



Research Article

A study on the change of droplet volume by the increase of flow rate



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Abstract

Drip-control type infusion pumps cause a flow rate error when the volume of the droplet dropping in the drip chamber changes. Therefore, the purpose of this study is to accurately measure the volume of one droplet as the flow rate increases. For measurement of droplet volume, a droplet bypassing device was prototyped. In the case of a 20 drop/mL drip nozzle, a volume error of + 7.6% occurred at a flow rate of 500 mL/min, compared to the theoretical volume of 50.0 mm³. In the case of a 60 drop/mL drip nozzle, a volume error of – 17.4% occurred at a flow rate of 300 mL/min, compared to the theoretical volume of 16.7 mm³. Moreover, the standard deviation of the measured value of the droplet volume increased as the flow rate increased. It was shown that even with proper use of the infusion set, significant flow rate errors can occur depending on the flow rate settings. Therefore, it is considered that the drip-control type infusion pump needs to be controlled by correcting the volume change due to the increase in the flow rate.

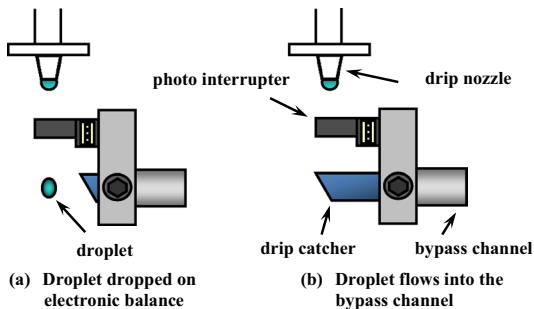
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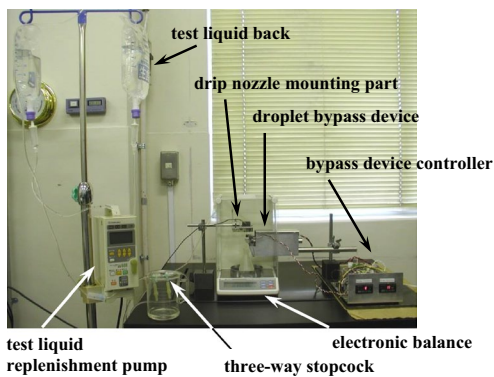
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Graphic Abstract

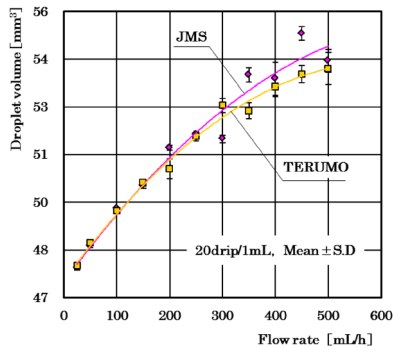
The volume of one droplet intermittently dropped from the drip nozzle using a droplet bypass device was accurately measured. The change in droplet volume with increasing flow rate was shown



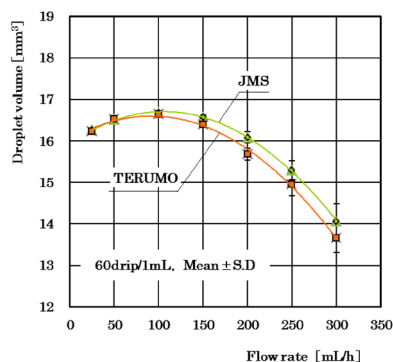
Schematic diagram of operation of droplet bypass device.



Photograph of measuring system



The change in droplet volume when using a 20drop/1mL drip nozzle.



The change in droplet volume when using a 60drop/1mL drip nozzle.

Keywords Infusion pump · Drip-control · Droplet volume · Droplet bypassing device · Drip nozzle

1 Introduction

Infusion pumps are one of the most frequently used medical devices in hospitals. There are a drop control method and a volume control method as the flow control methods of the linear peristaltic infusion pump. In the case of the drop control method, the number of droplets dropped in the drip chamber is counted for a fixed time, and feedback control is performed in comparison with the set flow rate. ISO 8536-4 defines only two drop rates, 20 drop/1 mL and 60 drop/1 mL. However, the volume of a drop may change under various conditions. One of these causes may be the liquid flow rate. When the volume of the droplet changes, both gravity-driven infusion sets and infusion pump of the drop control method does not function properly and generates a flow rate error. If there is an error in the dose of the drug solution, there is a possibility of seriously affecting the patient, depending on the type of the drug solution. Therefore, an important issue is to clarify the cause of the flow rate error.

Analyzes based on experiments and simulations have been conducted on the drop formation at the drip nozzle [1, 2]. In addition, measurement of the volume and velocity of the ejected droplets was performed in the field of inkjet printers [3–5]. Many image analysis methods using high-speed video pictures have been reported for measuring drop formation [6–8]. There are also reports of measuring the mass of 100 drops using a precision balance and determining the mass of one drop [9]. In addition, much research is being conducted in the field of eye drop bottles [10–12]. However, using the methods of counting the number of drops when a certain amount of droplets flow into a pipette [13] and using image analysis on droplet volume change [14], so far only a few studies have been reported that measure the drop volume using an infusion set.

The purpose of this study is to experimentally clarify the volume change of the droplet when the flow rate increased. A droplet bypass device developed by the author is used to accurately measure the volume of one

droplet that drops intermittently from a drip nozzle [15]. The change in droplet volume causes flow rate error. Therefore, the control parameter can be corrected in the drip-control type infusion pumps, and the precautions when adjusting the flow rate can be seen in the gravity-driven infusion sets.

In the following chapters of this paper, the experimental conditions are described in detail, the experimental results are shown, and the results are discussed and suggested contents are described.

2 Method

Infusion pumps are evaluated using the dynamic gravimetric facility [16]. In this study, droplet volume is calculated from droplet mass. The volume of the droplet dropped from a drip nozzle was calculated by dropping the droplet on a precision balance and measuring the mass of one droplet. The drip nozzle was used in the experiment by cutting the drip chamber at the flange part and connecting it to another infusion set.

The experiment was conducted by increasing the flow rate from 25 mL/h to 500 mL/h when the drip nozzle was at 20 drops/1 mL, and from 25 mL/h to 300 mL/h when the drip nozzle was at 60 drops/1 mL. Pure water produced by the ultrapure water system Direct-Q (Millipore) was used as the test liquid. Figure 1 shows the measurement system that was prototyped for the experiment. A steady flow was obtained by free fall between the test liquid bag and the drip nozzle. The adjustment of the flow rate was carried out by incorporating a three-way stop cock into the infusion set because the flow rate would change over time due to the creep phenomenon when a roller clamp is used. In addition, since the flow rate also changed due

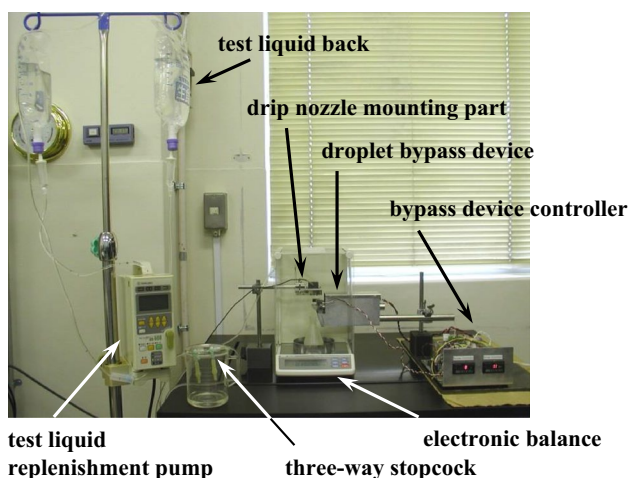


Fig. 1 Photograph of measuring system

to a decrease in the liquid level in the test liquid bag, the test liquid is supplied to the test liquid bag at the same flow rate as the set flow rate. The flow rate was measured by measuring the accumulated mass dropped for 5 min before and after the experiment and converting it into a flow rate, and it was confirmed that it was within $\pm 5\%$ of the set flow rate.

The test liquid flowing in the tube is formed into droplets by the drip nozzle and dropped onto the electronic balance GH-252 (A & D). The display accuracy of the electronic balance is 0.01 mg. The accumulated mass was recorded at a sampling interval of 0.5 s. The droplets were received in a small plastic Erlenmeyer flask so that the test liquid would not splash and go out of the electronic balance. In addition, the test solution was put in the same Erlenmeyer flask and placed near the weighing pan of the electronic balance, and the change in mass was measured before and after the experiment to correct for evaporation of the measured value.

The number of measured droplets was 100 droplets each. All experiments used pure water produced within 24 h. The room temperature of the laboratory was adjusted to 21–25 °C. Also, the density of the test liquid used was the value shown in Chronological Scientific Tables (National Astronomical Observatory) based on the room temperature at the time of the experiment.

2.1 Droplet bypass device

Figure 2a shows the output of the electronic balance when droplets are dropped on the electronic balance at a low flow rate. The vertical axis represents the output of the electronic balance in terms of mass, and the horizontal axis represents the weighing time. Since the measurement value of the electronic balance changes stepwise, it is possible to determine the mass of one drop from the difference W_d between the measurement points of the flat part where the measurement is stable. However, the electronic balance used requires about 8 s until the measured value becomes stable. If multiple droplets are dropped while the measurement value is unstable, the mass of one drop cannot be determined because there is no flat part. Figure 2 (b) shows the output of the electronic balance when droplets are dropped at a high flow rate, and it can be seen that it is difficult to determine the mass of one droplet. In view of this, the droplet bypass device shown in Fig. 3 was used to enable stable droplet weighing.

When the droplet is dropped on the electronic balance, the droplet bypass device causes the subsequent droplets to flow to the bypass channel until the electronic balance is stabilized, and after the electronic balance is stabilized, the next droplet is dropped on the electronic balance. This makes it possible to accurately weigh the mass of one drop

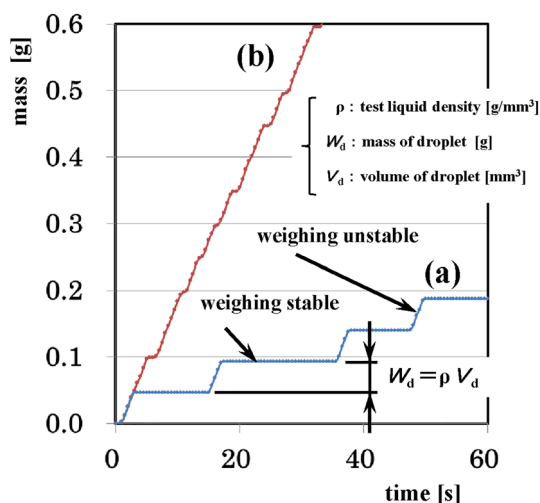


Fig. 2 Output of electronic balance

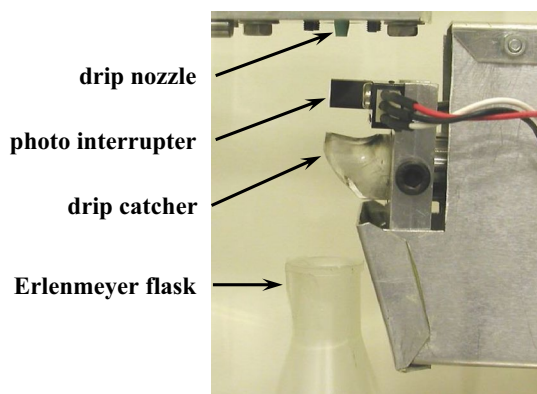


Fig. 3 Photograph of droplet bypass device

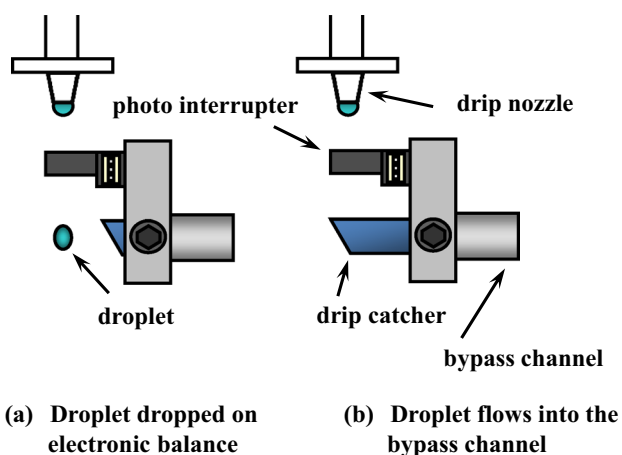


Fig. 4 Schematic diagram of operation of droplet bypass device

Table 1 Drip nozzle used in the experiment

Drip nozzle type	Manufacturer	Model	Diameter of the end face (mm)	
			Outside	Inside
20 drip/1 mL	JMS	JY-PB841C	3.670	3.059
	TERUMO	TI-U750P	3.156	3.156
60 drip/1 mL	JMS	JP-APSW811L01	0.978	0.675
	TERUMO	TK-U750P	0.967	0.628

at an arbitrary flow rate. As shown in Fig. 4a, the droplet passes through the photo interrupter and drops on the electronic balance. Next, as shown in Fig. 4b, in response to the output of the photo interrupter, a drip catcher is stuck out to bypass the droplets, and the set number of droplets to be dropped next flow through the bypass channel. The number of droplets to bypass is preset by the controller based on the flow rate of the test liquid. The controller is set to generate a display sound when 100 droplets have been dropped on the electronic balance and to stop with the drip catcher stuck out.

2.2 Drip nozzle used in the experiment

The infusion set used was manufactured by TERUMO Co. and JMS Co., Ltd. as shown in Table 1. Since the commercially available drip nozzle is built in the drip chamber, the drip chamber was cut off at the flange part, and only the drip nozzle part was used. The flange part of the drip chamber was machined with a lathe so that it was perpendicular to the center axis of the drip nozzle. The outer diameter and inner diameter of the tip of the drip nozzle were measured using a computer vision system PC-VJ14MEXOW (SAITOH KOUGAKU) [17]. Before the experiment, it was visually confirmed with a stereomicroscope that the lip part of the drip nozzle had no deformations or scratches.

3 Results

The measurement results of the droplet volume when the flow rate was increased are shown below. Table 2 and Fig. 5 show the change in droplet volume when using a 20 drop/1 mL drip nozzle. The flow rate was changed from 25 to 500 mL/h. As a result of using the drip nozzles made by TERUMO Co. and JMS Co., Ltd., both the droplet volume showed the same tendency to increase. The droplet volume was 47.5 mm³ at 25 mL/h, 50.1 mm³ at 150 mL/h, and 53.8 mm³ at 500 mL/h. The standard deviation of the measured value was 0.51 mm³ at the maximum. Table 3

Table 2 The change in droplet volume when using a 20drop/1 mL drip nozzle

Maker	Droplet volume (mm ³)			
	JMS		TERUMO	
	Mean	SD	Mean	SD
Flow rate (mL/h)				
25	47.43	0.07	47.49	0.06
50	48.11	0.05	48.22	0.04
100	49.30	0.03	49.22	0.06
150	50.02	0.09	50.11	0.10
200	51.21	0.08	50.55	0.31
250	51.63	0.11	51.58	0.15
300	51.49	0.11	52.54	0.22
350	53.49	0.23	52.38	0.26
400	53.38	0.51	53.12	0.30
450	54.80	0.22	53.52	0.28
500	53.95	0.37	53.70	0.50

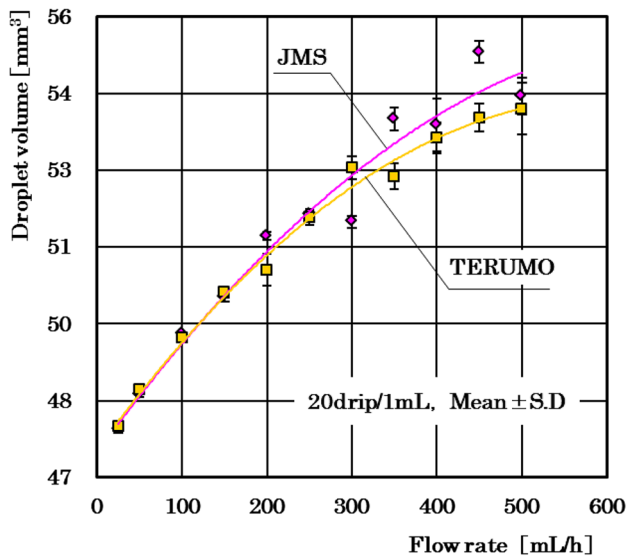


Fig. 5 The change in droplet volume when using a 20 drop/1 mL drip nozzle

Table 3 The change in droplet volume when using a 60drop/1 mL drip nozzle

Maker	Droplet volume (mm ³)			
	JMS		TERUMO	
	Mean	SD	Mean	SD
Flow rate (mL/h)				
25	16.26	0.06	16.24	0.03
50	16.51	0.03	16.53	0.03
100	16.68	0.03	16.65	0.02
150	16.57	0.06	16.39	0.03
200	16.08	0.13	15.68	0.14
250	15.30	0.23	14.95	0.27
300	14.06	0.42	13.65	0.34

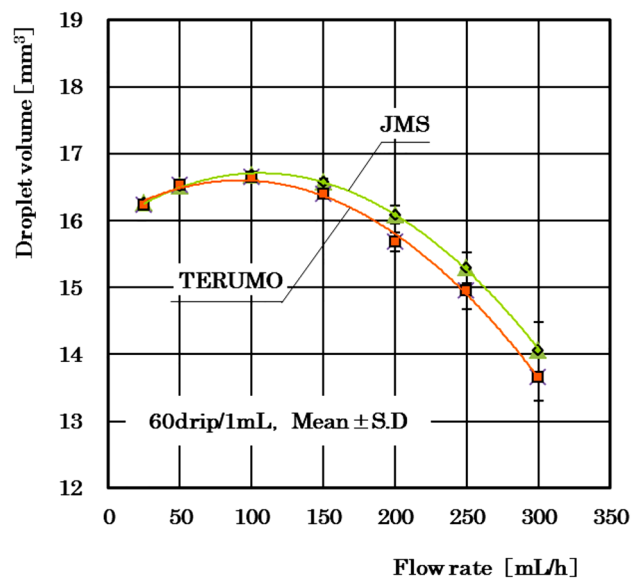


Fig. 6 The change in droplet volume when using a 60 drop/1 mL drip nozzle

and Fig. 6 show the change in droplet volume when using a 60 drop/1 mL drip nozzle. The flow rate was changed from 25 to 300 mL/h. As a result of using the drip nozzles made by TERUMO Co. and JMS Co., Ltd. the droplet volume increased until the flow rate was approximately 100 mL/h. In addition, it was shown that the droplet volume decreased when the flow rate exceeded about 100 mL/h. The droplet volume was 16.3 mm³ at 25 mL/h, 16.5 mm³ at 50 mL/h, 16.7 mm³ at 100 mL/h, and 13.8 mm³ at 300 mL/h. The standard deviation of the measured value was 0.42 mm³ at the maximum.

4 Discussion

Using the measurement system developed by the author, it was possible to precisely measure the volume of one droplet that drops from the drip nozzle. The standard deviation of the measured value was 0.51 mm³ or less. Therefore, it is estimated that the measurement error of the droplet volume was approximately ± 1 mm³ or less.

For a 20 drop/1 mL drip nozzle, the droplet volume should be 50.0 mm³. Similarly, for 60 drop/1 mL, the volume of the droplet needs to be 16.7 mm³. It is defined as The drip tube shall be such that 20 drops of distilled water or 60 drops of distilled water at (23 ± 2) °C at a flow rate of (50 ± 10) drops/min deliver a volume of (1 ± 0.1) ml or a mass of (1 ± 0.1) g in ISO 8536-4. In this case, the flow rate during the test is 150 mL/h for a drip nozzle of 20 drop/1 mL, and 50 mL/h for a drip nozzle of 60 drop/1 mL.

In the case of a 20 drop/1 mL drip nozzle, TERUMO Co. and JMS Co. produced similar droplet volume changes. Based on 50.0 mm^3 , the droplet volume was approximately 47.5 mm^3 at a flow rate of 25 mL/h, therefore the result error was -5.0% . Almost no error occurred at 150 mL/h. The droplet volume was 53.8 mm^3 at a flow rate of 500 mL/h, therefore the result error was $+7.6\%$. Similarly, for the 60 drop/1 mL drip nozzle, TERUMO Co. and JMS Co. produced similar droplet volume changes. Based on 16.7 mm^3 , the droplet volume was 16.3 mm^3 at a flow rate of 25 mL/h, therefore the result error was -2.4% . As the flow rate increased, the droplet volume reached its maximum value at approximately 100 mL/h, and no error occurred. As the flow rate increased further, the droplet volume gradually decreased. The droplet volume was approximately 13.8 mm^3 at a flow rate of 300 mL/h, therefore the result error was -17.4% . It was found that the flow rate error was small near the test flow rate specified in ISO8536-4. The flow rate error of the linear peristaltic infusion pump is considered to be $\pm 5\%$ or less, so the change in droplet volume at high flow rates is extremely large value [18].

Regarding the droplet volume change due to the flow rate, George F. Scheele et al. include a velocity term that passes through the nozzle in the equation for determining the volume of the droplet after separation from the drip nozzle, indicating that the volume of the droplet depends on the flow velocity [1]. In addition, Sato et al. show that when the drip nozzle has no difference between the inner and outer diameter, the droplet volume increases as the flow rate increases. And, it shows that the droplet volume may decrease after increasing depending on the shape of the drip nozzle [19]. In this experiment, in the case of a 20 drop/1 mL drip nozzle, the droplet volume increased monotonically as the flow rate increased, but in the case of a 60 drop/1 mL drip nozzle, the maximum droplet volume was reached when the flow rate was approximately 100 mL/h and the droplet volume decreased as the flow rate increased further.

During the droplet formation process, the liquid flowing in the tube gradually grows from the tip of the drip nozzle. After that, the liquid formed at the tip of the drip nozzle balances gravity and surface tension at the necking part. Furthermore, when the volume of the droplet increases, the balance between gravity and surface tension is lost, and the liquid is divided into a droplet and a residual liquid that stays at the tip of the drip nozzle. Finally, the droplet drops while performing shape vibration. The reason why the volume of droplets dropped from the 20 drop/1 mL drip nozzle increased corresponding with the flow rate is thought to be due to an increase in the amount of inflow that flows into the droplet after the balance between gravity and surface tension is lost. When the inner diameter of

the drip nozzle becomes extremely small, the jet collision velocity at the gas–liquid interface increases, so the downward force increases due to the momentum increase [19]. Therefore, in the case of the 60 drop/1 mL drip nozzle, it is considered that the liquid was pushed out quickly and the droplet volume was reduced.

As the flow rate of the test liquid increased, the standard deviation of the measured value of the droplet volume increased. The reason why the measured value became unstable is considered to be due to the kinetic energy changed to the vibration of the droplet due to the increase in the flow rate of the test liquid.

So far, changes in droplet volume due to tilting of the drip chamber have been shown [15]. This was when the infusion set was used incorrectly. Even though the infusion set was used correctly this time, it was surprising that a significant flow rate error could occur depending on the flow rate setting conditions. Therefore, when the flow rate is set using the number of drops, caution is required at a high flow rate. In addition, in the drop-control type infusion pump, it is necessary to correct the volume of the droplet to control the flow rate.

It has been reported that satellite droplets are formed after the droplets break up from the nozzle [20, 21]. In the case of image measurement, the volume of the satellite droplet becomes an error factor when calculating the flow rate. In this experiment, the occurrence of satellite droplets could not be detected. Even if satellite droplets are generated, they are included in the mass of one droplet. However, even when the flow rate is calculated by including satellite droplets in the mass of one drop, it is considered that no error in flow rate occurs.

The infusion fluid that is actually used may differ greatly from pure water in properties that affect the droplet volume depending on the components. The test liquid used this time was pure water only, and a study using an actual infusion fluid is considered to be a future issue for research.

5 Conclusion

In both the gravity-driven infusion sets and the drip-control type infusion pumps, a flow rate error occurs when the volume of the droplet dropped from the drip nozzle changes. The purpose of this study was to experimentally clarify the volume change of the droplet when the flow rate increased. The volume of one drop was precision measured when the flow rate increased by creating a prototype of a droplet bypass device. In the case of a 20 drop/mL drip nozzle, a volume error of $+7.6\%$ occurred at a flow rate of 500 mL/min compared to the theoretical volume of 50.0 mm^3 . In the case of a 60 drop/mL drip nozzle, a volume error of -17.4% occurred at a flow rate of 300 mL/min

compared to the theoretical volume of 16.7 mm^3 . Moreover, the standard deviation of the measured value of the droplet volume increased as the flow rate increased. It was shown that even with proper use of the infusion set, significant flow rate errors can occur depending on the using condition. Therefore, it is considered that the drip-control type infusion pump needs to be controlled by correcting the volume change due to the increase in the flow rate. In addition, when adjusting the flow rate by counting the number of drops, it is necessary to understand the characteristics of the flow rate error before use. The limitation of this study is that the only test solution used was pure water. Conducting experiments using actual infusion fluids is a future research topic.

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Compliance with ethical standards

Conflict of interest The author declares that he has no conflict of interest.

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