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Developing a Mask to Aid Thoracic Surgeons in Assessing Patient Recovery

EEC 136AB

Senior Design Final Report

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Current methods of assessing patients' cardiopulmonary recovery after lung re-sectioning are too involved in both the setup and time required to operate. Therefore these methods are unattractive for thoracic surgeons. This paper explores a solution that addresses this gap. OOCOO is a mobile mask system designed to measure oxygen and carbon dioxide levels in respiration, as well as activity levels. Oxygen, carbon dioxide and activity data is communicated from the mask to an Android Application. The data collected can then be used to more efficiently and effectively determine preoperative risk factors of lung resection patients.

1 Introduction

Current VO2 Max testing requires the ill patients to maximally exercise and entails testing at a certain location. Therefore, current testing is often very cumbersome for patients and doctors. Since VO2 Max testing procedures are very demanding, doctors often do not perform this test as often as they would like for their patients; doctors often estimate the risk when assessing patients without VO2 Max testing. Therefore, a less vigorous solution to pulmonary function testing for lung resection patients needs to be developed. The system (OOCOO Mask) outlined in this paper allows for doctors to more precisely assess patients on their preoperative risk before lung resection surgery and their recovery after.

The mask is a mobile system used to measure trends in the concentration of oxygen and carbon dioxide in a patient's respiration, along with their physical activity. Data from the mask is sent over Bluetooth Low Energy to a smart phone where doctors can view data in real-time through the mobile application. This data can show a correlation between respiration and physical activity intensity in a patient. These correlations can give insight into the pulmonary function of the patient. The data from the mask is an alternative or complement to current VO2 Max testing in prognosis and decision making for lung re-sectioning patients.

2 Background Theory

To select the oxygen and carbon dioxide sensors with acceptable concentration ranges for the mask, it is necessary to know the oxygen and carbon dioxide concentrations in the average human respiration. At rest, humans exhale 3.6% carbon dioxide and 16% oxygen on average. At higher levels of exertion, humans will exhale upwards of 7% carbon dioxide. The atmospheric concentrations of oxygen and carbon dioxide are, on average, 21% and 0.04% respectively.

3 Design

3.1 Sensors

3.1.1 Oxygen Sensor

The oxygen sensor in the mask is a SST LOX-O2 Sensor. This sensor uses fluorescence quenching to detect the changes in oxygen concentration. Fluorescence quenching uses an optical probe that contains an indicator dye sensitive to oxygen. This dye is then excited by an LED light source. The fluorescence emission of the dye decays; however, if oxygen is present, an energy transfer occurs and decreases the flourescence decay. This is known as the oxygen "quenching" the fluorescence. The amount of "quenching" that occurs determines the amount of oxygen present.

This sensor has the oxygen detection range of 0-25%. The human breath is about 16% oxygen, therefore, the 0-25% detection range allows this sensor to detect the oxygen concentration in human respiration. The oxygen sensor has a relatively short warm-up time of 15 seconds. A short warm-up time is beneficial for the application, since users of the mask will be able to use it immediately on start up. The sensor has an accuracy of +/-2% within the measure value and a sampling rate of once per second, allowing the measurement of proper trends in respiration.

Figure 1: SST LOX-02 Oxygen Sensor

3.1.2 Carbon Dioxide Sensor

The mask uses a MinIR 100% CO2 Sensor. The MinIR 100% CO2 sensor uses Nondispersive Infrared (NDIR) detection. Nondispersive Infrared detection works by using an infrared lamp and infrared light detector. The infrared lamp directs waves of light through a tube filled with air towards an infrared light detector. As light passes through the tube, the CO2 molecules absorb their corresponding wavelength of light while letting the rest of the light pass through. This remaining light is then passed through an optical filter that absorbs every wavelength of light except for the one absorbed by CO2. An infrared light detector then measures this amount of light not absorbed by CO2. The difference between the light radiated from the infrared lamp and the light detected by the infrared light detector determines the number of CO2 molecules in the air inside the tube.

This sensor has high measurement accuracy of +/- 70 ppm +/-5% within the measured value, allowing mask users to observe small variations in CO2 concentrations. The CO2 sensor is refreshed at twice per second to allow the mask to exhibit trends in respiration.

Figure 2: MinIR 100% CO2 Sensor

3.1.3 Accelerometer

The accelerometer tracks the patients' activity. Activity data can be matched with respiration data to correlate exertion levels with CO2 and O2 respiration levels. The accelerometer is used in 2g mode, where the magnitude of the maximum output is at 2 times gravity, or 39.2 m/s^2. The 2g activity data is filtered and placed into 10 different thresholds of activity. Numbers between 0 and 10 are assigned to each threshold of activity, with a 0 corresponding to the lowest level of activity and a 10 corresponding to the highest level of activity.

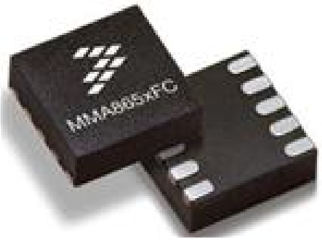

Figure 3: Freescale MMA8652FCR1 Accelerometer

3.2 System Design

3.2.1 Power Analysis

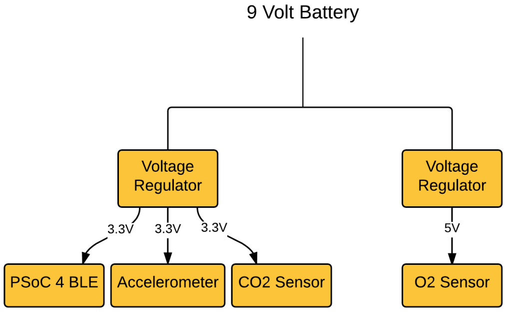

Figure 4: Power Diagram

Component	I_{avg}	V_{avg}
Oxygen	10mA	5V
Carbon Dioxide	1.5mA	3.3V
Accelerometer	0.184mA	3.3V
PSoC	1.7mA	3.3V

Power is supplied by a 9V Battery to allow doctors to easily change the battery in between uses, as commonly done before using medical equipment. The 9V from the battery is regulated down to 3.3V and 5V. Both regulators have an output current of 800mA. The 3.3V regulator output powers the PSoC 4 BLE, Accelerometer and CO2 Sensor, which require 1.7mA, 0.184mA and 1.5mA of current respectively. The 5V regulator powers the O2 Sensor, which requires 10mA of current.

Component	P_{avg}
Oxygen	50mW
Carbon Dioxide	4.95mW
Accelerometer	0.6072mW
PSoC	5.61mW
Total Power	**61.1672 mW**

$$P_{acc} = V_{acc} I_{acc} \tag{1}$$

$$P_{ox} = V_{ox} I_{ox} \tag{2}$$

$$P_{co2} = V_{co2} I_{co2} \tag{3}$$

$$P_{PSoC} = V_{psoc} I_{psoc} \tag{4}$$

$$P_{total} = P_{acc} + P_{ox} + P_{co2} + P_{psoc} \tag{5}$$

$$E_{batt} = 550mAh * 9V = 4950mWh \tag{6}$$

$$Hours = E_{batt}/P_{total} = 81hours \tag{7}$$

The 9V battery has about 4950 mWh. Therefore, each battery should last about 81 hours of continuous run time before it needs to be replaced.

3.2.2 Communications

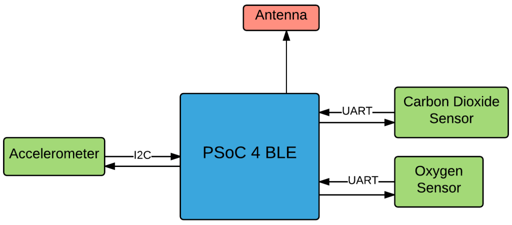

Figure 5: Communications Diagram

The oxygen and carbon dioxide sensors use UART to communicate with the PSoC 4 microcontroller, while the accelerometer uses I2C. Both the carbon dioxide sensor and oxygen sensor output eight bytes of data at a baud rate of 9600.

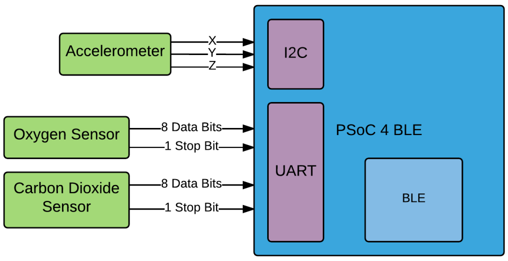

Figure 6: Signals Diagram

The accelerometer is a three axis accelerometer with x, y, and z data available. For this implementation, the accelerometer is configured for 8-bit data output which allows for faster read times. With a sampling rate set at 800 Hz, the axes data is first passed through an internal high pass filter with a cutoff frequency of 2 Hz. By doing so, the offset due to gravitational acceleration is removed from the output and all axes read zero when not moving. The data from all three axes are then passed through a moving filter to average the magnitudes and from there the activity level can be calculated. The PSoC UART blocks are configured for eight data bits and one stop bit for both the oxygen and carbon dioxide sensors. The sensors are set into polling mode in which it will only respond when given a request for data. When the data comes in, it is parsed to separate the five data bytes and then converted into integers to be stored into an array. This array of integers allows the sensor data to be sent over bluetooth low energy to the phone and easily displayed on the application.

3.2.3 Mask Design

Figure 7: VO2 MAX Mask Design

The OOCOO Mask is comprised of a rubber face mask and a neoprene cover to hold the rubber face mask in place. The rubber face mask contains three holes: one hole for free air flow, one for the oxygen sensor, and one for the carbon dioxide sensor. The carbon dioxide and oxygen sensors are contained on circular PCB's sized to fit neatly into the mask holes. The carbon dioxide and oxygen sensor PCB's are then sealed into the two mask holes with glue. The battery and main PCB are housed in a 3D printed encasing on the back strap of the neoprene cover.

3.3 Device Firmware

3.3.1 System Diagram

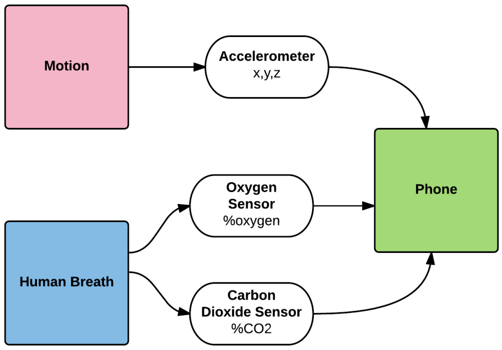

Figure 8: System Overview

Motion and the human breath are the two main sources of information. The accelerometer axes data are collected into three separate arrays that are then passed through a moving average filter. From there, the activity level can be determined.

The human breath is observed through oxygen and carbon dioxide sensors. Because data from UART is in ASCII, each character must first be parsed then converted into integers so that the mobile application can easily display the oxygen and carbon dioxide levels as percentages. The integers are stored into an array before they are sent over bluetooth to the mobile application.

3.3.2 State Machine

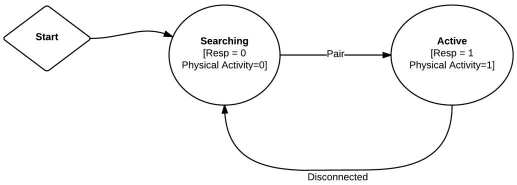

Figure 9: State Machine

The system begins in the start state. It automatically moves into the searching state, where no data is being transmitted. In the searching state the PSOC initializes the gas sensors and accelerometer. The PSOC puts the oxygen and carbon dioxide sensors into polling mode, where the sensors output data only when receiving the request from PSOC. The accelerometer is initialized by the PSOC into 2g fast read mode. In this mode the data from the accelerometer is 8 bits long and the resolution is 2g. This resolution and data length makes it so that each bit is 15.6 mG. Once the phone and the PSoC are paired over BLE, the system moves into the active state. The respiration and activity data are both read by the PSOC and displayed on the phone application in the active state. Once the phone application and the PSoC disconnect, the system moves back into the searching state.

3.4 Mobile Application

The mask connects and transfers data to a cellphone through a Bluetooth low energy connection with a Qt Android Mobile Application. This mobile application shows live carbon dioxide, oxygen and accelerometer data. The mobile application also displays the current battery level percentage of the device.

4 Testing Procedures

To verify the mask design and functionality of the two gas sensors, three tests were completed. The first test performed served to establish a baseline reading for the sensors and acted as the control. The volunteer wore the mask for a session of 20 minutes and was told to remain sitting. Data was recorded every three minutes

After establishing the resting data, the volunteer then performed a running test. The test was ran for 15 minutes: 10 minutes of running on a treadmill plus 5 minutes of rest. Data was recorded every minute to establish the trend. The volunteer's height, weight, age, sex, and average running speed were also collected. These tests were repeated on multiple users in order to verify the results from the mask.

The third test performed observed respiration level trends for varying levels of exertion. The volunteer completed 21 minutes of testing: 5 minutes of resting, 5 minutes of walking, 5 minutes of speed-walking, 1 minute of running, and 5 minutes of resting. CO2 and O2 levels were recorded every 15 seconds during the running portion, and every minute throughout the rest of the test. The height, weight, age, sex, and treadmill speeds during all exertion levels were collected as well.

5 Results and Discussion

Time (min)	**O2 (%)**	**CO2 (%)**
0	18.1	2.47
1	16.81	3.10
2	17.09	3.19
3	17.21	3.27
4	17.29	3.09
5	17.32	3.00
6	17.37	3.05
7	17.52	2.90
8	17.46	2.88
9	17.19	2.95
10	17.47	2.87
11	17.67	2.82
12	17.87	2.53
13	18.26	2.08
14	17.94	2.32
15	18.08	2.2

Table 1: Running Test Data

The baseline resting test results yielded an average of 18.1% oxygen and 2.35% carbon dioxide in respiration at rest. Figure 10 displays the observed trends in carbon dioxide and oxygen levels resulting from the running test. The values graphed in Figure 10 are the change in oxygen and carbon dioxide values from the baseline values observed in the initial test. When users initially put on the mask at time 0 minutes, the O2 and CO2 levels rose from the atmospheric levels to the user's resting respiration levels. Once the users began to workout at one minute, their carbon dioxide levels increased, while oxygen levels decreased. At ten minutes when the users stopped working out and began the resting period, oxygen and carbon dioxide respiration levels returned to the resting levels observed at the start of the testing period. As expected, the specific oxygen and carbon dioxide levels varied from user to user, however, each test yielded the same trends mentioned above.

Time (min)	**O2 (%)**	**CO2 (%)**
0	17.45	2.95
1	17.72	2.86
2	17.68	2.77
3	17.44	2.76
4	17.51	2.84
5	16.89	2.81
6	17.19	2.92
7	17.24	2.95
8	17.38	2.92
9	17.15	3.06
10	17.2	2.94
11	17.43	3.22
12	17.05	3.31
13	17.5	3.16
14	17.24	3.31
15	17.21	3.20
15.25	17.25	3.18
15.5	17.20	3.38
15.75	17.12	3.42
16	17.44	3.63
17	18.18	3.44
18	18.57	3.01
19	18.64	2.67
20	18.54	2.55

Table 2: Exertion Level Test

The exertion level test results yielded similar trends to the running test. However, there was a gradual increase in carbon dioxide and decrease in oxygen as the volunteer progressed from resting, to walking, and then to running. The values displayed in Figure 11 are the change in oxygen and carbon dioxide values from average resting carbon dioxide and oxygen levels during the 5 minutes of resting at the start of the test. From 0 to 4 minutes, the oxygen and carbon dioxide levels remained relatively flat with minor variations. At time 5 minutes when the volunteer began to run, the carbon dioxide levels increased and the oxygen levels decreased as expected. Both oxygen and carbon dioxide levels saw minor fluctuations, but remained relatively flat until time 10 minutes. At time 10 minutes when the volunteer began to walk at quicker pace, the carbon dioxide levels again rose and the oxygen levels also saw an overall decrease. However, the oxygen levels experienced a much smaller decrease than the increase the carbon dioxide levels saw. The levels remained relatively constant with minor fluctuations until time 15 minutes. When the volunteer began to run at time 15 minutes, there was a larger increase from in carbon dioxide and a larger decrease in oxygen from their initial values. At time 16 minutes when the volunteer began the final resting period, carbon dioxide levels decreased to below their initial resting levels, and the oxygen levels increased to above their initial resting levels.

Possible sources of error in the results are imperfect mask seal and user biasing. The rubber mask seal works very well for some face shapes, while it may leak very slightly for other face shapes. However, the imperfect mask seal only results in small amounts of leakage and does not affect testing results. User biasing is accounted for by performing the same test on multiple users. The initial tests were performed on OOCOO Mask group members, where it was found that members often attempted to adjust their breathing patterns to produce the results they wanted. Tests were performed on users who had no knowledge of the functionality of the mask to verify trends were not caused by user biasing. These tests yielded the same trends as the initial tests on OOCOO Mask group members. Therefore, user biasing does not create a large enough error to affect testing results.

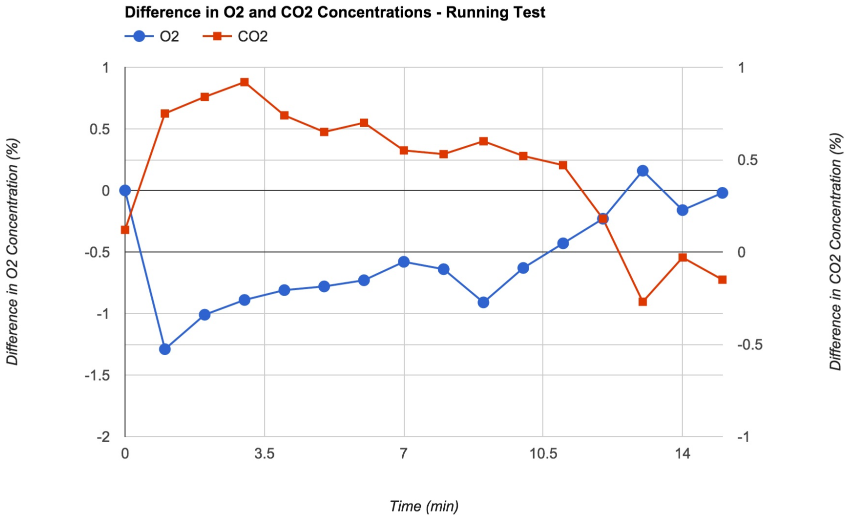

Figure 10: Results from Running Testing

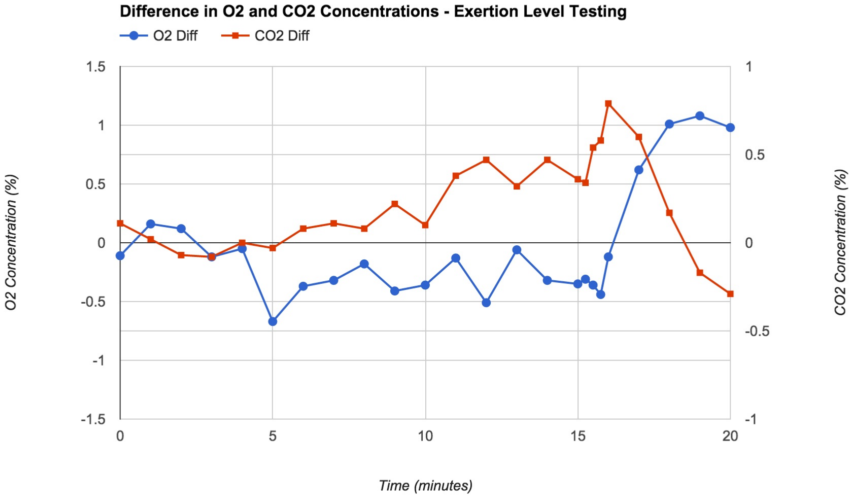

Figure 11: Results from Exertion Level Testing