Drop volume estimation of intravenous set

using gravimetric method

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Abstract

Intravenous Administration Set (IV Set) is one of medical devices that have been generally used in hospitals. Then, the primary standard calibration system appeared in this paper was set according to the IEC60601-2-24. The flow rate, volume and mass of distilled water which flowing through different IV sets are measured by using 1 mg resolution weighing balance, photoelectric sensors and data acquisition system. This is paper presents drop volume estimation compared with three different methods; surface tension calculation, drop counted by photoelectric sensor and gravimetric method. The results show comparison of the drop volume with the three different methods and error less than 5% for each IV set type. The uncertainty of measurement is 0.752% of reading (k=2).

Introduction

IV Set is a medical device which is used to inject solution into bloodstream. This research, therefore, proposes for some experimental guidelines which emphasize on comparing drop volume of the solution gained from IV Set. The three methods proposed for the experiment include the calculation according to the Tate's Law, Gravimetric Method (IE60601-2-24) [1], and drop counted by photoelectric sensor. The calculations were under the assumption that drop volumes gained form IV Set at the flowrates of low, medium, and high level are not different. In this experiment, 20 drop/ml and 60 drop/ml IV Sets were selected for testing. The Gravimetric Method, furthermore, were applied according to the criteria corresponding to the standard of IE60601-2-24, or as called Particular Requirements for the Safety of Infusion Pump and Controllers, under the item of 50.103 "Accuracy Tests for Drip-Rate Infusion Controllers and Drip-Rate Infusion Pumps". This method is aimed to measure drop volume of solution, by having distilled water weighed on a balance with resolution value of 1 mg. The balance was connected to a computer through RS-232 cable. The solution drop was counted by having Photoelectric Sensor connected to a computer through Data Acquisition System (DAQ). With 2.5 hours of experiment duration, the evaporation of solution in container on the weighing balance is protected by oil-film. The drop volume gained from the measurement, which was operated according to Gravimetric Method,

was brought to compare with the drop volume calculated by the Surface Tension Theory of Tate. The comparison are purposed for proving the accuracy of the experimental methods and creating reliability for the calibration system. Moreover, the error values gained from IV Set experimenting should not exceed (1±0.1) ml, according to the ISO 8536-4 Standard of Infusion Equipment for Medical Use-Infusion Sets for Single Use, Gravity Feed [2].

Theory

Surface Tension [3]

Tate's Law is a fundamental method to measure surface tension of water drop, by calculating from water drop mass. The mentioned mass can be calculated from each drop of solution. Hence, each drop volume of solution can be known. Volume per-drop mass of solution, can be calculated from the equation (1).

$$m = \frac{2\pi r\gamma}{g} - \frac{\pi r^2 \Delta p}{g} \qquad (1)$$

$$\Delta p = p_{liquid} - p_{atm} \qquad (2)$$

In equation (1) and (2), m is drop weight of IV Set (kg.), r is a radius of drip tube (m), γ is the value of the 0.0728 N/m surface tension of distilled water, g is gravitational acceleration = 9.78312 m/s^2 at NIMT, Δp is pressure difference between liquid and gas (Pa), P_{liquid} is liquid pressure (Pa), and P_{atm} is atmospheric pressure (Pa).

Figure 1 shows the shape of water drop, which was collected from capillary tube with 0.5 and 1.5 mm. radii. It, moreover, shows the shape of certain slow drop.
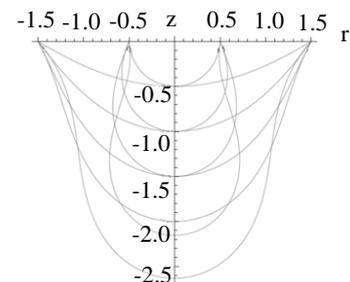

Figure 1 Set of static drop shape which dropped from the mouth of the capillary Tube of which radii (r) were 0.5 and 1.5 mm [3].

Converting Mass Unit into Volume

According to Tate's Law, mass of each water drop can be calculated from the result in kg unit. Therefore, converting mass unit into volume is important in order to apply the data to compare drop volumes of the solution values which were gained from the three methods. Then, the principle for converting mass into volume was in accordance with the standard of ISO/TR 20461[4], Determination of Uncertainty for Volume Measurements Made Using the Gravimetric Methods, as follows.

$$V_{20} = \frac{m}{\rho_b} \cdot \frac{\rho_b - \rho_a}{\rho_w - \rho_a} \cdot [1 - \alpha_c(t_d - t_{d20})] \qquad (3)$$

Where
$$\rho_w = \sum_{i=0}^{4} a_i t_w^i$$

t_w is water temperature, a_o is 999.853 kg/m^3, a_1 is 6.327 x 10^{-2} °C^{-1} kg/m^3, a_2 is -8.524 x 10^{-3} °C^{-2} kg/m^3, a_3 is 6.943 x 10^{-5} °C^{-3} kg/m^3, a_4 is -3.821 x 10^{-7} °C^{-4} kg/m^3 α_c is cubic expansion coefficient (°C^{-1}), ρ_a is the value of air density and ρ_b is 8,000 kg/m^3, which can be calculated from the CIPM formula (1981/91) [5].

$$\rho_a = \frac{0.34848p - 0.009(hr) \times e^{0.061t}}{273.15 + t} \qquad (4)$$

When p is for pressure (hPa), hr is relative humidity (%Rh) and t is temperature (°C)

IEC 60601-2-24 [1]

Calibration System for Intravenous Set (IV Set) was in accordance with the IEC60601-2-24 Standard, a reliable international standard for calibrating Infusion Pump and Controller. The standard can be applied to use with Calibration System for Intravenous Set (IV Set) Infusion Pump, Drip-Rate Type. The experiment of IV Set was environmentally controlled at room temperature between (5-40) °C and humidity between (20-90)%Rh. This IV Set can be used to calculate flowrate and trumpet curve of drop volume as follows.

Flowrate Calculation

Flowrate of Intravenous can be calculated by using the following equations.

$$Q = \frac{60V}{ime} \qquad (5)$$

$$V = \frac{N_i}{Set} \qquad (6)$$

Where Q is flowrate (ml/h), V is IV Set's accumulated volume (ml), *time* is the time of experiments (min), Ni is the ith total drop-count sample collected from the experiment period, and *Set* is type of intravenous set (drop/ml).

Drop Volume Calculation

Calculating drop volume of IV Set refers to a calculation for a reference point. The reference point was

used to limit the acceptable error value, according to ISO 8536-4 standard, which can be calculated from;

$$V_i = \frac{(N_i - N_{i-1})}{Set} \qquad (7)$$

$$V_w = \frac{V_{20}}{N_i} \qquad (8)$$

Where V_i is drop volume from drop-count by photoelectric sensor (ml) and V_w is standard volume from balance (gravimetric method).

Trumpet Curve Calculation

Trumpet curve of drop volume can be calculated by using the following equations [3].

$$E_p(max.) = MAX_{j=1}^{m} \left[\frac{S}{P} \times \sum_{i=j}^{j+\frac{P}{S}-1} 100 \times \left(\frac{V_i - V_w}{V_w} \right) \right] \quad (9)$$

$$E_p(min.) = MIN_{j=1}^{m} \left[\frac{S}{P} \times \sum_{i=j}^{j+\frac{P}{S}-1} 100 \times \left(\frac{V_i - V_w}{V_w} \right) \right] \quad (10)$$

$$m = \frac{T - P}{S} + 1 \qquad (11)$$

Where $E_p(max.)$ and $E_p(min.)$ refer to percentage variations within an observation window, S stands for sample interval (min.), P refers to observation windows of durations P =1, 2, 5, 22, 19, 31 and T is analyzing period (min).

Experimental Method

Calibration System for Intravenous Set (IV Set) corresponds to the IEC 60601-2-24 standard. The equipments used in this system include 1 mg resolution weighing balance which corrected to a computer via RS-232 cable for data collection at every 30 seconds and a photoelectric sensor which also connected to a computer via DAQ for solution drop counting. The experimental data were collected via Labview program and recorded to MS Excel. Figure 2 shows the calibration setting and data transfer for execution.
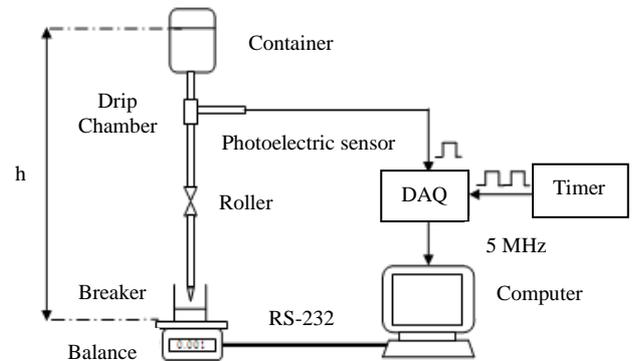

Figure 2 The experimental setting

The equipments in the experiment were set as shown in figure 2 and each IV Set was tested with flowrate as shown in Table 1. The most important concern in calibration was water level between the container and the balances (h) that has to be constant

throughout the calibration duration. In this setting, the height, *h*, was set at about 1.5 metres. The data collection of each IV Set and flowrate was done approximately 2.5 hours duration. The drop volume of each setting was calculated as described in theory section.

Table 1 Flowrates of the calibration system

Type of IV Set	Flowrate (ml/h)		
20 drop/cc	50	150	250
60 drop/cc	10	50	120

Due to the system require long duration in each test, the evaporation protection was another factor of this experiment. Then, the 1000 ml beaker contains 100 ml volume of water covered with 50 ml oil-film and it was left in the room for 5 hours. The evaporation rate was considered very little because the water disappeared from the beaker less than 1 mg within 5 hours.

Result

In the experiment, two types of IV Set, 20 drop/ml and 60 drop/ml, were tested at different flowrates with three methods. The per-drop volume of each IV Set calculated by Tate's Law and gravimetric method was averaged with three different flowrates. The results of per-drop volume of both IV Set are shown in figure 3 and 4. On calculating the error value, the value gained from the calculation of IV Set was used as a reference point. As a result, for 20 drop/ml. IV Set, its acceptable error value should have per-drop volume of between (0.05±0.005) ml. As for 60 drop/ml IV Set, its acceptable error value should have per-drop volume of between (0.0167±0.00167) ml.

The results of 20 drop/ml IV Set were found that all the three IV Sets passed the required standard. Comparing per-drop volume of the IV Sets, as calculated by the Law of Tate, with per-drop volume of the balance, both were equal. Also, per-drop volume obtained from different flowrates were approximate valve were equal.
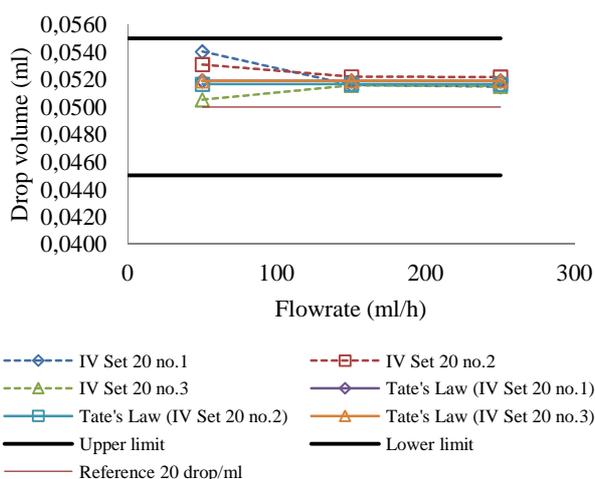

Figure 3 The drop volume of 20 drop/ml IV Set at flowrates; 50, 150, 250 ml/h.

The results of 60 drop/ml IV Set were found that IV Set 60 no.2 did not pass the standard of ISO8536-4, as compared to the reference point of (0.0167±0.00167) ml. IV Set 20 no.2 had as much average drop volume from the balance as 0.0189 ml. The

value of 0.0187 ml corresponds to the calculation based on Tate's Law. Moreover, the drop volume of IV Set 60 no.1 and IV Set 60 no.3 passed the required standard. Furthermore, the calculation based on Tate's Law with the result from measuring drop volume, as weighed on the balance, both methods give the comparable drop volumes.
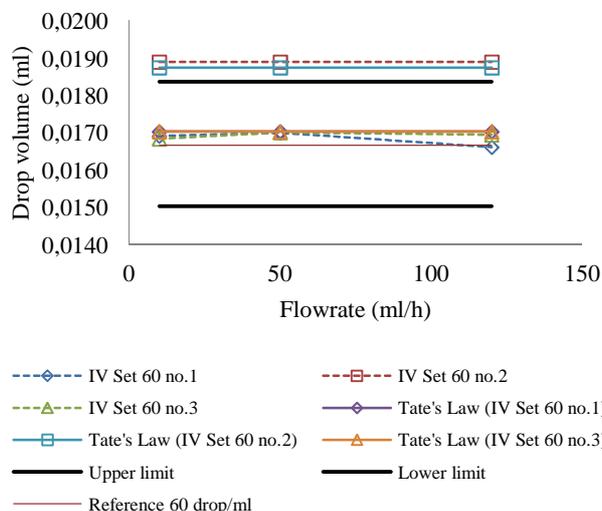

Figure 4 The drop volume of 60 drop/cc IV Set at flowrates; 10, 50, 120 ml/h.

Table 2 Comparison of drop volumes of IV Set 20 drop/ml.

Number of IV Set	Methods	Average of drop volume (ml/drop)	Error (%)
IV Set 20 no.1	IV Set Balance Tate's Law	0.0500 0.0524 0.0519	4.74 3.82
IV Set 20 no.2	IV Set Balance Tate's Law	0.0500 0.0525 0.0517	4.99 3.35
IV Set 20 no.3	IV Set Balance Tate's Law	0.0500 0.0512 0.0519	2.42 3.82

Table 3 Comparison of drop volumes of IV Set 60 drop/ml.

Number of IV Set	Methods	Average of drop volume (ml/drop)	Error (%)
IV Set 60 no.1	IV Set Balance Tate's Law	0.0167 0.0169 0.0170	1.06 2.19
IV Set 60 no.2	IV Set Balance Tate's Law	0.0167 0.0189 0.0187	13.17 12.27
IV Set 60 no.3	IV Set Balance Tate's Law	0.0167 0.0168 0.0170	1.60 2.19

The average drop volumes are calculated from three different flowrates of each IV Set. Table 2 shows that the error values of all the three 20 drop/ml IV Sets are acceptable within ±5%. Therefore, all the three IV Sets can be brought to use with critical patients since their error values do not exceed ±5%. In table 3, the

maximum error values of IV Set 60 no.2 are 12.3% compared to Tate's Law calculation, and 13.2% compared to the balance. Furthermore, the error values of IV Set 60 no.2 and IV Set 60 no.3 do not exceed ±5%. These values, hence, can be used with critical patients and infusion pump.

Since the result of drop volume calculated from Tate's law and the balance are approximately equal, the accuracy and reliability of the calibration system can be proved. According to ISO 8536-4, the acceptable error value must not exceed ±10% at 1 ml.

The results from the experiment are used to plot trumpet curves. The trumpet curve calculation is based on statistic analysis. They are useful in identifying the performance of each IV Set.

Figure 5 shows the trumpet curve of IV Set 20 no.3. The error value was less than 5% for flowrate 150 ml/h and 250 ml/h but error value was more than 10% at flowrate 50 ml/h.

Figure 6 shows the trumpet curve of IV Set 60 no.2. Its error value was more than 10% which is over the limit specified by ISO 8536-4. By this error value, it is obvious that the quality of IV Set 60 no.2 is below standard and the IV Set should not be brought to use with patients.
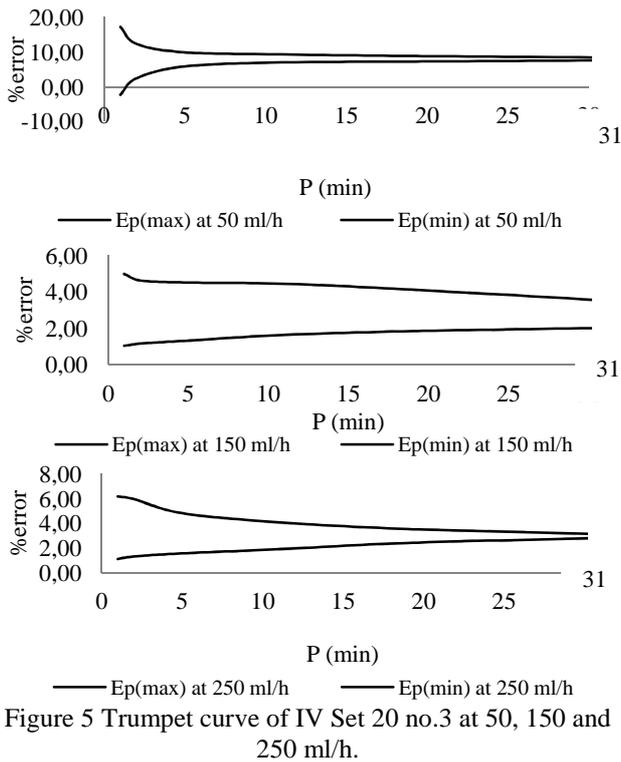

Figure 5 Trumpet curve of IV Set 20 no.3 at 50, 150 and 250 ml/h.
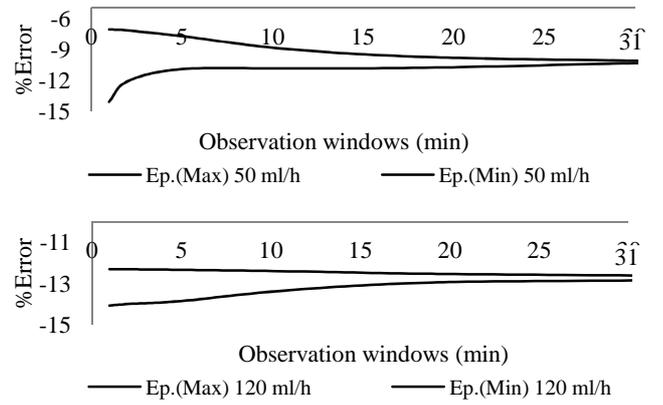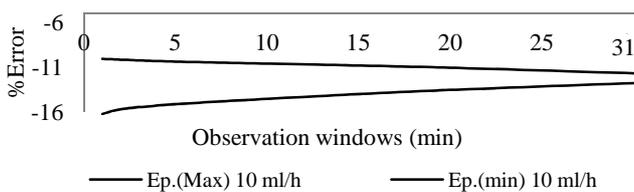

Figure 6 Trumpet curve of IV Set 60 no.2 at 10, 50 and 120 ml/h.

Evaluation on Uncertainty

The evaluation on uncertainty of IV Set measurement is based on the standard of ISO Guide25. Type A evaluation was based on statistic uncertainty calculation. And, Type B evaluation was based on dynamic analysis. The uncertainty of the intravenous set volume calibration system can be calculated as follows.

Uncertainty of Drop Volume(u_V)
Uncertainty of drop volume can be calculated by using the formula of $\frac{SD}{\sqrt{n}}$, where SD stands for standard deviation, and n stands for the number of sampling.

Uncertainty of Balance (u_b)
Uncertainty measurement of the balance was from the calibration of the balance, of which expanded uncertainty $0.0012 + (7 \times 10^{-6}) \times$ weight (g) [6]. Thus, the relative sensitivity coefficient is

$$c_m = \frac{\rho_b - \rho_a}{\rho_w \rho_b - \rho_w \rho_a}[1 - \alpha_c(t_d - t_{d20})] \qquad (12)$$

Uncertainty of Air Density (u_a)
Air density have been taken according to the recommendation CIPM formula. The relative uncertainty of air density is 2×10^4 in the range 900 hPa < p < 1100 hPa, 10°C < t < 30°C [5]. Thus, the relative sensitivity coefficient is

$$c_{\rho a} = \left[\frac{m}{\rho_b}[1 - \alpha_c(t_d - t_{d20})]\right] \times \left[\frac{(\rho_w - \rho_a)(\rho_b - 1) + (\rho_w - \rho_a)}{(\rho_w - \rho_a)^2}\right](13)$$

Uncertainty of Water Density (u_w)
Water density have been taken according to the BIPM [5]. The sensitivity coefficients can be obtained by differentiating Eq.(3). Thus, the relative sensitivity coefficient is

$$c_{\rho w} = \left[\frac{m}{\rho_b}[1 - \alpha_c(t_d - t_{d20})]\right] \times \left[\frac{\rho_a - \rho_b}{(\rho_w - \rho_a)^2}\right] \qquad (14)$$

Uncertainty of Temperature (U_{td})
Temperature affect to expansion of volume. In this experiment have control temperature at (20±2)°C and humidity (55±15)%Rh. The sensitivity coefficients can be obtained by differentiating Eq.(3). Thus, the relative sensitivity coefficient is

$$c_{td} = \left[\frac{m}{\rho_b} \cdot \frac{\rho_b - \rho_a}{\rho_w - \rho_a}\right] \times (-\propto_c) \qquad (15)$$

Hence, the combined uncertainty can be calculated by

$$u(v) = \sqrt{u_v^2 c_v^2 + u_b^2 c_b^2 + u_a^2 c_a^2 + u_w^2 c_w^2 + u_t^2 c_t^2} \quad (16)$$

The effective degree of freedom that is required for the verification of k value can be calculated by the Welch-Satterthwaite equation as follows.

$$v_{eff} = \frac{u(v)^4}{\sum_{i=1}^{N} \frac{[c_i u_i]^4}{degree\ of\ freedom}} \qquad (17)$$

The value of the effective degree of freedom from Equation (18) was used to consider the system's reliability. Moreover, the value can be brought to find k value from two-tailed student's table. So, the value of expanded uncertainty, according to ISO Guide 25, can be calculated by using the equation.

$$U = k \times u(V) \qquad (18)$$

The calculation of the measurement uncertainty, at the volume of reading, of the intravenous set was shown in Table 4.

Table 4: Expanded uncertainty ($k=2$) of calibration system

Uncertainty Components	type	u_i	c_i	$u_i c_i$	v_{eff}
u_V	A	1.88×10^{-3}	1	1.88×10^{-3}	74
u_b	B	1.20×10^{-3}	1×10^{-3}	1.20×10^{-6}	∞
u_a	B	2.0×10^{-4}	1.55×10^{-5}	1.00×10^{-8}	∞
u_w	B	8.40×10^{-4}	-1.55×10^{-8}	-4.22×10^{-11}	∞
U_{td}	B	0.4	-3.33×10^{-9}	-4.29×10^{-9}	∞
Combined Uncertainty (ml)				1.88×10^{-5}	74
Expanded Uncertainty (ml), $k=2$				3.76×10^{-4}	
Expanded Uncertainty (%)				0.752	

Conclusion

The calibration system of intravenous set was done according to the standard of IEC 60601-2-24. It was used to find the error value and uncertainty of IV Set. The measurement of the calibration system was based on the principle of gravimetric method. Also, oil film was used to lessen the evaporation rate of water. From all the three methods of measuring per-drop volume of intravenous set, it was found that the calculations based on Tate's Law were comparable with the calculations from the balance. The calculations, therefore, assure that the calibration system of IV Set (from balance) is accurate and in accordance with the related theories. Furthermore, calibrating IV set with the balance, it was found that IV Set 60 no.2 had more than 10% error value which exceeds the standard of ISO 8536-4. By this calibration system of IV Set, uncertainty was found at 0.752% of reading ($k=2$). This calibration system of IV Set can be used to verify the quality of IV Set, in the aspect of accuracy, in order to verify equipments prior to use with patients. This calibration system can assist in verifying IV Set and calculating its error value before application.

Acknowledgement

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