

EVOLUTION OF THE BIOSIGNAL ACQUISITION SYSTEM



Key Scientific References:

- Scientific Papers:

- [001] - E. Fujita, Y. Ogura, N. Ochiai, E. Yasuda, S. Doi, K. Murata, T. Kamei, Y. Ueno, and S. Kaneko, "Development of simplified appraisal method of fatigue on sitting for extended periods by the data of finger plethysmogram" *The Japanese Journal of Ergonomics*, vol. 40, no. 5, pp. 254–263, Oct. 2004, [doi: 10.5100/jje.40.254](https://doi.org/10.5100/jje.40.254), in Japanese
- [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
- [004] - K. Murata, E. Fujita, S. Kojima, S. Maeda, Y. Ogura, T. Kamei, T. Tsuji, S. Kaneko, M. Yoshizumi, and N. Suzuki, "Noninvasive biological sensor system for detection of drunk driving" *IEEE Trans. Inf. Technol. Biomed.*, vol. 15, no. 1, pp. 19–25, Jan. 2011, [doi: 10.1109/TITB.2010.2091646](https://doi.org/10.1109/TITB.2010.2091646)
- [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)
- [007] - Y. Nobuhiro, E. Fujita, R. Uchikawa, S. Maeda, S. Kojima, Y. Ogura, T. Kamei, K. Murata, M. Yoshizumi, and S. Kaneko, "Development of physical condition fluctuation prediction model using trunk biosignals" in *Vibration Engineering for a Sustainable Future: Numerical and Analytical Methods to Study Dynamical Systems*, vol. 3, S. Oberst, B. Halkon, J. Ji, and T. Brown, Eds. Cham, Switzerland: Springer, 2021, pp. 353–359, [doi: 10.1007/978-3-030-46466-0_47](https://doi.org/10.1007/978-3-030-46466-0_47)
- [008] - N. Hagiya, H. Hirano, A. Mito, Z. Soh, E. Fujita, Y. Ogura, S. Kaneko, R. Nakamura, N. Saeki, 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)
- [010] - H. Tsujimura, H. Suzuki, T. Kitahara, K. Taoda, Y. Ogura, and E. Fujita, "Development of an algorithm for deriving the moment of a urine volume increase until the need to void using the acoustic pulse wave via the body trunk among some healthy persons" *Jpn. J. Ergonom.*, vol. 57, no. 6, pp. 333–340, Dec. 2021, [doi: 10.5100/jje.57.333](https://doi.org/10.5100/jje.57.333), in Japanese

- 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
- [014] - S. Maeda, N. Ochiai, Y. Ogura, Y. Enoki, E. Fujita, K. Murata, T. Kamei, Y. Ueno, and S. Kaneko, “The simple measuring method of bio signal from the buttocks” in *Proc. 37th Annu. Conf. Chugoku-Shikoku Branch, Japan Ergonomics Society*, Hiroshima, Japan, Nov. 27, 2004, pp. 8–9, in Japanese
- [016] - S. Maeda, E. Fujita, Y. Ogura, K. Murata, T. Kamei, and S. Kaneko, “A method for measuring biological signals through the buttocks” in *Proc. 2005 JSAE Spring Annual Congress*, Yokohama, Japan, May 18, 2005, paper 20055254, no. 11-05, pp. 1–4, in Japanese
- [021] - S. Maeda, E. Fujita, Y. Ogura, and S. Kaneko, “The sensing method of biological signal from the hips” in *Proc. JSME Annual Meeting 2005*, vol. 7, Chofu, Tokyo, Japan, Sep. 2005, pp. 313–314, [doi: 10.1299/jsmemecjo.2005.7.0_313](https://doi.org/10.1299/jsmemecjo.2005.7.0_313) (in Japanese)
- [022] - S. Maeda, E. Fujita, Y. Ogura, and S. Kaneko, “Measurement method of biological signal from the hips” in *Proc. 2006 JSAE Annual Congress (Spring)*, Yokohama, Japan, May 2006, no. 78-06, paper no. 20065247, pp. 9–12 (in Japanese)
- [023] - S. Maeda, E. Fujita, Y. Ogura, and S. Kaneko, “A research on sensing method of biological signals from the hips” in *Proc. JSME Annual Meeting 2006*, vol. 5, Kumamoto, Japan, Sep. 2006, pp. 79–80, [doi: 10.1299/jsmemecjo.2006.5.0_79](https://doi.org/10.1299/jsmemecjo.2006.5.0_79) (in Japanese)
- [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)
- [027] - S. Maeda, E. Fujita, Y. Ogura, M. Enokizono, and S. Kaneko, “Trial manufacture of a car seat having a noninvasive biological signal sensing function” in *Proc. 39th Annual Meeting of the Chugoku-Shikoku Branch, Japan Ergonomics Society*, Higashihiroshima, Japan, Nov. 25, 2006, pp. 40–41 (in Japanese)
- [028] - S. Maeda, E. Fujita, Y. Ogura, S. Kojima, and S. Kaneko, “Research on car seat for biological signal sensing” in *Proc. 2007 JSAE Annual Congress (Spring)*, Yokohama, Japan, May 2007, no. 57-07, paper no. 20075174, pp. 7–10 (in Japanese)
- [030] - N. Ochiai, S. Maeda, S. Kojima, S. Wagata, Y. Ogura, E. Fujita, K. Murata, T. Kamei, Y. Ueno, and S. Kaneko, “自動車用シートに組み込んだ着座センサによる飲酒状態の検知方法 [The method for drinking detection by an automobile seat with the built-in seat sensor]” *The Japanese Journal of Ergonomics*, vol. 43, no. 2 Supplement, pp. 192–193, Jun. 2007, [doi: 10.5100/jje.43.2Supplement_192](https://doi.org/10.5100/jje.43.2Supplement_192) (in Japanese)
- [032] - S. Maeda, E. Fujita, Y. Ogura, S. Kojima, and N. Nakagawa, “生体信号検出用空気圧センサの開発 [Development of air-pressure sensor for biological

- sensing]” in *Proc. Dynamics & Design Conf. 2007*, paper 333, pp. 333-1–333-4, Sep. 2007, [doi: 10.1299/jsmedmc.2007.333-1](https://doi.org/10.1299/jsmedmc.2007.333-1) (in Japanese)
- [034] - S. Kojima, S. Maeda, Y. Ogura, E. Fujita, S. Kaneko, and Y. Ueno, “生体信号検出のためのシート特性に関する研究 [A study about the seat characteristic for biological signal sensing]” in *Proc. 40th Annual Meeting of the Chugoku-Shikoku Branch, Japan Ergonomics Society*, Takamatsu, Japan, pp. 34–35, Dec. 2007 (in Japanese)
 - [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)
 - [037] - S. Kojima, S. Maeda, Y. Ogura, E. Fujita, K. Murata, T. Kamei, and S. Kaneko, “生体信号を用いた飲酒・非飲酒状態検知に関する研究 [The method for drinking detection by biological signals]” in *Proc. Dynamics & Design Conf. 2008*, paper 349, pp. 349-1–349-6, Sep. 2008, [doi: 10.1299/jsmedmc.2008.349-1](https://doi.org/10.1299/jsmedmc.2008.349-1) (in Japanese)
 - [038] - S. Kojima, K. Murata, E. Fujita, S. Maeda, Y. Ogura, T. Kamei, T. Tsuji, R. Miyoshi, and S. Kaneko, “シート組み込み型エアパックセンサシステムの開発 [Development of air-pressure sensor with the built-in seat]” in *Proc. 23rd Symposium on Biological and Physiological Engineering (BPES 2008)*, pp. 239–242, 2008 (in Japanese)
 - [042] - S. Kojima, S. Maeda, Y. Ogura, E. Fujita, K. Murata, T. Kamei, T. Tsuji, S. Kaneko, and M. Yoshizumi, “エアパックセンサを用いた飲酒検知システムに関する研究 [A study on a drinking detection system using an air-pack sensor]” in *Proc. 2009 JSAE Annual Congress (Spring)*, Yokohama, Japan, paper 10-20095355, pp. 15–18, May 2009 (in Japanese)
 - [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)
 - [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)
 - [051] - S. Kojima *et al.*, “Noninvasive biological sensor system for detection of drunk driving” in *Proc. 9th Int. Conf. Information Technology and Applications in Biomedicine (ITAB 2009)*, Larnaca, Cyprus, Nov. 5–7, 2009, pp. 1–4, [doi: 10.1109/ITAB.2009.5394324](https://doi.org/10.1109/ITAB.2009.5394324)
 - [052] - Y. Nobuhiro *et al.*, “心循環系の変化による状態推定法の開発 [Development of the state estimation method by the cardiocirculatory change]” in *Proc. 2010 JSAE Annual Congress (Spring)*, Yokohama, Japan, May 19–21, 2010, no. 66-10, paper 20105383, pp. 7–10 (in Japanese)

- **[053]** - S. Kojima *et al.*, “非侵襲センサより得られた生体信号による飲酒検知 [Noninvasive biological sensor system for detection of drunk driving]” in *Proc. 2010 JSAE Annual Congress (Spring)*, Yokohama, Japan, May 19–21, 2010, no. 66-10, paper 20105399, pp. 11–14 (in Japanese)
- **[054]** - S. Kojima *et al.*, “非拘束による生体信号センシングのための自動車用シートの特性 [Characteristics of an automotive seat for unconstrained biosignal sensing]” in *Proc. 2010 Autumn Research Presentation Conf., Japan Society for Design Engineering (JSDE)*, Kochi, Japan, paper D13, pp. 54–57, Oct. 23, 2010 (in Japanese)
- **[058]** - M. Mukai, E. Fujita, Y. Ogura, Y. Nobuhiro, and M. Yoshizumi, “体幹から採取される圧力波に関する実験的研究 [Experimental research on pressure wave obtained from a body trunk]” in *Proc. 43rd Annual Conference of the Chugoku-Shikoku Branch, Japan Ergonomics Society*, Hiroshima, Japan, Oct. 30, 2010 (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)
- **[063]** - S. Kojima *et al.*, “非拘束センサによる生体信号検知のための自動車用シートの特性に関する研究 [Characteristic of car seat for biological signal sensing by non-restriction]” in *Proc. Dynamics & Design Conf. 2011*, Kami, Japan, Sep. 5–9, 2011, paper 607, pp. 607-1–607-9, [doi: 10.1299/jsmedmc.2011.607-1](https://doi.org/10.1299/jsmedmc.2011.607-1) (in Japanese).
- **[065]** - N. Ochiai *et al.*, “体表脈波を用いたトラック運転手の体調推定法 [The estimate method of physical condition of the truck driver using the pulse wave of body surface]” 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. 68–69 (in Japanese)
- **[066]** - S. Maeda *et al.*, “トラック運転手用体表脈波計測装置の開発 [Development of body surface pulse measurement device for truck driver]” 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. 98–99 (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)
- **[074]** - S. Kojima *et al.*, “体表脈波と心音・指尖容積脈波との相関関係に関する研究 [Study on correlation with Aortic pulse wave, the heartbeat and finger photoplethysmogram]” in *Proc. 45th Annu. Conf. Chugoku-Shikoku Branch, Japan Ergonomics Society*, Kurashiki, Japan, Dec. 15, 2012, paper 404, pp. 108–109 (in Japanese)
- **[081]** - S. Kojima *et al.*, “共鳴を利用した背部体幹直接音センシングシステムの開発 [Development of a direct sound sensing system from the back trunk using resonance]” in *Proc. 46th Annu. Conf. Chugoku-Shikoku Branch, Japan*

Ergonomics Society, Hiroshima, Japan, Dec. 8, 2013, paper 101, pp. 24–25 (in Japanese)

- **[083]** - S. Maeda, K. Aoi, Y. Ogura, E. Fujita, S. Kaneko, and M. Yoshizumi, “心音情報を用いた体表脈波(APW)検出 [Detection of APW by using heart sound information]” in *Proc. 46th Annu. Conf. Chugoku-Shikoku Branch, Japan Ergonomics Society*, Hiroshima, Japan, Dec. 8, 2013, paper 102, pp. 26–27 (in Japanese)
- **[086]** - S. Kojima *et al.*, “音・振動情報を捉える共鳴構造を利用した体表脈波センシングシステムの開発 [Development of a body-surface pulse wave sensing system using a resonance structure for detecting sound and vibration information]” in *Proc. 2014 Research Presentation Meeting of the Chugoku Branch, Japan Society for Design Engineering*, no. 31, Hiroshima, Japan, Jun. 7, 2014 (in Japanese)
- **[092]** - M. Horikawa *et al.*, “疑似心音を用いたドライバーの体調の簡易推定法 [Simple method for estimating driver’s physical condition using quasi heart sound]” in *Proc. 48th Annu. Meeting of the Chugoku-Shikoku Branch, Japan Ergonomics Society*, Hiroshima, Japan, Dec. 13, 2015, paper 304 (in Japanese)
- **[100]** - E. Fujita *et al.*, “背部体表音波を用いた疑似心音と疑似呼吸波形の再生 [Reconstruction of virtual phonocardiogram and virtual respiratory waveforms using dorsal body-surface acoustic waves]” *脈管学 (J. Jpn. Coll. Angiol.)*, vol. 58, suppl., pp. S197–S198, Oct. 2018, abstract O-28-2 (in Japanese), [doi: 10.7133/jca.18-90009](https://doi.org/10.7133/jca.18-90009)
- **[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)

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From Peripheral Measurement to Physiological Representation Development

The development of the biosignal acquisition system by Delta Tooling originated from the search for a measurement approach sufficiently simple to monitor participants during prolonged activities, while retaining the ability to derive meaningful information about their physiological state. From the earliest experiments, the objective was to avoid, whenever possible, more complex techniques such as electromyography or electroencephalography, in favor of a minimally invasive solution suitable for continuous monitoring and compatible with experimental conditions closely resembling the normal use of an automotive seat^[001].

The first instrument selected for this purpose was an infrared plethysmograph attached to a finger. An LED and a phototransistor optically detect changes in peripheral blood volume, generating an analog signal that is digitized using a 12-bit analog-to-digital converter at a sampling rate of 200 Hz and subsequently transferred to a personal computer. The system therefore uses a deliberately minimal architecture: the hardware is kept simple, while digital signal processing is used to extract the physiological information of interest^[001].

This choice already embodied one of the key principles that would characterize much of the subsequent development. The value of the measurement was not equated with the complexity of the transducer, but rather with the quantity and quality of the information that the entire acquisition chain could extract from the available signal. Rather than being considered solely in its raw form, the photoplethysmogram thus became the basis for subsequent mathematical processing aimed at deriving indicators related both to the muscular component of fatigue and to the level of alertness. From the outset, therefore, the relative simplicity of the physical device was complemented by an increasing ability to interpret the acquired signal^[001].

The robustness of this approach was assessed by testing the same configuration under different experimental conditions. The system was used in prolonged trials involving variations in posture, seat type, and the characteristics of whole-body vibration exposure, without requiring any modification of the acquisition instrumentation. The peripheral measurement approach thus proved capable of supporting different experimental settings while maintaining signal continuity and adequate stability^[001].

Once the photoplethysmogram had been established as a source of physiological information, the research focused on extracting additional information from the signal rather than immediately introducing new devices. The peripheral pulse was no longer regarded merely as a sequence of beats, but as a time-varying phenomenon from which time series describing the evolution of cardiovascular regulation could be derived. Variations in frequency, signal slopes, transformations of these slopes, and temporal relationships between successive events thus expanded the available information content while leaving the instrument generating the original signal essentially unchanged^{[002],[003]}.

A broader concept of measurement thus emerges: the sensor serves as the input to a processing chain in which signal acquisition and physiological representation are closely integrated. Although the choice of transducer remains fundamental, equal importance is assigned to how the generated signal is preserved, transformed, and rendered physiologically interpretable^{[002],[003]}.

However, experience gained with this initial platform highlighted its principal practical limitation. Regardless of the amount of information that could be extracted from the

photoplethysmogram, the plethysmographic sensor still had to be attached directly to the body. The participant therefore remained physically connected to the measurement system—a condition acceptable in the laboratory but less suitable for monitoring during daily activities and, above all, inconsistent with the objective of monitoring the driver without requiring any specific action or intervention^[003].

This limitation prompted the subsequent shift in perspective. Rather than continuing to refine only the information obtainable from peripheral measurements, the research began to explore the possibility of relocating the acquisition site itself: from a sensor attached to the participant to a surface with which the body is already naturally in contact. The seat thus emerged as a potential platform for capturing physiological oscillations without interfering with the individual's activity^{[011],[014]}.

From the Body to the Seat: Development of an Unconstrained Biosignal Acquisition System

The transition from body-worn sensing to seat-based sensing fundamentally changes the technical challenge. Rather than directly detecting variations in blood volume using an optical sensor placed on the skin, the system must capture the small mechanical oscillations generated by cardiovascular and respiratory activity after they have propagated through the body and reached the supporting surface. The normal contact between the participant and the seat therefore becomes the measurement interface^{[011],[014]}.

The initial experiments adopted this approach by embedding piezoelectric films in the seat backrest and seat pan. Minute pressure variations generated by movements of the torso deformed the piezoelectric material and were directly converted into electrical signals. This made it possible to detect both respiratory and cardiac components without attaching electrodes or other sensors to the participant. For the first time, physiological oscillations were therefore acquired indirectly through the structure with which the body is normally in contact^[011].

This result also introduced a new design variable. Once the transducer was no longer rigidly coupled to the body, measurement quality inevitably depended on the materials and structures located between the physiological source and the sensing element. Stiffness, compliance, damping, and contact stability were no longer merely characteristics of the seat; they began to directly affect signal quality. The mechanical interface thus became an integral part of the signal-acquisition problem^{[011],[014]}.

Within this context, the piezoelectric solution was initially supplemented and subsequently replaced by a pneumatic configuration based on the Air Pack. The sensing principle changed: trunk oscillations no longer directly deformed a piezoelectric element but instead generated pressure variations within an air chamber connected to a condenser microphone. The microphone then converted these pressure fluctuations into an electrical signal^{[014],[016]}.

The Air Pack, however, was not designed as a simple air-filled chamber positioned between the body and the microphone. Its mechanical response was deliberately matched to that of the lumbar region to ensure sufficiently efficient transmission of the weak fluctuations associated with respiration and cardiovascular activity. A three-dimensional mesh was incorporated within the chamber to act as an elastic element and determine its stiffness, while airflow contributed to viscous damping. The structure also provided mechanical filtering, helping to

select the relevant components of the pulsatile signal before it reached the electronic circuitry^{[021],[023],[032],[038]}.

The interaction between the sensor and the seat therefore became increasingly important. Once integrated into the seat structure, the Air Pack no longer retained the mechanical properties observed under isolated conditions, as its interaction with the padding and the occupant's body altered both its stiffness and damping. Greater interface compliance reduced the effects of external vibrations while improving the detection of low-frequency respiratory and pulsatile components. The sensor and seat were thus tuned as components of a single mechanical system, with the aim of maintaining stable contact with the body and separating the biosignal, as far as possible, from vehicle-induced disturbances^{[021][023][032]}.

Subsequent characterization of the Air Pack enabled a more precise definition of the measurement architecture. Two pneumatic chambers were stacked and operated in a differential configuration: one chamber was dedicated to signal detection, while the other compensated for common-mode disturbances. During the same period, the frequency response of the condenser microphone and the filtering bands required to distinguish the respiratory and cardiac components were investigated. This work established a hardware architecture that remained substantially unchanged throughout the subsequent stages of development^[022].

The materials physically separating the body from the Air Pack were also progressively treated as integral components of the measurement system. Two different padding materials were layered over the sensor with a dual purpose: to allow physiological oscillations to reach the pneumatic chamber while minimizing the occupant's perception of the device within the seat backrest. Static characterization of the individual layers and their combination showed substantially linear behavior for deformations of up to 1 mm. Moreover, the response of the composite system—consisting of the two materials layered over the Air Pack—remained close to that of the sensor tested in isolation. The padding therefore ceased to function merely as a covering and became an integral component of the biosignal transmission chain^{[036],[042],[051]}.

At this stage, it became possible to define more precisely what the seat-integrated sensor was actually measuring. An initial answer was provided by comparing the pulsatile signal detected by the Air Pack with the peripheral photoplethysmogram and the electrocardiogram. Its frequency characteristics were substantially consistent with those of the peripheral pulse, while derivative analysis revealed features related to systolic–diastolic dynamics. Comparison with the photoplethysmogram showed close agreement in peak timing and interpeak intervals. The dicrotic notch associated with aortic valve closure was also identifiable, and the fundamental frequency and principal harmonics showed corresponding spectral components. The pulsatile signal acquired through the seat backrest could therefore be related to aortic dynamics in the lumbar region and, more generally, to central hemodynamic activity^{[037],[043]}.

Subsequent spectral comparison with the finger photoplethysmogram further supported this interpretation: the principal frequency peaks of the AP-PW and the peripheral pulse were nearly superimposable. At least in the context of noninvasive driver monitoring, the seat-based measurement could therefore assume the role previously fulfilled by the peripheral sensor attached to the finger^[004].

The cardiovascular nature of the signal acquired from the back was further investigated through multimodal recordings. In participants in the supine position, the APW detected near the dorsal region was recorded simultaneously with heart sounds and the finger photoplethysmogram.

The α and β fiducial points identified in the second derivative of the APW occurred at time points consistent with events of the cardiac cycle: α was located between the first heart sound and the photoplethysmographic a wave, whereas β occurred near the second heart sound. Thus, without modifying the device, the cardiovascular component transmitted through the torso and detected by the sensor could be characterized more precisely^[074].

The pneumatic platform was subsequently described as a noninvasive waveguide-type sensor, with the body and seat structure forming the transmission pathway through which oscillations originating in the cardiac region and aorta reached the measurement system. The signal acquired through the back was therefore attributed to aortic pulsations detectable in the seated position. At this stage, the sensor design remained unchanged; instead, the functional understanding of the signals acquired by the seat-integrated configuration was refined.^{[052],[053]}

From Signal Validation to Control of the Mechanical Environment

Once it had been established that the pulsatile signal acquired through the seat backrest retained a meaningful relationship with central cardiovascular dynamics, the focus shifted from the mere detectability of the biosignal to its stability under real-world operating conditions. In particular, the transition from static to dynamic measurements highlighted the influence of the mechanical environment surrounding the sensor. Tests conducted under vibration exposure showed different effects on the principal physiological components. The respiratory component remained relatively easy to identify even when the seat was exposed to external disturbances, whereas the cardiac component was more vulnerable. Signal degradation could not be attributed solely to vehicle-induced vibration; the relative movements generated between the body, seat backrest, and sensor were equally important. Visceral resonance at approximately 5–8 Hz, body movements at around 1–2 Hz, and the intrinsic mechanical response of the seat backrest could destabilize contact with the Air Pack and introduce oscillations unrelated to the target pulsatile signal^{[022],[024],[034]}.

This observation prompted an important change in the design approach. Improving signal quality no longer involved modifying only the Air Pack or its associated electronics, but also controlling the mechanical transmission path through which vibrations reached the sensor. Suspension systems, three-dimensional meshes, elastic elements, and differential Air Pack configurations were therefore regarded as complementary components of the same architecture, all serving to attenuate mechanical disturbances before they became superimposed on the biosignal^[025].

The seat thus assumed a role extending beyond that of a simple ergonomic support. Its geometry and pressure distribution became design parameters to be defined in relation to signal-acquisition quality. The position of the Air Pack was selected by considering not only its anatomical alignment with the lumbar region, but also the areas in which contact remained more stable and vibration had a less detrimental effect. Sensor placement was therefore progressively determined by balancing biomechanical requirements with measurement needs^[027].

The same design principle was extended to the dynamic structure of the seat. Torsion bars, elastic elements, the three-dimensional mesh, and the stiffness distribution were dimensioned to create a vibration-attenuation zone between the seat frame and the body-contact surface. The

objective was to prevent vehicle-induced vibrations from being transmitted directly to the sensor while preserving the physiological oscillations transmitted by the occupant. The seat thus began to perform a true mechanical signal-preconditioning function upstream of pneumatic and electrical transduction^[028].

This approach was subsequently translated into quantitative design criteria. Because the principal pulsatile components of interest are concentrated approximately within the 1–3 Hz range, whereas accelerations transmitted through the vehicle floor decrease markedly above 45 Hz, a seat frame with a natural frequency of approximately 45–50 Hz was developed, together with a seat-cushion elastic response tuned to approximately 4–5 Hz. Experimentally, the frame resonance was shifted from approximately 35 to 45 Hz, while the vertical resonance of the seat was shifted from approximately 5 to 4 Hz. Under static conditions, the unconstrained sensor integrated into the seat backrest consequently produced a pulse waveform that more closely matched the photoplethysmogram than that obtained using a retrofit configuration installed on a conventional seat^[054].

The significance of this stage is therefore clear: acquisition quality no longer depends solely on the transducer, but on the dynamic matching among the body, sensor, and seat. The Air Pack remains the core component of the pneumatic measurement system; however, its performance is progressively determined by the entire set of elements that influence the transmission of physiological oscillations before they reach the microphone.

Towards sensors designed for the quality of information

At this stage, seat design and sensor design began to converge. The objective was no longer merely to develop a structure capable of housing the Air Pack, but to create a configuration in which every component contributed to establishing the mechanical conditions most favorable for measurement. Stiffness, damping, pressure distribution, and the degree of relative motion between the body and the seat backrest thus became parameters directly related to biosignal quality^{[025],[027],[028]}.

A particularly important development was the creation of a dedicated sensing zone. Postural support of the torso was shifted toward the pelvic region and iliac crest, thereby creating an area within the seat backrest where the sensor could be installed without the high-stiffness elements normally required to support the body. Within this area, the APW sensor was mounted in a semi-floating configuration using a tensioned support structure. This arrangement partially decoupled the sensor from the seat frame while maintaining sufficient mechanical coupling with the torso to track its oscillations^[063].

The difference in stiffness between the seat frame and the tensioned structure also created a shear-stress zone that helped attenuate disturbances transmitted from the seat. The elastic connection to the sensing element was deliberately designed to be compliant, thereby promoting coupled motion between the sensor and the body rather than between the sensor and the rigid structure. A design principle that would also guide subsequent generations thus became increasingly clear: the transducer should be isolated from sources of mechanical interference and coupled, as far as possible, to the physiological source^[063].

In parallel, the selection of the anatomical sensing site was refined. The Air Pack was positioned along the iliocostalis lumborum muscle, and comparison with electromyographic

activity recorded from the back muscles indicated that some cardiac and pulsatile fluctuations reached the sensor through the mechanical response of the muscle tissues. The acquired pulsatile signal was therefore not the result of localized contact with a single anatomical structure, but rather the outcome of the propagation and transformation of oscillations through the torso, followed by their interaction with the pneumatic sensing system^{[021],[023],[027],[028],[030]}. This understanding prompted a more systematic investigation of the anatomical sites at which the biosignal could be acquired with the greatest stability. An eight-channel, noninvasive waveguide-type sensor system was developed to enable simultaneous measurements at four locations. Pressure waves were recorded from the thoracic, abdominal, and dorsal regions in both seated and recumbent positions, together with the peripheral photoplethysmogram and electrocardiogram^[058].

Comparison across the different anatomical regions showed that the dorsal waveform was less affected by body morphology than signals acquired from the thoracic and abdominal regions. The back therefore emerged not only as a convenient site for integrating a sensor into a seat backrest, but also as an experimentally more favorable location for measurement reproducibility. The multichannel architecture thus served an exploratory function: although it did not yet represent the final system, it enabled identification of the most stable anatomical region for unconstrained monitoring^[058].

Nevertheless, the limitations of the pneumatic configuration remained evident under dynamic conditions. The respiratory component retained good detectability, whereas the cardiac component continued to be more susceptible to vehicle-induced vibrations. This limitation did not call into question the feasibility of seat-based measurement; rather, it indicated that the mechanical transmission pathway upstream of the sensor required more effective control^{[022],[024],[027]}.

Development therefore proceeded primarily through iterative refinements rather than repeated replacement of the transducer. The elastic response of the Air Pack, differential measurement configuration, stiffness distribution, and dynamic behavior of the structure were progressively optimized. During this phase, the useful physiological signal and mechanical noise were increasingly treated as two components that should be separated upstream of electrical transduction^{[021],[022],[023],[024],[025],[027],[028]}.

The result was a mature conception of the acquisition system. The sensor represented only one component of the measurement chain; the seat, suspension system, elastic materials, pneumatic chamber, and body interface all contributed to shaping the signal subsequently processed. In other words, the measurement device was no longer identified solely with the component generating the electrical output, but with the entire physical pathway that enabled physiological oscillations to reach that component under controlled conditions^{[025],[027],[028]}.

From Experimental Testing to an Operational Platform

Once sufficient mechanical maturity had been achieved, the same architecture was applied to an increasingly broad range of applications without requiring fundamental changes to the sensing principle. Fatigue, alertness, respiration, and cardiovascular oscillations were monitored using a platform sufficiently stable for transfer from the laboratory to on-road use. The configuration developed for commercial vehicles integrated an APW sensor mat into the

seat backrest, connected to a main processing unit and a power supply unit. Through the microphone, the sensor unit recorded a pressure waveform containing pulsatile and respiratory components, as well as oscillations associated with body movement^{[060],[065],[066]}.

In the version marketed as Sleep Buster®, the signal initially acquired from the back by the microphone was also termed the *quasi-heart sound*. An oscillatory waveform centered around 1 Hz, designated the Aortic Pulse Wave (APW), was subsequently derived from this acoustic-pressure signal. This distinction clarifies that the APW does not necessarily correspond to the raw signal generated by the transducer, but rather represents a pulsatile waveform derived from the physical signal detected through the seat backrest^[092].

The signal was digitized at 5-ms intervals, corresponding to a sampling frequency of 200 Hz, and transmitted to an onboard CPU for real-time processing. Long-duration driving trials involving professional drivers demonstrated that the unconstrained monitoring platform could be transferred from the experimental environment to operational use without requiring substantial modification of the underlying measurement principle^{[060],[065],[066]}.

The significance of this transition lies less in the introduction of a new sensor than in the transformation of the experimental solution into a self-contained acquisition platform that could be integrated into the vehicle and operated continuously during the driver's normal activities^{[014],[016],[021],[022],[024],[025],[027],[028],[060]}.

Extending Biosignal Measurement Beyond the Automotive Seat

The stability achieved by the unconstrained configuration made it possible to assess whether the same sensing principle could be transferred to other support surfaces and postural conditions. The first extension concerned sleep monitoring. The Air Pack was integrated directly into a mattress and used to acquire dorsal pulsations during sleep. The pneumatic sensing principle remained unchanged, but the sensor was transferred from a seating surface to one designed for prolonged contact with the body in the supine position. Unconstrained measurement was thus shown to remain feasible even when the participant was neither seated nor engaged in a driving task^[047].

A different configuration positioned the sensor directly between the participant's back and the bed during sleep-induction trials. Although this study provided no additional information on the device's construction, it documented a further practical coupling method: the system could operate without being integrated into the mattress structure, provided that it remained mechanically coupled to the torso through the support surface^[072].

In parallel, the pneumatic sensing principle was adapted for localized measurements using a smaller Air Pack. The sensor was applied at several anatomical sites—including the back, neck, arm, radial region, and thigh—in both seated and supine positions. Comparison with the electrocardiogram showed particularly stable correspondence for the dorsal pulse, as well as good agreement at the cervical site^[049].

These experiments broadened the role of the Air Pack: from a sensing element integrated into a seat or mattress, it also became a localized sensor for monitoring the propagation of cardiovascular oscillations across different anatomical regions. The research therefore did not move away from the pneumatic sensing principle, but progressively explored its operational limits and adaptability.

From Pressure Variations to Direct Detection of Vibroacoustic Information

The subsequent evolution was driven by the need to overcome an inherent limitation of the pneumatic configuration. Although the Air Pack effectively detected pressure variations transmitted through the torso, the underlying physiological phenomenon also contained a richer vibroacoustic component that could be observed before being reduced to pressure oscillations within the chamber. This requirement led to the development of the 3SR sensor, designed to directly detect sounds and vibrations transmitted from the posterior torso. The system retained the ability to be integrated into a seat backrest or bed, but substantially changed the mechanism by which the signal reached the transducer. Rather than relying primarily on pressure variations within a pneumatic chamber, it used a resonant structure designed to capture, selectively transmit, and amplify body-transmitted acoustic oscillations^[081].

The architecture comprised three functional layers. The first layer, positioned in contact with the back, consisted of a three-dimensional mesh that increased the surface area over which vibrations were collected. The second layer formed the primary sensing core, providing the resonance function and housing the microphone. The third layer, also based on a three-dimensional structure, helped reduce the influence of externally transmitted vibrations^[081].

The change therefore extended beyond the simple replacement of the sensor. The structure upstream of the microphone was deliberately used to modify the mechanical content of the signal before electrical transduction, thereby transforming the transducer support into an active measurement stage. This principle was embodied in the internal geometry of the resonator. The enclosure contained expanded polypropylene bead foam, urethane elastomer sheets, and a three-dimensional mesh, which together formed the sensing structure. A section of the mesh was secured at its ends by vibration welding, producing behavior similar to that of a tensioned string and directly incorporating the microphone. An air gap was maintained between the mesh and the elastomer; body-transmitted oscillations generated pressure variations within this gap, which were ultimately converted into an electrical signal^[005].

Mechanical compatibility with the body remained a fundamental requirement. The 3SR sensor structure exhibited an overall stiffness of approximately 20 kN/m, comparable to the values measured for human musculature under seated and supine conditions—approximately 22 and 32 kN/m, respectively. The system could therefore deform in response to the contour and motion of the participant's back without losing its resonant function, thereby facilitating transmission of vibroacoustic information to the microphone^[005].

The natural frequencies of the three-dimensional mesh and expanded material were also set above 100 Hz, taking into account the spectral characteristics of the signal transmitted from the torso. When the participant's body weight tensioned the structure, the combined vibration of its mechanical elements excited the air within the cavity. Oscillations generated within the body and propagated through bone, muscle, skin, and clothing were thus collected over a large surface area and enhanced by resonance before reaching the microphone. The sensing area measured approximately $480 \times 325 \text{ mm}^2$, allowing contributions from a broad region of the back to be integrated^{[081],[083],[086]}.

Resonance thus served a dual function: it increased signal amplitude while also stabilizing the physiologically relevant component by reducing dependence on a highly localized contact

point. Cardiovascular information was therefore no longer measured solely as a pressure oscillation, but as vibroacoustic activity distributed across the torso.

From the Resonant Structure to the Resonance Carrier

La nuova architettura permette anche di distinguere in modo più chiaro il fenomeno fisico acquisito dalla rappresentazione APW ottenuta successivamente. Le variazioni di pressione prodotte nella cavità vengono prima convertite dal microfono in segnale elettrico e quindi sottoposte a filtraggio passa-banda tra 10 e 30Hz. Ne deriva una componente concentrata prevalentemente tra 15 e 30Hz, prossima alle frequenze associate al primo e al secondo tono cardiaco, definita Resonance Carrier (RC)^{[081],[086]}.

La RC rappresenta quindi un livello intermedio della catena di misura:

**Torso vibroacoustic activity → resonant structure → microphone →
Resonance Carrier → APW**

This distinction is important because it separates the signal physically acquired by the sensor from the waveform reconstructed through subsequent processing. The APW does not correspond to the raw signal detected by the microphone; rather, it is derived from a resonant component that retains the cardiovascular information transmitted through the body. Full-wave rectification and detection reduce components attributable to respiratory modulation, together with some mechanical and electrical disturbances. Subsequent filtering within the 0.5–5.0 Hz range then yields the Aortic Pulse Wave^{[081],[086]}.

Resonance also remained a key factor under dynamic conditions. The resonant structure and its oscillator enhanced the RC component around 20 Hz, allowing cardiac periodicity to be preserved despite the vibrations typically encountered during driving. Simultaneous comparison with the electrocardiogram, heart sounds, and photoplethysmogram confirmed the temporal consistency of the acquired signal^{[081],[086]}.

From Mechanical Resonance to Stochastic Resonance: Development of the 4SR System

On this basis, a more advanced configuration, termed 4SR, was developed in which the mechanical amplification produced by the harmonic oscillator was combined with a stochastic-resonance mechanism^[006]. The system consisted of a coupled Air-Pack and Gel-Pack. The Air-Pack incorporated an approximately 10-mm-thick three-dimensional mesh enclosed within an elastomeric membrane, whereas the Gel-Pack housed the microphone within a deformable, gel-filled plastic enclosure^[006].

When the participant's body weight loaded the structure, the monofilament elements of the three-dimensional mesh, arranged in an X-shaped configuration, were flexed and placed under tension. This deformation produced two complementary effects. First, the mesh behaved as a harmonic oscillator with a natural frequency of approximately 20 Hz. Second, mechanical interactions among its elements generated vibrations that contributed to the conditions required for stochastic resonance^[006].

The Air-Pack and Gel-Pack therefore functioned as coupled elastic and damping elements. Their role was not merely to transmit the signal to the microphone, but to physically amplify acoustic microvibrations before transduction, thereby extending the acquisition bandwidth to the specified range of 0.5–80 Hz^[006].

This effect was quantified by comparing the signal detected by the 4SR system with microvibrations recorded using a microphone placed directly over the same precordial site. The gain reached approximately 42 dB within the fundamental-frequency band of the apex beat, exceeded 30 dB in the harmonic-frequency region, and remained around 20 dB within the 20–30 Hz range associated with the harmonic oscillator. The peak gain exceeded 40 dB, corresponding to an approximately 200-fold increase in amplitude^[006].

This characterization definitively established the role of the resonant structure: it was no longer merely a coupling interface between the body and the microphone, but rather a primary mechanical amplification stage operating upstream of electrical signal transduction.

From Dorsal Signal Acquisition to Localized Precordial Measurement

The 4SR system also expanded the applications of acoustic-resonant sensing. Whereas previous configurations had been developed primarily to acquire signals through the back, the new system was applied directly to the precordial region at the left fifth intercostal space^[006].

At this site, an Acoustic Pulse Wave could be acquired that contained both the mechanical components of the apex beat and the acoustic components associated with the heart sounds. The measurement was thus obtained closer to the cardiovascular source, shortening the propagation pathway through the torso and enabling direct detection of microvibrations that, in the dorsal configuration, had been recorded only after transmission through multiple body structures^[006].

This development did not replace dorsal acquisition but expanded the range of possible configurations. The acoustic-resonant system could be used either as a sensor integrated into a support surface or as a localized sensing element applied in proximity to the physiological source.

From Localized Measurement to a Multisite Configuration

The subsequent development concerned the spatial distribution of measurement sites. The 4SR system was extended to a multisite configuration designed for continuous acquisition of vibroacoustic waves through the back^[007].

The system comprised three microphones designated L, M, and R. The L and R sensors were positioned approximately 6 cm to the left and right of the trunk midline, respectively, at the level of the fifth rib. The M sensor was positioned posteriorly over the region between the third and fourth lumbar vertebrae^[007].

The arrangement was not merely geometric; the different measurement sites were selected to preferentially capture distinct cardiovascular components. The L channel yielded a thoracic waveform influenced by the apex beat and the ejection wave transmitted to the thorax, whereas the M channel provided an abdominal component attributed to pulsation of the abdominal aorta^[007].

The 4SR thus evolved from a localized acoustic-resonant sensor into a multisite platform in which the anatomical location of each transducer became an integral part of the measurement definition. This approach was further developed by distinguishing among the L, R, and M dorsal regions. The L site was predominantly associated with signals originating from the left side of the heart, including the influence of the apex beat, as well as respiratory components attributable to the left lung. The R region was associated with signals from the right side of the heart and with respiration of the right lung. By contrast, the M site, positioned near the fourth lumbar vertebra and below the diaphragm, showed less direct influence from the apex beat and a greater contribution from the descending aorta and diaphragmatic–abdominal motion^[100].

The significance of dorsal measurement therefore changed once again. Rather than seeking a single universally optimal location, the measurement site was selected according to the physiological information to be preferentially captured. The M configuration was evaluated using synchronized recordings of the dorsal acoustic waveform, phonocardiogram, electrocardiogram, finger photoplethysmogram, and respiration. Signals were recorded for 10 minutes at a sampling frequency of 1,000 Hz. The acquired signal retained information related to both the cardiac cycle and respiration, confirming that sensor placement could be used as a criterion for selecting the physiological source of interest^[100].

This approach also led to a distinction between application-specific configurations. For automotive monitoring, single-site configurations—primarily at the L or M locations—could be used with a sampling frequency of 200 Hz. For medical applications, a three-site platform with higher temporal resolution, within the 1–10 kHz range, was proposed^[100].

The APW sensor thus became increasingly independent of any single deployment geometry: anatomical location, number of acquisition channels, and sampling frequency were selected according to the physiological information required.

From Multisite Acquisition to the APW Scope: Development of a Compact Wireless Sensor

The progressive extension of acoustic sensing to different anatomical sites subsequently led to the development of a compact device specifically intended for localized measurements. This stage is represented by the APW Scope, the latest APW sensor configuration developed by Delta Tooling and documented in the development pathway considered here. Designed for carotid pulse wave acquisition, the device brings the mechanical sensing principles established through the preceding generations into a portable wireless instrument^[104].

The configuration described in the study consists of a cylindrical unit approximately 45.5 mm in diameter and 23.5 mm in height. The sensing structure, microphone, electronic circuitry, and lithium coin-cell power supply are incorporated into the same housing, with specifications allowing wireless communication with a smartphone. This arrangement extends the acquisition architecture beyond installation within a seat or mattress and makes the sensor suitable for positioning at a selected anatomical site^[104].

Miniaturization preserves the role of the mechanical structure in shaping the signal before electrical transduction. A three-dimensional mesh is positioned at the sensing surface, where contact and vibration between its monofilaments generate mechanical fluctuations. The authors describe these fluctuations as contributing to stochastic resonance and the enhancement of the

physiological signal. An elastomer film forms an air layer and provides a mechanical oscillator through which acoustic vibrations are transmitted toward the microphone^[104].

The remaining components perform complementary functions within this transmission pathway. A low-frequency microphone, identified as model UA377E3, converts the acoustic vibrations into an electrical signal, while the gel incorporated into the device attenuates externally introduced acoustic disturbances. The compact architecture therefore retains the functional distinction between enhancing the physiological component, transmitting it to the transducer, and reducing interference from the surrounding environment^[104].

The significance of this development extends beyond the reduction in sensor dimensions. The principles previously implemented within a larger supporting structure are brought together in a localized sensing unit. Mechanical coupling, resonance, disturbance attenuation, and electrical conversion remain integrated aspects of the measurement system, while the anatomical site can be selected according to the information required^[104].

Application over the carotid artery introduces a deliberate form of direct contact with the body. The APW Scope consequently complements the configurations developed for unconstrained acquisition through supporting surfaces by providing access to a defined vascular site. Its compact format and wireless capability support flexible positioning, while contact conditions remain an essential part of the acquisition procedure^[104].

From Carotid Pulse Measurement to Physiological Interpretation

The carotid study also addressed how the acquired signal could be interpreted in relation to the cardiac cycle. The authors distinguished the acoustic pulse wave recorded at the cardiac apex, termed FAPW, from the waveform acquired over the carotid artery using the APW Scope, termed NAPW. These measurements provided observations of precordial mechanical activity and the arterial pulse at the neck, allowing their temporal relationships to be examined within a synchronized recording^[104].

This distinction further develops the concept of anatomical placement as an information-selection parameter. At the precordial site, the waveform contains contributions associated with the mechanical action of the apex beat and cardiac acoustic activity. At the carotid site, the recorded waveform reflects pulsatile activity transmitted to the artery. The two locations therefore provide related observations of the cardiovascular sequence whose interpretation depends on both their timing and their physical origin^[104].

The study also extracted the components designated Cardiac Apex Beat, or CAB, and Cardiac Acoustic Sound, or CAS, through filtering of the recorded APW signals. Separating the lower-frequency mechanical component from the acoustic component made it possible to examine additional features within each cardiac cycle. The acquired waveform thus served as the basis for several physiological representations, continuing the principle that meaningful information emerges from the combined acquisition and processing chain^[104].

Experimental measurements were obtained from four healthy adult males aged between 25 and 44 years. A precordial sensor was positioned at the fifth intercostal space, approximately 100 mm to the left of the chest midline, while the APW Scope was applied directly over the carotid artery. Electrocardiographic leads I and II, FAPW, and NAPW were recorded synchronously

using Delta Tooling's APW Analyzer 200. The recordings lasted 30 seconds in the resting seated position, with a sampling frequency of 200 Hz^[104].

Comparison with the electrocardiogram supported the selection of recurring waveform features for estimating cardiac cycle duration. The coefficients of determination between ECG R–R intervals and the selected FAPW peak-to-peak intervals ranged from 0.9709 to 0.9949. For the carotid NAPW, the corresponding values ranged from 0.9652 to 0.9974. These results indicate a strong relationship between the timing of successive APW features and the duration of the cardiac cycle under the conditions examined^[104].

The analysis also considered the position of these features within the cardiac sequence. In the representative participant discussed in detail, the selected FAPW peak occurred approximately 0.110 seconds after the electrocardiographic R wave, while the corresponding NAPW peak occurred approximately 0.125 seconds after it. The resulting difference of 0.015 seconds was interpreted by the authors as reflecting pulse propagation between the measurement sites. This observation demonstrated the possibility of comparing temporal features across the precordial and carotid recordings, while further validation is needed to establish their use as quantitative indicators of vascular properties^[104].

The contribution of the APW Scope therefore involves both localized acquisition and the interpretation of the resulting waveform. Its value lies in making pulsatile and acoustic information available within a framework that relates recurring features, cardiac cycle duration, and differences between anatomical sites. Sensor development and physiological interpretation become increasingly interdependent^[104].

From Physiological Measurement to an Analysis Tool Supporting Diagnostic Activity

These capabilities provide a basis for extending the role of APW technology toward analytical applications for researchers, technicians, and healthcare professionals. Within this perspective, the APW Scope offers a portable means of acquiring localized physiological waveforms that can be inspected, compared with other recordings, and examined in relation to specific experimental or clinical questions.

For researchers, synchronized precordial and carotid measurements create opportunities to investigate relationships between cardiac mechanical activity, acoustic events, and arterial pulse timing. For technicians, the compact architecture provides a basis for developing acquisition procedures and characterizing the influence of sensor placement and contact conditions. For healthcare professionals, the prospective contribution concerns additional physiological information that could complement diagnostic assessment as the relevant measurement methods and indicators undergo clinical validation.

The study explicitly considers the possibility of extending acoustic analysis to the assessment of cardiac valve function. This proposal is based on the relationship between valve activity, the sounds it generates, and the anatomical locations at which those sounds can be detected. Localized sensing could therefore support investigation of acoustic features relevant to functional assessment, with the measurement site selected according to the component of interest^[104].

The experimental evidence establishes an initial foundation for this direction. The study demonstrates the acquisition of precordial and carotid waveforms and their temporal relationship with the electrocardiogram in a small sample of healthy participants. Diagnostic performance in patients with valve disease or other cardiovascular conditions was not evaluated. The proposed clinical applications consequently require further studies to determine the reproducibility, specificity, and diagnostic significance of the measured features^[104].

Within these boundaries, the APW Scope represents a development toward an instrument that supports professional analysis. The combination of localized acquisition, mechanical and acoustic information, and synchronized temporal comparison creates a technological basis for supplying researchers, technicians, and healthcare professionals with data relevant to physiological interpretation. Its prospective diagnostic contribution depends on connecting this information with validated assessment methods and the wider clinical context.

From Peripheral Sensing to a Multisite Acoustic Platform

Overall, the development pathway described here encompasses successive changes in sensing principle, mechanical coupling, anatomical placement, and acquisition format. The research began with optical peripheral measurement, progressed through seat-integrated mechanical and pneumatic sensing, and subsequently introduced structures designed to enhance body-generated vibroacoustic information. Precordial and multisite configurations expanded the physiological sources that could be investigated, while the APW Scope translated these principles into a compact wireless device for localized measurement^{[005],[006],[007],[100],[104]}.

The resulting platform accommodates different measurement requirements. Sensors integrated into supporting surfaces enable acquisition during normal contact with a seat or bed, while localized configurations provide access to selected anatomical regions. Across these arrangements, the body interface, mechanical structure, transducer, and processing chain jointly determine the information available for interpretation.

As the latest configuration documented in this pathway, the APW Scope extends Delta Tooling's technology toward portable physiological analysis. The carotid study illustrates how sensor development can be accompanied by a more explicit interpretation of waveform features and their relationship to cardiac timing. This combination supports the progression from monitoring physiological state toward providing information that can contribute to research and, following appropriate validation, diagnostic assessment^[104].

Concluding Summary of the Evolution of the Biosignal Acquisition System

Over approximately two decades, the development of Delta Tooling's biosignal acquisition system followed a coherent progression from peripheral optical measurement to an adaptable platform for acquiring mechanical and acoustic physiological information. Throughout this evolution, the measurement system came to include the complete pathway through which body-generated oscillations reach the transducer: the anatomical source, contact interface, supporting materials, mechanical structure, and sensing element.

The transition to piezoelectric and pneumatic configurations integrated into the seat established the feasibility of unconstrained acquisition through supporting surfaces. The Air-Pack demonstrated the importance of stiffness, damping, padding, and seat dynamics in determining

signal quality. The subsequent 3SR and 4SR systems extended this approach by using resonant structures to enhance physiological microvibrations before electrical transduction[005],[006]. Precordial and multisite measurements introduced anatomical location as an additional design variable. The sensing site could be selected according to the physiological contribution to be examined, allowing different mechanical, acoustic, and pulsatile components to be compared. The platform consequently became adaptable to a wider range of experimental configurations and analytical objectives^{[007],[100]}.

The APW Scope represents the latest development documented in this sequence. Its compact structure, battery power, and wireless capability bring localized acoustic acquisition into a portable instrument, while the carotid study establishes an initial framework for relating its waveform features to cardiac cycle duration and timing between measurement sites. This development links the physical evolution of the sensor with an increasingly explicit interpretation of the information it produces^[104].

The broader significance of this progression lies in the possibility of providing researchers, technicians, and healthcare professionals with an adaptable tool for physiological analysis. Research applications can investigate the mechanisms underlying the recorded waveforms, technical development can improve acquisition consistency, and clinical studies can determine which features contribute meaningfully to diagnostic assessment.

From this perspective, Delta Tooling's development pathway provides a foundation for tools that combine practical acquisition with physiologically interpretable information. The APW Scope carries this approach into localized measurement, supporting further work toward validated indicators that can assist professional observation, cardiovascular analysis, and diagnostic activity^[104].