Monitoring Drivers' Ventilation Using an Electrical Bioimpedance System: Tests in a Controlled Environment

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Abstract. As improving road safety is one of the first aims in the automotive world, several new techniques and methods are being researched in recent years. Some of them consist of monitoring the driver behavior to detect non-appropriate states for driving, *e.g. drowsy driving or drunk driving*. Usually, the appearance of these non-appropriate states is related to changes in several physiological parameters. This work is divided into two main parts. The first one presents an electrical bioimpedance system capable of monitoring the ventilation using textile electrodes. Apart from describing the system, in this part some tests done in a controlled environment are also shown. In the second part of this paper, an enhancement of the system is described and checked using a patient simulator.

Keywords: Bioimpedance · Ventilation · Textile electrodes · Textrodes · Automotive

1 Introduction

According to [1], most of traffic crashes occur during the appearance of non-appropriate states for driving, *e.g. drowsy driving or drunk driving*. Therefore, apart from improving the vehicle performance, automotive companies are also focused on monitoring the driver behavior. To achieve that, several systems are being researched. These systems can be mainly classified on three types. The first type is based on driving performances *i.e. unintended lane departures, steerings and brakes*. The second one is based on camera systems that detect the percentage of eye closure (PERCLOS), head movements and blinkings, as described in [2]. Finally, the third type is based on recording biomedical signals. In [3], signals from electroencephalography (EEG), electrocardiography (ECG) and heart rate variability (HRV) are used. On the other hand, electroocculography (EOG) and ventilation are used in [4] and in [5], respectively.

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Focusing on the third type, regardless of the physiological parameter to be measured, any system should fulfill three requirements at least. Firstly, the system must be capable of recording signals in a very noisy environment. In a vehicle, there are not only artifacts produced by the car engine but also artifacts caused by other reasons like body motion or the state of the roads. As for the second feature, a long-term monitoring system is required because the appearance of non-appropriate states while driving is a slow process. Moreover, the system should also be non-invasive and non-annoying to allow driving as comfortable as possible. Therefore, the use of hospital devices is not recommended and the design of new biodevices is required.

In the first part of this paper, a new biodevice suitable for automotive applications is shown. This device consists of an electrical bioimpedance (EBI) system capable of monitoring the ventilation, and also the heart rate, using textile electrodes placed on the steering wheel and also on the car seat. In addition, to check the device, two kinds of tests are done. In the first one, the signal obtained by the EBI system is compared to one which has been recorded by a commercial thoracic band. In the second group, the system is checked according to several parameters such as the electrode configuration, the frequency of the injected signal or the clothing thickness.

In addition, there is also a second part in this work where an enhancement of the EBI system is proposed. Finally, this improved system is also checked using a patient simulator.

2 System Description

As mentioned above, the biodevice is based on an EBI instrumentation system. The proposed system and also its enhancement are shown in Fig. 1. It is worth mentioning that both systems are designed following the guidelines described in [6]. Comparing both block diagrams, three main blocks are observed in both systems: Signal Generator (GEN), Analog Front-End (AFE), and Demodulator & Acquisition (DEM). In addition to these main blocks, there are also several textile electrodes placed on the steering wheel and the car seat.

The main difference between both systems is in the AFE block. The enhanced system adds a multiplexing-demultiplexing stage capable of selecting the best electrode configuration to measure in order to allow measuring when the driver is not in contact with all the electrodes, e.g. with only one hand in the steering wheel.

2.1 EBI System

Briefly, the EBI system works as follows. The voltage-driven signal generated by the generator is converted into a current-driven signal. Then, this current-driven signal is injected into the driver's body using a pair of textile electrodes. Using the same, or other, pair of textile electrodes, the voltage drop due to the injected current is measured. Finally, in the demodulation and acquisition

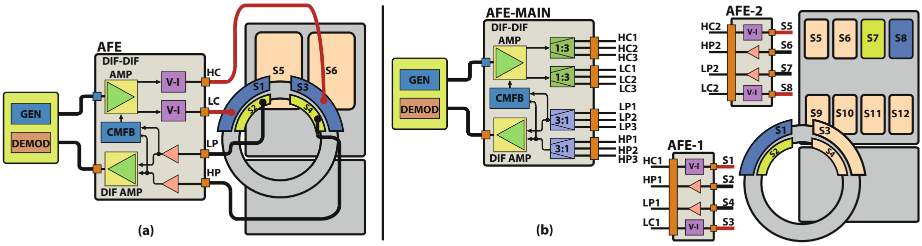

Fig. 1. Block diagrams of the EBI device (left) and the enhanced one (right). In both cases, whereas electrodes connected to (LC) and (HC) are the driving electrodes, the ones connected to (LP) and (HP) are the sensing electrodes.

block, the value of the impedance is obtained. It is worth mentioning that changes in the value of this impedance are related to changes in the gas-fluid ratio during the inhalation-exhalation process, i.e. the ventilation.

Signal Generator. Although it can take several forms, e.g. from a simple linear oscillator or digital clock to a Direct Digital Synthesizer (DDS) able to produce sinusoidal waveforms or arbitrary waveforms in a wide range of frequencies and amplitudes, [6], in the present system, two different kinds of signal generator are used. In the case where the overall system is checked, the excitation signal is an adjustable amplitude single tone waveform of 62.5 kHz generated by a microcontroller, PIC18F1320. In the other case, if only the proper behavior of the AFE is checked, a sine wave with an adjustable frequency is generated using a PXI solution by National Instruments.

Analog Front-End. Once the signal is generated, this is sent to the AFE. Basically, the AFE consists of two main stages: the current injection stage and the voltage sensing one. In the first stage, the excitation signal is sent to a differential-differential amplifier, AD8138, in order to have a differential excitation signal. However, instead of appling directly the voltage of these two outputs to the driving electrodes, each one is used as an input of a voltage-current (V-I) converter based on a second-generation current conveyor (CCII). Thus, the V-I converter acts as a voltage-controlled current source (VCCS), [7]. In this way, using current driving instead of voltage driving, a current limiting mechanism is achieved and the possible nonlinearities are also reduced. So the guidelines of safety risks provided by the IEC-60601-1 standard can be fulfilled. Furthermore, using differential-floating excitation helps reducing the effect of electrode impedance mismatch effect.

In the voltage sensing stage, a differential to single ended voltage conversion is done by a wideband differential amplifier. However, before this conversion, the voltage difference between the pair of sensing electrodes is measured by a pair of high-impedance buffers. These buffers are used because of their input impedances are higher than the input impedance of the differential amplifier, allowing to measure the common-mode voltage without disturbing the signal quality.

In addition, as much in the current injection stage as in the sensing one, filter capacitors are also required to avoid the flow of the Direct-Current (DC) to the body. Furthermore, there is also a Common-Mode Feedback (CMFB) stage in the AFE which is useful to reduce the effect of high electrode mismatch. Finally, it is also worth mentioning that active shielding is also used to reduce the capacitive effect of coaxial cables, interferences and crosstalk.

Textile Electrodes. As the electrodes should be as non-invasive and non-annoying as possible for the driver, using standard metal electrodes seems to be not the better option. In addition, as cited in [8], during long-term monitoring, the hidrogel used with this kind of electrodes can cause irritation and allergy problems.

So, in this system instead of using standard metal electrodes, electrodes made of textiles, also called textrodes, are chosen. In this way, not only irritation and allergy problems are solved but also a higher comfort for the driver is achieved. However, the main drawback of the textrodes is that the electrode impedance shows a strong capacitive behavior, [9]. In addition, as the textrode is not directly in contact the skin, this capacitive behavior depends on the exerted pressure and factors related to the clothing of the driver like material, thickness or number of layers, [10]. Furthermore, in order to cope with the impedance of the electrodes, to use a different pair of electrodes to the driving and the sensing stage is required, i.e. to use the four-wire technique, [11].

Demodulation & Acquisition. Two different demodulation techniques are used. In the case where the overall system is checked, a switching demodulator is used. This switching demodulator is based on a switch controlled by the same square signal generated by the microcontroller. Furthermore, after the switching demodulator, the signal is driven to a third-order Sallen-Key low-pass filter (LPF). Then using this output signal from the LPF, the measured voltage is acquired. In addition, by using a high-pass filter (HPF) and a basic circuitry, the relative variations of the measured voltage are also amplified and acquired. These voltage variations should be amplified before recording because of their low amplitude and also the poor accuracy that the 10-bit Analog-to-Digital Converter (ADC) of the microcontroller can provide. Later the acquired data are sent from the microcontroller to a computer by a mini USB-Serial UART development module. Finally, the impedance value is estimated using a LabVIEW application.

The second demodulation technique is an In-phase & Quadrature (IQ) demodulation. Using the PXI solution, the real and imaginary part of the measured signal are obtained. Later, the magnitude and the phase of the impedance are estimated using a LabVIEW application.

2.2 Enhanced System

As mentioned previously, the enhanced system adds a multiplexing-demultiplexing stage in the AFE block. In this way, instead of fixing the electrode configuration during the monitoring, the system is capable of changing automatically to the best electrode configuration. To achieve this, a pair of 1-to-8 multiplexers (MUXs) and 8-to-1 demultiplexers (DEMUXs) are added in the sensing and the injection stages, respectively. Thus, in the injection stage, previously to the voltage-current conversion, the pair of driving electrodes is chosen. In the same way, in the sensing stage, the two inputs to the wideband differential amplifier are chosen by the pair of 8-to-1 MUXs which are connected to the high-impedance buffers. Note that in the enhanced system, the AFE block is divided into several boards instead of being only one board. In that way, as the current-drivers and voltage buffers are closer to the textile electrodes, i.e. shorter wires, the system is stronger in front of parasitic effects.

It is also worth mentioning that an integrated circuit (IC), AD5933 by Analog Devices, is chosen as solution in the generation and demodulation blocks. Basically, AD5933 is a low cost, system-on-chip high precision impedance converter system solution that combines an on-board frequency generator with a 12-bit, 1 MSPS, analog-to-digital converter (ADC). Furthermore, the signal sampled by the on-board ADC and a discrete Fourier transform (DFT) is processed by an on-board DSP, [12]. Finally, the real and imaginary values of the estimated impedance are sent to a LabVIEW application using the I2C protocol.

3 Methods

A set of tests is done to check the proper functioning of both systems. It should be reminded that any test is done in a controlled environment where no artifacts due to engine vibrations or the state of the road are present.

3.1 EBI System

To check that the EBI system works properly, several measurements are carried out. These measurements can be classified into three groups according to:

- Comparison to a reference signal
- Configuration of electrodes, i.e., the placement of the driving and sensing electrodes in the car seat and steering wheel
- Influence of the thickness of clothing

Comparison to a Reference Signal. In this group, several subjects are monitored by the designed EBI system and also by a commercial device made by BIOPAC Systems. The commercial device acquires the ventilation signal at a sampling frequency of 1000 samples per second using a piezoresistive thoracic band. Then, this signal is used as reference signal to verify the correct operation of the designed device.

About the EBI system, in this case, only the proper behavior of the AFE is checked, i.e. the PXI solution is used in the GEN and DEM blocks. Thus, a single frequency sine wave of 300 kHz is generated as excitation signal and the measured signal is sampled at 25 samples per second in the DEM block. The reasons to apply a frequency of 300 kHz are mainly two. First, using the PXI solution, the hardware limitation is less strong as the one imposed by the PIC solution. Second, the higher the frequency, the better response of the system is achieved because of the capacitive behavior of the textile electrodes.

It is worth mentioning that the system is considered to work properly if the inhalation-exhalation ratio is the same that the obtained by the commercial device.

Configuration of Electrodes. In the second group of measurements, the overall system, i.e. a single tone at 62.5 kHz as excitation signal and switching demodulation, is checked according three differents configurations according to the placement of electrodes. It is worth mentioning that the protocol done in all measurements consists of a two-minute monitoring and, around the last 30 s, five deep breathing are taken.

The first one is the steering wheel-steering wheel configuration. In this case, whereas a driving electrode and a sensing electrode are in contact with the right hand of the driver, the other pair of driving-sensing electrodes are in contact with the left hand. The second configuration is the steering wheel-back seat configuration. In this, whereas a driving and a sensing electrode remain in the steering wheel, the other driving and sensing electrode are moved to the upper half of the back seat. The last configuration tested is the back seat-back seat configuration. Here, whereas a pair of driving-sensing electrodes are in the left electrode of the back seat, the other pair is in the right electrode of the back seat. Note, in the back seat-back seat configuration, instead of using the 4-wire technique, the 2-wire technique is carried out because of both textile electrodes on the back seat act as driving and sensing.

Influence of the Thickness of Clothing. Using the same protocol than before, i.e. two-minute monitoring and at the end five deep breathing, and fixing the electrode configuration to the steering wheel-back seat configuration, the ventilation is monitored under certain situations according to the clothes that the subject is wearing. In the best situation tested, the subject is only wearing a thin T-shirt. On the other hand, in worse situations, the subject is wearing over the same thin T-shirt either a thin jacket or a thick sweater.

It should be pointed that as the capacitive behavior of the textile electrodes is strong in these situations, the PXI solution is chosen to be able to use excitation signals with a higher frequency than 62.5 kHz.

3.2 Enhanced System

Due to the enhanced system is only in the first stages of development, the tests are done using a patient simulator, Fluke PS420. Using this device, a rate of a 15 breathings per minute with 3-ohm impedance variations over a 500-ohm baseline is chosen. Under these conditions, the patient simulator is connected not only to the four electrodes placed on the steering wheel but also to the four electrodes placed on the upper side of the back seat. Therefore, during 4 min and 30 s, the ventilation is recorded and, at any arbitrary time, an electrode is disconnected. Furthermore, two 12-second apneas are also simulated at the middle and at the end of the test.

It is worth mentioning that a priority table is allocated to the system. Thus, the steering wheel-steering wheel configuration and the back seat-back seat configuration are the most and the least priority, respectively.

4 Results

As in previous section, the results are discussed based on the two systems.

4.1 EBI System

Comparison to a Reference Signal. As mentioned previously, the signal acquired by the thoracic band acts as a reference to check the signal from the designed biodevice. Thus, the biodevice works properly if the measured signal fits to the reference, i.e. for the same period of time, the exhalation-inhalation ratio is the same in both signals.

For each volunteer, two different configurations are tested. In the upper graphs of the Figs. 2, 3 and 4, as a driving electrode and a sensing electrode are in contact to the left hand, the second driving and the second sensing electrode are placed in the right and left side of the back seat, respectively. On the other hand, in the bottom graphs whereas the electrodes on the back seat remain at the same point, both electrodes on the steering wheel are moved to the right side.

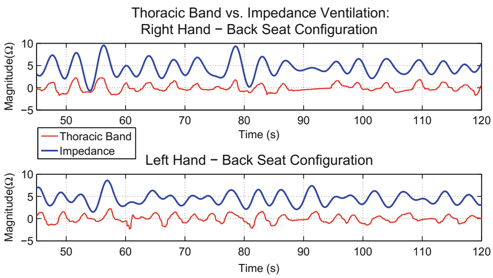

Fig. 2. Comparison between the Thoracic Band and the EBI system for the first volunteer. (Top) Configuration where both driving electrodes are in the right side of the body. (Bottom) Configuration where the driving electrode of the steering wheel is in the left hand and the other driving electrode is in the right side of the back. In both plots, the upper line is related to the bioimpedance device and the bottom one comes from the thoracic band.

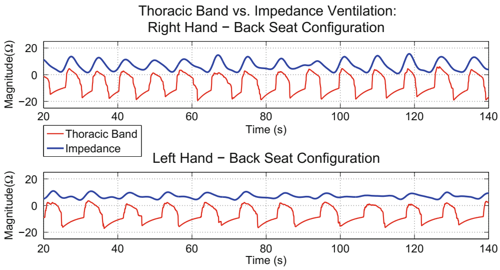

Fig. 3. Comparison between the Thoracic Band and the EBI system for the second volunteer. (Top) Both driving electrodes are in the right side of the body. (Bottom) The driving electrode of the steering wheel is in the left the other driving electrode is in the right side of the back.

Note that for all cases except one (bottom graph in Fig. 4), both signals, from the bioimpedance device and from the thoracic band, match up. The special case can be due to the lack of contact between any textrode and the volunteer.

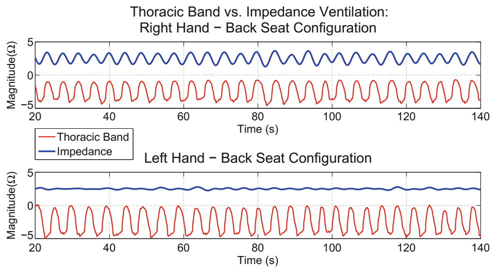

Fig. 4. Comparison between the Thoracic Band and the EBI system for the third volunteer. (Top) Both driving electrodes are in the right side of the body. (Bottom) The driving electrode of the steering wheel is in the left the other driving electrode is in the right side of the back.

Furthermore, whereas the Figs. 2 and 4 show a normal respiration rate, i.e. between 12 and 20 breaths per minute in adults and in normal conditions, in the Fig. 3 a slower respiration rate, around 6–7 breaths per minute, can be observed.

Configuration of Electrodes. In this group of measurements, the influence of the placement of the electrodes in the measured signal is checked. Then, as mentioned in the previous section, three configurations are tested.

As shown in Fig. 5, three signals are plotted. The middle one is the raw signal measured by the EBI system and without processing. Note that this signal is based on two components: a low-frequency component, between 0.1 Hz and 0.3 Hz, and a high-frequency component, over 1 Hz. Furthermore, whereas the lower component is related to ventilation, the higher one is related to the heart rate.

Checking the Figs. 5, 6, 7 and 8, a first issue can be observed. As in Figs. 5 and 7, the high frequency component is noticed easily, in Fig. 8 this component is insignificant. Therefore, it seems to be in contact directly to one hand, at least, is required to obtain the component related to the heart rate.

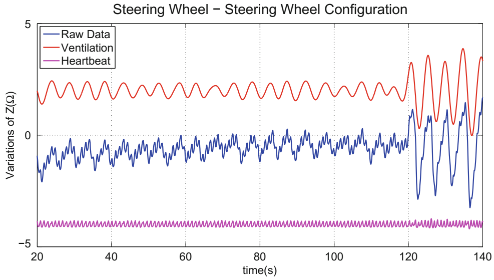

Fig. 5. Steering Wheel - Steering Wheel Configuration. (Middle) The raw data obtained from the bioimpedance device. (Top) Signal related to the ventilation. (Bottom) Signal related to the heart rate.

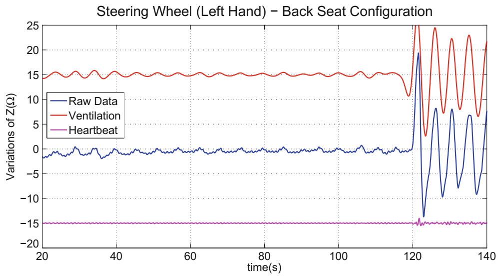

Fig. 6. Steering Wheel - Back Seat Configuration with a driving electrode in the left hand and the other in the right side of the back. (Middle) The raw data. (Top) The ventilation signal. (Bottom) The signal related to the heart rate.

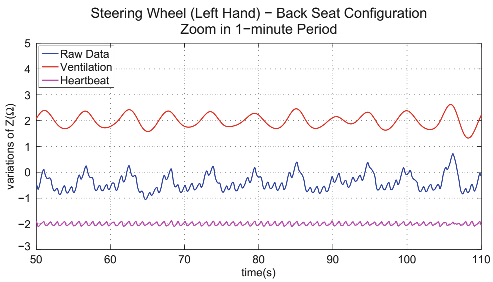

Fig. 7. Zoom in to the Fig. 6 in a one-minute period. (Middle) The raw data. (Top) The ventilation signal. (Bottom) The signal related to the heart rate.

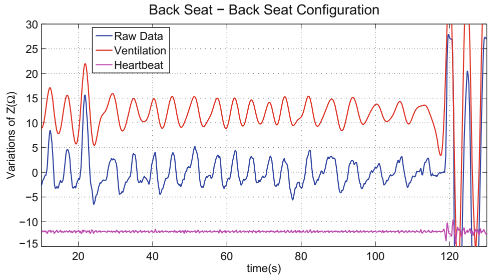

Fig. 8. Back Seat - Back Seat Configuration using a 2-wire measurement technique. (Middle) The raw data. (Top) The ventilation signal. (Bottom) The signal related to the heart rate.

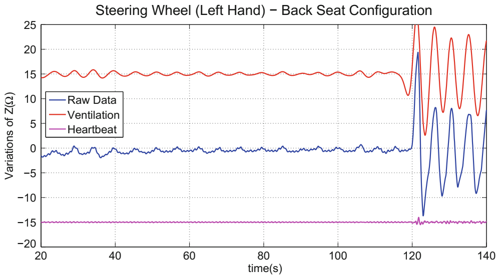

Fig. 9. Steering Wheel - Back Seat Configuration with the driving electrodes in the left hand and in the right side of the back, respectively. The subject is wearing a thin T-shirt made of cotton (100 %). (Middle) The raw data. (Top) The ventilation signal. (Bottom) The signal related to the heart rate.

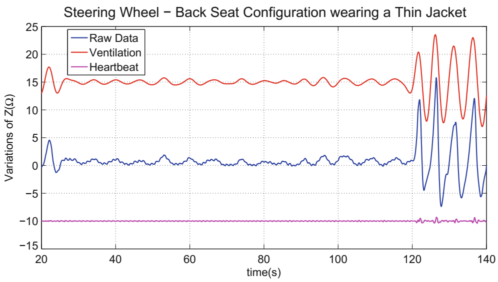

Fig. 10. Steering Wheel - Back Seat Configuration with the driving electrodes in the left hand and in the right side of the back, respectively. The subject is wearing a thin jacket made of polyester (100 %) over a thin T-shirt made of cotton (100 %). (Middle) The raw data. (Top) The ventilation signal. (Bottom) The signal related to the heart rate.

Influence of the Thickness of Clothing. In the last tests, dependencies on clothing are checked. In Fig. 9, applying the previous protocol and the steering

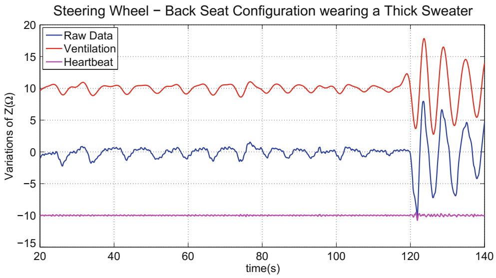

Fig. 11. Steering Wheel - Back Seat Configuration with the driving electrodes in the left hand and in the right side of the back, respectively. The subject is wearing a thick sweater made of woolen (33 %), polyester (27 %), acrylic (27 %) and polyurethane (13 %) over a thin T-shirt made of cotton (100 %). (Middle) The raw data. (Top) The ventilation signal. (Bottom) The signal related to the heart rate.

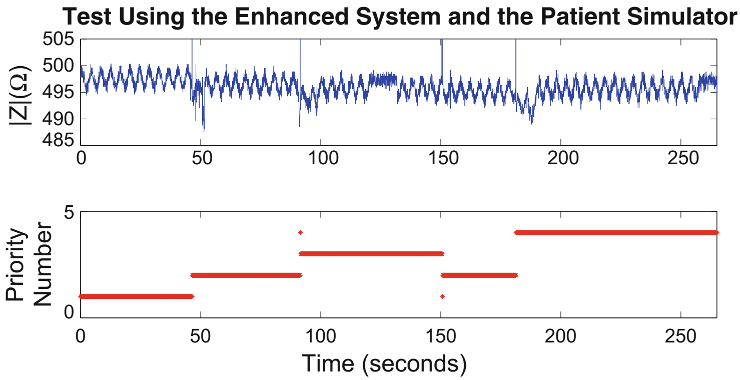

Fig. 12. Test of the enhanced system using a patient simulator. (Top) Ventilation signal acquired without filtering. (Bottom) Priority number of the electrode configuration used during monitoring.

wheel - back seat configuration, a subject is monitored wearing a thin 100 % cotton T-shirt. On the other hand, in Figs. 10 and 11, the subject is wearing over the same T-shirt a thin 100 % polyester jacket and a thick sweater, respectively.

Note that the respiration rate is different in the three figures. Whereas a normal rate of 11 breaths per minute can be observed in Fig. 9, in Figs. 10 and 11, the respiration rate is lower. There seems to be a correlation between clothing and the measured signal. As thicker the clothing, the measured signal is less similar to the reference ventilation signal, i.e. the signal obtained by the thoracic band. Therefore, depending on the clothings, the EBI system could not work properly because of some inhalations or exhalations cannot be monitored.

Table 1. Priority order of the electrode configurations.

Priority	Driving Electrodes	Sensing Electrodes
1	S1–S3	S2–S4
2	S1–S8	S2–S7
3	S3–S5	S4–S6
4	S5–S8	S6–S7

4.2 Enhanced System

Figure 12 shows two plots. Whereas the upper plot is related to the ventilation signal acquired using the enhanced system and the patient simulator, the lower plot shows the priority number according to the electrode configuration described in Table 1.

As observed in both plots, any change of the electrode configuration matches a high value of the impedance magnitude. Furthermore, note that the apneas are done in the second minute and at the end of the test as previously mentioned.

5 Conclusions

As shown in this paper, using an EBI system, signals related to physiological parameters can be monitored. In this particular case, not only signals related to the ventilation are measured but also signals related to the heart rate. However, due to the fact that the use of standard metal electrodes are not recommended, new challenges related to the textile electrodes arise such as the high electrode mismatch or the behavior of the clothing-textrode interface. In addition, testing the bioimpedance system in a real environment is also required. But, in any case, the tests in a controlled environment show a proper operation of the system. This system is capable of monitoring the ventilation signal just like a thoracic band. Furthermore, the system is also able to acquire the signal related to the heart rate.

In addition, although the enhanced system is only in the first stages of development, the automatic selection of the best electrode configuration during monitoring seems to be a solution for the lack of contact between electrodes and the driver. Therefore, this system seems to be a further step to obtain a non-annoying non-invasive biodevice capable of monitoring some physiological parameters in a vehicle environment.

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References

1. Anund, A., Kecklund, G., Peters, B., Åkerstedt, T.: Driver sleepiness and individual differences in preferences for countermeasures. J. Sleep. Res. **17**, 16–22 (2008)
2. García, I., Bronte, S., Bergasa, L.M., Hernandez, N., Delgado, B., Sevillano, M.: Vision-based drowsiness detector for a realistic driving simulator. In: 13th International IEEE Conference on Intelligent Transportation Systems, Portugal, pp. 887–894 (2010)
3. Michail, E., Kokonozi, A., Chouvarda, I., Maglaveras, N.: EEG and HRV markers of sleepiness and loss of control during car driving. In: Proceedings of the 30th Annual International Conference of the IEEE EMBS, Vancouver, pp. 2566–2569 (2008)
4. Lal, S.K.L., Craig, A.: A critical review of the psychophysiology of driver fatigue. Biol. Psychol. **55**(3), 173–194 (2001)
5. Folke, M., Cernerud, L., Ekström, M., Hök, B.: Critical review of non-invasive respiratory monitoring in medical care. Med. Biol. Eng. Comput. **41**(4), 377–383 (2003)
6. Riu, P., Bragos, R., Rosell, J.: Instrumentation for Bio-Impedance Measurements. In: An Anthology of Developments in Clinical Engineering and Bioimpedance, Norway, pp. 225–250 (2009)
7. Bragós, R., Rosell, J., Riu, P.: A wide-band AC-coupled current source for electrical impedance tomography. Physiol. Meas. **15**, A91–A99 (1994)
8. Wheelwright, C.D.: Physiological Sensors for Use in Project Mercury. In: NASA Technical Note D-1082. Washington, D.C. (1962). http://catalog.hathitrust.org/Record/011447015. Accessed 12th April 2012
9. Beckmann, L., Neuhaus, C., Medrano, G., Jungbecker, N., Walter, M., Gries, T., Leonhardt, S.: Characterization of textile electrodes and conductors using standardized measurement setups. Physiol. Meas. **31**(2), 233–247 (2010)
10. Macías, R., Fernández, M., Bragós, R.: Textile electrode characterization: dependencies in the skin-clothing-electrode interface. J. Phys.: Conf. Ser. **434**, 1–4 (2013)
11. Schwan, H.P., Ferris, C.D.: Four-electrode null techniques for impedance measurement with high resolution. Rev. Sci. Instrum. **39**(4), 481–485 (1968)
12. Analog Devices AD5933. http://www.analog.com/en/rfif-components/direct-digital-synthesis-dds/ad5933/products/product.html