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Influence of localized skin level temperature on blood velocity in peripheral artery

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Abstract

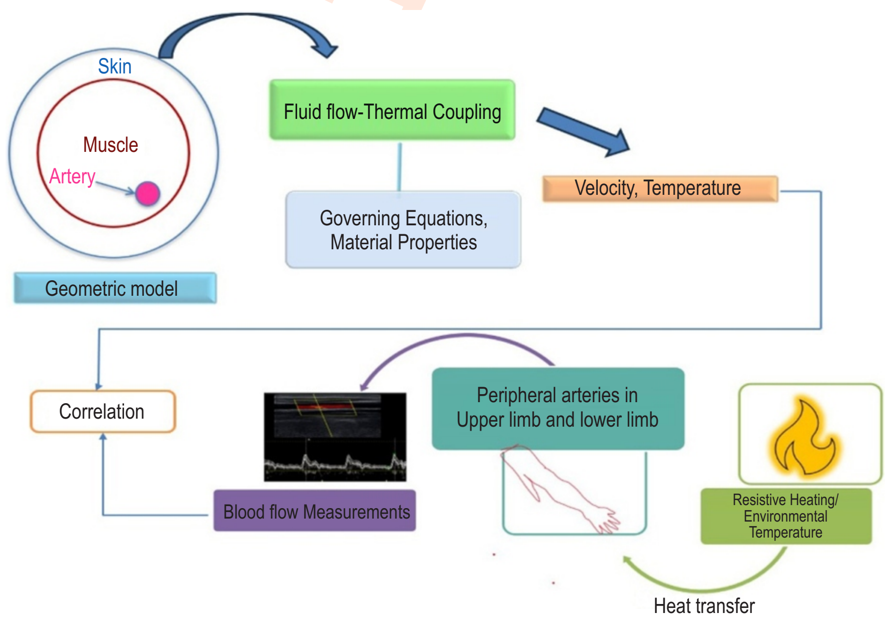
Aim: To study the influence of skin temperature on peripheral arteries, with increase in the surrounding temperature.

Methodology: The experiment was carried out by increasing the room temperature through resistive heaters, and the velocity of blood in peripheral arteries, like brachial, radial, and tibial, was measured through ultrasound technique. Among these three, the response of the brachial artery was higher. Therefore, the inverse response of brachial artery was studied by finding the effect of a change in the blood velocity on skin temperature. For this, the upper arm with brachial artery was numerically modelled with fluid and thermal properties. To create a change in blood velocity, a block of two different sizes were introduced in the brachial artery, which resulted in three models, one being normal and the other two with stenosis.

Results: When executed in COMSOL Multiphysics with suitable boundary and initial conditions, the result showed that the velocity of blood increased by 30% with stenosis, which in turn increased the surface temperature to 2°C, as equivalent to the outcome of the thermal study.

Interpretation: This observation clearly proves the mutual effect of surrounding temperature with time of exposure and velocity in brachial artery. Hence, temperature distribution on the upper arm becomes an additional parameter during any medical procedure.

Key words: Brachial artery, Fluid-thermal Coupling, Thermographic imaging



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Introduction

Blood is a fluid tissue responsible for carrying nutrients to all parts of the body by flowing through vessels like arteries, veins, and microcapillaries. It also eliminates the metabolic waste like carbon dioxide, urea, and other toxic nitrogenous waste produced by the cell through the lungs and kidneys, thereby maintaining the homeostasis of the body. Its flow at the correct rate and volume is essential for maintaining coordination and energy in the muscular and nervous systems. Various physiological factors influence the blood flow velocity such as heart rate, viscosity, stenosis, and thermoregulation. Higher concentration of red blood cells (RBC) increases the blood viscosity, which in turn causes a decrease in the blood flow velocity due to vascular resistance. Any change in the hemodynamic parameter could be a sign of diseases like such as atherosclerosis, thrombosis and aneurysms, and hence its prediction becomes important. Peripheral blood vessels like the brachial artery (BA), radial artery (RA), and tibial artery (TA) are a few of the major blood vessels that are responsible for circulating blood in the arms and limbs (Chakravarthi *et al.,* 2014).

The blood flow is also responsible for maintaining thermoregulation, like radiating out the core body temperature (Kenney *et al.,* 1993). Blood flow in the peripheral arteries (Pas) generates thermal waves that propagate towards the skin surface, facilitating heat transfer from the subcutaneous region. The magnitude of this temperature is directly dependent on the blood flow velocity (Jorge *et al.,* 2021). In addition, the peripheral thermal sensors located on the skin surface are responsible for both sensing the outer temperature and dissipating heat based on the instruction of central thermoregulation mechanism primarily governed by the brain with feedback from thermoreceptors in the thoracic and abdominal regions.(Kuht *et al.,* 2018; Charkoudian, 2003). Thus, blood velocity is influenced by the pathway in the artery and environmental temperature. The effect of one is felt on the other; as these two are mutually influenced (Liu *et al.,* 2007). When the external temperature rises, the thermal receptors in the skin send signals to the hypothalamus thermoregulatory center. In response to this, the hypothalamus activates cholinergic nerves to release acetylcholine (ACh). This ACh acts on muscarinic receptors in blood vessels to release nitric oxide (NO). The NO diffuses into the vascular smooth muscle and causes relaxation of the vascular wall. This further increases both blood flow volume and velocity (Vuksanović *et al.,* 2008).

Though this phenomenon happens in all the arteries, brachial artery, radial artery and tibial artery come in direct exposure to the atmosphere, as they are present in the arms and limbs. Especially, the brachial artery is one of the major peripheral arteries that carry blood to the arm and hand from the aorta valve (Coombs *et al.,* 2021). It is also a common site of investigation before carrying out any medical procedure where two vital parameters are typically measured: blood pressure and core body temperature. Radio-frequency techniques are used to determine the relationship between blood flow and skin temperature by carefully capturing energy from the perfused layers of the skin (Robles *et al.,* 2025). The vice versa is also true; the outer skin temperature can alter the blood flow perfusion (Larson *et al.,* 2021). Video capillaroscopy is a technique that measures the velocity of blood, particularly RBCs in the capillaries, based on vasoconstriction and vasodilation effects. It enables quantification of capillary morphology with high-resolution visualization and utilizes powerful machine learning tools and image processing algorithms for precise assessment of real time blood flow changes. This technique, when performed in the nail fold helps in the diagnosis and monitoring of scleroderma (Gurov *et al.,* 2018). Infrared thermography measures the infrared radiation emitted from the skin surface, providing a noninvasive assessment of skin temperature (Herrick *et al.,* 2018). Several techniques based on optics, thermocouples, portable heat stimulated blood flow measuring instruments are under research to map skin temperature to blood flow (Chaseling *et al.,* 2020).

Currently, the blood flow parameters are measured using techniques such as ultrasound, computed tomography, and magnetic resonance imaging. Although these methods are clinically used, they are limited by accessibility, cost, and invasiveness. With advancements in simulation-based medical research, computational tools now offer powerful alternatives for studying and analyzing complex physiological phenomena. Blood flow in the artery produces small physical changes in the associated tissues, such as muscles and skin (Liu *et al.,* 2007). Since these changes are very small, in the order of micro- or nanometers, capturing skin-level electrical and thermal changes (Jamali *et al.,* 2019) caused by blood flow in normal and clogged arteries could be a possible solution for the identification of plaque in the artery. Saxena *et al.* (2020) used numerical modelling to compute the temperature distribution on the skin due to stenosis in the carotid artery and found a variation of 0.82°C in the neck among healthy subjects and those with carotid stenosis. This is also validated through thermograph readings (Jorge *et al.,* 2021). Chu *et al.* (2024) performed a three-dimensional numerical simulation of blood flow in both symmetric and asymmetric diverging bifurcated vessels using the Newtonian assumption of blood. The simulations, carried out in FLUENT, used pulsatile inlet conditions and solved the time-dependent Navier–Stokes equations. Among the major peripheral arteries in the limb, brachial artery is closer to systemic circulation; its accessibility and large lumen size make it more viable for capturing thermal variations due to hemodynamics at the skin surface. Furthermore, measurement of temperature in brachial artery is a promising index for core body temperature (Pawley *et al.,* 2013).

In view of the above, this study focuses on finding the mutual influence between thermal changes in the skin of the upper arm and blood flow in the brachial artery through geometrical models and experimental procedure (Wang *et al.,* 2022).

Materials and Methods

Outline of the work: The temperature on the skin of the upper arm mainly depends on three factors; one is the core temperature, flow dynamics of the blood and finally the environment (Carter *et al.,* 2014). Also, the blood flow changes with variations in the environmental or outer skin temperature. For this, the study was approached in two stages. At first, the blood velocity of peripheral arteries like brachial artery, radial artery and tibial artery were measured for varied skin surrounding temperature. After confirming the sensitivity of brachial artery to skin level temperature, brachial artery was (inside the upper arm that looks long and straight) modelled as a cylinder consisting of skin, muscle, brachial artery and blood inside with suitable parameters related to flow, thermal and electrical. Thereafter, the model was simulated for temperature variations due to blood flow with suitable thermal and flow properties. The results of this study suggest the mutual relationship between these two. The workflow of this study is shown in Fig. 1.

Influence of environmental heat on blood flow: When the environmental temperature increases, particularly during peak summer in tropical regions, the skin surface temperature rises. During this time, the blood supply to micro blood vessels in the skin increases, thereby enhancing the blood flow rate and velocity (Chato,1980). To examine the influence of external temperature on hemodynamic, the following experimental analysis was carried out in the age group between 20 and 40 years.

Test procedure: A total of 20 volunteers with no history of health problem (physically and mentally normal and stable) participated in this study. The volunteers included both men and women, with a mean age of 31.25 and standard deviation 5.51. All these participants were informed about the nature and purpose of study. They were allowed to take part only after getting written consent. This study was approved by the Institutional Ethical Committee (REC/IEC/004/2024). The recording room was facilitated with Doppler ultrasound scan Mindray M7 premium US machine for measuring the blood flow velocity. The measurements were taken from the brachial artery, 5 cm above the elbow crease with insonation angle maintained at ≤ 60° using pulsed wave doppler with transducer frequency ranging from 4 to 12 MHz. This room also had a warmer from which temperature of 30°C (T_1), 35°C (T_2) and 38°C (T_3) was maintained. To attain the maximum and stabilized vasodilatory response, the participants were exposed to warm temperature for 15 min, thereafter, the blood flow was recorded (Kellogg *et al.,* 1999; Erofsky *et al.,* 2011). This procedure was repeated for all three temperatures. At the same time, thermal images were also taken using Fluke Tix 580 thermal camera.

Data recording: Considered here is the region related to peripheral arteries like brachial artery, radial artery and tibial artery in upper arm, forearm, and lower limb, respectively. Any variation in the skin temperature could result in change in the blood velocity due to centrally available temperature sensitive mechanism. This gives vascular alterations in terms of dilation or flow rate is an important aspect, especially in the peripheral arteries like brachial artery, tibial artery and radial artery (Coombs

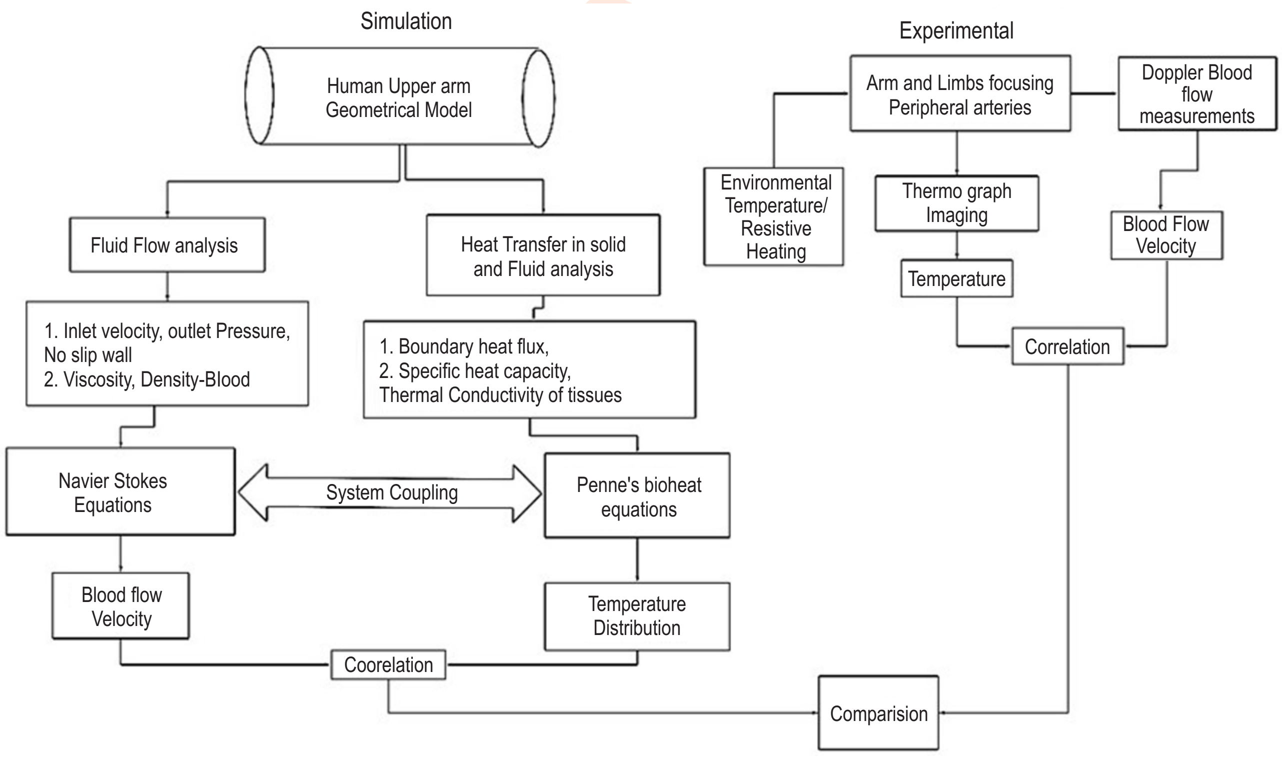

Fig. 1: Block diagram showing the workflow.

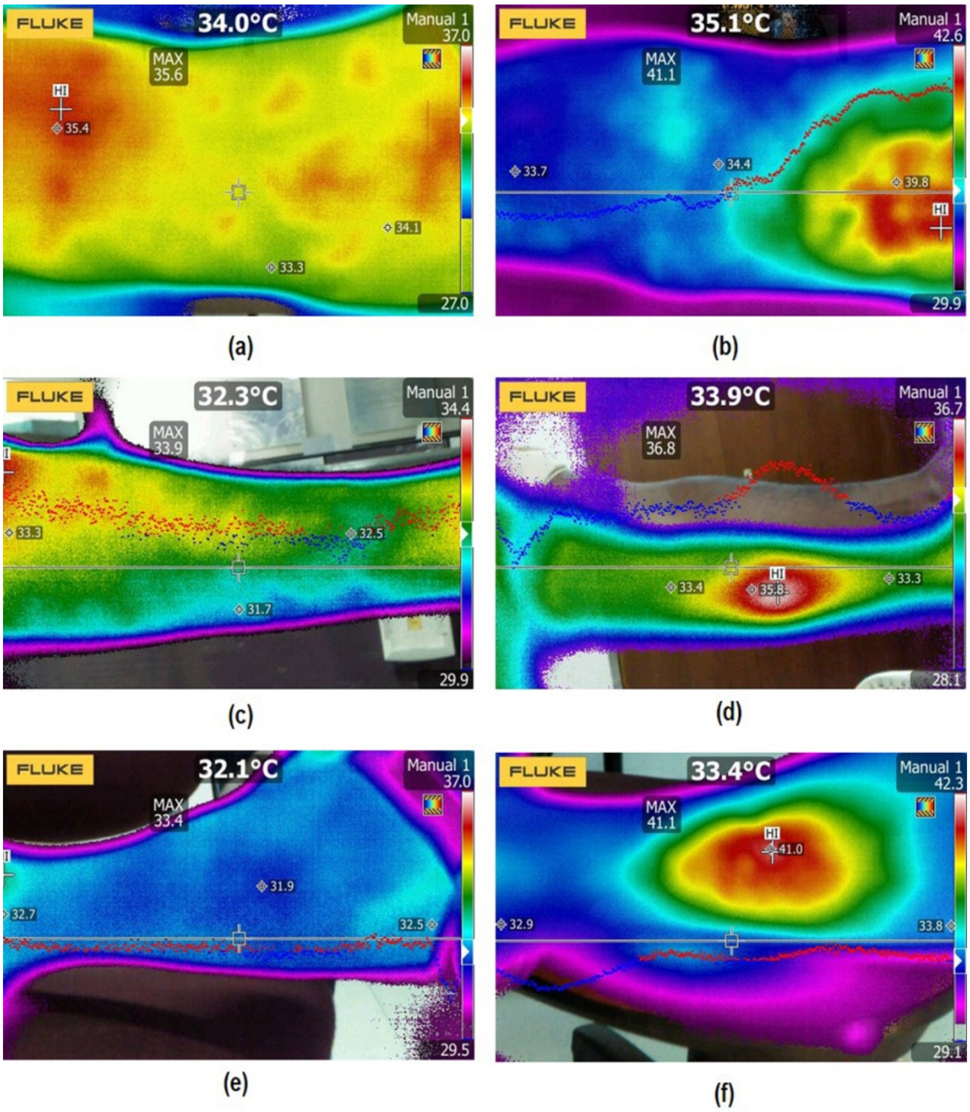

Fig. 2: Thermal images: (a) and (b) Upper arm at T_1 and T_3, (c) and (d) Forearm at T_1 and T_3, (e) and (f) Lower leg at T_1 and T_3.

et al., 2021; Chiesa *et al.,* 2016). Blood velocity and thermal images were recorded from the upper arm, forearm, and lower arm of each participant three times, one at room temperature of 30°C and other two at elevated temperatures of 35°C and 38°C. Sample of thermal image obtained at 30°C and 38°C are presented in Fig. 2. The blood velocity at three different room temperatures obtained from all the participants were averaged and plotted against the average temperature of skin surface (Fig. 3). It could be observed that the velocity of blood increases with external temperature, especially brachial artery showed higher response.

Effect of blood flow in skin temperature

Modelling of flow dynamics: The upper arm was modelled as a cylindrical structure comprising four tissues: skin, muscle, brachial artery and blood. Within the brachial artery, a fat deposit was introduced to simulate a blockage in the blood flow. Two stenotic blocks, corresponding to 45 and 30% area reduction of the brachial artery cross-section, were introduced. Thus, three models were considered: B1 and B2 with blockages, and one representing the no-block (NB) condition. A cross section and isometric view of the model is presented in Fig. 4. By assigning suitable values to the properties like fluid density, terminal velocity and pressure, viscosity, Poisson's ratio and Young's modulus (Zhao *et al.,* 1998; Kandasamy *et al.,* 2025; Baldewsing *et al.,* 2004), these models constructed in solid works were imported and executed in the COMSOL Multiphysics 6.1 environment. In this study, the blood flow was modelled using the Newtonian assumption, which simplifies the analysis and provides useful

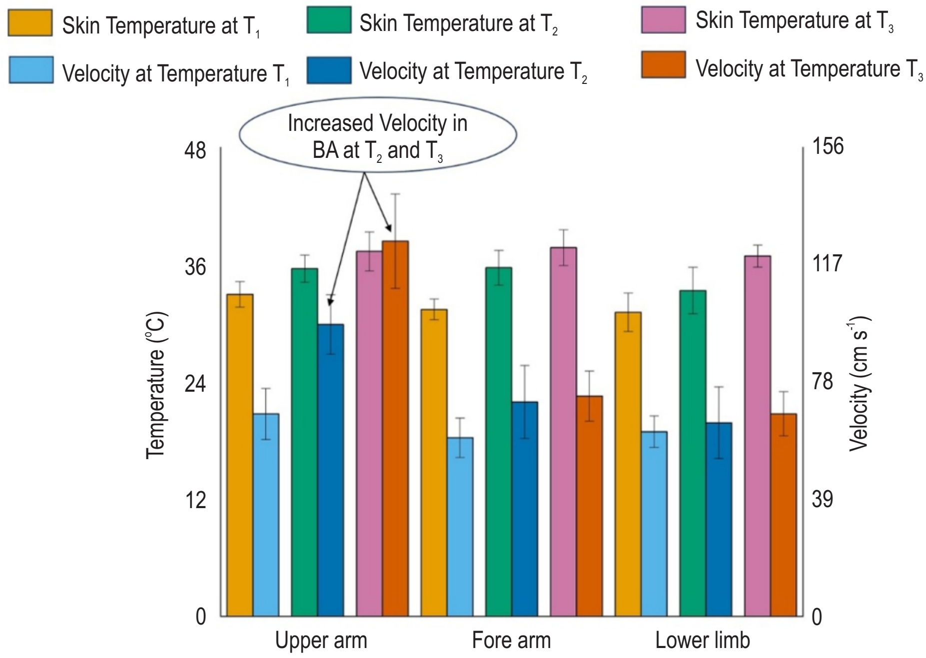

Fig. 3: Bar chart showing relationship between skin surface temperature and blood velocity in the peripheral artery at three different locations.

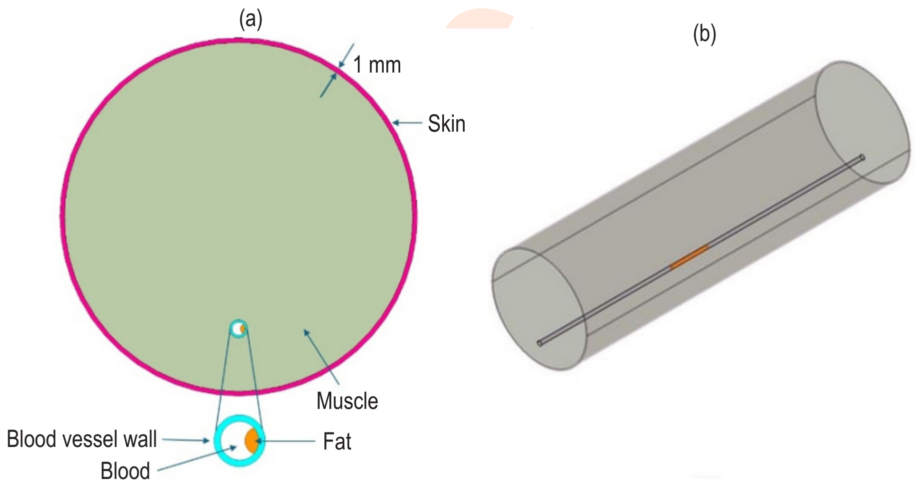

Fig. 4: Geometric model 27 cm long, diameter 8 cm (a) Cross section view and (b) Isometric view.

insights into the hemodynamic behaviour under stenotic conditions (O'Callaghan *et al.,* 2006). For the blood domain, the velocity inlet boundary conditions were assigned a user defined time-dependent pulsatile function mimicking the physiological flow rates in the brachial artery, while the outlet was set at zero pressure to allow the natural outflow. All walls in the blood and arterial domain were treated as no-slip boundaries, enforcing zero velocity at the walls (Zhao *et al.,* 1998).

Flow-thermal coupling mechanism: All the domains of the upper arm model were discretized using free tetrahedral meshing, with mesh refinement applied near the stenotic region to acquire detailed variations in the external temperature (Zaman *et al.,* 2016). Skin and muscle layers were discretized into structured meshes, while the arterial wall and plaque regions were meshed with an unstructured grid mesh composed of triangular elements. The number of mesh elements generated for the skin, brachial artery and muscle in the two models B1 and B2 were 64855, 43444 and 282760 for B1, and 64855, 42343 and 281641 for B2, respectively (Fig. 5). The

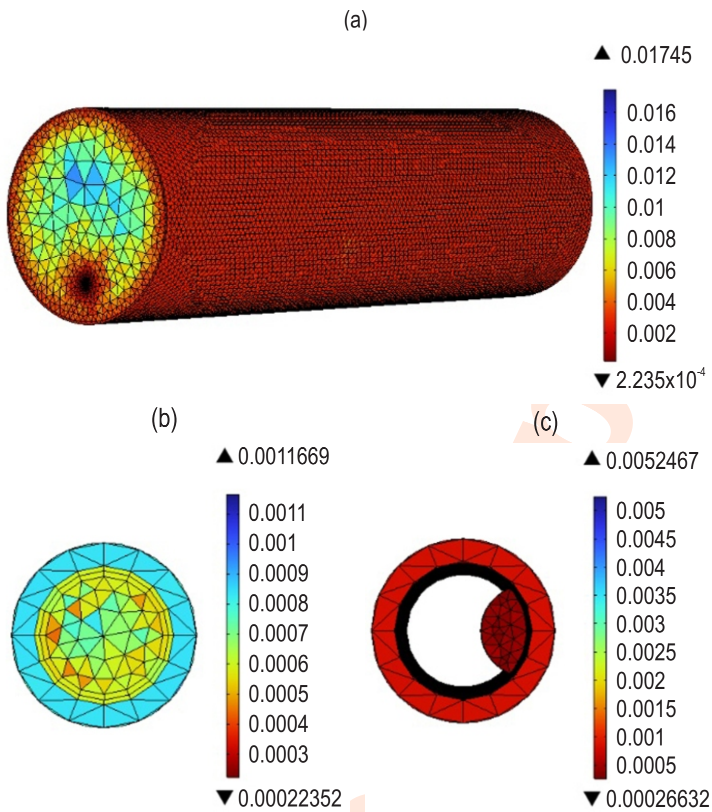

Fig. 5: Meshing of the domain showing element size in m (a) Skin and Muscle (b) Arterial wall and blood domain (c) Plaque inside wall.

meshed model was now subjected to simulation interfacing blood flow through the arterial lumen under Newtonian assumptions and the resultant temperature conduction in solid layers (skin, muscle, artery, stenosis) and convective heat transport within the blood.

Initial conditions were assigned with a uniform body temperature and zero initial velocity. The pulsatile inlet velocity was defined as a time-dependent function based on the physiological waveforms. Heat transfer conditions included continuity at interfaces and a convective flux condition at the skin surface to represent ambient cooling (Zaman *et al.,* 2016). The solver configuration used a time-dependent study with the backward differentiation time-stepping algorithm. A fixed time step of 0.05 sec was used, and simulation was run up to 20 sec, allowing capture of transient changes in both flow and temperature. The maximum differentiation step order was increased to 5 for better stability and convergence. In general, the human body maintains thermal balance unless there is any deviation in blood perfusion or vessel obstruction that could lead to localized temperature changes leading to propagation towards the skin (Wang *et al.,* 2022). In this study, computational simulation was used to estimate the heat distribution from the brachial artery through the artery wall, muscle, and ultimately the skin, offering a non-invasive thermal marker. The temperature modelling framework was developed using COMSOL Multiphysics by combining fluid flow simulations and thermal transport using the Pennes bioheat transfer equation, a commonly used model for capturing the thermal response of perfused tissues (Chiesa *et al.,* 2016). The heat transfer in solids and fluids module of COMSOL Multiphysics 6.1 was used to simulate temperature changes in both blood and tissue domains. The blood domain undergoes convective heat transfer due to fluid motion, while the solid domains of artery wall, muscle, and skin undergo conduction as a primary mode of heat transport.

In this study, perfusion and metabolic terms were defined for solid tissue layers. The convective coupling between the flowing blood and the arterial wall was established using Multiphysics continuity conditions, allowing heat transfer from the blood to the tissue. A convective heat flux boundary condition was applied to the outer skin surface to represent heat loss to the environment. The integration of the bioheat equation within the Multiphysics framework enables the model for simulation of temperature propagation from the arterial lumen to the external skin surface. This is crucial for validating the thermal variations of stenotic effects at the skin level, providing a potential non-invasive diagnostic approach.

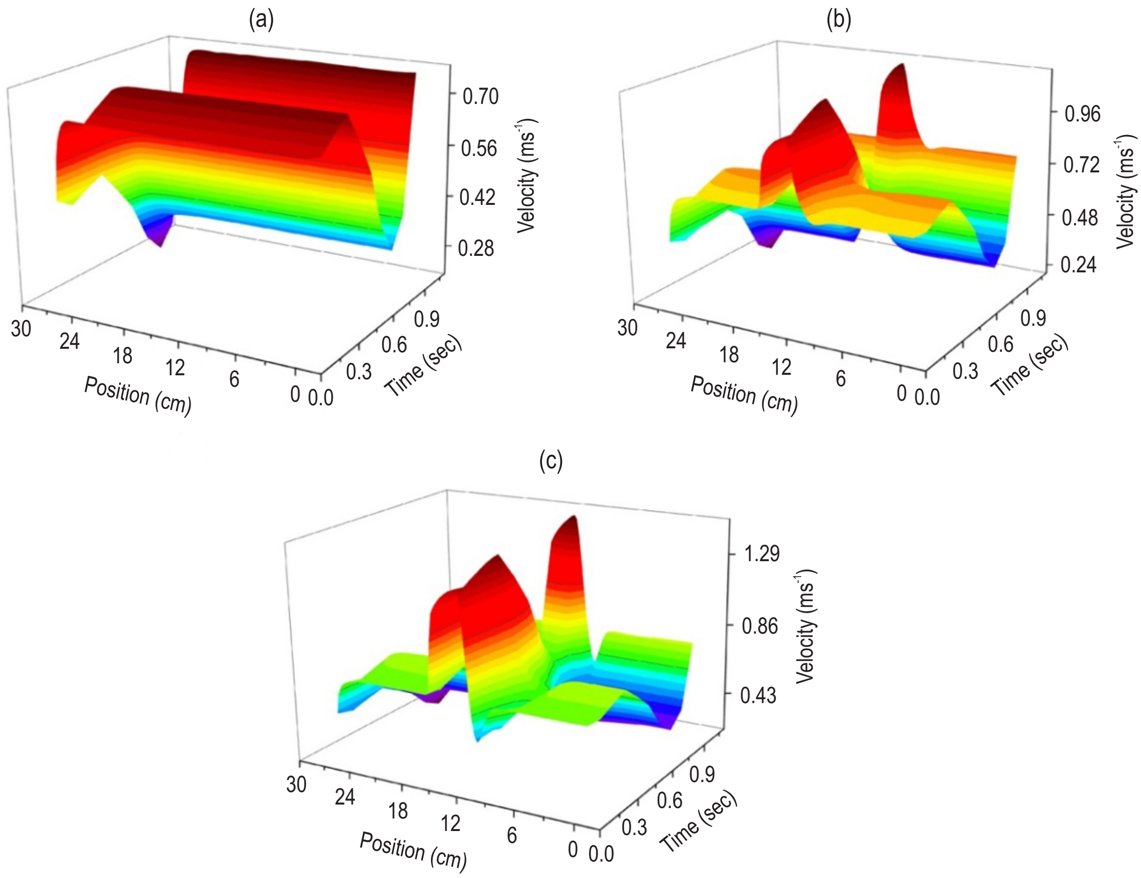

Fig. 6: 3D plot of axial velocity in (a) NB, (b) B1 and (c) B2.

Results and Discussion

To study the effect of temperature changes on the skin, blocks were introduced in the brachial artery model in order to change the velocity (Fig. 6). Thus, in stenosis regions, the narrowing of lumen increased the velocity at the plaque site, as shown in Fig. 6 (b) and (c) when compared to Fig. 6 (a), corresponding to NB. These disturbed flow patterns decreased the perfusion rate in adjacent tissues, causing localized heat accumulation. This relation between the abnormal hemodynamic and external temperature distribution provides a non-invasive indication of vascular pathology as shown in Fig. 7 for all three models. The interaction between thermal stress and vascular response has important implications for peripheral vascular disease, cardiovascular responses to physical activity, and diabetes management (Valli *et al.,* 2022). Conversely, the cold surrounding temperature would reduce the blood flow, resulting in frostbite. At rest, under room temperature conditions, the blood flow in the skin was approximately 250 ml min^{-1}, resulting in a heat dissipation of about 80–90 kcal h^{-1}. When the core body temperature rises, thermoregulatory mechanisms produce cutaneous vasodilation and sweating to increase the heat loss (Charkoudian, 2003). To study this continuous feedback system, attempted here is to experimentally verify the impact of thermal stress on the peripheral blood flow. Focused here were three arteries brachial artery, radial artery and tibial artery. From the experimental phase of the work (Fig. 2), the response of brachial artery was higher when compared with the other two arteries. For every 2°C rise in skin temperature, an average blood velocity changed by 25% in brachial artery, whereas radial artery and tibial artery showed change of less than 5%. The correlation coefficients between skin temperature and blood flow in different arteries is presented in Table 1. It was observed that the brachial artery exhibited higher correlation with the surrounding temperature, confirming the thermal response of blood in brachial artery relatively to be larger when compared to radial artery and tibial artery. This could be due to the proximity of the brachial artery to the skin surface, providing closer coupling between skin temperature and arterial blood flow. Brachial artery also shows relatively higher sensitivity to shear stress (Larson *et al.,* 2021). In general, the average velocities of blood in brachial artery, radial artery and tibial artery are 60–100 cm s^{-1}, 40–70 cm s^{-1} and 59–81 cm s^{-1}, respectively (Hill *et al.,* 2018). From Fig. 3, it could be noticed that the blood velocity in brachial artery goes beyond the normal range (reaches 126 cm s^{-1}) at T_3, which further proves the sensitivity of brachial artery to localized temperature.

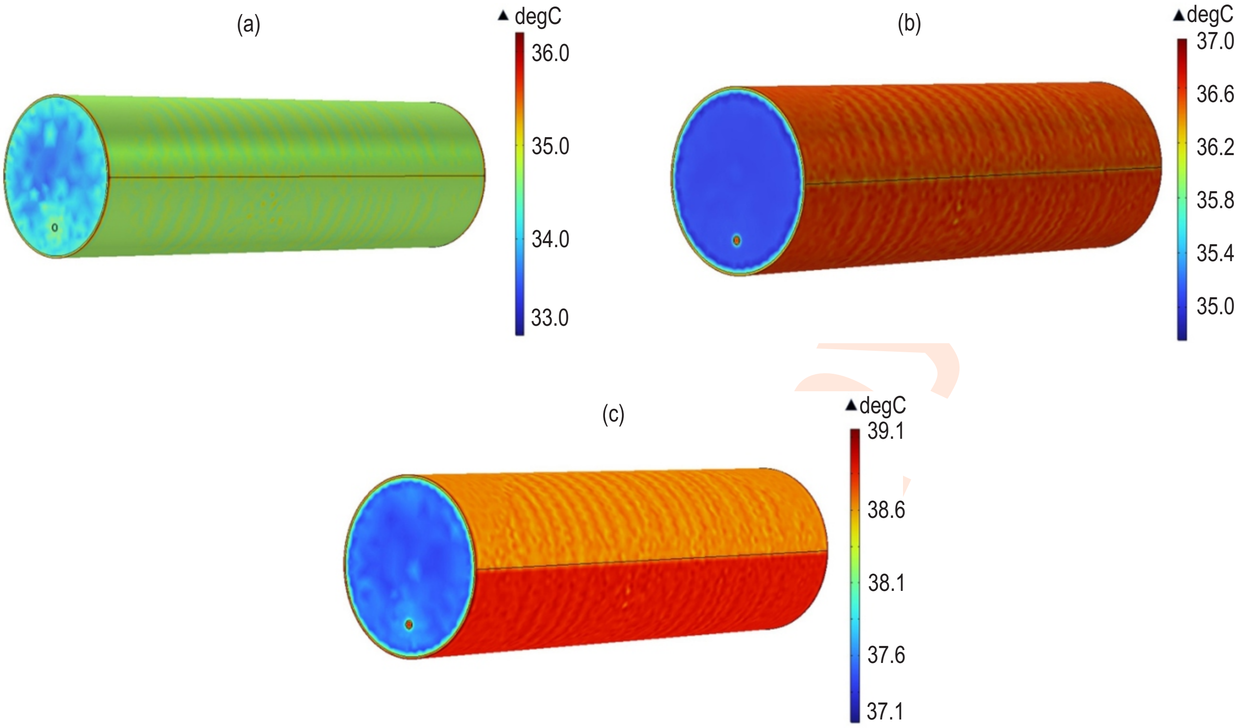

Fig. 7: Skin temperature distribution in (a) NB (b) B1 (c) B2.

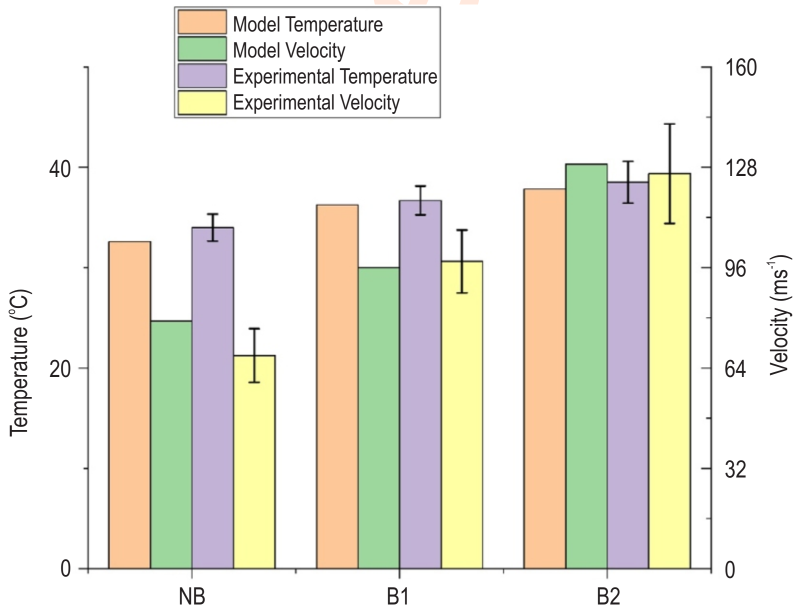

Fig. 8: Comparison bar chart between experimental and simulation outputs.

Artery wall is composed of three layers *viz.,* tunica intima, tunica media and tunica adventitia. On localized heating, the intima layer releases NO making the smooth muscle in media layer to increase the diameter of the vessel and the last layer provides mechanical support. This process is called flow-mediated dilation where the velocity of the blood and shear stress increases as the total volume of the blood increases (Coombs *et al.,* 2021). The other factors affecting the blood flow

Table 1: Correlation coefficient between skin temperature and blood velocity

BA	RA	TA
0.941	0.72	0.701

velocities are the blood density, viscosity, cardiac output, vascular resistance, blood volume, and physical activity. The rise in blood density due to change in blood plasma composition increases the Reynolds number thereby cousing turbulence in certain conditions. Thickening of blood due to RBC aggregation and dehydration increases blood viscosity, resulting in decreased blood flow velocity and increased vascular flow resistance. Any elevation in heart rate and stroke volume leads to an increase in blood flow velocity and pressure (Wieneke *et al.,* 2004). However, narrowing of artery is the only one medical condition simulated here by introducing a block of different size. To investigate the effect of blood velocity on skin temperature, a model was developed which induced an increase in both blood velocity and shear stress. Hence, a numerical simulation was performed using COMSOL Multiphysics by inserting a block in the artery. Since brachial artery showed higher relevance, flow and temperature effects were studied for this artery. Block in the brachial artery is introduced to alter the velocity which in turn coupled to assess temperature distribution on skin. Fig. 7 shows that, the temperature distribution is uniform in the upper arm during normal flow condition. When stenosis occurs in the flow, an increased temperature is observed on the arm surface that is close to the brachial artery, located in the lower half of the model. This could be because the higher velocity causes an increase in the convective heat transfer coefficient at the blood vessel wall, thereby altering the heat exchange between the blood, vessel wall, and the surrounding tissues (Zaman *et al.,* 2016). Furthermore, the temperature and velocity obtained through the model were similar to the experimental values, as illustrated in Fig. 8.

Although the radial artery is more sensitive to room temperature, as it is close to the skin surface when compared to other peripheral arteries, for localized and focused temperature variations, brachial artery exhibited higher sensitivity. Because, brachial artery has a well-developed thickened endothelial cells lining in the inner wall, that regulates the vascular tone by producing NO through endothelial nitric oxide synthase (eNOS) activity (Cockcroft, 2005). Thus, through the proposed method (producing localized heating), eNOS could be stimulated, which would serve as an indicator of health of the artery. Flow mediated dilation could be useful in studies linked to atherosclerosis, diabetes and cardio-vascular disease. At present it is measured by inflating cuff above systolic pressure for five minutes and measuring using high resolution ultrasound technique. This is a painful procedure which can be overcomed by the proposed method of increasing localized temperature and measuring blood velocity.

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Authors' contribution: K. Sankar: Conducted experiments and simulation; Wrote the research paper; **R. Kalpana:** Research supervisor; **R. Nandhini:** Medical doctor, who validated the results.

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Data availability: Not applicable.

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