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Computational Fluid Dynamics (CFD) Analysis of Catheter Obstruction in the Implantable Intraperitoneal Insulin Pump to Support Sustainable Development Goals (SDGs)

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ABSTRACT

Fibrotic obstruction compromises long-term intraperitoneal insulin delivery. This study aimed to quantify how progressive lumen narrowing alters hydrodynamics at a catheter tip. We built a three-dimensional model and performed computational fluid dynamics with laminar, steady flow, insulin treated as a Newtonian fluid, and pressure outlet boundary conditions; pressure fields were mapped onto a finite element obstruction for fluid-structure assessment. Simulations showed a nonlinear rise in wall pressure and a decline in flow as occlusion advanced; high narrowing created recirculation, stagnation, and elevated wall shear near the obstruction, while structural deformation remained at the nanoscale but spatially anisotropic. These trends arise because reduced effective area increases resistance and accelerates jets that separate and trap fluid in low-velocity pockets, favoring protein and collagen deposition. The model identifies failure thresholds and guides design: rounded tips, optimized port geometry, and low-fouling, zwitterionic surfaces, together with pressure-based flushing or smart actuation, could improve long-term reliability in practice. This study supports the Sustainable Development Goals (SDGs).

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1. INTRODUCTION

The global burden of diabetes mellitus continues to rise, with over 830 million people affected as of 2022, positioning it among the most prevalent non-communicable diseases worldwide (see https://www.who.int/news-room/fact-sheets/detail/diabetes). Many reports regarding diabetes mellitus have been well-documented [1-5]. In Colombia, the number of diagnosed cases has nearly doubled from 2 million in 2018 to a projected 4 million by 2030, reflecting an urgent national public health challenge. Among the various forms of diabetes, type 1 diabetes (T1D) poses significant clinical management difficulties, as it involves autoimmune destruction of pancreatic β-cells, thereby requiring lifelong insulin therapy.

To address the demand for stable insulin delivery, implantable intraperitoneal insulin pumps have emerged as an alternative to subcutaneous systems, offering precise and continuous insulin administration into the peritoneal cavity. However, this approach is hampered by device longevity issues, most notably catheter obstruction due to the foreign body response. Following implantation, the immune system often initiates fibrosis, leading to the deposition of extracellular matrix proteins, particularly type I collagen, around the catheter tip [6-7]. This fibrotic encapsulation reduces insulin flow efficiency, potentially leading to complete occlusion in up to 30% of patients, posing critical risks to glycemic control and patient safety.

The obstruction process typically evolves in three stages: localized tip blockage, partial encapsulation, and eventual full occlusion. Despite ongoing efforts to develop anti-fouling materials or enzyme-based degradative therapies, a gap remains in understanding the dynamic fluid-structure interaction within obstructed catheters. This knowledge is vital because flow alterations directly influence protein aggregation and pressure build-up, which are precursors to mechanical failure. Therefore, a science- and technology-based approach integrating fluid dynamics modeling, material engineering, and simulation becomes essential to tackle this problem and align with Sustainable Development Goals (SDGs) (Ragadhita et al., 2026) by promoting technological innovation for health system improvement.

Based on previous studies on Computational Fluid Dynamics (CFD) [9-14], this study aims to quantitatively model how progressive fibrotic obstruction impacts pressure and flow at the catheter tip using CFD. The novelty lies in the combination of hydrodynamic and mechanical simulations to map structural stress over collagen-mimicking obstructions and define obstruction thresholds. The findings are expected to inform next-generation catheter designs optimized for biocompatibility, resistance to fibrosis, and pressure-guided flushing strategies, thus enhancing the long-term reliability of implantable insulin delivery systems.

2. LITERATURE REVIEW

Research into implantable drug delivery systems has been increasing [15,16]. Especially, they focused on the interaction between device surfaces and the immune environment. Previous studies [17] utilized atomic force microscopy to characterize the mechanical behavior of collagen fibrils, laying the groundwork for understanding fibrotic responses to implants. This cellular behavior is influenced by implant geometry and material properties. Spherical implants of specific sizes reduced macrophage adhesion and fibrosis in both rodent and primate models, underscoring geometry as a determinant of immune modulation [18].

Material science has responded with innovations such as hydrophilic biomaterials, notably hydrogels, which minimize protein and cell adhesion due to reduced interfacial energy [19,20]. These hydrogels are now used in vascular access devices to mitigate thrombotic and

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obstructive complications, although their limited mechanical strength remains a concern for long-term intraperitoneal applications.

Further investigations [21] explored insulin catheter obstructions through macroscopic and histological studies. Although amyloid aggregation was suspected, the findings pointed instead to fibrotic tissue as the primary cause. In a follow-up study, other researchers [21] compared catheter geometries (circular, triangular, and pentagonal) to evaluate flow performance and obstruction resistance, revealing a clear link between lumen shape and fibrotic deposition.

In computational domains, CFD modeling has been pivotal for visualizing internal catheter dynamics. Some researchers simulated cryogenic flow in narrow ducts to examine cavitation effects and vortex formation, findings that apply to insulin catheters under partial obstruction. Similarly, other researchers [22,23] validated CFD approaches for analyzing air and liquid distribution in biological and industrial contexts, highlighting how material roughness and geometry affect flow uniformity and particle behavior.

More recently, biomedical coatings such as zwitterionic materials have shown promise. Some reports [24,25] developed anti-inflammatory, protein-resistant surfaces that extend catheter life without compromising mechanical integrity. These studies suggest the potential for pressure-guided or self-cleaning catheter systems using pressure pulses to disrupt early fibrotic deposition.

Despite these advances, an integrated approach that couples CFD modeling with mechanical deformation analysis of collagen-based obstructions has not been fully explored. The present study addresses this gap by simulating pressure-induced deformation on catheter-occluding masses, offering a predictive framework for catheter design and operational limits.

3. METHODS

Figure 1 presents the three-dimensional CAD model of the catheter tip, including the distal and lateral openings used for fluid outflow. This configuration was constructed using SolidWorks 2022 and represents typical geometrical features observed in implantable intraperitoneal insulin delivery systems.

This study adopts an in silico approach based on Computational Fluid Dynamics (CFD) and finite element analysis (FEA) to simulate the behavior of insulin flow through a partially obstructed catheter tip. The obstruction, which mimics fibrotic collagen deposition, was modeled as spherical elements placed concentrically within the catheter lumen. The model's purpose is to evaluate pressure distribution, vorticity, and mechanical deformation of the obstruction in response to fluid dynamics, under conditions replicating physiological insulin delivery.

The three-dimensional geometry was exported in STEP format and imported into ANSYS Fluent, a widely used simulation platform for biomedical CFD modeling. The fluid used in the simulations was insulin, assumed to behave as a Newtonian fluid with a dynamic viscosity of 3.2 cP. Steady-state, laminar flow conditions were imposed. The inlet velocity was set to 0.01 m/s, consistent with clinically relevant flow rates in low-pressure infusion systems. The outlet boundary was defined as a pressure opening at 0 Pascals, simulating an open-end catheter environment.

Following the CFD simulation, the resulting pressure fields on the obstruction surface were extracted and used as input loads for finite element analysis using the Von Mises strain energy method. This allowed a structural evaluation of the deformation behavior of the fibrotic obstruction due to flow-induced stress. The deformation analysis is crucial for assessing the

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mechanical impact of long-term fluid interaction with biological deposits and its implications for catheter performance degradation.

The simulation variables included three primary obstruction levels: 10, 50, and 90% of lumen reduction. These percentages were defined based on the diameter of the spherical obstruction in relation to the catheter's internal diameter. For example, a 90% obstruction corresponded to a spherical diameter of 2.06 mm, while the catheter tip's fixed internal diameter was 2.29 mm. The geometric and flow parameters were kept constant across all obstruction scenarios to isolate the influence of lumen narrowing on pressure and deformation behavior.

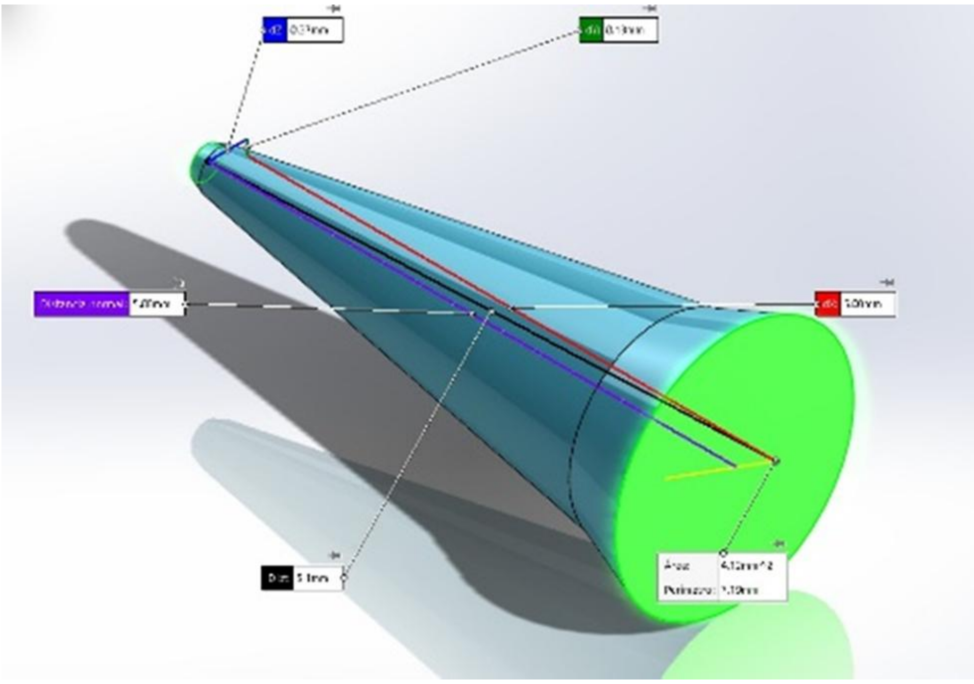

Figure 1. CAD representation of the Tip with its dimensions.

4. RESULTS AND DISCUSSION

Figure 2 displays the velocity vector field of the insulin flow through the catheter tip, particularly as it approaches the obstructed zone. The fluid trajectories, shown in blue, reveal high flow density near the obstruction margins, accompanied by the development of recirculation zones and local stagnation pockets.

This localized increase in flow density and vortex formation can be attributed to the sharp transition in cross-sectional area, leading to flow acceleration, separation, and turbulence downstream of the obstruction. Such patterns are known to promote the adhesion of proteins and macromolecules, which, over time, exacerbate the severity of obstruction and reduce catheter patency. The conical shape of the flow passage, as illustrated in **Figure 3**, amplifies this effect by producing a Venturi-like narrowing that increases jet velocity and causes abrupt expansion downstream, ideal conditions for fibrotic or protein accumulation.

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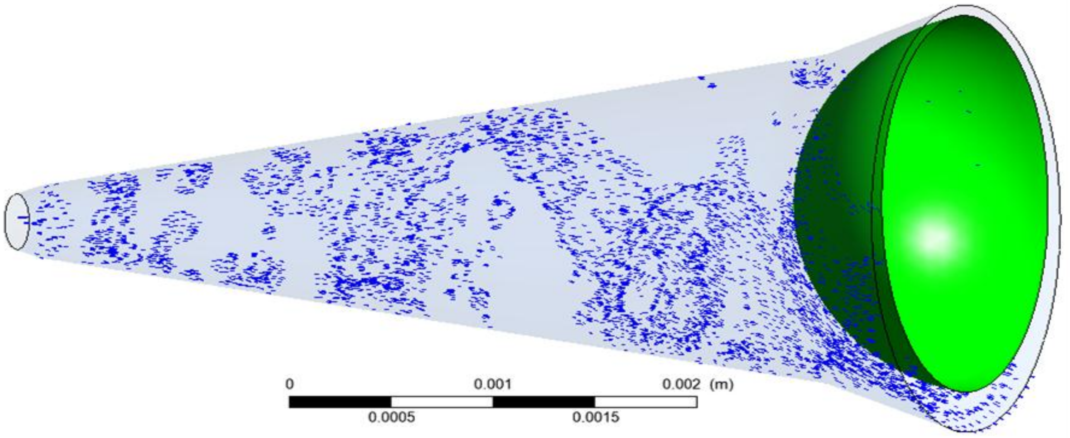

Figure 2. Vector representation of the vorticity at the catheter tip.

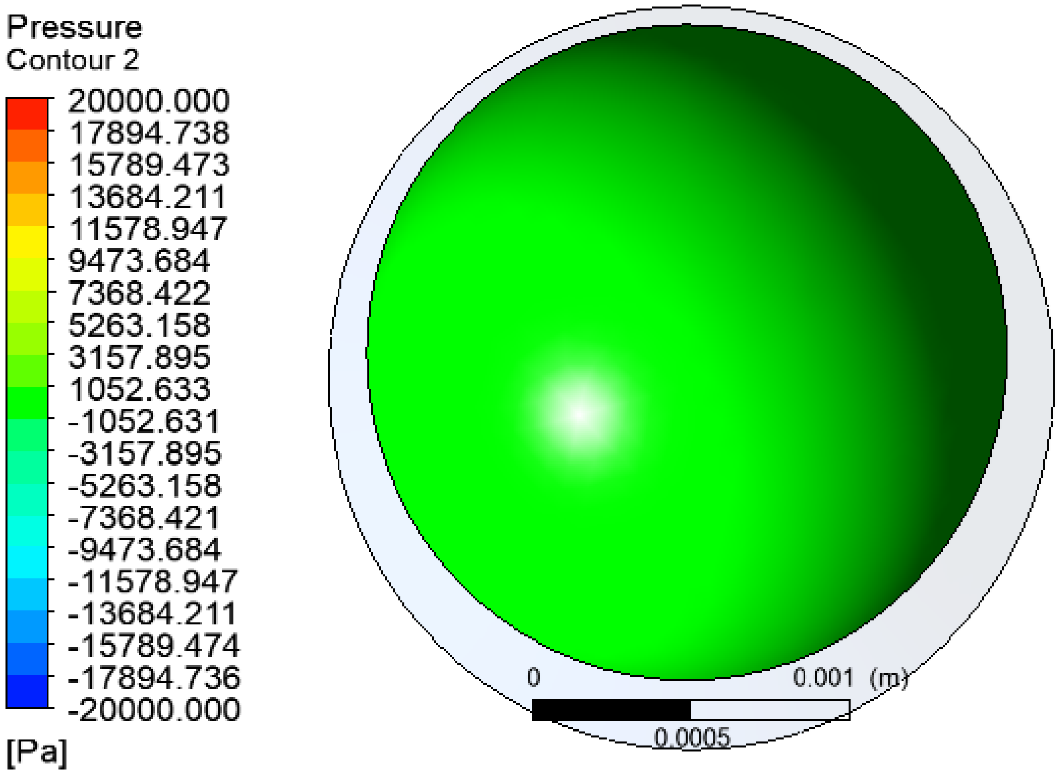

Figure 3. Pressure value over obstruction of 0.21 Pascals at a 90% obstruction percentage.

The simulated pressure distribution under a 90% obstruction condition revealed a localized wall pressure of approximately 0.021 Pascals at the surface of the obstruction. While this value may appear low in absolute terms, its spatial concentration and directional gradient are clinically significant, particularly in promoting stagnation and flow reversal in low-velocity zones. This observation supports previous findings [26], who categorized intraperitoneal catheter obstructions into three primary types based on laparoscopic diagnosis: tip blockage, tip encapsulation, and complete occlusion.

Figure 4, as cited from their study, visually confirms the progressive nature of fibrotic deposition across the catheter surface, with initial collagen coverage below 10% and advanced obstruction stages approaching 60%. Although various immune cells and proteins are involved in this inflammatory cascade, this study focuses on type I collagen accumulation

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driven by fibroblast activity, as it constitutes the primary mechanical component of obstruction.

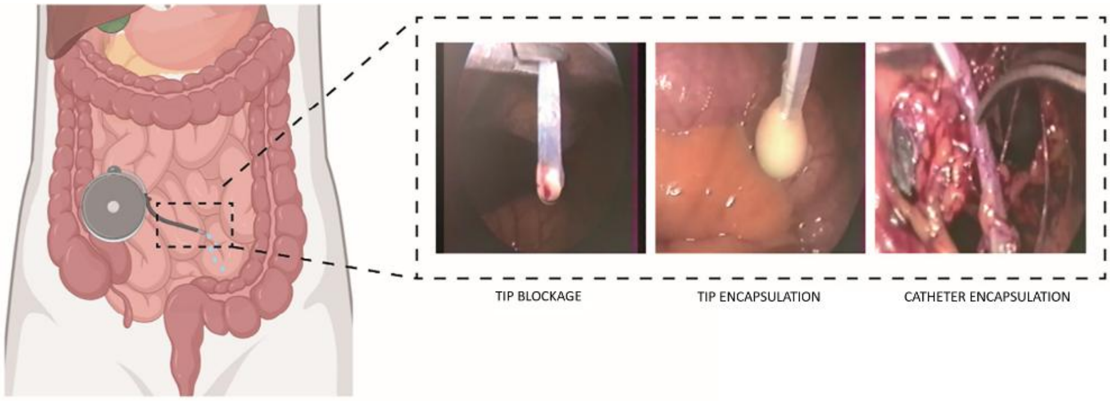

Figure 4. Laparoscopic diagnosis of three major types of catheter obstructions in patients with T1D.

Figure 5 presents the structural deformation map generated by applying the CFD-derived pressure onto the obstruction surface. The deformation, while remaining in the nanometer range, demonstrates a pronounced spatial gradient, indicating higher mechanical stress at specific loci. These findings align with previous research on pressure-induced mechanical fatigue and suggest potential sites for long-term biofilm adhesion or microfractures in the obstruction matrix.

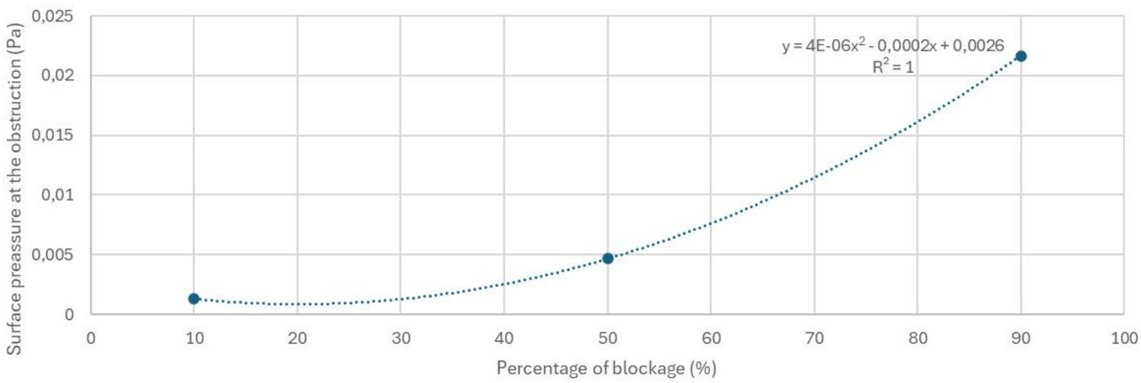

Figure 5. Structural deformation of the obstruction at 90% occlusion.

The quadratic relationship between obstruction percentage and surface pressure is further quantified in the simulation results, with a best-fit polynomial of the form of equation (1):

$$y = 4 \times 10 - 6x2 - 0.0002x + 0.0026 \quad (1)$$

where *x* represents the obstruction percentage and *y* the pressure in Pascals. This highly deterministic fit ($R^2 = 1$) emphasizes the nonlinear escalation of pressure as the effective flow area narrows. **Table 1** complements this relationship by detailing the diameter values associated with each obstruction level and their corresponding flow areas.

Using the standard flow equation, we can consider equation (2)

$$Q = A \cdot v \quad (2)$$

where *Q* is the volumetric flow rate (m^3/s), *A* is the open cross-sectional area (m^2), and *v* is the fluid velocity (m/s), the results indicate a steep decline in flow with increasing obstruction. Under baseline conditions (no obstruction), the catheter tip with an area of 4.12 mm^2 and a

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velocity of 0.01 m/s yields a flow rate of 2.47 mL/min. At 90% obstruction, the open area is reduced to only 0.79 mm^2, resulting in a drastically lower flow rate of approximately 0.474 mL/min. This represents an 80% reduction, underscoring the clinical significance of even partial occlusions.

Table 1. Relationship between obstruction diameters and obstruction percentages relative to the fixed diameter of the catheter tip.

Obstruction Percentage (%)	Obstruction Diameter (mm)	Catheter Tip Diameter (mm)
10	0.22	2.29
50	1.14	2.29
90	2.06	2.29

The open area denotes the remaining pathway through which fluid can circulate along the inner wall of the catheter tip. As the obstruction percentage increases, this available space narrows significantly, resulting in a notable decline in flow rate. This reduction is particularly critical for insulin-dependent patients utilizing implantable insulin pump systems, as it may compromise metabolic control. A clear trend of progressively decreasing flow rate corresponding to increasing obstruction percentage is illustrated in **Figure 6**, which demonstrates a quadratic relationship given by equation (3):

$$f(x) = -2.5 \times 10^{-4} \cdot x^2 + 2.5 \times 10^{-4} \cdot x + 2.4725 \quad (3)$$

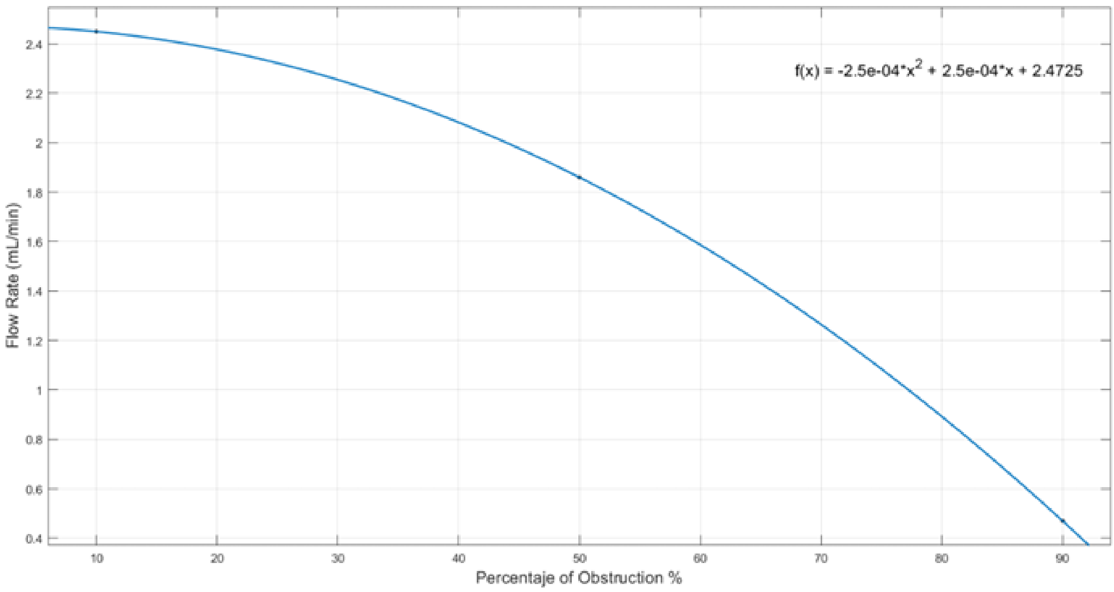

Figure 6. Relationship between obstruction percentage and flow rate (mL/min) at the catheter tip. The quadratic trendline illustrates a progressive decrease in flow rate as the percentage of obstruction increases, indicating potential risks for fluid delivery performance in implantable systems.

Figure 7 visualizes this trend, showing the correlation between obstruction severity and flow rate reduction. As the obstruction increases, the catheter's ability to maintain therapeutic insulin delivery rapidly deteriorates, confirming that obstruction not only impairs mechanical performance but also undermines glycemic control in patients.

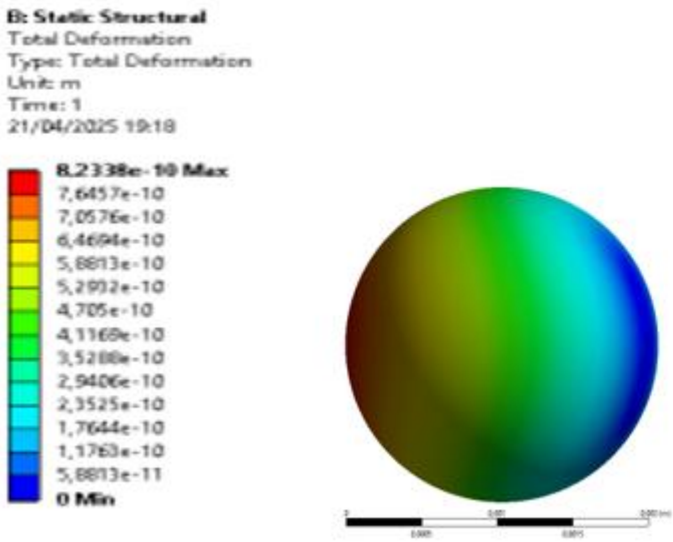

Figure 7. Flow rate vs. obstruction percentage

In addition to evaluating the direct hydrodynamic effects of progressive lumen reduction, this study explored the structural implications of flow-induced stresses acting on collagen-like obstructions. As previously shown in **Figure 5**, despite the relatively low pressure magnitude at 90% occlusion, the spatial distribution of deformation revealed anisotropic stress fields. These mechanical gradients could act as initiation sites for biofilm formation or microstructural fatigue over prolonged exposure.

This anisotropy is relevant not only from a biomechanical standpoint but also in terms of biophysical interactions with proteins and cells. Studies have indicated that surfaces subjected to uneven stress distributions are more prone to surface fouling and cellular adhesion [27]. Although the deformation values remain below critical failure thresholds, their distribution may influence adhesion phenomena, including the attachment of neutrophils, fibroblasts, or epithelial cells, key actors in fibrosis.

Further supporting this hypothesis, pressure mapping under varying obstruction levels revealed that at intermediate obstruction values (about 50%), pressures peaked significantly higher than at extreme cases. For instance, stagnation phenomena at 50% narrowing produced local pressure spikes exceeding 13,000 Pascals, especially when flow velocity was artificially increased. This pressure surge corresponds to kinetic energy buildup in the narrowed flow passage, which, if prolonged, may trigger wall collapse or backpressure effects detrimental to pump function. Thus, the intermediate stages of obstruction could represent a critical, often-overlooked transition point for clinical intervention.

Comparative studies reinforce these simulation-based conclusions. Some researchers [28] demonstrated in neonatal catheters that partial occlusions caused abrupt in-line pressure surges even in low-compliance vessels. Similarly, the differential pressure between the ventricle and catheter tip in hydrocephalus models increased markedly due to astrocyte proliferation, particularly in catheters with adhesive coatings such as barium [29]. Their results confirmed that both material properties and cellular interactions are crucial in obstruction dynamics.

In the present CFD model, although the catheter material was not explicitly varied, surface roughness and geometry effects are implicitly included through boundary conditions and flow contour profiles. These results suggest that optimized tip geometry (specifically, rounded or multi-port outlets) can minimize stagnation zones and reduce the likelihood of pressure accumulation. Indeed, conical tips in hepatic/peritoneal catheters exhibited greater collagen

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deposition and local irritation compared to rounded designs [21]. This design insight complements the CFD findings here, where sharp-edged or conical transitions generated vorticity and backflow, while smooth profiles facilitated laminar outflow and shear uniformity.

Another key insight is the potential for pressure-based flushing protocols to clear partial obstructions before they progress to complete occlusion. As the flow simulations showed, pressure remains low at near-total obstruction due to stagnation, rendering conventional flushing less effective. However, in earlier stages (10-50% obstruction), the pressure–velocity interaction creates conditions where targeted pressure pulses could dislodge adherent tissue. This idea is consistent with previous studies [25], who demonstrated that elastomer-based catheters with zwitterionic surfaces maintained mechanical integrity under pulsed flow while preventing protein adsorption.

This mechanical feasibility supports the concept of integrating smart materials or MEMS-based systems in future catheter designs. Such systems could monitor flow and pressure in real-time and respond with mechanical actuation (e.g., micro-expansion or vibration) to disrupt early-stage fibrotic deposition. These innovations align with the goals of SDG 3 (Good Health and Well-being), emphasizing technological advancement for chronic disease management and patient-centered care.

Beyond mechanical interventions, biochemical strategies such as collagenase application also hold promise. Although not modeled in the current simulation, previous studies [23,30] have highlighted the efficacy of collagenase in degrading fibrotic tissue within catheters. Integrating such enzymatic agents into the catheter's surface or lumen could enhance long-term patency, especially if guided by pressure thresholds predicted via CFD.

The robustness of the simulation model is reinforced by its internal consistency and agreement with published experimental data. For example, the pressure–obstruction curve's perfect quadratic fit ($R^2 = 1$) indicates deterministic behavior under the defined assumptions, supporting its utility for predictive modeling. This is essential for preclinical design validation, where experimental resources may be limited.

Nonetheless, the study acknowledges several limitations. First, biological variability (such as patient-specific immune responses, insulin formulation stability, and tissue interaction) was not incorporated. Second, the mechanical model assumes a homogeneous, spherical collagen obstruction, which, although useful for baseline simulation, may oversimplify the complex geometry of actual fibrotic masses. Future models could incorporate irregular shapes, multilayered deposits, or time-based growth to reflect more realistic conditions.

Another limitation involves the simulation's steady-state nature. While this allows for simplified boundary conditions and direct comparison across obstruction levels, it does not capture transient events such as intermittent flow, pulsed insulin delivery, or mechanical shock (e.g., coughing or movement). Incorporating unsteady flow conditions would enhance the model's clinical relevance, particularly in simulating real-time failure scenarios.

Despite these limitations, the present study successfully establishes a foundation for future exploration into obstruction mitigation strategies. The integrated use of CFD and structural analysis not only quantifies the hydrodynamic effects of fibrotic occlusion but also translates these effects into mechanical outcomes that inform design and therapy.

This modeling framework may serve as a decision-support tool for biomedical engineers developing next-generation implantable drug delivery systems. It offers quantifiable metrics for evaluating catheter tip geometry, surface treatments, and flushing protocols, and could be extended to other medical applications where flow-tissue interaction is critical, such as cerebrospinal fluid shunts, ureteral stents, or cardiovascular grafts.

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In summary, the simulation results confirm that catheter obstruction is a dynamic, geometry-sensitive, and pressure-dependent process. Effective intervention must target the early stages of obstruction, where flow and pressure gradients are still modifiable, and must be supported by innovations in material science, design, and real-time monitoring. With continued development and experimental validation, this approach holds promise for improving patient outcomes and extending the life of implantable insulin delivery devices. Finally, this finding contributes to SDG 3 (Good Health and Well-being) by supporting the development of safer, more reliable biomedical devices for chronic disease management.

5. CONCLUSION

This study addressed a critical limitation in long-term intraperitoneal insulin therapy: the obstruction of implantable catheters due to fibrotic tissue accumulation. Using a CFD model and structural deformation analysis, we quantified the impact of progressive lumen reduction on hydrodynamic behavior and mechanical stress. The results demonstrated a nonlinear increase in wall pressure and a significant reduction in flow rate as the obstruction progressed, with a perfect quadratic correlation between obstruction percentage and surface pressure. At high occlusion levels, vorticity and stagnation zones emerged, favoring further collagen deposition. Structural deformation remained minimal but spatially anisotropic, suggesting localized stress accumulation that could initiate biofilm formation. These findings confirm that early-stage obstruction is both detectable and potentially reversible, offering a window for pressure-based intervention. Future strategies may combine optimized catheter geometry, antifouling materials, and smart actuation technologies to maintain patency and enhance therapeutic safety. This integrative approach supports the development of resilient insulin delivery systems aligned with global health goals.

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7. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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