Designing and Modeling a Hypertension Control System During Surgery

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***Abstract*— Monitoring and regulating blood pressure (BP) is critical to successful surgical outcomes. Conventionally, intraoperative treatment of BP involves manual administration of vasoactive compounds under continuous BP monitoring. In order to optimize and automate the regulation of BP during surgery, a PID-controlled system that intravenously injects vasodilators is proposed. Using control theory, this work aims to abstract patient hypertension as a dynamic biosystem then model and simulate the proposed PID control system to determine if BP is regulated at operable levels.**

The results demonstrate that a closed-loop system may represent a patient experiencing hypertension. The introduction of a sodium nitroprusside (SNP) injector closed-loop system fulfills the desired goal of bringing patient BP down to healthy levels, with significant improvements to responsiveness and efficacy when a PID-controller is integrated. Though simulations suggest that this control system successfully monitors and regulates patient BP, assumptions not grounded in reality, physical limitations, and other design factors must be considered prior to translating this system into a tangible medical solution. Regardless, this work provides the theoretical groundwork for modeling hypertension during surgery and designing a control system used to monitor and regulate patient BP.

***Clinical Relevance*— Properly modeling and characterizing treatment for intraoperative hypertension is important for increasing treatment and surgery efficacy. Therefore, the proposed system may result in better outcomes than current protocols which involve manual monitoring and regulation.**

Many operations require conditions favoring hypotension. For example, in operations such as microsurgery in the ear, dacrocystorhinostomy, transsphenoidal hypophysectomy, orthopedic procedures, and repair of intracranial aneurysms, hypotension might be desired [1]. In other cases, people may experience a large rise in BP which could be caused by incorrect dosing of anesthesia, manipulating large vessels, or cross clamping of vessels. Additionally, certain surgeries, such as cardiopulmonary bypass, require the patient to be in a certain blood pressure range, but natural or induced fluctuations could raise BP higher than the desired range [2].

Summarily, perioperative hypertension can increase undesirable surgery complications [3]. In all of these circumstances, surgeons aim to reduce BP, and a dynamic control system offers a more precise and responsive option for monitoring and regulating BP.

I. INTRODUCTION

Blood pressure (BP) regulation in the human body can be modeled as a homeostatic control system. Baroreceptors integrated throughout the body's vasculature feed BP readings to the medullary cardiovascular center in the brain via highly-sensitive mechanosensory neurons. The strength of the neurons' signals (i.e. action potential firing rate) relates directly to the degree to which the vessels conform, ultimately functioning as sensors for determining how much BP needs to change in order to reach the body's setpoint. The body responds to change in BP in two ways: it can change cardiac output and total peripheral resistance (TPR). TPR changes by modulating arteriole radius using vasoactive compounds. Vasoconstrictors decrease vessel radius thereby increasing BP, while vasodilators increase vessel radius thereby decreasing BP [4].

Vasodilators are generally used for treating hypertension. Sodium nitroprusside (SNP) is a standard vasodilator intravenously administered when patients experience intraoperative hypertension during surgery. Due to its rapid onset and short duration period, it is assumed that the vasodilating effects are caused by the drug itself rather than a metabolite. In addition to treating hypertension, surgeries require patients to stay in specific BP ranges. Heightened BP during surgery can increase complications by 35%, and 25% of patients having non-cardiac surgery have perioperative high BP and this number increases to 80% during cardiac surgery [3, 6-8]. To improve upon the laborious methods used to regulate and monitor BP during surgery, a PID-controlled system would provide healthcare workers an automated and responsive option for monitoring and regulating hypertension.

II. METHODS

A. Proposed Solution

In order to control BP during surgery, the control system features a closed loop system with a BP sensor, SNP injector/actuator, and a PID controller. SNP will be injected intravenously, and the PID controller will regulate SNP dosage dependent on the difference between the readings provided by the BP sensor and the desired BP target.

B. Assumptions

Prior to modeling and simulating the control system, the following set of assumptions are established. Firstly, it is assumed that the patient experiencing hypertension has a constant BP setpoint. The control system will seek to lower this BP as specified by a desired lower BP target. Secondly, the BP sensor is assumed to function ideally i.e. G(s) = 1.

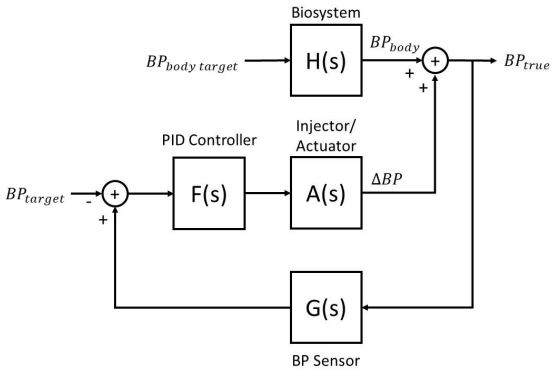

Figure 1. High level overview of the block diagram involving the biosystem, actuator, controller, and measurement.

This simplifies the closed loop transfer function and allows for modeling the system under ideal conditions. Thirdly, the operation that the patient undergoes is assumed to be in a short enough time frame such that the body does not develop a resistance to SNP. In cases where the surgery is long, the system will not account for the developed resistance to SNP, which may require alternative interventions to lowering BP. Lastly, the gain of control (K) within the biosystem is assumed to linearly characterize the patient's sensitivity to SNP [9]. Specifically, the patient's sensitivity within the biosystem is assumed to be 1 as a standard, positive value, keeping in line with the biosystem being a negative feedback system.

C. Differential Modeling of Control System

The human body functions as an independent homeostatic control system and can be modeled as a closed loop system. The biosystem consists of a block representing the brainstem as the controller, a block representing the heart and vasculature, and a baroreceptor that serves as negative feedback to control the biosystem [9].

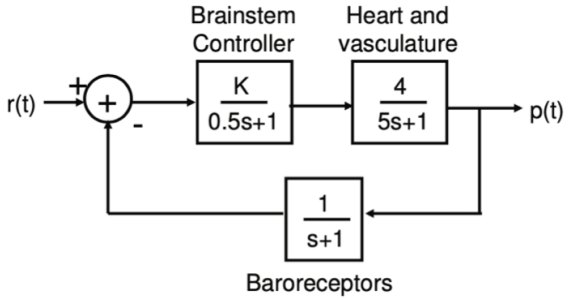

Figure 2. Block diagram of the biosystem, including the brainstem controller, the heart and vasculature, and the measurement transfer function from the baroreceptors [9].

An actuator/SNP injector is used to reduce the BP of the patient during the surgery. The following transfer function relates the SNP infusion rate to the change in BP [10]:

$$\mathrm{A(s)} = \frac{\Delta P_d(s)}{I(s)} = \frac{ke^{-T_i s}(1+e^{-T_c s})}{\tau s+1}$$

where the constant k indicates the SNP sensitivity of the different patients, T_i indicates the time delay for the drug to transport to the body, T_c indicates the time for the drug to circulate throughout the body, and $\boldsymbol{\tau}$ is the system's time constant [10]. The constants characterize body sensitivity, and are unique to each and every patient. To simplify this problem, patients are split into three groups, sensitive, nominal, and insensitive. A table for these values is shown below [10]. Nominal values will be used for simulations.

TABLE I. Transfer Function Variables

Parameter	Sensitive	Nominal	Insensitive
k	-9	-0.7143	-0.1786
α	0	0.4	0.4
T_i	20	30	60
T_c	30	45	75
τ	30	40	60

A fractional-order PID controller was used in similar works [10]:

$$F(s) = K_p + \frac{K_i}{s^\lambda} + K_d s^\mu$$

where λ and μ can be anywhere between 0 and 2. To solve for values of K_i , K_p, and K_d, the poles of the transfer function in the Fourier domain with the actuator and controller were found. Then, matrix equations were used to find their values on different planes [10]. On the K_p K_i plane,

$$K_p = -K_d \omega^\mu \frac{\sin\left(\frac{\pi}{2}(\lambda+\mu)\right)}{\sin\left(\frac{\pi}{2}\lambda\right)} - \frac{R(\omega) - \cos\left(\frac{\pi}{2}\lambda\right) I(\omega)}{R^2(\omega) + I^2(\omega)}$$

$$K_i = K_d \omega^{\mu+\lambda} \frac{\sin\left(\frac{\pi}{2}\mu\right)}{\sin\left(\frac{\pi}{2}\lambda\right)} - \frac{\omega^2 I(\omega)}{\sin\left(\frac{\pi}{2}\lambda\right) + \left(R^2(\omega) + I^2(\omega)\right)}$$

On the K_p K_d plane,

$$K_i = -K_p \frac{\omega^\lambda \sin\left(\frac{\pi}{2}(\mu)\right)}{\sin\left(\frac{\pi}{2}(\lambda+\mu)\right)} - \frac{\omega^\lambda \left(\sin\left(\frac{\pi}{2}\mu\right) R(\omega) + \cos\left(\frac{\pi}{2}\mu\right) I(\omega)\right)}{\sin\left(\frac{\pi}{2}(\lambda+\mu)\right)\left(R^2(\omega) + I^2(\omega)\right)}$$

$$K_d = \left(\frac{K_p}{\omega^\mu}\right) \frac{\sin\left(\frac{\pi}{2}(\mu)\right)}{\sin\left(\frac{\pi}{2}(\lambda+\mu)\right)} - \frac{\sin\left(\frac{\pi}{2}\mu\right) R(\omega) - \cos\left(\frac{\pi}{2}\mu\right) I(\omega)}{\omega^\mu \sin\left(\frac{\pi}{2}(\lambda+\mu)\right)\left(R^2(\omega) + I^2(\omega)\right)}$$

For the sake of simplifying the model, a normal PID controller will be used and analyzed.

III. RESULTS

The closed loop transfer function for the biosystem is simplified:

$$\frac{4K}{2.5s^3 + 8s^2 + 6.5s + 1 + 4K}$$

where K = 1, so the transfer function becomes:

$$\frac{4}{2.5s^3 + 8s^2 + 6.5s + 5}$$

The block diagram, which can be seen below, for the biosystem was simply constructed using the transfer function block:

Figure 3. Simulink block diagram showing only the transfer function of the biosystem

The step input had an initial value of 130 mmHg and a final value of 90 mmHg, meaning that the desired mean arterial BP is 90 mmHg. The simulation is shown below.

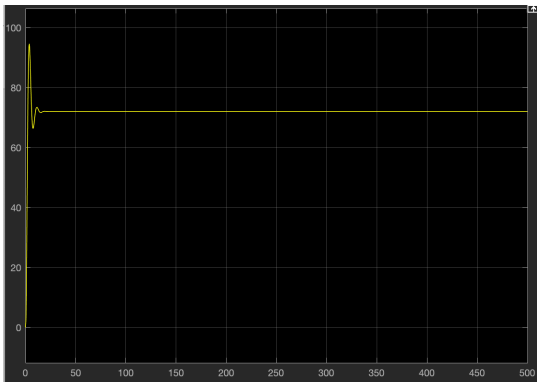

Figure 4. Simulink simulation of the biosystem.

As expected, the system is stable but there is a steady state error of approximately 15 mmHg between the target value of 90mmHg and the steady state value of ~75mmHg.

The actuator is introduced to the system which uses the transport delay blocks to account for the drug delivery and recirculation time. It should be noted that the values used in the transfer functions were the nominal values seen in Fig. 4.

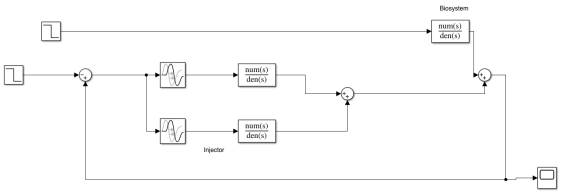

Figure 5. Simulink block diagram of the biosystem and the injector/actuator.

The simulation can be seen below (Fig. 6). The target value for the biosystem is higher than the target input by the surgeons. In this simulation, the target of the biosystem is 100 mmHg and time delay of 10 seconds and the target for the injector is 80 mmHg with a time delay of 25 seconds, both with an initial value of 130 mmHg. The reasoning behind a 25 second delay is that it takes approximately 25 seconds for the biosystem, on its own, to reach a steady state.

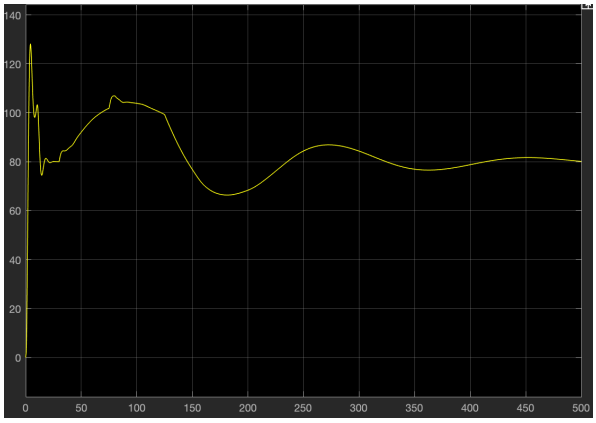

Figure 6. Simulink simulation for the actuator controlling the BP of the biosystem.

The addition of the actuator introduces oscillations to the biosystem, increasing BP settling time. To address this, a controller must be used.

With a PID controller attached, the block diagram is shown below:

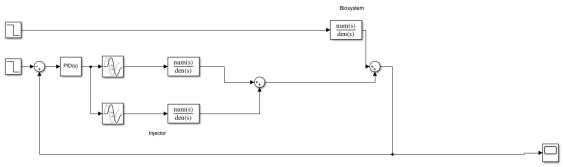

Figure 7. Simulink block diagram of the biosystem, the injector/actuator, and the PID controller.

After careful testing with the PID parameters, using the table below, a PD controller was determined to work best for stabilizing the system [11]. The values were found as follows: Kp = 0.001, Ki = 0.00005, Kd = 0.

TABLE II. PID Tuning Parameters

Parameter Increase	Rise time	Overshoot	Settling Time	Steady-state error
Kp	↓	↑	Small Change	↓
Ki	↓	↑	↑	Great reduce
Kd	Small Change	↓	↓	Small Change

The simulation for the whole system is shown below (Fig. 7). The initial value of BP is 130 mmHg, the target for the biosystem is 100 mmHg with a 10 second time delay, and the target of the injector is 80 mmHg with a 25 step time delay.

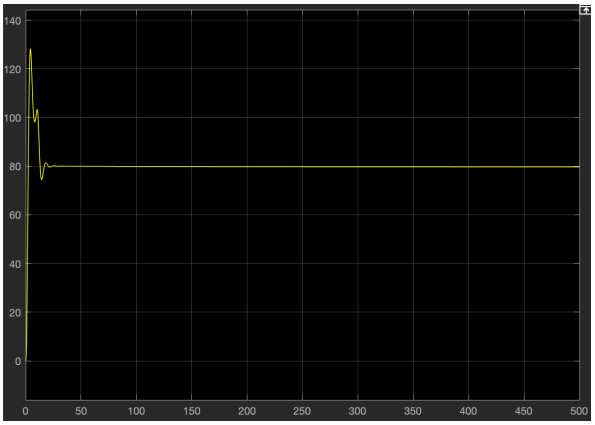

Figure 7. Simulink simulation of the whole system with the tuned PID controller.

Blood pressure reaches steady state at the target BP of 80 mmHg, so that the steady state error is largely reduced. The system also reaches the steady state BP in about 25 seconds.

IV. DISCUSSION

This work provides a model and solution for treating hypertension during surgery. However, it does not provide an examination of the system tuned to patients with higher or lower levels of sensitivity to SNP. Further work would examine the degree of change necessary to accommodate the variable sensitivities of patients.

Additionally, the assumptions established may deviate from realistic outcomes. Firstly, patients' BP is dynamic and the body's target BP is not constant. Secondly, the BP sensors may behave far from ideal expectations which will cause the system to behave differently. Lastly, other physical limitations play an important role when translating the system to a physical product. For example, the harmful effects of injecting too much SNP over a period of time must be considered.

For future work, a drug that increases BP, such as a vasopressor, may be introduced to the control system to treat hypotension, allowing for the system to exert total control over the patient's BP. A completed model - accounting for variable patient sensitivities and the new drug's effects - could then be translated to a real BP management device.

V. CONCLUSION

The successful modeling of the SNP-based hypertension control system demonstrates its viability as a means of managing BP in conditions where hypertension is a risk or where lower BP is desired. The control system is able to lower a patient's BP to

the desired value quickly and maintain the BP at that level. As a result, it can largely reduce the risk of hypertension, make surgical operations safer, and reduce the rate of complications.

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