NONINVASIVE MEASUREMENT OF BLOOD ACID-BASE (pH) USING CONCENTRATIONS OF EXHALED GASES

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Abstract: An important property of blood is its degree of acidity and alkalinity which is referred to as acid-base balance. The acidity or alkalinity of the blood is indicated on the pH scale. The blood pH has a serious effect on all of the body's systems and the body uses different mechanisms to control the blood's acid-base balance. Acid-base imbalances result primarily from metabolic or respiratory failures, both imbalances cause changing in the normal range of CO2 in the blood. The concentrations of oxygen and carbon dioxide from the exhaled breath were used to evaluate the pH of the blood. The results show the relation between concentration of the exhaled CO2 and the blood acid-base pH; decreasing CO2 causes the blood to be alkaline, while increasing CO2 leads the blood to become acidic.

1 INTRODUCTION

During exercise the muscles are working harder than normal and, as a result, they require more energy than normal. Since the ATP energy used by the muscles is generated with the aid of oxygen, it follows that an increase in exercise intensity will result in an increase in muscular oxygen demands. Therefore, increased exercise intensity ultimately corresponds to an increased in the volume of the consumed oxygen. As the muscles working harder they release more CO2 this will affect the balance of O2 and CO2 in the blood, this is the reason that breathing gets progressively faster and deeper as exercise intensity increases, the body is trying to provide more oxygen to the working muscles and release the resulting carbon dioxide so that they can generate enough ATP energy to keep the athlete moving. Homeostasis is the overall process of maintaining stability of the body's internal physical and chemical systems. These processes involve rapid correction of disturbances that may arise, as well as instance by instance adjustments to prevent gross disturbance from arising. A simple example is that if the heart rate and the respiratory rate did not increase during physical exertion, body chemistry would be significantly altered by the resulting deficit in oxygen and accumulation of carbon dioxide. The amount of carbon dioxide in the blood has an immediate and direct effect on the body's acid-base balance, a key aspect of the internal chemical state.

1.1 Effect of the O2 and CO2 on the pH

Hydrogen ion activity can significantly affect the metabolic function of the cells. Bicarbonate ion (HCO_3) is the most important form of CO2, both HCO_3 and H^+ are carriage by blood. CO2 combines with water to form carbonic acid, and this dissociates to HCO_3 and H^+. The conversion of CO2 to H^+ and HCO_3^- ions has tremendous implications for acid–base physiology. Every day, resting metabolism produces more than 15,000 mmol of CO2, or 15,000 mmol/L of carbonic acid, and this acid leaves the body through the lungs. By comparison, the kidneys typically excrete only 100 mmol/L of acid per day. The ability to change blood pCO2 levels rapidly by changing ventilation has a powerful effect on blood pH, so acid–base balance depends on the integrated function of respiratory and renal systems. Regulation of hydrogen ion (H^+) balance is similar in some ways to the regulation of other ions in the body. For instance, to achieve

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homeostasis, there must be a balance between the intake or production of H+ and the net removal of H+ from the body.

1.2 Chemical Relations of CO2 in the Blood

Hydration (combination with water) of dissolved carbon dioxide sets up an equilibrium with carbonic acid, which plays a key role in acid-base balance:

$$H_2O + CO_2 \rightleftharpoons H_2CO_3$$

In turn, dissociation of this weak acid yields hydrogen ion and the conjugate base, bicarbonate ion:

$$H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$$

Therefore carbonic acid can be viewed as a traditional stage between the hydration of dissolved carbon dioxide on one side, and the dissociation into hydrogen and bicarbonate ions on the other side:

$$H_2O + CO_2 \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$$

Increasing one of the chemical species in a system pushes the equilibrium toward the opposite side. Thus a rise in carbon dioxide levels in the blood causes an increase in the hydrogen ion concentration. Blood acid-base (pH) varies inversely with hydrogen ion concentration according to the relation below:

$$\mathrm{pH} = \log\frac{1}{\mathrm{H}^+} \tag{1}$$

Table 1: pH values with H^+ ion concentration.

pH	Ion Concentration (gram equivalent per liter)	Type of Solution
0	1.0	Acid Solution - Hydrogen ions - H^+
1	0.1	
2	0.01	
3	0.001	
4	0.0001	
5	0.00001	
6	0.000001	
7	0.0000001	Neutral Solution
8	0.000001	Basic (alkaline) Solution - Hydroxide ions - OH^-
9	0.00001	
10	0.0001	
11	0.001	
12	0.01	
13	0.1	
14	1.0	

The pure water have pH of 7 which considered neutral, acid solutions have pH less than 7 like the orange juice (3-4) while the basic solutions have pH more than 7 like soapy water (12). Table 1 showed the pH values with the corresponding hydrogen ion concentration and the type of solution.

2 METHODS

Because of the direct relation between the carbon dioxide in the blood and the pH, determining the level of carbon dioxide in the blood is very important. The air we inhale is roughly 78% by volume nitrogen, 21% oxygen, 0.96% argon and the rest 0.04% contain carbon dioxide, helium, water, and other gases. The permanent gases in the breath we exhale are roughly 4% to 5% more carbon dioxide and 4% to 5% less oxygen than was inhaled.

There are different methods to determine the CO_2 level in the blood, one of the important one which is invasive is the Arterial Blood Gas Analysis method which gives the partial pressure of the O2 and CO2, but what was accomplished in this research is non-invasive method of determining pCO_2 and pO_2 in the arterial blood. Measurements using the Vista-MX device from (Vacu•Med) were taken from 60 person (45 male, 15 female) in the rest and for 5 Athletes during exercise. These measurements give many parameters of the exhaled breath, we use some of these parameters which are VO_2, VCO_2, O_2% and CO_2%. The meaning of each of these parameters is:

VO_2: Oxygen consumption in liter per minute.

VCO_2: CO_2 output in liter per minute.

O_2% and CO_2%: the concentrations of oxygen and carbon dioxide in the exhaled breath.

According to the ideal gas law VO_2 and VCO_2 were converted to pressure which is then multiplied by the concentration of the related gas to give the partial pressure of the oxygen and carbon dioxide in the exhaled breath (pO_2 and pCO_2).

$$\mathrm{P} = \frac{\mathrm{n.T.K}}{\mathrm{V}} \tag{2}$$

n: number of moles, T: temperature, K: Boltzmann constant and V: volume. Table 2 shows some gases constants used to calculate the number of moles for the above equation.

Table 2: O_2 and CO_2 constants.

	O_2	CO_2
molecular weight	31.9989	44.01
Density(kg/m^3) at 25ºC	1.308	1.799

After obtaining the partial pressure of oxygen and carbon dioxide (pO2, pCO2) in the exhaled breath, paO2 and paCO2 have to be calculated in the arterial, this can be done by using the ventilatory exchange ratio (R), which can be calculated from the ratio between the carbon dioxide output and the oxygen uptake:

$$R = \frac{VCO2}{VO2} \quad (3)$$

Figure 1 shows ventilatory exchange ratio (R=0.8) plotted in the pO_2- pCO_2 plane. The figure shows four important points for the values of pO2 and pCO2 (E: Exhaled, A:Alveoli i:ideal and a:arterial). These four points play the main idea in the calculations of the partial pressure of oxygen and carbon dioxide in the arterial blood.

A method is developed in this research to estimate the actual values of pAO2 and pACO2 in the Alveoli according to the ventilatory exchange ratio (R). The ideal values for the pO2 and pCO2 in the arterial blood are 100 and 40 respectively. But the actual values may be different from these values. Most of the references state that the partial pressure of the carbon dioxide is the same in the alveoli and the alveoli arteries. The arterial partial pressure of oxygen was calculated from alveoli pAO2 using the equation below which gives the normal gradient between the partial pressure of oxygen in the alveoli and the arterial:

$$\text{Normal A-a gradient} = (\text{Age}+10) / 4 \quad (4)$$

After getting the arterial partial pressure of the oxygen and carbon dioxide, a neural network was built to determine the level of blood acid-base (pH). The neural network based on the arterial pO2 and pCO2 which are directly related to the pH of the blood.

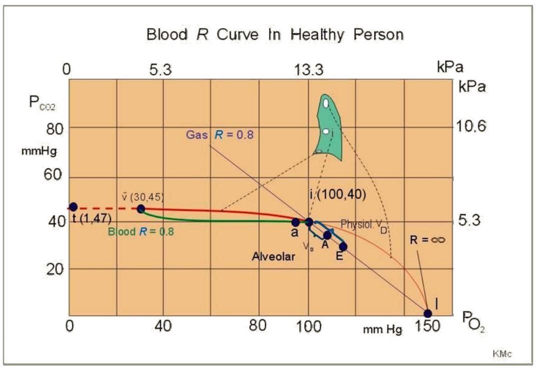

Figure 1: Ventilatory exchange ratio (R).

3 RESULTS

The theoretical chemical reaction states that increase the carbon dioxide in the blood causes increasing hydrogen ion in the blood which results in lower pH (the logarithmic relation), that means the blood becomes acidic. Also vice versa is correct, when the carbon dioxide decreases in the blood causes decreasing the hydrogen ion which results in higher pH and the blood becomes alkaline.

At the beginning the developed algorithm was applied to the data obtained from the athletes. As stated in the introduction section about the consumed oxygen which is increased during the exercise that results the concentration of the exhaled oxygen to be decreased. Figure 2 (Up) clarifies the decrease in oxygen concentrations with the respiratory rate in the exhaled breath during exercise. While the opposite happened with the carbon dioxide concentration which is increased with increasing the respiratory rate as shown in figure 2 (Down).

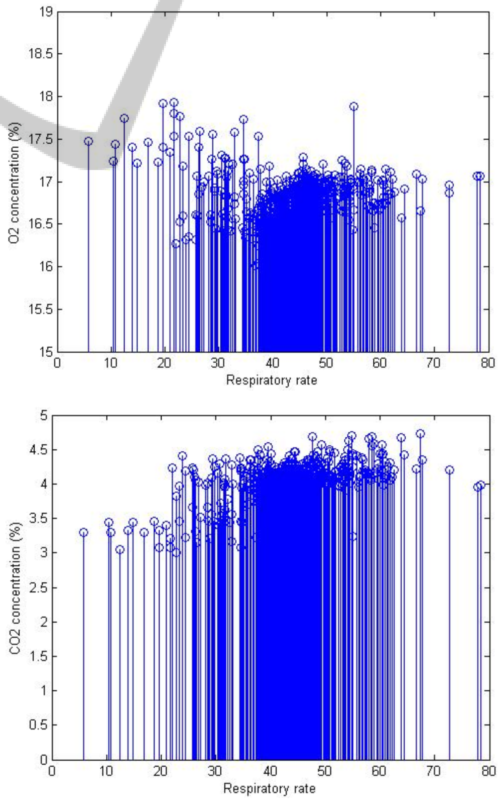

Figure 2: Up: change of the O2 concentration with the respiratory rate. Down: change of the CO2 concentration with the respiratory rate.

When the muscles are working harder they release more carbon dioxide, this will causes the partial pressure of carbon dioxide in the blood to be raised, and as a result the concentration of the CO2 in the exhaled breath will be increased. The body respond to this change in gases concentrations by raises the respiratory rate to throw out more CO2 from the body. Figure 3 shows the change of the CO2 concentration in the exhaled breath with the partial pressure of CO2 in the Blood. Figure 4 shows the increase of the partial pressure of the carbon dioxide with the respiratory rate.

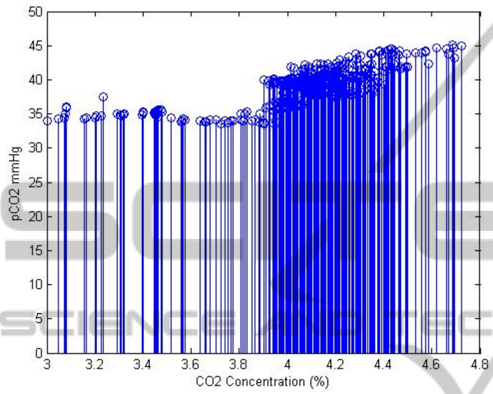

Figure 3: Change of the pCO2 in the arterial with the CO2 concentration in the exhaled breath.

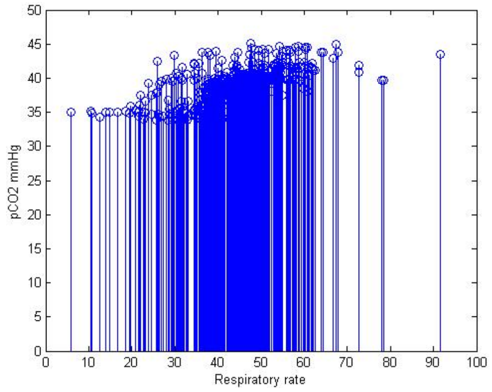

Figure 4: Change of the pCO2 in the arterial with the respiratory rate.

After the practical proof of the direct relation between the concentration of the exhaled gases with the partial pressure of these gases in the blood, a neural network has been designed to determine the blood acid-base level depending on the partial pressure of the gases. A neural network was built, two types of the neural networks achieved the goals, the characteristics of the two neural networks chosen are listed in the table 3.

The network was trained by data sets (from rats) have been taken from Bioinformatics Program of Human & Molecular Genetics Center-Medical College of Wisconsin, USA. Two data groups were used the first one contain 673 data sets and the second contain 860 data sets. During the network training many of learning functions were used and many performances of the network were obtained. One of the best performances of the neural network is shown in the figure 5.

Table 3: Neural network characteristics.

Network type	Layer Recurrent	Elman bachprop
Training function	Traingdm	Traingdm
Adaption learning function	Learngdm	Learngdm
No. Of Layers	2	2
No. Of neurons	10	10
Transfer function	Purelin	Purelin, Tansig

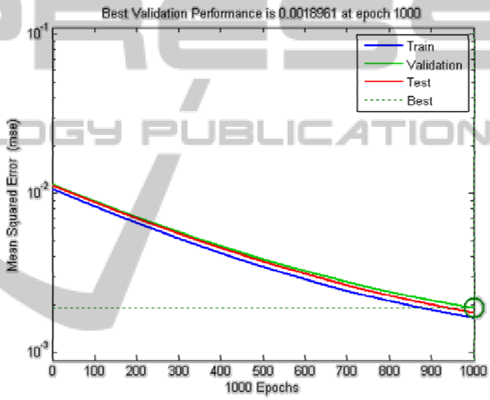

Figure 5: Neural network performance.

The results given by the neural network are clear. They give that the change of the blood acid-base level is directly related to the change of the partial pressure of the CO2 in the blood. Figure 6 shows the clear inversely change of the pH with the partial pressure of the carbon dioxide in the blood.

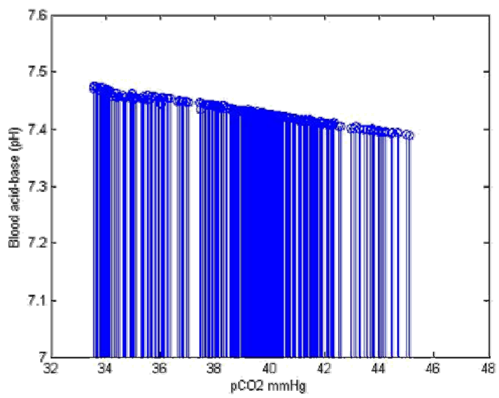

Figure 6: Change of the pH with the pCO2.

Then it will be obvious that the pH will be changed with the concentration of the CO2 in the exhaled breath because of the change of pCO2 with CO2 concentration, figure 7 shows this change.

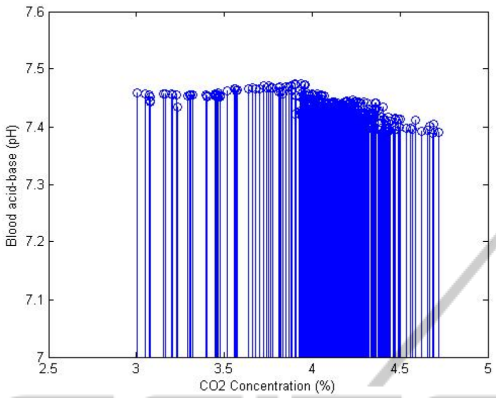

Figure 7: Change of the pH with the concentration of CO2 in the exhaled breath.

As stated in the beginning of the result section all of the above results were for the athletes during exercise. Also the same algorithms were applied to individuals at the rest. The obtained results show the inverse changes of the pH level with the increase/decrease of CO2 in the blood. Figure 8 shows the results of inversely change of pH with the partial pressure of CO2 in the arterial blood for individuals.

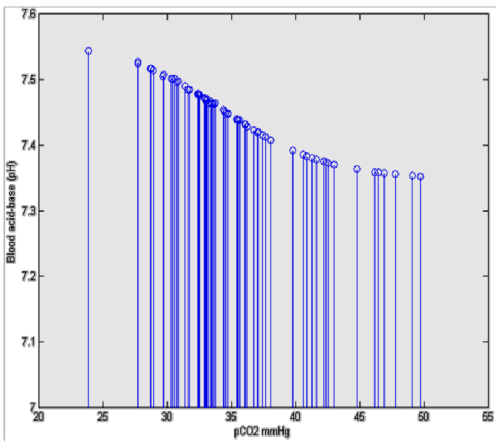

Figure 8: Change of the pH with the pCO2 for persons at the rest.

4 CONCLUSIONS

Blood pH is tightly regulated by a system of buffers that continuously maintain it in a normal range of 7.35 to 7.45 (slightly alkaline). Carbon dioxide is one of the central roles in this blood pH abnormality. Resting metabolism produces more than 15,000 mmol of CO2, or 15,000 mmol/L of carbonic acid, and this acid leaves the body through the lungs. More CO2 in the blood causes more hydrogen ion which is the major factor specifies the blood acid-base level pH. This means that the respiratory system is playing an important role in the regulation of blood acid-base level pH. This fact lead us to develop a noninvasive method for finding pH depending on exhaled gases.

A direct method to noninvasively determine the blood acid-base level pH was developed. The developed method depends on the concentration of the carbon dioxide that the person exhaled. The CO2 concentration is associated with the level of the partial pressure of CO2 in the blood which we used to determine the pH level. The increase of CO2 causes the blood to be acidic while decrease CO2 makes the blood more alkaline. Increasing the CO2 in the blood causes increasing the respiratory rate to exhaled more CO2 which results the pH to be returned to its normal level.

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