Optical Measurement Techniques for Urinary Blood Concentration to Automate Urine Management Tasks

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Japan is facing a declining birthrate and an aging population. While demand for medical care increases, the workload of medical professionals is also increasing due to a shortage of personnel, and there is a growing need to maintain and improve the quality of medical care as well[1]. As part of the solution, implementation of medical digital transformation through digitization and the use of big data is highly anticipated for improving efficiency and maintaining quality in the medical field. In particular, automation, such as remote management and data utilization, in areas that are primarily analog work is expected to create new value.

With this social background in mind, OKI focused its research on urine management tasks. Specifically, effort was placed on automating urinary blood concentration measurement (hematuria measurement) and developing an optical measurement technique that is easy to use in clinical settings.

Current Urine Volume / Hematuria Measurement and Issues

Patients who have undergone major surgery often have difficulty urinating on their own. In such cases, a catheter is inserted from the urethra to the bladder, and urine is drained through the catheter into a urinary drainage bag.

The details of urine management tasks vary by hospital, but typically, the urine in the drainage bag is visually observed/measured every hour, and the urine volume and color of hematuria are manually entered into an electronic medical record, as shown in **Figure 1**.

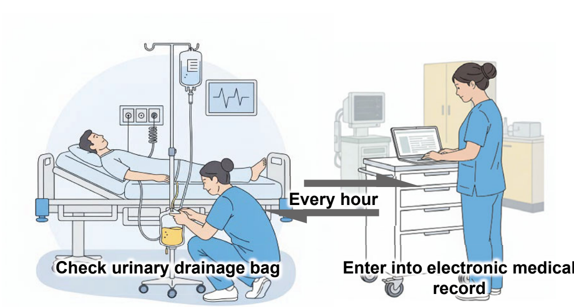

Figure 1. Typical Urine Management Tasks

For cases involving hematuria, a visual five-level assessment is generally performed using a hematuria scale, which is a color sample for each Ht (hematocrit: the percentage of red blood cells in the sample), as shown in **Figure 2**. If abnormalities are observed, urine sample is collected for a more thorough testing.

However, these tasks pose efficiency issues, such as an increased risk of recording errors and work delays during busy times. They are dependent on the experience and subjectivity of the personnel in charge, and are prone to human errors, including reduced visibility at night and variations in assessment.

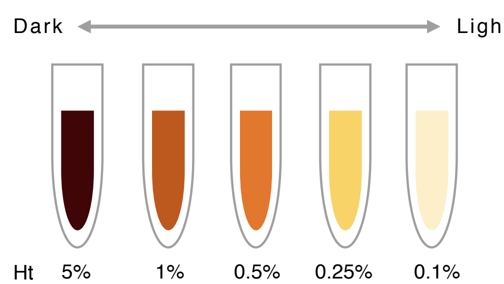

Figure 2. Five-Level Hematuria Scale

While urine volume measurement is becoming increasingly automated, hematuria measurement still relies on visual inspection.

Establishing Measurement Accuracy

The measurement accuracy for the research was established based on the five-level hematuria scale shown in **Figure 2**, with an error threshold of “within ±1 level” as shown in **Figure 3**.

For example, if Ht is between 0.175% and 0.375%, it is considered to fall within the Ht 0.25% range on the hematuria scale. In this case, the lower limit of error tolerance was set to Ht 0%, which is the lower limit of the Ht 0.1% range (-1 level), and the upper limit of error tolerance was set to Ht 0.75%, which is the upper limit of the Ht 0.5% range (+1 level).

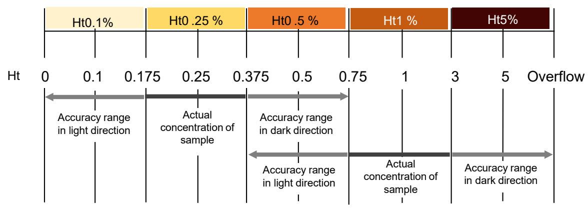

Figure 3. Hematuria Accuracy Range

This measurement accuracy is considered to be practically sufficient for the purpose of initial screening, which is to determine if additional examination or medical attention is needed, as well as to confirm the progress of recovery from hematuria.

Experimental Method

The principle behind hematuria measurement is the use of wavelength absorption spectrum characteristics of hemoglobin[2]. From the perspective of low cost and compactness, measurement techniques that combine LEDs and a photodiode were considered. Based on the optical characteristics of hemoglobin, a red LED (635nm), which is less absorbent, and a green LED (530nm), which is more absorbent, were chosen.

When measuring hematuria using transmitted or reflected/scattered light, the following relationship exists according to Beer-Lambert's law.

$$I_{color} = I_{0,color} \cdot e^{-\varepsilon_{color} Cl} \quad \cdots \ (1)$$

Here, $I_{0,color}$,color is the incident light intensity, I_{color} is the transmitted or reflected/scattered light intensity, ε is the absorption coefficient, C is the concentration of the solution (hemoglobin concentration), and l is the sample length (constant).

Dividing equation (1) by I_{red} as the numerator and I_{green} as the denominator results in the following equation.

$$\frac{I_{red}}{I_{green}} = \frac{I_{0,red} e^{-\varepsilon_{red} cl}}{I_{0,green} e^{-\varepsilon_{green} cl}} = \frac{I_{0,red}}{I_{0,green}} \cdot e^{-(\varepsilon_{red} - \varepsilon_{green})Cl} \quad \cdots (2)$$

When the logarithm of both sides of equation (2) is taken, the result is the following equation.

$$log\left(\frac{I_{red}}{I_{green}}\right) = log\left(\frac{I_{0,red}}{I_{0,green}}\right) - (\varepsilon_{red} - \varepsilon_{green})Cl \cdot log\, e \quad \cdots \ (3)$$

Here, $\frac{I_{0,red}}{I_{0,green}}$ can be controlled by adjusting the output in the experimental environment, therefore it is considered to be a constant A.

Additionally, $(\varepsilon_{red} - \varepsilon_{green})l \cdot log\, e$ is determined by the wavelength (LED color) and the path length, and if this is considered to be coefficient K, then the equation becomes:

$$log\left(\frac{I_{red}}{I_{green}}\right) = A - KC \quad \cdots \ (4)$$

In a controlled experimental environment where the LED brightness and sample length are constant, the ratio of red LED to green LED can be calculated to obtain a value that correlates with C (hemoglobin concentration).

To ensure measurement accuracy and reproducibility during the experiment, a metal jig shown in **Figure 4** was prepared. One side of the jig has a groove for securing the tube containing the sample. The top surface has holes for inserting and fixing two types of LEDs and a light receiving photodiode. The bottom surface also has a hole for inserting and fixing an LED.

These features ensured a consistent sample length and element arrangement.

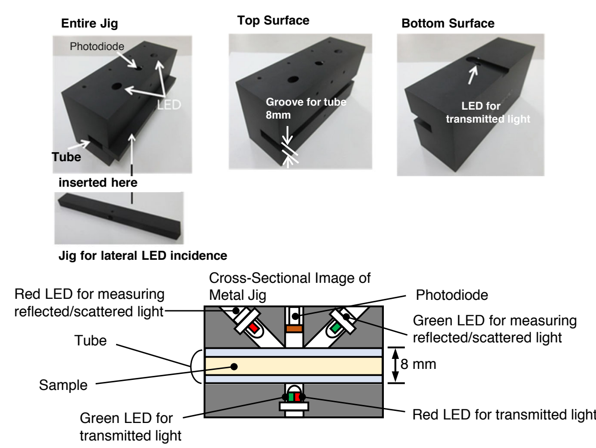

Figure 4. Metal Jig for Measurements

For ethical and safety reasons, the samples used were pig blood (collected from three pigs) diluted with physiological saline, and a small amount of heparin added to prevent blood coagulation. The samples were placed into tubes (outer diameter 9mm, thickness 1.3mm) that came with the urinary drainage bag, ensuring no air bubbles were introduced, and then inserted into the aforementioned metal jig, making sure the minor axis remains uniform at 8mm.

Experiment Results

First, each sample was measured using transmitted light, and the ratios of transmitted light intensity from the red and green LEDs derived from the equation below were plotted along the vertical axis.

$$log\left(\frac{I_{red}}{I_{green}}\right)$$

Along the horizontal axis, the actual hemoglobin concentrations were plotted, and the result is shown in **Figure 5**. It is known that the change in Beer-Lambert's law slows down as the concentration increases due to multiple scattering. Therefore, an exponential function was used as the regression equation for the plotted data. Furthermore, the plot with the smallest margin relative to the previously set target accuracy range is circled.

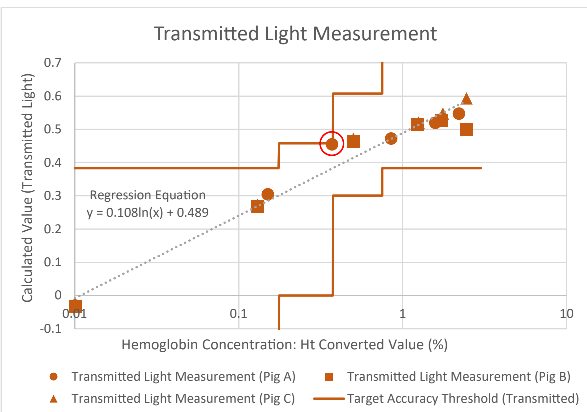

Figure 5. Result of Hematuria Measurement using Transmitted Light

In the transmitted light measurement, all plotted data fell within the target accuracy threshold, but a sufficient margin was not obtained. The sample size was also small (**N=3**), and increasing the sample size would likely cause the data to fall outside the threshold.

Next, measurement of each sample was performed using reflected/scattered light. Similar to the transmitted light measurement, the ratios of reflected/scattered light from the red and green LEDs, using the equation below, were plotted along the vertical axis.

$$log\left(\frac{I_{red}}{I_{green}}\right)$$

Along the horizontal axis, the actual hemoglobin concentrations were plotted, and the result is shown in **Figure 6**. Reflected/scattered light measurement often detect light that is reflected and diffused at the sample surface or very shallow areas, and compared to transmitted light measurement, data remains linear up to high concentrations. Therefore, a linear function was used in the regression equation. Similar again to the transmitted light measurement, the plot with the smallest margin relative to the target accuracy range is circled in red.

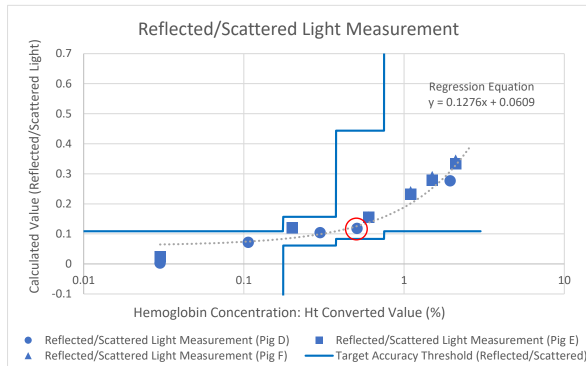

Figure 6. Result of Hematuria Measurement using Reflected/Scattered Light

Reflected/scattered light measurement showed improvement over transmitted light measurement in terms of margin from the target accuracy threshold.

Consideration and Hybrid Measurement

Although the previous experiments showed that measurement using reflected/scattered light had improved margins compared to transmitted light measurement, techniques for further improvement were considered.

When blood concentration is low, the sample is clear, allowing light to pass through easily. Therefore, it is relatively easier to ensure accuracy with transmitted light measurement.

When blood concentration is high, the turbidity of the sample also becomes high, making it difficult for light to pass through. On the other hand, this means there are more substances that reflect/scatter light, making reflected/scattered light measurement relatively advantageous.

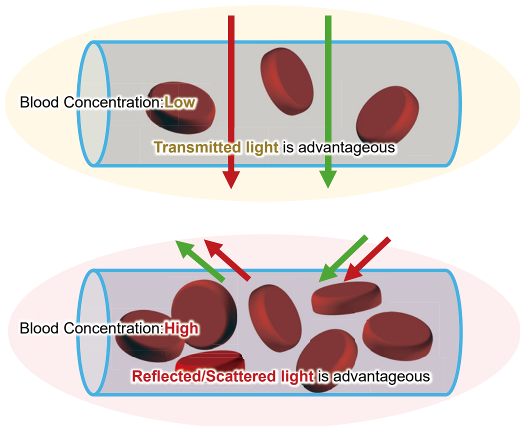

Figure 7. Blood Concentration Levels and Advantage of Each Measurement Technique

Therefore, a hybrid measurement, which switches measurement technique depending on the hemoglobin concentration, was considered. Based on experimental data, a hemoglobin concentration (Ht converted) of 1% was set as the threshold. Below this level, measurements were performed using transmitted light, and above this level, reflected/scattered light was used. **Figure 8** shows the measurement result. As before, the light intensity ratios for each measurement technique were plotted along the vertical axis, and the actual hemoglobin concentrations were plotted along the horizontal axis.

Due to the insufficient number of samples in the experiment, the threshold was provisionally set at a point where the regression equation's coefficient of determination was the highest using the data obtained. In actual practice, the actual Ht is unknown, and it is desirable to set the threshold using a regression equation calculated from sufficient data samples. Hence, verification, including sample acquisition, is an issue requiring further research.

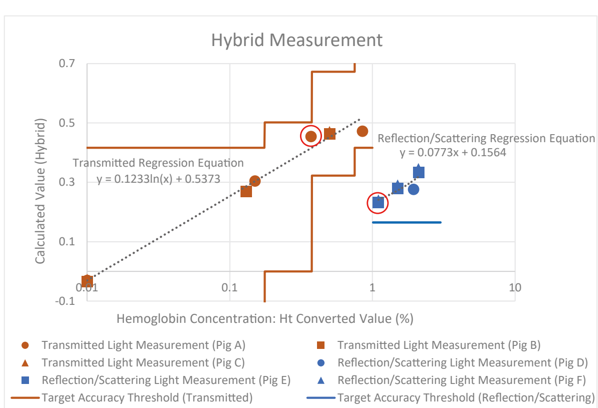

Figure 8. Result of Hematuria Measurement using Hybrid Measurement

The results of the "transmitted light measurement," "reflected/scattered light measurement," and "hybrid measurement" were compared to identify the technique that provides the most accurate measurements.

From the "transmitted light measurement" and "reflected/scattered light measurement" plots, the points with the smallest margin relative to the target accuracy threshold (circled in **Figures 5** and **6**) were extracted and compared with the margin at the same Ht value in "hybrid measurement." The results are summarized in **Table 1**.

Table 1. Margin Comparison Between Each Measurement Technique and Hybrid Measurement

	Transmitted Light	Hybrid	Reflected/ Scattered Light	Hybrid
Ht [%]	0.37	0.37	0.5	0.5
Calculated Value	0.455	0.455	0.118	0.464
Margin	0.003	0.047	0.035	0.048

As shown in **Table 1**, the hybrid measurement obtained a margin approximately 15 times greater than the transmitted light measurement against the target accuracy threshold at Ht of 0.37%. Similarly, when the hybrid measurement was compared with the reflected/scattered light measurement, a margin of approximately 1.4 times greater was obtained.

Under the measurement conditions of the experiment in this article, it was confirmed that "hybrid measurement," which changes the measurement technique according to the hemoglobin concentration, produces better accuracy results than single measurements such as the "transmitted light measurement" or "reflected/scattered light measurement."

Future Developments

Under the conditions of the research in this article, the "transmitted light only" or "reflected/scattered light only" measurements failed to overcome the problem of inconsistent accuracy that is dependent on the blood concentration. However, the "hybrid measurement", which switches the measurement technique according to the blood concentration, has the potential to provide higher accuracy.

Currently, there are no devices that non-invasively measure urinary blood concentration through the tube attached to urinary drainage bags using hybrid measurement. It is believed that this research is a pioneering study in this field.

However, the research had limitations as the samples were obtained from animals and sample size was small. For clinical application, it is essential to address various types of tubing, as well as non-ideal factors such as air bubble contamination, and to conduct thorough additional verification. Further research and development are expected for expansion aimed at ensuring stable medical care. ◆◆

References

1) Future Projection of Medical Demand, Ministry of Health, Labour and Welfare (in Japanese)
2) B.L. Horecker: The Absorption Spectra of Hemoglobin and Its Derivatives in the Visible and Near Infrared Regions
3) Hematuria Diagnostic Guidelines 2013, Editorial Committee for Hematuria Diagnostic Guidelines (in Japanese)

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