordinated transformation of pulse wave dynamics. The focus of the research thus shifts from identifying the final physiological state to describing the process that progressively leads to its emergence^[011].

This observation introduces a fundamental conceptual shift. The pulse wave is no longer regarded as a simple indicator of the physiological state, but as a source of information about the dynamics of physiological regulation. It therefore becomes necessary to characterize not only the values assumed by physiological variables, but also the manner in which they evolve over time. Comparison between the pulse wave and electroencephalographic activity further supports this interpretation. Their respective time series exhibit consistent transformations during the decline in vigilance, with a progressive shift of spectral content toward lower frequencies. Similarly, changes in seating conditions produce concordant changes in both brain activity and pulse wave dynamics, indicating that physiological regulation emerges from the continuous interaction between neurophysiological processes and the biomechanical conditions of the organism^[019].

Once the consistency among different physiological systems has been demonstrated, the next challenge is to translate this representation into a measurement approach compatible with everyday use. To this end, a pneumatic sensor integrated into the seat is developed to acquire the subtle mechanical fluctuations generated by cardiac and respiratory activity without requiring sensors to be attached directly to the body. The physiological changes associated with the preparation for sleep remain identifiable through this new acquisition modality, demonstrating that physiological information does not depend on the specific sensor employed, but on the ability to reconstruct the same underlying dynamic organization from different physiological signals^[024].

Analysis of the cardiac and respiratory components further demonstrates that they make complementary contributions to the characterization of the physiological state. The cardiac component more effectively represents the succession of wakefulness, sleep, and awakenings, whereas the respiratory component provides a more stable characterization of fatigue progression. Physiological regulation is thus no longer interpreted through a single parameter, but is progressively described by integrating information derived from different physiological manifestations of the same underlying biological process^[025].

Once physiological meaning has been attributed to the pulse wave descriptors, the validity of the resulting representation can no longer depend on the specific technology used to acquire the signal. If the extracted information truly reflects an underlying physiological process, it should be preserved regardless of the measurement modality. Verifying this property therefore becomes an essential step in demonstrating that the representation characterizes the organism's physiological regulation rather than the characteristics of the acquisition device. Comparative analyses across different sensing technologies confirm this hypothesis, showing that the underlying physiological information remains substantially unchanged^{[031],[036]}.

Extending physiological measurement to real-world environments ultimately requires preserving the physiological information contained in the signal even in the presence of vehicle-induced vibrations. To this end, a dedicated signal-processing pipeline is developed, integrating signal differentiation and time-series reconstruction to improve the separation between physiological variations and mechanical disturbances. The principal physiological patterns associated with drowsiness and sleep onset remain identifiable even during dynamic driving tests, thereby demonstrating the robustness of the proposed representation under real-world operating conditions^[040].

The availability of a reliable measurement platform therefore makes it possible to address a broader scientific question: understanding how physiological regulation evolves throughout the entire trajectory leading from wakefulness to sleep. Integrated analysis of the pulse wave, photoplethysmographic signal, electroencephalographic activity, and autonomic indices demonstrates that these different signals characterize distinct phases of the same underlying physiological process. Some anticipate the onset of drowsiness, whereas others more closely reflect subjective perception and the actual transition into sleep. Furthermore, the temporal evolution of the mean pulse rate enables continuous reconstruction of the sequence of the principal regulatory phases, demonstrating that sleep onset is the outcome of a progressive physiological transformation rather than an abrupt event^[043].

Taken together, these findings clearly demonstrate that no single descriptor, when considered in isolation, is sufficient to represent the complexity of physiological regulation. A multilevel interpretation framework is therefore developed, in which the different processing approaches applied to the pulse wave—including Peak Detection, Zero Crossing, gradient analysis, integral-based measures, and descriptive functions—are used in a complementary manner to reconstruct the organism's physiological state. Classification is thus no longer based on a single parameter, but on the hierarchical integration of heterogeneous physiological information, definitively redirecting the research from the mere identification of physiological events toward the representation of their dynamic organization^[049].

Final validation under real-world driving conditions demonstrates that the physiological patterns derived from the pulse wave remain closely associated with both driver behavior and the operating conditions recorded by the tachograph, indicating that physiological fatigue may evolve before it becomes consciously perceived. The representation of physiological regulation thus assumes the role of an objective description of the organism's functional state, independent of both the acquisition technology and subjective perception alone. Once the robustness of the methodology has been demonstrated under real-world operating conditions, the central challenge is no longer the detection of the physiological preparation for sleep, but the ability to characterize the physiological organization of the entire sleep–wake cycle^[060].

From the Reconstruction of Sleep Architecture to the Functional Representation of Physiological Regulation

Having demonstrated the ability of the proposed methodology to represent the evolution of drowsiness under real-world operating conditions, attention is extended to the entire sleep–wake cycle. The objective is no longer to identify the approach of sleep onset, but to determine whether pulse wave dynamics can characterize the physiological organization of sleep as a whole^[047].

Reconstruction of sleep architecture requires a representation capable of following the continuous evolution of physiological regulation. No single descriptor, when considered in isolation, contains sufficient information to represent this organization; it therefore becomes necessary to integrate Peak Detection, Zero Crossing, mean pulse rate, pulse rate gradient, absolute gradient, cumulative integral curve, and their corresponding spectral representations into a unified descriptive framework. In this way, each indicator retains its own physiological significance while simultaneously contributing to the coordinated reconstruction of the dynamics of the entire regulatory system^[047].

The different sleep cycles emerge as dynamic configurations endowed with their own internal organization. The conventional succession of sleep stages progressively gives way to a continuous representation of physiological regulation, in which each phase is identified through the coordinated evolution of multiple descriptors rather than by the simple crossing of predefined thresholds^[047].

This finding has implications that extend beyond sleep classification. The ability to reconstruct the architecture of the entire sleep cycle using the dorsal pulse wave alone demonstrates that cardiovascular regulation constitutes a continuous manifestation of the physiological organization of sleep, rather than merely an ancillary indicator of its progression^[047].

This finding, however, highlights the need for a new level of physiological interpretation. If the pulse wave can represent the organization of sleep, it becomes necessary to understand the physiological meaning embodied in the different descriptors used to construct this representation. Up to this point, the time series obtained through Peak Detection and Zero Crossing had been regarded primarily as alternative mathematical processing approaches applied to the same signal. What remained to be clarified was why these two representations exhibited different sensitivities during the transition from wakefulness to sleep^[068].

Simultaneous comparison of the superficial aortic pulse wave, photoplethysmographic signal, electrocardiogram, and electroencephalogram makes it possible, for the first time, to assign a precise physiological meaning to the two time series. The points identified by the Zero Crossing method are associated with the timing of aortic valve closure and predominantly characterize the elastic behavior of the arterial system during diastole. In contrast, the time series obtained through Peak Detection integrates information originating from both systole and diastole, thereby jointly representing cardiac and vascular function. The two processing approaches therefore do not constitute merely alternative mathematical representations of the same signal, but rather describe distinct functional levels of cardiovascular regulation^[068].

Spectral analysis further reinforces this interpretation. During the onset of drowsiness, the time series derived using the Zero Crossing method exhibits a marked spectral change in the vicinity

of 0.01 Hz, which is interpreted as the expression of the sympathetic response accompanying the early stages of the decline in vigilance. As sleep onset approaches, however, both time series converge toward the characteristic bifurcation around 0.0053 Hz, previously identified in earlier studies. During stable sleep, the entire spectral distribution progressively evolves toward a behavior consistent with the $1/f$ law, indicating the establishment of a new equilibrium configuration of autonomic regulation^[068].

The scientific implications of these findings are particularly significant. Cardiovascular regulation is no longer interpreted as a unitary system that can be characterized through a single indicator, but rather as the coordinated interaction of distinct physiological components, each providing specific information about the behavior of the autonomic nervous system. The representation of physiological regulation thus acquires a new level of descriptive depth: understanding the organism's physiological state requires first distinguishing its different functional components and then integrating them into a unified representation^[068].

This interpretation, however, highlights a further challenge. If the different components of the pulse truly describe specific physiological phenomena of the cardiac cycle, their significance should not depend exclusively on the anatomical location at which the signal is acquired. It therefore becomes necessary to determine whether the same functional organisation can also be identified at other sites within the cardiovascular system while preserving its correspondence with the mechanical events of the heart^[104].

To address this question, a miniaturised wireless version of the APW sensor is developed for the direct measurement of the carotid pulse. The new configuration retains the acquisition principle based on stochastic resonance, while adapting the mechanical structure to the anatomical characteristics of the neck through the use of a three-dimensional mesh, an elastomeric membrane, a resonance chamber, and a highly sensitive microphone capable of selectively amplifying the vibrations generated by pulse wave propagation. The measurement is therefore no longer limited to the dorsal pulse or to the pulse detected near the cardiac apex, but is extended directly to a large artery, making it possible to observe the propagation of the pressure wave throughout the vascular system^[104].

The simultaneous analysis of the electrocardiogram, the apical pulse, and the carotid pulse makes it possible to interpret the physiological significance of the different signal components. The principal pulse oscillations are shown to correlate with aortic valve opening and closure, the ventricular ejection phase, and the subsequent propagation of the pressure wave through the arterial system. The pulse is therefore no longer described as a simple sequence of mechanical oscillations, but as the temporal representation of the entire cardiac cycle, in which each component can be related to a specific physiological event^[104].

The correspondence between the temporal intervals obtained from the electrocardiogram, the apical pulse, and the carotid pulse reveals an almost linear relationship among the different acquisition modalities. The intervals derived from the pulse peaks exhibit a high correlation with the electrocardiographic R–R intervals, while comparison among the different acquisition sites makes it possible to estimate directly the pulse wave transit time throughout the arterial system. The measurement thus acquires a new dimension: in addition to describing the dynamics of cardiovascular regulation, it also enables the mechanical behaviour of pressure wave propagation to be observed^[104].

This finding substantially broadens the significance attributed to the superficial aortic pulse. The information obtained no longer depends on the specific anatomical site of acquisition, but instead reflects properties of cardiovascular dynamics itself. The same functional organisation can be recognised at the cardiac apex, in the dorsal region, and in the carotid pulse, demonstrating that the representation of physiological regulation describes a phenomenon distributed throughout the entire cardiovascular system rather than a local characteristic of the measurement site^[104].

This extension, however, opens an even more significant perspective. If the physiological representation remains valid when the signal is acquired at different anatomical sites, it becomes possible to determine whether it can describe not only overall cardiovascular regulation, but also the hemodynamic changes that directly accompany the reduction in vigilance at the cranial level. The objective of the measurement thus expands from the simple observation of arterial pulse wave propagation to the possibility of monitoring the evolution of cerebral circulation during the wake-to-sleep transition^[105].

To address this question, the APW Scope sensor is applied bilaterally over the superficial temporal regions, enabling continuous acquisition of the cranial pulse without the use of electrodes or invasive devices. The cranial measurement is simultaneously compared with the dorsal pulse, the seat-derived pulse, photoplethysmography, and the electrocardiogram to determine whether the dynamic patterns identified in the previous studies remain recognisable in the cranial region. The results demonstrate that the time series obtained from the different anatomical locations evolve in substantially equivalent ways, confirming that the representation of physiological regulation preserves its consistency regardless of sensor location^[105].

The analysis further demonstrates that the characteristic transformations associated with drowsiness and the preparation for sleep onset can be recognised directly from the cranial superficial pulse. Variations in frequency, gradient time series, and the corresponding signal-processing parameters follow the same evolution previously observed in the dorsal pulse, while the classification criteria developed in the earlier studies continue to identify the configurations associated with the onset of fatigue, drowsiness, and sleep. The methodology therefore demonstrates that the information used to characterise physiological regulation is not specific to a particular measurement site, but instead represents a common property of the organism's dynamic regulatory organisation^[105].

The study also introduces an entirely new physiological interpretation. By synchronising the electrocardiogram with the cranial pulse, it becomes possible to measure the time required for the pressure wave to reach the cranial circulation and to follow its evolution throughout the different stages of decreasing vigilance. The analysis shows that, during the onset of drowsiness and the prodromal phase of sleep onset, the variability of pulse transit time increases markedly compared with both full wakefulness and established sleep. Pulse wave propagation is therefore employed not only as an indicator of cardiovascular function, but also as a descriptor of the changes in cerebral circulation accompanying the progressive reorganisation of physiological state^[105].

Particularly significant is the fact that these findings are also confirmed during experiments conducted under real-world driving conditions. Despite vehicle-induced vibrations, the cranial pulse retains sufficient physiological information to identify the configurations associated with

the onset of drowsiness and sleep, demonstrating that the representation developed in the previous studies can also be extended to the continuous monitoring of the cranial region during normal operational activities. The robustness of the methodology therefore depends not only on the stability of the acquired signal, but also on its ability to preserve the physiological meaning of the representation even in the presence of the disturbances characteristic of real-world environments^[105].

With this contribution, the representation of physiological regulation reaches a further level of completeness. Having demonstrated that the different pulse components possess specific physiological significance and that this significance is independent of the anatomical site of acquisition, the research further shows that the same methodology can be employed to monitor indirectly the changes in cerebral circulation occurring during the wake-to-sleep transition. The cranial superficial pulse thus becomes a new observational window onto physiological regulation, integrating within a single representation both systemic cardiovascular dynamics and the cerebral hemodynamic transformations accompanying the progressive onset of sleep^[105].

This interpretation naturally opens an even broader perspective. If the different components of the pulse describe specific aspects of cardiovascular regulation, they can be used not only to reconstruct sleep architecture, but also to continuously monitor the evolution of the organism's functional state during normal daily activities. The objective of the measurement therefore shifts from the identification of a single physiological event to the dynamic estimation of the individual's overall condition, in which levels of activation, relaxation, fatigue, drowsiness, and recovery represent different configurations of the same underlying regulatory process^[46].

To enable this extension, the processing of the pulse-derived time series is further developed. The information obtained through Peak Detection and Zero Crossing is transformed into the corresponding frequency, gradient, absolute gradient, and cumulative integral curve time series, while their evolution is also described by means of a transfer function capable of representing the dynamic response of the cardiovascular system to external stimuli. Physiological regulation is thus interpreted as a dynamic system in which changes in the organism's state do not depend on the value of a single parameter, but on the manner in which the entire system responds and reorganises itself over time^[46].

The representation of physiological state consequently acquires a hierarchical structure. A first descriptive level distinguishes general states of activation and relaxation; a second level identifies intermediate configurations such as fatigue, drowsiness, microsleep, and recovery; and a third level follows the evolutionary trajectory of the system, making it possible to observe the trends that precede the emergence of different functional states. Sleep onset prediction is therefore reframed as a more general problem of reconstructing the dynamics of physiological regulation^[46].

Particularly significant is the fact that this representation is obtained using the unconstrained sensor integrated into the seat. Measurement no longer requires devices attached directly to the body and can be performed during normal driving, maintaining sufficient observational continuity to follow the progressive transformations of cardiovascular and autonomic regulation. The methodology therefore demonstrates that the dynamic patterns identified in sleep studies can also be recognised under real operating conditions, extending their

significance from the physiology of sleep to the continuous assessment of the driver's physiological state^[46].

This development completes a fundamental stage of the research. The investigation has progressed from the identification of the prodromal phenomenon of sleep onset to the reconstruction of sleep architecture, then to the physiological interpretation of the mechanisms underlying it, and subsequently to the continuous estimation of its evolution during normal daily activities. The regulation of the organism is no longer described as the variation of individual parameters, but as a multilevel organised structure in which the different cardiovascular components cooperate to generate recognisable dynamic configurations throughout the entire sleep–wake cycle and across the various functional states of the organism. This perspective provides the foundation upon which the subsequent relational, geometric, and systems-level representations of physiological regulation are developed^{[047],[068],[046]}.

From Relational Representation to the Geometry of Physiological Regulation

Once it has been established that the time series derived from Peak Detection and Zero Crossing describe distinct functional components of cardiovascular regulation, the focus of the research shifts to the way these components interact. If each descriptor represents a different level of autonomic regulation, then their reciprocal evolution may itself constitute an independent source of physiological information. The emphasis is therefore no longer placed on the behavior of individual variables, but on the organization of the relationships they establish during the progressive decline in vigilance^[072].

To characterize this organization, a new indicator is introduced by directly comparing the time series derived from Peak Detection and Zero Crossing. The area enclosed between the two representations quantifies their dynamic divergence and provides a synthetic descriptor of the physiological state, based not on the value of a single parameter but on the degree of coordination between distinct components of cardiovascular regulation^[072].

The analysis demonstrates that this area progressively decreases during the transition from wakefulness to sleep. As parasympathetic regulation gradually becomes predominant, the two components increasingly evolve in a similar manner, indicating a progressive convergence of cardiovascular organization. The decline in vigilance is therefore no longer interpreted as the simple variation of a physiological parameter, but rather as a process of reorganization of the autonomic system's internal equilibrium, in which the distinct functional components progressively lose the functional separation that characterizes the waking state^[072].

This interpretation is further reinforced by the analysis of the ultra-low-frequency (ULF) components. The progressive reduction of the component centered around 0.6 Hz is found to be closely associated with the decrease in the divergence between the two time series, suggesting that both phenomena represent distinct manifestations of the same underlying regulatory transformation. Furthermore, the absence of this component in the photoplethysmographic signal confirms that the superficial aortic pulse wave contains physiological information that cannot be directly observed in conventional peripheral signals, thereby reinforcing its role as a preferred source for the investigation of physiological regulation^[072].

The methodological significance of these findings is particularly profound. The physiological state is no longer defined exclusively by the values assumed by the observed variables, but by the configuration of the relationships established among them. Convergence and divergence between distinct physiological components themselves become physiological properties, thereby paving the way for a relational representation of autonomic regulation^[072].

Once it has been demonstrated that the relationships among physiological components possess their own physiological significance, a new question emerges: if physiological regulation evolves through the progressive reorganization of the relationships among its constituent components, is it possible to identify the sequence according to which these transformations occur? The focus of the research therefore shifts from the structure of these relationships to their temporal evolution, introducing a representation of physiological regulation as an organized process rather than as a static configuration^[073].

Analysis of the principal ultra-low-frequency (ULF) components demonstrates that they do not emerge randomly, but according to a physiologically ordered sequence. The component centered around 0.0053 Hz is interpreted as the expression of the initial sympathetic response counteracting the decline in vigilance. Subsequently, a component around 0.0017 Hz emerges, associated with the increased cognitive effort required to maintain performance. Finally, the component centered at approximately 0.0035 Hz becomes predominant, accompanying the progressive predominance of parasympathetic regulation and the onset of subjectively perceived drowsiness^[073].

Physiological information therefore resides not in the mere presence of a particular frequency component, but in the sequence according to which distinct regulatory configurations emerge during the evolution of the organism's physiological state. Cardiovascular regulation thus assumes the form of a dynamic trajectory, in which each configuration prepares the next, describing a continuous process of adaptation to the organism's functional demands^[073].

Experimental evidence further supports this interpretation from an applied perspective. Under real-world driving conditions, the sequence of ultra-low-frequency (ULF) components consistently precedes the onset of subjectively perceived drowsiness, whereas this sequence is considerably less pronounced during static laboratory experiments. These findings demonstrate that physiological regulation depends not only on the organism's internal state, but also on its continuous interaction with the operational environment and the cognitive demands imposed by the task being performed^[073].

The representation of physiological regulation thus acquires a new dimension. Having first been characterized through physiological parameters, functional components, and their reciprocal relationships, it is now interpreted as an ordered succession of dynamic configurations, in which each state arises from the evolution of its predecessor. Physiological regulation no longer appears as a sequence of independent events, but rather as a continuous trajectory accompanying the organism through transitions between distinct functional states^{[072],[073]}.

This evolution naturally leads to a further conceptual transformation. If physiological dynamics can be characterized through relationships and trajectories, then the overall shape according to which these relationships are distributed across the frequency domain may itself convey biologically meaningful information. The focus of the research therefore shifts from the presence of individual spectral components to the geometry of their organization, introducing

a descriptive level in which the global spectral configuration itself becomes an indicator of physiological regulation^[085].

The spectrum obtained from the Fourier transform of the frequency gradient is partitioned into distinct functional regions, each characterized by regression lines and geometric parameters describing its shape. Physiological significance is no longer attributed to the amplitude of individual spectral components, but rather to the overall configuration of the spectral distribution—that is, to the manner in which the different regions of the spectrum are organized relative to one another^[085].

Experimental validation demonstrates that this geometric representation systematically discriminates between wakefulness and sleep with greater accuracy than previous methodologies. The significance of this finding extends beyond an improvement in discriminative performance: it demonstrates that the geometry of the spectrum constitutes an intrinsic property of physiological regulation rather than merely a mathematical representation of the data. The spectral shape thus becomes an integral component of the biological characterization of the organism^[085].

This development completes a methodological transformation that began with the earliest contributions of the research program. The analysis progressively evolved from the instantaneous values of physiological variables to their temporal dynamics, then to functional components, reciprocal relationships, evolutionary trajectories, and ultimately to the overall geometry of their organization. Physiological regulation thus emerges as a multilevel structure in which physiological parameters, relationships, and geometric configurations collectively characterize a single dynamic process, laying the foundation for the final stage of the research, devoted to demonstrating that this organization constitutes a fundamental property of the organism as a whole rather than of the cardiovascular system alone^{[072],[073],[085]}.

The Unified Representation of Physiological Regulation

The methodological evolution developed throughout the preceding contributions naturally leads to a broader question. If the configurations observed in the pulse wave genuinely reflect the organization of physiological regulation, they should also be identifiable under conditions fundamentally different from the wake–sleep transition. The research therefore progressively broadens its scope of investigation, examining whether the same descriptive framework can be recognized across pathological conditions, diverse operational contexts, and different levels of subjective perception^[090].

The first step consists of simultaneously comparing signals originating from different physiological systems. The superficial aortic pulse wave is analyzed together with the photoplethysmographic signal, the electrocardiogram, respiration, and other cardiovascular signals to identify potential common properties in their dynamic organization. The findings demonstrate that, although these signals originate from distinct physiological mechanisms, they evolve according to coherent temporal configurations, suggesting the existence of a shared regulatory organization that coordinates the behavior of the organism as a whole. The superficial aortic pulse wave therefore does not represent an isolated physiological phenomenon, but rather one of the observable manifestations of a common regulatory structure^[090].

This interpretation fundamentally redefines the role assigned to the physiological signal. The objective is no longer to extract the greatest possible amount of information from a single measurement, but rather to identify a representation capable of characterizing the overall organization of biological regulation. The different physiological signals are thus interpreted as distinct manifestations through which the same underlying physiological dynamics become observable, making it possible to achieve a unified representation that is independent of the specific acquisition technology^[090].

The validity of this framework is subsequently evaluated under pathological conditions. Analysis of subjects with obstructive sleep apnea syndrome (OSAS) demonstrates that the organization of cardiovascular regulation is systematically altered compared with that of healthy individuals. These changes are not limited to the occurrence of abnormal respiratory events, but involve the entire organization of the dynamic components that characterize autonomic regulation. The pathological condition therefore emerges as a distinct configuration of physiological regulation, rather than as the mere occurrence of isolated pathological events^[088].

The same principle is subsequently extended to transient physiological phenomena, such as yawning. The analysis demonstrates that this behavior, traditionally interpreted as a reflex response, is accompanied by a well-defined reorganization of cardiovascular dynamics that is detectable even before the motor manifestation occurs. Once again, the observable phenomenon represents the final expression of a regulatory process that evolves progressively over time, confirming that the representational framework developed in the preceding contributions is applicable to physiological phenomena of diverse nature^[089].

A further validation is provided by comparing the physiological response with the subjective perception of fatigue. Measurements obtained during prolonged activities demonstrate that changes in cardiovascular regulation frequently precede the conscious awareness of fatigue. The organism modifies its functional equilibrium before the individual becomes consciously aware of this change, indicating that physiological regulation constitutes an autonomous process that is only partially reflected in subjective experience. Its objective characterization therefore provides complementary information to conventional assessments based on self-perceived fatigue^[094].

The analysis of operational conditions provides further support for this interpretation. Comparisons between drivers with different levels of experience demonstrate that physiological regulation depends not only on task duration or the degree of accumulated fatigue, but also on the manner in which the individual interacts with the task being performed. Experience modifies the organization of the physiological response, enabling more efficient management of cognitive demands and reducing the need for continuous autonomic adjustments. Physiological regulation is thus interpreted as the outcome of the interaction among biological characteristics, operational demands, and acquired experience^[095].

These observations ultimately lead to a final extension of the representational framework. If physiological regulation emerges from the continuous interaction of multiple physiological components, its overall organization can likewise be characterized using analytical approaches derived from complex systems theory. Analysis of the fractal structure of the time series demonstrates that the complexity of physiological regulation varies systematically as a function of the physiological state, indicating that the organization of the organism depends not only on

the values assumed by individual physiological parameters, but also on the degree of complexity with which they are coordinated over time^[099].

Complexity is therefore no longer interpreted as an ancillary characteristic of the physiological signal, but rather as an intrinsic property of biological regulation. Physiological states can likewise be distinguished by their distinct fractal organization, demonstrating that the evolution of physiological regulation can be characterized simultaneously at the functional, relational, and structural levels. The representational framework thus acquires a systems-level dimension, in which order, adaptation, and variability constitute complementary aspects of the same underlying biological process^[099].

This phase completes the scientific trajectory reconstructed throughout this chapter. The investigation begins with the identification of the physiological transformations preceding sleep onset, progresses through the development of dynamic descriptors, their physiological interpretation, and the reconstruction of the relationships linking them, and ultimately culminates in a representational framework in which the organization of physiological regulation emerges as a common property of the organism as a whole. The superficial aortic pulse wave is thereby confirmed as a privileged observational window into this process, not because it contains exclusive physiological information, but because it enables the continuous and non-invasive reconstruction of the coordinated dynamics through which the different physiological systems maintain their functional equilibrium^{[088],[089],[090],[094],[095],[099]}.