A Review of Blood Gas Sensors and a Proposed Portable Solution


*School of Electrical Engineering*, Faculty of Health, Engineering and Science, Victoria University
Melbourne, Australia

** Director, Marian Cardiac Centre and Research Foundation
Pune, Maharashtra, India

Abstract- Blood gases are one of the vital signs monitored by medical practitioners for critically ill patients and as preventive health care measures for potential heart disease patients. Measurement of blood gases in a quick, effective way, without compromising on accuracy is one of the fundamental topics for research today and is in tune with the demands of the medical fraternity.

The objective of this paper is to review the theory of blood gas measurement and the current technological solutions used to measure blood gases non-invasively and continuously. This paper finally presents proposed research that will foresee portable, non-invasive blood gas monitoring solutions.

I. INTRODUCTION

Non invasive measurement of blood gases and other blood analytes is widely acknowledged to be one of the most technological and path breaking advances in monitoring clinical patients[1]. Traditionally blood gases were measured by taking samples from patients and sensing the samples to a laboratory for further analysis. This has proven to be a tedious and time consuming process and the availability of the results becomes very important and a hindrance for the doctor to take further steps when treating a critically ill patient. The delay between the event itself and blood sampling, plus the delay in obtaining the results, means that this sort of analysis may be misleading. [2]

The paper is divided into 6 sections. Part II deals with the theory of blood gases, part III deals with the different measurement techniques, part IV deals with current solutions and their inherent drawbacks, part V deals with a proposed solution and part VI summarizes the discussion.

II. THEORY OF BLOOD GASES

Blood gas analysis, also known as arterial blood gas (ABG) analysis, is a test which measures the amounts of oxygen and carbon dioxide in the blood, as well as the acidity (pH) levels of blood. An ABG analysis evaluates how effectively the lungs are delivering oxygen to the blood and how efficiently they are eliminating carbon dioxide from it. The test also indicates how well the lungs and kidneys are interacting to maintain normal blood pH (acid-base balance). In addition, the component of the test provides information on kidney function [5].

Oxygen in the lungs is carried to tissues through the bloodstream, but only a small amount of this oxygen can actually dissolve in arterial blood. How much dissolves depends on the partial pressure of the oxygen (the pressure that the gas exerts on the walls of the arteries). Therefore, testing the partial pressure of oxygen is actually measuring how much oxygen the lungs are delivering to the blood. The remainder of oxygen that is not dissolved in blood combines with hemoglobin, a protein-iron compound found in red blood cells. The oxygen content measurement in an ABG analysis indicates how much oxygen is combined with the hemoglobin. A related value is the oxygen saturation, which compares the amount of oxygen actually combined with hemoglobin to the total amount of oxygen that the hemoglobin is capable of combining with. Carbon dioxide dissolves more readily in the blood than oxygen, primarily forming bicarbonate and smaller amounts of carbonic acid. When present in normal amounts, the ratio of carbonic acid to bicarbonate creates an acid-base balance in the blood, helping to keep the pH at a level where the body's cellular functions are most efficient. The lungs and kidneys both participate in maintaining the carbonic acid-bicarbonate balance. The lungs control the carbonic acid level and the kidneys regulate the bicarbonate. If either organ is not functioning properly, an acid-base imbalance can result. Determination of bicarbonate and pH levels, aids in diagnosing the cause of abnormal blood gas values [5].

<table>
<thead>
<tr>
<th>Sr. No</th>
<th>Quantities Measured in Blood Gas Analysis</th>
<th>Normal Values for a Healthy Patient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Partial pressure of oxygen (PaO2)</td>
<td>75-100 mm Hg</td>
</tr>
<tr>
<td>2.</td>
<td>Partial pressure of carbon dioxide (PaCO2)</td>
<td>35-45 mm Hg</td>
</tr>
<tr>
<td>3.</td>
<td>Oxygen saturation (SaO2)</td>
<td>94-100%</td>
</tr>
<tr>
<td>5.</td>
<td>Bicarbonate (HCO3)</td>
<td>22-26 mEq/litre</td>
</tr>
<tr>
<td>6.</td>
<td>Acidity (pH)</td>
<td>7.35-7.45</td>
</tr>
</tbody>
</table>

TABLE 1: Normal values for blood analysis in a healthy patient [5]

III. MEASUREMENT AND TECHNIQUES

A. Oxygen Tension:

The partial pressure of oxygen is always measured in the
The concentration of oxygen, \( C \), is given by:

\[
C = \alpha \times PO_2
\]

(1)

Where \( \alpha \) is the solubility coefficient [4].

Similarly, the rate of diffusion of oxygen will increase with a difference in partial pressures of oxygen in blood and the surrounding tissue. The oxygen delivery rate, \( D_o \), is defined by

\[
D_o = (C_o O_2 - C_v O_2) \times R
\]

(2)

Where \( D_o \) is the oxygen delivery rate, \( C_o O_2 \) is the concentration of arterial oxygen and \( C_v O_2 \) is the concentration of venous oxygen [4].

The partial pressure of oxygen can be measured in three basic ways:

1. **Electrochemical Measurements**: It has been observed that oxygen has an affinity to platinum, and the reaction generates a current proportional to the oxygen content. For the measurement, a reference value is set (preferably to zero). Change in partial pressure of oxygen will change the current flow accordingly [3].

2. **Transcutaneous partial pressure of oxygen**: Transcutaneous oxygen tension measurement (TCOM) is a measurement of oxygen perfusion of the skin. Transcutaneous monitoring is non-invasive and relatively simple to use. In neonates and small infants, this monitoring technique may provide very useful clinical information. Transcutaneous gas monitoring, using conventional electrochemical techniques, provides a means of measuring the values of PaO2 and PaCO2 in most patients with relatively normal cardiovascular function. Typically, the skin of the patient is heated to 44 °C [4].

3. **Optical based measurement**: The principle used in optical sensors is the fluorescent quenching properties of oxygen. The device includes an optical waveguide and an oxygen sensing medium disposed on the waveguide. The sensing medium fluoresces in response to light from a light source such that the intensity of fluorescence is dependent on the partial pressure of oxygen in the environment. The sensing medium includes an oxygen sensitive fluorescent dye in a matrix consisting of a plasticized polymer. A zero state can be measured by filling the chamber with oxygen concentration mixture. The measured intensity is compared with the incident light source and is used to calculate the concentration of the sample. The oxygen tension is calculated using the Stern-Volmer quenching formula and the PO2 value is calculated empirically [3].

\[
I_o / I = 1 + K(PO_2)
\]

(3)

Where \( I(PO_2) \) is the fluorescence intensity in presence of oxygen, \( I_o \) is fluorescence intensity in absence of oxygen and \( K \) is the overall quenching constant.

### B. Oxygen Saturation:

Oxygen saturation in blood is one more important factor that is measured by medical practitioners. There is an important relationship between oxygen saturation and partial pressure of oxygen. Partial pressure of oxygen falls at a linear rate with a fall in oxygen saturation and is a good indicator of ability of oxygen to diffuse into the body tissue. Partial pressure of 13.3 KPa (100 mm Hg) translates into 100% saturation possible. If PO2 is more than 13.3 KPa it indicates presence of oxygen which is not bound by hemoglobin and does not diffuse into the tissue. In the above discussion PO2 relates to oxygen saturation in arterial blood (SaO2) and not venous blood oxygen saturation (SvO2). [3]

Oxygen Saturation in blood can be measured in three basic ways:

1. **Transmission Oximetry**: The basic concept in transmission oximetry is to transmit light through a blood sample where the blood absorbs a determined amount of light according to Beer’s law [3]. The assumption made is the hemoglobin present in blood is basically a combination of two substances, oxygenated hemoglobin or oxyhemoglobin (O2Hb) and deoxygenated hemoglobin (RHB). Both of the substances can be measured by using two separate wavelengths of light. The wavelengths used are the red (660nm) and the infrared (940nm) [8]. Red has the largest difference between the two extinction curves of O2Hb and RHB while the infrared has maximal difference after the isoelectric point where the two extinction curves cross.

The Oxygen saturation equation is:

\[
SaO_2 = C_r (C_o + C_r) \times 100
\]

(4)

Where \( C_r \) is the concentration of deoxygenated hemoglobin and \( C_o \) is the concentration of oxygenated hemoglobin. [3]

2. **Pulse Oximetry**: It is a simple non-invasive method of monitoring the percentage of hemoglobin (Hb) which is saturated with oxygen. The pulse oximeter consists of a probe attached to the patient’s finger or ear lobe which is linked to a computerized unit. The unit displays the percentage of Hb saturated with oxygen together with an audible signal for each pulse beat, a calculated heart rate and in some models, a graphical display of the blood flow past the probe. The basis of pulse oximetry relies on the difference in optical absorbance of deoxyhemoglobin (Hb) and oxyhemoglobin (HbO2). HbO2 absorbs less light in the red region of the spectrum (660nm) than does Hb. Therefore oxygenated blood is distinctively red and venous blood has a bluish tinge. For an infrared wavelength of light at 940nm, the absorbance of HbO2 is slightly greater than that of Hb.

Oxygen saturation is given by the equation...
\[ \text{SaO}_2 = A - B \frac{A_1}{A_2} \]

Where \( A \) and \( B \) are functions of the specific absorptivities of Hb and HbO\(_2\) respectively and \( \lambda \) is wavelength of light [6]

3. Reflectance Oximetry: This method is similar to pulse oximetry with difference being in the placement of the light emitters and the photo diode receptors. In reflectance oximetry the two are placed side by side and are separated by a optical barrier. The capillary bed under the skin is used to reflect the incident rays back to the photo diode [3].

IV. PROBLEMS FACED WITH NON INVASIVE SENSORS AND RECENT DEVELOPMENTS

Continuous and non invasive means blood gas analysis is the future aim of the medical fraternity. The current bottleneck to achieve this aim is directly related to the current technologies. It is a major challenge to implement a portable marketable solution as compared to today’s the bulky blood gas analyzers currently in the market. One of the key factors which prevent non invasive sensors over the traditional solution is accuracy which is very important considering that the very reason for the analysis is healthcare. The problem is due to the nature of non invasive sensors which prohibit direct contact with the blood to be analyzed. Instead, the non invasive sensors concentrate on detecting and measuring secondary factors which are in turn dependant on changes in the blood gas values.

A good example is a pulse oximeter, because the measurement relies on detecting a change in the absorbance of light due to the pulsating arterial bed (AC component). If the pulse is not strong enough, the variations in the AC component would be too small to process further. So this puts a physical limitation on where the sensor should be placed on the body and at the same time renders the readings inaccurate for a patient who suffers from problems like hypotension, vasoconstriction or hypothermia [8]. A second problem is with motion artifacts, because the sensor is on the surface of the skin any transient motion relative to the skin and the sensor (shivering, seizure activity) on it will introduce errors when the changes in the pulsatile readings are taken. The variations in the AC component are very small compared to the whole signal and any errors in this variation will translate into a huge loss in accuracy. Some manufacturers use the R wave (analogous to the pulsating AC component in pulse oximetry) of the patient’s electrocardiogram to synchronize the optical measurements and there by improve the detection of noisy pulsatile signals by enhancing the signal to noise ratio through the use of multiple time averages signals [8].

The Department of Electronic Engineering, Bioelectronic Laboratory, Gyeongsang National University and Department of Computer and Information Technology, YONAM College of Engineering has come with a solution to counter motion artifacts in pulse oximetry sensors. Generally speaking, the frequency band of the motion artifact signal generated from the patient’s movement is overlapped with that of the patient’s pulse wave which is measured by the received light sensor. Accordingly, it is difficult to filter the motion artifact of the pulse wave by using a filter which has a cut-off frequency that is fixed. In this study, the motion artifact is removed using a filter bank and a matched filter. Compared with traditional adaptive filter methods, the ratio variation is 50% lower than that of the moving average filter, allowing more stable measurement of oxygen saturation despite the patient’s movement. But presence of venous blood in the pulsatile component reading is still a problem [9].

A more practical problem would be that of power consumption by the whole device. The device is to work as a continuous and mobile device on the body of the patient. So the whole design has to be very energy conscious and the development of a energy saving algorithm specific to the device in question is a must. The choice of the right design for the transmitter is also essential as the RF part of the device will consume the most power in its duty cycle.

The above mentioned solution is a oxygen saturation measuring device. But the relationship between SpO\(_2\) and PO\(_2\) is nonlinear and sigmoidal. The relationship is also dependent on pH and temperature, thus under normal conditions the relation stays true but deviates in altered conditions e.g., low perfusion. Thus 100% oxygenation saturation does not translate to effective or medically recommended tissue perfusion. Therefore detecting the PO\(_2\) of oxygen is critical rather than measuring oxygen saturation [3].

The current solutions for measuring PO\(_2\) are all either invasive or bulky. Fig 1 is an example of the current analyzers used in hospitals to measure PO\(_2\).

![Fig 1: AVL Compact 2 Blood Gas Analyzer (Current Solution)](image)

Choice of sensor type is critical. Electrochemical sensors are mostly electrodes which require taking samples. There are some electrodes which can sense blood gas through the skin but in all cases are not suitable for continuous monitoring of patient. In addition to the electrochemical reaction on the transducer and compound deposition on the transducer surface are further issues and need to be addressed periodically to maintain accuracy [3].
An ideal blood gas analyzer would be one which is noninvasive, portable and if possible continuous. All these aspects are difficult to integrate into a single solution with the currently available technologies. The reason for that is related to the very nature of noninvasive measurements, wherein secondary parameters are measured from which information about blood gases is derived. The problem lies in the fact that the parameters sensed do not translate into true values of blood gases unless the measurement is performed under known conditions, hence there is a trade off between accuracy and noninvasive nature of instruments.

The proposed research is aimed at an optical based blood gas sensor solution for critically ill patients which will be both accurate and portable. A block diagram of the proposed solution is presented in Fig. 2. The sensor will feature three sets of red and infrared LEDs sources and photo detectors which will detect the gases. The sensor will detect blood gas values (PCO2, PO2 and pH) from a drawn blood sample. The proposed technologies to realize such a solution are Micro Electro Mechanical Systems (MEMS) and advanced VLSI techniques. These techniques will aid in reducing power consumption. The use of MEMS technologies will aid in developing a sensor, which is considerably smaller and portable than the current bulky analyzers. The sensor will also feature the necessary computing power required and telemetry to transmit the data reducing the time to get the results considerably.

The signal from the three photo detectors will be digitized using a low power biomedical ADC. The ADC featured in the solution will be low speed (maximum 100 kilocycles) and high resolution (10 to 12 bits). The signal is then passed on to the digital signal processing block where the signal will be analyzed and the blood gas values will be computed based on ratio metric analysis algorithms. The DSP block will also feature a controller which will control the multiplexer which controls property to be measured and will switch on the relevant circuitry to measure it. The DSP will execute the algorithm accordingly to compute the values required. These measures will aid in reducing the power consumption. The computed values will be transmitted via wireless telemetry.

The proposed solution being portable will reduce the time for analysis and also allow the practitioner to provide a quick response to the change in the conditions. The portability of the solution also allows diagnosing of patients who don’t have access to the facilities and also patients who are being treated at home. The solution is minimally invasive hence will be more accurate than the current noninvasive solutions.

V. PROPOSED SOLUTION

VI. CONCLUSION

This paper reviews the existing methodologies available for measurement of blood gases. The paper details out various techniques and aims to propose an alternative and viable method for blood gas analysis. The current noninvasive solutions are not fully accurate and there is no way to test if the sensor is working. On the other hand, the blood gas analyzers currently used in hospitals are highly accurate but have the disadvantage of being bulky and not portable. The future in blood gas analysis lies in combining the best feature of the invasive and noninvasive measurement techniques using existing technology to provide the medical fraternity with a device that not only guarantees high accuracy but also is considerable smaller in size and portable. The proposed solution is a step in bridging these gaps in existing methodologies.

REFERENCES

[6] J.Baustin , J.Kaunders, A.Strik, B.Vojnovic, A.Van Der Kogel, “Optical sensor-based oxygen tension measurements correspond with hypoxia marker binding in three human tumor xenograft lines” Department of Radiation Oncology, UMC St Radboud Joint Centre for Radiation Oncology Arnhem-Nijmegen, P.O. Box 9101, 6500 The Netherlands.