Application of Hybrid Petri Nets for a Drawing Blood Flow from Fingertip

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Keywords: Hybrid Petri Nets, Fluid Dynamic, Elastic Dynamic, Blood Flow, Fingertip.

Abstract: Our objective of this study are to make a fluid dynamical model and to conduct the flow simulation for obtaining a large amount of drawing blood from a fingertip. The processes of drawing blood are hybrid systems including both the continuity system of blood flow and the discrete systems of cuff pressing and puncture. Therefore, we made the modelling of the fingertip drwaing blood process from the analogy of fluid daynamic tank and pipe systems control using hybrid Petri nets. Using the hybrid Petri nets simulation with cuff pressing and puncture modeled as discrete and blood flow modeled as continuity, we confirmed that the simulation results were agreement with the experimental drawing blood data.

1 INTRODUCTION

The concept of a self-managing healthy society is important for the countries facing the aging population. To realize a self-managing healthy society, it is imperative to develop an innovative system for prophylaxis, diagnosis and treatment that dramatically reduces hospitalization and visits to the doctor's office. Under such a background, the POCT (Point of Care Testing) using a drawing blood from a fingertip is one of the preferable technologies to reduce visits to the doctor's office (Kumar and Webster, 2016). That is the reason why the drawing blood from a fingertip is possible to draw by oneself, as compared with the drawing blood from an arm by a nurse at the doctor's office. Therefore, POCT using a drawing blood from a fingertip at home and drugstore has increased in recent years.

The recent POCT using a drawing blood from a fingertip covers many items of inspection for lifestyle-related diseases such as high blood pressure, diabetes, cancers such as stomach, large intestine, lungs. The self-drawn blood is delivered to the inspection agency by mail, and the user receives the inspection results after one week. However, the problems of the self -drawing blood from a fingertip are the complicated drawing blood process and too small amount of blood. In case of check a blood glucose level, the amount of blood is small such as under 1 μL, but it is necessary for the above lifestyle-related diseases and cancers inspection to obtain the large amount of blood such as over 100 μL. The use of a cuff band for fastening finger is one of the preferable methods to obtain the large amount of blood from a fingertip (Kuramoto, 2007). Based on the above background, our motivation is to make an automatic drawing blood machine from fingertip. As the first step, we think it is very important to understand the fingertip blood flow.

From the point of simulation around a fingertip, there are some researches about CFD (Computational Fluid Dynamics) analysis of the fingertip temperature and oxygen transport in the human breast tumor under laser irradiation (He et al., 2006), and about FEM (Finite Element Method) analysis of the fingertip contact pressure for developing robot hands (Maeno et al., 1997). Moreover, from the point of simulation inside the human body, there are many researches about CFD analysis of the blood flow in the human organs (Oshima et al., 2001; Liang et al., 2015).

Togashi, S., Takenaka, K., Uchida, K., Irie, T., Sakazume, T. and Miyake, R.
Application of Hybrid Petri Nets for a Drawing Blood Flow from Fingertip.
DOI: 10.5220/0006877701360143
In *Proceedings of 8th International Conference on Simulation and Modeling Methodologies, Technologies and Applications (SIMULTECH 2018)*, pages 136-143
ISBN: 978-989-758-323-0

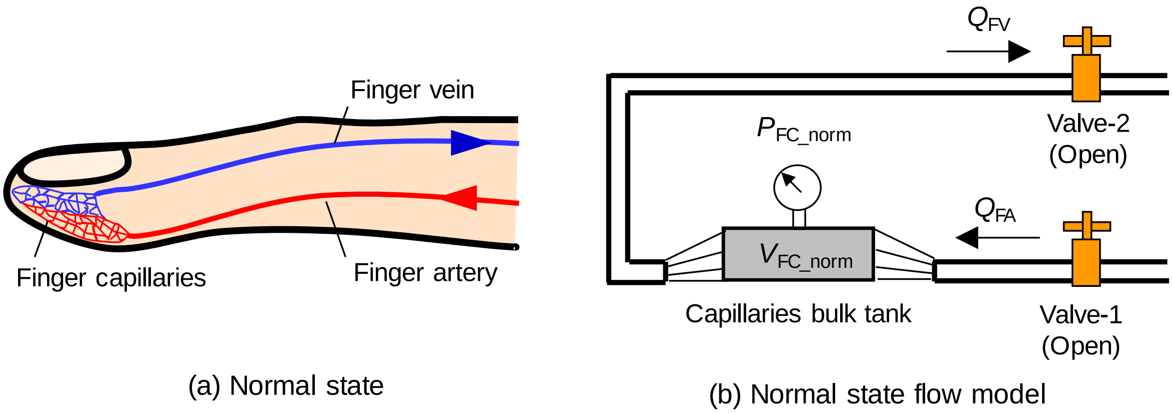


Figure 1: Close tank and pipes connection flow modelling of fingertip blood in normal state.

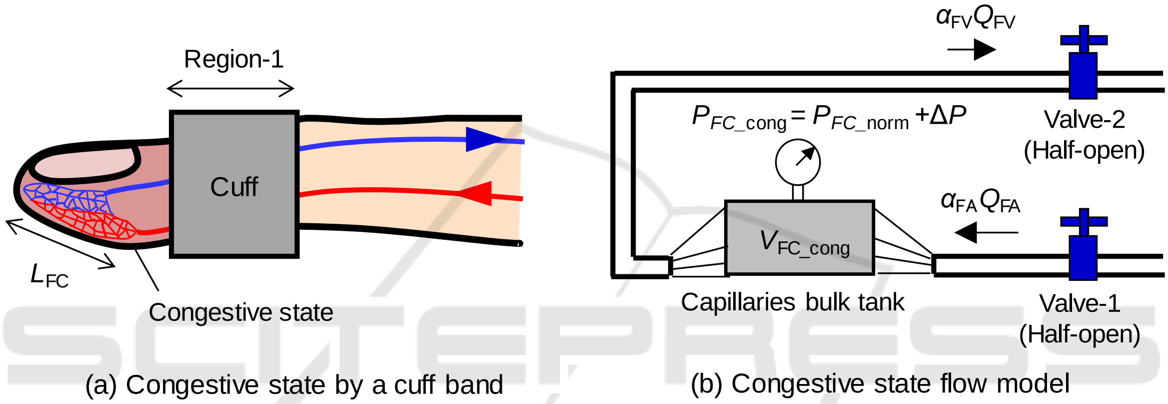


Figure 2: Close tank and pipes connection flow modelling of fingertip blood in congestive state by a cuff band.

However, there is no research for obtaining an amount of drawing blood from a fingertip. It is for the reason that the processes of drawing blood are hybrid systems including both the continuity system of blood flow and the discrete systems of cuff pressing and puncture. For the above solution, hybrid Petri nets (Herajy and Heiner, 2012) is good simulation tool.

Based on the above background, our objective of this study are to make a fluid dynamical model and to conduct the flow simulation for obtaining a large amount of drawing blood from a fingertip using hybrid Petri nets.

2 MODELLING OF FINGERTIP BLOOD FLOW

2.1 Fluid Dynamical and Elastic Dynamical Model

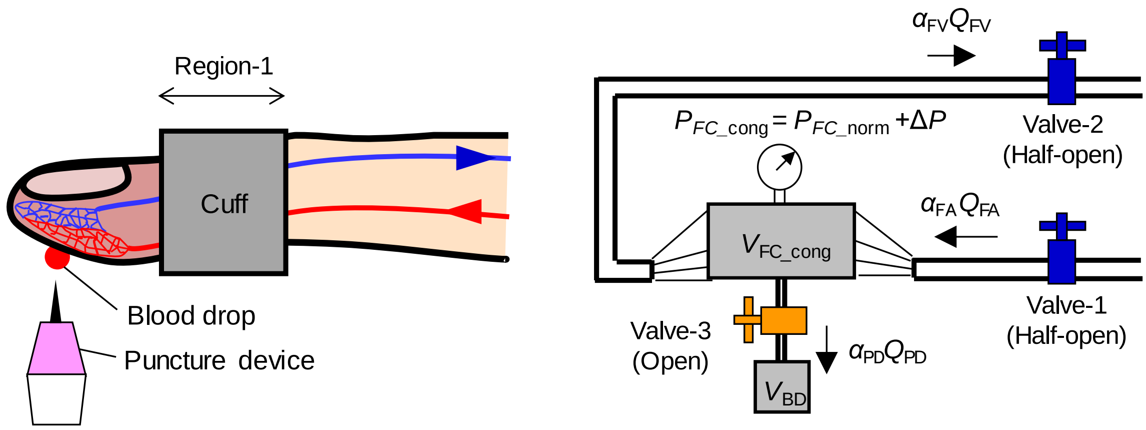
Figure 1(a) shows the normal state with the finger artery, the capillaries and the finger vein in the fingertip. Figure 1(b) is corresponding to the fluid dynamical pipes and close tank connection modelling of Fig.1(a), that is the finger artery (flow rate : Q_{FA}) and finger vein (flow rate : Q_{FV}) are represented as the pipes, and the capillaries are represented as the bundled capillaries bulk tank (Volume: V_{FC_norm}).

Figure 2(a) shows the congestive state by a cuff band (Yamakoshi et al., 1982), and Figure 2(b) is corresponding to the fluid dynamical modelling of Fig.2 (a). In this case, the pressed finger artery (flow rate: $\alpha_{FA}Q_{FA}$) and the pressed finger vein (flow rate :$\alpha_{FV}Q_{FV}$) by a cuff band are represented as the pipes with the half-open valves.

Therefore, the increased blood volume ($\Delta V = V_{FC\_cong} - V_{FC\_norm}$) in the modelled capillaries bulk tank is represented as the difference of the flow rate between the pressed finger artery and vein as shown in Eq. (1).

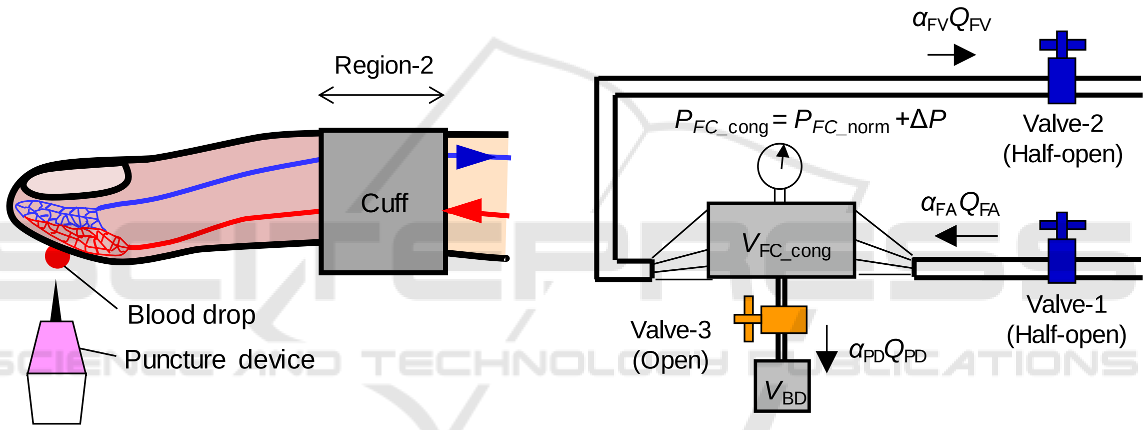
$$\Delta V = (\alpha_{FA}Q_{FA} - \alpha_{FV}Q_{FV})\Delta t, \tag{1}$$

where Δt is the valve close time. Moreover, the increased blood pressure ($\Delta P = P_{FC\_cong} - P_{FC\_norm}$) in the modelled capillaries bulk tank is represented as



(a) Drawing blood state by a puncture device (b) Drawing blood state flow model

Figure 3: Close tank and pipes connection flow modelling of fingertip blood in drawing blood state with a cuff band on the region-1 by a puncture device.



(a) Drawing blood state by a puncture device (b) Drawing blood state flow model

Figure 4: Close tank and pipes connection flow modelling of fingertip blood in drawing blood state with a cuff band on the region-2 by a puncture device.

the elastic dynamic modelling of the blood vessel wall based on the increased blood volume ΔV as shown in Eq.(2).

$$\Delta P = \{ Eh / (2 - v)\, r \}\, \Delta V / V_{FC\_norm} \tag{2}$$

where E is the Young's modulus, v is the Poisson's ratio, h is the thickness, and r is the radius of the blood vessel wall, respectively.

Figure 3(a) shows the drawing blood state with a cuff band on the region-1 by a puncture device, and Figure 3(b) is corresponding to the fluid dynamical modelling of Fig.3 (a) based on the valve set under the modelled capillaries bulk tank. The amount of drawing blood V_{BD} is represented as the analogy of the Venturi effect as shown in Eq.(3).

$$V_{BD} = \alpha_{PD} A_{FC} \sqrt{2\Delta P / \rho \;(A_{FC}^2 / A_{PD}^2 - 1)}\; \Delta t \tag{3}$$

where A_{FC} is the bottom area of the modelled capillaries bulk tank, A_{PD} is the hole area made by the puncture device, ρ is the blood density, and α_{PD} is the discharge coefficient of puncture hole, respectively.

Figure 4 shows the drawing blood state with a cuff band on the region-2 by a puncture device, instead of region-1 as shown in Fig.3.

2.2 Hybrid Petri Nets of Fluid-Dynamical Model

A Petri net is an algebraic and graphical tool for modelling phenomena by using three kinds of elements: "places," "transitions," and connecting "arcs" as shown in Table 1 (Petri, 1962). The hybrid Petri nets can use both continuous variables (real numbers) and discrete variables (integers), and for execution of the numerical analysis reported here we used the hybrid Petri nets tool called Visual Object Net (VON)++ (Peleg et al., 2005).

The basic diagram of the hybrid Petri nets using VON++ is represented as the combination and the connection of discrete place, static test arc, continuous transition, normal arc, continuous place, inhibitor arc, and discrete transition as shown in Fig.5 (Renganathan and Bhaskar, 2012).

The processes of drawing blood are hybrid systems including both the continuity system of blood flow and the discrete systems of cuff pressing and puncture. Therefore, we made the modelling of the fingertip drwaing blood process from the analogy of three-tank reconfiguration control using hybrid Petri nets (Lunze et al., 2001; Wu et al., 2010; Mendoza et al., 2012).

Figure 6 shows the modelling of the fingertip drwaing blood process using hybrid Petri nets based on the fluid dynamical pipes and close tank connection modelling as shown in Figs. 1(b), 2(b), 3(b) and 4(b). The cuff band pressing and the puncture by a lancet device are represented as discrete variables, and the blood flow is represented as continuous variables.

Moreover, the fingertip blood flow is assumed as the Newtonian steady flow, and the blood pulsation is small enough to be ignored.

Table 1: Basic components of Petri nets model.

	Place	Transition	Arc	
Discrete				Normal arc
				Static test arc
Continuity				Inhibitor arc

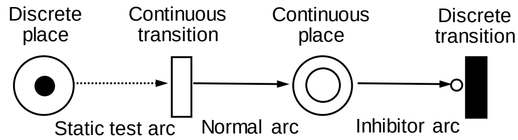


Figure 5: Basic diagram of hybrid Petri nets.

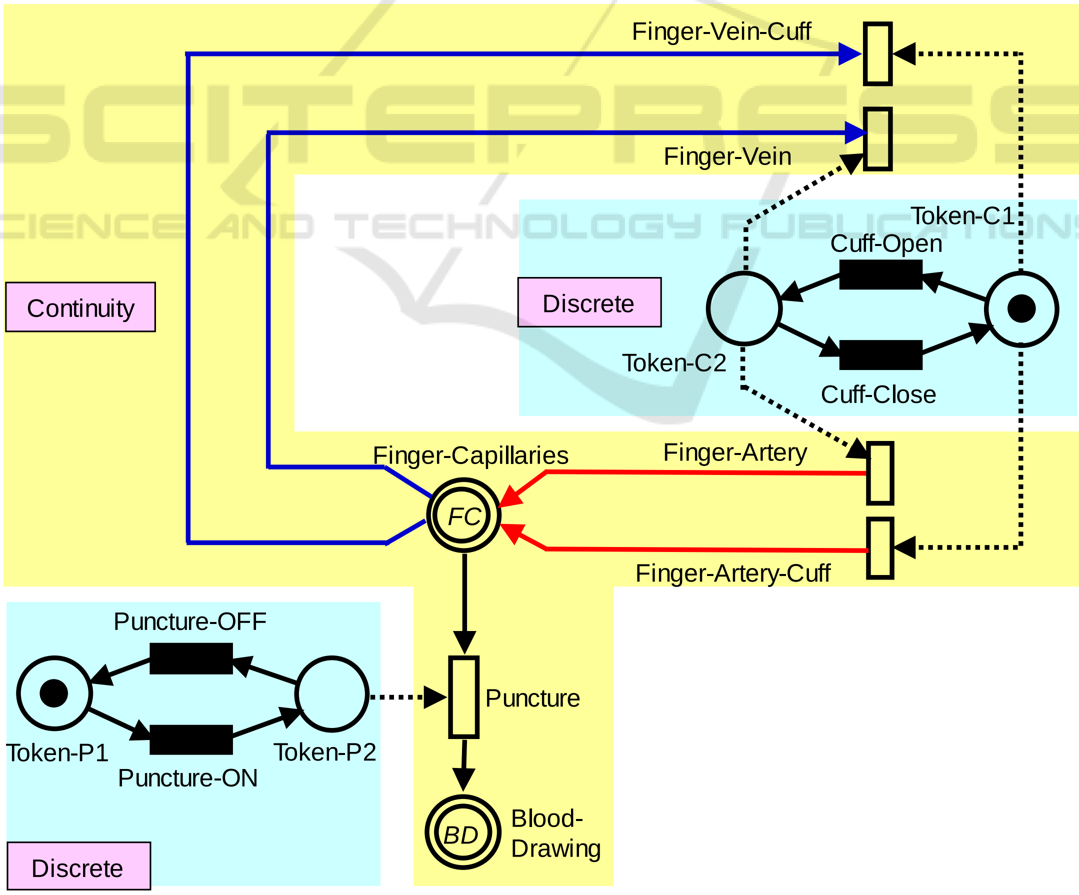


Figure 6: Fingertip drawing blood process model using hybrid Petri nets.

2.3 Flow Simulation of Fingertip Blood

Table 2 shows the five simulation cases using hybrid Petri nets. The Case F1 is the normal state corresponding the fluid dynamical modelling as shown in Fig. 1(b). The Case F2 is the congestive state corresponding the fluid dynamical modelling as shown in Fig. 1(d). The Case F3 is the drawing blood state by a puncture device without a cuff band. The Case F4 is the drawing blood state by a puncture device with a cuff band on the region-1 corresponding the fluid dynamical modelling as shown in Fig. 1(f). Finally, the Case F5 is the drawing blood state by a puncture device with a cuff band on the region-2.

Table 3 shows the estimation of the blood flow rate in a finger artery as the initial condition. The blood velocity U_{FA} and the diameter D_{FA} of a finger artery are known as U_{FA} =50 mm/s and D_{FA} =0.35 mm (average value from 0.20 to 0.50 mm) (Shore, 2000), respectively. Therefore, the flow rate Q_{FA} ($=U_{FA}\times\pi D_F^2 /4$) is set to 4.8 µL/s.

Table 4 shows the estimation of the blood volume in finger capillaries as the initial condition. The velocity U_{FC} and the area length L_{Fc} as shown in Fig. 1(c) of the finger capillaries are known as U_{FC} =0.75 mm/s (average value from 0.5 to 1.0 mm/s) and L_{FC} =10 mm (Yamakoshi et al., 1980), respectively. Therefore, the modelled capillaries bulk tank V_{FC} ($=Q_{FA} \times L_{FC} /U_{FC}$) is set to 64.0 µL. In case of the congestive state by a cuff band, the area length L_{FC} and the modelled capillaries bulk tank V_{FC} are different according to the cuff band position (region-1 or 2).

Table 2: Hybrid Petri nets simulation cases.

Case	Corresponding fluid dynamical modelling	Cuff band		Puncture
		Region-1	Region-2	
F1	Fig.1(b)	-	-	-
F2	Fig.2(b)	○	-	-
F3	Fig.1(b)	-	-	○
F4	Fig.3(b)	○	-	○
F5	Fig.4(b)	-	○	○

Table 3: Estimation of the blood flow rate in a finger artery.

U_{FA} (mm/s)	D_{FA} (mm)	Q_{FA} (µL/s)
50	0.35	4.8

Table 4: Estimation of the blood volume in finger capillaries.

U_{FC} (mm/s)	L_{FC} (mm)	V_{FC} (µL)	Cuff
0.75	10.0	64.0	Region-1
		128.0	Region-2

Table 5: Physical properties for calculation of blood capillary using Eq.(2).

E (Pa)	v	h (mm)
5.0×10^5	0.45	0.2

Table 6: Physical properties for calculation of drawing blood using Eq.(3).

α_{PD}	A_{FC} (mm^2)	A_{PD} (mm^2)	ρ (kg / m^3)
0.61	78	0.5	1.05×10^3

Table 5 shows the physical properties for calculation of blood capillary using Eq.(2), and Table 6 shows the physical properties for calculation of drawing blood using Eq.(3), respectively.

Table 7 shows the five cases initial conditions of places and transitions. Moreover, the periodical pressing by a cuff band is 10 s interval, and the simulation of the each case is conducted to 100 s with the time increment of 1 s.

2.4 Flow Simulation Results of Fingertip Blood

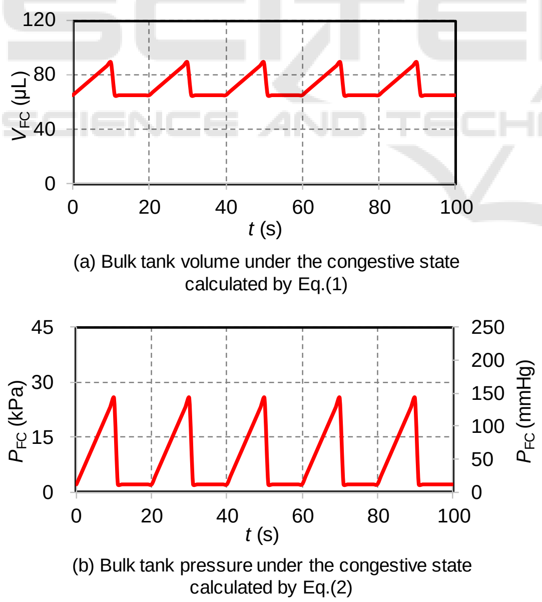
Figure 7 shows the simulation results of Case F2. The results of Case F2 are corresponding to the periodical congestive state by a cuff band, it is found that the residential blood volume VFC as shown in Fig.7(a) and the blood pressure PFC as shown in Fig.7(b) in the capillaries bulk tank are periodically increased by a cuff band of 10s interval.

Figure 8 shows the simulation results of Case F3, Case F4 and Case F5 with the drawing blood by a puncture device with the periodically congestive state by a cuff band of 10 s interval. It is found that the amount of drawing blood from a fingertip VBD increases in the following order: Case F3 (without a cuff) < Case F5 (a cuff on region-2) < Case F4 (a cuff on region-1).

Moreover, the experimental drawing blood data shown in Table 8 are also plotted with the same condition as the simulation in Fig.8. The above exper-

Table 7: Initial conditions of fingertip blood flow model using hybrid Petri nets.

Element			Initial conditions and equations				
			Case F1	Case F2	Case F3	Case F4	Case F5
Discrete	Place	Token-C1	-	1	1	1	1
		Token-C2	-	0	0	0	0
		Token-P1	-	-	1	1	1
		Token-P2	-	-	0	0	0
	Transition	Cuff-Open	-	10 (s)	10 (s)	10 (s)	10 (s)
		Cuff-Close	-	10 (s)	10 (s)	10 (s)	10 (s)
		Puncture-ON	-	-	10 (s)	10 (s)	10 (s)
		Puncture-OFF	-	-	90 (s)	90 (s)	90 (s)
Continuity	Place	Finger-Capillary	FC = 64.0 (μL)				
		Blood-Drawing	BD = 0 (μL)				
	Transition	Finger-Artery	4.8 (μL)				
		Finger-Artery-Cuff	-	4.8 × α_{FA} (μL) with Eq.(2)			
		Finger-Vein	4.8 (μL)				
		Finger-Vein-Cuff	-	4.8 × α_{FA} (μL) with Eq.(2)			
		Puncture	-	-	Eqs.(3)–(5)		



(a) Bulk tank volume under the congestive state calculated by Eq.(1)

(b) Bulk tank pressure under the congestive state calculated by Eq.(2)

Figure 7: Simulation results of bulk tank volume and pressure.

iment of the drawing blood from nine volunteers was approved by the ethics committee of Hitachi group headquarters. It is found that the simulation results were agreement with the experimental drawing blood data of 76 - 86μL and 169 - 231μL with the different pressing region by a cuff band. Consequently, It is effective for obtaining a large amount of drawing blood from a fingertip to the use of a cuff band on the region-1 with the periodical pressing of 10 s interval.

3 DISCUSSION

The processes of drawing blood are hybrid systems including both the continuity system of blood flow and the discrete systems of cuff pressing and puncture. Therefore, we made the modelling of the fingertip drwaing blood process from the analogy of three-tank reconfiguration control using hybrid Petri nets, and we confirmed the advantages of using hybrid Petri nets. On the other hand, the scatter of the experimental data is caused by the individual difference of the volunteers. Therefore, the modelling in consideration of the individual difference is necessary in the future.

In this study, the amount of drawing blood within 90s is proportional to the drawing time as shown in Fig.8. However, we have to consider the effect of the blood coagulation in case of more than 180 s and make the model of non-Newtonian flow.

According to the manuals of some blood analyzers, the required minimum amount is over 900

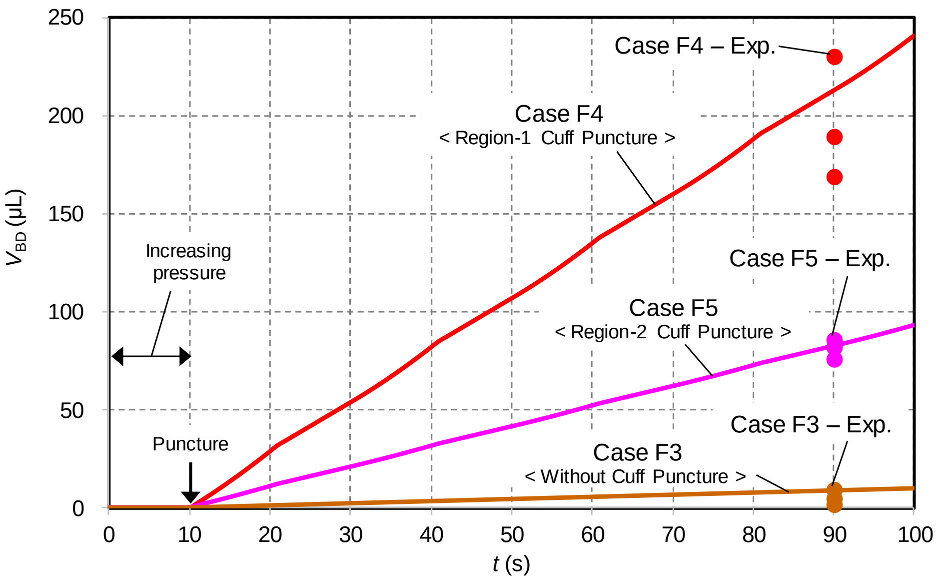


Figure 8: Comparison of the drawing blood between Hybrid Petri nets simulation.

Table 8: Experimental drawing blood data from nine volunteers.

Age	Sex of nine volunteers		Drawing time (s)	Classification of nine volunteers		
	Male	Female		Case F3	Case F4	Case F5
29 - 61	7	2	90	3	3	3

μL for simultaneous biochemical, immune and blood cell count inspection. It seems be impossible to use only cuff band for fastening finger. Therefore,we next try to use the vaccum suction pump concurrently.

4 CONCLUSIONS

Using the hybrid Petri nets simulation with cuff pressing and puncture modeled as discrete and blood flow modeled as continuity, we confirmed that the simulation results were agreement with the experimental drawing blood data. Consequently, we confirmed the advantages of using hybrid Petri nets.

Our final target is to make an automatic drawing blood machine from fingertip. As the next work, we design the control system of an automatic drawing blood machine by the optimized simulation results usung the hybrid Petri nets.

ACKNOWLEDGEMENTS

The part of this study is supported with the research project of the University of Tokyo COI (Center of Innovation). The authors would like to thank the organization of the University of Tokyo COI.

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