VOCNEA: Sleep Apnea and Hypopnea Detection Using a Novel Tiny Gas Sensor

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ABSTRACT
Sleep breathing disorder is a serious threat to a large share of the population. This paper presents a low-cost, tiny sensor system based on Volatile Organic Component (VOC) sensing for the detection of sleep apnea/hypopnea. We present two designs, discuss wearability aspects and show that the sensor works similar to gold standard Polysomnography (PSG).

ACM Classification Keywords
J.3 Life and Medical Sciences: Medical information systems; H.5.m Information Interfaces and Presentation (e.g., HCI): Miscellaneous

Author Keywords
Wearable; Apnea; Hypopnea; Information System; Health

INTRODUCTION AND RELATED WORK
People with sleep apnea repeatedly stop breathing for 10 sec in their sleep. A significant share of the population (24% of men, 9% of woman in the US [2]) is affected. Obstructive Sleep Apnea (OSA) is diagnosed if apnea (breathing suspension) and hypopnea (breathing reduction) occur more than 5 (mild apnea), 15 (moderate) or 30 (severe) times per hour. The gold standard for detection is Polysomnography (PSG), where nasal and oral airflow is measured with pressure transducers (Fig. 1). In sleep laboratories, additional data is recorded (e.g. EEG, EOG, EMG, ECG, pulse oximetry, audio, video), which allows medical practitioners to diagnose the type of sleep disorder. To simply detect breathing apnea/hypopnea, airflow measurements suffice.

Several approaches to detect sleep apnea have been published, using blood oxygen level sensing, mobile ECG, thermistors attached to the nose, wave reflection changes (e.g. sonar, radar, depth video), change of chest volume, Peripheral Arterial Tonometry and combinations thereof. Mobile devices (e.g. Somnapatch) measure only nasal respiration. Accuracy ranges from 50-98%, depending on factors such as used equipment (from smart watches to medical devices) and evaluation methodology (see [3], [1], [5]). These approaches are either uncomfortable (e.g. PSG), non PSG-like precision (e.g. Smartwatch, chest belt (moving while sleep), sensor mat) or have restrictions regarding use (e.g. sonar, radar with multiple persons in a room).

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VOCNEA DEVICE WORKING PRINCIPLE
In contrast to previous work, our goal was to measure exhalation of air *directly* and not via an indirect indicator. This is similar to the airflow measurements in gold standard PSG. In contrast to PSG, our design goal was a tiny and cheap device that provides an indication for a patient using a simple-to-use system, but not to develop a replacement for sleep lab examination. Still, it should be capable of calculating the Apnea-Hypopnea Index (AHI) precisely without requiring a nasal cannula or face-covering mask.

VOCNEA (VOC Apnea and Hypopnea Detection) is implemented as a tiny "electronic" patch. The measurement principle is based on VOC (Volatile Organic Compound) gas sensing. During exhalation, the VOC concentration constantly rises, whereas it immediately drops while inhaling when gases mix with the surrounding air. The VOC background in ambient air is normally below 10 ppb and will not rise over 1 ppm even in highly polluted indoor environments (e.g. due to toxic furniture or painting exposure) [4]. Human breath contains ~2 ppm VOC (ammonia, methanol, ethanol and other volatile organic compounds) due to biological processes. Thus, sensing the difference between breath and background VOC is a clear and simple method for supervising human breathing.

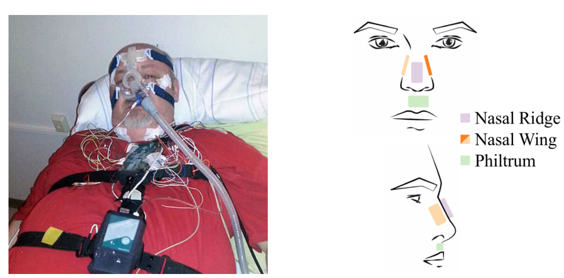

Figure 1. Left: A sleep lab setting with PSG airflow measurement and other sensors (image CC BY-SA 3.0 Wikimedia Commons/Halicki). Right: Potential attachment points for the VOCNEA device.

DESIGN AND WEARABILITY
According to wearability constraints [6], there are two possible positions for the sensor: around the chest or mouth/nose. For

VOC only the area around the nose/mouth is useful. Weight and size constraints for this area [6] restrict a device to less than 200g and much less than 20mm. We started by designing four options for attachment: Nasal ridge (right, left), nasal wing or philtrum (Fig. 4). Electronics are integrated into a patch of tape (Fig. 3). The sticky side of the patch is attached to the skin at 4 possible positions as depicted in Fig. 1 (right). Positions were tested in a small study with 8 subjects on the street (random sample of convenience; 50% female, age 21-54 (mean 32), four eyeglasses wearer). They had to stick the patch mockup to given locations and rate the relative comfort as rank (1,2,3) and overall comfort (very comfortable to very uncomfortable). Candidates show a clear preference for nasal wing followed by nasal ridge, rating them as comfortable or very comfortable to wear (Fig. 2). The design consequence was that only the tiny VOC sensor is attached on the most sensitive philtrum with a cable/flex board connecting to the battery and main electronics on the nasal wings.

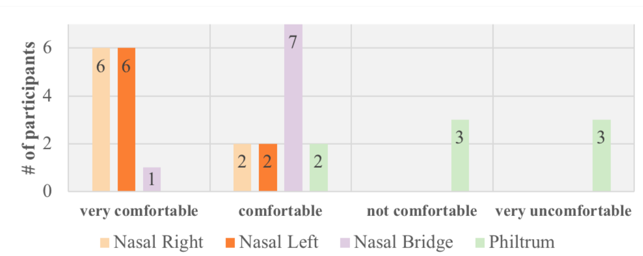

Figure 2. Wearability comfort by position

VOCNEA DEVICE TECHNICAL DESIGN

We conducted a 2-step prototyping process, with a proof-of-concept phase in between: In the first phase, off-the-shelf modules were used, and after design adaption, an integrated flex-board for unobtrusive integration into a standard patch was assembled. Technical basis is the Bosch BME680 ultra-low power gas sensor module (12mA with 2.5 Hz sampling freq.). It contains a VOC, temp. and humidity sensor (for calibration), analog and digital circuitry in a tiny package (3x3x1mm) and can detect VOC reliably with high precision (~0.02ppm).

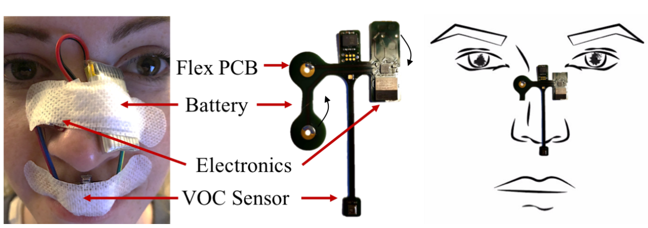

Figure 3. first (left) and second (right) phase prototype.

The overall system consists of a BLENano2 module for sending the measurement to a smartphone that calculates AHI. and a LiPo rechargeable battery. Power management is done by the BLE nano module. After proof of concept, a novel device has been designed based on the same electrical components but using an integrated 0.3mm thick Flex PCB (Fig. 3 right) as the basis for electronics and the connection between the sensor, battery, and electronics. The 2nd prototype weighs 2.1g (<1mg at philtrum) excluding patch. The size is 40x50x5mm outline. Electronics are PU-coated (1µm) for environmental protection. A single piece BOM is 20€(BME680:8€, BLE-module nRF52832: 9€, LIR2450: 3€) plus FlexPCB. The time of battery operation is >8h.

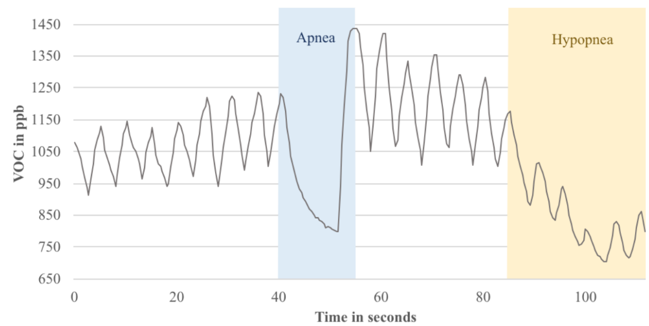

Figure 4. Graph for sleep disorder detection (x-axis: time [s], y-axis: VOC [ppb]). Apnea event marked blue, hypopnea yellow.

RESULTS AND OUTLOOK

Fig. 4 shows a typical sleep disorder detection. Since breathing is a periodical process, we employed a spectral analysis on moving time intervals of 30s. The spectrum shows a clear breathing peak with a period of 5-8s. Apnea is detected if this peak does not occur. Hypopnea is detected if it gets blurred or its amplitude falls below a given (relative) threshold. In general, this method allows for on-the-fly calibration via anomaly detection. Differences between mouth/nose breathing are not significant. As expected, our tests with 2 subjects yielded a 100% detection rate of apnea and hypopnea events. Future designs and tests will be done by a lab certified for medical-grade devices, including a long-term comparison study with gold standard PSG.

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