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# Wearable Patch for Mass Casualty Screening with Graphene Sensors

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***Abstract*—Wearable sensors are reaching maturity, at the same time as technologies for communicating physiological data and those for analyzing massive amounts of data. The combination of the three technologies invites for applications in mass screening of personal health through smart algorithm deployment on data from wearable patches. We propose and present an architecture for a wearable patch to be used in mass casualty emergency situations, or for hospital bedside monitoring. The proposed patch will contain multiple sensors of physiological parameters. We propose to create respiration and heartbeat sensors made of laser induced graphene. We show that graphene on flexible substrates can be utilized in conjunction with the Python heart rate analysis toolkit - HeartPy to reliably acquire physiological data from human subjects.**

***Keywords—wearables, graphene, Python, sensors, electronics***

## I. INTRODUCTION

Wearable sensors are a growing field of research, with applications in telehealth [1], fitness tracking [2], and mass casualty incident management [3]. Various forms of wearable sensors of physiological parameters have been developed, such as patches [4]–[7], bands [8]–[10] or watches [11]. Although wearable sensors have been made to monitor numerous different physiological parameters, such as blood pressure, heart rate, ECG, sweat composition, and respiration rate and volume, monitoring several different parameters with the same device would be of interest for severely ill patients and for use in emergencies. In situations where patients suffer from life-threatening conditions, it is of vital importance to continuously monitor respiration, heartbeat, blood pressure and ECG. We propose to create a device that contains multiple sensors integrated in a wearable patch, connected to power and communication modules, paired with advanced data analysis based on artificial intelligence, as depicted in Figure 1.

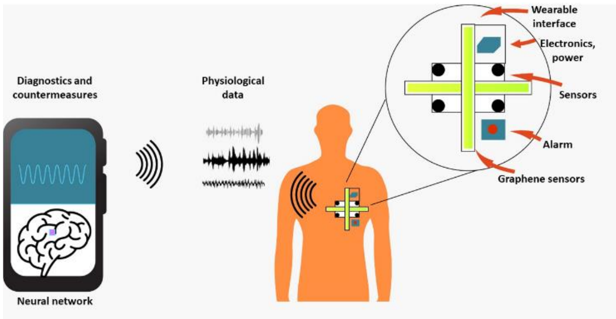


Figure 1: A sketch of the proposed telehealth monitoring system.

As steps towards this goal, we developed sensors for heart rate and respiration monitoring based on the novel material graphene [12].

The paper is organized as follows. In Section II we discuss the background of graphene, with particular focus on laser-induced graphene sensors. We also discuss commercially available wearable respiration and heartbeat sensors, including their advantages and limitations. We propose a wearable patch that contains graphene sensors for monitoring several physiological parameters at once. In Section III we describe the fabrication of graphene sensors, their use for physiological parameter monitoring, and signal analysis using the HeartPy module, followed by conclusions in Section IV.

## II. BACKGROUND AND STATE OF THE ART

The discovery of graphene [13] has caused a research flurry, due to its unique and favorable electronic, optical, chemical and mechanical properties. The material is abundant, thin, flexible, electrically conductive, with a possibility to tailor its chemical reactivity by geometry and functionalization. Various embodiments of graphene sensors have been made for respiration monitoring [14]–[18]. Most recently, laser-induced graphene (LIG) has emerged as a platform for sensors that can be made in custom shapes and dimensions with a facile fabrication process [19]. The use of LIG for respiration monitoring has been demonstrated [20]–[22]. We propose to make use of LIG respiration sensors as a viable technology that is competitive to state-of-the-art respiration monitoring technologies, both on the market and in development.

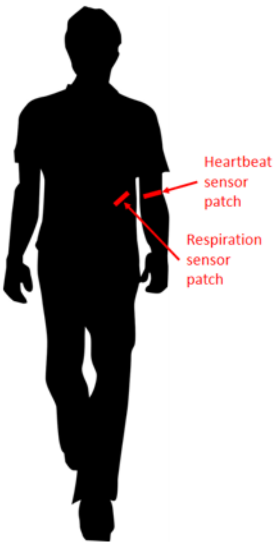


Figure 2: Sketch of the graphene sensor placement for respiration and heartbeat monitoring.

There are few scientific and commercially available solutions to monitor human respiration. One notable technology that has potential for use in wearable respiration sensors is piezoresistive thin films. The technology has been utilized in conjunction with a Bluetooth integrated system, as a standalone wearable respiration monitoring system [23]. The system can simultaneously measure both respiration rate (if only one sensor is attached to the body) and volume (if two sensors are attached to the body) with high fidelity. The standalone nature of the system, coupled with low invasiveness, is prospective for monitoring respiratory disease in real time and over extended periods. However, the piezoresistive sensors have a complex structure, requiring special laboratory conditions for fabrication. There are also a number of commercially available piezoresistive thin film products that can be utilized as components of such a wearable device.

Another technology that has been demonstrated in academic research is based on the triboelectric effect [24]. The solution makes use of a multilayer structure that has triboelectric properties. The structure is attached to a specially designed belt which is worn around the abdomen. As the wearer inhales and exhales, the belt stretches, pulling on the triboelectric structure. Electrodes connected to the structure are used to detect compression and strain due to respiration. The data is transferred wirelessly by connection with a Wi-Fi module. Advantages of this solution include the ease of fabrication and low cost, as the structure makes use of widely available foil materials such as copper, nylon, and PTFE. Also, the solution has been shown to have little interference from wearer activity, such as walking and standing up. Disadvantages include the belt format, which is restrictive and may not be applicable in emergency situations.

Aside from these academic research results, several solutions exist on the market or in commercial development. One of the most complete systems that is directly commercially available is respiBAN [25] — a professionally designed wearable respiration sensor with real-time acquisition and high respiration and motion data performance. The respiBAN has data-logging capabilities, allowing out-of-the-lab signal acquisitions without needing a permanent Bluetooth connection with a computer. It allows data acquisitions with up to 16-bit resolution at up to 3000 Hz sampling rate and continuous data streaming via Bluetooth for ten hours. The system houses three accelerometers and an inductive sensor, and the provided desktop software offers the option to export the raw signals for further analysis, as well as real-time visualization. Additional input/output ports are available for connecting other sensors, with the same company offering ECG, PPG, body temperature, and other sensors of physiological parameters that are compatible with the system. As with the solution based on the triboelectric effect, one disadvantage is that the belt is necessary for respiration measurement. A second disadvantage is the price, coming at ~ 2,000 EUR per piece.

RESPA [26] is a respiration sensor designed for fitness. The device has the shape of a miniature clip-on box that can be attached to the collar of a sweatshirt. The box can contain, apart from the respiration monitor, a microphone, motion sensor, or elevation sensor. All the sensors connect wirelessly to an app installed on the wearer's smart portable device. The app is geared towards fitness monitoring, tracking parameters such as ventilatory threshold. At the moment of writing it is not clear whether this solution is fully commercially available. There are several disadvantages to this solution, including the fact that there is no local storage option (the wearer's smartphone must be nearby during exercise, which most amateur and professional athletes will not agree to), and that the app does not provide access to the raw data files for custom analysis.

The wearable respiratory monitoring system from Resmetrix Medical [27] is geared towards detecting respiration abnormalities associated with conditions such as asthma, Chronic Obstructive Pulmonary Disease (COPD), or COVID-19. This product is designed to provide early warnings of acute episodes, alerting patients and their doctors. Also, real-time monitoring and connecting to a smartphone is available. Resmetrix makes use of a proprietary AI-powered algorithm that analyses patient condition and progress. The device comes in the form of a patch that is attached to the chest. As many other solutions, this one is not available for commercial purchase at the moment of writing, and it also does not seem to offer user access to the raw data for custom analysis.

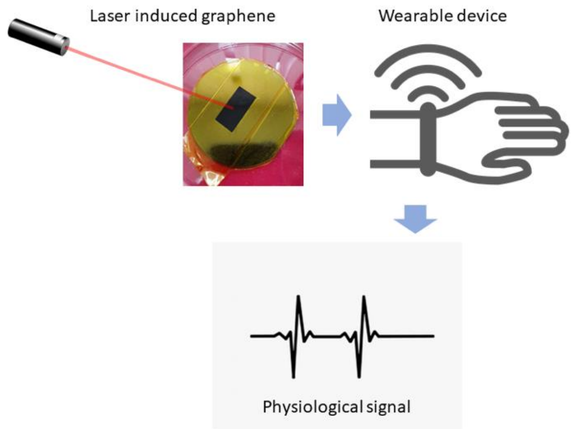


Figure 3: The process of making laser induced graphene, producing a wearable sensor, and obtaining physiological parameter data.

An athletic wearables company, Sweetzpot, makes a device (FLOW) to measure oxygen intake from breath [28]. Nevertheless, the device is not commercially available, and the performance or usage methodology are not clearly indicated for this device.

There are also solutions that are specialized for certain applications, such as the iBreve [29], which tracks breathing, activity and stress levels. The device is geared towards "achieving calmness" and is paired to an app that trains the user for relaxed breathing. Such specialized devices are not compatible with use in other case scenarios because they most commonly do not let the user directly access the data, and are designed with limited use in mind.

Our proposal is to make LIG-based sensors that will independently measure heartbeat and respiration. This can be performed by attaching LIG sensors to two different parts of the body, as in Figure 2. A sensor attached to the forearm, across the median cubital vein, can detect heartbeat as the vein pulses. The LIG acts as a flexure sensor, employing the piezoresistive property of LIG on a flexible substrate. LIG has been used before to measure heartbeat and even ECG [22]. The same physical principle can be utilized to detect respiration, when the sensor is placed on the person's ribcage. As the person breathes, the strain across the sensor changes, which causes changes in the measured resistance which are proportional to chest volume changes. The LIG sensor can be made to be stand-alone, attached to a portable battery supply and a communication module, similar to what has been shown with other, more complex sensors [23].

In a second iteration, the two different graphene devices can be integrated in the same patch that could be used to monitor both respiration and heartbeat simultaneously. It is likely that advanced signal processing would be necessary in that case, in order to filter out the heartbeat signal which will most likely be weak when measured on the chest.

## III. Experiments and discussion

We produce laser-induced graphene in a similar manner as described before [19]. LIG was produced by scanning a CO2 laser beam across the surface of polyimide tape. The laser used was a DBK FL-350 with maximum power of 60 W, with power set to 20%, scanning speed 900 mm/s, and resolution of 600 DPI. The devices were formed by laser-writing LIG in the shape of rectangles with dimensions 10x20 mm. Electrical contacts were made to the LIG by attaching wires with silver paste at the ends of the device, or by attaching conductive copper tape. Material analysis, including Raman spectroscopy, scanning electron microscopy, electron diffraction spectroscopy, and Fourier transform infrared spectroscopy confirms the presence of graphene, with a level of oxide depending on the laser illumination conditions. Graphene devices were attaching the adhesive side of the polyimide tape to an adequate place on a subject's body. For heartbeat measurements, the sensor was attached to the cubital vein on the forearm. For respiration monitoring, the sensor was attached to the ribcage. Wires that are connected to the sensor were connected to a Keithley 2450 SMU, which was interfaced to a desktop computer. Measurements were performed in the constant current mode with current set to 1 mA, and the voltage was measured over a period of several minutes. As a reference, the heart rate was measured with a free app installed on a smartphone. The reference respiration rate was obtained by manual counting. The process flow of the experiment is shown in Figure 3.

In the case of respiration monitoring, there was immediate and good agreement between the respiration rate measured with our sensor and that acquired by manual counting. In the case of heartbeat, the data was processed with the HeartPy module for Python [30]. The HeartPy process function allows different pre-processing options to clean up signals, including finite impulse response (FIR) filtering and outlier detection. The filtering was necessary when the signals contained noise due to subject motion or other external parameters. This function requires the input signal and frequency as input parameters and returns 13 different signal features, including bmp which represents the heart rate. It also returns the feature breathing rate in Hz which can be used for comparison with the sensor respiratory rate. Preliminary results indicate that both respiration and heartbeat monitoring are performed well by our LIG sensor, which is lightweight, unobtrusive, flexible, and inexpensive. An example of the value of physiological parameters measured in this way, returned by HeartPy, is shown in Table 1. The algorithm measures a heart rate of 81.50 bpm, which is in agreement with that measured during the experiment with the reference app.

| | | | |
|---|---|---|---|
| ibi: 736.2 | sdnn: 153.3 | sdsd: 109.9 | rmssd: 214.0 |
| pnn20: 0.917 | pnn50: 0.833 | hr_mad: 122.45 | sd1: 149.4 |
| sd2: 154.0 | s: 72295 | sd1/sd2: 0.970 | br: 0.20 |

Table 1: Parameters returned by HeartPy. Ibi: inter-beat interval, sdnn: standard deviation of intervals sdsd: standard deviation of successive differences between adjacent R-R intervals, rmssd: RMS of successive differences between adjacent R-R intervals, pnn50/pnn20: proportion of differences greater than 50ms / 20ms, hr_mad: median absolute deviation, Poincare analysis (sd1, sd2, s, sd1/sd2), br: breathing rate in Hz.

## IV. Conclusion

The proposed graphene sensors are a good solution for wearable monitoring of physiological parameters such as heartbeat and respiration. Combined with the Python toolkit HeartPy, the signals can be processed in a satisfactory level as the existing commercial Heart rate and Respiratory rate sensors. Even more, several sensors integrated into a single wearable smart-patch, together with power and communication modules, and coupled with smart algorithms are a very promising solution for rapid and continuous mass casualty monitoring [31]. A drawback of using LIG sensors is the large accompanying noise in the signal, which needs to be removed.

## V. ACKNOWLEDGMENT

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