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Automatic Control of Fraction of Inspired Oxygen in Neonatal Oxygen Therapy using Fuzzy Logic Control

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***Abstract*:** Premature babies of less than 37 weeks gestation might require oxygen therapy as an integral part of treatment and respiratory support. Because of their under-developed lungs, these so-called "preemies" might contract respiratory distress syndrome (RDS). To treat RDS, neonatal oxygen therapy is administered, where controlled oxygen gas is measured as a fraction of inspired oxygen (FiO_2). However, exposure to high oxygen content during long treatment could cause oxygen intoxication, which might cause permanent blindness due to retinopathy of prematurity (ROP), whereas insufficient oxygen exposure could cause severe hypoxia. A doctor would use oxygen saturation (SpO_2) data and prescribe a dose of FiO_2 to maintain SpO_2 within a suitable range. One objective is to maintain SpO_2 within the acceptable range using FiO_2 that is as low as possible. Adjustment of FiO_2 would normally be done by nurses every 15 to 30 minutes, which might not be safe in many situations. An error in FiO_2 adjustment during a manual procedure could be as large as +/- 2.5%. This paper presents a system that can determine an FiO_2 value suitable to the current SpO_2 and that automatically adjusts FiO_2 with an error clearance of +/- 0.25%.

***Keywords*:** Fuzzy logic control, Fraction of inspired oxygen, Neonatal oxygen therapy

1. Introduction

Oxygen saturation (SpO_2) is a parameter used to indicate the percentage of oxygen content in hemoglobin blood cells (oximetry), and it can be measured without an invasive procedure by using a device called an oxygen pulse meter. The measurement is done by clamping the sensor of the oxygen pulse meter onto a patient's fingertip. People with normal lung function have SpO_2 levels between 98% and 100% [1]. If a person has an SpO_2 level below 90%, it means that person is suffering from hypoxia (inadequate oxygen supply for the body). Premature infants born at less than 37 weeks gestation often have lung development problems. These patients might not have full lung function, which can result in SpO_2 levels less than 90%. To improve the SpO_2 level, an external oxygen supply is required via ventilation machine. In order to help a patient develop a normal lung function and to minimize complications from respiratory distress syndrome (RDS), doctors prescribe oxygen therapy. Oxygen therapy is medical intervention with the administration of oxygen in order to ensure adequate tissue oxygenation and cell metabolism. The main purpose of oxygen therapy in premature infants is not only to support life, but to also stimulate lung development. The procedure supplies a mixture of oxygen and pure pressurized medical-grade air via ventilation machine in order to maintain the SpO_2 level between 90% and 95% [2, 3]. Fraction of inspired oxygen (FiO_2) is a parameter that indicates the percentage of oxygen content in air, and it has a value between 21% and 100% [4]. If oxygen content is too high (i.e., the FiO_2 percentage is too high), a patient might suffer from oxygen intoxication, which can cause retinopathy of prematurity (ROP) resulting in permanent blindness. On the other hand, inadequate oxygen content (an FiO_2 percentage that is too low) cannot help to maintain an appropriate SpO_2 level and could introduce hypoxia resulting in death. To provide oxygen therapy, registered nurses are responsible for adjusting FiO_2 based on the patient's current SpO_2 level. Although we have limited knowledge as to how much oxygen these patients actually need, or how much oxygen is safe to give, it is in the best interest of the patient to adjust the FiO_2 level in as close to real time as possible [1-3, 5]. Lim et al. [6] compared the effectiveness of oxygen therapy in preterm infants via manual FiO_2 adjustment against automatic FiO_2 adjustment. The results concluded that automatic FiO_2 adjustment meant infant patients required less average oxygen content in order to maintain an SpO_2 level within an appropriate range. Because SpO_2 can be monitored nearly in real time, an automatic control system for FiO_2 can be designed and implemented [7, 8]. However, control algorithms [6-8] are still subject to rule-based control that could cause an abrupt change in the FiO_2 level. In many situations, an abrupt change in FiO_2 level could cause an unstable SpO_2 level and reduce the benefit of oxygen therapy. Morozoff and Saif [9] used a MATLAB Simulink model to compare the performance of a manual system, a fuzzy logic control system, and a proportional-integral-derivative (PID) control system in order to maintain the stability of FiO_2 and SpO_2 levels. The results presented by Morozoff and Saif [9] showed that a fuzzy logic control system tends to provide better results from a robustness and precision perspective, compared with manual and PID control systems. Taube and Bhutani [10] used a classic feedback PID control methodology to control peripheral capillary saturation (SaO_2), which has a linear relationship to SpO_2 level. A PID control system presented a large time lag in FiO_2 adjustment, and was too slow in responding to a neonatal with unstable RDS.

Work in this paper designs and implements a fuzzy logic embedded system for FiO_2 control based on computed oxygen and air flow rate settings for digitally controllable valves. The system was tested by using three sets of data from three premature infants recorded in the neonatal intensive care unit (NICU) for the Department of Pediatrics, Ramathibodi Hospital, Bangkok, Thailand. The results demonstrated that with this system, the FiO_2 level fluctuates less than seen in other rule-based control results [7, 8]. This paper also shows how a fuzzy logic control algorithm implemented in an embedded system responds to a change in FiO_2 level. The error clearance of the implemented system controlling FiO_2 level is +/- 0.25%, compared with +/- 1% to +/- 2.5% with manual FiO_2 level adjustment using oxygen–air mixture equipment.

2. Design of the System

The system is composed of two independent digital mass flow controllable valves (SmartTrak 50 mass flow controller from Sierra Inc.) for oxygen and medical compressed air. The SmartTrak 50 mass flow controller has an error clearance of +/- 1% of the full-scale flow rate in units of standard liters per minute (SLPM). Lim et al. [6] showed that FiO_2 and SpO_2 levels have a strong mathematical positive correlation. As a result, to reduce the SpO_2 level means reducing the FiO_2 level, and vice versa. Since no one can control SpO_2 directly, the only possible non-invasive way of controlling SpO_2 is to control the FiO_2 level instead. FiO_2 can be adjusted by propor-tional flow rate control of air and oxygen as follows:

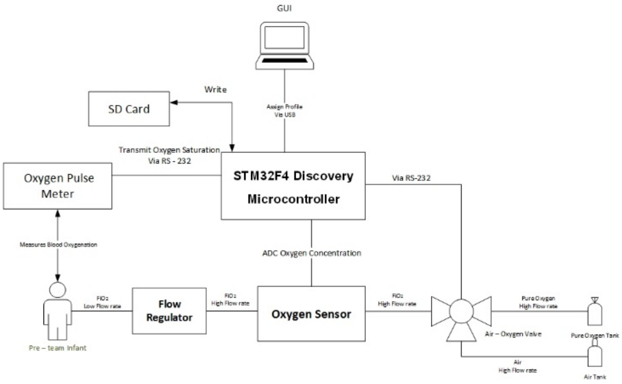


Fig. 1. The overview of system components.

$$FiO_2 = \frac{0.21F_{air} + F_{oxygen}}{F_{air} + F_{oxygen}} \tag{1}$$

where FiO_2 is a percentage of fractional inspired oxygen, and F_{air} and F_{oxygen} are flow rates in SLPM of pure medical air and oxygen gas, respectively.

The control system is composed of one microcontroller, two digital mass flow controllers for compressed medical air and medical-grade oxygen, one gas mixing chamber, one medical oxygen sensor, one oximeter, and two mass flow meters, as shown in Fig. 1. An oximeter measures the SpO_2 of the patient and sends data on the SpO_2 percentage and the subject's pulse rate to a microcontroller via an RS-232 (UART) port. Once the data are received, the microcontroller uses a fuzzy logic control algorithm to determine the desired FiO_2 according to the current SpO_2 level. Then, the desired FiO_2 is computed by setting air flow rate and oxygen flow rate using a fuzzy logic control algorithm. These settings are sent to the mass flow controllers to adjust air flow rate and oxygen flow rate in order to change the content of the intake gases in a gas mixing chamber designed specifically for this system. It was designed to create vortex gases to help the gas content mixing process. The gas mixing chamber is an important component in this control system. It directly contributes to FiO_2 response time and FiO_2 volatility due to the physics of fluid motion. If the chamber was designed to contain large amounts of mixed gas (more than 0.1 liters of O_2 and medical air), then the response time with FiO_2 changes would increase while FiO_2 volatility would be reduced. On the another hand, if the chamber contains lower amounts of mixed gas, the response to FiO_2 changes would be fast, but FiO_2 volatility might increase. In this research, the gas mixing chamber was designed to contain mixed gas of approximately 0.05 liters at a room temperature of 25 degrees centigrade. Then, actual mass flow rates of air and oxygen are measured in SLPM and are sent back to the microcontroller as error feedback data. A medically

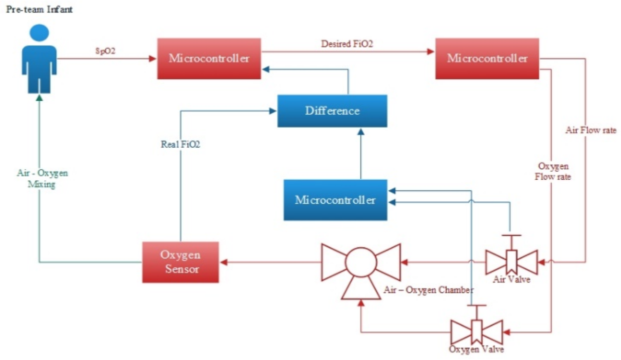
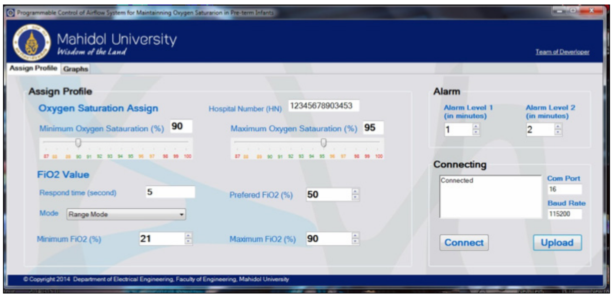


Fig. 2. Data flow of the control system.



Assign Profile

Oxygen Saturation Assign

Hospital Number (HN) 12345678903453

Minimum Oxygen Satauration (%) 90

Maximum Oxygen Satauration (%) 95

FiO2 Value

Respond time (second) 5

Prefered FiO2 (%) 50

Mode Range Mode

Minimum FiO2 (%) 21

Maximum FiO2 (%) 90

Alarm

Alarm Level 1 (in minutes) 1

Alarm Level 2 (in minutes) 2

Connecting

Connected

Com Port 16

Baud Rate 115200

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Fig. 3. Example GUI for patient profile setting.

approved oxygen sensor (MAX-16 from Maxtec) is used to measure real FiO_2. The sensor output is from 12mV at 21% FiO_2 to 60mV at 100% FiO_2. This output is amplified using a rail-to-rail instrumental amplifier, then digitized via ADC module (12-bit quantization from 0.1V to 3.3V at a sampling rate of 1 sample per second). Fig. 2 shows how these data are sent back to the control system.

Patient data, including SpO_2, settings for air and oxygen flow rates, actual flow rates, desired FiO_2, and real FiO_2 are recorded in real time on an SD card. These data are essential, so nurses and doctors can evaluate patient progress and create a better care plan suitable to a particular patient. To change the FiO_2 prescription dosage in oxygen therapy, doctors enter the following parameters: desired FiO_2 range (%), desired SpO_2 range (%), response time (seconds), and alarm condition. They create a patient treatment profile using the graphical user interface (GUI) of the customized application which is shown in Fig. 3. The profile is sent to the microcontroller via USB port. Input for the response time is a setting for the time period that the system allows a subject's SpO_2 to exceed the SpO_2 range (assigned by minimum and maximum oxygen saturation percentages). If a subject's SpO_2 is outside the acceptable range longer than the response time, the system starts to control FiO_2 to adjust the SpO_2, bringing it back into the acceptable range. There are two levels of system alarm: alarm level one and alarm level two. If an alarm is engaged, it means a patient's SpO_2 is outside the acceptable range longer than the time period set for either alarm level one or alarm level two. Alarm level one has a light–visual alert using a super-bright LED, and alarm level two adds a sound alert. When the alarm is activated, the system immediately initiates an FiO_2 manual override control feature for medical staff.

3. System Control Methodology

3.1 Oxygen Saturation Control

3.1.1 SpO_2 Control Using Rule Bases

The system was designed to maintain current SpO_2 at a preferred level, which is a middle point of the desired SpO_2 range [7, 8]. An algorithm increases the FiO_2 percentage if the current SpO_2 is below the preferred SpO_2 longer than the response time set in the patient's profile. On the other hand, it decreases the FiO_2 percentage if the current SpO_2 exceeds the preferred SpO_2 for longer than the set response time. The FiO_2 adjustment range is from 2% to 6% depending on the error of the preferred SpO_2 and the actual SpO_2. The alarm condition in a patient profile helps to alert medical staff in case actual SpO_2 cannot be achieved and it is outside the desired SpO_2 range longer than a predefined time window.

3.1.2 SpO_2 Control Using Fuzzy Logic Control

The system uses fuzzy logic control in order to achieve better control of FiO_2 and SpO_2 according to the patient's profile. The system receives the patient's profile information, including the range of the desired SpO_2 for the particular subject. For example, a desired SpO_2 range might be between 90% and 95% for a particular patient.

The fuzzy logic control system requires two types of SpO_2 input: absolute error and an error rate. The absolute error is a value outside the SpO_2 range. If the current SpO_2 percentage level is within the desired SpO_2 range (which in this example was set to 90-95%), the error is equal to zero. The error rate is the value of SpO_2 compared to values at the beginning and in the present. The membership functions of a fuzzy set are positive big (PB), positive medium (PM), positive small (PS), zero (ZO), negative small (NS), negative medium (NM), and negative big (NB). The error rate inputs have membership functions in the fuzzy set of very positive (VP), positive (P), zero (ZO), negative (N) and very negative (VN). Output is the desired gain in FiO_2 value, which depends on the look-up table for the error input and the error rate input [9]. Then, this desired gain in FiO_2 is transformed into two settings for air and oxygen mass flow rates. The system records actual data every second and re-evaluates the desired FiO_2 percentage in every response time period predefined in the patient's profile.

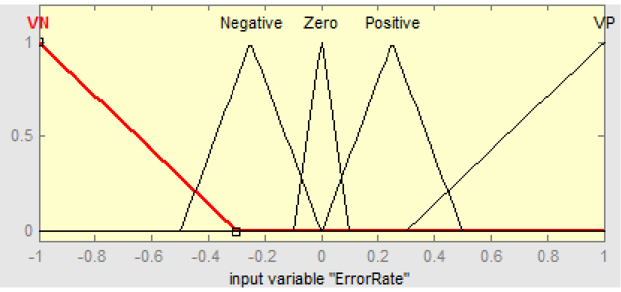

Fig. 4. The membership functions of the "error rate" input.

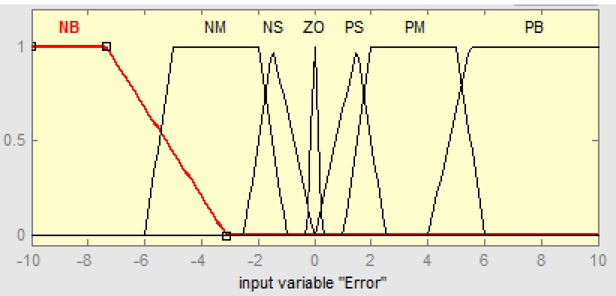

Fig. 5. The membership functions of the "error" input.

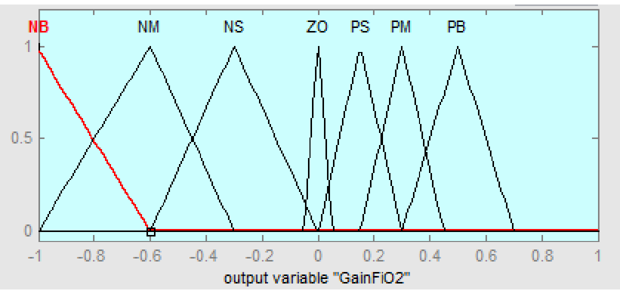

Fig. 6. The output membership functions.

3.2 FiO$_2$ Control

The system will control air flow rates and oxygen flow rates to control the error in FiO$_2$ percentage level, maintaining a range of +/- 0.25% from the preferred FiO$_2$ percentage level. This error of +/- 0.25% is better than from using the mechanical gas mixture valve normally used in the NICU, which has an error of +/- 1% to +/- 2.5% when controlling FiO$_2$ level. Also, with this control algorithm, the designed system can help reduce the cost of using high-performance mass flow controller valves in order to achieve highly accurate control of FiO$_2$ percentage levels.

3.2.1 Nature of FiO$_2$ Percentage Level Control

The control model was designed based on the assumption that FiO$_2$ percentage level can be controlled according to the system transfer function in (1). The function shows that FiO$_2$ percentage level is a function of oxygen flow rate (F_{oxygen}) and medical air flow rate (F_{air}) in SLPM at a room temperature of 25 degrees centigrade. To increase the FiO$_2$ percentage level, the system has to increase F_{oxygen} and either decrease or maintain the value of F_{air} depending on the value of the desired FiO$_2$ percentage level set for current patient's SpO$_2$. To decrease the FiO$_2$ percentage level, the system has to decrease F_{oxygen} and either increase or maintain the value of F_{air} depending on the value of the FiO$_2$ percentage level set for the patient's SpO$_2$. However, increments and reductions of either F_{air} or F_{oxygen} will increase or decrease the total gas flow rate supplied to a gas mixing chamber, and has a direct effect on the output mixed gas flow rate of a ventilator. As a result, the output minimum and maximum gas flow rates of the system are set to 0 SLPM to 15 SLPM for each type of gas. The minimum total flow rate of mixed gas is 0 SLPM, and the maximum total flow rate of mixed gas is 30 SLPM. In normal operation, the system attempts to maintain total flow rates at less than 15 SLPM in order to comply with the flow regulator used in a hospital.

3.2.2 FiO$_2$ Control Using a Fuzzy Logic Control Algorithm

After the desired FiO$_2$ percentage suitable to the current SpO$_2$ of a patient has been identified, the suggested FiO$_2$ percentage is used to determine values of F_{air} and F_{oxygen} to use as initial points in FiO$_2$ control.

The inputs to fuzzy logic control are FiO$_2$ error, current F_{air}, and current F_{oxygen}. FiO$_2$ error is the difference between current FiO$_2$ and the desired FiO$_2$. The actual current flow rates of air and oxygen are read from mass flow meters in units of SLPM. The membership functions of the FiO$_2$ error are very negative (VN), medium negative (MN), zero (ZO), medium positive (MP), and very positive (VP). The membership functions of the current flow rate of

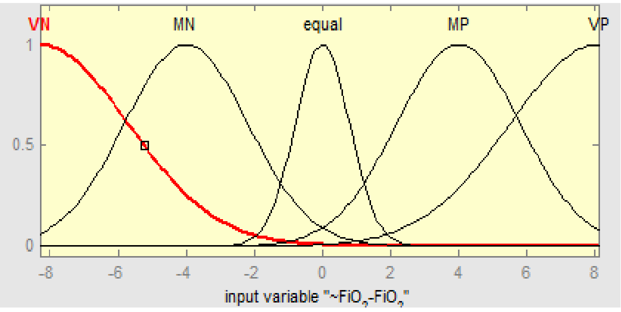

Fig. 7. The membership functions for FiO$_2$ error input.

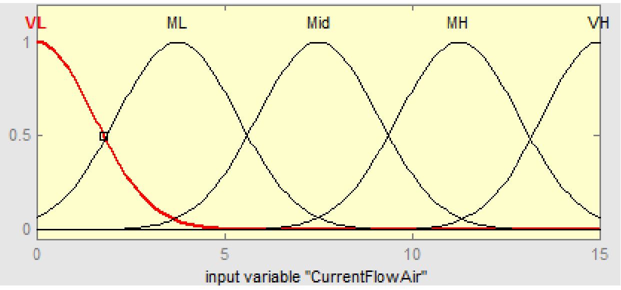

Fig. 8. The membership functions for current air flow rate input.

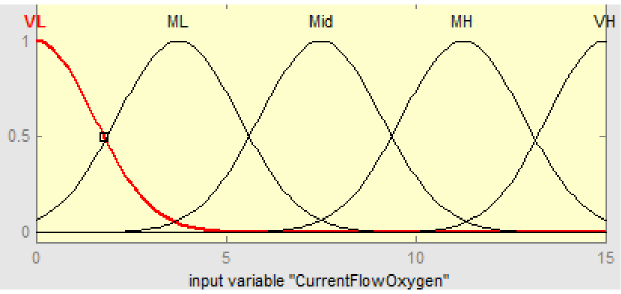

Fig. 9. The membership functions for current oxygen flow rate.

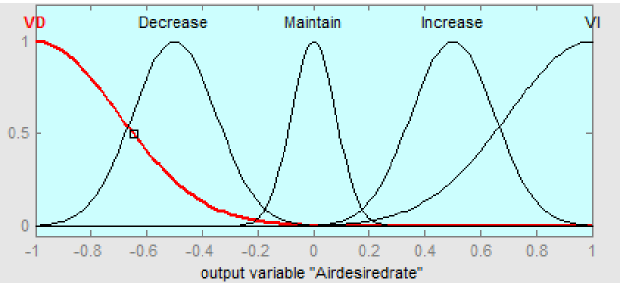

Fig. 10. The membership functions for desired air output.

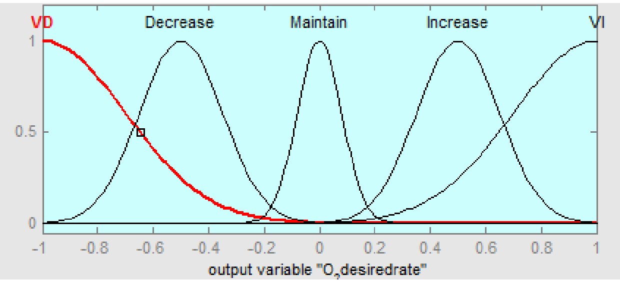

Fig. 11. The membership functions for desired oxygen output.

Table 1. Look-up table for FiO_2 percentage fuzzy control.

		Current Air	VL		ML		Mid		MH		VH	
		Current O_2	O_2 output	Air output	O_2 output	Air output	O_2 output	Air output	O_2 output	Air output	O_2 output	Air output
Error FiO2	Negative	VL	VI	D	VI	D	VI	VD	VI	VD	VI	VD
		ML	VI	D	VI	D	VI	VD	VI	VD	VI	VD
		Mid	I	D	I	D	I	D	I	VD	VI	VD
		MH	M	D	I	D	I	D	I	VD	I	VD
		VP	M	D	M	VD	M	VD	M	VD	M	VD
	MN	VL	I	M	I	M	VI	D	I	D	VI	VD
		ML	I	M	I	M	I	D	I	D	I	VD
		Mid	I	M	I	D	I	D	M	D	I	VD
		MH	M	D	M	D	M	D	M	D	M	VD
		VP	M	D	M	VD	M	VD	M	VD	D	VD
	Zero	VL	M	M	M	M	M	M	M	M	M	M
		ML	M	M	M	M	M	M	M	M	M	M
		Mid	M	M	M	M	M	M	M	M	M	M
		MH	M	M	M	M	M	M	M	M	M	M
		VP	M	M	M	M	M	M	M	M	M	M
	MP	VL	M	VI	M	I	D	VI	D	I	D	M
		ML	D	I	D	I	D	I	D	VI	D	M
		Mid	D	I	D	I	D	I	VD	I	VD	M
		MH	D	I	VD	I	D	I	VD	I	VD	M
		VP	VD	VI	VD	I	VD	I	VD	I	VD	M
	Positive	VL	D	VI	D	VI	D	VI	D	I	D	M
		ML	D	VI	D	VI	D	VI	D	I	D	M
		Mid	D	VI	D	VI	D	VI	VD	I	VD	M
		MH	VD	VI	VD	VI	VD	VI	VD	M	VD	M
		VP	VD	VI	VD	VI	VD	VI	VD	M	VD	M

air and oxygen are very low (VL), medium low (ML), middle (Mid), medium high (MH) and very high (VH).

The outputs of fuzzy logic control are the desired oxygen flow rate and the desired air flow rate, which depend on a look-up table for FiO_2 error input, the current air flow rate, and the current oxygen flow rate. Both output flow rate values will be combined with the current flow rates and the desired flow rates. The responses to both outputs are rapid decrease (VD), decrease (D), maintain (M), increase (I), and rapid increase (VI).

4. Experiments and Results

4.1 Oxygen Saturation Control

To test both a rule-based control algorithm and a fuzzy logic control algorithm, three unrelated babies who were born at less than 37 weeks gestation and diagnosed with respiratory distress syndrome by pediatricians were selected as subjects for study. They had been prescribed oxygen therapy and were admitted to the neonatal

Table 2. Look-up table for SpO_2 fuzzy control.

	Error rate				
Error	**Very Positive**	**Positive**	**Zero**	**Negative**	**Very Negative**
PB	NB	NB	NM	NS	ZO
PM	NB	NM	NM	NS	ZO
PS	NM	NS	NS	ZO	PS
ZO	NM	NS	ZO	PS	PM
NS	NS	ZO	PS	PS	PM
NM	ZO	PS	PM	PM	PB
NB	ZO	PS	PM	PB	PB

intensive care unit of Ramathibodi Hospital, Mahidol University, Bangkok, Thailand. The safety of the patients was top priority, and the medical staff was on duty during the experiments. Since the system is a prototype and the main purpose of testing was to ensure the outcome of FiO_2 percentage level under real SpO_2 data, the experiments were designed to only use the system to receive SpO_2 and pulse data from the subjects, but it did not supply mixed gas directly. The SpO_2 data were sent to the micro-controller to compute a desired FiO_2 percentage based on an allowable SpO_2 range of 90-95%. Then, the system determined two settings for air and oxygen flow rates, which were sent to two mass flow controllers. The response time of the system was set to 20 seconds for all subjects for both testing algorithms (a rule-based control system and a fuzzy control system). All mass flow controllers were connected to gas supply outlets for pressurized medical air and pressurized medical oxygen. The input pressures of medical oxygen and medical air were above 65 psi. The temperature of the gases was approximately 25 degrees centigrade. The maximum flow rates of the gases were set at 15 SLPM via normal gas flow regulators, while the mass flow controllers could control flow rates from 0.1 SLPM to 20 SLPM with a clearance of +/- 1% of 20 SLPM. The oxygen sensor was exposed to normal room temperature (25-28 degrees centigrade) and a normal atmosphere (1 atm) for at least 30 minutes before being used in the experiments. The profiles were unique for all three subjects and were set by using the GUI shown in Fig. 3. The actual FiO_2 values were measured by an oxygen sensor (MAX-16 from Maxtec Inc.) then amplified and digitized (12-bit quantization from 0.1V to 3.3V) for every 1 second. The length of the experiments for each subject was 2,600 seconds.

Figs. 12, 13, and 14 for subjects 1, 2, and 3, respec-

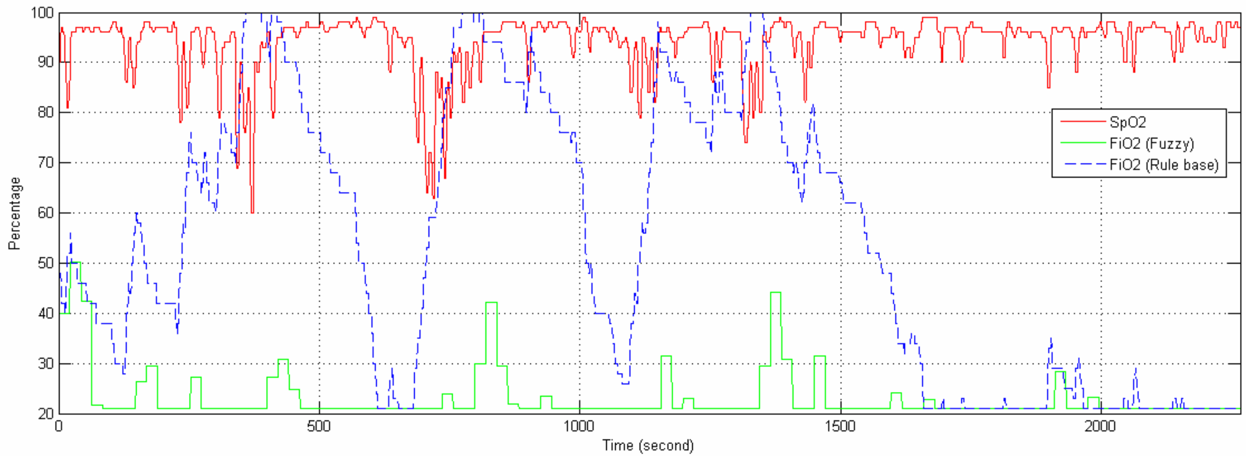

Fig. 12. The results of SpO_2 and FiO_2 response from rule-based and fuzzy control in subject 1.

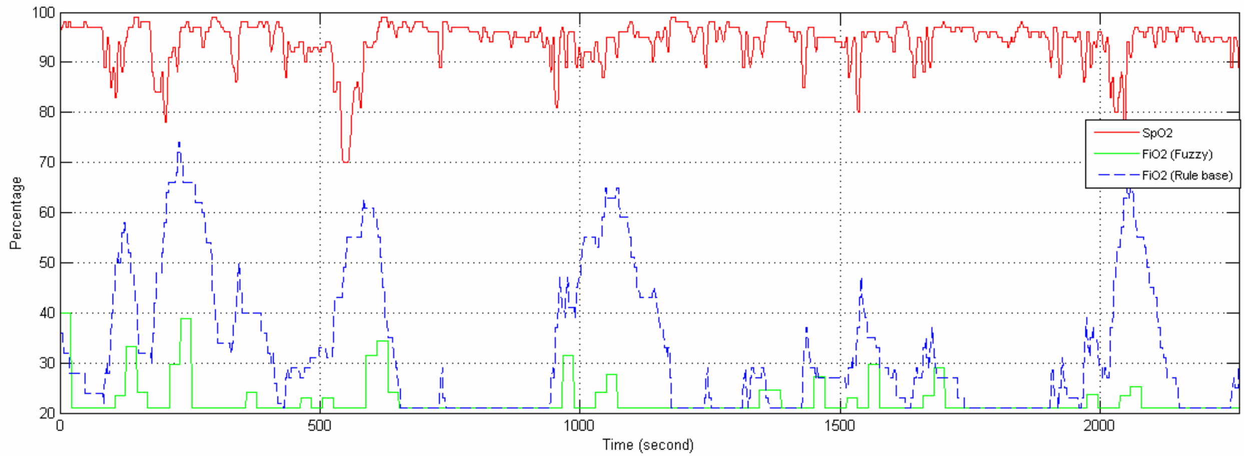

Fig. 13. The results of SpO_2 and FiO_2 response from rule-based and fuzzy control in subject 2.

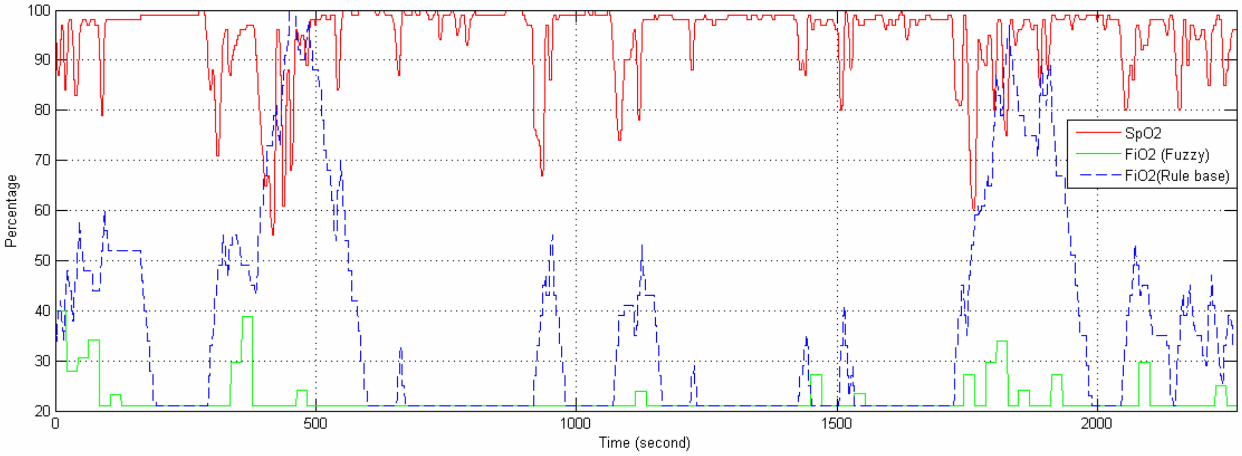

Fig. 14. The results of SpO_2 and FiO_2 response from rule-based and fuzzy control in subject 3.

tively, illustrate the percentages of actual FiO_2 values from the rule-based algorithm (blue dash lines) and from the fuzzy logic algorithm (green solid lines). SpO_2 data of a subject are shown as a red solid line. Subject 1 had the most fluctuation in oxygen saturation, according to the SpO_2 data shown in Fig. 12. The actual FiO_2 results for subject 1 from both algorithms were also the most volatile, compared with the actual FiO_2 results of subject 2 and subject 3. To consider peaks of actual FiO_2 results from both algorithms, Figs. 12, 13 and 14 show that both algorithms are associated with sudden drops in the subjects' SpO_2. The reason for these drops could be from either deterioration of the subjects' respiratory systems, including a blockage of the upper airways caused by RDS, or interruption of mixed gas supply to the subjects. Since the experiment was closely supervised by medical staff, and the system could easily detect a sudden drop in air flow rates due to interruption of the gas supply, a sudden drop in SpO_2 was considered to be from RDS. The FiO_2 results of the rule-based control system were much higher than actual FiO_2 results from the fuzzy control system. In generally, the low FiO_2 is preferable because it reduces the risk of ROP and can help to stimulate the subjects' lung development. Table 3 illustrates the first order statistical data of SpO_2 percentages and FiO_2 percentages from both algorithms. The average values of FiO_2 from rule-based control in all subjects were higher than FiO_2 percentages from fuzzy logic control. The maximum FiO_2 percentages from rule-based control could reach 100%, which is unrealistic in normal situations. Supplying 100% medical oxygen to subjects would be a risk to the subjects' health and had to be avoided.

Table 3. Results of SpO_2 and FiO_2 from both control algorithms.

		Subject 1	Subject 2	Subject 3
SpO_2	Average	94.0273%	91.7375%	94.9031%
	Maximum	99%	99%	100%
	Minimum	60%	61%	55%
FiO_2 Rule-based	Average	53.9096%	59.7367%	36.3604%
	Maximum	100%	100%	100%
	Minimum	21%	21%	21%
FiO_2 Fuzzy logic	Average	23.1672%	25.0031%	22.3116%
	Maximum	50.2648%	92.1455%	40%
	Minimum	21%	21%	21%

4.2 Results of FiO_2 Control

The linear control experiment and the fuzzy logic control experiment were tested by using pressurized medical air and pressurized medical oxygen in the Eye and Otolaryngology in-patient department ward, Ramithibodi Hospital, Mahidol University, Bangkok, Thailand. Pressurized medical gases were delivered from hospital gas pipelines via two standard individual gas outlets. Two normal gas flow regulators were used to connect gas pipes of the test system to air and oxygen gas outlets. Both flow regulators were controlled for maximum flow rates of 15 SLPM.

For the linear control algorithm, the system initially set the oxygen flow rate to 15 SLPM and the air flow rate to 0 SLPM. The system decreased the oxygen flow rates by 0.5 SLPM per step, and increased the air flow rates by 0.5 SLPM per step. Then, the system waited 20 seconds for an oxygen sensor to send back an actual reading of the FiO_2 value. Fig. 15 illustrates the results of the percentages of actual FiO_2 from linear control, compared to the ideal FiO_2 from calculations using the system transfer function in (1). The results of the real FiO_2 readings can be seen as a linear function, but a gradient of the function is not the same as an ideal FiO_2 according to the system transfer function. The maximal error under linear control is 5.26% at the high and low FiO_2 values; the minimal linear control error is 0.224% at the medium FiO_2 value; and the average linear control error is 2.6454%. These errors were considered too large for use in a critical application, such as the one in this paper. As a result, a better control algorithm for FiO_2 had to be developed in order to set an actual FiO_2 to be exact at the desired FiO_2 as determined by the current SpO_2 of a patient.

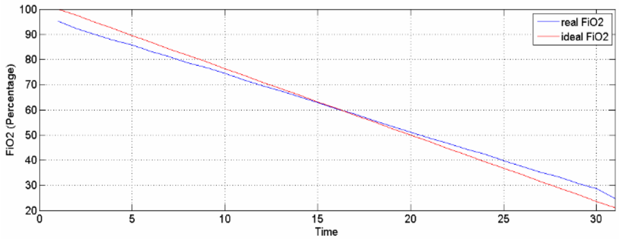

Fig. 15. The response of a fuzzy control system to control output of FiO_2 from 21% to 100% compared with the FiO_2 transfer function.

For the fuzzy logic control algorithm, the system set the target FiO_2 according to the desired FiO_2 determined by the current SpO_2 of a subject, and the system increased or decreased either air flow rate or oxygen flow rate based on the fuzzy logic control algorithm. The allowable error clearance of the control system was set to +/- 0.25% of the FiO_2 level. The read method for an actual FiO_2 percentage level was set to be the same as in previous experiments. The convergence time of the fuzzy logic control experiment would depend on the difference between a desired FiO_2 and the current FiO_2. Figs. 16 to 25 illustrate the results of fuzzy logic control for a set of desired FiO_2

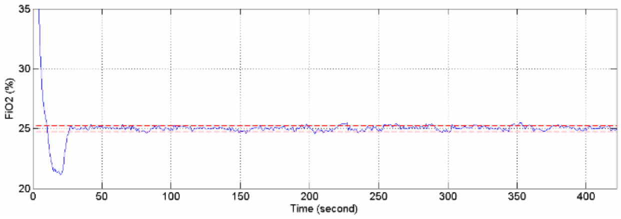

Fig. 16. The FiO_2 control result using fuzzy logic control (desired FiO_2 = 25%, initiated FiO_2 = 50%, time to desired FiO_2 target = 30 seconds).

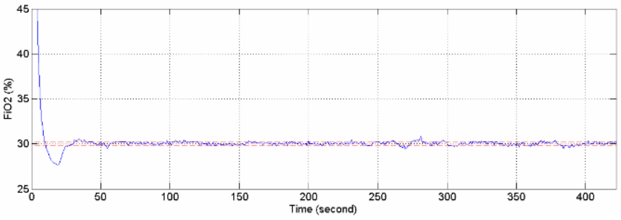

Fig. 17. The FiO_2 control result using fuzzy logic control (desired FiO_2 = 30%, initiated FiO_2 = 50%, time to desired FiO_2 target = 68 seconds).

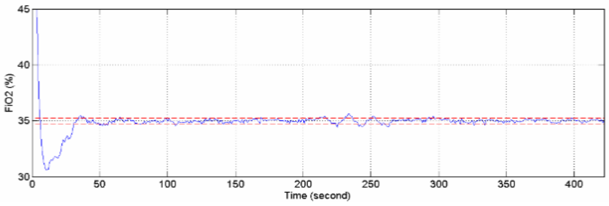

Fig. 18. The FiO_2 control result using fuzzy logic control (desired FiO_2 = 35%, initiated FiO_2 = 50%, time to desired FiO_2 target = 58 seconds).

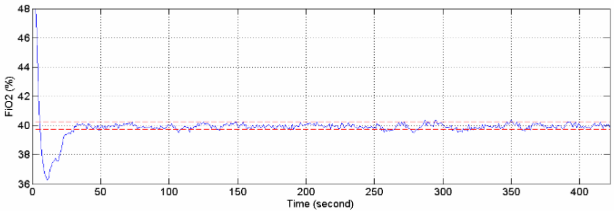

Fig. 19. The FiO_2 control result using fuzzy logic control (desired FiO_2 = 40%, initiated FiO_2 = 50%, time to desired FiO_2 target = 35 seconds).

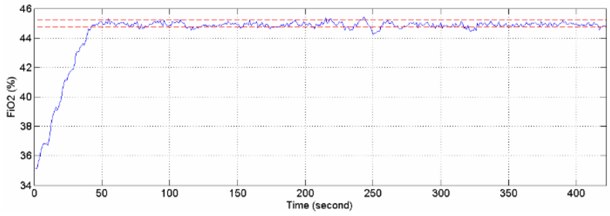

Fig. 20. The FiO_2 control result using fuzzy logic control (desired FiO_2 = 45%, initiated FiO_2 = 21%, time to desired FiO_2 target = 48 seconds).

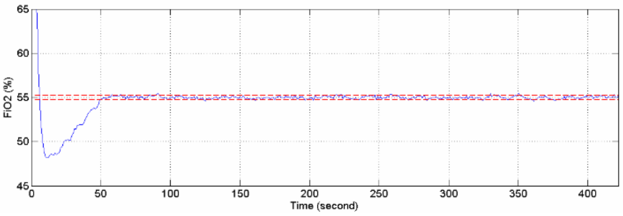

Fig. 21. The FiO_2 control result using fuzzy logic control (desired FiO_2 = 55%, initiated FiO_2 = 80%, time to desired FiO_2 target = 51 seconds).

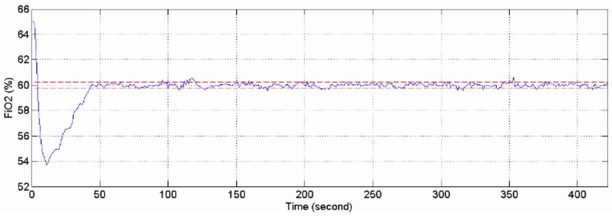

Fig. 22. The FiO_2 control result using fuzzy logic control (desired FiO_2 = 60%, initiated FiO_2 = 65%, time to desired FiO_2 target = 45 seconds).

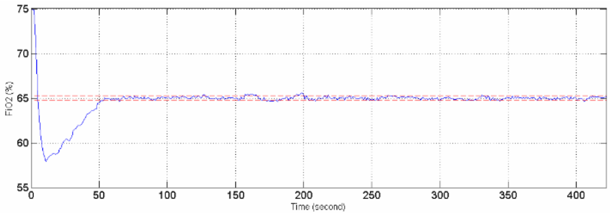

Fig. 23. The FiO_2 control result using fuzzy logic control (desired FiO_2 = 65%, initiated FiO_2 = 80%, time to desired FiO_2 target = 52 seconds).

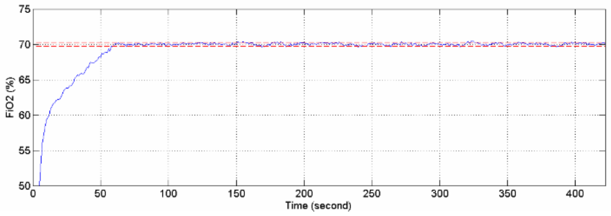

Fig. 24. The FiO_2 control result using fuzzy logic control (desired FiO_2 = 70%, initiated FiO_2 = 21%, time to desired FiO_2 target = 63 seconds).

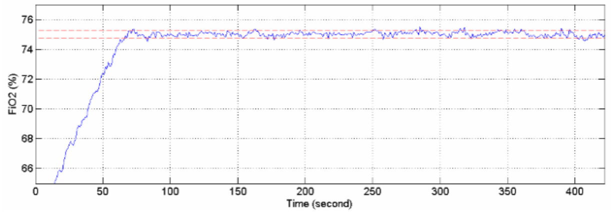

Fig. 25. The FiO_2 control result using fuzzy logic control (desired FiO_2 = 75%, initiated FiO_2 = 21%, time to desired FiO_2 target = 80 seconds).

levels of 25%, 30%, 35%, 40%, 45%, 55%, 60%, 65%, 70%, and 75%, respectively. The convergence time to reach the convergence state – desired FiO_2 at +/- 0.25% – was between 30 and 80 seconds, and the average error was 0.13%. The time to the desired FiO_2 target was the time for an actual FiO_2 to convert to a range of +/- 0.25% of the desired FiO_2 target, and to maintain that level within the range for longer than 20 seconds.

5. Conclusion

Based on the experimental results, an automatic closed-loop control system for gas mixture can be achieved. The fuzzy control algorithm and the rule-based control algorithm appropriately responded to changes in SpO_2 in all three subjects. The results from fuzzy control seemed to produce a lower FiO_2 response time than rule-based control. Even though a system with fuzzy control might have reduced the risk of ROP, it might introduce the risk of hypoxia instead, because convergence time in some cases of the experiment seemed to be too long. To speed up convergence time for the FiO_2 percentage, a hybrid control of a rule-based algorithm and a fuzzy logic control algorithm had to be studied further. The idea of hybrid control was to find a better initial value of F_{air} and F_{oxygen} in the system transfer function in (1) that could place an initial FiO_2 closer to the desired FiO_2 target (+/- 2% from the target), and then let fuzzy control take over. As a result, a rule-based algorithm set up the initial values of F_{air} and F_{oxygen} according to the system transfer function in order to set initiated FiO_2 to be close to the desired FiO_2, then used fuzzy logic control to carefully adjust the actual FiO_2 to meet the desired FiO_2. Using this technique might help to reduce the time to convergence and might help minimize the chance of hypoxia in a patient. In a hybrid system, system calibration and learning algorithms had to be developed in order to find the optimal F_{air} and F_{oxygen} parameters with respect to a full range of FiO_2 output (21% to 100%). The fuzzy control system allowed doctors to prescribe an appropriate dosage of oxygen therapy for RDS treatment. The system can also help doctors to understand how much oxygen is required for treatment of RDS in premature infants without the risks of ROP and hypoxia and can help them to develop a better oxygen therapy procedure.

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