Automatic Control for Oxygen Intake via Nasal Cannula

Deacha Chumlert, Anan Wongjan, and Kitiphol Chitsakul, *Members, IAENG*

***Abstract*— In the present, oxygen supplying using nasal cannula is the first aide for a patient who has the problems in respiratory system by example in a newborn baby in which the incompetence of respiratory system on early days of birth is concerned. An indicator of this kind of symptom is physiological Jaundice, yellowish discoloration of the skin. Direct oxygen intake is a usual caretaking for this group of patients. Basically manual valve control of feeding oxygen by caretaker is a treatment by using pulse oximetry value as monitoring of effectiveness. This treatment is either time or labor consuming in a corona care unit. The purpose of this research is to develop an automatic control for oxygen intake. By studying the mechanism of arterial oxygen saturation in blood (SaO_2) under the partial pressure of feeding oxygen (PiO_2), the effective model can be applied as control value of oxygen for this group of patient.**

***Index Terms*— Pulse Oximeter, SpO_2, Oxyhemoglobin dissociation curve, SaO_2, PaO_2, Alveolar air equation, PiO_2, Oxygen, Nasal Cannula.**

I. Introduction

At present, the primary aiding device for a patient who has a problem concerning in respiratory system is respirator called "Nasal Cannula" [1]. The device helps to deliver oxygen in rate of fraction of inspired oxygen (FiO_2) of 0.24-0.44 which depends on arterial oxygen saturation in blood of the patient.

Nasal Cannula is a simple, not expensive medical device. The oxygen intake via this device depends on a difference between the controlled pressure of a gas source and nasal pressure. In fact the effectiveness of treatment by this device depends on lung pathology, the potential of physician to select the proper quantity of intake and also tending while using the device [2]-[4].

We propose in this paper a new computer based system combining to the nasal cannula for automatically controlling quantity of oxygen intake. By using a pulse oximeter as indicator for arterial oxygen saturation in blood (SaO_2) in the feedback loop control, oxygen intake needed, calculated from the model is fed via controlled valves. The process operates on a microcomputer programmed on the LabVIEW™.

The performances of the proposed system were evaluated at the Biomedical Instrument Calibration Unit, Siriraj Hospital, Bangkok, Thailand. The BIO-TEK model index2 series SpO_2 simulators to generate functional pulsatile oxygen saturation levels (%SpO_2) and pulse rate levels, MASIMO pulse oximeter model Rad-9 and HUMONICS model 730 digital flow-meter were employed, respectively. Test results demonstrating close agreement with reference signals are also presented.

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II. Procedure Measurement Description

A. Proposed Measurement and Control Concept

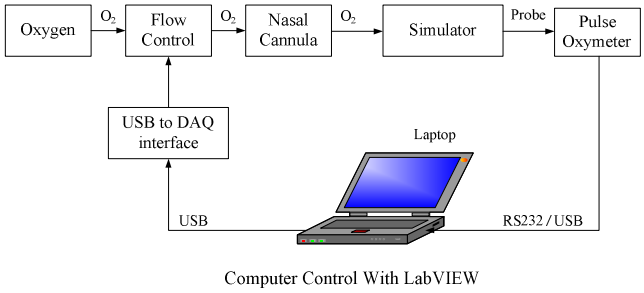

Fig. 1. Proposed measurement and control concept.

Block diagram of operation and main components of the designed system applied to BIO-TEK model index2 series SpO_2 simulators is shown in Fig. 1 consisting of;

1) Pulse oximeter,
2) Computer control with LabVIEW™,
3) USB to DAQ (Data Acquisition) interface,
4) Flow control device,
5) Oxygen container,
6) Nasal Cannula.

The pulse oximetry probe was placed on the simulator of neonate. There were two parameters monitored on the assessments, SpO_2 rate which shown the hemoglobin saturation of the object and heart rate pulse which normally is 60-80 beats/minute [5]. Normally initial pulse oximetry values are obtained in one to three minutes after cord clamping. Oxygen intake are needed when the hemoglobin saturation is indicated below 89 – 94 % such as found in newborn baby who had physiological jaundice or yellowish discoloration of the skin marked arterial desaturation during the early neonatal period [6].

The MASIMO pulse oximeter model Rad-9 was connected to the PC via the serial port (RS232) in order to transfer SpO_2 data used in the process. The rate of partial pressure of oxygen in arterial blood (PaO_2) was then calculated from the model to obtain FiO_2 rate form the Alveolar air equation.

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Finally, Oxygen supplied rate needed as input to nasal cannula was estimated by using FiO_2 rate (as shown in the section D). The suitable oxygen supplied rate could be adjusted by a controlling valve installed between supplying source (oxygen tank) and nasal cannula.

B. Pulse Oximeter

Pulse oximeter is currently used in a variety of clinical settings for noninvasive and continuous monitoring of arterial oxygenation in adults, children and infants. It provides reliable measurement, display and alerts for, functional pulsatile oxygen saturation (SpO_2) and pulse rate [7].

$$\text{Functional Saturation} = \frac{HbO_2}{100-(COHb+METHb)} \quad (1)$$

where HbO_2 is Fractional Hemoglobin, COHb is Carboxy-hemogiobin, and METHb is Methemoglobin [8].

Equation (1) is a functional saturation represents the amount of oxyhemoglobin as a percentage of the hemoglobin that can be oxygenated. Dysfunctional hemoglobins (COHb and METHb) are not included in the measurement of functional saturation. Pulse Rate is calculated by measuring the time interval between the peaks of the infrared light waveform. The inverse of this measurement is displayed as pulse rate.

Pulse oximeter can communicate with other devices using the built-in RS232 compatible serial port. Several serial communications modes are available. They include full format mode. Default mode is usually used for general purpose data collection.

C. Oxyhemoglobin dissociation curve

The oxygen dissociation curve (ODC) [9] of hemoglobin (Hb) has been widely studied and mathematically described for nearly a century. Numerous mathematical models have been designed to predict with ever-increasing accuracy the behavior of oxygen transport by Hb in differing conditions of pH, carbon dioxide, temperature, Hb levels, and 2, 3-diphosphoglycerate concentrations that enable their applications in various clinical situations. The modeling techniques employed in many existing models are notably borrowed from advanced and highly sophisticated mathematics that are likely to surpass the comprehensibility of many medical and bioscience.

A close observation of its sigmoidal shape in Fig. 2 quickly reveals a couple of unique properties, namely, that oxygen saturation (SaO_2) approaches a horizontal asymptote as PaO_2 exceeds 70 mmHg, while it declines precipitously down the steep slope toward a point of inflexion when PaO_2 falls off the "shoulder" of the ODC below 60 mmHg.

One of the earliest mathematical descriptions of the ODC of Hb is the well-known Hill's equation a simple equation proposed in 1910 by Archibald Vivian Hill (1886-1977), a British physiologist and Nobel laureate in Physiology or Medicine [10]. S_{HbO_2}, saturation of HbO_2 ; K_{HBO_2}, net association constant of HbO_2; *n*, Hill coefficient, as in

$$S_{HbO_2} = \frac{[HbO_2]}{[Hb]} \quad (2)$$

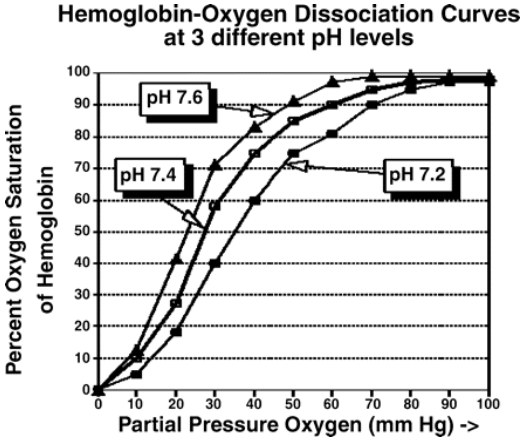

Fig. 2. Oxygen dissociation curves (ODCs) for human hemoglobin (Hb) at 3 different pH levels. The "S" shape of the curves is due to the fact that Hb begins to absorb oxygen rapidly when PaO_2 levels are between 20 and 40 mmHg. The Bohr effect is illustrated here by the shift of the curve to the right as pH decreases. [Reproduced, with kind permission, from Prof. Dave McShaffrey (http://www.marietta.Edu/ mcshaffd).]

$$S_{HBO_2} = \frac{K_{HBO_2}[O_2]^n}{1 + K_{HBO_2}[O_2]^n} \quad (3)$$

These models are unquestionably more complex. As such, it is helpful to introduce students of physiology and biomedicine to the ODC by using only the simplest mathematical principles to achieve better understanding, from which the more discerning and interested with greater mathematical aptitude may subsequently delve further to more complex models if they so desire.

Consider the oxygenation of a Hb molecule as four sequential steps, given that each of the four heme groups within the two α-globin and two β-globin chains binds to a molecule of oxygen. This expression is readily identifiable as having a form similar to the Hill's equation. Refer to (3). SaO_2, can be stated as [11]

$$SaO_2(\%) = \frac{\text{total oxyhemoglobin}}{\text{total Hb}} \times 100 \quad (4)$$

$$SaO_2 = \frac{K[O_2]^4}{1 + K[O_2]^4} \quad (5)$$

Let $x = PaO_2$, where PaO_2 is the partial pressure of oxygen, and let $y = SaO_2$, such that we can then represent (5) algebraically with *y* as a function of *x* as follows:

$$y = \frac{Kx^4}{1 + Kx^4} \quad (6)$$

The configuration of this mathematical relation can be solved by determining the presence of any turning points, points of inflexion, and horizontal or vertical asymptotes. Hence, differentiating *y* with respect to *x* and examine the second derivative of *x* to determine the existence of any points of inflexion along the curve. Hence, differentiating *dy/dx* with respect to *x* yields. This point of inflexion, the value of $y = SaO_2$ from (6) is 37.5 % and $x = \sqrt[4]{3/(5K)}$, $x = PaO_2$ is 22.4 mmHg.

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D. Alveolar air equation

The partial pressure of oxygen in alveoli (PAO_2) is a partial pressure which the crucial step before the gas exchange happened and also specified the variation of oxygenation which helps to monitor the cure result and for understanding clearly the pathology. The oxygen is transferred to cell by simply principle because normally the oxygen is absorbed from high to low intense that called "Diffusion" effected to oxygen deficit [12].

At the atmospheric pressure 760 mmHg, consisted of FiO_2 0.21 and PiO_2 (partial pressure of inspired oxygen) 159.6 mmHg therefore we search for PiO_2 from the equation as below

$$PiO_2 = FiO_2 \times PB \tag{7}$$

The alveolar gas equation [13] for calculating PAO_2 is essential to understanding any PaO_2 value and in assessing if the lungs are properly transferring oxygen into the blood. To clinically interpret PaO_2 [14] one has to also know the patient's partial pressure of carbon dioxide in arterial blood ($PaCO_2$), FiO_2 and the P_B (barometric pressure), all components of the equation for PAO_2 :

$$PAO_2 = (713 \times FiO_2) - \frac{PaCO_2}{0.85} \tag{8}$$

Find V_E (Minute Ventilation) from VT (Tidal volume) and f (Respiratory rate) , then we get [15]

$$V_E = VT \times f \tag{9}$$

$$new\ PaCO_2 \times V_E = old\ PaCO_2 \times V_E \tag{10}$$

$$f_{new} = \frac{PaCO_2}{40} \times f_{old} \tag{11}$$

Solve oxygen (O_2) from nasal cannula

$$O_2(nasal\ cannula) = \frac{X}{60} \times t_{in} + \frac{X}{240} \times t_{out} \tag{12}$$

$$O_2(nasal\ cannula) = \frac{500X}{f} \tag{13}$$

$$O_2(external) = O_2(lung) - O_2(nasal\ cannula) \tag{14}$$

$$O_2(external) = 10m - \frac{500X}{f} \tag{15}$$

were O_2 (litres), f (beats/minute) and, m (kg.)

$$O_2(total) = O_2(nasal\ cannula) + O_2(external) \tag{16}$$

Therefore, in total we can say:

$$FiO_2 = \left[\frac{158{,}000\,X}{m \times old\ PaCO_2 \times f_{old}} + 21\right] \tag{17}$$

$$FiO_2 = \left[1{,}580 \times \frac{X}{PaCO_2 \times f \times m} + 0.21\right] \tag{18}$$

$$PaO_2 \propto PAO_2 \tag{19}$$

$$new\ \frac{PaO_2}{PAO_2} = old\ \frac{PaO_2}{PAO_2} \tag{20}$$

We get the oxygen from nasal cannula:

$$X = \left|\left(\frac{12.96}{PaO_2} - 0.15\right) \times \left(\frac{PaCO_2 \times f \times m}{1580}\right)\right| \quad \text{LPM} \tag{21}$$

E. Software Design

To continuously display SpO_2 and Pulse rate data, the graphical user interface on computer screen has been developed on the LabVIEW™. Fig. 3 shows the block diagram of measured data from pulse oximeter. The adjustable alarm limits for detecting low pulse rate and low SpO_2 events are provided. The pulse oximeter probe-off alarm is also included. And data present as the percentage of SpO_2 into procedure shown in Fig. 4 for drawing graph.

The percentage of SpO_2 data is mapped onto ODC, when ODC already received S-curve file from memory, it will integrate the case history in order to process data for getting PaO_2 rate then calculate for oxygen supplying rate.

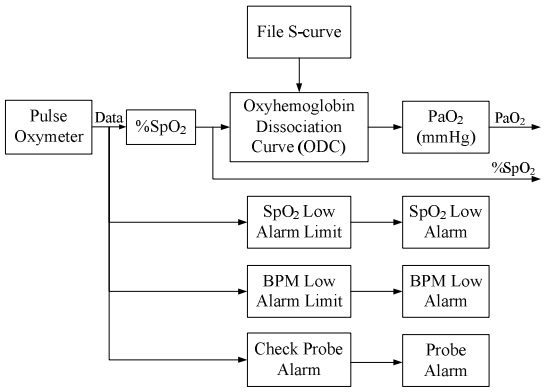

Fig. 3. Block diagram of system data processing.

The rate of Fig. 4 PaO_2 which is calculated by using (21). This equation will program which search for oxygen rate. The input rate is consisted of $PaCo_2$, respiratory rate and mass and this project already have a default for the normal newborn baby which not be a incurrent disease.

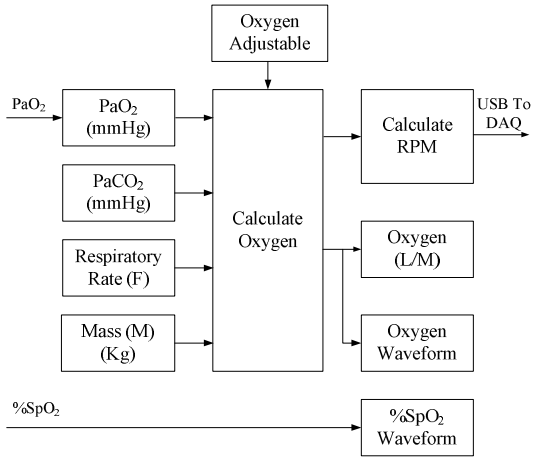

Fig. 4. Block diagram of software data processing.

For $PaCo_2$ rate, We should do the blood gas for getting the accurate oxygen rate. Oxygen rate that received from nasal cannula shows the result as number which measured by litres per minute (LPM) and also presents in waveform then,

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searching for revolutions per minute (RPM) of stepping motor by using oxygen rate and compare with the standard rate by calibration.

F. Flow control of Oxygen

Fig. 5 shows a mechanical part of the system used for oxygen flow control. The commands are transferred from computer into DAQ interface by USB port and DAQ then sends digital data, 8 bits to driver of stepping motor for speed control. The flow is controlled by using rubber tube connecting with oxygen tank pass through a roller tile established on the motoring axle. The rotating speed of this part controls delivering of supplemental oxygen to the nasal cannula. This device consists of a plastic tube which fits behind the ears, and a set of two prongs which are placed in the nostrils. Oxygen flows from these prongs.

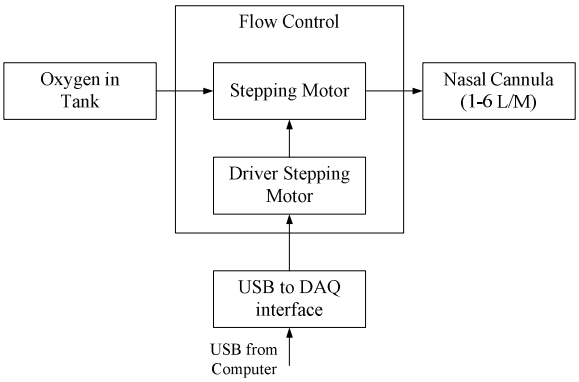

Fig. 5. Block diagram of Flow control Oxygen.

Normally a using nasal cannula is connected to an oxygen tank, a portable oxygen generator, or a wall connection in a hospital via a flow-meter. The nasal cannula delivers 1–6 litres of oxygen per minute. There are also infant or neonatal nasal cannula which carry less than one litre per minute with smaller prongs. The oxygen fraction provided to the patient ranges roughly from 24% to 44%.

We also, in the experiments, tested the proportion of oxygen flow rate and rotating rate of driving stepping motor by using digital flow-meter with flow control oxygen to control the quantity of fleeting oxygen as calculated rate.

III. Experimental Results

To preliminarily verify the performances of the automatic control oxygen intake from blood oxygen saturation, we used the BIO-TEK model index2 series SpO_2 simulators to generate variable SpO_2 and employed MASIMO pulse oximeter model Rad-9 for measuring the SpO_2.

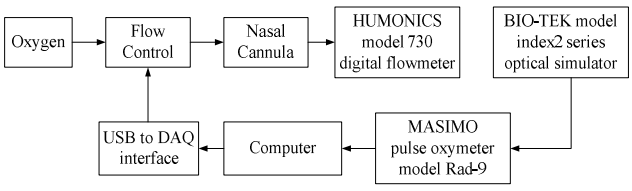

Fig. 6. Block diagram of system data processing.

The generated SpO_2 of 50% to 100% corresponding pulse rate of 50 to 100 bpm were used as calibrating values for adjustment of the flow rate. A precision flow-mete (HUMONICS model 730 digital) was used to measure oxygen flow rate at nasal cannula tip as shown in Fig. 6.

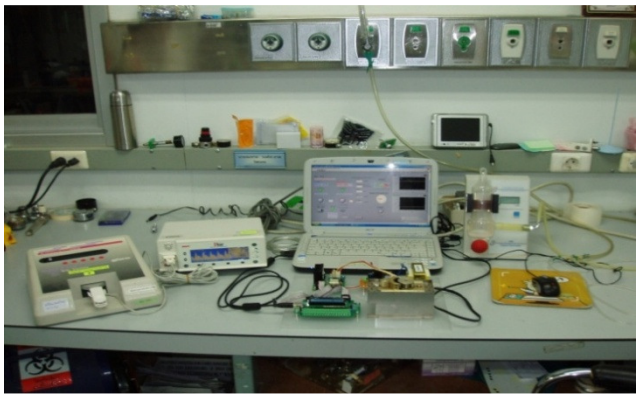

Fig. 7. Overall hardware of the proposed system.

Fig. 7 shows the overall hardware connection of the proposed system for experiment setup. Measured results for eleven different values of $\%SpO_2$ level, i.e. 100%, 95%, 90%,85%,80%, 75%, 70%, 65%,60%, 55%, and 50% are summarized in Table 1. To test the repeatability, the measurement was similarly carried on five times for each $\%SpO_2$ value. Setting parameters such as $PaCo_2$ of 40 mmHg, respiratory rate of 50 beats/minute and body weight of 3 kg. was used for simulated normal newborn baby [16].

TABLE I
MEASURED RESULTS FOR SPO_2 AND OXYGEN FLOW RATE

% SpO_2	Measured Value of Oxygen (L/M)					Average	Caculated
	1st	2nd	3th	4th	5th		
100	0	0	0	0	0	0	0
95	0.06	0.06	0.06	0.06	0.06	0.06	0.063
90	0.22	0.23	0.23	0.22	0.24	0.228	0.23
85	0.35	0.34	0.37	0.35	0.38	0.358	0.37
80	0.5	0.49	0.53	0.5	0.5	0.504	0.51
75	0.61	0.65	0.62	0.63	0.62	0.626	0.63
70	0.74	0.75	0.75	0.73	0.74	0.742	0.74
65	0.85	0.84	0.84	0.85	0.86	0.848	0.85
60	0.95	0.93	0.94	0.95	0.95	0.944	0.95
55	1.0	1.1	1.0	1.0	1.1	1.040	1.05
50	1.3	1.1	1.1	1.2	1.2	1.18	1.2

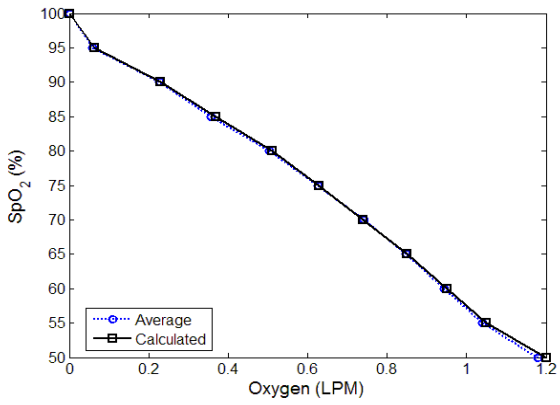

Fig. 8. The results of the system from Table 1.

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The very close correlation of measured oxygen flow rate needed to compensate for changed SpO_2 with one from calculation are shown in Fig. 8.

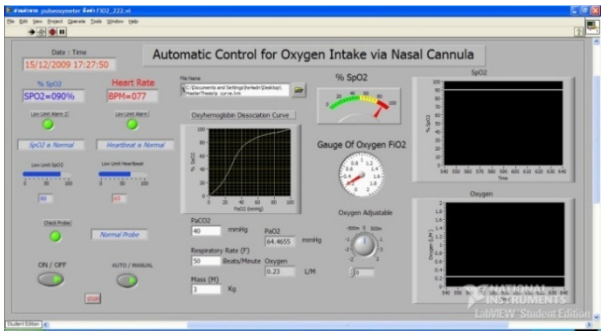

Fig. 9. Sample of developed LabVIEW window.

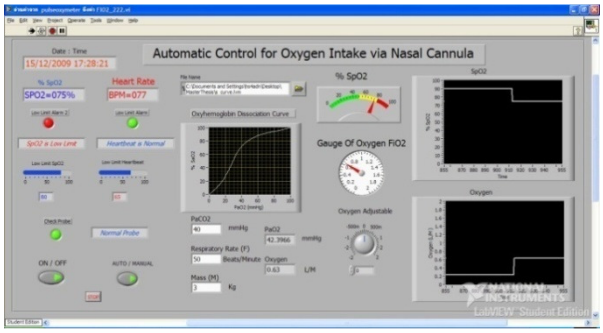

Fig. 10. SpO_2 alarm and warning message.

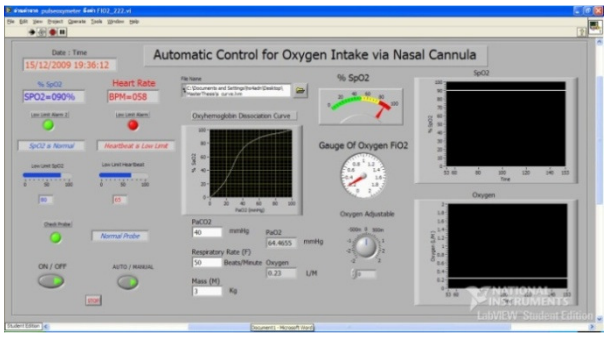

Fig. 11. Pulse rate alarm and warning message.

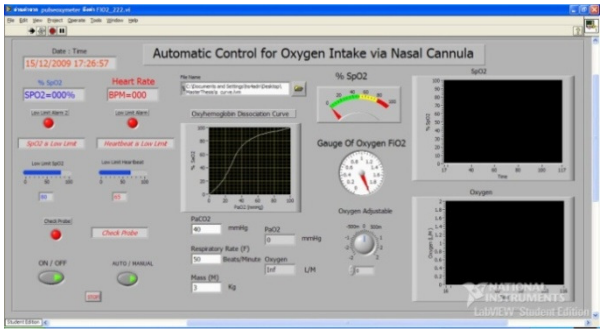

Fig.12. Probe-off alarm and warning message.

Fig. 9 to Fig. 12 shows the samples of the developed LabVIEW windows during operations. Some measured parameters are monitored with warning messages such as probe-off alarm and over and under setting value alarms.

IV. CONCLUSIONS

A design and implementation of system used for automatically supply oxygen intake via nasal cannula has been proposed. The blood oxygen saturation obtained from a pulse oximeter is employed to estimate, from purposed model, the quantity of oxygen needed for a patient. The performance of the system was evaluated by operating with a SpO_2 simulator showing satisfied results as we have targeted. In future work we will apply the system to neonates.

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