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Estimation of Blood Oxygen Saturation in the Circulation Circuit for Extracorporeal Membrane Oxygenation

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ABSTRACT Extracorporeal membrane oxygenation (ECMO) is a treatment that supports heart and lung functions with a circulation circuit external to the body. In ECMO, it is important to monitor blood oxygen saturation (SO_2) in the circulation tube. As a means of continuous SO_2 measuring, a special connector is inserted into the circuit. However, this method is unsuitable for emergency treatment. Therefore, it is necessary to measure blood SO_2 in the tube without the connector. However, this creates problems for SO_2 estimation, due to varying blood concentration and flow velocity, hemolysis, and wall thickness of the tube. Therefore, we developed a SO_2 estimation method that can calibrate the variation in blood concentration. The method is based on a conversion model between absorbance and SO_2 (CAS), which varies depending on the concentration. In this method, the CAS for the SO_2 estimation is estimated by CAS corresponding to two blood samples prepared in advance with different concentrations. The experiment for SO_2 estimation was conducted with a spectroscope, a halogen light source, and a cut tube. We confirmed that the average error of estimated SO_2 against the SO_2 values measured by a gas analysis was 3.8% within a blood volume concentration range from 50 to 90%. In future work, to improve the estimation accuracy, we will improve our method by investigating other factors that may affect the accuracy.

INDEX TERMS Biomedical monitoring, spectroscopy, circulators.

I. INTRODUCTION

A. EXTRACORPOREAL MEMBRANE OXYGENATION

Extracorporeal membrane oxygenation (ECMO) has been employed for patients who need support for heart and lung function (e.g., heart failure or lung transplant) since 1971 [1]. An ECMO system mainly consists of circulation tubes, an artificial pump, and an artificial lung external to the body. In this system, venous blood is extracorporeally withdrawn from a patient through a catheter placed in the vena cava and blood flow is generated by the centrifugal pump. After the blood is oxygenated and decarboxylated by the artificial lung, it is returned to the patient. When the blood flows though the artificial lung, the O_2 and CO_2 of the blood by the semipermeable membrane are exchanged. To ensure sufficient oxygen supply during ECMO treatment, it is necessary to monitor the patient's venous oxygen saturation (SO_2). Currently, two methods are typically used to monitor the SO_2 in ECMO.

One method is to measure the SO_2 of blood sampled from the tube using blood gas analysis. This method can measure SO_2 with high accuracy. However, it is not practical to sample blood repeatedly for continuous monitoring of SO_2. Moreover, withdrawing blood samples from the tube increases the risk of medical accident, such as the mixing of air bubbles in blood, infection, and leakage of blood. The other method is to estimate SO_2 from the reflected light intensity measured through a connector that works as a transparent cuvette for optical measurement. To use this connector, it must be installed in the extracorporeal circulation circuit. However,

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in some cases, ECMO treatment is started without setting this connector, usually during emergencies, when medical staff may not have enough time to connect it in the ECMO circuit. This is because the connection procedure is difficult to perform without leakage when the blood flow pressure is high. In addition, preparation for the connection requires sterilization of both the connector and the hands. When ECMO is immediately needed, an increase in the preparation time leads to high patient mortality. Furthermore, smaller hospitals do not always stock the connector because the ECMO system is used infrequently. Another disadvantage in using the connector is that it may cause infection or blood coagulation. Therefore, inserting additional parts into the circuit is not preferable. Some products incorporate the connector into the circuit in advance, which may solve these problems. However, simple products without the special circuit are still widely used because it can be started quickly.

To estimate SO_2 in blood vessels, various estimation methods have been used. A pulse oximeter has been used to estimate arterial SO_2 in clinical fields [2]–[4]. However, a pulse oximeter, which requires the detection of a pulse wave, cannot be used in ECMO systems because they employ a centrifugal pump, which produces no pulse wave in the ECMO circuit. Recently, near-infrared (NIR) spectroscopy has also been used to measure regional SO_2 of cerebral blood [5], [6]. Moreover, there are many NIR-based tissue oximeters, for example, NIRO-200NX (Hamamatsu Photonics K.K., Shizuoka, Japan), FORE-SIGHT ELITE (CAS Medical Systems Inc., Branford, CT, USA), SenSmart-X100 (Nonin Medical Inc., Plymouth, MN, USA), OxiplexTS (ISS Inc., Champaign, IL, USA), INVOS 5100C (Medtronic plc, Dublin, Ireland), and OxyPrem (OxyPrem AG, Zurich, Switzerland). Kleiser *et al.* compared the SO_2 values measured from the same phantom using these products and reported that the values varied among them [7]. Furthermore, when the measurement point was changed, the SO_2 value also changed. Therefore, these products are not applicable for monitoring SO_2 in ECMO because the SO_2 value estimated from these products has low reliability in this application. For these reasons, it is desirable that the SO_2 be directly estimated in the ECMO circuit tube without a connector. Thus, this study developed a method for estimating blood SO_2 in an ECMO tube without the connector. Our study will contribute to the monitoring of blood SO2 during ECMO treatment quickly and safely.

B. PROBLEMS IN SO_2 ESTIMATION

We estimated the blood SO_2 in an ECMO tube using absorbance analysis. Compared to tissue oximeters, the estimation of blood SO_2 in a tube seems to be easier than estimation in tissue because tissue composition is more complex. However, there are also some problems for the estimation within the ECMO circuit, caused by, for example, blood concentration, blood flow velocity, hemolysis, and wall thickness of the tube. Especially, because infusion is administered to a patient for enhancing circulation during ECMO treatment,

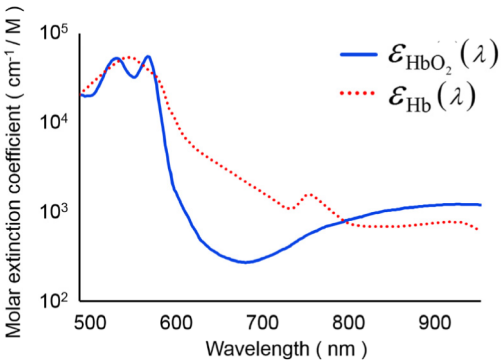

FIGURE 1. Molar extinction coefficients of HbO_2 and Hb.

the blood concentration can rapidly and significantly vary. This leads to changes in light absorption and scattering, which affects SO_2 estimation. In addition, the blood flow velocity in the circulation tube is adjusted depending on the variation of oxygen supply quantity during the treatment. Thus, when the number of red cells per unit time and the orientation of the cells vary by changing the velocity, this also leads to a change in blood light properties. Especially, because red blood cells are disk shaped with the center recessed inward, their orientation affects the light scattering. Moreover, light transmission is changed by hemolysis as red cells are destroyed by the ECMO pump and internal tube pressure. These factors affect the estimation of blood SO_2 in an ECMO system. In this study, we focused on the blood concentration and analyzed the relationship between the blood concentration and absorbance. In addition, we developed a calibration method for SO_2 estimation. The detailed analysis and estimation process are described in the following sections.

II. ESTIMATION METHODS

A. ESTIMATION PRINCIPLE

The main light absorbers in the human blood are oxy-hemoglobin (HbO_2) and deoxy-hemoglobin (Hb). Therefore, blood SO_2 is defined as the ratio of HbO_2 concentration to the total Hb concentration. Blood SO_2 can be estimated by measuring the blood absorbance because Hb and HbO_2 have different optical properties [8], as shown in Fig. 1. Absorbance $A(\lambda)$ is defined as

$$A(\lambda) = -\log T(\lambda) = -\log \frac{I_{\text{out}}(\lambda)}{I_{\text{in}}(\lambda)}, \tag{1}$$

where $I_{\text{in}}(\lambda)$ and $I_{\text{out}}(\lambda)$ describe the intensities of incident and transmitted light, respectively.

In addition, absorbance $A(\lambda)$ can be expressed based on Lambert-Beer's law as follows:

$$A(\lambda) = \left[\varepsilon_{\text{HbO}_2}(\lambda) C_{\text{HbO}_2} + \varepsilon_{\text{Hb}}(\lambda) C_{\text{Hb}}\right] l, \tag{2}$$

where l, $\varepsilon(\lambda)$, and C denote the path length of the transmitted light, the molar extinction coefficient, and the molar concentration, respectively. In addition, SO_2 is expressed by

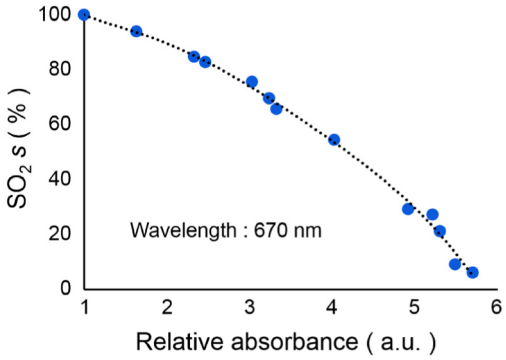

FIGURE 2. Relationship between blood absorbance and SO_2 obtained by spectroscope and blood gas analyzer.

Hb concentration as

$$s = \frac{C_{\mathrm{HbO_2}}}{C_{\mathrm{HbO_2}} + C_{\mathrm{Hb}}} \times 100, \tag{3}$$

where s denotes SO_2. From (2) and (3), the relationship between SO_2 and the absorbance can be expressed based on Lambert-Beer's law by

$$\begin{aligned} A(\lambda) &= \left[\varepsilon_{\mathrm{HbO_2}}(\lambda)\, SO_2 + \varepsilon_{\mathrm{Hb}}(\lambda)(1 - SO_2)\right] C_{\mathrm{HbT}} \cdot l, \\ C_{\mathrm{HbT}} &= C_{\mathrm{Hb}} + C_{\mathrm{HbO_2}}, \end{aligned} \tag{4}$$

where C_{HbT} denotes total Hb concentration. If the path length l is constant, the absorbance can be expressed by linearly combining the substances' molar extinction coefficients. Therefore, SO_2 can be estimated by solving a simple linear regression problem [9]. However, in reality, the path length l is not constant due to light scattering, and it must be defined as the optical path length function of the wavelength. Fig. 2 shows the relationship between SO_2 and absorbance that were measured using a blood gas analyzer (i-STAT Analyzer 300F, Abbott Point of Care, Princeton, NJ, USA). As shown in Fig. 2, the relationship is nonlinear and is not based on Lambert-Beer's law. For this reason, it is difficult to estimate the blood SO_2 in an ECMO tube based on (2).

A previous study proposed a SO_2 estimation method based on a conversion model between absorbance and SO_2 (CAS) [10]. CAS is given by the conversion table that is created by sets of the known blood SO_2 and measured absorbance of the blood. As long as the blood concentration and measuring environment do not change, CAS is effective as a method in consideration of the scattering and wavelength dependency of the path length. However, the estimation accuracy of CAS decreases when the blood concentration or the measuring environment changes. Hence, we propose a CAS correction method using two types of CAS, which are calculated in the preparation step.

B. PROPOSED METHOD FOR ESTIMATING SO_2

First, we describe the basic concept of the proposed method to estimate SO_2 in response to various blood concentrations. However, it is difficult to prepare a table for the calibration of the blood concentration in advance, because we must measure many blood samples by changing blood concentration and SO_2 within a wide range. Therefore, in our method, we used two types of CAS based on the approximation functions between absorbance and SO_2. The functions are calculated from data obtained from two blood samples with high or low blood concentration. The two types of CAS for the preparation are defined as CASP_h and CASP_l for high and low concentrations, respectively. Fig. 3 shows the data for both CAS preparations with respect to both SO_2 and blood concentration. As shown in Fig. 3, the data reflecting high blood concentration are used to obtain CASP_h, whereas those reflecting low blood concentration are used to obtain CASP_l. The two concentrations are determined so as to satisfy the assumed range of the concentration during ECMO treatment. The SO_2 of arbitrary blood concentration between CASP_h and CASP_l is estimated from model-based approximation. Next, we explain the procedures of our method in detail.

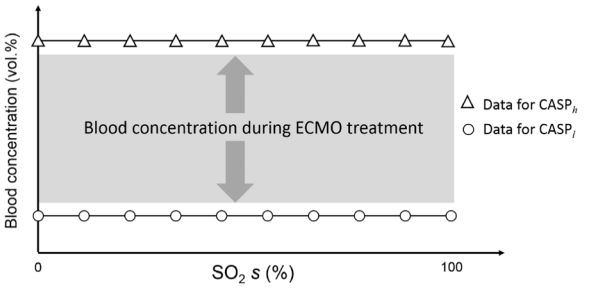

FIGURE 3. Absorbance data required for estimating blood SO_2 in ECMO tube.

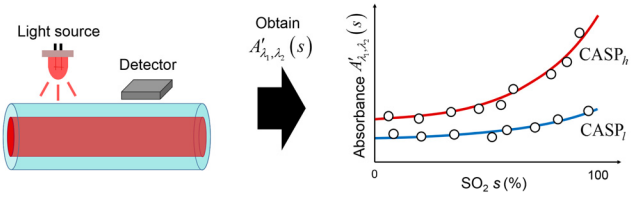

FIGURE 4. Overview of preparation step. Absorbance values of blood with various SO_2 and two types of concentration were obtained. CASP_h and CASP_l were then acquired by an approximating function.

The proposed estimation method has two steps, a preparation step and an estimation step. Fig. 4 shows the preparation step that is intended to be conducted in the manufacturing process. In this step, we obtain CASP_h and CASP_l. Although CASP requires a large amount of data, this process is expected to be completed before clinical application.

In the first process, the absorbance of the blood with respect to SO_2 is measured by two wavelengths. As illustrated in Fig. 3, the absorbance data are obtained by changing the SO_2. The two types of blood concentrations, high and low, are preferably set so that the assumed range of blood concentration can be covered. Measurement with narrow SO_2 intervals is desirable because CASP is obtained by approximating the relationship between SO_2 and absorbance. After measuring

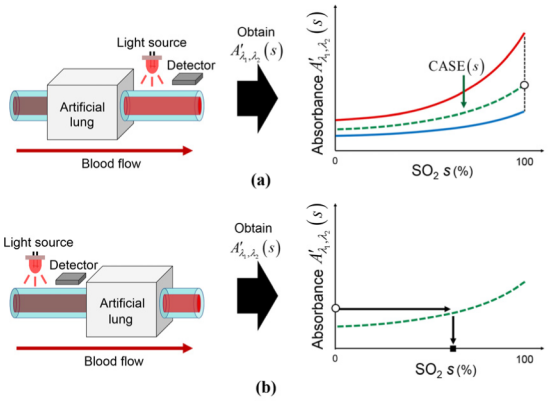

FIGURE 5. Overview of estimation step. (a) Blood concentration calibration, (b) estimation process of SO_2 using CASE. The blood absorbance with 100% SO_2 is acquired at the outflow tube. CASE is then generated by $CASP_h$, $CASP_l$ (two solid curves), and the acquired absorbance (dashed curve). The blood absorbance is obtained at the inflow tube, and SO_2 is estimated with this absorbance and CASE.

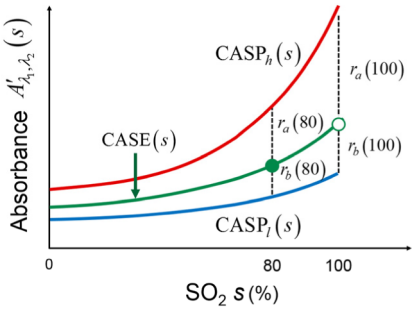

FIGURE 6. Relationship of $CASP_h$, $CASP_l$, and CASE.

the blood absorbance, $CASP_h$ and $CASP_l$ were calculated. In our method, absorbance $A'_{\lambda_1,\lambda_2}(s)$ with two wavelengths λ_1 and λ_2 for CAS was calculated as

$$A'_{\lambda_1,\lambda_2}(s) = \frac{A_{\lambda_1}(s) + d}{A_{\lambda_2}(s) + d}, \tag{5}$$

where d denotes an arbitrary constant value. This absorbance shows the ratio between the absorbance with two wavelengths and was used to enhance the influence of SO_2. If the proper wavelengths are set, when SO_2 changes, the absorbance of the numerator increases or decreases, whereas that of the denominator decreases or increases. In this study, two wavelengths, 663 nm and 933 nm, were selected because the SO_2 error that was estimated using these wavelengths was the smallest when SO_2 was estimated by selecting two wavelengths at 1 nm intervals from 650 nm to 950 nm. Furthermore, to prevent the denominator from being negative, d was determined. Thus, the optimal d varies depending on the wavelength selection and we set $d = -1.1$ in this study. After calculation of (5), we acquired the CASP (s) approximation with a function including an exponent by

$$A'_{\lambda_1,\lambda_2}(s) = \mathrm{CASP}(s) = \alpha e^{\beta s} + \gamma. \tag{6}$$

From (6), $CASP_h(s)$ and $CASP_l(s)$ were obtained.

Fig. 5 shows the estimation step that is intended to be conducted during ECMO treatment. CAS is estimated by employing the CASP generated in the preparation step. The CAS for estimation is defined as CASE. Finally, we can acquire the SO_2 of the blood by applying this CASE. First, the absorbance of the blood flow that was oxygenated through the artificial lung was measured with two wavelengths. We assumed that the SO_2 of the blood is 100% after it passes through the artificial lung and the blood concentration does not vary before and after the artificial lung. Although the absorbance varies depending on blood concentration, our method enables calibration of the blood concentration. In this step, CASE is expressed with $CASP_h(s)$ and $CASP_l(s)$ as follows:

$$\begin{aligned} A'_{\lambda_1,\lambda_2}(s) &= \mathrm{CASE}(s) \\ &= r_h(s)\,\mathrm{CASP}_h(s) + r_l(s)\,\mathrm{CASP}_l(s), \end{aligned} \tag{7}$$

where $r_h(s)$ and $r_l(s)$ represent the ratio of CASE(s) between the two types of CASP. As shown in Fig. 6, these ratios were calculated by

$$r_h(s) = \frac{|\mathrm{CASE}(s) - \mathrm{CASP}_h(s)|}{|\mathrm{CASP}_h(s) - \mathrm{CASP}_l(s)|}, \tag{8}$$

$$r_l(s) = \frac{|\mathrm{CASE}(s) - \mathrm{CASP}_l(s)|}{|\mathrm{CASP}_h(s) - \mathrm{CASP}_l(s)|}. \tag{9}$$

We assumed that $r_h(s)$ and $r_l(s)$ do not depend on s under the condition of constant blood concentration. Therefore, (7) could be rewritten based on this assumption as follows:

$$r_h(s) = r_h(100), \quad r_l(s) = r_l(100), \tag{10}$$

$$\begin{aligned} A'_{\lambda_1,\lambda_2}(s) &= \mathrm{CASE}(s) \\ &= r_h(100)\,\mathrm{CASP}_h(s) + r_l(100)\,\mathrm{CASP}_l(s). \end{aligned} \tag{11}$$

The ratios $r_h(100)$ and $r_l(100)$ were calculated by (8) and (9), respectively. CASE(100) was calculated by measuring the absorbance of the blood passed from the artificial lung. Therefore, after calculating these ratios, the calibrated CASE(s) was calculated by (11). Therefore, even if the blood concentration is unknown during ECMO treatment, CASE(s) can be calibrated by both $CASP_h(s)$ and $CASP_l(s)$ obtained in the preparation step. Finally, as shown in Fig. 5(b), the estimated value $\hat{s}$ of SO_2 was calculated with the measured absorbance A'_{λ_1,λ_2} before the oxygenation and the inverse function $\mathrm{CASE}^{-1}(s)$ by

$$\hat{s} = \mathrm{CASE}^{-1}\left(A'_{\lambda_1,\lambda_2}\right). \tag{12}$$

III. EXPERIMENTS

A. BLOOD PREPARATION

In our experiments, bovine blood was selected for circulation in an ECMO tube. To prevent the blood from clotting, sodium citrate and heparin sodium were added to the blood as anticoagulant. To prepare blood samples with various concentrations, the blood samples were diluted by saline for volume concentrations (VCs) from 40% to 100% in 10%

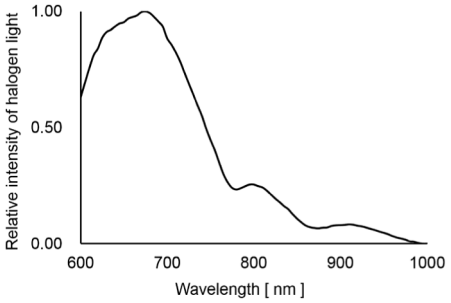

FIGURE 7. Relative intensity of halogen light.

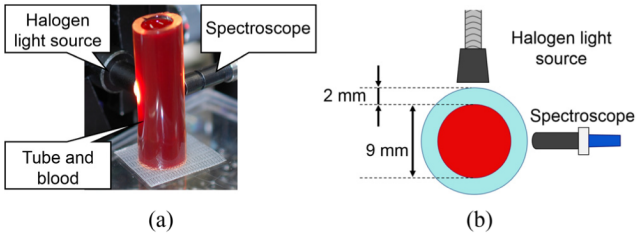

FIGURE 8. Measurement environment of blood absorbance, (a) overall view and (b) top view with size of tube.

intervals. The SO_2 of the blood was changed with air stirring for oxygenation and mixing with sodium hypochlorite for deoxygenation between 0% and 100%. Both the Hb concentration and SO_2 of the prepared blood samples were measured by a blood gas analyzer (i-STAT Analyzer 300F, Abbott Point of Care, Princeton, NJ, USA). The average Hb concentration of 100% VC was 10.6 g/dl. The SO_2 of the blood was changed from 0% to 100%. Moreover, the VC was also changed in 10% increments from 40% to 100%. First, to calculate $CASP_h$ and $CASP_l$, the data with 40% and 100% VCs were used in the preparation step. Next, to calculate both r_h (100) and r_l (100), the data corresponding to 100% SO_2 were used. After obtaining the result for (11), the remaining data were used for the evaluation of our method.

B. ABSORBANCE MEASUREMENT

To calculate the blood absorbance in an ECMO tube (CAPIOX custom pack, TERUMO Corp., Tokyo, Japan), the transmitted light intensity was measured using a spectroscope (USB Flame, Ocean Optics Inc., FL, USA) and a halogen light source (MHF-G150LR, MORITEX Corp., Saitama, Japan). We used a spectroscope as light detector. Fig.7 shows the relative intensity of the light source that was measured using the spectroscope. The spectroscope was used to examine many combinations of two wavelengths. Fig. 8 shows the experimental conditions for the measurement. The length of the cut tube shown in Fig. 8(a) was 4.7 cm. The internal diameter and wall thickness of the tube were 9.0 mm and 2.0 mm, respectively. To prevent the spectrometer and light source from interfering with each other, these devices were offset vertically. Moreover, the transmitted light and the dark current were measured in a dark room. After water was

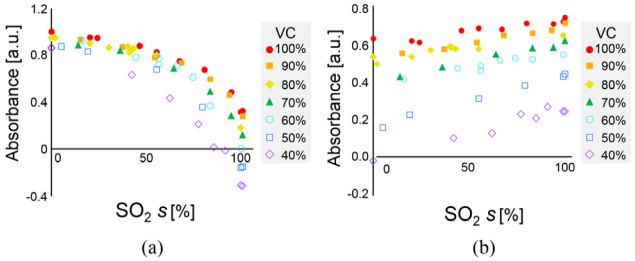

FIGURE 9. Obtained blood absorbance for various VC and SO_2 values at each wavelength, (a) 663 nm and (b) 933 nm.

TABLE 1. Approximation error of CASPs corresponding to 100% VC and 40% VC (error, Eso_2, was calculated in the ranges of 0–100%, 0–60%, and 60–100% SO_2).

CASP (VC)	E_{SO_2} (%) (SO_2: 0–100)	E_{SO_2} (%) (SO_2: 0–60)	E_{SO_2} (%) (SO_2: 60–100)
$CASP_h$ (100%)	5.1	7.2	1.8
$CASP_l$ (40%)	0.92	0.67	1.1

TABLE 2. Error evaluation of SO_2 estimation for each blood VC.

VC (%)	Average error (%)	Maximum error (%)	Standard deviation (%)
50–90	3.8	12	3.1
90	2.7	4.5	1.3
80	4.7	9.5	3.5
70	2.3	5.4	1.9
60	5.5	12	3.7
50	2.7	6.3	2.3

poured into the tube, the light intensity transmitted through the tube was also measured instead of the light incident on the blood. The blood absorbance was calculated by

$$A(\lambda) = -\log \frac{I_{\text{blood}}(\lambda) - I_{\text{dark}}(\lambda)}{I_{\text{water}}(\lambda) - I_{\text{dark}}(\lambda)}, \tag{13}$$

where $I_{\text{blood}}(\lambda)$, $I_{\text{water}}(\lambda)$, and $I_{\text{dark}}(\lambda)$ are the light intensity transmitted through blood, water, and dark current, respectively.

IV. RESULTS AND DISCUSSION

Fig. 9 shows the change in the absorbance $A(\lambda)$ of the blood as the SO_2 and VC of the blood were changed. Fig. 9(a) and (b) shows the results for 663 nm and 933 nm, respectively. The absorbance at 663 nm decreased with the increase of SO_2, whereas that of 933 nm increased. This result can be explained with the molar extinction coefficient of Hb (Fig. 1) as follows. From Fig. 1, the light absorption of Hb at 663 nm is stronger than that of HbO_2. Thus, the absorbance decreased as SO_2 increased. In contrast, the light absorption of HbO_2 at 933 nm is a little stronger than that of Hb. Therefore, the absorbance became higher gradually as SO_2 increased. Furthermore, the absorbance of both wavelengths decreased as VC decreased. This is because the light absorption became weak as the Hb concentration decreased.

TABLE 3. SO_2 estimation error for each range of blood SO_2.

Range of SO_2 (%)	Average error (%)	Maximum error (%)	Standard deviation (%)
60–100	2.7	8.0	1.9
0–60	4.1	12	3.3

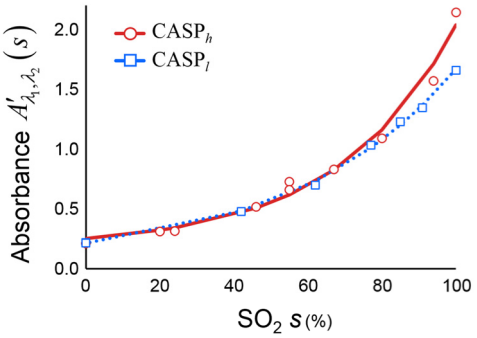

FIGURE 10. Acquired CASP$_h$ from 100% VC and CASP$_l$ from 40% VC. Red and blue symbols indicate measured absorbance data. Red and blue curves are the CASPs extrapolated from the measurement points.

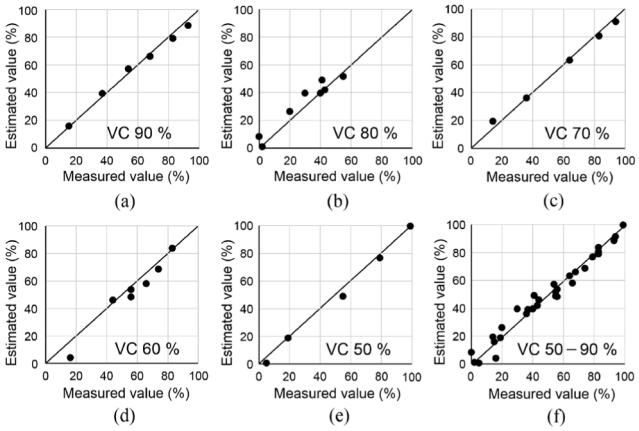

FIGURE 11. Result of SO_2 estimation for blood for various VC values, (a) 90%, (b) 80%, (c) 70%, (d) 60%, (e) 50%, (f) 50–90%.

In this experiment, the relationship between SO_2 and the absorbance, especially in Fig. 9(a), was nonlinear, similar to that shown in Fig. 2, which gives us measurement results from the blood gas analyzer. In addition, as shown in Fig. 9, some absorbance data were negative. The data showed that the light intensity transmitted through water was higher than that transmitted through blood. Light absorption by Hb is stronger than that by water. However, because the spectroscope was set above the light source against the tube in our experiment, the detected light was not a straight beam from the light source, but rather bent light. When the light absorption by the Hb was strong, the absorbance had a positive value because the light intensity transmitted through the blood is much weaker than that of water. Conversely, when the light absorption by Hb was weak, we assumed that light intensity scattered by Hb was stronger than the light transmitted through water. As a result, the absorbance became negative. However, as discussed above, even if the absorbance becomes negative, CASPs can be calculated by (5).

Fig. 10 shows the CASP$_h$ and CASP$_l$ estimated in the preparation step. Although the two types of CASPs had similar values from 0% to 70%, they showed different tendencies as SO_2 increased. These CASP functions were obtained by making the measured data fit (5) as follows:

$$\mathrm{CASP}_h(s) = 0.0764e^{0.0319s} + 0.178, \quad (14)$$

$$\mathrm{CASP}_l(s) = 0.169e^{0.0226s} + 0.0462. \quad (15)$$

Herein, the approximation accuracy of CASPs shown in Fig. 10 between the estimated SO_2 values and the SO_2 values measured by the gas analyzer was calculated by

$$E_{\mathrm{so}_2} = \frac{1}{N}\sum_{i=1}^{N}\left|s_i - \mathrm{CASP}^{-1}(x_i)\right|, \quad (16)$$

where s_i is the SO_2 value measured by the gas analyzer of the i-th blood absorbance datum and x_i is the SO_2 value estimated from i-th absorbance datum. Table 1 shows the SO_2 errors for both CASPs. These values indicate the influence of the approximation error for SO_2 estimation. The average SO_2 errors by CASP$_h$(VC=100%) and CASP$_l$(VC=40%) estimation were 5.1% and 0.92%, respectively. In addition, from the results of CASP$_h$, the approximation error in the SO_2 range of 0–60% was higher than that in the range of 60–100%. As discussed above, the light absorption by Hb at 663 nm is strong. Thus, when VC is high and SO_2 is low, the measured light intensity through the blood was low and affected by noise.

Fig. 11 shows the results of SO_2 estimation. Tables 2 and 3 show the estimation error of SO_2 for each blood VC and each SO_2, respectively. In Table 2, it is seen that the average error was 3.8% within the VC range of 50% to 90%. In addition, the maximum error and standard deviation were 12% and 3.1%, respectively. Moreover, the average errors were all less than 5.5% for all VC values. Table 3 shows that the average error of data in the low range of SO_2, 0–60%, is higher than that of data in the high range, 60–100%. As shown in Table 1, the results were due to stronger light absorption by Hb. Moreover, all average errors were less than 4.1% for both ranges of SO_2.

V. CONCLUSION

In the present study, we developed a method that can robustly estimate the SO_2 of blood in a tube, such as used in an ECMO circulation circuit, regardless of changes in blood concentration. In this study, to evaluate our method, blood absorbance was measured under conditions with various blood concentrations and SO_2 values. The SO_2 estimation is

based on the CAS. First, in the preparation step, we prepared two blood samples having different concentrations and varied the blood SO_2. After pouring each blood sample into the tube, the absorbance of the blood in the tube was measured using a spectroscope and halogen light source. After we obtained two functions between absorbance and SO_2, which were defined as CASP, we obtained CASE to estimate the blood SO_2 in the ECMO tube by employing CASPs for blood VC calibration. Our SO_2 estimation method shows 3.8% average error within a blood VC range from 50 to 90%. Moreover, all average errors were also less than 5.5% for all values of VC: 50%, 60%, 70%, 80%, 90%, and 50–90%. Therefore, we confirmed that our method could estimate SO_2 in a tube with the stated accuracy. In future work, to achieve higher estimation accuracy, we will investigate the factors that may affect it, such as the thickness of the tube wall, blood flow, hemolysis, humidity, temperature, and cholesterol. Moreover, we will compare the results between our method and state of the art ECMO systems. We will improve our method using further investigation and prepare it for clinical use.

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