Application of System Dynamics to Cardiovascular System Biofeedback Regulation of BP for Hypertensives

Zhu Mingjie and Zhu Zhiyuan

Department of Automatic Control and Electronic Engineering
East China University of Chemical Technology

Abstract

The modern researches on physiology verify that there are close relationships between central nervous system (CNS) and autonomic nervous system (ANS) and some autonomic functions can be regulated by CNS to some extent. In this paper, the mechanisms of cardiovascular system, especially of BP regulation, under CNS control are researched. A blood circulatory system dynamic model is established and applied practically to treatment of hypertensives trained with biofeedback technique, in which pulse transit time (PTT) is employed as an indirect index of BP change. The result shows that the curative effect of this method is efficient for BP control.

Introduction

Cardiovascular diseases, especially hypertension, are very common in modern society. There are evidences that essential hypertension is related to various behavioral, social, and environmental conditions. Many approaches to BP reduction have been developed. The behavioral approaches, such as biofeedback technique and meditation-relaxation, are some of them, with which, several disadvantages of medication treatment are prevented. Meaningful BP reductions were obtained in various literature sources [1,2], in which subjects were trained with biofeedback technique. But the measurement of BP is still an obstacle for BP Biofeedback program, in which it is also lack of research on theory. This paper attempts to make some contributions in these aspects.

With System Dynamics, we have researched the physiological mechanisms of cardiovascular system and presented its dynamic model under CNS control. As an application, the model was used to instruct the biofeedback training of BP regulation for hypertensives, in which the BP was measured from PTT indirectly. The results from clinical practices show this method is efficient for treatment of hypertension.

Dynamics of Cardiovascular System and BP Control under CNS

It is able to analyze and model conveniently the circulatory system by means of System Dynamics. In this paper, the blood volume is referred to basic level variable,
and based on the process of nervous adjusting of BP, the
dynamic model of cardiovascular system is researched for
cardiac rhythm and muscle adjusting on non-invasive measure
and biofeedback control.

The circulatory system includes both pulmonary and
systemic circulations. With the automatically rhythmical
systole of sino-atrial node, cardiac impulses are
transmitted to ventricular muscle through nerve fibers. In
terms of Frank-Starling rule, the blood flowing in heart is
completely injected into arteries. Under the action of
pressure, blood flows from ventricles to arterioles,
capillaries veins, finally, to vein in sequence. From fig.1,
it can be found that there are two main factors which
affect the arterial pressure: 1) cardiac output Q, 2) prihperal
resistance R. The cardiac output is related to
stroke volume (SV) and cardiac rhythm (HF).

\[ Q = SV + HF \]

According to the Frank-Starling rule, SV is equal to the
venous return, which may also be adjusted by humoral system.
The peripheral resistance

\[ R = 8\eta l / \pi r \]

where \( \eta \) represents the blood viscosity, and \( l \) and \( r \)
denote the length and the internal radius of the vessel,
respectively.

During the process of nervous adjusting of BP, autonomic
nervous control centers in lower level brain can inhibit
vasomotor centers if they receive the signal of BP
increasing, sometimes, excite vagal centers, as a result,
the radius of vessel is expanded, the cardiac rhythm and
contraction is weakened. Then the BP is decreased. In
general, this kind of feedback control of BP is completed by
pressurerceptors in aorta. But since the pressurerceptors
may be adaptive to hypertension, and if it remains one or
two days for increased BP they will loss their adjusting
function. It makes that they are uselessless in treatment for
hypertensives[3]. In terms of the principle of biofeedback
technology, if BP is immediately reflected to CNS, the
cardiovascular control centers will be stimulated to reduce
BP by the regulating mechanisms existing between CNS and
ANS. In fact, the practices in biofeedback technique and
researches on nervous mechanisms have shown that there are
close relationships between CNS and ANS. Many autonomic
functions can be regulated by CNS with instruments outside
body. With a BP receptor and feedback instruments, a new BP
control system -- biofeedback control system is constructed,
in which BP information is detected continuously and
accurately by BP receptor and is sent efficiently to CNS by
ways such as audition and vision etc., and then signals are
in turn transmitted to ANS. Hence the vagal centers are
excited and the stroke volume and peripheral resistance are
changed, see fig.2. The feedback instruments outside body
take an important role in BP regulation instead of pressureresceptors inside body. Through stimulating of gratified nervos centers and training gradually the subjects may 'remember' or 'enforce' the regulating process between CNS and ANS. By this way, the hypertensives can regulate the BP by themselves after a period of training so as to reach the goal of long-time treatment for hypertension. This system is self-learning and is described in the system dynamics model.

PTT and Cardiovascular Performance

It is very important to get information about activity of the autonomic function in biofeedback control system. General sphygmomanometer in which Korotkoff (K) sound is used to determine BP level, cannot be employed in biofeedback control program because of discrete and inaccurate. With an automated constant cuff-pressure system developed by D. Shapiro et al. [4][5], systolic blood pressure (SBP) or diastolic blood pressure (DBP) level can be measured beat-by-beat. But this has several disadvantages for psychophysiological experiments like biofeedback program etc.. Firstly, it has subjects fell uncomfortable, and secondly, the inflated cuff may cause the artery to be clogged or partly clogged. Arterial pulse transit time (PTT) has been used as a measure of cardiovascular performances in past decades [6][7], mainly as an index of BP change. In reference [9], Zhu Mingjie presented a new instrument to detect PTT with arterial pulse wave (PW) and electrocardiogram (ECG) and established a model to describe the relationship between PTT and BP. The regression equation is:

$$\Delta \text{MBP} = -1.313 \times \Delta \text{PTT}$$

where MBP represents the change of mean BP (mmHg), and \( \Delta \text{PTT} \) stands for the change of PTT (ms).

By this method, the change of BP can be detected continuously and noninvasively, which is desirable for biofeedback BP control experiments.

Application to Biofeedback BP Control

a. Subjects and method

22 essential hypertensives were randomly assigned to three groups A, B, and C. They were asked to complete training session once daily 6 days a week for three weeks. A training session took approximately 30 minutes. Thus 18 sessions were completed for each subject over the training program.

Subjects in feedback session were given feedback information about their BP change measured with PTT indirectly, in pseudo-feedback session, the subjects were given random signals which were irrelevant with their BP. In relaxation session, subjects were asked to sit quietly, relax their muscles, without feedback information. Subjects
In group A were trained with feedback session in whole program, these in group B were trained with feedback and relaxation session alternately and in group C they were trained with pseudo-feedback session.

In biofeedback session, PTT was used as a measure of BP change. The PTT was got from the arterial pulse wave (PW) and electrocardiogram (ECG), where the PW was detected with a photo-electronic transducer, and ECG was got from standard lead II.

b. Results
1). There are significant BP reductions in both group A and group B over three weeks, average magnitudes are 27.8/22.6 mmHg (see fig. 3) and 24.5/16.9 mmHg, respectively. But significant differences between them cannot be found.

2). There is no significant change in average BP of Group C over the Program.

3). There is significant differences between biofeedback and relaxation in within-session average SBP reduction (average reductions are 6.9 mmHg and 4.7 mmHg respectively).

4). There are no significant across-session reductions in average magnitudes of BP for either relaxation or pseudo-feedback session.

5). Mean reduction of SBP for biofeedback session is significant, magnitude is 6.9 mmHg.

Discussion

Significant BP reductions of subjects trained with biofeedback technique successively is obtained, average magnitude is 27.8/22.6 mmHg (the last three to the first three sessions). This is superior to other reported results [11][12] and supports the suggestion that voluntary regulation of some autonomic functions may be helpful for clinical treatment of the diseases caused by stress, mainly hypertension. In addition, it is also found that there are major differences between hypertensives and normal persons on the distributions of the PTT parameter and its components -- the cardiac pre-ejection period (PEP) and the pulse transit interval (PTI). The PEP and PTT also provide some information about cardiovascular performance. By means of model and method of System Dynamics, computer technology, artificial intelligence and modern electronic techniques, a computer-aided diagnosis and treatment system can be constructed in which experiences of experts and various parameters reflecting cardiovascular activity such as PTT, PEP, PTI and etc. are useful.
References

Fig. 2: Diagram of biofeedback control of BP

Fig. 3: Changes of BP during the program

Fig. 4: Cause-effect diagram