Abstract—Study of Arterial pressure and flow variation when external pressure applied is critical in understanding clinical relevance of pulse. A distributed model of entire human arterial tree proposed to describe the hemodynamic changes due to pressure applied on the brachial artery. Input to this distributed model is from a four element Windkessel model. The morphological changes in both the model with baroreflex, and the experiment were analyzed. It is observed that the pulse morphology changes with the applied pressure in both radial pressure pulse from the model and the finger volume pulse (PPG) from the experiment. The normalized values of pulse height, maximum systolic slope, maximum diastolic slope, and peak to peak interval (PPI) were calculated for each beat. The model with baroreflex parameters are positively correlated with the measured parameters (for maximum systolic slope $r = 0.98$; for maximum diastolic slope $r = 0.981$; for pulse height $r = 0.97$ when $P < 0.05$). The PPI variation is different for each subject reflecting the reflex properties of the individual. With the integration of baroreflex loop in the model, the experimental parameters are accurately predicted. The model of the baroreflex system considered only the Heart Rate variations. Variable elastance and reflex systrem with all parameters such as stroke volume, contractility, and peripheral resistance variation should be incorporated in the model in order to accurately predict the experimental results.

Index Terms—Cardiovascular modeling, transmission line model, Windkessel model, baroreflex control system, photoplethysmography, heart rate

INTRODUCTION

The mathematical models of cardiovascular system can improve diagnosis and treatment of heart diseases. The arterial pressure and flow pulse are important resources in the diagnosis of heart diseases. Various models have been proposed to simulate human systemic circulation [1]-[4]. Windkessel models, one of the lumped models, are widely used for such simulation [4]-[7]. Lumped models do not consider the effect of wave reflection and hence such models do not predict amplification, shape alteration in pressure and flow waveforms and variations in input impedance spectra of arterial tree [2],[10]. In order to overcome this limitation distributed parameter models based on transmission line theory were used [1], [2].

Vascular occlusion induces hemodynamic changes that allow for noninvasive, optical measurements of physiologically important parameters and also useful in designing non-invasive patient monitoring systems [7]. Though vascular occlusion experiments were reported well in the literature, no distributed model was reported for such study.

This work reports the response of electrical transmission line model of the human arterial system when an external pressure is applied on the upper arm brachial artery. Baroreflex control system has been added in our model based on [6], considering both mean pressure and pulsatility. Beat to beat fluctuations in heart rate due to the rise in mean aortic pressure has been studied. In order to validate our model, Photoplethysmography (PPG), which is a simple and low cost optical technique that can be used to detect blood volume changes in the microvascular bed, has been used [10]. The beat to beat morphological changes such as pulse height, systolic slope, diastolic slope and peak to peak interval in the model as well as in the finger PPG are studied.

METHODOLOGY

A. Aortic Pressure waveform duplication using a four element Windkessel model

Windkessel models describe the blood flow using closed electrical circuits. Four element Windkessel model includes inductance $L$ represents inertia of blood flow which is neglected in the two element and three element Windkessel models [4]. The 4-element model has been used as it describes the pressure and flow most accurately, better than the two and three element models. Aortic flow has been modeled as a current source in the Windkessel model. The aortic pressure is the voltage measured across the four elements. This pressure signal was used as input to the transmission line model.

B. Baroreflex Control system with Windkessel model

The baroreflex control of heart rate has been implemented based on [6]. The input to the baroreceptor element is the beat to beat mean value of the aortic pressure signal ($P_{ao}$) from the Windkessel model. The output ($N$) is instantaneous firing frequency of the baroreceptor. The input-output relationship is characterized using (1).

$$N(s) = \frac{K \times (1+0.036s)}{1+0.0018s(1+0.0018s)(1+0.036s)}$$

(1)

where $K$ is the gain (1.05) and $a$ is the time constant (0.001).

C. Electrical Transmission Line model

The similarity between the one dimensional Navier-Stokes equations of fluid dynamics and telegraph equations of the electromagnetic waves propagation has been long used in modeling arterial system [2].

Fluid dynamic system parameters such as fluid volume, pressure, flow, fluid inertia, hydraulic resistance, compliance
The morphological parameters such as maximum value, minimum value, maximum time, maximum of first derivative (maximum systolic slope) and minimum of first derivative (maximum diastolic slope) were observed in each beat of the finger PPG. Calculating the difference between maxima and minima of amplitude, the pulse height was found and then normalized it with corresponding values at zero cuff pressure. The peak to peak interval (PPI) was calculated from the time interval of successive peaks and normalized with zero pressure PPI. Due to rise in aortic pressure baroreflex control system will reduce the heart rate and also mean aortic pressure and then will bring back to original set point value as shown in Fig. 2.

Increase in cuff pressure raises mean aortic pressure which is modeled by varying the mean aortic pressure from 80 mmHg to 129 mmHg in 7 mmHg steps. This variation results in reduction of HR from 72 BPM to 40 BPM. Observed variations in pulsatile aortic pressure, radial pressure, mean arterial pressure and heart rate (Fig. 3).

The normalized parameters of both the model without baroreflex and the experiment were analyzed with paired student’s t-test indicating that all parameters except PPI are statistically significant and positively correlated with model parameters (mean normalized maximum systolic slope: r =
with experimental data. Though this is a simple relation, the results are matching corresponding increase in aortic pressure was assumed. One parameter could predict the others. Measuring the four parameters may be redundant and any reflex properties of the individual. Also, it is interesting to note that all the normalized parameters from the experiment follow the same trend. This means that measuring the four parameters may be redundant and any one parameter could predict the others.

A linear relation between external pressure and corresponding increase in aortic pressure was assumed. Though this is a simple relation, the results are matching with experimental data.

**V. Conclusion**

Instead of lumped model, distributed model of entire human arterial tree with and without baroreflex system was used for simulating the externally applied cuff pressure in upper arm. The variation of pulse height, PPI and slope was analyzed for the model and experiment. The model with baroreflex predicts the experimental parameters closely, however with little mismatch. While the elastance in the experiment varies with pressure, in the model it is constant and might be a reason for the mismatch. With the reflex and elastance changes incorporated in the model, its clinical relevance can be studied for different diseased conditions. In the current baroreflex model, only the HR variation was considered. However, completely occluding the brachial artery, total volume pumped by heart reduces and hence stroke volume reduces. Therefore stroke volume variation, contractility and peripheral resistance variation should be considered for retaining the shape of the aortic and peripheral pulse to fit the model accurately with the experimental value. Although rapid and dynamic physiological functions, such as breathing, importantly affect baroreflex function, other influences such as aging and physical reconditioning must be recognized when interpreting changes in baroreflex function and cardiovascular variability.

**IV. Discussion**

The results from the model with baroreflex as shown in Fig.4 indicate that maximum slope, minimum slope and PPI, all normalized, slightly rises with external pressure until 20mmHg, while the normalized pulse height monotonically decreases. However the initial rise in the parameters is closer to the experimental parameters compared to that of model without baroreflex. It was observed that all the parameters were predicted closer to the experimental values in the model with baroreflex.

Only the radial artery pressure was evaluated in the model, while in the experiment digital volume pulse was evaluated. The derivative of arterial pressure is directly proportional to that of the arterial volume with the elastance as the proportionality constant. While the model elastance does not change, in the external cuff experiment the elastance does not remain constant. This could be one of the reasons for the discrepancy between the model and experiment.

It was observed that volume pulse starts to disappear and becomes irregular for all the subjects above 100mmHg. The PPI variation graph is different for each subject reflecting the reflex properties of the individual. Also, it is interesting to note that all the normalized parameters from the experiment follow the same trend. This means that measuring the four parameters may be redundant and any one parameter could predict the others.

**References**