AN ONLINE FUZZY GAIN SCHEDULING FOR BLOOD PRESSURE REGULATION

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Abstract: This paper presents a method of fuzzy gain scheduling for a PID controller applied to mean arterial pressure (MAP) regulation during general anesthesia by sodium nitroprusside (SNP) infusion. A supervising algorithm is used for online updating the fuzzy gain scheduler of the PID controller to act stronger against the body reaction. A new model based on Slate's model and Furutani's ideas was developed for testing the controller. Simulation and clinical results in deep hypotensive controls at 40mmHg on pigs indicate the safety and stability of designed controller.

Keywords: Fuzzy control, fuzzy logic, PID control, scheduling algorithms, medical systems, medical applications, blood pressure.

1. INTRODUCTION

Maintaining the mean arterial pressure (MAP) at a substantially low level is of vital importance in many clinical situations. During cardiac surgery, it reduces intraoperative bleeding, which causes the side effects, such as increased risk of sepsis and organ failure. In patient's postsurgery, it promotes healing (Furutani *et al.*, 1995, 04; Er and Gao, 2003; Chen *et al.*, 1997). The MAP is often decreased by intravenous drug infusion of sodium nitroprusside (SNP). This drug is a potent fast-acting vasodilator that can quickly relax the muscle of the peripheral vasculature, resulting in reduction of MAP within minutes (Slate, 1980; Ying and Sheppard, 1994). Great caution is required to handle the wide range of patient sensitivities to the drugs because an overdose of SNP could, however, cause toxic side effects (Er and Gao, 2003). Manual adjustment of the SNP infusion rate by clinical personnel can be very tedious, time-consuming, and consequently of poor quality sometimes (Slate and Sheppard,1982; Chen *et al.*,1997; Gao and Er, 2003). The need for improved care of patients requires automatic control. Regulating MAP systems using SNP on humans has been incessantly studied since the late 1970's. However, they have been only used for hypertension (Slate and Sheppard, 1982; Chen *et al.*,1997; Gao and Er, 2003) and normotension (Furutani *et al.*, 1995, 04) control purposes. Moreover, due to the nonlinear nature of the input/output response, the interaction of drugs, the variation of response from patient to patient and the variation in the same patient under different conditions, blood pressure regulation is an actual research topic.

The objective of this paper is to develop an online fuzzy gain scheduling method of PID controller for blood pressure regulation purpose, especially in deep hypotension with special problems of body reaction. At 40mmHg of MAP, the overshoot response is dangerous, so the controller is firstly tested on pigs.

2. CONTROL STRUCTURE

The structure of the MAP regulation system uses two computers. The management computer receives and stores patient's data from DATEX AS/3 monitor system every 5 seconds. The current MAP will be sent to the control computer. Based on this feedback value, the controller on this computer generates a next infusion rate for a microinfusion pump (Graseby 3400) and the sodium nitroprusside drug (SNP) will be delivered to combine with intravenous (IV) fluid maintained at a constant rate.

This control system was applied to 25 clinical experiments on 7 pigs at Clinic of Anesthesiology and Intensive Care, University of Rostock, Germany. The first results indicated the safety and stability of the controller.

3. MODELING PROBLEM

The well-known model of dynamic response of MAP to SNP was obtained by Slate *et al.* This model is a linear first-order transfer function with two time delay components, which can be expressed in form of (Slate, 1980; Slate and Sheppard, 1982)

$$\frac{\Delta MAP(s)}{SNP(s)} = \frac{Ke^{-T_1 s}(1+\alpha e^{-T_2 s})}{1+\tau s} \qquad (1)$$

where $\Delta MAP(s)$ and $SNP(s)$ illustrate the change of MAP and the drug infusion rate, respectively. K describes the patient sensitive to the drug. T_1 and α present the initial transport delay and the recirculation fraction of SNP, respectively. T_2 is the recirculation time, and τ denotes the response time constant.

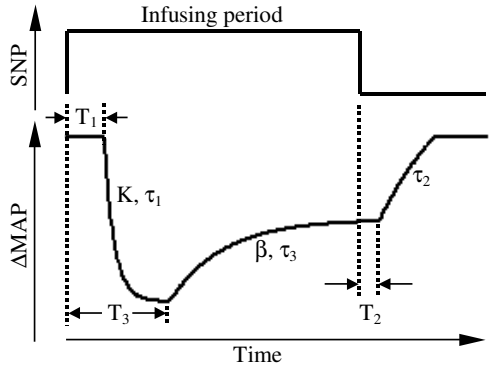

Fig. 1. Model parameters for identification.

Clinical experiment results on pigs showed that when the drug infusion rate is set at a constant level, after reaching steady response, the MAP is increased by the body reaction (Fig.1). This was not presented in Slate's model. However, in the complete systems of Sheppard and Slate, it was considered as the impact of respiration, the random variations due to sympathetic stimulation and the angiotensin reflex (Slate, 1980). Moreover, when the pump is stopped the response time constant τ becomes longer, and the transport delay T_1 is shorter, especially in reducing MAP from normotension to deep hypotension (40mmHg). The change in transport delay T_1 was investigated by Furutani *et al.*, in blood pressure control using trimethaphan camsilate hypotensive drug for dogs (Furutani *et al.*, 1995, 04).

Using Furutani's ideas, the model from Slate is modified as follows:

$$\frac{\Delta MAP(s)}{SNP(s)} = K\left(\frac{e^{-Ts}}{1+\tau s} + \frac{\beta e^{-T_3 s}}{1+\tau_3 s}\right) \qquad (2)$$

$$T = \begin{cases} T_1 & decreasing\ MAP \\ T_2 & increasing\ MAP \end{cases}, \quad \tau = \begin{cases} \tau_1 & decreasing\ MAP \\ \tau_2 & increasing\ MAP \end{cases}$$

where the transport delay T is set to T_1 when blood pressure has been decreased, and set to T_2 when it has been increased. The response time constant τ also changes similarly. A negative value of β presents a factor of body reaction other than the recirculation fraction of drug α ($\alpha \geq 0$) in Slate's model. T_3 and τ_3 describe the transport delay and the response time constant of body reaction, respectively.

Table 1 Parameters of Pigs (n=7)

Para.	Ave.	Min.	Max.	Unit
K	-0.7	-0.1	-2.3	mmHg/ml/h
β	-0.4	-0.05	-0.9	-
τ_1	40	30	75	sec
τ_2	290	225	390	sec
τ_3	375	300	425	sec
T_1	60	20	175	sec
T_2	15	1	30	sec
T_3	400	300	820	sec

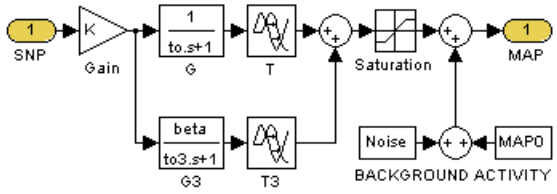

Fig. 2. Simulink model of MAP response to SNP

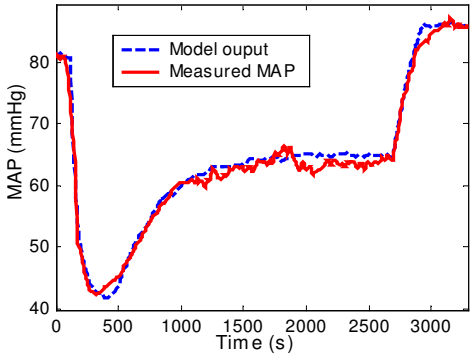

Fig. 3. Measured MAP and model output for a rectangle infusion period of SNP at 40ml/h.

All individual parameters of this model are given in Table 1, obtained by statistics on the measured MAP from 25 clinical experiments on 7 pigs. In Fig.2, the simulation model in MATLAB/Simulink is presented. The background activity in Fig.2 is the sum of an initial MAP and stochastic activity illustrated in Fig.9. The initial MAP is obtained from identification period. The stochastic activity was modeled similar to (Slate, 1980). A comparison between model output and measured MAP is also demonstrated in Fig.3.

4. PID CONTROLLER

The transfer function of an ideal PID controller has the form

$$G_c(s) = K_p\left(1+\frac{1}{T_i s}+T_d s\right) \qquad (3)$$

where K_p is proportional gain. T_i and T_d present integral and derivative time constants, respectively.

A discrete-time version for PID control in this paper

$$u(k) = K_p e(k) + K_i T_s \sum_{i=1}^{k} e(i) + \frac{K_d}{T_s}\Delta e(k) \qquad (4)$$

is applied (Zhao *et al.,* 1993).

Where, $K_i=K_p/T_i$ and $K_d=K_pT_d$. K_i and K_d are known as the integral and derivative gains, respectively. $u(k)$ presents the control signal, $e(k)$ denotes the error between the reference and process output, T_s is the sampling period, and $\Delta e(k) = e(k) - e(k-1)$.

There are some methods for tuning the PID controller effectively, such as Ziegler-Nichols', Cohen-Coon's, etc.. However, in animal experiments, sometimes a fixed gain controller is not flexible enough to adapt to different clinical conditions. The following section describes an online gain scheduling scheme of the PID controller based on fuzzy logic.

5. FUZZY GAIN SCHEDULING

5.1 Overview

The PID control system with a fuzzy gain scheduler applied to blood pressure regulation is presented in Fig.4. In this diagram, the patient's block is the model shown in Fig.2, sampled in 5s intervals. The observer supervises the current infusion rate and MAP for online updating the fuzzy gain scheduler.

It is assumed that the PID gains K_p, K_d and K_i are in prescribed ranges $[K_{p,min}, K_{p,max}]$, $[K_{d,min}, K_{d,max}]$, $[K_{i,min}, K_{i,max}]$, respectively (Zhao *et al.,* 1993). The appropriate ranges are determined experimentally and will be given in (5). Based on the error between setpoint and process output and the change of error, the fuzzy gain scheduler adjusts for the suitable values of K_p, K_d and K_i in these ranges for the PID controller.

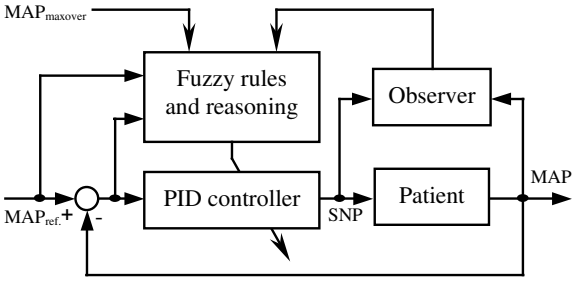

Fig. 4. PID control system with fuzzy gain scheduler.

5.2 Fuzzy gain scheduler design

Selecting the ranges of K_p, K_d and K_i for the gain scheduler requires estimating the dead time L and slope R of the output response curve similar to Ziegler-Nichols tuning method. However, in Ziegler-Nichols', the identification of maximum slope R takes a long time of waiting for the steady-state output response. For reducing identification time, this control system only determines the 'early' slope R, when the MAP has decreased around 10mmHg (Kähler *et al.*, 2004). Simulation results show that this method is at least 2 min. shorter than Ziegler-Nichols' for normal and sensitive pigs.

Fig.5 illustrates a method of calculating the dead time L and early slope R. The MAP response curve was inverted. Let h and h_{max} be the distance and maximum distance between MAP curve and the base of a triangle, respectively. L is determined at the time of $h=h_{max}$ (Kähler *et al.,* 2004). To reduce error of this estimation method, it is important to cut the overshoot behavior (the dash line in Fig.5).

In animal experiments, this method is effective with normal and sensitive pigs. However, for insensitive ones, the MAP is only decreased around 2-4mmHg during identifying period, and it often reaches steady-state response. In this case, R and L are determined by Ziegler-Nichols method.

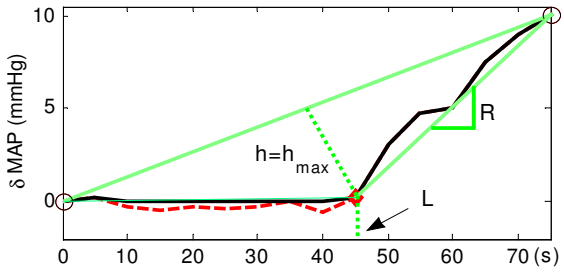

Fig. 5. Identifying L and R of MAP response curve.

After estimating R and L, the initial K_p*, K_d* and K_i* are calculated as shown in Table 2 and Table 3 (K_d*=K_p*T_d* and K_i*=K_p*/T_i*). These parameters are used to determine the ranges of K_p, K_d and K_i in equation 5, which obtained by hand through simulations (K_p, K_d and K_i < 0):

$$K_p \in [1.75K_p^*,\ 0.75K_p^*]$$
$$K_d \in [1.25K_d^*,\ 0.25K_d^*] \qquad (5)$$
$$K_i \in [2.25K_i^*,\ 0.75K_i^*]$$

Table 2 Calculating T_d^* and T_i^* due to L

L (sec)	[20-30]	(31-60]	(60-90]	(90-175]
Td*	0.75L	0.35L	0.2L	0.1L
Ti*	3.5Td*	3.5Td*	4Td*	4Td*

Table 3 Calculating K_p^* due to R

-R	[min-.05]	(.05-.4]	(.4-1]	(1-max]
K_p*	2/RL	6/RL	8/RL	12/RL

Notes: (*) presents that K_p^*, T_d^* and T_i^* are only initial values. These ones are used for presetting the fuzzy gain scheduler other than using for PID controller directly.

The fuzzy gain scheduler with 2 inputs and 3 outputs is designed for estimating K_p, K_d and K_i within above ranges. The membership functions of input fuzzy sets (for $e(k)$ and $\Delta e(k)$) and output's (for K_p, K_d and K_i) are given in Fig.6. In this figure, N presents negative, P positive, S small, B big, M medium and ZO approximately zero. Thus NS stands for negative-small, NM for negative-medium, NB for negative-big, PS for positive-small, PM for positive-medium and PB for positive-big.

Before control action, the fuzzy sets of inputs and outputs are calculated due to the reference level and the initial MAP measured in identifying period. Let MAP_{ref} be the setpoint, MAP_0 be the initial MAP, and $MAP_{maxover}$ be acceptable maximum overshoot. The input fuzzy sets are modified by changing the ranges of $[E_{min}, E_{max}]$ and $[dE_{min}, dE_{max}]$ in Fig.6.

$$E_{\min} = MAP_{ref} - MAP_0 \ [mmHg]$$
$$E_{\max} = MAP_{\max over} \ [mmHg] \qquad (6)$$
$$dE_{\min} = -1;\ \ dE_{\max} = 1$$

Here, dE_{min} and dE_{max} are determined by simulations. A saturation block in range [-1, 1] is also used for the input $\Delta e(k)$. The output fuzzy sets are modified in the ranges given in (5). Moreover, these will be updated during control by a supervising algorithm that will be presented in following section.

The fuzzy rules for tuning PID gains are described in Table 4, which were experimentally selected from simulations.

5.3 Supervising algorithm

In animal trials, the MAP response reaches the setpoint within 5min. without overshoot. However, the controller was not strong enough against the body reaction.

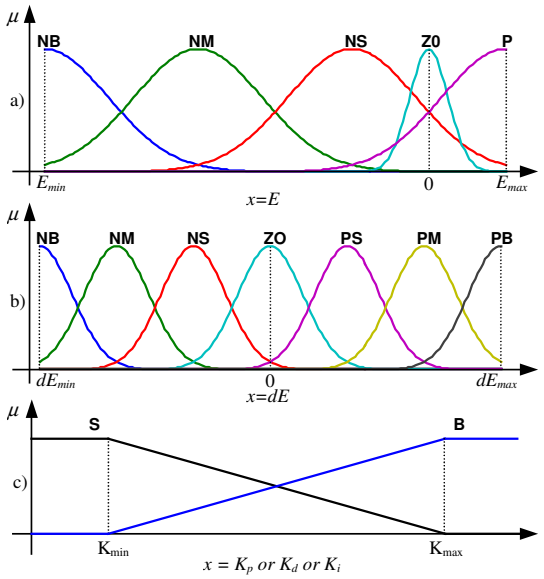

Fig. 6. a-b) membership functions for $e(k)$ and $\Delta e(k)$; c) membership functions for K_p, K_d and K_i

Table 4 Fuzzy tuning rules for K_p, K_d and K_i

K_p / K_d / K_i		$\Delta e(k)$ NB	NM	NS	ZO	PS	PM	PB
		S	S	S	S	S	S	S
	NB	B	B	B	B	B	B	B
		S	S	S	S	S	S	S
		B	S	S	S	S	S	B
	NM	S	S	B	B	B	S	S
		B	B	S	S	S	B	B
		B	B	S	S	S	B	B
$e(k)$	NS	S	S	S	B	S	S	S
		B	B	B	S	B	B	B
		B	B	B	S	B	B	B
	ZO	S	S	S	S	S	S	S
		B	B	B	B	B	B	B
		B	B	S	S	S	B	B
	P	S	S	S	B	S	S	S
		B	B	B	S	B	B	B

Notes: K_p, $K_i \rightarrow$ S & $K_d \rightarrow$ B: risetime ↓, overshoot ↑

To prevent this situation, a supervising algorithm based on results of Isaka *et al.* was developed (Isaka and Sebald, 1993). During operations, when the MAP response does not reach the target, the output ranges $[K_{min}, K_{max}]$ in Fig.6 (output fuzzy sets) will be updated for the controller acts stronger. And when the overshoot appears, they will be changed to act weaker. This algorithm can be described in a diagram given in Fig.7. The changes of PID gains K_p, K_d and K_i are demonstrated in Fig.8 during a simulation.

6. SIMULATIONS

The simulation results show that the MAP reaches the setpoint (40mmHg) after 5min from starting time (Fig.9). Fig.9a presents the stochastic of the background activity given in Fig.2. The MAP

responses have no overshoot and maintain at reference level during control, see Fig 9b. A result of a traditional PID controller is also compared in Fig.9c.

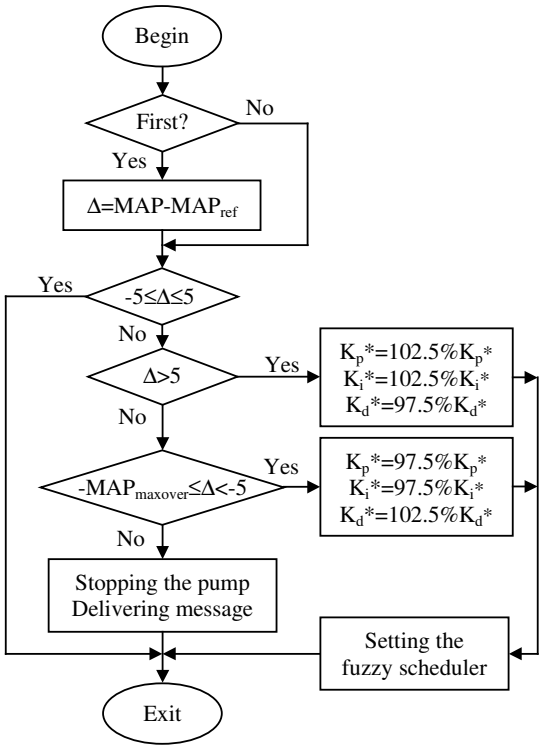

Fig. 7. Supervising algorithm diagram.

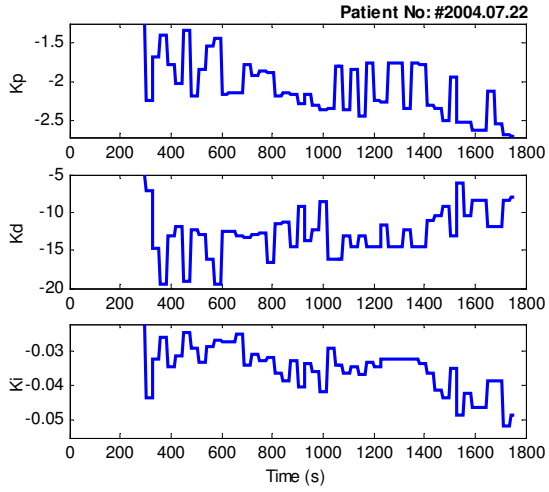

Fig. 8. PID parameters during control

Controlling progress can be summarized as follows:

- In first 15 seconds, the initial MAP is measured.
- A high infusion rate at 300ml/h is generated in 1 sample (5s) to fill up the infusion catheter.
- An identifying period is started at the time of 25s with infusion rate set at 30ml/h. This value is maintained until MAP has decreased more than 10mmHg from initial level for normal and sensitive patients, or until maximum time reached (4-6min.) for insensitive ones.
- The dead time L and early slope R are calculated.
- The fuzzy gain scheduler is set.
- The PID controller is turned on.
- The supervising algorithm will be used for online updating the gain scheduler every 30s.

Simulation results under different conditions indicate the stability of the controller.

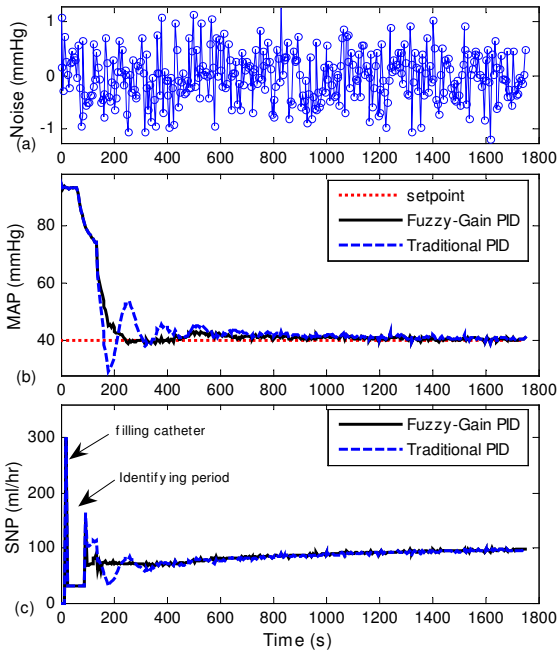

Fig. 9. Simulation results – A comparison between fuzzy gain-scheduled (solid) and traditional (dot) PID Controller.

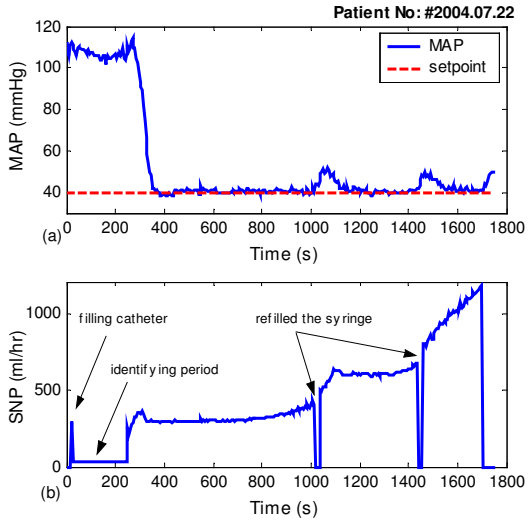

Fig. 10. A result of clinical trial on pig.

7. CLINICAL EXPERIMENTS

A selected result from clinical experiments on pigs is demonstrated in Fig.10. The MAP response reaches the reference level set at 40mmHg within 340s without overshoot. The results show that the controller is safe, effective and stable. However, there

is a problem on increasing MAP every time of changing a new syringe.

8. DISCUSSION

In simulations and clinical experiments, there exist some problems that require more discussions:

1. For very insensitive pigs, the identifying period of dead time L and early slope R can be disturbed by noises. Although a Wavelet's filter is used, estimating result of dead time L has a little error.
2. The ranges of K_p, K_d and K_i in equation 5 require optimization, which were only determined by hand through simulations.
3. For an insensitive pig, a high infusion rate is involved, which makes the syringe-50ml empty after a short time. Although the other syringe was only changed in a short time, the MAP was increased too fast (Fig.10). To avoid this problem, it would be better to use an infusion pump with 2 syringes. When the first one is empty it could switch to the second one automatically.
4. When the infusion rate reaches the saturation (1200ml/h for Graseby 3400 infusion pump), the MAP will be increased (in Fig.10, after the time of 30min., MAP is increased). For this case, we plan to use two infusion pumps. The second one will be started when the first one is saturated. However, an overdose of SNP is dangerous, so another drug may be used.

9. CONCLUSIONS

The paper summarizes the method of MAP control by SNP infusion using online fuzzy gain scheduling of PID controller. The model of MAP response to SNP was modified based on Slate's model and Furutani's ideas. It was not only used for designing and testing the PID controller but also for seeking the parameters of the fuzzy gain scheduler. The solution of calculating the dead time L and early slope R of the MAP response curve for tuning the controller was also presented. In animal experiments, this was effective in reducing identification period. Isaka's supervising algorithm for online updating the fuzzy sets of the gain scheduler illustrated a good way to handle the body reactions during surgeries, especially in deep hypotension control.

Although laboratory animal testing results indicate that designed controller is effective, safe and stable, there exist some problems presented in the discussion that require solving in further works.

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