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A Critique on Baroreceptor and their Effective Reflex Action on Compartmental Cardiovascular Modeling in Regulating Hemodynamic Parameters

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Abstract*: Baroreceptor is the feedback unit present in the living beings which acts as a sensor that is located in the walls of blood vessels. This sensor senses the deformation in the blood vessels which causes change in arterial blood pressure and regulates it via Central Nervous System (CNS) and the information are autonomic reflexes that has a great influence on circulatory system elements such as peripheral systemic resistance (Rpsym), contractility of the ventricles (Emax), unstressed volume of the ventricles (Vus_ven) and heart rate (HR). The dynamic behaviour of the baroreceptor is modeled and substantiated by applying the negative feedback mechanism. A detailed modeling and simulation study is presented considering various testing conditions in regulating the circulatory system elements which oversees the Mean Arterial Pressure (MAP) in cardiovascular system. The Total Artificial Cardiovascular model (TAH-CVS) is also developed using pressure, volume and flow related differential equations. Based on the testing conducted under various conditions, the feedback-mechanism of the baroreceptor model is combined with the continuous TAH-CVS closed loop model to validate the effectiveness of the baroreceptor model. The simulation results of TAH-CVS model at initial conditions are compared with the TAH-CVS model with baroreceptor.

***Keywords* : Circulatory system, closed loop, hear, feedback, nerve activity, testing.**

I. INTRODUCTION

There are several feedback loops present in the human body for maintaining hormone levels, blood sugar, temperature, pH and blood pressure. The control mechanism that shows an immediate effect in regulating the blood pressure is baroreceptor whereas the other mechanisms namely humoral, renal and tissue regulations are deliberate [1-4]. The feedback actions taken by baroreceptor are autonomic reflexes that have influence in change of sympathetic nerve activity of the cardiovascular system [5], [6].

Baroreceptor usually receives change in arterial pressure through mechanical distortion and deformation of the blood vessels [7]. This causes change in R_{sys}, E_{max}, V_{us_ven} and HR. The baroreflexes are then transferred to CNS. The CNS generates nervous activities in two ways such as sympathetic and parasympathetic. The neural activities are transferred by the efferent part to change the R_{sys}, E_{max}, V_{us_ven} and HR. The afferent part contains the receptor which provides nerve activity based on the change in arterial pressure. Based on the changes in these parameters, the arterial blood pressure is regulated, the action if baroreceptor is increased initially and is then transformed over time as the arterial pressure reached nominal value. This is justified by applying the baroreceptor model as the feedback system to the TAH-CVS model and their simulation results are compared.

II. MATERIALS AND METHODS

A. Baroreceptor Model

Baroreceptor is stretch receptor situated on the walls of the blood vessels, the most approachable of which are located in aortic arch and in the carotid sinus. Carotid sinus baroreceptor is situated commonly in the particular part of the two carotid sinus arteries [8] Aortic arch baroreceptor on the other hand, is situated on the walls of the aortic arch. The carotid sinus and aortic arch receptors are assumed to be functionally similar, expect that the operating condition of aortic arch receptor is at a higher pressure level [9-11]. The baroreceptor modeled here is concentrated on the carotid sinus which has nerve ending and respond to deformation in the walls of the blood vessels as shown in Fig. 1.

The nerve activity develops from two sections, a pressure-mechanical and electro-mechanical component [12]. The carotid sinus receptor produces nerve activity which are called firing rates. The baroreceptor acts immediately to irregularities in the walls of blood vessel by a pressure-mechanical mechanism [13], [14]. The electro-mechanical component generates the baroreceptor firing rate by the electro-mechanical mechanism inbuilt in the receptor. The cardio inhibitory and vasomotor center of the CNS generates sympathetic nerve activity [15]. The efferent pathway transmits the nerve activity to the TAH-CVS model.

The input function to the baroreceptor model is expressed in Eq. (1) [16], [17].

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The parameters that are influenced by autonomic reflexes are modeled in such a way that it provides continuous control action to regulate the MAP as shown in Eq. (2)-(5). The nominal values such as MAP_{nom}, $R_{psym_{base}}$, $Els_{max_{base}}$, $V_{us\_ven_{base}}$ and HR_{base} discussed in Eq. (1)-(5) are shown in Table 1.

B. Baroreceptor with Cardiovascular Model

The neural activity transmitted from the CNS causes rapid modification in R_{psym}, Els_{max}, V_{us_ven} and HR. These stimuli are given as the feedback signal to the TAH-CVS model [18], [19]. The TAH-CVS model is a four compartment model namely left heart, systemic circulatory system, right heart and pulmonary circulatory system. The continuous process of TAH-CVS model is simulated with MAP input from the baroreceptor model.

In this model, the left and right heart is partitioned into two atrial parts and three ventricular parts. When the left ventricular pressure exceeds the systemic aortic pressure, the aortic valve opens and the blood enters into systemic circulation through peripheral systemic resistance R_{psym}. The veins return the blood to right atrium. When the right atrial pressure exceeds right ventricular pressure, the tricuspid valve opens and the blood enters into right ventricle [20], [21]. When the right ventricular pressure exceeds the pulmonary aortic pressure, the blood enters into pulmonary circulation through pulmonary valve. The veins return the blood to left atrium. When the left atrial pressure exceeds the left ventricular pressure, the blood enters into left ventricle by the opening of mitral valve. In this way, the TAH-CVS is modeled which represents the continuous closed loop system. The modeling equations are classified based on the relationship between pressure, volume and flow as shown in Eq. (6)-(8).

The Cardiovascular modeling is carried out by compartmental approach with six main compartments such as left heart, right heart, systemic circulation, systemic veins, pulmonary circulation and pulmonary veins as shown in Eq. (9)-(50).

C. Left Heart

The equations representing left heart is expressed in Eq. (9)-(17).

D. Right Heart

The equations representing left heart is expressed in Eq. (18)-(26).

E. Systemic circulation

The systemic circulatory system is further sub classified into three arterial sections and two venous sections as shown in Eq. (27)-(38).

F. Pulmonary Circulation

The pulmonary circulatory system is further sub classified into three arterial sections and two venous sections as shown in Eq. (39)-(50).

III. RESULTS AND DISCUSSION

Following the modeling of baroreceptor and TAH-CVS model, the baroreceptor model is tested by varying the MAP values within the range of 30-140 mmHg. The MAP inputs to the baroreceptor model provided wide range of values for the circulatory system parameters shown in Table 2.

The values obtained from Table 2 are then specified in the TAH-CVS model and the effective reflex actions by the baroreceptor are shown in Fig. 2 -9 which shows that baroreceptor model is dynamic and provides rapid action.

Usually the peripheral systemic resistance, maximum elastance and heart rate decreases with increase in MAP, hence they are inversely proportional. On other hand, unstressed ventricular volume increases with increase in MAP and implies to be directly proportional. This condition is proved in Fig. 2-5 and the obtained circulatory system parameters are implemented in the TAH-CVS model to test for the dynamics of baroreceptor model and their results are shown in Fig. 6-9.

Based on the testing conducted under various conditions, the feedback-mechanism of the baroreceptor model is combined with the continuous TAH-CVS closed loop model to validate the effectiveness of the baroreceptor model and their rapid action to the change in MAP. The simulation results of TAH-CVS model at initial conditions are compared with the TAH-CVS model with baroreceptor in Fig. 10-11. These results imply that the baroreceptor plays a major role in auto regulation of MAP.

From the Fig. 10-11, it is seen that the MAP value is having a peak of about 200/110 mmHg which is immediately regulated to 160/99 mmHg by baroreceptor feedback mechanism. In this way, baroreceptor helps to regulate the mean arterial blood pressure (MAP) in a closed loop feedback control mechanism. The nominal value of MAP endured around 99 mmHg in TAH-CVS model without baroreceptor mechanism. When the baroreceptor model was implemented along with TAH-CVS model and simulated, the automatic feedback mechanism took place and the nominal value of MAP was lowered to 92 mmHg. Thus crucial role of baroreceptor is henceforth proved as shown in Fig. 12.

IV. CONCLUSION

Thus the dynamic baroreceptor model is developed with TAH-CVS model which helps in initial study on the hemodynamic parameters since conducting trial run or tests on living subjects involves various legal issues. The variations in the MAP make the baroreceptor model to take an immediate feedback action to regulate the mean arterial pressure until the nominal range is obtained. Furthermore, the work is extended to study the baroreceptor and TAH-CVS model mechanisms for the drug model by varying drug input actions of Sodium Nitroprusside and Dopamine.

APPENDIX

$$BFC_{in} = \frac{exp^{\alpha(MAP-MAP_{nom})}}{1+exp^{\alpha(MAP-MAP_{nom})}} \quad (1)$$

Where MAP_{nom} is the nominal value of MAP and α is the constant.

$$R_{psym} = R_{psym_{base}} - \left(B_{R_{psym}}\right)R_{psym_{base}} \quad (2)$$

$$Els_{max} = Els_{max_{base}} - \left(B_{Els_{max}}\right)Els_{max_{base}} \quad (3)$$

$$V_{us\_ven} = V_{us\_ven_{base}} - \left(B_{V_{us\_ven}}\right)V_{us\_ven_{base}} \quad (4)$$

$$HR = HR_{base} - (B_{HR})HR_{base} \quad (5)$$

Where $B_{R_{psym}}$, $B_{Els_{max}}$, $B_{V_{us\_ven}}$ and B_{HR} represents the output from baroreceptor model for that instant.

$$P_{sys1} - P_{sys2} = R_{sys1}Q_{sys1} + L_{sys1}\frac{dQ_{sys1}}{dt} \quad (6)$$

$$\frac{dV_{sys1}}{dt} = Q_{lv} - Q_{sys1} \quad (7)$$

$$P_{sys1} = \frac{1}{C_{sys1}}(V_{sys1} - V_{us,sys1}) \quad (8)$$

Where P_{sys1} and P_{sys2} are the aortic systemic pressure in partition 1 and partition 2. R_{sys1} represents viscosity, L_{sys1} represents inertia and C_{sys1} represents elastance properties, Q_{sys1} and V_{sys1} represents flow and volume and V_{us} represents unstressed volume.

C. Left Heart

$$\frac{dQ_{la}}{dt} = \frac{1}{L_{la}}(P_{la} - P_{lv}) - \frac{R_{la}}{L_{la}}Q_{la}, \text{ when mitral valve is open} \quad (9)$$

$$Q_{la} = 0, \text{ when mitral valve is closed} \quad (10)$$

$$\frac{dV_{la}}{dt} = Q_{l2} - Q_{la} \quad (11)$$

$$P_{la} = E_{la}(V_{la} - V_{dla}) \quad (12)$$

where Q_{la} is flowrate of left atria
L_{la} is inertial vessel properties of left atria
P_{la} is left atrial pressure
P_{lv} is left ventricular pressure
R_{la} is resistance of left atria
V_{la} is volume of left atria
Q_{l2} is flowrate of pulmonary venous section2
E_{la} is elastance of left atria
V_{dla} is volume of left atria at zero pressure

D. Right Heart

$$\frac{dQ_{lv}}{dt} = \frac{1}{L_{lv}}(P_{lv} - P_{as}), \text{ when aortic valve is open} \quad (13)$$

$$Q_{lv} = 0, \text{ when aortic valve is closed} \quad (14)$$

$$\frac{dV_{lv}}{dt} = Q_{la} - Q_{lv} \quad (15)$$

$$P_{lv} = E_{lv}(V_{lv} - V_{dlv}) \quad (16)$$

$$P_{as} = R_{0s}Q_{lv} + P_{a1} \quad (17)$$

where Q_{lv} is left ventricular flowrate
L_{lv} is inertial vessel properties of left ventricle
P_{lv} is left ventricular pressure
P_{as} is systemic aortic pressure
V_{lv} is left ventricular volume
E_{lv} is elastance of left ventricle
V_{dlv} is left ventricular volume at zero pressure
R_{0s} is systemic resistance
P_{a1} is pressure at systemic arterial section 1

E. Systemic Circulation

$$\frac{dQ_{ra}}{dt} = \frac{1}{L_{ra}}(P_{ra} - P_{rv}) - \frac{R_{ra}}{L_{ra}}Q_{ra}, \text{ when tricuspid valve is open} \quad (18)$$

$$Q_{ra} = 0, \text{ when tricuspid valve is closed} \quad (19)$$

$$\frac{dV_{ra}}{dt} = Q_{r2} - Q_{ra} \quad (20)$$

$$P_{ra} = E_{ra}(V_{ra} - V_{dra}) \quad (21)$$

where Q_{ra} is flowrate of right atria
L_{ra} is inertial vessel properties of right atria
P_{ra} is lright atrial pressure
P_{rv} is right ventricular pressure
R_{ra} is resistance of right atria
V_{ra} is volume of right atria
Q_{r2} is flowrate of pulmonary arterial section2
E_{ra} is elastance of right atria
V_{dra} is volume of right atria at zero pressure

$$\frac{dQ_{rv}}{dt} = \frac{1}{L_{rv}}(P_{rv} - P_{ap}), \text{ when pulmonary valve is open} \quad (22)$$

$$Q_{rv} = 0, \text{ when pulmonary valve is closed} \quad (23)$$

$$\frac{dV_{rv}}{dt} = Q_{ra} - Q_{rv} \quad (24)$$

$$P_{rv} = E_{rv}(V_{rv} - V_{drv}) \quad (25)$$

$$P_{ap} = R_{0p}Q_{rv} + P_{p1} \quad (26)$$

where Q_{rv} is right ventricular flowrate
L_{rv} is inertial vessel properties of right ventricle
P_{rv} is right ventricular pressure
P_{ap} is aortic pulmonary pressure
V_{rv} is rightventricular volume
E_{rv} is elastance of right ventricle
V_{drv} is right ventricular volume at zero pressure
R_{0p} is pulmonary resistance
P_{p1} is pressure at pulmonary arterial section 1

Arterial section 1

$$\frac{dQ_{a1}}{dt} = \frac{1}{L_{a1}}(P_{a1} - P_{a2}) - \frac{R_{a1}}{L_{a1}}Q_{a1} \quad (27)$$

$$\frac{dV_{a1}}{dt} = Q_{lv} - Q_{a1} \quad (28)$$

$$P_{a1} = \frac{1}{C_{a1}}(V_{a1} - V_{una1}) \quad (29)$$

Arterial section 2

$$\frac{dV_{a2}}{dt} = Q_{a1} - \frac{(P_{a2} - P_{a3})}{R_{a2}} \quad (30)$$

$$P_{a2} = \frac{1}{C_{a2}}(V_{a2} - V_{una2}) \quad (31)$$

Arterial section 3

$$\frac{dV_{a3}}{dt} = \frac{(P_{a2} - P_{a3})}{R_{a2}} - \frac{(P_{a3} - P_{v1})}{R_{a3}} \quad (32)$$

$$P_{a3} = \frac{1}{C_{a3}}(V_{a3} - V_{una3}) \quad (33)$$

where Q_{a1} is the flowarte of arterial section 1
R_{a1}, R_{a2}, R_{a3} are the viscoscity of arterial sections 1,2 and 3
C_{a1}, C_{a2}, C_{a3} are the elastic properties of arterial sections 1,2 and 3
L_{a1} is the inertial vessel properties of arterial section1
P_{a2}, P_{a3} are the pressure at arterial sections 2 and 3
V_{a1}, V_{a2}, V_{a3} are the volume of arterial sections 1, 2 and 3
V_{una1} is the volume of arterial section 1 at zero pressure
V_{una3} is the volume of arterial section 3 at zero pressure

Venous section 1

$$\frac{dV_{v1}}{dt} = \frac{(P_{a3} - P_{v1})}{R_{a3}} - \frac{(P_{v1} - P_{v2})}{R_{v1}} \quad (34)$$

$$P_{v1} = \frac{1}{C_{v1}}(V_{v1} - V_{unv1}) \quad (35)$$

Venous section 2

$$\frac{dQ_{v2}}{dt} = \frac{1}{L_{v2}}(P_{v2} - P_{ra}) - \frac{R_{v2}}{L_{v2}}Q_{v2} \quad (36)$$

$$\frac{dV_{v2}}{dt} = \frac{P_{v1} - P_{v2}}{R_{v1}} - Q_{v2} \quad (37)$$

$$P_{v2} = \frac{1}{C_{v2}}(V_{v2} - V_{unv2}) \quad (38)$$

where Q_{v2} is the flowarte of venous section 1
R_{v1}, R_{v2} are the viscoscity of venous sections 1 and 2
C_{v1}, C_{v2} are the elastic properties of venous sections 1 and 2
L_{v2} is the inertial vessel properties of venous section2
P_{v1}, P_{v2} are the pressure at venous sections 1 and 2
V_{v1}, V_{v2} are the volume of venous sections 1 and 2
V_{unv1} is the volume of venous section 1 at zero pressure
V_{unv2} is the volume of venous section 2 at zero pressure

F. Pulmonary Circulation

Arterial section 1

$$\frac{dQ_{p1}}{dt} = \frac{1}{L_{p1}}(P_{p1} - P_{p2}) - \frac{R_{p1}}{L_{p1}}Q_{p1} \quad (39)$$

$$\frac{dV_{p1}}{dt} = Q_{rv} - Q_{p1} \quad (40)$$

$$P_{p1} = \frac{1}{C_{p1}}(V_{p1} - V_{unp1}) \quad (41)$$

Arterial section 2

$$\frac{dV_{p2}}{dt} = Q_{p1} - \frac{(P_{p2} - P_{p3})}{R_{p2}} \quad (42)$$

$$P_{p2} = \frac{1}{C_{p2}}(V_{p2} - V_{unp2}) \quad (43)$$

Arterial section 3

$$\frac{dV_{p3}}{dt} = \frac{(P_{p2} - P_{p3})}{R_{a2}} - \frac{(P_{p3} - P_{l1})}{R_{a3}} \quad (44)$$

$$P_{a3} = \frac{1}{C_{p3}}(V_{p3} - V_{unp3}) \quad (45)$$

where Q_{p1} is the flowarte of pulmonary section 1
R_{p1}, R_{p2}, R_{p3} are the viscoscity of pulmonary sections 1,2 and 3
C_{p1}, C_{p2}, C_{p3} are the elastic properties of pulmonary sections 1,2 and 3
L_{p1} is the inertial vessel properties of pulmonary section1
P_{p2}, P_{p3} are the pressure at pulmonary sections 2 and 3
V_{p1}, V_{p2}, V_{p3} are the volume of pulmonary sections 1, 2 and 3
V_{unp1} is the volume of pulmonary section 1 at zero pressure
V_{unp3} is the volume of pulmonary section 3 at zero pressure

Venous section 1

$$\frac{dV_{l1}}{dt} = \frac{(P_{p3} - P_{l1})}{R_{p3}} - \frac{(P_{l1} - P_{l2})}{R_{l1}} \quad (46)$$

$$P_{l1} = \frac{1}{C_{l1}}(V_{l1} - V_{unl1}) \quad (47)$$

Venous section 2

$$\frac{dQ_{l2}}{dt} = \frac{1}{L_{l2}}(P_{l2} - P_{la}) - \frac{R_{l2}}{L_{l2}}Q_{l2} \quad (48)$$

$$\frac{dV_{l2}}{dt} = \frac{P_{l1} - P_{l2}}{R_{l1}} - Q_{l2} \quad (49)$$

$$P_{l2} = \frac{1}{C_{l2}}(V_{l2} - V_{unl2}) \quad (50)$$

where Q_{l2} is the flowarte of venous section 1
R_{l1}, R_{l2} are the viscoscity of venous sections 1 and 2
C_{l1}, C_{l2} are the elastic properties of venous sections 1 and 2
L_{l2} is the inertial vessel properties of venous section2
P_{l1}, P_{l2} are the pressure at venous sections 1 and 2
V_{l1}, V_{l2} are the volume of venous sections 1 and 2
V_{unl1} is the volume of venous section 1 at zero pressure
V_{unl2} is the volume of venous section 2 at zero pressure

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Figures

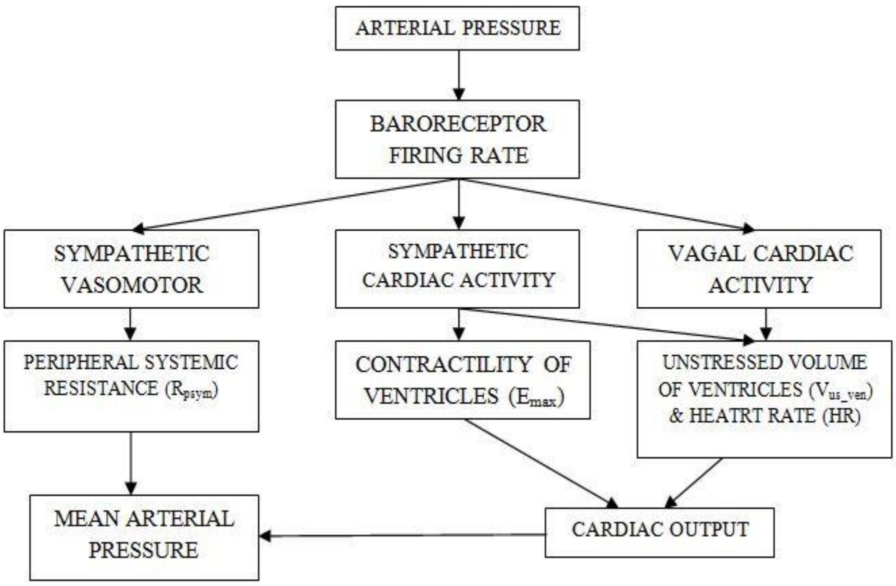

Fig. 1 Schematic representation of baroreceptor

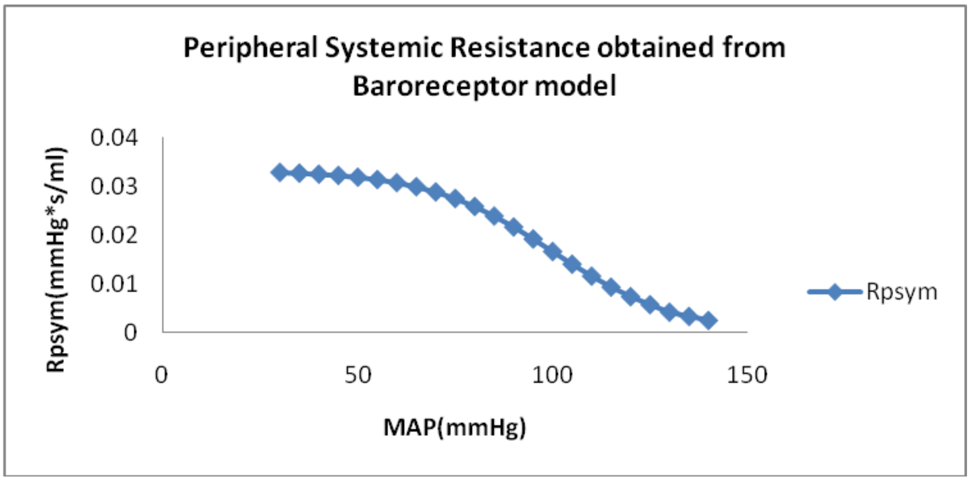

Fig. 2 R_{psym} values obtained from baroreceptor model for various MAP

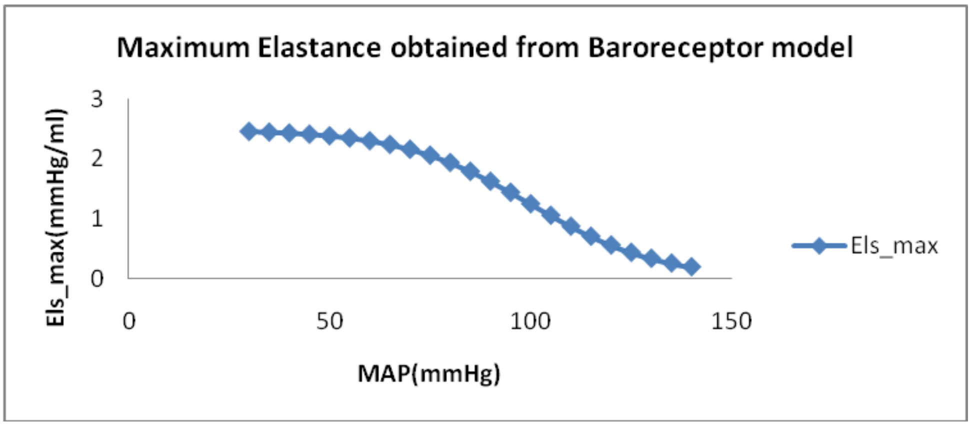

Fig. 3 Els_{max} values obtained from baroreceptor model for various MAP

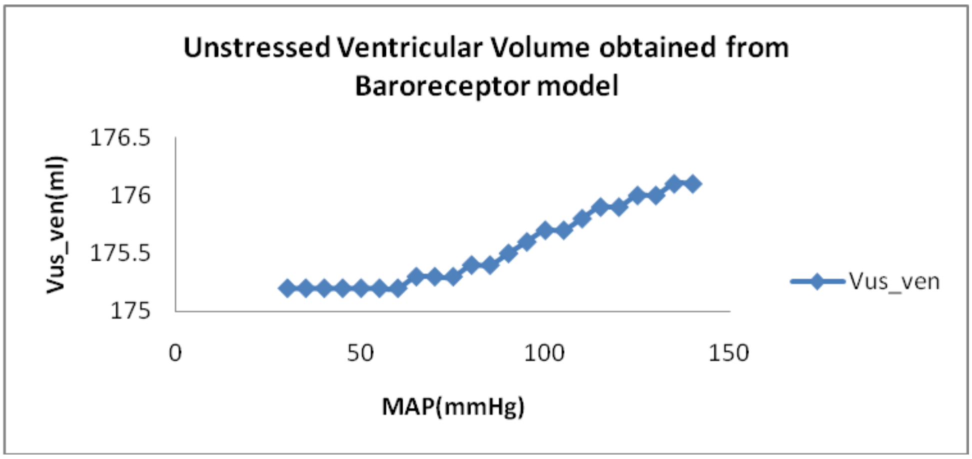

Fig. 4 V_{us_ven} values obtained from baroreceptor model for various MAP

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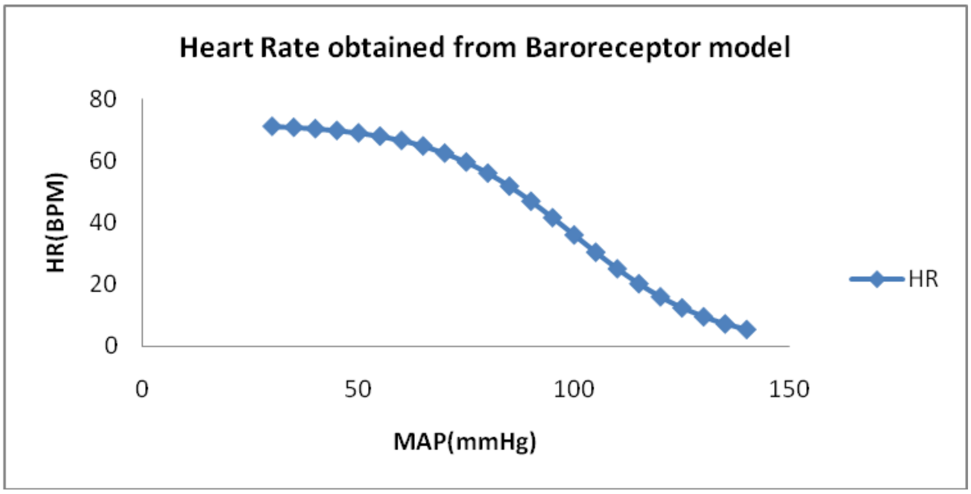

Fig. 5 HR values obtained from baroreceptor model for various MAP

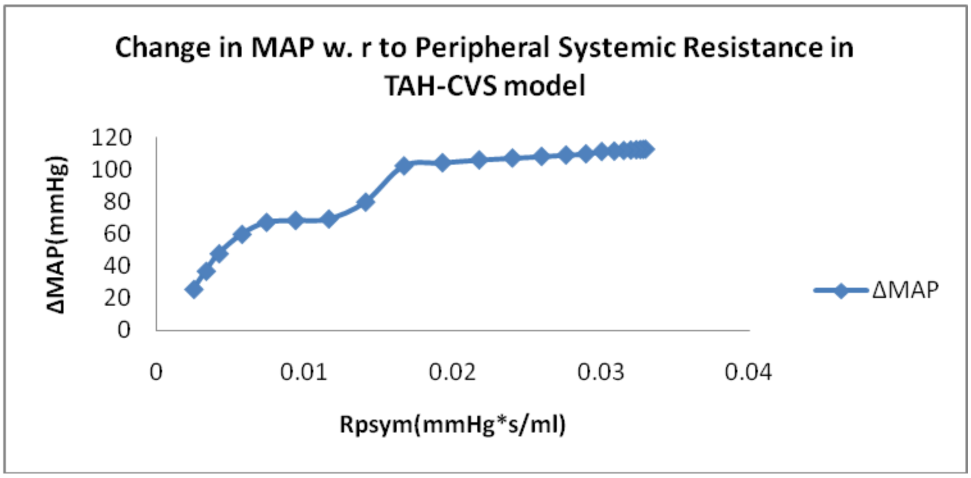

Fig. 6 ΔMAP values obtained for R_{psym} from baroreceptor model

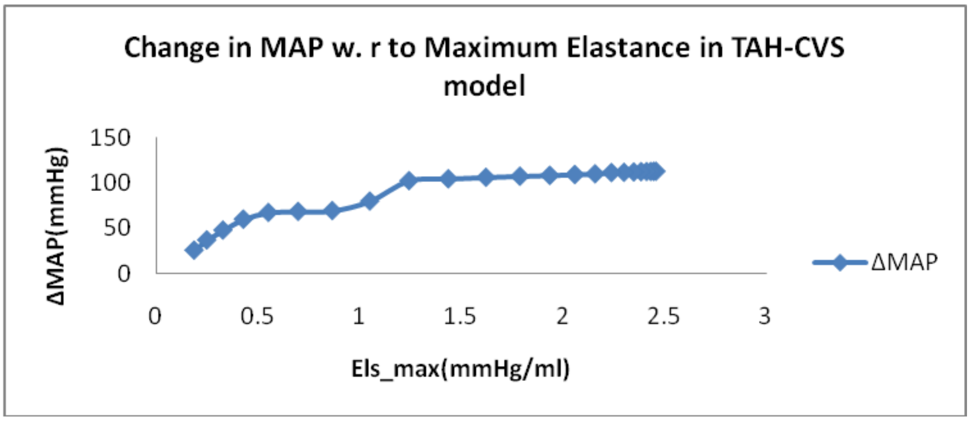

Fig. 7 ΔMAP values obtained for Els_{max} from baroreceptor model

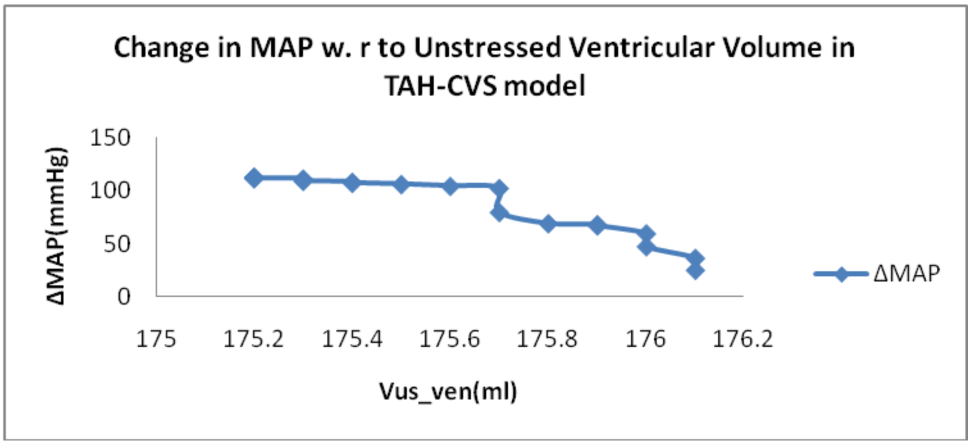

Fig. 8 ΔMAP values obtained for V_{us_ven} from baroreceptor model

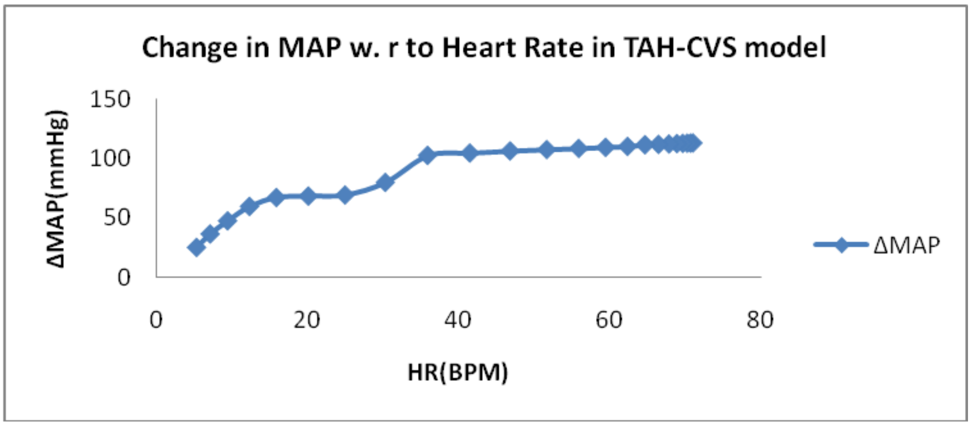

Fig. 9 ΔMAP values obtained for HR from baroreceptor model

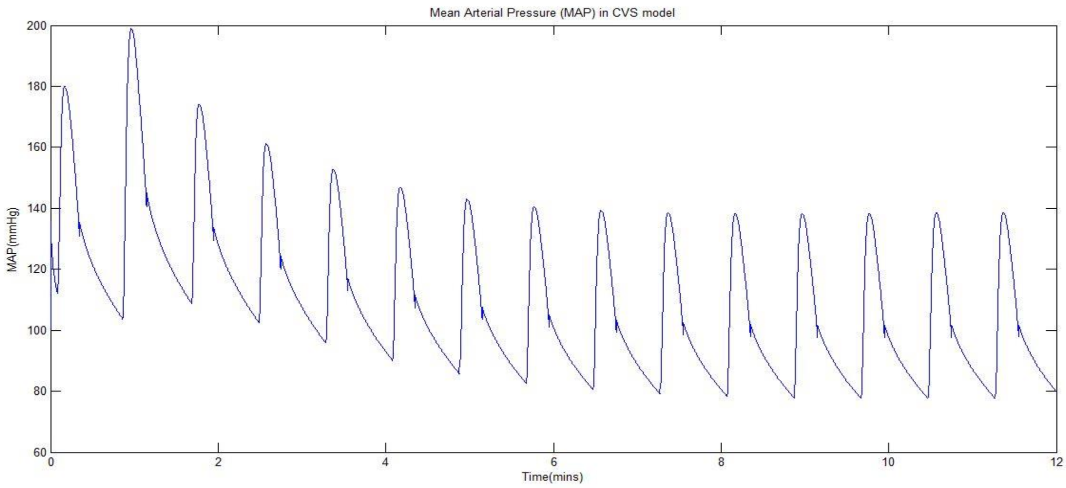

Fig. 10 Simulink result of MAP at initial condition of TAH-CVS model

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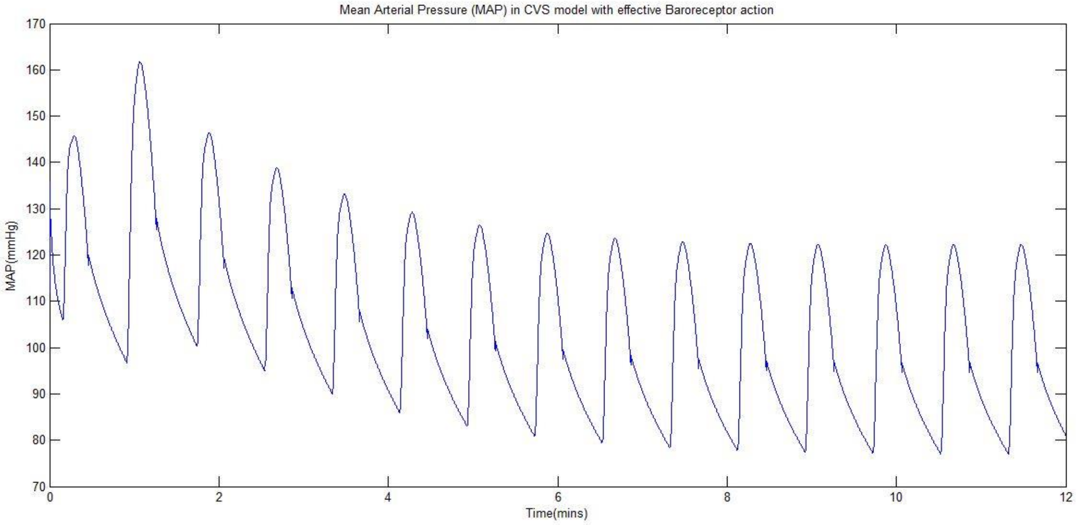

Fig. 11 Simulink result of MAP in TAH-CVS model by concurrent baroreflex action

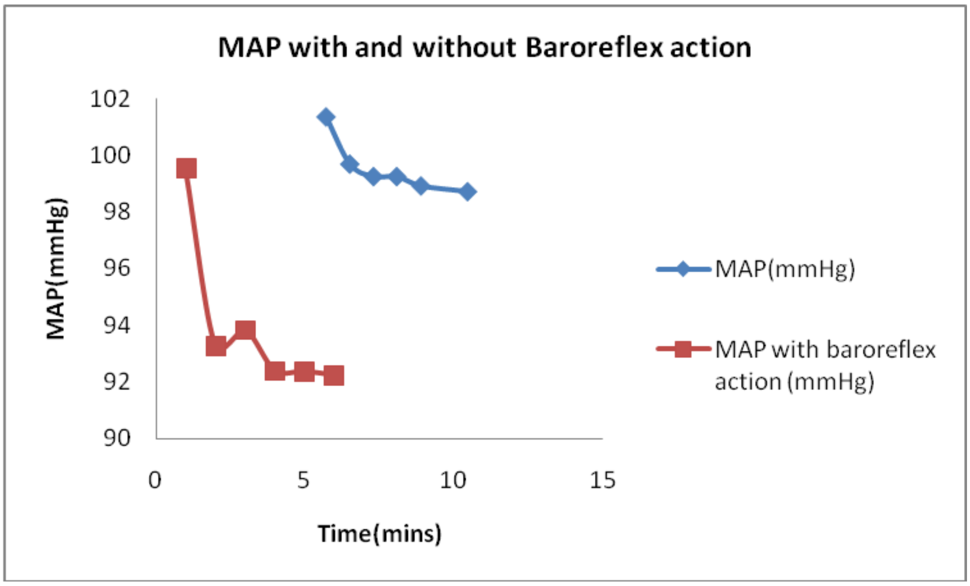

Fig. 12 Correlative analysis of MAP with and without baroreceptor in TAH-CVS model

Tables

Table I Nominal values of the circulatory system parameters

PARAMETERS	NOMINAL/BASE VALUES
α	**0.067**
MAP_{nom}	**100 mmHg**
$R_{psym_{base}}$	**0.0334 mmHg*s/ml**
$Els_{max_{base}}$	**2.49 mmHg**

$V_{us\_ven_{base}}$	175.549 ml
HR_{base}	72 BPM

Table II Circulatory system parameters obtained from baroreceptor model for MAP as input

PERIPHERAL SYSTEMIC RESISTANCE (R_{psym}) mmHg*s/ml	MAXIMUM ELASTANCE (Els_{max}) mmHg	UNSTRESSED VENTRICULAR VOLUME (V_{us_ven}) ml	HEART RATE (HR) BPM
0.03299	2.459	175.2	71.11
0.03284	2.448	175.2	70.79
0.03264	2.433	175.2	70.36
0.03237	2.413	175.2	69.77
0.032	2.386	175.2	68.99
0.03152	2.35	175.2	67.94
0.03088	2.302	175.2	66.56
0.03004	2.24	175.3	64.77
0.02897	2.16	175.3	62.46
0.02763	2.06	175.3	59.56
0.02598	1.937	175.4	56
0.02401	1.79	175.4	51.77
0.02177	1.623	175.5	46.92
0.01929	1.438	175.6	41.59
0.0167	1.245	175.7	36
0.01411	1.052	175.7	30.41
0.01163	0.8674	175.8	25.08
0.009386	0.6997	175.9	20.23
0.007423	0.5534	175.9	16
0.005772	0.4303	176	12.44
0.004426	0.33	176	9.541
0.003356	0.2502	176.1	7.234
0.002522	0.188	176.1	5.436

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