Harnessing Aerospace Fluid Mechanics and Cavitation for Biomedical Engineering: Advancing Non-Invasive Therapies, Drug Delivery, and Medical Devices

Jubel Kurian*
Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 24061, United States of America

Aerospace engineering has contributed significantly to medical advancements through the application of fluid mechanics and cavitation principles. This paper explores how aerospace-derived methodologies have influenced modern medicine, particularly in non-invasive therapies, drug delivery, and biomedical device design. Theoretical foundations such as the Navier-Stokes equations for non-Newtonian blood flow, cavitation bubble dynamics, and fluid-structure interactions provide a framework for translating aerospace innovations into medical applications. Case studies including shock wave lithotripsy (SWL), histotripsy, microbubble drug delivery, and computational fluid dynamics (CFD) in cardiovascular modeling demonstrate the successful adaptation of aerospace techniques to enhance biomedical efficacy. Despite the potential, challenges remain in modeling biological complexities, ensuring experimental validation, and navigating regulatory pathways. Future research should focus on integrating advanced computational methods, machine learning, and high-fidelity experimental techniques to bridge existing knowledge gaps. This paper reviews and underscores the critical role of cross-disciplinary collaboration in fostering medical breakthroughs driven by aerospace technology. A key contribution of this study is the identification of existing gaps in biomedical research and the proposal of advanced computational and experimental methodologies to overcome these limitations. By bridging knowledge gaps between aerospace and medicine, this paper offers a novel pathway for future interdisciplinary innovations, ultimately driving transformative improvements in patient therapy, care and biomedical device performance guided by aerospace principles.

I. Introduction

A. Background and Motivation

Aerospace engineering has long served as a driving force for cutting-edge innovation, particularly in fields requiring robust, high-performance solutions. Although originally aimed at overcoming challenges related to atmospheric flight and space exploration, these technological breakthroughs have gradually expanded into the biomedical sphere. In this process—often described as "spin-off" or "dual-use" innovation [1]—materials, methods, and systems developed for aerospace applications are repurposed to advance patient care, medical devices, and diagnostic tools (For example, Figure 1). One such cross-disciplinary success story involves fluid mechanics and the phenomenon of cavitation. Within aerospace engineering, fluid mechanics underpins the analysis and design of aircraft wings, propulsion systems, and space vehicles [2]. A deeper understanding of turbulence, boundary layers, multiphase flows, and shock waves has translated directly into insights for biomedical problems, especially in hemodynamics [3] and fluid-based drug delivery systems [4]. Cavitation—initially a research focal point for mitigating erosion in rocket turbopumps and marine propellers—has similarly evolved into a crucial mechanism in non-invasive therapies [5]. By exploiting the rapid formation and collapse of vapor bubbles, physicians employ techniques such as shock wave lithotripsy (SWL) [6] to fragment kidney stones without surgical intervention [7], capitalizing on knowledge that was first refined for aerospace propulsion systems [8]. Furthermore, ultrasound-driven cavitation microbubbles, originally studied as part of

*Graduate Student, Department of Aerospace and Ocean Engineering, Student Member AIAA

Large Language Models were used to refine sentences for clarity and professionalism in this paper.

high-intensity pressure-wave control, are now employed to deliver therapeutic agents precisely to targeted tissue sites [9].

Fig. 1 VITAL (Ventilator Intervention Technology Accessible Locally): Device developed by engineers at NASA's Jet Propulsion Laboratory (JPL) [10]. It is an innovative, rapidly developed ventilator designed for efficient and scalable deployment in emergency medical scenarios, proving NASA's engineering expertise to address critical healthcare needs leveraging space technologies for terrestrial use.

Another significant link between aerospace and medicine lies in advanced fluid management techniques. In microgravity environments, spacecraft designers must ensure consistent liquid transport without the aid of gravity, leading to the development of capillary-driven flow technologies [11]. These solutions have since informed improvements to intravenous (IV) infusion systems [12] and other gravity-independent medical fluid delivery devices. Aerospace materials research also dovetails with biomedical applications. Titanium alloys, prized for their favorable strength-to-weight ratio and corrosion resistance in aircraft frames, have been adopted broadly for orthopedic implants and prosthetic devices due to their superior biocompatibility and mechanical properties [13]. Similarly, shape memory alloys (SMAs), once envisioned for morphing aerospace structures, are now widely utilized in stents and orthodontic archwires, leveraging their temperature-induced superelasticity to achieve minimally invasive delivery and self-deployment [14]. Computational fluid dynamics (CFD), originally developed to characterize complex flows around aerodynamic surfaces and within rocket engine components, is another realm where aerospace principles have aided biomedicine tremendously. By adapting CFD tools [15] to simulate pulsatile, non-Newtonian blood flow in geometries such as the left ventricle or vascular grafts, biomedical engineers can better predict device performance, hemolysis risk, and thrombosis potential—parameters critical to patient outcomes [16]. This synergy underscores the value of direct cross-pollination between aerospace and medical researchers, bridging the gap between aerodynamic design principles and human physiological constraints. Nevertheless, challenges persist. Biological fluids and tissues exhibit complexity far exceeding that of most engineered systems, characterized by time-dependent properties, rheological variability, and the influence of living cells [17]. Moreover, adopting aerospace-derived techniques in medicine often requires addressing stringent regulatory hurdles and ethical considerations, especially when dual-use technologies have potential defense applications. Despite these obstacles, the momentum of cross-disciplinary collaboration continues to grow, fueling new insights and promising solutions to pressing healthcare needs.

This paper provides a comprehensive review of how aerospace-driven fluid mechanics and cavitation research are actively transforming modern medicine. Following a survey of pertinent literature, key theoretical and methodological concepts are introduced, emphasizing the foundational fluid dynamic principles that have proven instrumental in biomedical contexts. We then examine specific cases of breakthroughs in Shock Wave Lithotripsy (SWL), histotripsy, microbubble drug delivery, fluid management in medical devices, and computational modelling for cardiovascular treatments. Finally, we discuss the ongoing challenges, considerations, and prospective pathways for further innovation in this fertile intersection between aerospace engineering and medicine.

II. Theoretical Foundations and Key Concepts

A. Overview: From Aerospace to Biomedical Fluid Mechanics

Aerospace fluid mechanics emphasizes high as well as low-Reynolds-number flows, compressibility effects, and phase transitions such as cavitation to optimize propeller efficiency and propulsion systems [2]. In contrast, biomedical fluid mechanics often concerns non-Newtonian behavior (e.g., blood rheology), compliant boundaries (e.g., vessel walls), and targeted use of cavitation in therapeutic interventions. Nevertheless, the underlying physics—mass, momentum, and energy conservation in multiphase or high-speed flows—remains consistent, allowing direct knowledge transfer from aerospace to medical applications upto some extent.

B. Governing Equations in Biomedical Flow Contexts

1. Navier–Stokes Equations for Non-Newtonian Blood Flow

Although many aerospace analyses treat fluids as Newtonian and incompressible, blood and other biofluids can display shear-dependent viscosity [18]. A generalized form of the momentum equation is:

$$\nabla \cdot \mathbf{u} = 0, \quad \rho \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \mathbf{f}, \tag{3.1}$$

where $\boldsymbol{\tau}$ is the deviatoric stress tensor incorporating a non-Newtonian viscosity model, $\mathbf{u}$ is the velocity field, ρ is density, and $\mathbf{f}$ is a body force term. Computational frameworks originally developed for aerospace CFD now accommodate these rheological complexities to simulate flow in artificial heart valves or ventricular assist devices [19].

2. Dimensionless Parameters for Biomedical Flows

Dimensionless groups guide the design and scaling of experiments and numerical models. The *Womersley number*, for instance, is crucial in pulsatile arterial flow:

$$\alpha = \sqrt{\frac{\omega \, \rho \, R^2}{\mu}}, \tag{3.2}$$

where ω is the angular frequency of the cardiac cycle, R is a characteristic radius of the vessel, and μ is the (effective) viscosity. High Womersley values indicate substantial inertial effects relative to viscous forces [20]. Meanwhile, the *cavitation number*, originally used to predict bubble formation in propellers, has analogous utility for assessing cavitation onset in high-flow biomedical devices [8].

C. Cavitation and Bubble Dynamics

1. Rayleigh–Plesset Equation for Medical Applications

The Rayleigh–Plesset equation underlies bubble dynamics in both turbomachinery and biomedical interventions such as SWL:

$$\rho \left(R \frac{d^2 R}{dt^2} + \frac{3}{2} \left(\frac{dR}{dt} \right)^2 \right) = p_\infty(t) - p_v - \frac{2\,\sigma_s}{R} - \frac{4\,\mu}{R} \frac{dR}{dt}. \tag{3.3}$$

Here, R is the bubble radius, p_v is vapor pressure, σ_s is surface tension, and μ is viscosity [21]. In aerospace, this equation helps prevent erosive bubble collapse. In medicine, it is exploited to fragment kidney stones or deliver localized therapy via inertial cavitation, with pulse frequency and amplitude carefully tuned to induce rapid, targeted collapses as discussed earlier.

2. Collapse-Induced Shock and Jet Formation

When a cavitation bubble implodes, intense microjets and shock waves can damage nearby surfaces. In biomedical lithotripsy, this controlled damage is harnessed to break stones or selectively ablate tissue. By contrast, in cardiovascular devices (e.g., blood pumps), unintended cavitation can cause hemolysis or degrade device components [R8]. Insights from aerospace on mitigating bubble damage near propeller blades guide design strategies to reduce shear stress peaks and bubble trapping within biomedical systems.

D. Fluid–Structure Interaction (FSI) in Biomedicine

Blood vessels and heart tissues are deformable and viscoelastic, unlike the rigid metal walls of aircraft fuel lines. Still, the same fluid–structure coupling principles studied in aeroelasticity (e.g., aircraft wing flutter) apply. An FSI approach couples the fluid momentum equations to structural deformation:

$$\mathbf{M}_s \frac{d^2\mathbf{d}}{dt^2} + \mathbf{C}_s \frac{d\mathbf{d}}{dt} + \mathbf{K}_s \mathbf{d} = -\int_{\Gamma_{\text{int}}} \boldsymbol{\sigma}_{\text{fluid}}\, \mathbf{n}\; d\Gamma, \tag{3.4}$$

where $\mathbf{d}$ is structural displacement, and $\mathbf{M}_s$, $\mathbf{C}_s$, $\mathbf{K}_s$ are mass, damping, and stiffness matrices, respectively [R9]. Accounting for vessel or tissue compliance has proven essential in predicting cavitation onset in pulsatile environments, reducing adverse outcomes like mechanical valve failures or vascular wall fatigue.

E. Acoustic Cavitation: Ultrasound and Shock Wave Contexts

Focusing high-intensity acoustic fields on a target region can trigger cavitation in a controlled manner. Nonlinear acoustics—once crucial for understanding supersonic flows in rocket nozzles—now informs *focused ultrasound therapies*, where shock-like wavefronts create transient low-pressure zones for bubble nucleation. By adjusting the frequency (kHz–MHz range) and pulse amplitude, clinicians can drive stable or inertial cavitation for drug delivery or tissue emulsification [22]. Translational studies directly link wave-propagation models from supersonic flows to high-intensity focused ultrasound (HIFU) beam-forming strategies in oncology [23].

Overall, aerospace-derived fluid mechanics and cavitation theories provide the fundamental scaffolding for numerous biomedical innovations, some of which are as highlighted in above sections.

III. Examples of Aerospace-Derived Fluid Mechanics and Cavitation in Biomedical Applications

A. Overview

The transition of aerospace fluid mechanics and cavitation research into biomedical applications represents a powerful cross-disciplinary synergy. Aerospace engineering has long been at the forefront of developing robust high-performance solutions for extreme environments, particularly in fluid transport, turbulence modeling, cavitation control, and computational simulations. These developments, initially aimed at enhancing aircraft efficiency and propulsion system longevity, have unexpectedly paved the way for novel biomedical innovations [24]. Theoretical and computational advances in aerospace engineering—particularly in multiphase flow modeling, cavitation physics, and Computational Fluid Dynamics (CFD)—have been seamlessly repurposed to solve biomedical challenges.

From Shock Wave Lithotripsy (SWL) and histotripsy to microbubble drug delivery and cardiovascular fluid modeling, the application of aerospace-driven methodologies has revolutionized medical technology. The following section systematically reviews some of such niche cross-domain advancements, providing a critical perspective on the key aerospace concepts adapted into biomedical fields, their impact on clinical applications, and future challenges that must be addressed to unlock their full potential.

B. Case Studies of Biomedicine Applications

1. Shock Wave Lithotripsy (SWL) and Cavitation Control

One of the earliest biomedical breakthroughs leveraging aerospace cavitation research is Shock Wave Lithotripsy (SWL) (Figure 2a)—a non-invasive kidney stone treatment that applies high-intensity focused acoustic pulses to induce cavitation bubble collapse around kidney stones, fragmenting them into smaller passable pieces[25].

The core principles of SWL originated from aerospace research into propeller cavitation and supersonic flow disturbances, where scientists sought to predict and mitigate cavitation erosion in turbomachinery components [8]. These same methodologies—such as pressure wave propagation analysis, computational bubble collapse models, and impact force predictions—have been directly repurposed to optimize SWL parameters, minimizing tissue damage while maximizing stone disintegration efficiency.

Early SWL treatments suffered from inconsistent fragmentation and collateral tissue injury, leading to the development of computational models borrowed from aerospace turbopump studies, which allowed for:

- Precise calibration of pulse energy and duration based on cavitation cloud distribution [26].
- Optimization of shock wave focus points to prevent damage to surrounding tissues [27].
- Predictive algorithms for bubble-induced fragmentation thresholds, mirroring techniques used in aerospace bubble-collapse erosion studies. [28]

These advancements have led to modern SWL techniques that improve treatment success rates while reducing complications, showcasing how fundamental cavitation control strategies continue to be exploited to be leveraged to enhance biomedical applications.

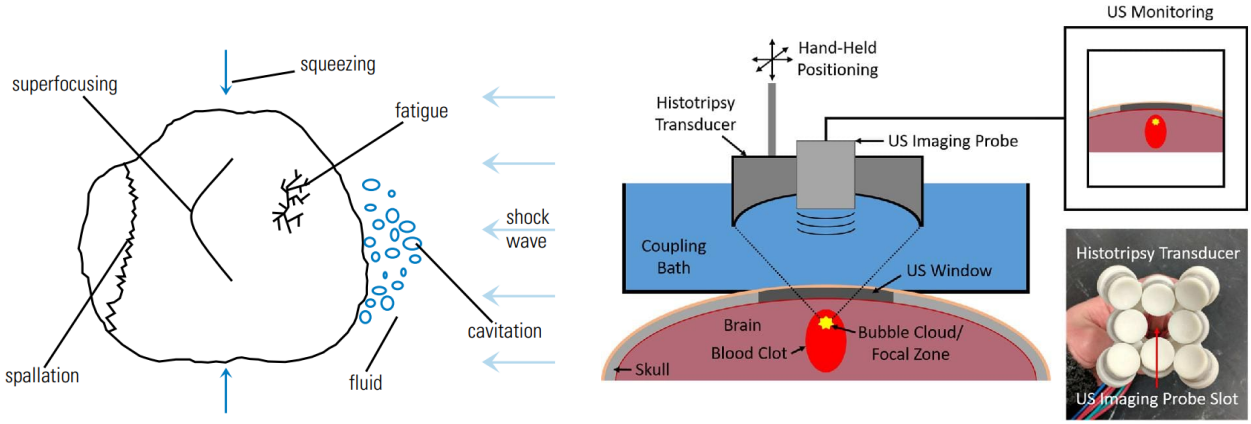

Fig. 2 (a) Schematic of shock wave comminution mechanisms during extracorporeal Shock Wave Lithotripsy (SWL). (b)Histotripsy- The noninvasive technique uses focused ultrasound to create cavitational microbubbles that can break up tissue. In the example shown here, histotripsy is being used to remove a blood clot in the brain non-invasively. [29]

2. Histotripsy: From Turbomachinery to Non-Invasive Tissue Ablation

Histotripsy, an advanced non-invasive ultrasound therapy, leverages precisely controlled cavitation bubbles to fractionate targeted tissues without relying on thermal energy [30], making it particularly effective for tumor ablation, liver treatments, and clot disruption (Figure 2b).

The mechanical destruction of tissues using cavitation bubble clouds in histotripsy mirrors erosion patterns observed

in aerospace turbopump blade damage studies. Research on shock-induced bubble collapse and high-speed liquid jets, originally developed to protect jet engine components, now provides the fundamental basis for:

- Optimizing cavitation bubble cloud densities for selective tissue destruction.
- Refining acoustic pulse modulation techniques, similar to turbulence suppression in aerospace applications.
- High-speed imaging and simulation methods, originally developed for blade erosion diagnostics, now used to monitor tissue destruction in real time.

These innovations make histotripsy another direct adaptation of cavitation research, reinforcing the strong link between high-speed aerodynamics and biomedical engineering.

3. Microbubble Drug Delivery: Aerospace-Driven Multiphase Flow Control

While aerospace engineers often aim to suppress cavitation and bubble formation in propulsion and hydrodynamic systems, biomedical researchers have successfully exploited controlled cavitation for targeted drug delivery. Microbubble-based drug delivery systems (Figure 3), which use ultrasound to induce cavitation-driven drug release, are a prime example of multiphase flow physics being repurposed for medicine.[31]

Aerospace research on bubble dynamics in fuel injection and cryogenic flow management directly informs:

- Microbubble stability modeling, ensuring prolonged circulation before cavitation-triggered drug release.
- Optimized ultrasound frequencies to trigger cavitation collapse at precise target sites.
- High-fidelity multiphase flow simulations, originally developed for liquid-fuel rocket engines, now used to predict drug transport efficiency in blood vessels.

This translation of aerospace-derived bubble dynamics and cavitation physics in resonance with acoustics has paved the way for minimally invasive, highly localized drug delivery systems, improving treatment efficacy while reducing systemic side effects.

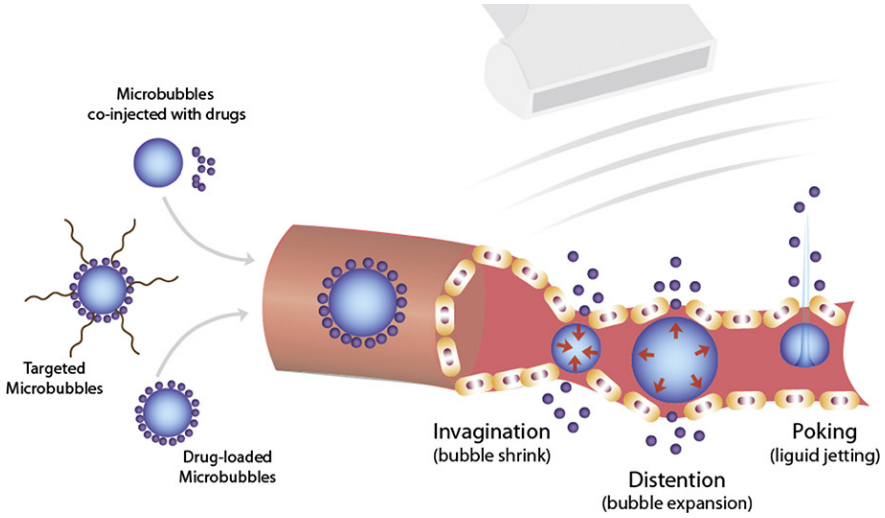

Fig. 3 Schematic showing ultrasound-directed medication administration. Microbubbles oscillate and collapse, which are amplified by ultrasound. This causes the vessel to deform, rupture, and the blood vessel vessel permeability is altered, increasing efficiency in drug delivery. All these events happen in a controlled time and space. Three examples of microbubble/ drug combinations are illustrated here.[32]

4. Advanced Fluid Transport in Medical Devices

Spacecraft liquid handling systems designed for microgravity conditions have significantly influenced gravity-independent biomedical fluid transport technologies. Key aerospace-derived contributions include:

- Capillary-driven microfluidic transport systems [33], now used in portable dialysis machines, drug delivery, and intravenous (IV) infusion devices [34].
- Bubble removal mechanisms, analogous to aerospace fuel lines, now preventing air embolism in infusion systems [35] (Figure 4).
- Centrifugal fluid separation methods [36], adapted from aerospace cryogenic propellant systems in addition to microfluidics geometries, now utilized in blood plasma filtration devices [37].

These technologies ensure consistent, controlled fluid delivery, enabling devices with the one or more of the following features: 1) Operate reliably in ambulatory or emergency environments, such as medevac helicopters or remote field clinics. 2) Maintain air-bubble detection and separation features, an outgrowth of aerospace air–fuel separation systems, to prevent embolism. 3) Reduce reliance on bulky gravitational setups, enabling more compact, portable medical equipment.

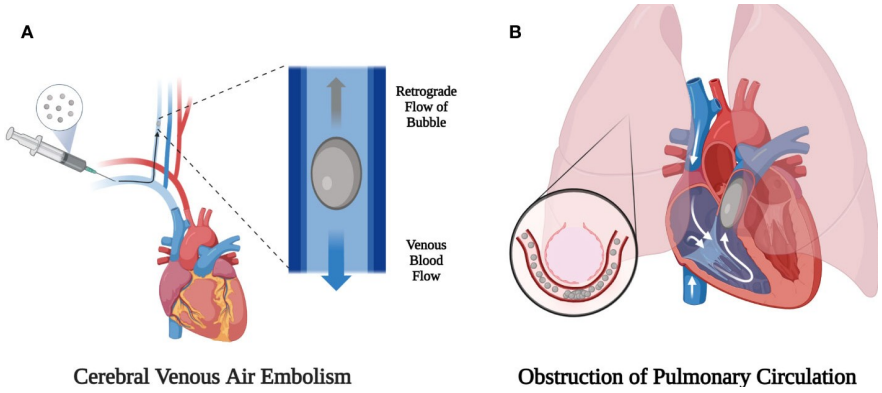

Fig. 4 Schematic showing mechanisms of air embolism and its physiological impacts. Air embolism introduced through intravenous (IV) lines can lead to obstruction of blood flow in critical vessels, causing tissue hypoxia, cardiovascular collapse, or neurological impairment depending on the size and location of the embolism.[38]

5. Computational Fluid Dynamics (CFD) in Cardiovascular Flow Modeling

Computational fluid dynamics (CFD), a cornerstone of modern aerospace design, has been extensively adapted for cardiovascular and other body fluid modeling, particularly in:

- Artificial heart valves and stents [39], using turbulence modeling techniques from jet engines.
- Ventricular assist devices (VADs) [40], where cavitation suppression strategies from aerospace propulsion are repurposed to prevent hemolysis and thrombosis.
- Non-Newtonian blood flow simulations [41], originally developed for aerospace boundary layer turbulence, now essential for predicting vascular shear stress and clot formation.

These derived CFD methodologies allow for patient-specific simulations, optimizing cardiovascular device performance while reducing medical risks.

IV. Challenges, Gaps in Literature, and Recommendations

A. Challenges in Aerospace-Derived Biomedical Fluid Mechanics

The primary challenge in adopting aerospace methodologies for biomedical applications is the fundamental difference between engineered and biological systems. Unlike aerospace systems, which typically involve well-defined boundary conditions and deterministic fluid dynamics, biological flows are inherently complex, exhibiting pulsatility, non-Newtonian behavior, and dynamic tissue interactions. In particular, the multiscale and multiphysics nature of biomedical flows presents a significant computational challenge. While aerospace CFD tools are generally designed for high-Reynolds-number flows in controlled environments, biomedical applications require models capable of resolving microvascular interactions, cellular-scale dynamics, and large-scale cardiovascular flows within the same computational framework. A further challenge lies in the incomplete understanding of cavitation-induced bioeffects in medical applications. While aerospace engineers have developed predictive models to mitigate cavitation erosion in turbomachinery, the biological consequences of cavitation exposure—such as mechanical stress on soft tissues, endothelial damage, and long-term cellular response—remain poorly understood. In shock wave lithotripsy (SWL), for example, cavitation bubbles play a critical role in fragmenting kidney stones, yet their interaction with renal tissues is not fully characterized [42]. Similarly, in histotripsy, where controlled cavitation is used to mechanically disrupt tissues, the secondary effects of shock wave propagation and tissue remodeling remain areas of active investigation [43].

Aerospace-derived computational methods also face limitations when applied to cardiovascular modeling and artificial organ design. While CFD has proven invaluable in studying turbulence in jet engines and optimizing propulsion efficiency, direct adaptation to biological flows requires additional complexity. Blood exhibits shear-thinning behavior with suspended cellular components, making it vastly different from conventional aerospace fluids. Additionally, vascular compliance and tissue deformation introduce significant computational challenges, necessitating fully coupled fluid-structure interaction (FSI) models. The transition from rigid aerospace structures to soft biological tissues remains a major computational hurdle, as existing aerospace-derived solvers often fail to capture the dynamic response of compliant vessels under pulsatile blood flow conditions. Another significant limitation is the lack of high-fidelity experimental validation. While computational methods have rapidly evolved, experimental data for benchmarking these models remain scarce.

B. Gaps in Literature

While the existing literature has successfully demonstrated the applicability of aerospace methodologies in medical fluid mechanics, several fundamental gaps remain. One of the most pressing gaps is the limited integration of cavitation models with biological systems. Most current studies on biomedical cavitation rely on empirical observations rather than predictive physics-based models. In contrast, engineers have developed highly refined models to predict cavitation inception, bubble collapse, and subsequent pressure wave interactions. However, the translation of these models into biomedical contexts is still in its infancy, with significant uncertainties in how cavitation events translate to tissue-level effects. Another gap lies in the inadequate modeling of blood-bubble interactions in multiphase flow studies. While research has extensively characterized bubble collapse in cryogenic fuel injectors and supersonic nozzles, relatively few studies have applied these principles to vascular embolism risks or cavitation-induced hemolysis in artificial circulatory systems. The complex interplay between bubble dynamics, endothelial shear stress, and vascular flow conditions remains insufficiently explored, limiting the accuracy of existing biomedical simulations.

Furthermore, machine learning and AI-driven optimization, widely employed in CFD for rapid aerodynamic design iteration, remain underutilized in biomedical fluid mechanics. While AI-based solvers have demonstrated remarkable success in optimizing propulsion systems and turbulence control, few studies have applied these techniques to personalized hemodynamic modeling, cavitation prediction, and AI-driven cardiovascular simulations. The lack of AI integration in adaptive mesh refinement, real-time flow diagnostics, and automated model calibration represents a significant technological gap that could dramatically enhance the accuracy and efficiency of biomedical CFD applications.

C. Recommendations for Future Research and Development

To address these challenges, future research must focus on the development of multiscale and multiphysics computational models that can accurately capture biological flow complexities while leveraging aerospace-derived methodologies. The next generation of biomedical CFD models should integrate non-Newtonian rheology, fluid-structure interactions, and cavitation dynamics within a unified simulation framework. This requires advances in high-fidelity turbulence modeling, hybrid computational approaches combining direct numerical simulation (DNS) and large-eddy simulation (LES), and real-time simulation techniques that allow for patient-specific predictions in clinical applications.

Experimental validation remains another critical area for improvement. Developing high-speed imaging techniques for cavitation in soft tissues, inspired by shock tunnel diagnostics, could provide much-needed validation for computational models. Additionally, the creation of standardized experimental platforms for biomedical cavitation researc—including tissue-mimicking materials, advanced optical flow diagnostics, and microfluidic vascular models—would provide valuable insights into bubble-induced bioeffects and fluid transport in medical devices. Collaborative efforts will be essential to establishing these benchmark datasets.

Another promising avenue for future research is the integration of machine learning and AI-driven optimization in biomedical fluid mechanics. AI has already revolutionized aerodynamic design and propulsion efficiency by enabling rapid parametric sweeps and automated solver calibration. Translating these capabilities into biomedical applications could enable real-time cavitation risk assessment, AI-driven shock wave lithotripsy optimization, and adaptive cardiovascular device simulations. Developing data-driven AI models trained on aerospace-derived cavitation databases could provide novel insights into biomedical cavitation events and therapeutic ultrasound targeting, which can further be refined according to needs and bio-specifications.

Finally, regulatory and translational challenges must be addressed. While aerospace engineering benefits from rapid prototyping cycles and extensive computational modeling, biomedical applications require stringent validation protocols, long-term safety assessments, and regulatory compliance. Establishing standardized guidelines for aerospace-based biomedical modeling—including validated CFD protocols, patient-specific cavitation risk models, and regulatory pathways for AI-assisted medical simulations—would accelerate the clinical adoption of these technologies. Significant challenges remain in modeling accuracy, experimental validation, and translational implementation. Addressing these issues requires a multifaceted approach.

V. Conclusion

This study demonstrates that aerospace-derived fluid mechanics and cavitation principles provide transformative solutions in biomedical engineering, particularly in diagnostics, therapy, and drug delivery. A key finding is that computational fluid dynamics (CFD) and fluid-structure interaction (FSI) methodologies originally developed for aerospace propulsion systems can be effectively adapted to optimize cardiovascular medical devices, improving hemodynamic efficiency and patient safety. Furthermore, cavitation-based techniques, such as shock wave lithotripsy (SWL) and histotripsy, have proven effective in non-invasive treatments, showcasing their potential to reduce surgical risks and enhance therapeutic precision.

Our analysis highlights that while aerospace-inspired innovations offer significant advantages, challenges remain in translating these concepts to biological systems. The inherent complexity of human tissues, non-Newtonian blood behavior, and multiphase flow interactions necessitate further refinements in computational modeling and experimental validation. Additionally, regulatory constraints and ethical considerations in biomedical applications call for a multidisciplinary approach to ensure both safety and efficacy.

Future research should focus on developing hybrid computational frameworks that integrate artificial intelligence, high-fidelity simulations, and machine learning to improve predictive modeling in biomedical applications. Moreover, advancing experimental validation techniques, such as high-speed imaging and in-vitro studies, will be critical in bridging the gap between theoretical advancements and practical implementations. By fostering collaboration between aerospace and biomedical researchers, this interdisciplinary approach has the potential to unlock new frontiers in medical technology, ultimately improving patient care and treatment outcomes.

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