Defining Elements of Roller Pump Occlusion in Cardiopulmonary Bypass Surgery

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Abstract: - In surgery, centrifugal pumps are used when safety and biocompatibility are priorities. On the other hand, when considering operability and economy, roller pumps are used. The roller pump occlusion has to pay attention to the long-time operation causing axis displacement; Our study carried out that perfusion temperature executed the technology as a rule factor of the occlusion. To evaluate the manifestation of the circumference of the occlusion, we used three kinds of different roller diameters and measured perfusion temperature (Pt) and the electrical resistivity (Er), a pressure degree of the occlusion. Based on Japan Industrial Standard -T1603, we observed the differences between the three pumps with degree of the occlusion which we were setting in the same condition as a change of the occlusion by the progress at a time. Pt and Er repeated the up-down motion in three pumps every 30-60 minutes. In addition, the occlusion extended the interval in progress at a time. The pressure level of the sensor rose every 30 minutes and became unmeasurable afterward. This phenomenon affects that perfusion temperature changes influence the blood viscosity and, we suppose that it influenced a rise in para-blood temperature and it appeared in pressure change and Er of the occlusion. Therefore, control of the Pt leads to the appropriate control of the roller pump and we will be able to carry out physiological extracorporeal considering an indispensable element as SDGs.

Key-Words: - Occlusion, Perfusion Temperature (Pt), Electrical Resistivity (Er), Circumferential runout, Pressure sensor, Blood cell destruction, Mechanical fracture.

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1 Introduction

As a characteristic of centrifugal pumps, the perfusion amount may change due to low head and changes in afterload, [1]. There are also reports that there is no significant difference in blood damage when comparing centrifugal pumps and roller pumps used in heart-lung surgery, [2], [3].

Roller pumps are easy to operate, but the drawback is that the occlusion cannot be adjusted during surgery. Furthermore, there is a concern that red blood cells may be destroyed due to changes in the occlusion. In the world of blood rheology, it is said that a decrease in the negative charge (zeta potential) contained in sialic acid in the red blood cell membrane and changes in the morphology of the outer membrane wall increase the aggregation of blood cells, [4], [5], [6]. Therefore, as a previous study, a method has been reported in which the occlusion of a roller pump is converted into an electrical resistance value (Er: Electrical Resistance) and then quantified intermittently, [7].

In this study, we focused on the behaviors of Er due to temperature changes (Pt : Perfusion Temperature) to continuously monitor changes in the occlusion during roller pump operation using simulated blood.

2 Materials and Methods

2.1 Experimental Equipment

Three types of pumps with different roller diameters are available : Terumo CV-8000 (roller diameter 42 mm), Technowood BP-150 (roller diameter 22 mm), and Livanova S5 (roller diameter 31 mm). used in the experiment (Figure 1).

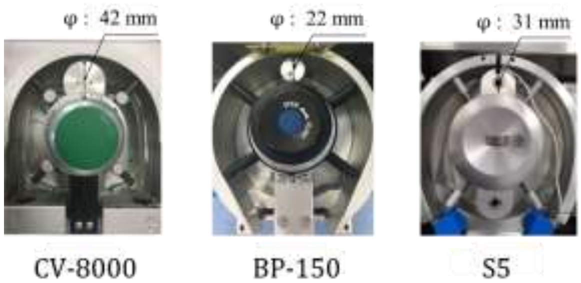

Fig. 1: Experimental used three roller parts diameters

For the blood circuit, a roller pump was set with a Mera Excel line H 3/8 inch tube (MERA Corp., Tokyo, Japan), inner diameter 9.5 mm, outer diameter 14.3 mm, Shore hardness A70 degrees, and tensile strength 13.4 MPa. The experimental environment temperature was set to 25 (±2) °C, and simulated blood mixed with glycerin and physiological saline (0.9% wt) and 40% glycerin aqueous solution (4.18 cP) were mixed with human blood at 25 °C (37 °C). The same viscosity) was prepared, [8], [9].

2. 2 How to Measure Controlling Factors

In addition, to confirm the change in perfusion amount when the solution was circulated through the tube, the pressure closure degree of CV-8000, BP-150, and S5 was set to 6 drops/min and 13 drops/min, and the maximum average value of five flow rate displays (ultrasonic flow meter and tachometer) was evaluated. When we compared the perfusion rates between the ultrasonic flowmeter and the tachometer, we found that the difference between the occlusion rate of 13 drops/min was smaller than the occlusion rate of 6 drops/min, so we decided to use the occlusion rate of 13 drops/min as the standard. The experiment was conducted (Table 1).

The experimental outline was as follows JIS-T1603: the occlusion of each pump was set to 13 drops/min, the perfusion fluid volume was 500 mL, the rotation speed was 97 rpm, the perfusion time was 180 minutes, and the pumps were moved every 30 minutes to an arbitrary point A (Figure 2), and the electrical resistance value Er and perfusion temperature Pt were sequentially measured under the same conditions, [10].

Table. 1 Volumetric flow rate of rotary flowmeter (R) and ultrasonic flowmeter (U) with occlusion of 6 drops and 13 drops

6 drops/min 97 rpm 25℃						
Time[min]		0	15	30	45	60
CV-8000	R	2480	2484	2488	2492	2492
	U	2718	2756	2796	2800	2804
BP -150	R	2580	2580	2580	2580	2580
	U	2634	2662	2654	2654	2652
S5	R	2520	2520	2520	2520	2520
	U	2548	2564	2582	2582	2582

6 drops/min 97 rpm 25℃						
Time[min]		0	15	30	45	60
CV-8000	R	2480	2484	2488	2492	2496
	U	2694	2704	2704	2738	2742
BP -150	R	2580	2580	2580	2580	2580
	U	2578	2562	2576	2566	2592
S5	R	2520	2520	2520	2520	2520
	U	2506	2494	2534	2532	2558

**R : Volumetric flow rate of rotary flowmeter*
**U : Ultrasonic flowmeter*

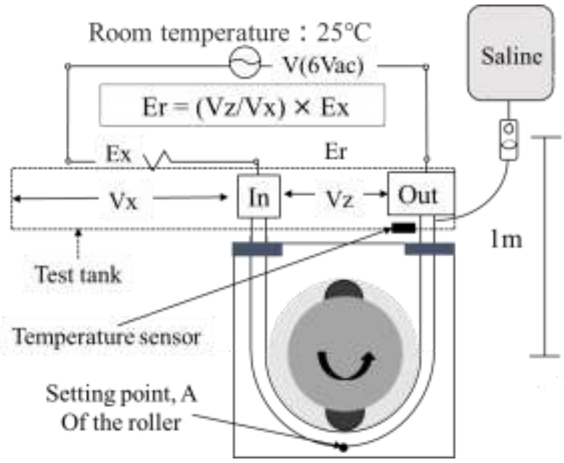

Fig. 2: Electrical resistivity measurement circuit

2.3 Pressure Measurement using a Pressure Sensor

A small pressure sensor PS-70KC M2: 7 MPa (Kyowa Dengyo Co. Ltd, Tokyo, Japan) was fixed to the area where the roller and raceway were crimped (Figure 3), and pressure changes were observed. WGI-400A-00 (Kyowa Dengyo Co. Ltd, Tokyo, Japan) was used as the measuring instrument, and measurements were made under the conditions of a sampling frequency of 50 Hz, a bridge power supply of DC2 V, 30 mA, and an output voltage of 10 V. In addition, the pressure value of the degree of closure was measured every 30 minutes.

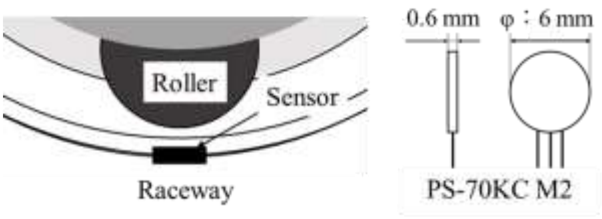

Fig. 3: Schema of pressure measurement sensor install site for occlusion pressure

3 Results

3. 1 Changes in the occlusion due to Er and Pt

(1) CV-8000

Figure 4 shows the average values of Er and Pt from the start of CV-8000 perfusion to 180 min. Furthermore, Er converged to 40 to 46 kΩ for a roller with a diameter of 42 mm.

Er decreased by 0.5 kΩ 30 min after the start, and after that, it repeated up and down movements. On the other hand, Pt showed a waveform with an opposite tendency. The correlation coefficient of regression analysis of Er and Pt was R^2 =0.74 (p<0.05), which showed a strong correlation.

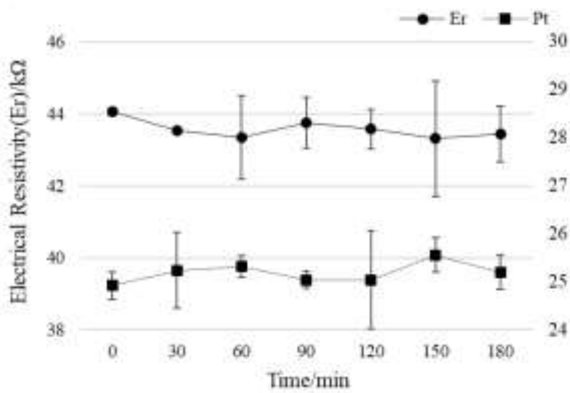

Fig. 4: Serial changes in Er and pt with CV-8000

(2) BP-150

Figure 5 shows the results for Er and Pt. The Er of BP-150 converged to 37 to 44 kΩ.

From Figure 5, Er decreased by 0.6 kΩ 30 min after the start, and then repeatedly fluctuated up and down. Pt showed a waveform with an opposite trend. The correlation coefficient of regression analysis of Er and Pt showed a significant correlation of R^2 =0.61 (p<0.05).

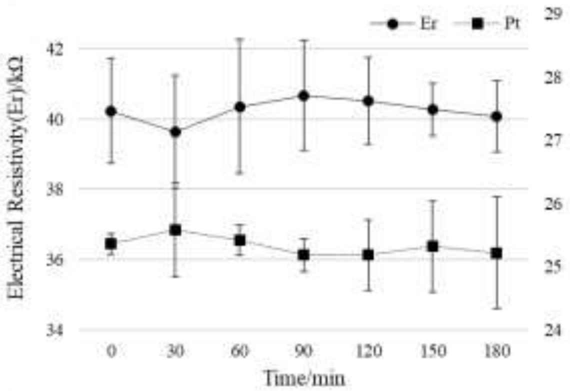

Fig. 5: Serial changes in Er and pt with BP-150

(3) S5

The results for Er and Pt are shown in Figure 6. The Er of S5 converged to 29 to 34 kΩ.

From Figure 6, Er decreased by 1 kΩ 30 min after the start, and then gradually decreased. The waveform increased 150 minutes after the start but decreased overall. On the contrary, Pt showed a waveform with a tendency opposite to that of Er. The correlation coefficient of regression analysis of Er and Pt showed a significant correlation with R^2=0.66 (p<0.05).

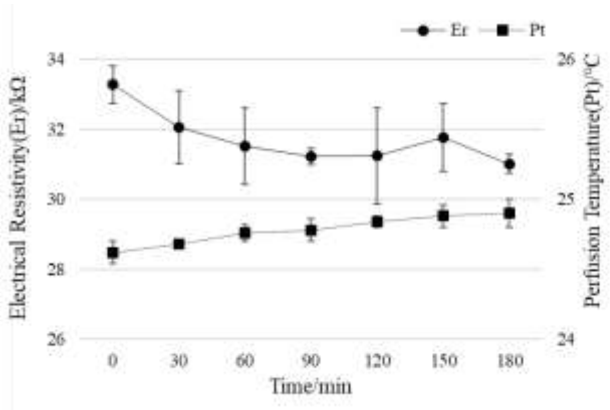

Fig. 6: Serial changes in Er and pt with S5

3.2 Changes in Pressure due to Changes in the Occlusion

Before the start of the experiment, the B-150's roller pump was set at a drop rate of 13 drops/min, and the pressure value for the occlusion was 6 MPa, but it increased to 7 MPa 30 minutes after the start, and 8 MPa after 60 minutes, pressure beyond the measurement range was applied, making measurement impossible.

4 Discussion

4.1 Degree of Occlusion Predicted from Pt

As a result of examining the correlation between Er and Pt using pumps with different roller diameters, the Er of the CV-8000 and BP-150 pumps converged within the optimal occlusion, and S5 converged around 30 to 34 kΩ. In S5, the value is lower than the optimum occlusion, and it is necessary to mention the internal structure of the pump related to pressure closure.

However, in all pumps, a negative correlation (inverse proportion) between Er and Pt was observed, and a phenomenon in which the occlusion (electrical resistance value) decreased as the perfusion temperature Pt increased was observed. Especially in BP-150, when the deviation of Pt is large, the deviation of Er also becomes large. This is thought to be due to the frictional heat caused by the roller rubbing against the tube as Pt increases, which activates the molecular motion of the perfused substance, making the density sparse and reducing the electrical resistance value Er. It is thought that the increase in Pt lowers the viscosity of the substance, indicating a state in which the electrical resistance decreases, and decreases Er.

In the case of continuous perfusion, frictional heat is accumulated when the roller contacts the tube, but since the perfusion temperature Pt is below 50°C, changes in the tube due to the viscosity of the perfusate were ignored, [11].

4.2 Relationship between Changes in Occlusion and Pressure Sensor

The pressure measuring device used in this study only displayed discrete instantaneous values and did not record waveforms, making it impossible to perform a detailed analysis of pressure sensor damage.

However, it is believed that the cause of the sensor damage was that the drive shaft supporting the rollers caused circumferential vibration, causing the rollers to approach the raceway and apply high pressure to the pressure sensor PS-70KC M2.

In addition, the pressure applied to the strain gauge is considered to be ① vertical pressure and pressure (shear stress) applied to the curved raceway due to the rotation of the rollers ② acting on the pressure sensor (Figure 7).

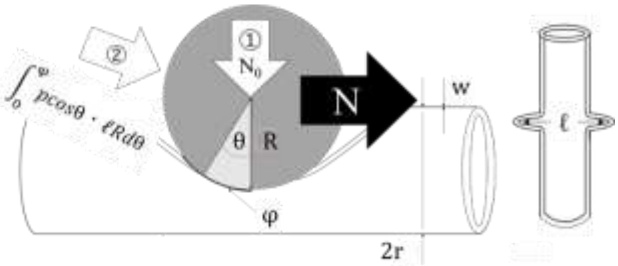

Fig. 7: Pressure to depended on a sensor and Transformation of the tube

The pressure can be expressed by the following equation, where N is the force with which the roller pushes out the tube, ① is the pressure N_0 that pushes out the tube in an unpressurized state, and ② is the fluid force acting on the roller, [12], (Figure 7)

$$N = N_0 + \int_0^{\varphi} p\cos\theta \times \ell R \, d\theta$$
$$= \frac{\pi p R}{4} \{(2r - 2w - R) \times \sin\theta + R\varphi\}$$

p : Tube internal pressure
w : Tube thickness
R : Radius of roller r: Outside radius of tube cross section
φ : Maximum contact angle between roller and tube
ℓ : Width of the tube at any point in contact with the roller

Based on the pressure measurement and calculation formula of the roller pump, it is predicted that the high pressure caused by circumferential vibration will cause a major disturbance to the actual blood because it will increase the perfusion temperature Pt.

4.3 Blood Cell Destruction Expected due to Circumferential Vibration

When using a roller pump in a clinical setting, it is necessary to pay attention to the fact that the frictional heat generated by rubbing the tube changes the plasma viscosity of the blood and changes the internal structure of red blood cells, [13]. Red blood cells are maintained at a constant distance by the electrical repulsion of the zeta potential on the membrane surface, [14]. However, the reduction in the amount of sialic acid and the loss of protein is thought to increase the rate of red blood cell aggregate formation and reduce the repulsive force between blood cells, thereby increasing blood aggregation, [15], [16]. Therefore, the frictional heat and pressure changes generated by the rotating rollers can be expected to disrupt the red blood cell membrane.

Therefore, the narrowing of the interval between the occlusion due to circumferential vibration leads to the collapse of blood cells, resulting in changes in plasma viscosity due to heat, mechanical collapse, and changes in blood viscosity due to mechanical destruction. Blood cell destruction significantly reduces biological homeostasis, so the occlusion of the roller pump must be adjusted from time to time.

4.4 As a Quantitative Monitor of the Occlusion

The need for quantitative monitoring of changes in the occlusion is an important issue in blood injury. JIS-B0621 sets standards for circumferential runout, but the occlusion changes from the time of setting. Therefore, continuous monitoring is necessary to ensure proper blood delivery, and it is desirable to adjust from time to time, [17].

As an indirect method for measuring the occlusion, it is necessary to monitor the electrical resistance value Er and simultaneously monitor the perfusion temperature Pt. Since Er changes depending on the viscosity of the perfused substance, it is important to quantify the occlusion because temperature, electrical resistance, and viscosity are factors that interfere with each other due to the temperature rise caused by circumferential vibration. becomes.

However, when using Er in a clinical setting, it is not practical because the current is higher than the minimum sensing current of the human body. Therefore, by installing thermometers before and after the roller and continuously monitoring changes in Pt, it becomes possible to continuously monitor the degree of pressure closure. As a control factor for the degree of pressure occlusion, perfusion temperature Pt is a useful monitoring item and is essential.

5 Conclusion

In surgery, roller pumps are used when considering operability and economy. The roller pump occlusion has to pay attention to the long-time operation causing axis displacement.

(1) Our study carried out that perfusion temperature executed the technology as a rule factor of the occlusion.

(2) To evaluate the manifestation of the circumference of the occlusion, we used three kinds of different roller diameters and measured perfusion temperature (Pt) and the electrical resistivity (Er), a pressure degree of the occlusion.

(3) Control the degree of pressure closure of roller pumps used in heart-lung machines, it was understood that the
degree of pressure closure changes due to many factors, such as circumferential runout and temperature changes.

(4) This study concludes that the degree of pressure occlusion changes and that relative monitoring of perfusion temperature is necessary.

(5) More detailed analysis and experiments are required, but since each console is expensive, we plan to confirm this in the future.

(6) Furthermore, we plan to compare not only the roller pump but also the centrifugal pump in terms of volumetric flow rate and blood cell morphology.

References:

[1] Glenn P. Gravlee, Richard F. Davis, Alfre H. Stammers, Ross M. *Ungerleider, Cardiopulmonary Bypass: Principles and Practice*, 3rd Edition, Lippincott Willams and Wilkins, 2007.

[2] J. W. Mulholland?J. C. Shelton?X. Y. Luo: Blood flow and damage by the roller pumps during cardiopulmonary bypass. *Journal of Fluid and Structures*, Vol. 20, Issue 1, pp129-140, 2005, https://doi.org/10.1016/j.jfluidstructs.2004.10.008.

[3] H Demirtas, E Iriz, CY Demirtas, D Erer, L Oktar, A Yener, M Arslan, Investigating the Effects of Two Different Pump Heads (Centrifugal vs. Roller Pump) on Hematological and Immunological

Mechanisms, Nigerian Journal of Clinical Practice, Vol. 21(7), pp.847-853, 2018. https://doi.org/10.4103/njcp.njcp_427_16.

[4] PMD Act: Pharmaceutical and Medical Device Act, Report on the results of the 3rd Meeting on Measures for the Safe Use of Pharmaceuticals, Medical Devices, and Regenerative Medical Products, 2015, [Online]. https://www.pmda.go.jp/files/000210376.pdf, (Access Date: March 22, 2024).

[5] Nitesh Kumar, Numerical Investigation on the effect of blood pressure on Wall Shear Stress and Vorticity, *WSEAS Transaction on Biology and Biomedicine*, Vol. 18, pp63-65, 2021, https://doi.org/10.37394/23208.2021.18.7.

[6] Shota Kato, Tadashi Handa, Jun Yoshioka, Kazuhiko Nakadate, Yasutomo Nomura and Hitoshi Kijima, Evaluation of Blood Cells Destruction by Measuring Occlusion Distance, *WSEAS Transactions on Biology on Biomedicine*, Vol. 20, pp. 313-320, 2023. https://doi.org/10.37394/23208.2023.20.32.

[7] Naoki Momose, Asami Kitamura and Noriaki Ono among other things, Electric Measurement of Occlusion degree in a Roller Pump-driven Circuit, *Japanese Journal of Extra-Corporeal Technology*, Vol.30, No.1, pp. 22-25 2003.

[8] Wataru Hijikata, Jun Rao, Shodai Abe, Setuo Takatani, Tadahiko Shinshi, Sensorless Viscosity Measurement in a Magnetically-Levitated Rotary Blood Pump, *Artificial Organs*, Vol. 39(7), pp. 559-568, 2016, https://doi.org/10.1111/aor.12440.

[9] Kun-Lin Lee, Glen Kowach, Fang Li and Ioana Voiculescu, Liquid Viscosity Sensor Using a Surface Acoustic Wave Device for Medical Applications Including Blood and Plasma, *Sensor*, Vol. 23(13), 5911, 2023, https://doi.org/10.3390/s23135911.

[10] JIS-T1603: Cardiopulmonary machine electric blood pump, Electric motor driven blood pump for cardiopulmonary bypass, 1995.

[11] Parisa Khoshnoud and Nidai Abu-Zahra, Properties of rigid polyvinyl chloride foam composites reinforced with different shape fillers, *Journal of Thermoplastic Composite Materials*, Vol. 30(11), pp. 1541-1559, 2017, https://doi.org/10.1177/0892705716646417.

[12] S. Mukhopadhyay, G.C. Layek, Sk. A. Samad, Study of MHD boundary layer flow over a heated stretching sheet with variable viscosity, *International Journal of Heat and Mass Transfer*, Vo. 48(21-22), pp. 4460-4466, 2005, https://doi.org/10.1016/j.ijheatmasstransfer.2005.05.027..

[13] Hideyuki Tsukagoshi, Seiichi Nozaki, Kouichi Nishizawa and Ato Kitagawa, Development and Motion Analysis of the Inscribed Pinch-roller Type Fluid Power Motor Driven by Tap Water Pressure, *Transactions of the Japan Fluid Power System Society*, Vol. 35(6), pp. 109-116, 2004, https://doi.org/10.5739/jfps.35.109.

[14] Artur S. Bartosik, Effect of High Solid Concentration on Friction in a Transitionaland Turbulent Flow of Bioliquid Suspension, *WSEAS Transaction on Fluid Mechanics*, Vol. 18, pp.10-23, 2023, https://doi.org/10.37394/232013.2023.18.2.

[15] Kung-Ming Jan, Shu Chien, Role of Surface Electric Charge in Red Blood Cell Interactions, *The Journal of general physiology*, Vol. 61(5), pp. 638-654, 1973, https://doi.org/10.1085/jgp.61.5.638.

[16] Takahiko Aoki, A Comprehensive Review of Our Current Understanding of Red Blood Cell (RBC) Glycoproteins, *Membranes*, Vol. 7(4), pp. 56-74, 2017, https://doi.org/10.3390/membranes7040056.

[17] ISO 1101: 1983(MOD), Maching Symbols, [Online]. https://www.scribd.com/doc/131937901/ISO-1101-1983-E-Maching-Symbols (Accessed Date: March 12, 2024).

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Shota Kato conducted all of the experiments and wrote the submitted paper.
- Shota Sogabe conducted an experiment on the volumetric flow rate of ultrasound.
- Jun Yoshioka created a blood cell preservation solution.
- Kazuhiko Nakadate provided mathematical advice.
- Hitoshi Kijima gave some electric advice.
- Yasutomo Nomura provided mathematical analysis and advice throughout the experiments.

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Conflict of Interest

The authors declare no conflicts of interest relevant to the content of this article.