Original Research Article

# A phantom study on the influence of viscosity of blood, percentage diameter stenosis, length of stenosis and cross-sectional area of blood vessel on blood flow dynamics in peripheral (brachial and femoral) artery models using Doppler ultrasound spectral analysis

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## Abstract

**Objectives:** To study the influence of viscosity of blood, percentage diameter stenosis, length of stenosis and cross-sectional area of blood vessel on blood flow dynamics in peripheral (brachial and femoral) artery models using Doppler ultrasound spectral analysis. **Methods/Analysis:** An experimental study was carried out using an indigenously fabricated Doppler ultrasound compatible blood flow phantom. Doppler frequency spectral analysis was the method used for the study. To study the influence of various factors on blood flow dynamics, brachial and femoral artery models with 25%, 50%, 75% diameter stenosis of 5mm, 10mm lengths and 2cP, 3cP, 4cP viscosity blood mimicking fluids (BMF) were used. To study the influence of the parameters, the change in ratios of Pre and Post stenotic Peak Systolic Velocities (PSV ratio) obtained with respect to change in the parameter were assessed. **Findings:** The magnitude and pattern of change in the PSV ratio with respect to pre-destined values of viscosity, percentage diameter stenosis, length of stenosis and cross-sectional area of the blood vessel were analysed. **Novelty:** As the analysis of flow dynamics under such conditions of variability cannot be exercised clinically (as a patient-based study), a model-based experimental study was performed with a cost-effective indigenously fabricated Doppler ultrasound blood flow phantom.

**Key Words:** Blood flow dynamics, Blood viscosity, Doppler spectral analysis, Length of stenosis, Percentage diameter stenosis, Peripheral artery models.

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Received Date: 04/09/2017 Revised Date: 14/10/2017 Accepted Date: 18/11/2017
DOI: https://doi.org/10.26611/2026211

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## INTRODUCTION

Vascular resistance is one of the major factors influencing blood flow dynamics. The vascular resistance mainly depends on the cross-sectional area of blood vessel, blood viscosity and length of the blood vessel. Blood viscosity is the inherent resistance of blood to flow. An important factor which determines the blood flow dynamics is blood viscosity as it is the only biological parameter that has been correlated with all of the major cardiovascular risk factors[2]. A normal human's whole blood viscosity is around 3 centipoise[3,4]. Due to aging or under certain

How to cite this article: Sudha Pattan, Santhosh Joseph, Venkata Sai P M, Aruna P, Ravishankar P. A phantom study on the influence of viscosity of blood, percentage diameter stenosis, length of stenosis and cross-sectional area of blood vessel on blood flow dynamics in peripheral (brachial and femoral) artery models using Doppler ultrasound spectral analysis. *International Journal of Recent Trends in Science and Technology*. February to April 2018; 26(2): 72-78. http://www.statperson.com

diseased conditions or under certain medications, blood viscosity may become lesser or greater than the normal value and this change may lead to changes in blood flow dynamics. The cross-sectional area ($\pi D^2/4$) of blood vessel is directly proportional to blood flow capacity and has the potential to modify blood flow dynamics. Blood flow capacity within two vessels of diameter $D_1$ and $D_2$ can be compared using a ratio of their diameter squared. $[(D_2)^2 : (D_1)^2]$ Arterial stenosis is narrowing or constriction of lumen of the artery, usually caused by atherosclerosis. Two facets of stenosis are percentage diameter stenosis and length of stenosis. Out of the peripheral arteries, femoral artery is a common site for narrowing or obstruction that occurs as a result of the atherosclerotic process. The atherosclerotic stenosis in peripheral arteries may lead to peripheral artery diseases (PAD) which will affect the normal blood flow pattern and thereby reduce flow of blood to the corresponding parts. The peripheral artery diseases may be asymptomatic or symptomatic, but when there is occlusion they have proved to show close relationship with increased risk of coronary heart disease, heart attack, stroke and transient ischemic attack (mini stroke). Apart from imaging the sections of patient's body and helping in taking accurate measurements of structures within, ultrasound is also being used for performing blood flow studies using the Doppler Effect. Doppler spectral analysis is a quantitative method which shows the distribution of Doppler frequency signals within the operator selected sample volume of the blood vessel over a period of time and hence is useful to do blood flow studies.

## MATERIALS AND METHODS

Doppler ultrasound machine - GE logic P5, linear array ultrasound probe of 12 MHz frequency, instead of patients / volunteers a Doppler ultrasound compatible blood flow phantom which induces pulsatile flow of blood mimicking fluid within brachial and femoral artery models presented with various percentage diameter stenotic conditions and lengths of stenosis kept embedded in tissue equivalent material[1]. The average inner diameters (ID) of brachial artery and femoral artery of normal healthy young adults were found to be around 4mm and 8mm respectively[1]. Ultrasound compatible blood vessel equivalent tubes with these specifications were used for the study[1]. The analysis of blood flow is done by Doppler spectrum. The spectral display is obtained using Fast Fourier Transformation (FFT) analyser which gets the distribution of Doppler frequency signals within the operator selected sample volume and in turn shows the velocity of blood flow. In this study the influence of parameters such as viscosity of blood ($\eta 1$ = 2 cP, $\eta 2$ = 3 cP and $\eta 3$ = 4 cP), percentage diameter stenosis (25%, 50% and 75% - symmetrical), length of stenosis (5mm and 10mm), and cross-sectional area of blood vessel (12.57 $mm^2$ for 4mm ID brachial artery and 50.29 $mm^2$ for 8mm ID femoral artery) on blood flow dynamics in brachial artery models and femoral artery models were analysed by varying only the influential parameter under study and keeping all other factors constant. The analysis of blood flow dynamics under such conditions of variability cannot be exercised clinically (as a patient-based study), hence a model-based experimental study was performed with a cost-effective indigenously fabricated Doppler ultrasound blood flow phantom[1]. Ultrasound scanner is initially operated in B-scan mode to image the vessel model. The Doppler ultrasound spectral display was activated by switching over to Pulsed Doppler mode in ultrasound scanner. The sample volume (SV of 1mm) is set at a location within the vessel before the simulated stenosed region. The Peak Systolic Velocities (PSV) of the Doppler Spectrum at the pre-stenotic region and also at the post-stenotic region of the blood vessel model noted. The same is repeated by using various other simulated conditions. The ratio of Post-stenotic PSV to Pre-stenotic PSV known as PSV ratio is calculated [Table - 1 and Table - 2]. The PSV ratio denotes the change in the flow dynamics due to the influence of the parameter under analysis. PSV ratio is taken into consideration rather than absolute PSV as there is a greater correlation observed between PSV ratio and stenosis than between absolute PSV and stenosis[4]. The various pre-destined flow conditions were carried out and the influences of each parameter on the blood flow dynamics were analysed.

## OBSERVATIONS AND RESULTS

Doppler Spectral analysis and flow data acquired using brachial and femoral artery models:

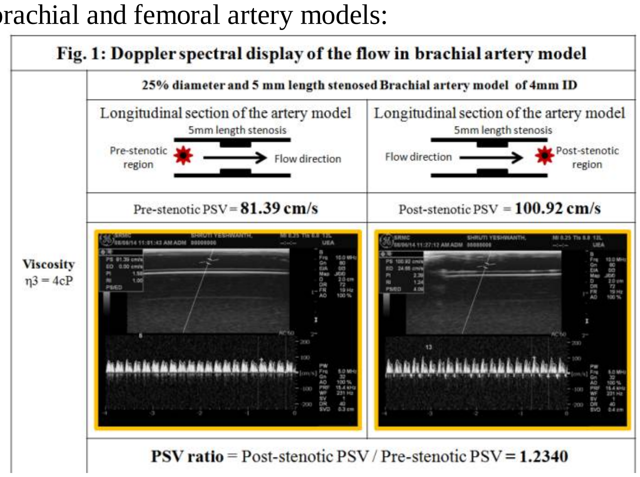


**Figure 1:**

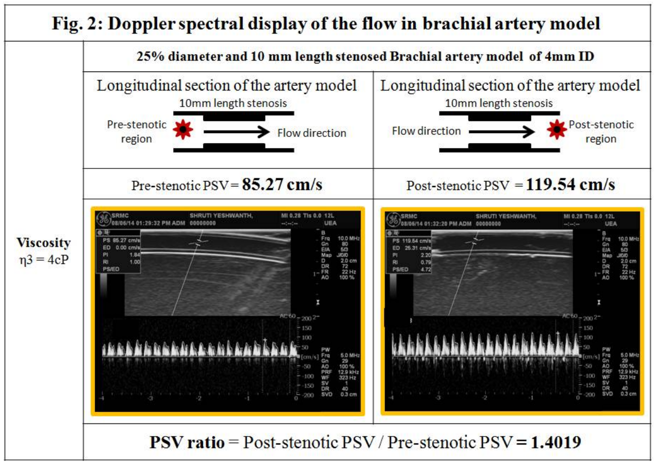


Figure 2:

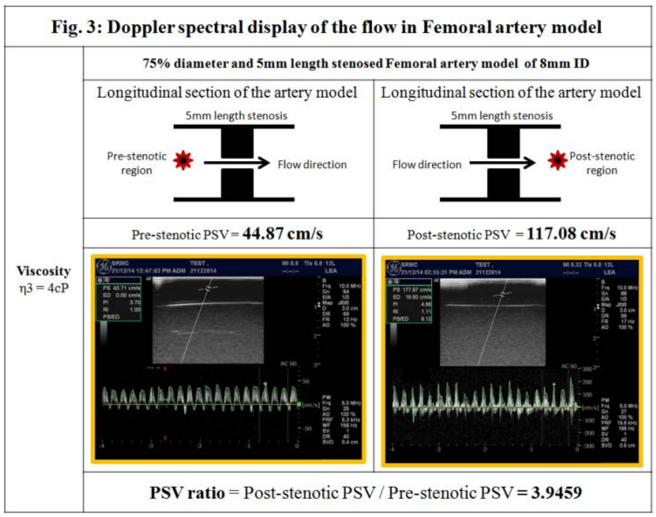


Figure 3:

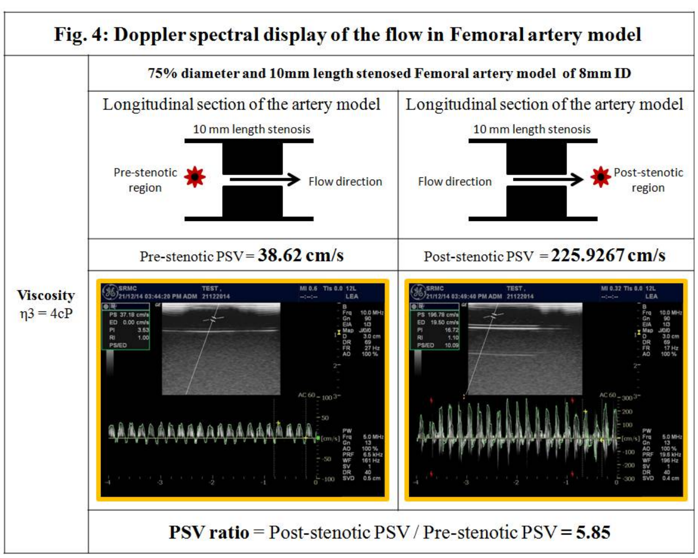


Figure 4:

**Table 1:** Flow data of Brachial Artery model

| Viscosity of BMF (cP) | Length of Stenosis (mm) | % Diameter Stenosis | PSV ratio |
|---|---|---|---|
| $\eta_1 = 2$ | 5 | 25 | 1.1956 |
| | | 50 | 1.5792 |
| | | 75 | 1.7743 |
| | 10 | 25 | 1.3032 |
| | | 50 | 1.3744 |
| | | 75 | 1.9564 |
| $\eta_2 = 3$ | 5 | 25 | 1.2085 |
| | | 50 | 1.5843 |
| | | 75 | 2.0716 |
| | 10 | 25 | 1.3686 |
| | | 50 | 1.5501 |
| | | 75 | 2.3353 |
| $\eta_3 = 4$ | 5 | 25 | 1.2340 |
| | | 50 | 1.7374 |
| | | 75 | 2.6245 |
| | 10 | 25 | 1.4019 |
| | | 50 | 1.7328 |
| | | 75 | 2.4859 |

BMF – Blood Mimicking Fluid, cP – centipoise, PSV – Peak Systolic Velocity

**Table 2:** Flow data of Femoral Artery model

| Viscosity of BMF (cP) | Length of Stenosis (mm) | % Diameter Stenosis | PSV ratio |
|---|---|---|---|
| $\eta_1 = 2$ | 5 | 25 | 1.1300 |
| | | 50 | 1.2776 |
| | | 75 | 2.6887 |
| | 10 | 25 | 1.0361 |
| | | 50 | 1.4559 |
| | | 75 | 2.8014 |
| $\eta_2 = 3$ | 5 | 25 | 1.1367 |
| | | 50 | 1.9790 |
| | | 75 | 3.9459 |
| | 10 | 25 | 1.0996 |
| | | 50 | 1.5031 |
| | | 75 | 4.7863 |
| $\eta_3 = 4$ | 5 | 25 | 1.1790 |
| | | 50 | 2.2289 |
| | | 75 | 5.3239 |
| | 10 | 25 | 1.1025 |
| | | 50 | 2.3566 |
| | | 75 | 5.8500 |

BMF – Blood Mimicking Fluid, cP – centipoise, PSV – Peak Systolic Velocity

## INTERPRETATION AND DISCUSSION:

### BRACHIAL ARTERY MODEL - 5mm length of stenosis

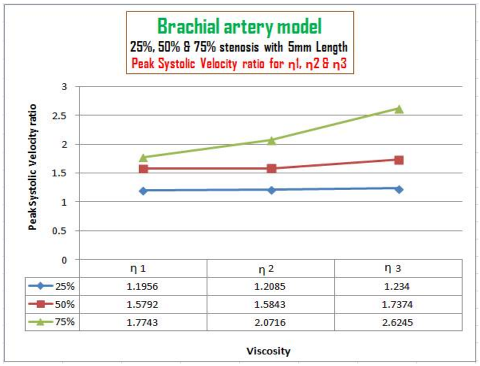


**Figure 5:** PSV ratio with respect to the variation in viscosity in Brachial artery models with stenosis of 5mm length having 25%, 50% and 75% diameter stenosis

### BRACHIAL ARTERY MODEL - 10mm length of stenosis

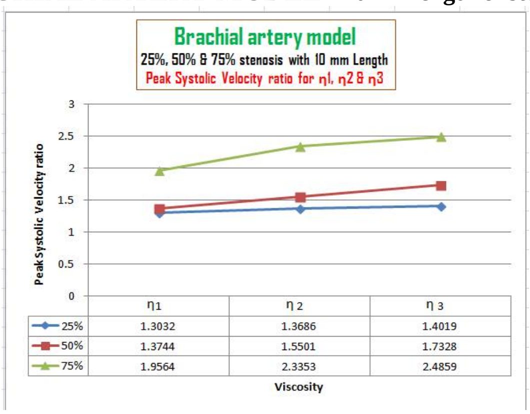


**Figure 6:** PSV ratio with respect to the variation in viscosity in Brachial artery models with stenosis of 10mm length having 25%, 50% and 75% diameter stenosis

### FEMORAL ARTERY MODEL - 5mm length of stenosis

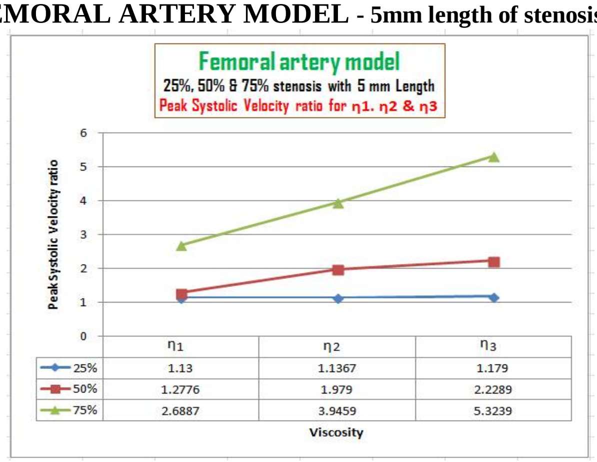


**Figure 7:** PSV ratio with respect to the variation in viscosity in Femoral artery models with stenosis of 5mm length having 25%, 50% and 75% diameter stenosis

### FEMORAL ARTERY MODEL - 10mm length of stenosis

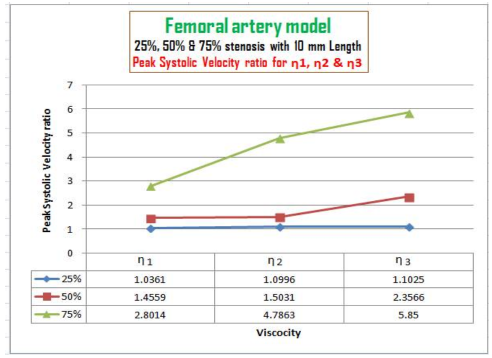


**Figure 8:** PSV ratio with respect to the variation in viscosity in Femoral artery models with stenosis of 10mm length having 25%, 50% and 75% diameter stenosis

### BRACHIAL ARTERY MODEL - 5mm length of stenosis

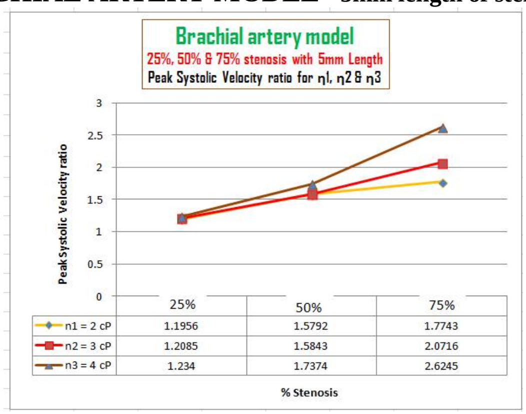


**Figure 9:** PSV ratio with respect to the percentage diameter stenosis in Brachial artery model with 5mm length of stenosis for various blood mimic viscosities

### BRACHIAL ARTERY MODEL - 10mm length of stenosis

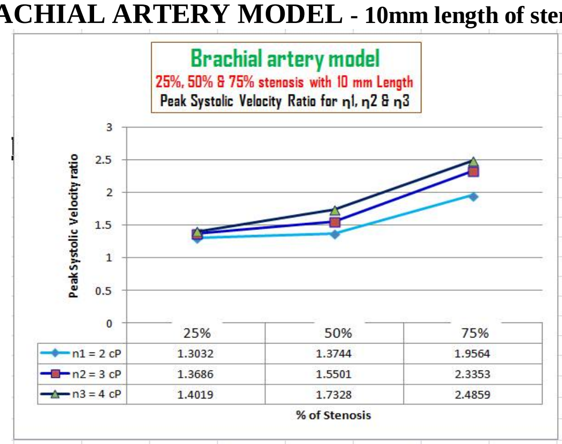


**Figure 10:** PSV ratio with respect to the percentage diameter stenosis in Brachial artery model with 10mm length of stenosis for various blood mimic viscosities

**FEMORAL ARTERY MODEL - 5mm length of stenosis**

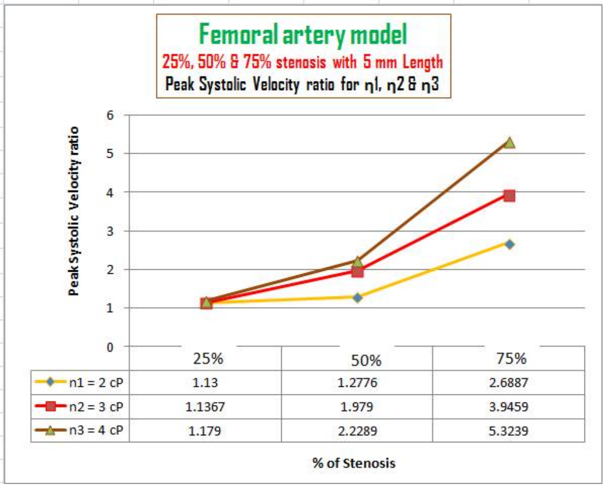


**Figure 11:** PSV ratio with respect to the percentage diameter stenosis in Femoral artery model with 5mm length of stenosis for various blood mimic viscosities

**FEMORAL ARTERY MODEL - 10mm length of stenosis**

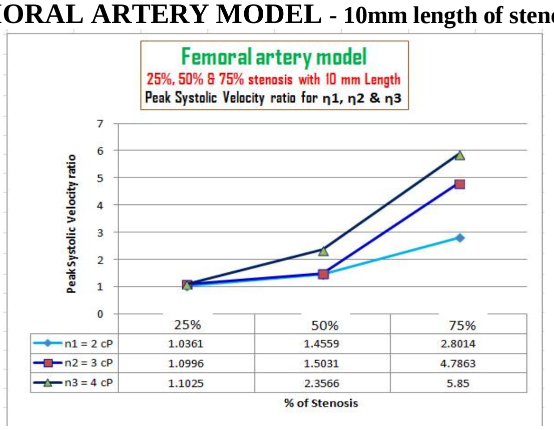


**Figure 12:** PSV ratio with respect to the percentage diameter stenosis in Femoral artery model with 10mm length of stenosis for various blood mimic viscosities

**Influence of Viscosity of BMF:** With variation in viscosity of the blood mimic, the PSV ratio of pre-and post-stenotic regions under various simulated conditions (Figures 5, 6, 7 and 8) are as follows. With increased viscosity of the blood mimic, for both 5mm and 10mm lengths of stenosis,

- Under 25% diameter stenotic conditions in the Brachial artery and Femoral artery models, there is trivial increase in PSV ratio of pre-and post-stenotic regions.
- Under 50% diameter stenotic conditions in the Brachial artery and Femoral artery models, there is notable and gradual increase in PSV ratio of pre-and post-stenotic regions.
- Under 75% diameter stenotic conditions in Brachial artery and Femoral artery models, there is significant increase in PSV ratio of pre-and post-stenotic regions.

With increased viscosity condition, the higher percentage diameter stenosis seems to show increased variation in PSV ratio.

**Influence of Percentage diameter Stenosis:** With the variation in percentage diameter stenosis, there will be a variation in the cross-sectional area of the lumen. This variation affects the flow capacity and hence percentage diameter stenosis is expected to be a more prominent factor to significantly change the flow pattern.

**Table 3:** Flow capacity variation due to percentage diameter stenosis in Brachial artery model

| BRACHIAL ARTERY MODEL | | | | |
|---|---|---|---|---|
| **% Diameter stenosis** | **0%** | **25%** | **50%** | **75%** |
| Diameter of the vessel (mm) | 4 | 3 | 2 | 1 |
| Cross-sectional area $(mm^2) = \pi D^2/4$ | 12.57 | 7.07 | 3.14 | 0.786 |
| Relative Flow capacity to 0% stenosis - $(D_2)^2$: $(D_1)^2$ | - | $4^2:3^2$ 1.78 times lesser | $4^2:2^2$ 4 times lesser | $4^2:1^2$ 16 times lesser |

**Table 4:** Flow capacity variation due to percentage diameter stenosis in Femoral artery model

| FEMORAL ARTERY MODEL | | | | |
|---|---|---|---|---|
| **% Diameter stenosis** | **0%** | **25%** | **50%** | **75%** |
| Diameter of the vessel (mm) | 8 | 6 | 4 | 2 |
| Cross-sectional area $(mm^2)$ | 50.29 | 28.29 | 12.57 | 3.14 |
| Relative Flow capacity to 0% stenosis - $(D_2)^2$: $(D_1)^2$ | - | $8^2:6^2$ 1.78 times lesser | $8^2:4^2$ 4 times lesser | $8^2:2^2$ 16 times lesser |

With increased percentage of stenosis, under constant viscosity flow in the Brachial artery and Femoral artery models, there is significant and also steep increase in PSV ratio which makes the curve look like a top-opening parabola (Figures 9, 10, 11 and 12), for which the equation being $y = mx^2 + b$. This suggests of uniform acceleration. This shows when there is more increase in percentage diameter stenosis (as high as 75%), the flow gets accelerated.

**Influence of length of stenosis:** For both 5mm length stenosed Brachial and Femoral arteries, with increased viscosity and for 75% diameter stenotic conditions, there is a steep increase in PSV ratio which makes the curve look like a top-opening parabola, for which the equation being y

$= mx^2 + b$ (Figures 5 and 7). This suggests of uniform acceleration. This shows when the high viscous flow is through 75% stenosis of lesser length (as less as 5mm), the flow get accelerated. Whereas, for both 10mm length stenosed Brachial and Femoral arteries, with increased viscosity and for 75% diameter stenotic conditions, there is a steep decrease in PSV ratio which makes the curve look like a side-opening parabola for which the equation being $y^2 = mx + b$ (Figures 6 and 8). This suggests of uniform retardation. This shows when the high viscous flow is through 75% stenosis of more length (as high as 10mm), the flow gets retarded.

**Influence of cross-sectional area of the blood vessel**

**Table 5:** Range of PSV ratio with respect to cross-sectional area of the blood vessel (from Tables 1 and 2)

| Artery model | Range of PSV ratio under various simulated conditions | | |
|---|---|---|---|
| | 25% diameter stenosis | 50% diameter stenosis | 75% diameter stenosis |
| Brachial artery model | 1.1956 to 1.4019 | 1.3744 to 1.7374 | 1.7743 to 2.6245 |
| Femoral artery model | 1.0361 to 1.179 | 1.2776 to 2.3566 | 2.6887 to 5.85 |

Brachial artery model with a cross-sectional area of $12.57mm^2$ showed notable variation in flow dynamics under lesser percentage of stenotic conditions itself but Femoral artery model with a cross-sectional area of $50.29mm^2$ showed good variation in flow dynamics only under higher percentage of stenotic conditions. This shows that to make significant variation in flow dynamics, the percentage of stenosis has to be comparable with the size of the vessel. In Brachial artery models, there is a gradual and less steep increase in PSV ratio with respect to % diameter stenosis. Whereas, in Femoral artery models, more steep increase in PSV ratio noted with respect to % diameter stenosis. This shows that with increased cross-sectional area, the flow gets more accelerated.

## CONCLUSION

The experimental study using the Doppler blood flow phantom shows the strong impact of viscosity of blood, stenotic conditions and cross-sectional area of the blood vessel on flow dynamics. Various studies have been published to prove the potential role of whole blood viscosity in haemodynamics and to support the need for the assessment of Whole blood viscosity in order to rule out various blood flow related diseased conditions[10,11]. In a study done by Ajmani RS *et al*, whole blood viscosity measurement with respect to aging and age-related diseases was discussed[2]. In spite of these, the measurement of whole blood viscosity of patients is still not a common practice in clinical laboratories. This study suggests that the measurement of whole human blood viscosity of the patients also shall be carried out along with other routine blood tests as this will prove to be a predictor or an indicator of blood flow related ailment in patients. The study also suggests that the peripheral artery diseases especially the stenotic conditions shall be noted as a sign of alarm for the upcoming serious morbidity and hence appropriate step has to be taken to avoid or manage the severity of the consequential problem.

## ACKNOWLEDGEMENT

We thank **Shri V.R.Venkataachalam**, the Chancellor of Sri Ramachandra Medical College & Research Institute for extending support by granting funds for the fabrication work of Doppler ultrasound compatible blood flow phantom under Young Faculty Research Starter grants – GATE projects to promote such research projects and for providing necessary facility and resources to accomplish my project. We express our sincere thanks to **Dr.K.V.Somasundaram**, the Dean of faculties and **Dr.S.P.Thyagarajan**, Professor of Eminence and Dean (Research), Central Research facility, SRU for all the motivation, support, help and encouragement. We sincerely thank **Dr.K.Thayalan**, Consultant Medical Physicist, Dr.Kamakshi Memorial Hospital for his inspiring guidance, motivation and constant encouragement towards this work.

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Source of Support: None Declared
Conflict of Interest: None Declared