How Smart Sensors Can Detect Stress Through Breath Analysis

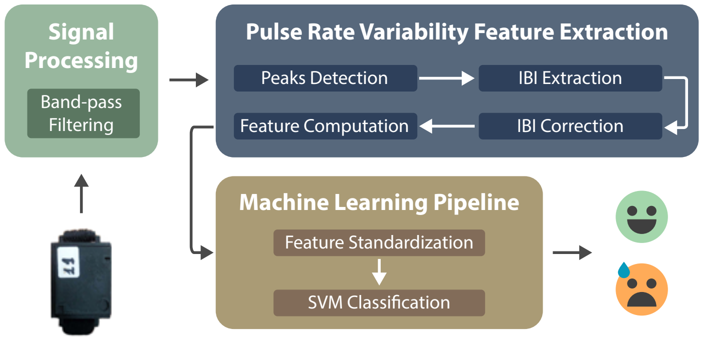
Stress: an invisible threat to health

Stress is defined as a person's physical, mental and emotional reaction to certain stimuli that cause strain in the human body. Such stimuli are often known as "stressors". Depending on the severity and the timing of a stressor, produced stress can negatively affect both physical and mental health, increasing the risk of conditions such as cardiovascular diseases, anxiety or even life-threatening results. Stressors are categorized based on the reactions they cause and are divided into two fundamental categories: physiological stressors and psychological or mental stressors. Monitoring stress levels is important as it helps people identify behaviors that trigger it, improve daily habits such as sleep or exercise and finally prevent or manage it. The development of smart wearable devices for monitoring human physiology and assisting in the betterment of people's lives has been the subject of several research works over the years.

Biosignal-based stress estimation

Biosignals are time-varying measures of the processes of the human body. They can be divided into two main categories: physical (e.g. respiratory rate, speech, skin temperature, pupil size or eye activity) and physiological (e.g. encephalography, electrocardiography, electrodermal activity or electromyography). Biosignals have been shown to be efficient indicators of stress as they are not subject to intentional or even partial conscious control unlike more manipulable behavioural and psychological components of stress. Various detectable biosignals have been utilized throughout the years: the ones proven to be most reliable and widely used to extract health state indicators, such as stress, are electrocardiogram (ECG), photoplethysmography (PPG), electromyogram (EMG) and electrodermal activity (EDA). These signals carry valuable information that is often captured through widely adopted derived measures such as Heart Rate Variability (HRV) and Pulse Rate Variability (PRV). For practical, non-obtrusive deployment in wearable devices, PPG, EDA, temperature (TEMP) and accelerometer (ACC) data have emerged as particularly suitable modalities for stress detection.

In that context, Mitro et al (2023) introduced a low-cost, easy-to-use and fully customized smart wristband, designed for stress detection[1]. A real-time ultra-short pulse rate variability process is conducted on the smart wristband, based on 30s PPG signal segments. A lightweight ML pipeline for stress detection is implemented, using an algorithm based on five time-domain features and one extra heart-rate-related feature, to provide a "stress" or "no stress" output. This ML pipeline is integrated into the embedded device. Their system has been evaluated in 2 stages: firstly, a 91% accuracy score was obtained on a previously unseen subset, held out from the cross-validation process; secondly, a 76% accuracy score was achieved in the context of an external validation process performed through a dedicated laboratory study.



Stress detection workflow based on pulse rate variability analysis and machine learning classification. IBI: interbeat interval.[1]

Breath analysis-based stress estimation

Multiple studies indicate that exhaled VOCs – notably acetone, isoprene, and selected aldehydes – show reproducible correlations with both acute and chronic stress states-related physiological states. These stress-induced metabolomic changes are linked to HPA axis activation, autonomic regulation, oxidative stress, lipid peroxidation, inflammation, and stress-related metabolic shifts. However, breath VOC profiles are highly variable and are influenced by age, gender, BMI, smoking, diet, physical activity, respiratory pattern, and environmental exposure. Therefore, the ability to distinguish stress-induced VOC changes from normal breath composition fluctuations is critical for developing reliable breath-based stress estimation tools.

State-of-the-Art VOC Biomarkers for Stress Detection

Current evidence supports several candidate VOC markers, but no fully validated and standardized stress-specific VOC panel exists yet. The most relevant markers include:

- Isoprene: endogenous hydrocarbon sensitive to ventilation, respiratory rate, and muscle workload; it can change rapidly during acute stress, exercise, or altered breathing patterns.
- Acetone: ketone body reflecting lipolysis, lipid oxidation, and metabolic stress; its changes are generally more metabolically driven and less immediate than isoprene.
- Aldehydes (C3-C7): products of lipid peroxidation and oxidative stress; elevated levels are associated with chronic stress, inflammation, and oxidative tissue processes.
- Acetic acid and pentane: associated with oxidative stress and metabolic reprogramming during stress responses.
- Propanol and methanol: influenced by demographic and lifestyle factors; potentially stress-responsive, but less specific and requiring cautious interpretation.

The current trend is moving from single-compound interpretation toward composite VOC profiles analyzed through multivariate models and AI-based pattern recognition. Standardized sampling, baseline correction, and longitudinal validation are therefore necessary before clinical or occupational use.

[1] Mitro, N., Argyri, K., Pavlopoulos, L., Kosyvas, D., Karagiannidis, L., Kostovasili, M., Misichroni, F., Ouzounoglou, E., & Amditis, A. (2023). AI-Enabled Smart Wristband Providing Real-Time Vital Signs and Stress Monitoring. Sensors, 23(5), 2821. https://doi.org/10.3390/s23052821

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Multi-pixel gas sensor platform

FOR A WIDE RANGE OF APPLIANCE AND CONSUMER MARKETS

The AMUSENS approach focuses on dynamic VOC profiling rather than isolated biomarkers. The investigation of exhaled breath using temperature-modulated multipixel sensors combined with AI aims to generate more informative VOC-specific patterns for real-time, point-of-care stress monitoring. The main research priorities cover the following:

- Develop compound-specific normalization and standardized sampling protocols to reduce physiological, environmental, and technical confounders;
- Investigate the interplay between endogenous VOC production, environmental exposures, and individual physiological factors.
- Monitor temporal VOC dynamics during acute and chronic stress under controlled and real-world conditions;
- Conduct longitudinal validation studies to establish demographic-adjusted reference ranges and assess the temporal stability of stress-related VOC signatures.

This approach addresses the main translational gap in the field: promising VOC candidates exist, but robust stress estimation requires standardized sampling, validated composite profiles, and real-world testing under controlled confounder conditions.

Testing the AMUSENS Breath Sensor for Stress Detection: Experimental Approach

Building on emerging evidence that breath composition changes under psychological stress, this task investigates whether the AMUSENS multipixel breath sensor can capture such stress-related changes. Stress will be induced in a controlled laboratory setting, with biosignal-based wearable sensing enhancing and complementing the ground truth for statistical evaluation of breath-extracted features.

A small cohort of healthy volunteers will be recruited following relevant ethical approvals. All participants will provide informed consent prior to taking part, ensuring full awareness of the experimental procedures and their right to withdraw at any time. Stress will be elicited in a controlled laboratory setting using well-established cognitive stressors (e.g. PASAT, driving simulation), validated in prior stress research literature.

Reliable label assignment is a key methodological consideration. Three complementary sources are combined supporting robust and reliable stress state labelling:

1. Task-based labels: stressed or non-stressed status assigned based on experimental phase (stress task vs baseline)
2. Physiological labels: continuous, objective stress state estimation from PPG/GSR wearable sensing
3. Self-reported labels: post-task interviews capturing perceived stress level

Breath-extracted features are compared between stressed and non-stressed instances using appropriate statistical tests. The primary outcome is whether the AMUSENS sensors capture statistically significant differences in breath composition between the two states, establishing the foundation for future model-based approaches. An additional objective is the creation of a dataset of correlated exhaled breath measurements and stress state labels, intended as a resource for future research within and beyond AMUSENS.

Expected benefits & next steps

The human-centred research conducted until now through surveys with experts and co-design workshops with end-users provides a grounded rationale for the stress-estimation use case and its relevance within the broader AMUSENS roadmap. Across the survey and co-design activities, the stress scenario emerged as one of the most widely endorsed application for the breath analysis sensor, surpassing both metabolic tracking and respiratory infection detection in terms of participant preference. Workshop participants consistently described it as the most relatable and personally meaningful scenario, valuing its potential to help individuals understand and manage their daily stress load.

A central benefit anticipated from this work is the opportunity to frame the sensor as a preventive and empowering tool. The evidence gathered shows that, for wellness-oriented applications such as stress monitoring, a majority of participants preferred self-monitoring over professionally assisted use. This preference points to a low-barrier adoption pathway, provided that the device offers the accuracy and interpretability that users require. When accuracy is assured and results are clearly communicated, users are willing to engage independently and regularly. For stress estimation, this translates into a sensor that can support everyday wellbeing management without requiring clinical intermediation at every step.

Findings underscore the importance of multi-source, triangulated approach: participants in the co-design sessions indicated that they trusted results more when different data sources converged and when the system could explain the basis of its outputs. Alongside these anticipated benefits, a set of conditions that must be addressed for the technology to achieve its potential. Data privacy emerged as the most significant adoption barrier across all breath analysis activities, with participants expressing strong concern about how personal health data would be managed, stored, and shared. Any commercial or opaque use of data was categorically rejected, and institutional affiliation with trusted healthcare or research bodies was seen as a critical trust enabler. These findings directly inform the next steps for the stress estimation use case. Accuracy and reliability remain the non-negotiable foundation: users across all activities confirmed that measurement precision is a universal, baseline requirement — independent of their level of technical expertise or prior experience with similar devices. Equally, immediate and interpreted feedback ranked as a core expectation: participants expect clear, actionable health insights. In the context of stress estimation, this means the system must be capable of translating breath composition patterns into meaningful, proportionate outputs that users can understand without specialist knowledge.

The **next phase** of work will therefore focus on three complementary directions. First, executing the controlled experiments with healthy volunteers. Second, engaging the stakeholder groups identified to validate result interpretability and refine technical specifications. Third, feeding the findings back into the multi-pixel sensor development activities, ensuring that the stress estimation use case contributes concrete, empirically grounded input to the functional and technical requirements that will shape the final platform.

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