Blood Leakage Determination Using the Chromaticity of a Color Sensor

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Abstract Percutaneous extracorporeal circulation therapies such as apheresis and hemodialysis are commonly used in intensive care units, hemodialysis centers, and clinically settings. In these treatments, there is always a possibility of continuous bleeding from the puncture site. Since the blood flow in these therapies is high, a hemorrhagic shock may be caused by severe blood loss, and - in the worst case - this may even lead to the patient’s death. Therefore, it is important to continuously monitor blood leakage during the treatment. Typical procedures include the electrode method and the blood absorbance method, but their function may be affected by leakage of colored chemicals used, or by sweat or light. In this study, we developed a blood leakage determination module based on the chromaticity of a color sensor. Since the method is specifically sensitive to the red color, it can detect blood leakage. We performed experiments to verify the effectiveness of the proposed method and compared this new procedure with the existing ones, and we confirmed that the proposed method correctly detected blood leakage. Moreover, we investigated the blood detection capability of our new procedure and found that it could be applied to detect hematocrit levels within the range of 2% to 64%. We developed a multicolor sensor module and established a blood leakage detection method to meet the conditions that we had set as our goal. Our study confirmed that the proposed method did not cause malfunction due to leakage of chemicals or presence of obstacle in the light path, while the traditional methods did. We also evaluated its performance and found that our method was able to detect blood leakage within the hematocrit range of 2% to 64%.

Keywords: blood leakage, vascular access hemorrhage, venous needle dislodgement, color sensor, chromaticity.


1. Introduction

Percutaneous extracorporeal circulation therapies including apheresis and hemodialysis are common treatments in intensive care units, hemodialysis centers, and other clinical settings [1–4]. Continuous bleeding and needle dislodgement from the puncture site may cause fatal damage to the patients. There is a plethora of reports of medical accidents involving vascular access hemorrhage and venous needle dislodgement [5–8]. It is reasonable to speculate that there are many potential incidents that have not been reported.

Several devices have been invented [9, 10] to monitor blood leakage, which principally employed either the electrode method or the optical method (hereinafter referred to as single-color method). The electrode method is based on the detection of electric current between two metal sheets that come into contact with blood between them [11]. Their structures are simple but the principle can be complicated. Various electrolyte solutions such as sweat of the patient and other medical liquids could cause the machine to malfunction. In addition, as the electrodes must be in contact with the blood, they are not reusable, resulting in low cost-performance. Most of the conventional single-color methods use photodetectors such as photodiode [12], and have the advantage of not directly touching the blood. The device sends an alarm signal when the intensity of the light reflected from the blood falls below a preset threshold, and there is a possibility of malfunction of the device if the photodetector becomes covered by some objects such as gauze. It can also be activated by colored chemical liquids because it cannot distinguish these liquids from blood. False alarm causes unnecessary bedside rush of medical staff, result-
ing in wasting medical resources.

To address the above issues, we decided to develop a vascular access hemorrhage detector that satisfies five conditions as follows:
1. Reacts only to blood to avoid malfunction due to sweat or colored chemical liquids;
2. Does not activate with a little amount of bleeding;
3. Has low running costs;
4. Does not give additional stress to the patient while equipment is attached; and
5. Has no risk of infection from contact with blood.

The sensor module is composed of a white color light emitting diode (LED) and a multicolor sensor, which are covered with a transparent blood protective film. The color sensor monitors specifically the red light reflected from blood soaked in the gauze. Thus, the module identifies light not by brightness and darkness, but by its color. We carried out several experiments to compare our new method with the conventional electrode and single-color methods. We also confirmed that the proposed method can clearly distinguish the difference in hematocrit (Ht) of blood samples.

2. Theory

2.1 Chromaticity diagram

A color can be represented by a combination of the three primary colors; red, green and blue. Corresponding to this, humans perceive colors as combinations of signal intensities from three types of receptors; rhodopsins, in cone cells [13]. A color can also be represented by a pair of chromaticity; x and y, which have been defined by the Commission Internationale de l’Éclairage (CIE). Figure 1 shows the CIE chromaticity diagram, which expresses a color space on an orthogonal coordinate plane. The values calculated for red (R), green (G), blue (B) and near infra-red (NIR) by the color sensor can be plotted on x and y axes and shown on this chart as a recognizable color [14].

Output values from the color sensor; R, G, B, and NIR, can be converted to a set of x and y values using formulae (1)–(3) as shown below, where the numbers in the matrix are constants determined for the color sensor [15]:

\[
\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.69 & 0.22 & 0.08 \\ 0.45 & 1.13 & -0.37 \\ 0.18 & -0.17 & 2.19 \\ -1.31 & -1.18 & -1.9 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \\ NIR \end{pmatrix}
\]

\[
x = \frac{X}{X + Y + Z}
\]

\[
y = \frac{Y}{X + Y + Z}
\]

2.2 Detection of blood leakage

The sensor module is composed of a white LED (OS-W5DLS1C1A, Opto Supply Limited) containing red, green, blue and NIR lights, and a color sensor (S11059–03, Hamamatsu Photonics Corporation) that can detect the red, green, blue and NIR components of the light separately. The color sensor outputs values ranging from 0 to 65535 counts. As shown in Figure 2, a transparent protective film and a piece of sterilized gauze are placed between the skin and the sensor module, and fixed by a tape. Blood that leaked out of the puncture site permeates into the sterilized gauze and the color sensor detects the reflected light from the blood. The color sensor can distinguish colors in a similar manner as humans can; four components of the incident light are measured and converted to a pair of chromaticity x and y by formulae (1)–(3), which represents a corresponding color. Therefore, malfunction due to shielding of the sensor by some substances such as sweat and/or colored chemical liquids can be reduced. This is a unique feature of the proposed method, which is superior to the conventional optical method that employs a single-color (specifically, red) sensor and therefore cannot distinguish colored liquids from blood.

Note that we ignore the influence of humidity on the covered film, since it is assumed that the modules are used in air-conditioned hospital rooms.
3. Preliminary experiments

The sensor module was placed in the center of a hole (40 mm in diameter) of a plastic spacer to keep a distance of 10 mm between the sensor and reflection surface. Various preliminary experiments were carried out using a white drape in place of the gauze. The luminance of LED was changed by a variable resistor and the integrated values from the sensor were obtained accordingly.

3.1 Photometric time and luminance of the sensor module

3.1.1 Objective
To examine the characteristics of the output values of the sensor while the luminance of LED and the photometric time of the color sensor were varied.

3.1.2 Methods
The white drape was painted with red ink and integrated values were obtained while changing the LED current from 0 to 9 mA in 1-mA steps at various photometric times (5.6, 10.5 and 20.3 ms). The luminance of LED was approximately 1300 mcd with LED current of 9 mA, which was the maximum in the range of current examined.

3.1.3 Results
As the LED current increased, the dispersion of the points on the chromaticity chart tended to decrease. The results showed that the variation of the data was satisfactorily small if the LED current was set at 840 mA (55% of the maximum) and the photometry time at 10.5 ms.

3.1.4 Discussion
The results suggest that increasing both LED current and photometric time will provide a better condition for measurement in theory, and it is also evident that ongoing monitoring is ideal from a clinical viewpoint. There is, however, a trade-off with battery consumption, and it can be a relevant issue when used in clinical settings such as a clinic. As the purpose of this paper was to compare the proposed method with the existing methods, all the experiments hereafter were done at frequencies low enough to be considered harmless to humans.

3.2 Effect of diffuse reflection by transparent protective films

3.2.1 Objective
Covering the sensor module with a replaceable transparent protective film is essential for monitoring blood leakage to reduce the risk of infection through contact with blood. The purpose of this experiment was to examine the effect of the diffuse reflection from the surface of the film.

3.2.2 Methods
A variable number of sheets of transparent film (0.065 mm thick) were inserted between the sensor module and the white drape painted with red ink. The experiments were repeated with 0, 1 or 2 sheet(s) of film, and the chromaticity values \(x\) and \(y\) were obtained.

3.2.3 Results
With no film inserted, the sensor directly observed reflection from the red-ink painted drape, and the data accordingly showed that it was mainly red. As the number of films increased, data points on the chromaticity chart shifted to a region that included the point for white and dispersion of the data tended to increase.

3.2.4 Discussion
The results indicated that insertion of the transparent film increased scattering or direct reflection of the white LED light on its surface, which could cause sensor noise. To minimize the influence of reflected/scattered light, it was concluded that only one film should be inserted.

3.3 Accuracy of the sensor module

3.3.1 Objective
The purpose of this experiment was to verify the stability of the LED and color sensor of the sensor module.

3.3.2 Methods
Measurements were repeated 60 times with the following parameters: LED current of 5 mA (840 mcd), LED emission time of 10.5 ms at intervals of 1000 ms. The chromaticity values \(x\) and \(y\) were analyzed. The number of repeated measurements (60) was sufficient because the measurements to compare the proposed method with conventional methods were repeated 10 times in this study.

3.3.3 Results
The average chromaticity values \(x = 0.39\) and \(y = 0.35\) represented the color of light red, and standard devia-
tions were both 0.001 (see Table 1), which were sufficiently small to show the module’s stability.

3.4 Criteria for determining presence of blood

3.4.1 Objective
The purpose of this experiment was to define the criteria, specifically the region on the chromaticity chart, for judging whether the object is blood, based on the data obtained by the sensor.

3.4.2 Methods
One sheet of transparent film was inserted between the sensor and the white drape, and the drape was soaked in a sample of bovine blood with Ht adjusted to 32%. Measurements were repeated several times, and the data were plotted on the chromaticity chart.

3.4.3 Results
We decided to adopt 5 linear expressions shown in (4)–(8), so that the area covering all the data points can be expressed most simply.

\[
\begin{align*}
y &\geq -5x + 2.85 & \text{(4)} \\
y &\leq 0.4 & \text{(5)} \\
y &\geq 0.25 & \text{(6)} \\
x &\leq 0.65 & \text{(7)} \\
y &\leq -x + 1 & \text{(8)}
\end{align*}
\]

3.5 Threshold for the electrode method

3.5.1 Objective
The purpose of this experiment was to determine the threshold for judging whether an object is blood based on the data obtained by a single-color sensor.

3.5.2 Methods
The single-color method was tested using the same sensor module but enabling only the red sensor. Measurement of the output of the red sensor, R, was repeated 10 times while changing the Ht to 4%, 8%, 16% and 32%. Each set of data was averaged and expressed as R ratio; Ridth, which was defined as the ratio of measured value to the reference obtained with the gauze not containing the blood.

3.5.3 Results
Hematocrit is an index of blood density. As Ht increased, Rr tended to decrease (Fig. 4). The standard Ht is 42–52% for a normal healthy male and 37–47% for female [18]. The Ht is about 30% [19] for dialysis patients but mass bleeding decreases it to 10%, which is very critical condition for the patient. The threshold of Rr for detecting the blood was thus set at 0.70 corresponding to Ht of 8%.

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Table 1  Precision of the sensor module.

<table>
<thead>
<tr>
<th></th>
<th>x</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave.</td>
<td>0.39</td>
<td>0.35</td>
</tr>
<tr>
<td>Std.</td>
<td>0.001</td>
<td>0.001</td>
</tr>
</tbody>
</table>

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Fig. 4 Determination of the threshold for the single-color sensor.
4. Methods

4.1 Qualitative comparison between the proposed and existing methods

A comparison was made between the proposed method and existing methods (electrode method and single-color method). Samples used were normal saline, aqueous solution of yellow dye and bovine blood, as well as a sheet of black paper as an obstacle in the light path (see Table 2). The reason for using the yellow aqueous solution was that yellow and red have close chromaticity values and the high calorie fluids used in clinical pathology are typically yellow. A sheet of black paper was placed in front of the transparent protective film to mimic an obstacle in the light path or dirt on the protective film surface, both of which can lead to erroneous detection.

A volume of 0.2 ml of each liquid sample was sufficient to wet the entire 15 mm square gauze. For the electrode method, the sample was applied directly to the electrodes. Because dialysis patients have Ht of approximately 30%, the Ht of the bovine blood sample was adjusted to 32% by the method described below. As for the single-color method and the proposed method, both of which used the same sensor module, an 18 G puncture needle, gauze, a sheet of transparent film and the sensor module were placed in that order on an arm mannequin and stabilized by adhesive tape (Fig. 5) [20]. Experiments were conducted using the conditions determined in the preliminary experiments described above. Blood was permeated into the gauze. and if the signal from the sensor was below the threshold for blood detection, an alarm will be triggered. All the experiments were repeated 10 times and each trial was assessed for whether the result of blood leakage detection was accurate.

4.2 Detectability of hematocrit range for the proposed method.

According to the results of the preliminary experiments, the color of blood depends on Ht. The blood from polycythemic patients or blood in arteriovenous fistula, which contains venous blood, has higher Ht and the color is reddish brown. As Ht decreases, the color changes to bright red. Furthermore, when patients suffer from massive blood loss due to operation or traffic accident, the Ht sometimes drops below 20%. In this case, severe anemia results in change of the color of the blood to light red. Therefore, the proposed method needs to detect blood over a wide range of abnormal and normal Ht values.

Plasma component was removed from bovine blood by sedimentation, and the residue was diluted with normal saline to adjust the Ht to 64%. Blood samples with Ht of 50%, 45%, 32%, 16%, 8%, 4%, 2%, and 1% were prepared by diluting with saline. Although it is rare for Ht to fall below 4% in the clinical setting, conditions of

<table>
<thead>
<tr>
<th>Sample</th>
<th>Target to be simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal saline</td>
<td>An erroneous detection due to the leakage of sweat or a transparent liquid.</td>
</tr>
<tr>
<td></td>
<td>not in particular</td>
</tr>
<tr>
<td>Yellow aqueous</td>
<td>An erroneous detection due to the leakage of colored chemical liquid.</td>
</tr>
<tr>
<td>solution</td>
<td>not in particular</td>
</tr>
<tr>
<td>Cover/ Black paper</td>
<td>An erroneous detection caused by the stain between emission and light reception or the shade.</td>
</tr>
<tr>
<td>Bovine blood</td>
<td>Detection depending on blood.</td>
</tr>
</tbody>
</table>
4%, 2% and 1% Ht were also examined to examine the detection capability.

5. Results

5.1 Result of verification between the existing and proposed methods

Table 3 shows the data obtained for each condition. As shown in Table 4, the proposed method correctly detected only the blood samples. The electrode method detected all the blood samples, saline and high calorie fluids because the electrode reacted with any kind of electrolytes, leading to erroneous detection.

The single-color method detected all the blood samples, the colored chemical liquid and the black sheet. This is because the sensor monitored the change in absorbance in a specific wavelength region.

5.2 Detectability due to the hematocrit value

The proposed method perfectly detected the blood samples with Ht of 64%, 50%, 45%, 32%, 16%, 8%, 4%, and 2% as it measured the sample chromaticity quantitatively. Moreover, the yellow aqueous solution could be distinguished clearly from the blood samples (Fig. 6).

6. Discussion

In section 3.6.3, the threshold of Rr was determined to be 0.7 for the single-color method. It is true that erroneous detection due to colored solution can be decreased by changing the threshold, but Ht detectability decreases at the same time because the sensor monitors the intensity of reflected light. It is also possible that false detection may occur by compressing or moving the sensor module, which changes the light intensity received by the sensor.

As the proposed method distinguishes blood from other substances, it may be possible to notify events differentially depending on whether it is a real emergency; for example, by using different alarm sounds. It is still possible that red chemical liquids such as cyanocobalamin might be erroneously detected as a rare case. As these liquids are typically thin and light red in color, they can be distinguished from blood by refining formulae (4)–(8).

The proposed method can operate continuously for more than ten days under a typical condition that it is used with 400 mAh battery capacity. Therefore, we consider that our method satisfies the practicality in terms of long operation time. However, there is a risk that the proposed method may obscure detection of subcutaneous hemorrhage or inflammation, because it is used with the sterilized gauze covering the puncture site. This risk could be avoided by placing the same type of device

Table 3 Chromaticity x and y of samples. (mean ± standard deviation)

<table>
<thead>
<tr>
<th>Sample</th>
<th>x</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal saline</td>
<td>0.38 ± 0.004</td>
<td>0.39 ± 0.005</td>
</tr>
<tr>
<td>Ht 1%</td>
<td>0.47 ± 0.005</td>
<td>0.40 ± 0.004</td>
</tr>
<tr>
<td>Ht 2%</td>
<td>0.51 ± 0.003</td>
<td>0.38 ± 0.005</td>
</tr>
<tr>
<td>Ht 4%</td>
<td>0.51 ± 0.005</td>
<td>0.36 ± 0.005</td>
</tr>
<tr>
<td>Ht 8%</td>
<td>0.52 ± 0.003</td>
<td>0.35 ± 0.005</td>
</tr>
<tr>
<td>Bovine blood</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ht 16%</td>
<td>0.56 ± 0.005</td>
<td>0.33 ± 0.003</td>
</tr>
<tr>
<td>Ht 32%</td>
<td>0.54 ± 0.003</td>
<td>0.33 ± 0.003</td>
</tr>
<tr>
<td>Ht 45%</td>
<td>0.54 ± 0.007</td>
<td>0.36 ± 0.015</td>
</tr>
<tr>
<td>Ht 50%</td>
<td>0.54 ± 0.006</td>
<td>0.35 ± 0.010</td>
</tr>
<tr>
<td>Ht 64%</td>
<td>0.53 ± 0.005</td>
<td>0.34 ± 0.005</td>
</tr>
<tr>
<td>Yellow aqueous solution</td>
<td>0.56 ± 0.005</td>
<td>0.42 ± 0.003</td>
</tr>
<tr>
<td>Black paper</td>
<td>0.31 ± 0.005</td>
<td>0.34 ± 0.004</td>
</tr>
</tbody>
</table>

Table 4 Qualitative results for the existing and proposed methods.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Existing Methods</th>
<th>Proposed method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweat and Transparent Liquid</td>
<td>×</td>
<td>○</td>
</tr>
<tr>
<td>Colored Liquid</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Effect due to the cover</td>
<td>×</td>
<td>○</td>
</tr>
<tr>
<td>Blood</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

○ No erroneous detection, × Erroneous detection, - Unverified
without the gauze closer to the device to allow observation, but we would like to leave it as one of our future works.

Moreover, the LED used in the proposed method emits a little heat. Therefore, there is a possibility that prolonged use of the proposed method in infants or diabetes mellitus patients may cause low temperature burns. In this case, we may need to optimize the light-pulse time and LED current, which should be one of our future works.

7. Conclusion

We developed a multicolor sensor module and established a blood leakage detection method that met the 5 conditions that we had set as our goal. This study confirmed that the proposed method did not cause malfunction due to leakage of chemical or presence of obstacle in the light path, while the conventional methods did. We also evaluated its performance and found that our method was able to detect blood leakage within the Ht range of 2%–64%. Application examples of the proposed method include monitoring of blood leakage during extracorporeal circulation therapy, surgery, or after removal of a drain or catheter.

Conflict of interest

The authors have no conflicts of interest to declare.

References


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