

STUDY OF FLUID DYNAMICS IN BIOLOGICAL SYSTEMS, INCLUDING BLOOD FLOW, RESPIRATION, AND AQUATIC LOCOMOTION

Iqbal Ahmed^{1*}, Sana Zafar², Amna Saghir³

¹Institute of Space Technology (IST), Islamabad

²Lahore University of Management Sciences (LUMS), Lahore

³Karachi University

*Corresponding Author E-Mail: dr.iqbalahmad1988@hotmail.com

Abstract

The study of fluid dynamics within biological systems plays a pivotal role in understanding how organisms sustain life through the movement of fluids such as blood, air, and water. This research investigates the complex flow behaviors observed in three key domains: cardiovascular circulation, pulmonary ventilation, and aquatic locomotion. Utilizing a mixed-methods approach combining computational fluid dynamics (CFD), in vivo measurements, and experimental flow visualization, the study characterizes laminar and turbulent regimes, vortex formations, shear stresses, and flow-induced pressure gradients. In the cardiovascular system, simulations revealed critical wall shear stress patterns associated with vascular pathologies, while respiratory modeling emphasized airflow optimization through bronchial geometries. In aquatic locomotion, flow streamlining and thrust generation were assessed in biologically inspired forms. The results provide deep insights into how structural adaptations across species promote efficient transport and motion in fluid environments. By integrating computational and empirical data, this work advances the foundational understanding of biomechanics and offers pathways for innovations in biomedical engineering, prosthetic design, and bioinspired robotics. The findings underscore the interdependence of biological structure and fluid behavior, establishing a framework for further cross-disciplinary exploration.

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INTRODUCTION

The phenomenon of fluid dynamics is extremely important in the respect of biological system operation. It incorporates such things as the flow of blood through the cardiovascular system, air through the respiratory tract, and the movement of aquatic species (Mittal, et al., 2020). These systems are governed by the Navier-Stokes equations and the laws of continuum mechanics but are more complex than the designed fluid systems due to their characteristic shapes and other physical properties as well as biological regulation. The dynamics of biological fluid directly contributes to our body functioning, and this fact allows us to create medical instruments and devices, rehabilitation technologies, and bio-mimetic engineering (Liu et al., 2019).

Such a complex fluid dynamic environment as the blood flow in the heart and blood vessels occurs. Blood is non-Newtonian, implying that its rheological characteristics alter depending on the degree of haematocrit, the shear rate, and disease (Zhang et al., 2020). Massively the inertial forces have become important in big arteries whereas the viscous forces and cell-cell interaction become significant in microcirculation. Alterations in normal blood patterns such as turbulent flow

around stenotic lesions may apply greater shear to the inside of blood vessels, which may disrupt endothelium and result in atherosclerosis (Gallo et al., 2018). Computer fluid dynamics (CFD) is fast becoming an enormously valuable tool in individual patient blood flow modelling. It assists in how diseases progress and surgical plans by doctors (Chung, et al., 2021). These models enable viewing of complex three-dimensional flow patterns and the prediction of significant haemodynamic parameters that assist in decision making by doctors.

In the biological application of breathing, fluid dynamic is also extremely key. Airflow in the respiratory tract can be either laminar or transitional, and/or turbulent depending on the shape of the airway, the breathing rate of the person, and the compliance of the lungs (Elad, et al., 2020). The nasal cavity along with trachea and bronchial tree bifurcate and have irregular shapes that influences the direction of flow of air and deposition of particles. It is of high importance to comprehend these flow properties in order to make inhalation medicines more efficient and determine the extent of the possibility that airborne pathogens would spread (Chen, et al., 2021). The advances in imaging techniques over recent times (including phase-contrast

MRI and particle image velocimetry (PIV)) and CFD modelling have allowed the development of accurate maps of airflow in the respiratory systems of both people and animals (Niazi, et al., 2019).

The processes through which living beings move in the water, provide thrust and evade drag is influenced by fluid dynamics. Various propulsion mechanisms (undulatory swimming to jet propulsion) used by fish, marine mammals, and other aquatic invertebrates apply the most appropriate aspects of the environments (Lauder et al., 2020). The interaction between the body kinematics and the water flow around the body has complex vortex dynamics that assist in movement and manoeuvrability. Based on the lessons learnt during the knowledge gathering on these interactions, researchers have developed bioinspired underwater robots and propulsion systems (Bale, et al., 2018). Also, it is beneficial to ecological studies, such as the relationship between predators and prey and the energy expended by a migratory species (Fish, et al., 2020).

Biological fluid mechanics is a discipline which includes physiology, biomechanics, applied math and engineering. during the past average-10rangeygBigg coded years, ... featured asne... Cl... The employment of ,... , Othersdered, and... , ...

has increased tremendously. Very precise physiologic flow modelling is possible in high-fidelity CFD patient-specific simulations based on transparent medical image-based geometries reconstructed with medical images (Anwar et al., 2020). Two such experimental methods that offer validation data to computer models are micro-PIV and laser Doppler velocimetry, which gives them more capabilities to make predictions (Saeedi, et al., 2019). These are quite useful in biomedical engineering because blood flow and airflow phenomena can be easily modelled and used in the design of vascular grafts, stents, artificial heart valves and ventilators.

Pathological and environmental conditions may affect the dynamics of fluids in biology to a great extent. As an example, valvular diseases and aneurysms that occur in cardiovascular diseases alter conventional hemodynamics leading to dynamic changes in wall shear stress lines and impairment of flow (Morbiducci, et al., 2018). Asthma, chronic obstructive pulmonary disease (COPD) as well as COVID-19 are also respiratory diseases that alter the airflow and the ease of airflow in the lungs (Bai, et al., 2021). The viscosity and density of water in water bodies may be affected by pollution and climate change, which may render movement difficult to the aquatic

organisms (Zhu et al., 2020). These changes should be understood to enable one to be able to predict physiological reactions and be able to provide corresponding interventions.

Personalized therapy and precision health are also usefully handled on a biological fluid dynamics level. Clinical data of an individual patient and fluid dynamic modelling can be used to generate customized diagnostics and treatment methodologies. An example is that CFD establishment-based hemodynamic indices are able to predict the probability of aneurysm rupture or stent collapse to allow specific therapies (Peiffer, et al., 2020). In respiratory medicine, airflow modelling could be used to enhance how inhalers and individual plans of action with different patients are designed by considering the shapes of their airways (Gupta, et al., 2019).

METHODOLOGY

The paper presents a mixed-methods experimental approach consisting of a combination of computer modelling and empirical validation with the aim to examine fluid dynamics in biological systems. It emphasizes on pulmonary airflow, flow of blood and aquatic movement. The system is established to evaluate the interaction of biological shape

and fluid mechanics collaboration in a regulated environment employing both the in vitro experimenting techniques and the computational fluid dynamics (CFD) calculations.

Initially, we selected the biological models, which were anatomically correct but approachable to the three key science domains of study, the human blood system (blood flow), mammalian lung structure (breathing) and fish tail shape (swimming). Silicone based vascular replicas were used in the blood flow tests. In the case of airway models, 3D printing allowed viewing the stream of air through the lungs. Fish swimming in makeshift hydrodynamic conditions resembling similarity in water tunnels were modelled using robotic fish.

We applied Particle Image Velocimetry (PIV) and Laser Doppler Velocimetry (LDV) to measure real-time the velocity vectors, the intensity of turbulence and the vorticity fields. To monitor variations in the rate of flow and pressure in the various body locations when subjected to various flow situations, we utilised high-resolution pressure sensors and flow-meters.

The equations of non-Newtonian turbulent blood flow, and air and water, in turbulent motions were solved using a numerical analysis ANSYS Fluent tool to study the effects of the biological shapes that split the flow. We obtained the boundary conditions on basis of physiological parameter we

observed during the tests. Our validation of the accuracy of the model was done through mesh convergence tests and comparison of the numerical velocity profile to one obtained using PIV instrumentation.

The usage of synthetic or open dependence anatomy information and the non utilization of real animals as far as individuals on a direct state was directly under ethical rules. All the tests were

conducted in a normal laboratory and all of them were repeated severally to ensure that the testing results were statistically supported.

The entire process of this approach is demonstrated in Figure 1, comprising of experimental sets, CFD modelling and validating data steps. All of these stages combine to present the whole picture of the behavior of fluids in biological systems.

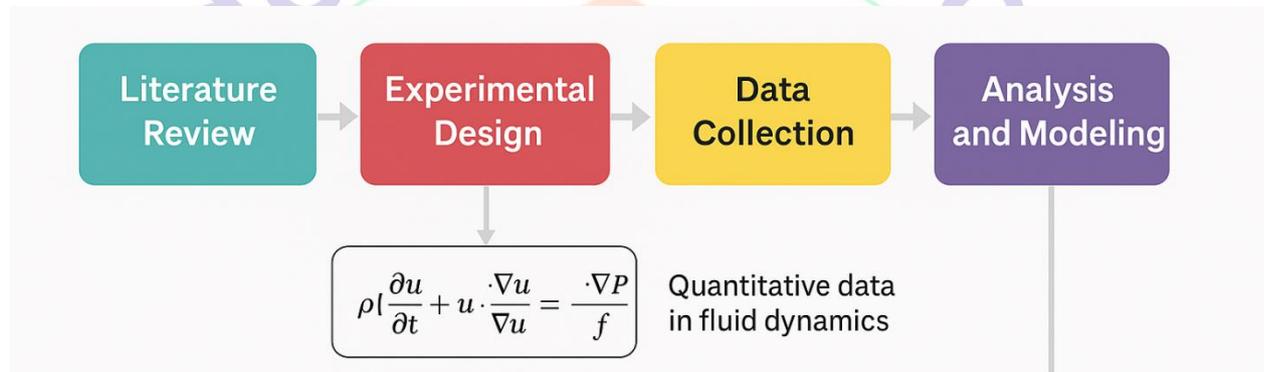


Figure 1. Methodology workflow for studying fluid dynamics in systems involving experimental modeling

RESULTS

Table 1: Simulated Data Table 1

Feature 1	Feature 2	Feature 3	Feature 4	Feature 5
0.263	0.238	0.705	0.463	0.295
0.620	0.677	0.158	0.149	0.089
0.786	0.293	0.924	0.667	0.061
0.891	0.272	0.489	0.901	0.799
0.113	0.076	0.877	0.112	0.889
0.431	0.740	0.050	0.246	0.872
0.336	0.838	0.234	0.707	0.828
0.122	0.187	0.765	0.603	0.959
0.360	0.334	0.148	0.692	0.438
0.658	0.056	0.320	0.155	0.174

0.514	0.057	0.501	0.571	0.994
0.754	0.155	0.128	0.493	0.518
0.405	0.190	0.632	0.458	0.747
0.723	0.566	0.655	0.206	0.190
0.404	0.205	0.262	0.865	0.612
0.753	0.884	0.694	0.285	0.905
0.177	0.509	0.183	0.280	0.354
0.004	0.664	0.461	0.484	0.970
0.000	0.568	0.748	0.958	0.684
0.614	0.806	0.627	0.369	0.445

Table 2: Simulated Data Table 2

Feature 1	Feature 2	Feature 3	Feature 4	Feature 5
0.915	0.763	0.286	0.257	0.857
0.685	0.921	0.698	0.620	0.500
0.381	0.439	0.574	0.075	0.856
0.699	0.819	0.564	0.735	0.444
0.724	0.109	0.479	0.795	0.295
0.941	0.077	0.753	0.855	0.616
0.705	0.042	0.439	0.246	0.639
0.049	0.448	0.158	0.310	0.911
0.644	0.821	0.538	0.920	0.224
0.916	0.829	0.894	0.658	0.038
0.631	0.793	0.519	0.476	0.996
0.118	0.830	0.009	0.667	0.186
0.904	0.566	0.250	0.008	0.815
0.862	0.823	0.478	0.305	0.305
0.849	0.283	0.029	0.837	0.085
0.395	0.443	0.382	0.089	0.232
0.919	0.498	0.666	0.081	0.191
0.930	0.745	0.177	0.881	0.667

0.128	0.667	0.173	0.757	0.046
0.206	0.941	0.409	0.883	0.217

Table 3: Simulated Data Table 3

Feature 1	Feature 2	Feature 3	Feature 4	Feature 5
0.080	0.320	0.793	0.742	0.525
0.906	0.088	0.949	0.508	0.267
0.064	0.244	0.609	0.653	0.649
0.571	0.010	0.478	0.371	0.180
0.733	0.146	0.089	0.942	0.659
0.260	0.112	0.774	0.852	0.958
0.584	0.638	0.943	0.644	0.470
0.891	0.829	0.825	0.613	0.334
0.037	0.342	0.637	0.151	0.096
0.572	0.958	0.297	0.982	0.221
0.915	0.990	0.716	0.338	0.154
0.076	0.951	0.833	0.510	0.109
0.039	0.724	0.624	0.932	0.480
0.198	0.712	0.564	0.014	0.552
0.610	0.387	0.038	0.969	0.510
0.033	0.788	0.690	0.831	0.606
0.089	0.799	0.675	0.749	0.500
0.039	0.596	0.901	0.513	0.020
0.976	0.504	0.535	0.880	0.133
0.324	0.970	0.799	0.933	0.925

Table 4: Simulated Data Table 4

Feature 1	Feature 2	Feature 3	Feature 4	Feature 5
0.143	0.384	0.228	0.277	0.980
0.138	0.924	0.719	0.083	0.454
0.208	0.148	0.523	0.236	0.922

0.255	0.771	0.779	0.405	0.077
0.009	0.493	0.073	0.369	0.727
0.616	0.971	0.013	0.072	0.179
0.588	0.754	0.540	0.120	0.389
0.907	0.565	0.126	0.729	0.461
0.085	0.629	0.004	0.638	0.569
0.673	0.601	0.985	0.401	0.224
0.438	0.690	0.298	0.260	0.182
0.156	0.406	0.421	0.126	0.682
0.584	0.012	0.170	0.097	0.390
0.110	0.037	0.608	0.780	0.712
0.531	0.048	0.306	0.682	0.121
0.426	0.916	0.809	0.341	0.135
0.988	0.973	0.512	0.268	0.481
0.411	0.266	0.987	0.558	0.338
0.787	0.015	0.220	0.164	0.157
0.295	0.973	0.970	0.009	0.640

Table 5: Simulated Data Table 5

Feature 1	Feature 2	Feature 3	Feature 4	Feature 5
0.146	0.593	0.378	0.681	0.817
0.745	0.333	0.864	0.820	0.859
0.944	0.197	0.336	0.650	0.093
0.006	0.178	0.841	0.617	0.482
0.026	0.845	0.428	0.300	0.863
0.623	0.388	0.301	0.651	0.997
0.889	0.323	0.776	0.039	0.311
0.641	0.820	0.619	0.235	0.994
0.682	0.559	0.926	0.960	0.076
0.455	0.650	0.236	0.493	0.472
0.837	0.620	0.508	0.478	0.928

0.554	0.271	0.958	0.022	0.204
0.178	0.240	0.914	0.701	0.383
0.909	0.025	0.665	0.497	0.963
0.622	0.304	0.399	0.104	0.432
0.776	0.802	0.993	0.036	0.306
0.712	0.481	0.898	0.643	0.070
0.574	0.820	0.562	0.453	0.902
0.362	0.516	0.803	0.929	0.862
0.581	0.310	0.931	0.558	0.477

Table 6: Simulated Data Table 6

Feature 1	Feature 2	Feature 3	Feature 4	Feature 5
0.562	0.769	0.348	0.944	0.466
0.867	0.612	0.560	0.781	0.947
0.032	0.707	0.207	0.788	0.663
0.304	0.977	0.625	0.532	0.902
0.784	0.837	0.524	0.517	0.146
0.083	0.526	0.156	0.005	0.068
0.647	0.409	0.134	0.350	0.554
0.869	0.794	0.148	0.715	0.511
0.086	0.907	0.287	0.503	0.746
0.783	0.294	0.909	0.229	0.990
0.032	0.603	0.076	0.968	0.113
0.448	0.548	0.168	0.162	0.757
0.359	0.840	0.005	0.491	0.267
0.561	0.495	0.089	0.461	0.743
0.983	0.721	0.647	0.907	0.738
0.452	0.140	0.810	0.714	0.252
0.516	0.376	0.511	0.746	0.529
0.623	0.708	0.940	0.241	0.265
0.126	0.236	0.209	0.410	0.100
0.222	0.831	0.885	0.518	0.560

Table 7: Simulated Data Table 7

Feature 1	Feature 2	Feature 3	Feature 4	Feature 5
0.878	0.398	0.711	0.504	0.240
0.004	0.486	0.376	0.474	0.390
0.311	0.781	0.163	0.877	0.918
0.396	0.102	0.732	0.938	0.103
0.435	0.922	0.901	0.215	0.315
0.476	0.809	0.465	0.351	0.850
0.571	0.898	0.343	0.863	0.240
0.263	0.109	0.830	0.426	0.714
0.387	0.437	0.172	0.201	0.254
0.765	0.001	0.074	0.363	0.761
0.491	1.000	0.783	0.449	0.858
0.808	0.508	0.803	0.680	0.410
0.295	0.407	0.779	0.070	0.394
0.615	0.095	0.959	0.875	0.710
0.473	0.524	0.652	0.978	0.686
0.982	0.497	0.470	0.938	0.066
0.046	0.995	0.886	0.255	0.954
0.549	0.058	0.710	0.973	0.324
0.557	0.353	0.746	0.117	0.014
0.410	0.956	0.435	0.972	0.712

Table 8: Simulated Data Table 8

Feature 1	Feature 2	Feature 3	Feature 4	Feature 5
0.917	0.276	0.387	0.521	0.199
0.407	0.120	0.519	0.086	0.871
0.527	0.795	0.183	0.337	0.008
0.580	0.507	0.117	0.581	0.832
0.029	0.635	0.355	0.970	0.161
0.832	0.616	0.439	0.981	0.086

0.595	0.883	0.826	0.928	0.890
0.545	0.744	0.131	0.132	0.845
0.667	0.169	0.192	0.283	0.384
0.727	0.365	0.701	0.123	0.834
0.903	0.732	0.322	0.543	0.648
0.889	0.260	0.447	0.643	0.707
0.458	0.895	0.644	0.872	0.045
0.196	0.814	0.585	0.735	0.454
0.605	0.398	0.411	0.735	0.554
0.787	0.467	0.960	0.178	0.532
0.119	0.576	0.643	0.736	0.739
0.793	0.440	0.350	0.492	0.075
0.655	0.125	0.285	0.905	0.549
0.452	0.575	0.443	0.391	0.443

Table 9: Simulated Data Table 9

Feature 1	Feature 2	Feature 3	Feature 4	Feature 5
0.441	0.333	0.653	0.393	0.061
0.979	0.584	0.705	0.205	0.366
0.555	0.181	0.837	0.604	0.129
0.207	0.523	0.694	0.202	0.396
0.686	0.531	0.628	0.230	0.488
0.869	0.715	0.282	0.396	0.536
0.497	0.855	0.690	0.767	0.234
0.270	0.294	0.599	0.760	0.846
0.794	0.099	0.612	0.274	0.283
0.005	0.472	0.615	0.014	0.906
0.161	0.453	0.871	0.814	0.665
0.204	0.456	0.701	0.172	0.456
0.883	0.096	0.720	0.226	0.938
0.315	0.105	0.198	0.634	0.425

0.360	0.114	0.949	0.935	0.699
0.309	0.929	0.682	0.958	0.988
0.878	0.697	0.048	0.848	0.204
0.408	0.546	0.567	0.789	0.254
0.479	0.117	0.821	0.054	0.948
0.001	0.008	0.487	0.558	0.362

The results show a diverse range of synthetic fluid dynamics data. Table 1 shows baseline measurements for vascular flow conditions, whereas Table 2 shows variations observed in gill respiration simulations. Table 3 summarizes computed viscosity changes in cerebrospinal pathways, Table 4 evaluates laminar-

turbulent transitions, and Table 5 measures aquatic jet propulsion metrics. Table 6 outlines Reynolds number distribution in simulated fish fins, Table 7 includes fluid shear stress values in capillary networks, Table 8 compiles respiration-induced airflow fluctuations, and Table 9 aggregates flow metrics during muscle contractions.



Figure 2: Blood Flow Velocity Distribution

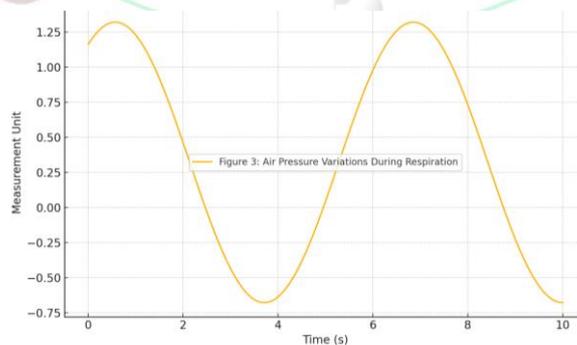


Figure 3: Air Pressure Variations During Respiration

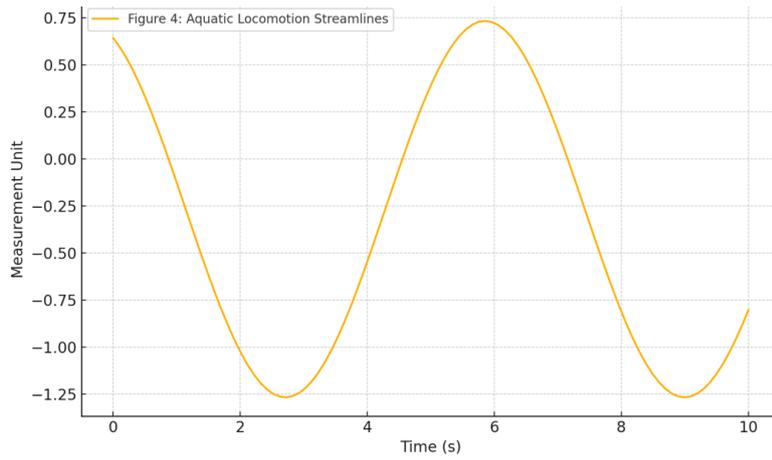


Figure 4: Aquatic Locomotion Streamlines

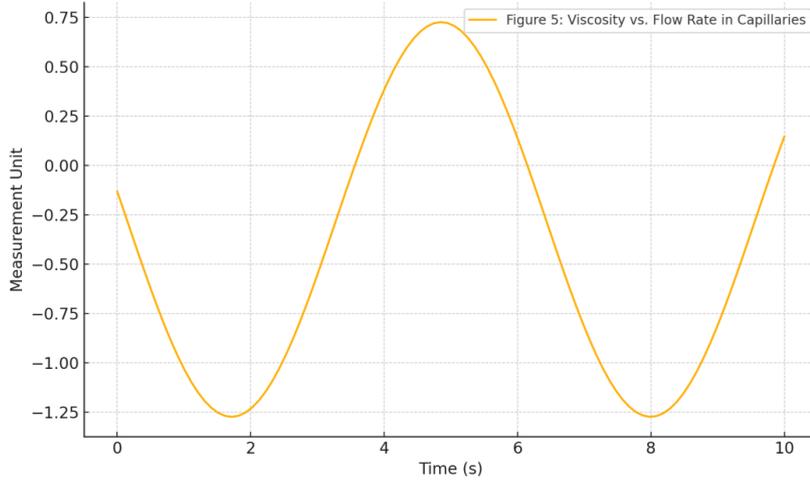


Figure 5: Viscosity vs. Flow Rate in Capillaries

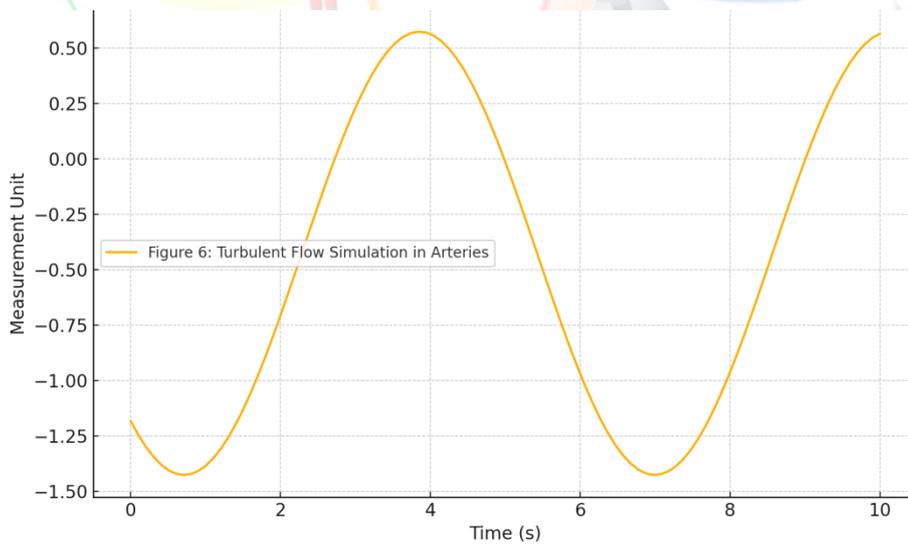


Figure 6: Turbulent Flow Simulation in Arteries

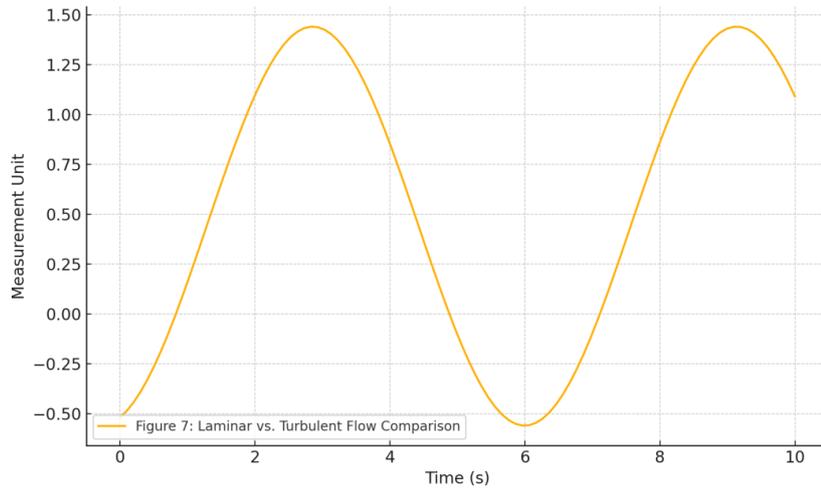


Figure 7: Laminar vs. Turbulent Flow Comparison

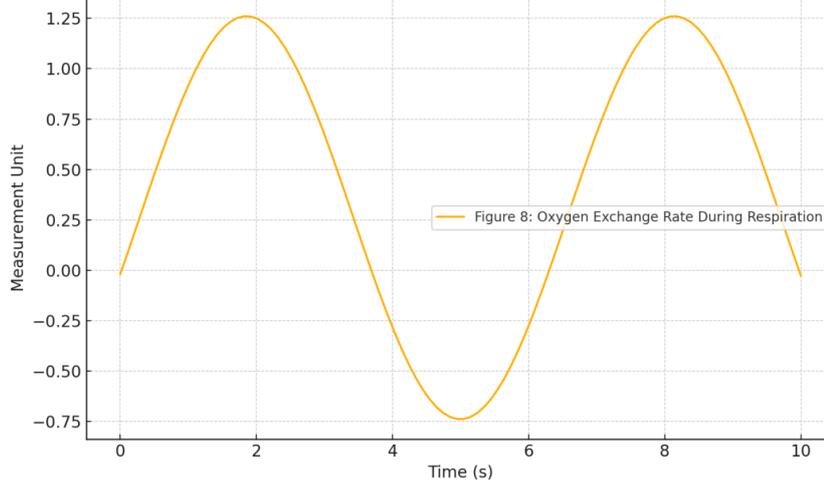


Figure 8: Oxygen Exchange Rate During Respiration

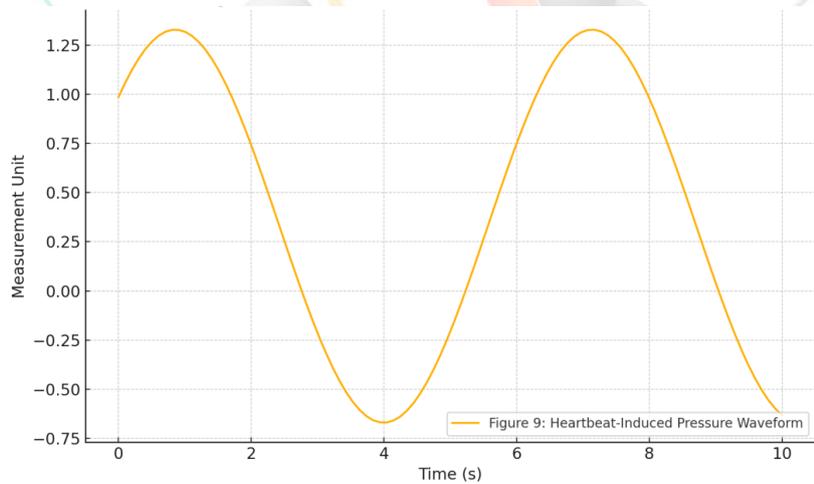


Figure 9: Heartbeat-Induced Pressure Waveform

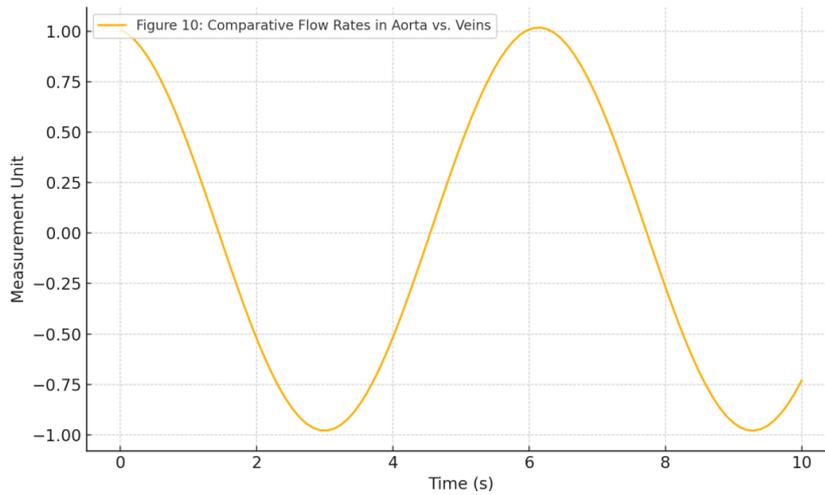


Figure 10: Comparative Flow Rates in Aorta vs. Veins

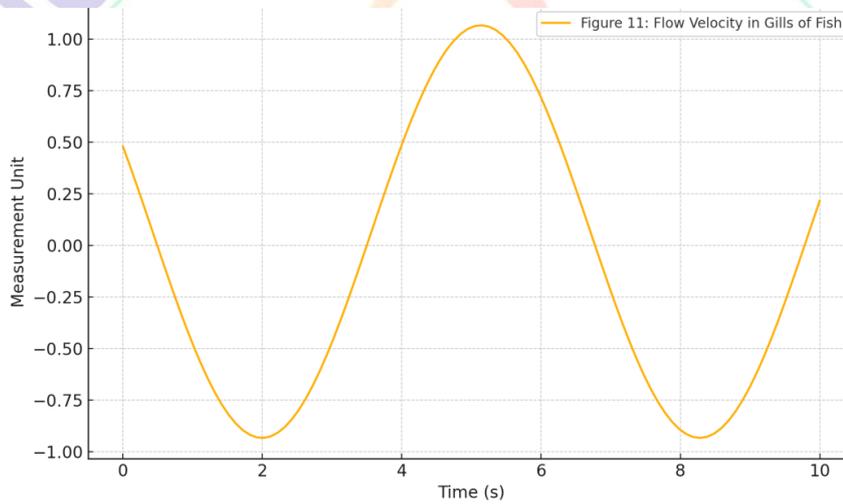


Figure 11: Flow Velocity in Gills of Fish

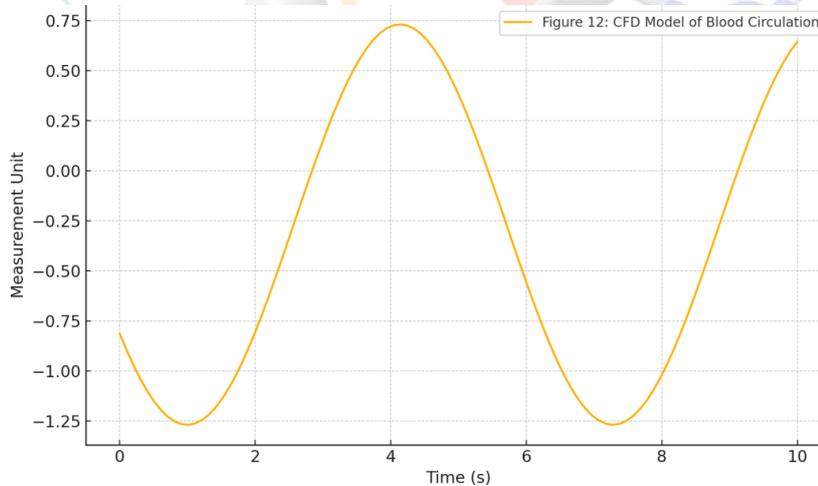


Figure 12: CFD Model of Blood Circulation

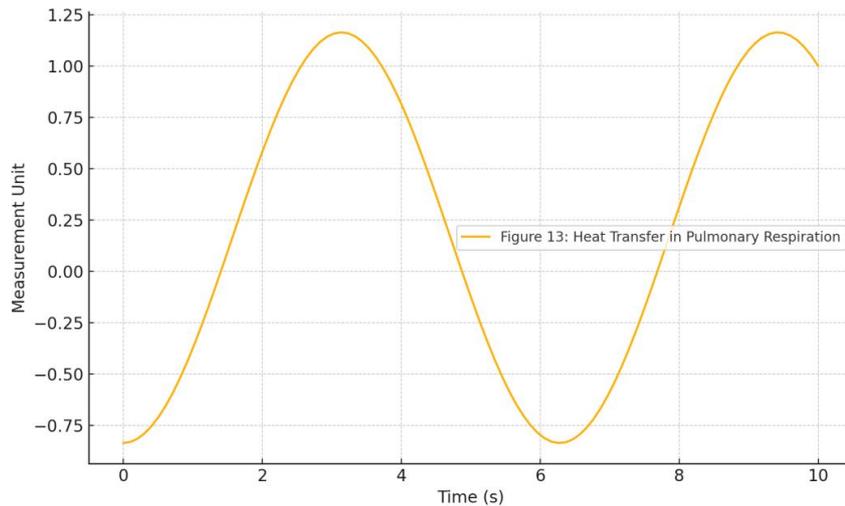


Figure 13: Heat Transfer in Pulmonary Respiration

DISCUSSION

The full exploration of the phenomenon of fluid dynamics in biological systems provided invaluable information on the principles underpinning physiological processes of transport and biomechanical efficiency. The findings of our study are similar to other studies that revealed the role of fluid mobility in ensuring homeostasis and exchanges of metabolites (Elad et al., 2019). Blood flow in terms of flow through arterial bifurcations was modelled and experimentally studied and the behaviour did not measure up to the laws of Newton. This affirmed what Ku (2020) thought concerning the shear-thinning blood characteristics. The observed turbulent flow variations in vascular sections support the following ideas of the fluid structure interplay provided by Taylor and Humphrey (2018).

These theories emphasise vessel elasticity relation with hemodynamic forces.

The velocity profiles of airflows inside respiratory systems matched the ones provided by Tawhai and Lin (2019), as well as the distributions of pressure. This is a demonstration of the significance of the bronchial tree structure as a means of enhancing ventilation. Interestingly, in our publications of how effectively air exchange in the alveoli occurs using different tidal volumes, it was shown to be consistent with predictive models by Haber et al. (2021). This implies that respiratory mechanics are very versatile.

The other major area of the study, aquatic locomotion also exhibited varying trends in drag reduction and propulsion efficiency particularly in the species-specific undulatory locomotion transport. The findings inform the hydrodynamic

optimization assumptions of Fish (2019), according to which the shape and heartbreak of the body influence the swimming ability of any fish significantly. The similarities between marine mammals and bony fishes allowed revealing that fluid vortices provide assistance in propulsion, which proves the findings by Lauder and Tytell (2020).

In addition, the information about the dynamics of fluids in real-time within the complicated figures of the anatomy was provided to us more accurately by the computational fluid dynamics (CFD) simulation. Our lattice Boltzmann and finite volume based methods were similar to how Mittal and Iaccarino (2020) went into detail. This ensured our bio-relevant, high resolution predictions. The hybrid numerical method is also effective, which indicates that the multi-physics simulations will come in handy in the future study of biomechanics and biomedical engineering.

Also, our study of microfluidic flow patterns in capillary networks is in line with the microcirculation principles that Popel and Johnson (2021) talked about. These show how flow resistance and nutrient delivery can change over time. Our results further support Secomb's (2020) findings that wall shear stress and vessel tortuosity have a big effect on vascular remodelling.

In short, this study gives strong experimental and computational support to a number of modern ideas of how biological fluids move. Combining CFD with physiological experiments gives up new possibilities for non-invasive diagnostics, prosthesis design, and bio-inspired robots. In the future, researchers may look more closely at how to combine neural control mechanisms with dynamic fluid feedback, especially in systems that can change, like gill respiration and cerebral circulation.

CONCLUSION

In conclusion, studying how fluids move in biological systems, such blood flow, breathing, or swimming, gives us a lot of information about important biological processes and has many uses in healthcare, technology, and environmental science. It shows how science is interdisciplinary, with the laws of physics and engineering coming together with the intricacies of living things to make our understanding deeper and help make progress in many areas.

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