# Flexible Sensor for Infant Monitoring of Oxygen, Carbon Dioxide, pH, Glucose and Heart Rate


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***Abstract*—Trauma from birth can manifest as serious health conditions such as hypoxia or cerebral palsy during the first hour of life of infants. To ensure immediate medical intervention during this period, a novel flexible quintuple sensor has been developed. Wrapped around the baby's foot like a boot, this sensor wirelessly transmits and algorithmically classifies live oxygen, carbon dioxide, pH, and glucose data for clinicians to monitor. In this paper, a prototype is created and tested to offer a proof of concept for future industrial applications.**



***Keywords—classification, sensor development, base excess, newborn monitoring***


## I. Introduction

Previous studies have shown that trauma from birth can leave a lasting effect on newborns that are later expressed as grave medical conditions within the first hour after birth. During this period, newborns are generally placed on the mother's chest to promote critical social bonding before being taken for a battery of medical tests. Regardless, a baby's vitals must not go unmonitored during skin-to-skin contact with the mother. To ensure that the mother-infant experience is preserved, and the baby's health is protected, a non-intruding, comprehensive, and highly sensitive device is proposed. Using a combination of electrochemical and optical sensors, a novel flexible device is created to be wrapped around a baby's foot to provide discreet, enhanced infant monitoring. Parameters such as oxygen, carbon dioxide, pH, glucose, and heart rate are prioritized and simultaneously monitored on the sensor.

Base excess, or the amount of H+ ions that would be required to restore a liter of blood to its normal pH at a partial pressure CO2 of 40 mmHg, has been correlated with the development of lifelong/shortening medical disorders in infants. The level of risk that a newborn's health is at can be correlated to the value of base excess calculated from measurements of its dermis pH and blood CO2 taken from a minimally-invasive micro-needle. Continuous observation of pH and CO2 circumvents the need for interval blood analysis by supporting the continuous evaluation of base excess for doctors to utilize.

To add to the convenience of the device's hardware design, a classification machine learning algorithm is applied to data collected to result in clear, binary outputs. While real-time data will be made available to clinicians to view, additionally programming is used to categorize incoming data to provide immediate notification of the onset of concerning vital parameters. Benchtop experiments were conducted to create a training set for a preliminary design of the algorithm. Measurements from animal testing and clinical trials can be used to refine the algorithm.

**Figure 1: Example of crucial skin-skin contact between infant and mother**

The research conducted shows the practicality and applicability of the quintuple sensor while highlighting the accuracy of its output despite the complexity of its design.

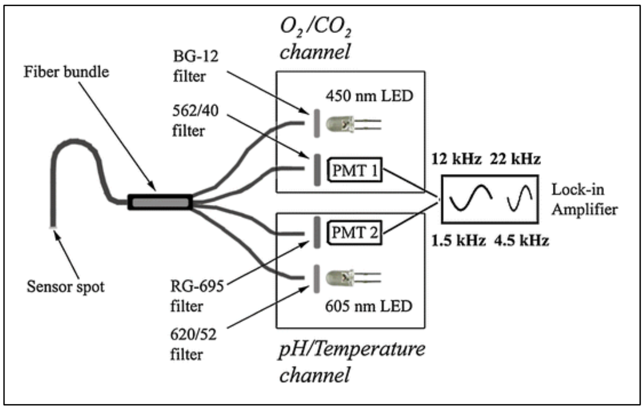


**Figure 2: Schematic representation of the device arrangement of the multi-analyte sensor**

## II. Methods

As the beginning of the REU coincided with the BEST lab's first exploration into this project, any research performed was significant. The goal was to search for off-the-shelf analyte sensors that could be easily taken apart and combined to create a proof-of-concept of the Baby Boot device. It was found that CO2 was a difficult analyte to find a sensor for. This is because it mainly used wet lab and is an invasive sensor. As we hoped to use our sensor non-invasively and for human use, it was determined that the


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CO2 sensor would be developed in-lab. However, it may take a long time to develop this lab-developed non-invasive sensor as it must also be vetted before human use. Additionally, as CO2 cannot be electrochemically sensed, developing a non-invasive sensor in-lab will also be its own challenge. The commercial availability of pH sensors was similar. As a result of their non-existent non-invasive usage in the medical field, it was difficult to find pH sensors approved for human use that were available for purchase. It is important to note that both data on CO2 and pH levels are the most direct methods of determining base excess and as a result, the health of the newborn. Research is being performed to determine if newborn help can be gauged using other readily accessible analytes. As oxygen and heart rate sensors are widely used in the medical industry, especially for neonatal care, it was determined that the focus of this project would be on evaluating the design of a glucose sensor for the Baby Boot project.

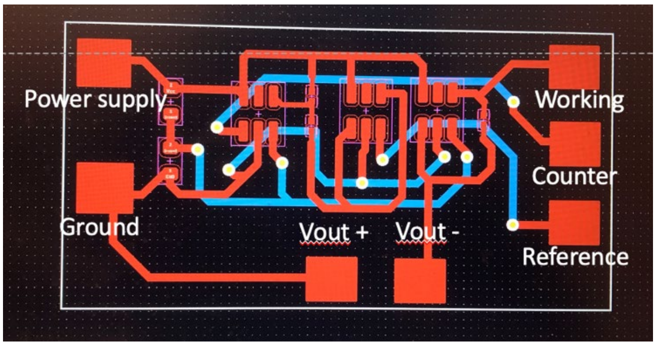


**Figure 3: Circuit schematic of a three-electrode system glucose sensor used in testing**

**Figure 4: Disassembled FreeStyle sensor**

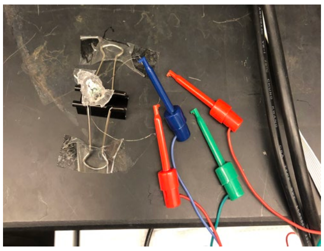

**Figure 5: pH sensor experimental set-up**

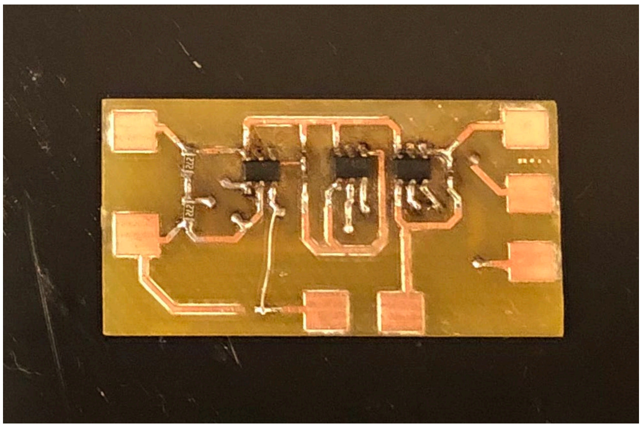

**Figure 6: Printed glucose sensor PCB**

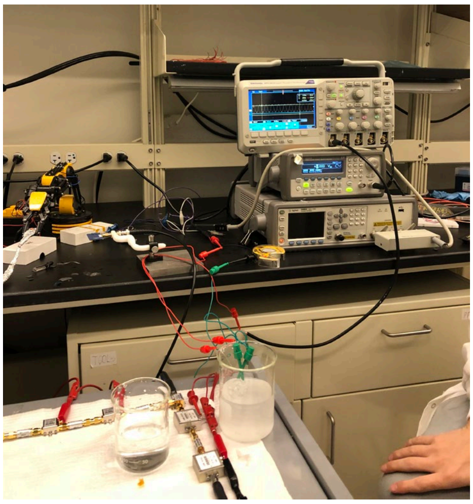

**Figure 7: Glucose experiments for data collection**

As a result of taking apart several different commercial glucose sensors, a glucose sensor circuit for testing in benchtop experiments. An investigation into the various electrode systems for glucose development was conducted and the glucose method of detection of popular sensors was identified. The knowledge gained during the pre-training phase of the REU came in handy to begin developing machine learning codes for the final product. Logistic regression was mainly used to classify experimental pH and glucose sensor data. Additionally, it was used with experimental data provided by the Keeping Labor Safe (KLS) group to determine the most important analytes in determining a healthy baby. Beginning with all analytes, the resulting machine learning confusion matrix was used to eliminate factors one by one depending on which factor affected the accuracy the least. As a result, an order of analytes of increasing importance can be determined.

## III. Results – Sensor Development

To discuss results in sensor development, as mentioned before, it will be difficult to implement CO2 in the Baby Boot prototype as more research needs to be done to determine how this analyte can be detected. Ian Akmine, a Ph.D. student in the BEST lab is already making pH sensors. He provided pH data to use in classification and will be helping us in setting up experiments to refine the sensitivity of pH. A lot of progress was made to further the lab's development of its own glucose sensor. This was done by hacking commercial glucose sensors, and understanding whether sensing was done using amperometry, voltammetry, or by impedance. A thorough literature review was conducted to learn about various electrode sensing systems and after a lot of trial and error, successfully determined that the popular Freestyle glucose sensors utilize a three-electrode system. There are many medically approved, noninvasive oxygen sensors already available. For this prototype, we will be using a commercial oxygen sensor. Additionally, progress was made in learning how to use Nordic Bluetooth products, specifically the Nordic Bluetooth development kit for data transfer between our interface and the Baby Boot prototype.

## IV. RESULTS – MACHINE LEARNING

A logistic regression machine learning algorithm was used to classify experimental pH and glucose data. This was done with very high accuracy, begging the question of whether machine learning is overkill in this aspect. However, as we continue to develop the sensors for these two analytes and integrate them, data collected may require an algorithm of such complexity. Logistic regression was also used to rank the importance of analytes from the KLS data set - results suggest that CO2 may not be of as high importance as we thought, but also in this data set, base excess is its own category, so results are not certain. The dataset is very old, almost 70 years. As a result, machine learning conclusions will need to be further verified.

| Metric | Value |
|---|---|
| Accuracy | 0.98 |

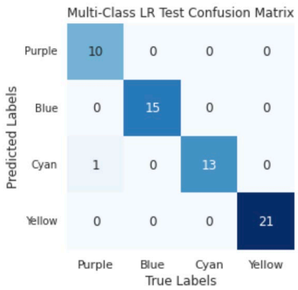


**Figure 8: pH classification confusion matrix**

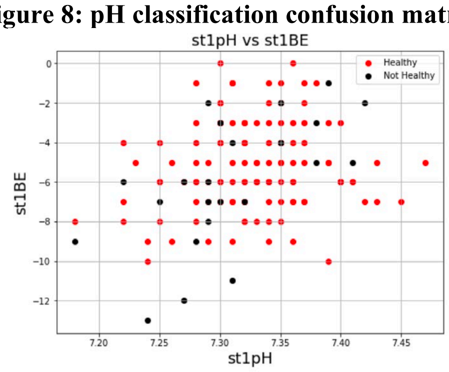


**Figure 9: Plot of pH vs. base excess (KLS data)**

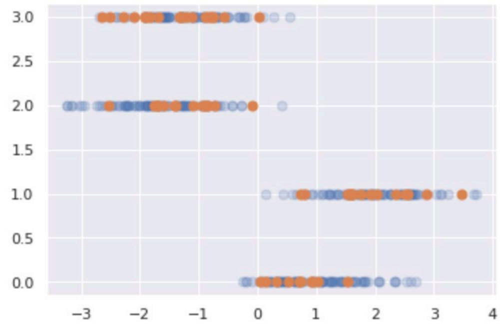

**Figure 10: pH data after logistic regression**

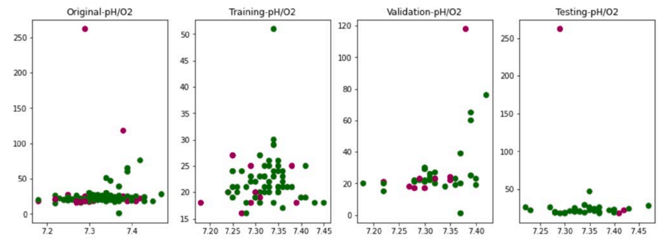


**Figure 11: Illustrates how data is split up to train the ML algorithm**

## V. DISCUSSION

The research done in these few short weeks has only just scratched the surface of this project. The goal in the future is to refine individual sensors developed in the lab, specifically glucose and pH, and integrate them into the first prototype which will include the commercial oxygen sensor. Whether or not CO2 will be added in as well is unclear. But the is to keep working with the KLS doctors to finalize the analyte selection, hopefully with better data to use in the machine learning logistic regression. The Bluetooth component will be further developed to allow for data transfer between the sensors and a handheld electronic device. The plan is to begin animal trials on rats by the end of the year.

## VI. CONCLUSION

To facilitate timely medical support for babies without compromising skin-to-skin contact, the baby boot project aims at developing a flexible electronic multimodal sensor that can be easily wrapped around the baby's foot like a boot and transmits pH, O2, CO2, and glucose data. Integrated with the sensor will be a logistic regression machine learning algorithm that easily classifies data points into clear danger level indicators for doctors to utilize for potential intervention. The research done this summer has provided the groundwork for what aspects of the project are easily attainable for the development of a working Baby Boot prototype that can be used for a proof-of-concept of the idea. As of now, much progress has been made in creating an invasive glucose sensor design that can be easily integrated with a Bluetooth component. Machine learning was used to classify pH and glucose data. Ongoing research is being conducted to determine if the existing analyte list must be revised to minimize device sensors while still maintaining the accuracy of baby health detection.

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