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Research Article

Unveiling Capillary-Tissue Fluid Exchange: Understanding Red Blood Cell Deformation in Constricted Vessels and its Clinical Significance

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Abstract: Capillary-tissue fluid exchange plays a critical role in maintaining tissue homeostasis, and understanding the behavior of red blood cells (RBCs) in narrow vessels is fundamental to elucidating this process. This paper explored the phenomenon of RBC deformation in constricted vessels and its clinical implications. This study delves into the intricate dynamics of blood flow within narrow capillaries, particularly focusing on situations where the diameter of these vessels is smaller than that of red blood cells (RBCs). In such confined spaces, the proximity between RBCs and the vessel walls is minimal, allowing plasma to permeate through. This research explored how various factors, including the shape of deformed RBCs, their velocity, and tissue permeability, influence blood flow patterns. It reveals that in scenarios where tissues exhibit lower permeability, blood flow tends to be more uniform, while faster-moving RBCs encounter less resistance. By comparing its findings with existing models, this study underscores its significance in advancing our understanding of blood flow dynamics in small vessels. Such insights hold promise for the development of novel diagnostic tools targeting a range of diseases. Additionally, this paper discussed the clinical relevance of RBC deformability in various pathological conditions, including microvascular diseases, ischemia-reperfusion injury, and inflammation. Understanding the complex interplay between RBC deformability, microvascular function, and disease pathology has significant implications for the development of novel diagnostic and therapeutic strategies targeting capillary-tissue fluid exchange.

***Keywords*:** microcirculation; permeability; blood flow dynamics; tissue perfusion; disease diagnosis

1. Introduction

Comprehending the intricate mechanics of red blood cell (RBC) deformation within narrow capillaries is essential for deciphering critical physiological processes and pathological conditions. A biomechanical approach, blending principles from mechanics and biology, provides a comprehensive framework for studying such phenomena. By investigating the mechanical responses of RBCs within confined spaces, this approach yields valuable insights into microscale blood flow dynamics. Our study aims to delve into the biomechanics of RBC deformation in narrow capillaries, aiming to elucidate the underlying principles governing their behavior. Focusing on the complex interplay between cellular morphology, fluid dynamics, and tissue biomechanics, our investigation seeks to unravel the intricacies of RBC motion in constrained microenvironments [13,18,24,44]. Through a synthesis of theoretical modeling, experimental observations, and clinical correlations, we endeavor to decode the biomechanical characteristics of RBC deformation and its relevance to health and disease

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[15,25,36,46]. By elucidating the fundamental principles dictating RBC behavior in narrow capillaries, we aspire to pave the way for innovative diagnostic and therapeutic interventions targeting microcirculatory disorders and associated pathologies. Thus, this biomechanical exploration serves as a cornerstone for advancing our understanding of microvascular blood flow dynamics, offering profound insights into the intricate interplay between mechanical forces and biological phenomena within the circulatory system [6,29,37].

Blood consists of small red blood cells suspended in a fluid known as plasma, akin to fruits in syrup within a fruit salad. Extensive scientific inquiry has been dedicated to understanding the workings of these red blood cells. Typically, under normal circumstances, red blood cells exhibit a disc-like shape, resembling miniature pancakes, with dimensions requiring microscopic observation. Enclosed within these cells is a viscous fluid, akin to thick syrup. The outer layer of red blood cells comprises a resilient membrane, akin to the peel of a fruit but notably thinner [9,23,33,42]. This membrane exhibits resistance to changes in size, akin to stretching or compressing a balloon, owing to its molecular structure consisting of two layers resembling a sandwich. While the molecules within these layers can slide past each other, they exhibit resistance to separation and bending, rendering the membrane relatively stiff compared to other materials [2,20,27,30]. As red blood cells navigate the bloodstream, this membrane resists alterations induced by external forces, analogous to the resilience of a rubber band against stretching or twisting. Sophisticated mathematical models have been devised to elucidate the behavior of this membrane when subjected to various forces. Such investigations contribute to our understanding of how red blood cells maintain their shape and mobility within the body, essential for preserving overall health [4,11,38,47].

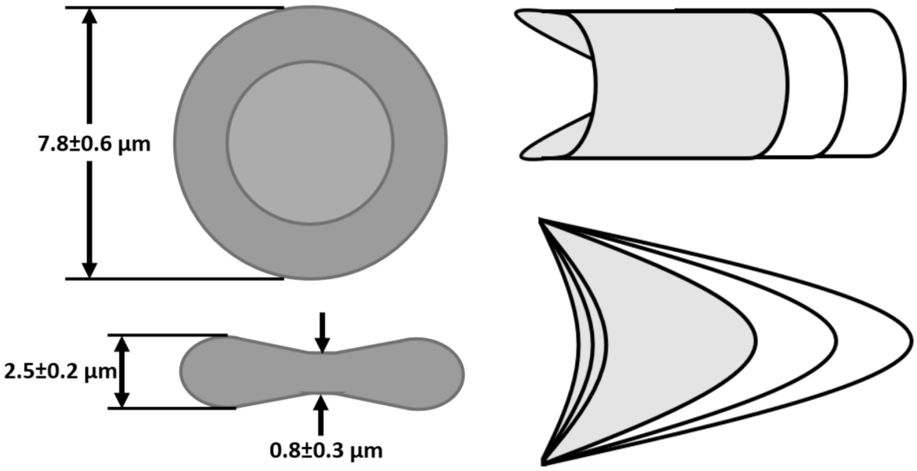

Figure 1. Deformation of Red Cells

Blood circulation is a fundamental process that serves as a vital transportation network within the human body, comparable to trucks delivering goods and removing waste in a bustling city. In healthy blood vessels, the flow of blood exhibits a seamless and steady movement akin to the gentle flow of water in a river [5,28,48]. However, any disruptions or irregularities in this circulation can lead to various medical conditions, including heart disease, underscoring the critical importance of maintaining a healthy blood flow. Among the intricate network of blood vessels, the minutest ones are the capillaries, which are even thinner than a single strand of hair. Despite their diminutive size, these capillaries play an outsized role in the body's overall function [1,17,34,41,53]. To visualize the challenges blood cells encounter within these narrow passageways, one can imagine navigating through a tight and narrow alley. Similarly, blood cells must negotiate tight squeezes within capillaries as they traverse through them. As blood cells make their way through these narrow capillaries, they undergo remarkable shape changes to fit through the constricted spaces. This process is akin to manoeuvring a large balloon through a narrow gap, requiring the balloon to squish and stretch as needed to pass through. Such deformation of blood cells is induced by the pressure exerted by the surrounding plasma, which is the fluid enveloping the cells [7,16,26,31,51]. This pressure renders the blood cells pliable enough to navigate through the narrow passages without causing damage to the vessel walls. Furthermore, a thin layer forms between the blood cell and the inner lining of the capillary wall. This layer plays a crucial role in facilitating the exchange of essential nutrients, oxygen, and waste products between the bloodstream and the surrounding tissues [3,19,35,52]. Additionally, it influences the dynamics of blood flow within the capillaries. These intricate processes are vital for maintaining optimal bodily function and ensuring the efficient distribution of essential substances throughout the body. They highlight the remarkable adaptability and resilience of the human circulatory system in navigating through the complexities of the microcirculation to sustain life and health. Thus, understanding these processes is essential for advancing our knowledge of human physiology and developing effective treatments for various medical conditions [8,12,22,39].

2. Defining the problem statement

This model conceptualizes red blood cells as axisymmetric structures containing incompressible fluid. It assumes a scenario where red blood cells flow singularly, without interactions between cells. In this framework, 'H' represents the thickness of the porous matrix, 'u' denotes the velocity of the cell at a specific point, and 'h' indicates the thickness of the fluid film. Furthermore, 'a' represents the focal length of the initially assumed parabolic shape, while [10,14] depicts further deformation resulting from increased pressure within the wedge formed between the parabolic shape and the capillary. The flow region is segmented into two distinct regions, and governing equations are formulated separately for each region, as delineated below.

Within the capillary region, equation is as follows:

$$\left(-\frac{\partial p'}{\partial x'}\right)+\mu\frac{\partial^2 u'}{\partial y'^2}=0 \tag{1}$$

the equation of continuity describes how the flow of fluid is conserved within a given system:

$$\frac{\partial u'}{\partial x'}+\frac{\partial v'}{\partial y'}=0 \tag{2}$$

In the porous region, the velocity components within the matrix can be described using Darcy's law.

$$\overrightarrow{u'} = (\mathrm{K}/\mu\,\frac{\overrightarrow{\partial P}}{\partial x'}) \tag{3}$$

$$\overrightarrow{v'} = (-\mathrm{K}/\mu\,\frac{\overrightarrow{\partial P}}{\partial y'}) \tag{4}$$

The equation that governs the distribution of pressure within the porous matrix is given by:

$$\frac{\partial^2\,\overline{p}'}{\partial x'^2}+\frac{\partial^2\,\overline{p}'}{\partial y'^2}=0 \tag{5}$$

To solve the aforementioned equations, the following matching and boundary conditions are introduced:

$$\begin{aligned}
&u' = u_0 && at \quad u' = h'\\
&u' = \left[(-\sigma)\left(\frac{\partial u'}{\partial x'}\right)\right] && at \quad y' = 0\\
&u' = \left[\ (-\mathrm{K}/\mu\,\frac{\overrightarrow{\partial P}}{\partial x'})\ \right] && at \quad y' = 0\\
&v' = 0 && at \quad y' = h'\\
&v' = \left[\ (-\mathrm{K}/\mu\,\frac{\overrightarrow{\partial P\prime}}{\partial y'})\ \right] && at \quad y' = 0\\
&\left(\frac{\overrightarrow{\partial P\prime}}{\partial x'}\right) = 0 && at \quad x' = 0\\
&\overrightarrow{p'} = 0 && at \quad x' = 1\\
&\left(\frac{\overrightarrow{\partial P\prime}}{\partial y'}\right) = 0 && at \quad y' = 0\\
&\overrightarrow{p'} = p_0 && at \quad x' = 0
\end{aligned} \tag{6}$$

The slip parameter, denoted as μ, characterizes the degree of ease with which objects can move past each other within a system. A higher μ value implies smoother sliding between components, whereas a lower value suggests greater resistance to movement. Moving on to the reference pressure, P_0, it acts as a pivotal starting point for discussing changes in pressure within a given context. It serves as the initial benchmark against which pressure alterations are measured and analyzed. Shifting focus to the radial compliances, Δr and $\Delta\theta$, these parameters quantify the ability of the capillary and cell to stretch or deform sideways. When combined ($\Delta r + \Delta\theta$), they offer insight into the collective flexibility of the system under consideration. Furthermore, the effective length of the capillary, represented as 2l, doubles the actual length to encompass both ends for analytical purposes. Finally, the initial gap at the point of intersection between the parabola and the capillary serves as a negligible space between the two surfaces. Its insignificance relative to the thickness (H) of the porous layer allows it to be disregarded, akin to overlooking a minuscule crack in a sidewalk.

The equations are solved using a non-dimensional scheme introduced as follows:

$$\begin{aligned}
&x = x'/H' ; && y = y'/H' ;\\
&p = p'/P_0 ; && u = u'/u_0 ;\\
&Re = \rho u_0 H/\mu ; && v = v'/u_0 ;\\
&(\alpha+\beta) = (\alpha+\beta)'/\left(H'^3/\rho u_0^{\,2}\right); &&\\
&p = p'/P_0 ; && \sigma = \sigma'/H' ;\\
&\varepsilon = H'/4a'/; && h = \eta(p-1) + \varepsilon x^2
\end{aligned} \tag{7}$$

To solve the aforementioned equations, the following boundary conditions and matching conditions are applied:

$$\begin{aligned}
&u = 1 && at \quad y = h\\
&u = \left[(-\sigma)\left(\frac{\partial\omega}{\partial y}\right)\right] && at \quad y = 0\\
&v = 0 && at \quad y = h\\
&v = \left[(-\mathrm{Kp}/\mu Uo\, H\,\frac{\partial \vec{P}}{\partial y})\right] && at \quad y = 0\\
&\left(\frac{\partial \vec{P}}{\partial x}\right) = 0 && at \quad x = 0\\
&\vec{P} = 0 && at \quad x = 1\\
&\left(\frac{\partial \vec{P}}{\partial y}\right) = 0 && at \quad y = -1\\
&p = 1 && at \quad x = 1
\end{aligned} \tag{8}$$

3. Problem Solution

We established that the blood flow is balanced, with the inflow equaling the outflow (as per the equation of continuity), and we define the parameters governing blood behavior at the boundaries (boundary and matching conditions), we can proceed to determine the precise velocity of blood flow at various locations within the capillary by solving these equations [21,32,40].

$$u = \frac{P_0 H}{U_0 \mu}\frac{\partial p}{\partial x}\left(y^2 - \frac{(y-\sigma)}{(h-\sigma)}h^2\right) + \frac{y-\sigma}{h-\sigma} \tag{9}$$

By solving above equation, we have

$$\bar{p} = \sum_{n=0}^{\infty} 2En\cosh\{\alpha_n(H+y)\}\cos(\alpha_n x) \tag{10}$$

where $\alpha_n = (2n+1)\pi/21)$

$$En = \frac{1}{\alpha_n}\operatorname{sech}(\alpha_n H)\cos(n\pi) \tag{11}$$

$$P = [Z_n(P_0A_1x^2+A_2x^4+A_3x^2)]-$$
$$[Z_n(\alpha_n^2/2)(P_0x^4(A_1/6)+x^6(2A_2/5)$$
$$+x^4(A_3/6))]+1-[Z_n(P_0A_1+A_2+A_3)]+ \tag{12}$$
$$[Z_n(\alpha_n^2/2)(P_0(A_1/6)+(2A_2/5)+(A_3/6))]$$

We determine the Flow Resistance as:

$$R^* = (1/Q)[Zn\left(P_0A_1x^2+A_2x^4+A_3x^2\right)]-$$
$$[Zn(\alpha_n^2/2)(P_0x^4(A_1/6)+x^6(2A_2/5)+x^4(A_3/6))] \tag{13}$$

Where $$Zn=[(3K/2H^2\sigma)\sum_{n=0}^{\infty} En\alpha_n^3 \sinh\alpha_n(H+y)] \tag{14}$$

$$A_1=((-3\sigma/2\eta^2)+(1/8\sigma)-(3/4\eta)),\ A_2=(-(3\varepsilon'\sigma/12\eta^3)+(\varepsilon'/48\sigma\eta)-(3\varepsilon'/24\eta^2))$$

$$A_3=(-(\sigma/2\eta^3)+(1/8\sigma\eta)-(3/8\eta^2)) \tag{15}$$

$$\eta=(H^2P_0(\alpha+\beta)/\rho U_0^2)$$

4. Results and discussion

Understanding the intricacies of blood flow parametres in narrow capillaries is essential for comprehending various physiological phenomena. To delve into this complex realm, we've developed sophisticated computer programs. These programs serve as invaluable tools, allowing us to quantify the impact of critical parameters such as cell shape and velocity on blood flow dynamics. By harnessing the power of computational simulations, we've generated extensive datasets that offer insights into how blood flow parameters behaves under normal physiological conditions. The utilization of these computer programs facilitates a meticulous evaluation of blood flow patterns, ensuring that our analyses accurately mirror real-world scenarios. This rigorous process guarantees that our computational models capture the nuances of blood flow within narrow capillaries with precision. Through these simulations, we can dissect the intricate interplay between various factors and their influence on blood flow resistance [43,49]. In Figure 2, the plotted data vividly illustrates the intricate relationship between velocity and axial distance within the capillary. A notable observation is the inverse correlation between these two parameters. As axial distance increases, there is a corresponding decrease in velocity. This phenomenon is attributable to alterations in pressure gradients within the wedge-shaped region of the capillary. These pressure differentials lead to deformations in both erythrocytes and the capillary wall, particularly near the narrowest part of the interstitial space. These deformations directly impact velocity, with higher pressure levels inducing more pronounced cell deformations, consequently resulting in a reduction in velocity. This observation is corroborated by existing literature, underscoring the reliability of our findings. In Figure 3, the graph provides further insights into the relationship between velocity and variations in the parameter H. As the values of H increase, there is a discernible decrease in velocity. These findings are consistent with prior research, reinforcing the validity of our observations [45,50]. Overall, our comprehensive approach, combining computational simulations with empirical data, enhances our understanding of blood flow dynamics in narrow capillaries and provides valuable insights into the intricate mechanisms governing physiological processes.

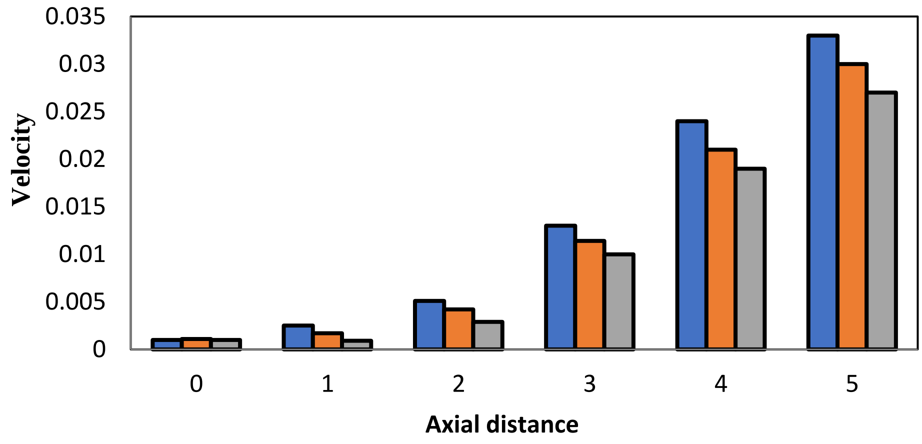

Figure 2. Velocity with axial distance for different shapes of cell

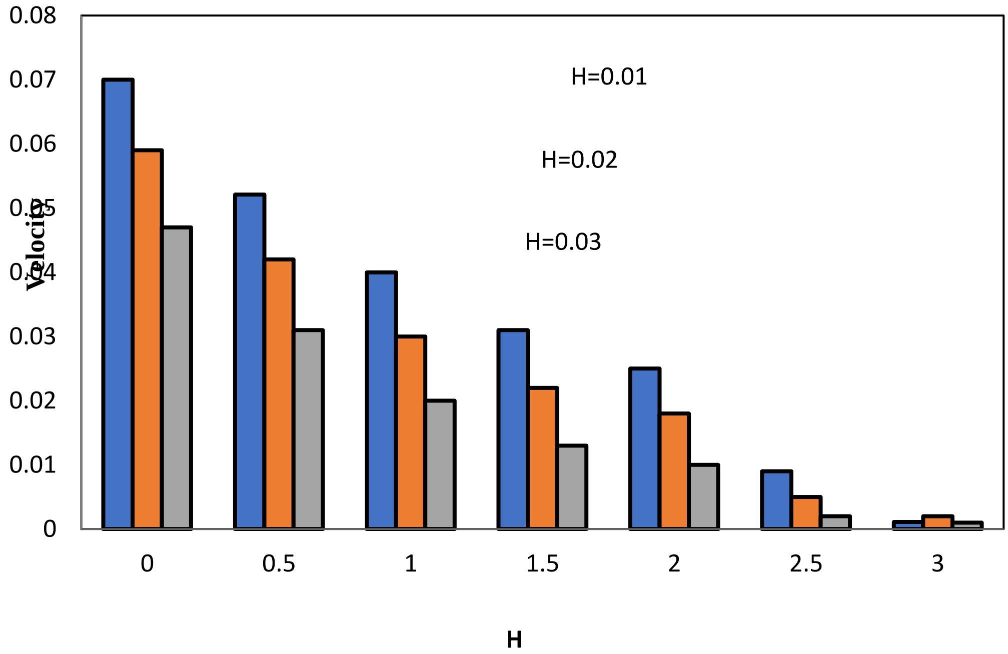

Figure 3. Velocity for different H

5. Conclusion

This study utilizes computational techniques to investigate how fluids move between capillaries and tissues when the capillary diameter is smaller than that of a red blood cell. The research focuses on understanding how velocity changes in different scenarios, including variations in the shapes of deformed red blood cells, their velocities, and the permeability of the tissues. The findings indicate a direct relationship between reduced permeability and decreased resistance to flow, resembling behaviors observed with impermeable surfaces in tissue environments. Additionally, the analysis reveals that velocity decreases within the gap as the velocity of the cells increases. Through a comparison with existing models, the study emphasizes the importance of the proposed computational approach, both in theory and practice. Notably, this model accurately predicts fundamental aspects of fluid dynamics in physiological settings, offering valuable insights for biomedical researchers and medical professionals.

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Conflict of interest

There is no conflict of interest for this study.

References

[1] Akbar, S.; Shah, S.R. The Effects of Prostaglandin Analogs on Intraocular Pressure in Human Eye for Open Angle Glaucoma. *Int. J. Innov. Technol. Explor. Eng.* **2020**, *10*, 176–180, https://doi.org/10.35940/ijitee.a8195.1210220.

[2] Akbar, S.; Shah, S.R. "DURYSTA" the first biodegradable sustained release implant for the treatment of open-angle glaucoma. *Int. J. Front. Biol. Pharm. Res.* **2021**, *1*, 001–007, https://doi.org/10.53294/ijfbpr.2021.1.2.0042.

[3] Chaturvedi, P.; Kumar, R.; Shah, S.R. Bio-Mechanical and Bio-Rheological Aspects of Sickle Red Cells in Microcirculation: A Mathematical Modelling Approach. *Fluids* **2021**, *6*, 322, https://doi.org/10.3390/fluids6090322.

[4] Chaturvedi, P.; Shah, S.R. Assessing the Clinical Outcomes of Voxelotor Treatment in Patients with Sickle Cell Disease. *Int. J. Appl. Sci. Biotechnol.* **2024**, *12*, 46–53, https://doi.org/10.3126/ijasbt.v12i1.64057.

[5] Chaturvedi, P.; Shah, S.R. Mathematical Analysis for the Flow of Sickle Red Blood Cells in Microvessels for Bio Medical Application. *Yale J. Biol. Med.* **2023**, *96*, 13–21, https://doi.org/10.59249/atvg1290.

[6] Geeta, Siddiqui, S. U., Sapna, "Mathematical Modelling of blood flow through catheterized artery under the influence of body acceleration with slip velocity", Application and applied Mathematics An international journal, 8(2),481-494, (2013). digitalcommons.pvamu.edu:aam-1333

[7] Siddiqui, S.; Shah, S.; Geeta A biomechanical approach to study the effect of body acceleration and slip velocity through stenotic artery. *Appl. Math. Comput.* **2015**, *261*, 148–155, https://doi.org/10.1016/j.amc.2015.03.082.

[8] Geeta, Siddiqui, S. U., Shah, S. R., "A Computational Analysis of a Two-Fluid non-Linear Mathematical model of pulsatile blood flow through Constricted Artery", E-Journal of science and Technology, 10(4), 65-78, (2015).

[9] Geeta, Siddiqui, S. U., Shah, S. R., "A Mathematical Model for two layered pulsatile blood flow through stenosed arteries", E-Journal of science and Technology, 109 (11), 27-41, (2015).

[10] Geeta, Siddiqui, S. U., Shah, S. R., "Effect of body acceleration and slip velocity on the pulsatile flow of casson fluid through stenosed artery", Advance in applied science research, 5(3), 231-225, (2014).

[11] Kumar, J. P., Sadique, Mo. Shah, S. R., "Mathematical study of blood flow through blood vessels under diseased condition, International Journal of Multidisciplinary Research and Development, 9(6), 2022, 31-44.

[12] Shah, S.R.; Kumar, P. A Hydromechanical Perspective to Study the Effect of Body Acceleration through Stenosed Artery. *Int. J. Math. Eng. Manag. Sci.* **2021**, *6*, 1381–1390, https://doi.org/10.33889/ijmems.2021.6.5.083.

[13] Shah, S.R.; Kumar, R. A Mathematical Approach to Study the Blood Flow Through Tapered Stenosed Artery with the Suspension of Nanoparticles. *DEStech Trans. Eng. Technol. Res.* **2017**, https://doi.org/10.12783/dtetr/amsm2017/14809.

[14] Shah, S.R.; Kumar, R. Mathematical Modeling of Blood Flow with the Suspension of Nanoparticles Through a Tapered Artery With a Blood Clot. *Front. Nanotechnol.* **2020**, *2*, https://doi.org/10.3389/fnano.2020.596475.

[15] Shah, S.R.; Kumar, R. Performance of Blood Flow with Suspension of Nanoparticles Through Tapered Stenosed Artery for Jeferey Fluid Model. *Int. J. Nanosci.* **2018**, *17*, https://doi.org/10.1142/S0219581X18500047.

[16] Kumar, R., Shah, S. R., "Study of blood flow with suspension of nanoparticles through tapered stenosed artery", Global Journal of Pure and Applied Mathematics, 13(10), 7387-7399, (2017).

[17] Kumar, V., Shah, S. R., "A Mathematical study for heat transfer phenomenological processes in human skin", International Journal of Mechanical Engineering, 7 (6), 2022, 683-692.

[18] Kumar, V., Shah, S. R., "Thermobiological Mathematical Model for the study of temperature response after cooling effects", SSRG, International Journal of Applied physics, 9 (2), 2022, 7-11.

[19] Kumar, V., Shah, S. R., "A mathematical approach to investigate the temperature distribution on skin surface with sinusoidal heat flux condition, International Journal of Multidisciplinary Research and Development, 9 (5), 2022, 141-146.

[20] Kumar, V., Shah, S. R., "Mathematical modelling to study the heat transfer between core and skin", SRMS, Journal of Mathematical Sciences, 7 (2021), 7-12, (10th March 2024). https://doi.org/10.29218/srmsmaths.v7i2.02

[21] Malik, M., Z., Kumar, R., Shah, S. R., "Effects of (Un)lockdown on COVID-19 transmission: A mathematical study of different phases in India, medRxiv The preprint server for health science, 1-13, (2020), doi: https://doi.org/10.1101/2020.08.19.20177840.

[22] Sadique, M.; Shah, S.R. Mathematical Model to Study the Squeeze Film Characteristics of Diseased Human Synovial Knee Joint. *World Sci. Annu. Rev. Biomech.* **2023**, *01*, https://doi.org/10.1142/s2810958923300044.

[23] Sadique, Mo., Shah, S. R., "Mathematical model to study the effect of PRG4, hyaluronic acid and lubricin on squeeze film characteristics of diseased synovial joint", International Journal of Mechanical Engineering, 7 (6), 2022, 832-848.

[24] Sadique, Mo., Shah, S. R., "Mathematical study for the synovial fluid flow in Osteoarthritic knee joint, Journal of Engineering and Applied Sciences, 17(2), 2022,.15-21.

[25] Sadique, M.; Shah, S.R.; Sharma, S.K.; Islam, S.M.N. Effect of Significant Parameters on Squeeze Film Characteristics in Pathological Synovial Joints. *Mathematics* **2023**, *11*, 1468, https://doi.org/10.3390/math11061468.

[26] Shah, S.R. A Biomechanical Approach for the Study of Deformation of Red Cells in Narrow Capillaries. *Int. J. Eng.* **2012**, *25*, https://doi.org/10.5829/idosi.ije.2012.25.04a.02.

[27] Shah, S.R. A Biomechanical Approach for the Study of Two-Phase Blood Flow Through Stenosed Artery. *J. Eng. Appl. Sci.* **2012**, *7*, 159–164, https://doi.org/10.3923/jeasci.2012.159.164.

[28] Shah, S. R., "An innovative solution for the problem of blood flow through stenosed artery using generalized bingham plastic fluid model", International Journal of research in applied and natural social sciences, (2013) 1(3),.97-140.

[29] Shah, S.R. An Innovative Study for non-Newtonian Behaviour of Blood Flow in Stenosed Artery using Herschel-Bulkley Fluid Model. *Int. J. Bio-Science Bio-Technology* **2013**, *5*, 233–240, https://doi.org/10.14257/ijbsbt.2013.5.5.24.

[30] Shah, S. R., "Effect of clopidogrel on blood flow through stenosed artery under diseased condition", International Journal of Experimental Pharmacology, 4(1),.887-893, (2014).

[31] Shah, S.R. Effects of Acetylsalicylic Acid on Blood Flow Through an Artery under Atherosclerotic Condition. *Int. J. Mol. Med. Adv. Sci.* **2011**, *7*, 19–24, https://doi.org/10.3923/ijmmas.2011.19.24.

[32] Shah, S.R. Effects of Antiplatelet Drugs on Blood Flow through Stenosed Blood Vessels. *J. Biomimetics, Biomater. Tissue Eng.* **2013**, *18*, 21–27, https://doi.org/10.4028/www.scientific.net/jbbte.18.21.

[33] Shah, S. R., "Impact of radially non-symmetric multiple stenoses on blood flow through an artery", International Journal of Physical and Social Sciences, 1 (3), 1-16, (2011).

[34] Shah, S.R. Non-Newtonian Flow of Blood Through an Atherosclerotic Artery. *Res. J. Appl. Sci.* **2011**, *6*, 76–80, https://doi.org/10.3923/rjasci.2011.76.80.

[35] Shah, S. R., "Performance modeling and analysis of magnetic field on nutritional transport capillary tissue system using modified Herschel-Bulkely fluid", International Journal of Advanced research in physical sciences, 1(1),.33-41, (2014).

[36] Shah, S.R.; Internationals, O. Significance of Aspirin on Blood Flow to Prevent Blood Clotting through Inclined Multi-Stenosed Artery. *Lett. Heal. Biol. Sci.* **2017**, *2*, 97–100, https://doi.org/10.15436/2475-6245.17.018.

[37] Shah, S.R.; Siddiqui, S.U. A Physiologic Model for the Problem of Blood Flow through Diseased Blood Vessels. *Int. J. Adv. Appl. Sci.* **2016**, *5*, 58–64, https://doi.org/10.11591/ijaas.v5.i2.pp58-64.

[38] Study of dispersion of drug in blood flow with the impact of chemical reaction through stenosed artery. *Int. J. Biosci. (IJB)* **2022**, https://doi.org/10.12692/ijb/21.3.199-208.

[39] Sharma, S., Alshehri, Mo., Gupta, P., Shah, S. R., "Detection and Diagnosis of Learning Disabilities in Children of Saudi Arabia with Artificial Intelligence", Research Square, 1-22, (2023). https://doi.org/10.21203/rs.3.rs-3301949/v1.

[40] Shah, S.R.; Siddiqui, S. Achievement of Pentoxifylline for Blood Flow through Stenosed Artery. *J. Biomimetics, Biomater. Tissue Eng.* **2012**, *13*, 81–89, https://doi.org/10.4028/www.scientific.net/jbbte.13.81.

[41] Siddiqui, S. U., Shah, S. R., "Two-phase model for the study of blood flow through stenosed artery, International Journal of Pharmacy and Biological Sciences, 1(3), 246-254, (2011).

[42] Siddiqui, S. U., Shah, S. R.,"A Comparative Study for the Non-Newtonian Behaviour of Blood Flow through Atherosclerotic Arterial Segment", International Journal of Pharmaceutical Sciences Review and Research, Vol.9 (2), 120-125, (2011).
[43] Singh, A., Shah, S. R., S.U. Siddiqui, "Mathematical Modeling and Numerical Simulation of Blood Flow through Tapered Artery", International Journal of Innovative Science, Engineering & Technology, 3, (2), 710-717, (2016).
[44] Singh, A., Shah, S. R., Siddiqui, S. U., "A Mathematical Model to study the similarities of blood fluid models through inclined multi-stenosed artery", International Journal of Engineering Research and Modern Education, 2, (1), 108-115, (2017).
[45] Shah, S.R.; Kumar, R. Mathematical Modeling of Blood Flow With the Suspension of Nanoparticles Through a Tapered Artery With a Blood Clot. *Front. Nanotechnol.* **2020**, *2*, https://doi.org/10.3389/fnano.2020.596475.
[46] Singh, A., Shah, S. R.,, S.U. Siddiqui, "Mathematical Modeling of peristaltic blood flow through a vertical blood vessel using prandtl fluid model", International Journal of Mathematics and Computer Research, 4, (9), 710-717, (2016).
[47] Singh, P.; Solanki, R.; Tasneem, A.; Suri, S.; Kaur, H.; Shah, S.R.; Dohare, R. Screening of miRNAs as prognostic biomarkers and their associated hub targets across Hepatocellular carcinoma using survival-based bioinformatics approach. *J. Genet. Eng. Biotechnol.* **2024**, *22*, 100337, https://doi.org/10.1016/j.jgeb.2023.100337.
[48] Shah, S.R. Clinical Significance of Aspirin on Blood Flow through Stenotic Blood Vessels. *J. Biomimetics, Biomater. Tissue Eng.* **2011**, *10*, 17–24, https://doi.org/10.4028/www.scientific.net/jbbte.10.17.
[49] Singh, S. Effects of shape of stenosis on arterial rheology under the influence of applied magnetic field. *Int. J. Biomed. Eng. Technol.* **2011**, *6*, 286, https://doi.org/10.1504/ijbet.2011.041466.
[50] Shah, S.R. A Biomechanical Approach for the Study of Deformation of Red Cells in Narrow Capillaries. *Int. J. Eng.* **2012**, *25*, https://doi.org/10.5829/idosi.ije.2012.25.04a.02.
[51] Shah, S.R. The Effect of Saline Water on Viscosity of Blood through Stenosed Blood Vessels Using Casson's Fluid Model. *J. Biomimetics, Biomater. Tissue Eng.* **2011**, *9*, 37–45, https://doi.org/10.4028/www.scientific.net/jbbte.9.37.
[52] Singh, S., Shah, R. R.,"A numerical model for the effect of stenosis shape on blood flow through an artery using power-law fluid", Advance in applied science research, An international peer reviewed journal of sciences, 1, 66-73, (2010).
[53] Kumar, R.; Shah, S.R.; Stiehl, T. Understanding the impact of feedback regulations on blood cell production and leukemia dynamics using model analysis and simulation of clinically relevant scenarios. *Appl. Math. Model.* **2024**, https://doi.org/10.1016/j.apm.2024.01.048.