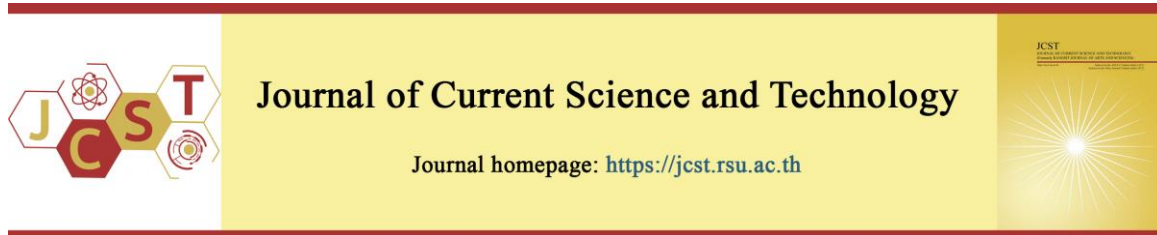


Cite this article: Vairungroj, A., & Pongsawasdi, P. (2026). Computational design optimization of internal ramp geometry in side-port embryo transfer catheters to minimize fluid recirculation and shear stress. *Journal of Current Science and Technology*, 16(4), Article 218. <https://doi.org/10.59796/jcst.V16N4.2026.218>



Computational Design Optimization of Internal Ramp Geometry in Side-Port Embryo Transfer Catheters to Minimize Fluid Recirculation and Shear Stress

Abhinat Vairungroj 
Punn Pongsawasdi*, 

Srinakharinwirot University Prasarnmit Demonstration School (Secondary), Bangkok 10110, Thailand

*Corresponding author; E-mail: punn.pongsawasdi@gmail.com

Received 2 March 2026; Revised 14 April 2026; Accepted 16 June 2026; Published 15 September 2026

Abstract

The success of *in vitro* fertilization (IVF) relies heavily on non-traumatic embryo delivery. While end-opening catheters provide direct flow, they pose a risk of endometrial injury and embryo displacement due to high-velocity jetting, whereas conventional side-port designs minimize trauma but inherently suffer from fluid stagnation and elevated shear stress. This study aims to resolve this critical hydrodynamic trade-off by proposing a novel 'Flow-Guiding Internal Ramp Architecture' (FGIRA) integrated with an oval lateral aperture to eliminate dead zones while maintaining safe, low-velocity expulsion. Three-dimensional computational fluid dynamics (CFD) simulations were conducted using SolidWorks Flow Simulation based on the finite volume method to solve the Navier–Stokes equations. The study modeled the fluid as a Newtonian standard culture medium at 310.15 K, utilizing a mesh refinement strategy optimized for grid independence to comparatively analyze the hydrodynamic performance of four catheter configurations, focusing on velocity distribution, vorticity, and Wall Shear Stress (WSS). The results demonstrated that the Oval-FGIRA design successfully eliminated fluid recirculation and achieved a maximum WSS of 1.21 Pa within the 0.04 m/s injection speed regime. This value falls well within the physiological safety threshold (< 2 Pa), supported by a stable laminar flow regime (Maximum Local Reynolds Number = 49.95). In conclusion, unlike traditional side-port designs that merely redirect flow at the cost of high shear stress, the Oval-FGIRA establishes a breakthrough. By simultaneously eliminating fluid stagnation and dampening mechanical forces, the synergy between the internal ramp and oval aperture creates a superior hydrodynamic environment that minimizes mechanotransduction-induced cellular damage, offering a paradigm shift in catheter geometry to improve clinical pregnancy rates. However, at the injection velocity of 0.08 m/s, maximum wall shear stress exceeded the safety threshold at 2.10 Pa. Consequently, clinical implementation of the Oval-FGIRA is recommended for slow-to-immediate injection protocols.

Keywords: catheter, catheter hydrodynamics, computational fluid dynamics, embryo transfer, *in vitro* fertilization, wall shear stress

1. Introduction

In the field of assisted reproductive technology, *in vitro* fertilization (IVF) is a standard method for managing infertility. Since the pioneering success (Edwards et al., 1980), the field has undergone a revolution in infertility treatment. Originally, the methodology was complex, often involving laparoscopy, blind placement, or the use of rigid catheters. Consequently, over the decades, the

clinical protocol has evolved towards non-invasive, ultrasound-guided techniques (Brown et al., 2016; D'Angelo et al., 2022). Despite these advancements, the embryo transfer step remains a critical variable, where the success rate is primarily dependent on the interaction between catheter geometry and the endometrial surface (Schoolcraft et al., 2001).

Contemporary catheters generally utilize two primary distal tip topologies: the end-opening and the

side-port. Historically, the end-opening catheter served as the primary tool. Characterized by a simple straight tube with a distal opening, this configuration remains common. However, it possesses critical hydrodynamic flaws. This model fails to prevent uterine trauma due to its rigid tip, which can damage the endometrium and cause bleeding that negatively impacts implantation (D'Angelo et al., 2022). Furthermore, the model generates high-velocity axial jets, inducing embryo displacement and harmful shear stress (Mrugacz et al., 2013; Nakamura et al., 2024). To mitigate this physical trauma, the fillet end-opening catheter was developed. Incorporating a rounded external edge, this modification successfully reduces direct endometrial injury. However, it fails to rectify the internal fluid dynamics; high-velocity axial jets remain an issue (Mrugacz et al., 2013).

To mitigate these risks, clinical practice has largely shifted toward side-port catheters (Brown et al., 2016). By closing the distal tip, these devices reduce direct endometrial contact and redirect axial flow laterally. Nevertheless, the abrupt 90° change in momentum generates a distal stagnation zone, in which embryos may become trapped within a recirculating vortex rather than being expelled from the catheter (Mains & Van Voorhis, 2010). Such retention frequently necessitates reinjection and is associated with significantly lower pregnancy and live-birth rates (Xu et al., 2020). Accumulation of cervical mucus within the stagnant region can further obstruct the flow path (Mains & Van Voorhis, 2010). Crucially, most prior optimization efforts have concentrated on external tip geometry or aperture placement, rather than on the internal hydrodynamics themselves. As a result, conventional designs lack internal flow-conditioning structures capable of managing momentum redirection, allowing vortices to persist.

Beyond the internal flow stagnation, the geometry of the aperture itself plays a critical role in fluid dynamic performance. In other biomedical fields, such as hemodialysis, computational studies have demonstrated that oval-shaped orifices significantly reduce shear stress and fibrin formation compared to traditional circular geometries (Owen et al., 2020; Yang et al., 2022). Despite its reported benefits in other biomedical applications, the use of oval-shaped apertures has yet to be investigated in embryo transfer, where minimizing shear-induced mechanotransduction is particularly important because embryos are highly sensitive to shear stress. As reported by Lin et al. (2024), shear stress is not merely physical trauma but a potent activator of

complex intracellular signaling pathways, such as YAP/TAZ. Furthermore, exposure to non-physiological levels of fluid shear stress triggers adverse mechanotransduction cascades, prominently including Mitogen-Activated Protein Kinase (MAPK) pathways and pro-apoptotic factors, which ultimately lead to cellular damage and apoptosis (Espina et al., 2023). Therefore, maintaining Wall Shear Stress (WSS) below the physiological safety threshold of 2 Pa is not just an engineering optimization, but a strict biological necessity to protect the highly sensitive embryo from shear-induced cellular death.

To address these dual challenges of fluid stagnation and shear stress, this study advanced the conventional side-port design by introducing the 'Flow-Guiding Internal Ramp Architecture' (FGIRA) configured with an optimized oval aperture. Designed to be manufacturable via micro-injection molding techniques, a process that optimizes the mechanical properties of medical-grade materials (Guerrero-Alvarado et al., 2026), this novel invention eliminates numerous deficiencies of the previous design. By synergizing a ramp-shaped internal structure to eliminate the dead zone with an oval orifice to minimize shear forces, the design aims to reduce the risk of embryo retention, a complication associated with significantly lower pregnancy and live-birth rates (Xu et al., 2020), to a negligible level.

The quantitative assessment of such geometrical modifications requires precise hydrodynamic analysis. While computational fluid dynamics (CFD) studied by Grygoruk et al. (2013) and Mrugacz et al. (2013) successfully established a relationship between injection velocity and shear stress in standard catheters, they did not account for complex internal architectural modifications, such as those proposed in this study. Moreover, the specific hydrodynamic impact of an oval versus a circular aperture in the context of embryo transfer has not been quantified. Therefore, a direct comparative simulation is necessary to verify that the Oval-FGIRA design effectively overcomes the limitation of traditional catheters.

To rectify the critical hydrodynamic flaws associated with conventional internal architectures and justify the efficiency of the proposed design, this study employs CFD to conduct a comparative analysis across four distinct configurations. We evaluated the standard end-opening and circular side-port catheters as clinical baselines, alongside a novel oval side-port model to isolate the specific hydrodynamic benefits of the aperture shape. Ultimately, these configurations were benchmarked against the proposed Oval-FGIRA

model to demonstrate the combined effect of internal flow guidance and aperture optimization on maximizing embryo viability and transfer efficiency. By advancing the standard of assisted reproductive technologies, this study aims to enhance clinical pregnancy rates, directly contributing to SDG 3 (Good Health and Well-Being) and establishing a foundational blueprint for the next generation of high-efficiency embryo transfer devices.

To bridge this literature gap and evaluate the proposed design against current clinical standards, this study employs CFD to conduct a comprehensive analysis. The primary contributions of this research are outlined as follows:

- Development of the Oval-FGIRA Catheter: Proposing a novel 'Flow-Guiding Internal Ramp Architecture' (FGIRA) integrated with an optimized oval aperture to systematically eliminate internal flow stagnation and safely redirect axial momentum.
- Quantitative Hydrodynamic Evaluation: Providing a systematic computational comparison across four catheter configurations under multiple clinical injection velocities.
- Mitigation of Mechanotransduction Risks: Demonstrating that the synergy of an internal ramp and an oval orifice significantly reduces WSS below the physiological threshold, thereby minimizing the risks of shear-induced cellular apoptosis and embryo retention.

2. Objectives

1) To quantitatively characterize the hydrodynamic deficiencies of conventional catheter models by measuring distal vorticity and peak wall shear stress (WSS) associated with embryo retention and cellular trauma.

2) To perform CFD analysis of the proposed Oval-FGIRA against clinical baseline models, evaluating hydrostatic pressure, pressure drop, wall shear stress, maximum velocity, Reynolds Number, and embryo trajectories.

3) To validate the efficacy of the 'Flow-Guiding Internal Ramp Architecture' in eliminating stagnation zones and maintaining WSS within the physiological safety threshold (< 2 Pa).

3. Materials and Methods

3.1 Overall Flowchart

The overall computational workflow adopted in this study, from geometry creation through post-processing, is summarized in Figure 1.

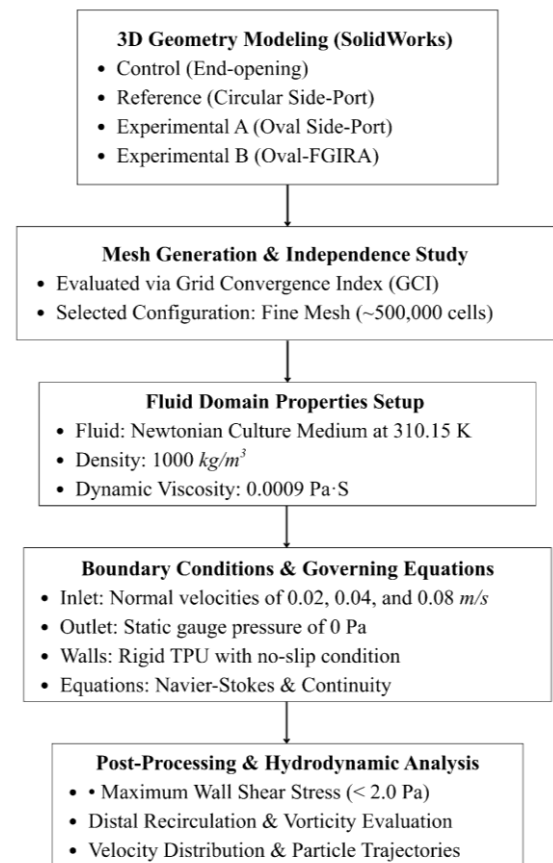


Figure 1 Flowchart illustrating the overall computational fluid dynamics (CFD) methodology

3.2 Catheter Design

The catheter geometry utilized in this research is based on a standard clinical benchmark for embryo transfer devices, an inner catheter with a circular lumen diameter of 0.5 mm, and an outer diameter of 0.9 mm. These measurements are consistent with standard commercial devices, such as the Transteb® Embryo Transfer Catheter (IVF Co., n.d.) and design standards described by Mrugacz et al. (2013). All geometry was created using SolidWorks (Dassault Systèmes). The internal flow-guiding ramp (length = 3.0 mm, height = 0.5 mm) features a continuous bi-radial profile, transitioning from a base curve (Radius = 22.0 mm, sweep angle = 7.14) to an apex curve (Radius = 1.5 mm, sweep angle = 16.22). In this study, we evaluated four distal tip configurations: Control Group, Reference Group, and two Experimental Groups.

1) Control Group (End-Opening): A standard end-opening catheter indicated by a straight, open distal tip, allowing for direct axial fluid expulsion.

2) Reference Group (Circular Side-Port): A standard side-port catheter characterized by a closed tip and a single lateral opening (0.6 mm diameter) positioned 2.5 mm proximal to the distal end, similar to commercial designs such as the Wallace® catheter.

3) Experimental Group A (Oval Side-Port): A novel side-port design featuring an oval aperture. To ensure a valid fluid dynamic comparison, the cross-sectional area of the oval orifice was designed to be mathematically equivalent to the circular reference. This group aims to test the hypothesis that an oval geometry can independently reduce wall shear stress compared to the circular baseline.

4) Experimental Group B (Oval-FGIRA): This advanced design incorporates the proposed 'Flow-Guiding Internal Ramp Architecture' (FGIRA) with the optimized oval aperture. This configuration represents a comprehensive solution, designed to eliminate the stagnation zone via the internal ramp and minimize shear stress via the oval surface.

3.3 Computational Fluid Dynamics Setup

3.3.1 Governing Equation

The simulation was conducted using SolidWorks Flow Simulation which solves the Navier-Stokes equations for mass and momentum conservation. Since the fluid is modeled as incompressible and viscosity-stabilized, the governing equations are defined as the Continuity Equation (Equation 1) and the Navier-Stokes Equation (Equation 2):

- Continuity Equation

$$\nabla \cdot \mathbf{v} = 0 \quad (1)$$

- Navier-Stokes Equation

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla P + \mu \nabla^2 \mathbf{v} \quad (2)$$

where ρ is fluid density, $\mathbf{v}$ is the velocity vector, P is pressure, and μ is dynamic viscosity.

The computational domain was defined to replicate realistic physiological conditions. The fluid model was defined as Standard Culture Media, with a density of 1000 kg/m^3 and a dynamic viscosity (μ) of $0.0009 \text{ Pa}\cdot\text{s}$ (Fontes et al., 2025) at 37°C or 310.15 K . Culture media used for embryo transfer exhibit near-Newtonian rheological behavior over the range of shear rates typically encountered in catheter-based microflows ($< 10^3 \text{ s}^{-1}$), as reported in prior rheological studies of IVF handling media. Therefore, a Newtonian fluid (a fluid with constant viscosity regardless of shear rate) approximation with constant

dynamic viscosity was adopted in this study to ensure numerical stability and physiological relevance. The solid structure was assigned the material properties of Medical-Grade Thermoplastic Polyurethane (TPU). This material selection aligns with the standards for commercial embryo transfer catheters, such as the Transteb® Echotip model (IVF Co., n.d.).

To validate the expectation of laminar flow, the Reynolds Number was calculated at the inlet by using Equation 3.

$$\text{Re} = \frac{\rho v D}{\mu} \quad (3)$$

Using the variables ($\rho = 1000 \text{ kg/m}^3$, $v = 0.02, 0.04, 0.08 \text{ m/s}$, $D = 0.0005 \text{ m}$, $\mu = 0.0009 \text{ Pa}\cdot\text{s}$). The theoretical Reynolds Numbers are approximately 11.1, 22.2, and 44.4, respectively, which are below the clinical threshold ($\text{Re} < 2300$) (Munson et al., 2013). In the context of embryo transfer, controlling the Reynolds Number is crucial for replicating the biomechanical safety of the uterine environment. Leftwich & Baumer (2024) affirm that natural embryo transport is governed by highly viscous fluid motion, which is mathematically described using lubrication theory, a regime characterized by low Reynolds Numbers. Therefore, maintaining a low Reynolds Number ($\text{Re} < 2300$) during catheter injection is essential to prevent turbulent vortices, ensuring the artificial flow closely mimics the physiological transport phenomena required for successful implantation.

While inlet velocities yield Reynolds Numbers below the safety threshold, local maximum Reynolds Numbers are also evaluated based on peak centerline and constriction velocities to capture localized hydrodynamic conditions.

3.4 Boundary Conditions

Defined to replicate physiological parameters of the procedure, boundary conditions were established for the inlet, outlet, and catheter walls. At the catheter inlet, three different velocities of $0.02, 0.04, \text{ and } 0.08 \text{ m/s}$ were applied to evaluate WSS. The baseline velocity of 0.08 m/s was derived from a standard injection fluid volume of $30 \text{ }\mu\text{L}$ delivered over an approximate duration of 1-2 seconds (Shi et al., 2022). Furthermore, as reported by Nakamura et al. (2024), these values fall within the clinical range. Specifically, the velocity of 0.02 m/s represents the 'Slow ET' group ($1.2 \pm 1.5 \text{ cm/s}$), 0.04 m/s represents an intermediate ET velocity, and 0.08 m/s aligns with the 'Fast ET' group ($7.2 \pm 2 \text{ cm/s}$). These selected

values ensure that the simulation reflects realistic scenarios used in clinical practice.

At the distal aperture, a static gauge pressure of 0 Pa was applied to simulate an unpressurized environment. In addition, all inner catheter walls were assigned a no-slip condition, assuming zero fluid velocity at the solid interface. In this computational model, the embryo transfer fluid loaded within the catheter was modeled as a Newtonian fluid. This assumption accurately represents real clinical conditions, as standard in vitro culture and transfer media typically exhibit low-viscosity Newtonian behavior, differing from the complex, non-Newtonian viscoelasticity of naturally occurring in vivo reproductive fluids (Fontes et al., 2025).

3.5 Mesh Independence Study

To ensure grid independence of the numerical solution, a mesh independence study was conducted across three levels of refinement Medium (N_3), Fine (N_2), and Ultra-Fine (N_1) using the global maximum velocity and wall shear stress as convergence metrics. The final simulations employed the Fine mesh configuration, consisting of approximately 500,000 fluid cells, as it exhibited relative differences of 1.79% (well below the accepted 5% threshold) when compared with the ultra-fine mesh. To validate this convergence and quantify numerical uncertainty, the procedure based on the Grid Convergence Index (GCI) framework was applied as recommended by Celik et al. (2008). The apparent order of accuracy (p) and the fine-grid convergence index (GCI_{fine}^{21}) were calculated using Richardson Extrapolation, with the findings summarized in Table 1. These confirmations ensure that the spatial discretization is sufficiently refined to resolve the steep velocity and shear gradients near the internal ramp and oval aperture without compromising numerical accuracy.

Table 1 Calculations of discretization error

Parameters	Value
N_1, N_2, N_3	600,000 500,000 300,000
r_{21}	1.063
r_{32}	1.186
ϕ_1	2.24
ϕ_2	2.20
ϕ_3	2.10
p	2.0
ϕ_{ext}^{21}	2.55
e_a^{21}	1.79%
e_{ext}^{21}	12.14%
GCI_{fine}^{21}	17.27%

Where N represents Number of Cells, r represents Refinement Factor, ϕ represents Wall Shear Stress on the specific mesh, p represents Apparent Order of Accuracy, ϕ_{ext} represents Extrapolated Value, e_{ext} represents Extrapolated Relative Error, e_a represents Approximate Relative Error, and GCI_{fine}^{21} represents Fine-Grid Convergence Index.

3.6 Model Validation

To validate the reliability of the CFD model, a simulated pressure drop was compared with a theoretical value calculated by the Hagen-Poiseuille equation. This equation describes the pressure loss for laminar flow of an incompressible Newtonian fluid through a cylindrical pipe, as defined in Equation 4:

$$\Delta P = \frac{32\mu L V_{avg}}{D^2} \quad (4)$$

where ΔP represents pressure drop across the catheter. The fluid properties are mentioned in the CFD setup; dynamic viscosity (μ) defined as 0.0009 Pa·s. The geometric and kinematic parameters include length (L), internal lumen diameter (D); defined as 0.0005 meters, and average inlet velocity (V_{avg}) which was maintained at 0.08 m/s.

3.7 Indicators

The CFD model's performance and safety were characterized based on the following criteria.

1) Maximum Velocity: Should not exceed 1 m/s to prevent trauma to the endometrium (Mrugacz et al., 2013)

2) Maximum Wall Shear Stress (Excluding Singularities): The peak shear stress acting on the embryo trajectory should remain below 2 Pa. Note that numerical singularities at the catheter outlet edges were filtered out to assess the biologically relevant stress exposure. Exceeding this critical value risks triggering adverse mechanotransduction signaling, a mechanism linked to reduced viability and implantation potential (Lin et al., 2024; Grygoruk et al., 2013).

3) Particle Trajectory Analysis: to visualize the embryo's flow path, serving to identify stagnant zones and observe abnormal flow behaviors within the catheter tip.

3.8 Data Processing and Visualization

Post-processing of the simulation results was conducted to extract quantitative hydrodynamics parameters. Global maximum values of velocity and wall shear stress were computed over the entire fluid domain. To evaluate the risk of embryo trauma,

surface WSS distributions were mapped along the catheter walls. Numerical singularities at the mesh boundaries were filtered to ensure that the reported maximum WSS reflected biologically relevant stress exposure within the catheter's tip. Additionally, flow trajectory streamlines were seeded from the inlet to visualize vorticity and identify recirculation zones within the distal cavity.

4. Results

4.1 Overview

The comparative hydrodynamic analysis demonstrates that internal geometric architecture significantly increases embryo safety and expulsion efficiency.

- **Elimination of Recirculation:** While the Reference Group (Circular Side-Port) exhibited intense flow recirculation at the distal tip, a known risk factor for embryo retention, the introduction of the Oval-FGIRA (Experimental Group B) successfully eliminated these vortices by providing a smooth momentum transition.

- **Wall Shear Stress Mitigation:** The Reference Group breached the 2.0 Pa physiological safety threshold, producing a maximum WSS of 2.04 Pa even at the intermediate injection speed of 0.04 m/s. In contrast, the Oval-FGIRA design effectively

mitigated mechanical stress, achieving a maximum WSS of 1.21 Pa at the same intermediate speed and a minimal WSS of 0.55 Pa at the slow speed (0.02 m/s), providing a non-traumatic environment under controlled protocols.

- **Flow Stability:** All configurations maintained a stable laminar flow regime ($Re < 2300$). The finding suggests that the synergy between an internal ramp and an oval aperture effectively overcomes the inherent trade-offs of traditional side-port designs, potentially enhancing clinical pregnancy rates by minimizing mechanotransduction-induced cellular damage.

4.2 Quantitative Hydrodynamic Analysis

To rectify the critical hydrodynamic flaws associated with conventional internal architectures and justify the efficiency of the proposed design, a comparative CFD analysis was conducted across four distinct configurations: Control Group (End-Opening), Reference Group (Circular Side-Port), Experimental Group A (Oval Side-Port), and Experimental Group B (Oval-FGIRA).

The quantitative results regarding hydrodynamic parameters, including maximum velocity, wall shear stress, and Reynolds Number, are summarized in Tables 2, 3, and 4.

Table 2 Comparative Hydrodynamic Parameters of Catheter Configurations (0.02 m/s)

Parameters	Control Group	Reference Group	Experimental Group A	Experimental Group B
Max Velocity (m/s)	0.04	0.04	0.04	0.06
Max Vorticity (1/s)	1683.20	1536.21	2966.05	2726.18
Max Shear Stress (Pa)	0.56	1.33	0.51	0.55
Maximum Reynolds Number	22.20	22.20	22.20	33.30

Table 3 Comparative Hydrodynamic Parameters of Catheter Configurations (0.04 m/s)

Parameters	Control Group	Reference Group	Experimental Group A	Experimental Group B
Max Velocity (m/s)	0.08	0.08	0.08	0.09
Max Vorticity (1/s)	2935.86	2463.45	5525.63	9025.78
Max Shear Stress (Pa)	1.32	2.04	1.25	1.21
Maximum Reynolds Number	44.40	44.40	44.40	49.95

Table 4 Comparative Hydrodynamic Parameters of Catheter Configurations (0.08 m/s)

Parameters	Control Group	Reference Group	Experimental Group A	Experimental Group B
Max Velocity (m/s)	0.16	0.16	0.16	0.168
Max Vorticity (1/s)	7025.85	5361.8	19901.00	36514.97
Max Shear Stress (Pa)	3.28	3.50	2.59	2.10
Maximum Reynolds Number	88.80	88.80	88.80	93.24

Note: The Reynolds numbers reported in this table are calculated based on the internal diameter (0.5 mm) of the main catheter lumen to evaluate the baseline flow regime and the local maximum velocity. The values across all configurations confirm a strictly stable laminar flow regime ($Re < 2300$).

At the injection velocity of 0.02 m/s , all evaluated catheter configurations maintained a stable and strictly laminar flow regime. The Control Group exhibited a maximum velocity of 0.04 m/s and minimal maximum Wall Shear Stress (WSS) of 0.56 Pa . The Reference Group recorded a higher WSS of 1.33 Pa . Moreover, the Oval Side-Port successfully maintained a WSS of 0.51 Pa . Similarly, the Oval-FGIRA design effectively maintained a maximum WSS of 0.55 Pa , confirming its biomechanical safety under slow injection protocols.

Increasing the injection velocity to the intermediate level of 0.04 m/s revealed diverging hydrodynamic behaviors among the designs. While the Control Group's maximum WSS climbed safely to 1.32 Pa , the Circular Side-Port breached the safety limit of 2 Pa with a maximum WSS of 2.04 Pa . Conversely, both Experimental Groups effectively managed the increased fluid momentum to remain within the threshold. The Oval Side-Port configuration maintained a safe WSS of 1.25 Pa . The Oval-FGIRA configuration demonstrated a maximum WSS of 1.21 Pa and a maximum internal velocity of 0.09 m/s . This

confirms that the design is highly protective at this intermediate speed.

At the fast injection velocity of 0.08 m/s , the hydrodynamic stress across all catheter designs drastically escalated, failing to protect the blastocyst. The Control Group generated a maximum WSS of 3.28 Pa , while the Reference Group exhibited a severe WSS of 3.50 Pa . The Oval Side-Port design surpassed the safety threshold with a WSS of 2.59 Pa . Consequently, the Oval-FGIRA design also breached the limit, reaching a maximum WSS of 2.10 Pa alongside a vorticity of $36,514.97 \text{ 1/s}$. These results confirm that under the fast ET (0.08 m/s) condition, the mechanical stress generated by all evaluated geometries inherently exceeds the 2.0 Pa safety limit, although the Oval-FGIRA exhibited the lowest relative stress magnitude among the designs.

4.3 Visualization of Flow Trajectories and Stress Distribution

To validate the numerical data, the flow trajectories and wall shear stress distributions of the fast velocity ET group (0.08 m/s) were visualized in Figure 2 to Figure 5.

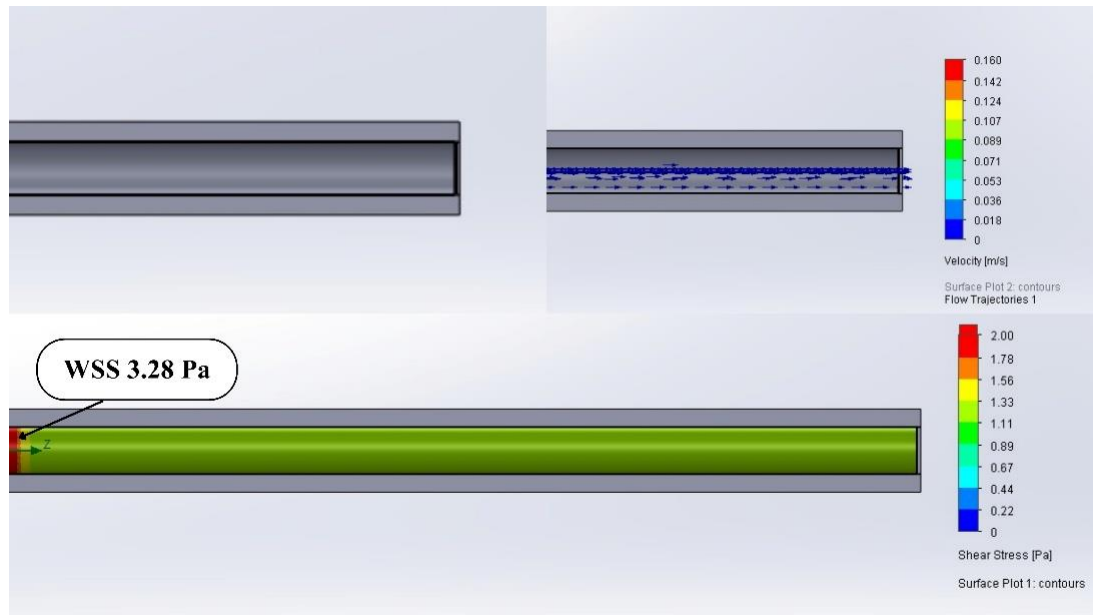


Figure 2 Maximum WSS distribution in the Control Group (End-Opening), displaying a high WSS of 3.28 Pa within the initial zone

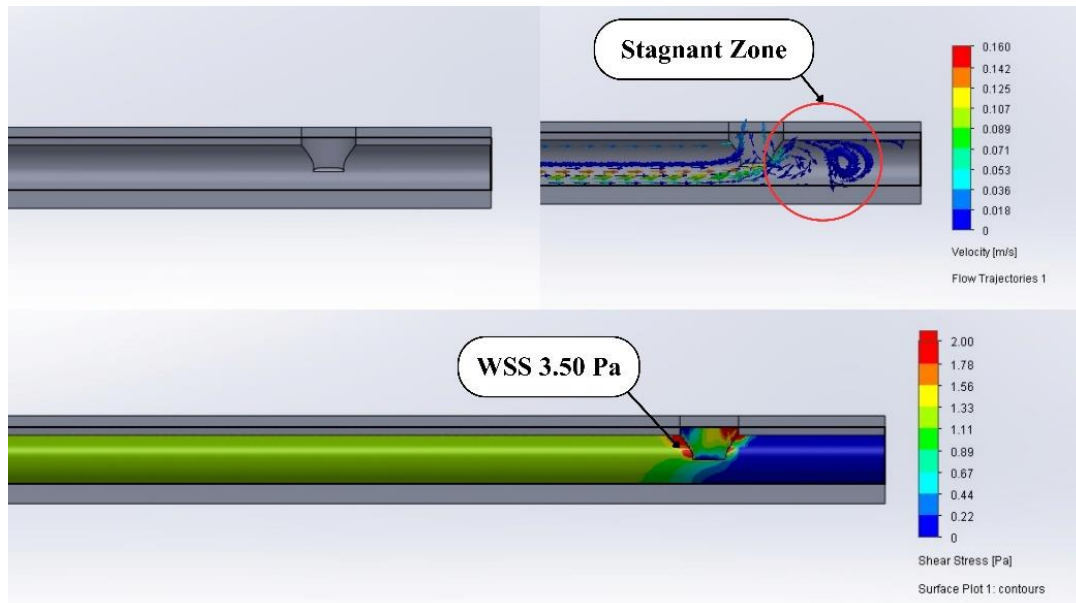


Figure 3 Flow characteristics of the Reference Group (Circular Side-Port), showing intense flow recirculation at the distal tip and a critical shear stress concentration of 3.50 Pa at the aperture edge

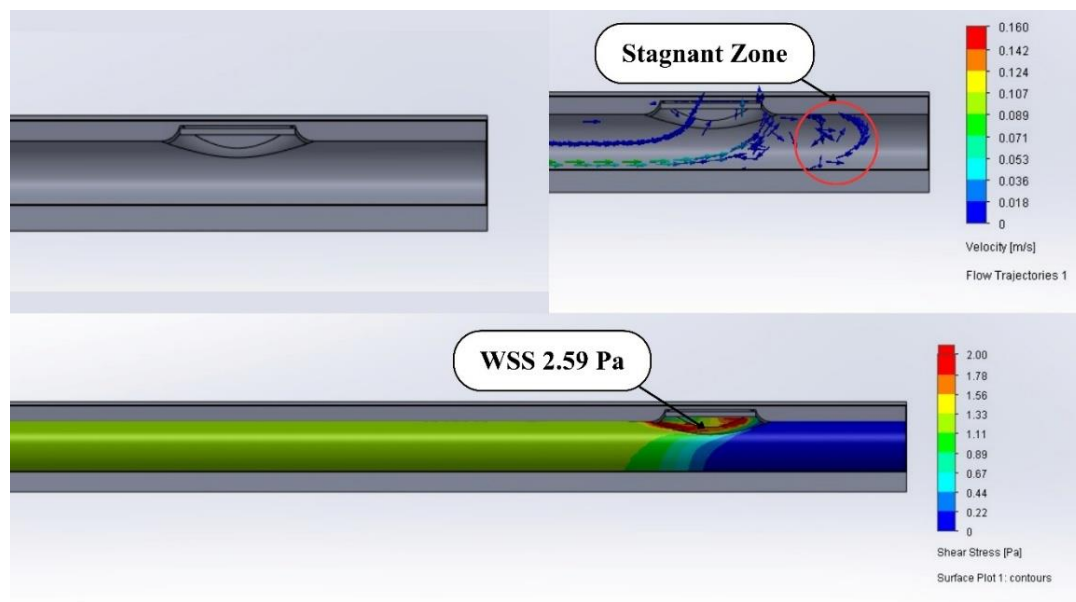


Figure 4 Flow behavior in Experimental Group A (Oval Side-Port), demonstrating less stagnation zone; however, a risk to embryo viability persists as the wall shear stress reaches 2.59 Pa

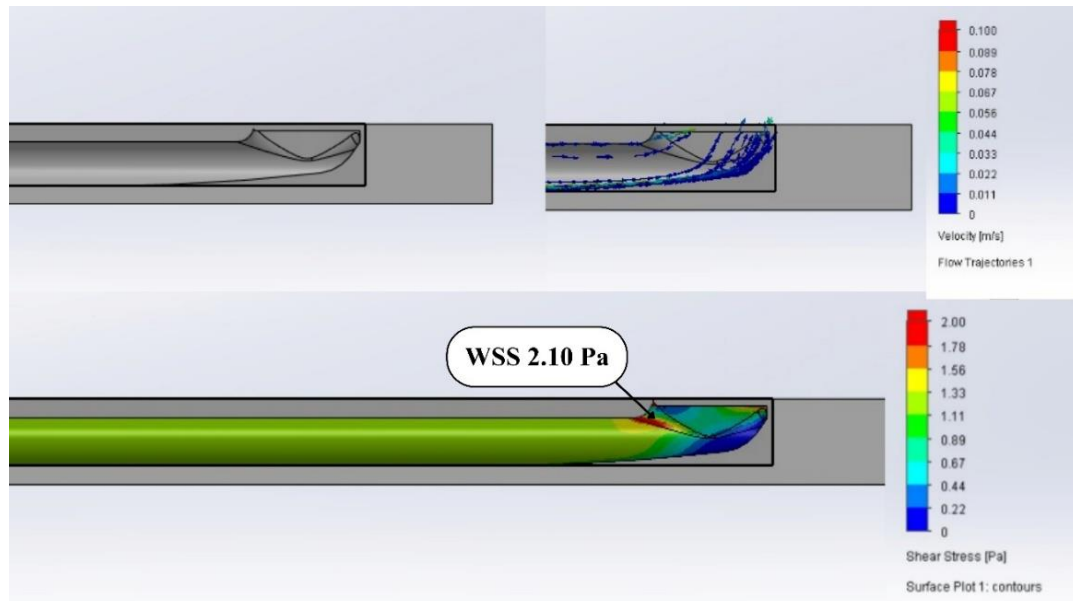


Figure 5 Hydrodynamic performance of the Oval-FGIRA, demonstrating the elimination of the stagnation zone via the internal ramp architecture which guides the flow smoothly to the exit. Conversely, the model exhibits a maximum WSS of 2.10 Pa.

The analysis began with the Control Group (End-Opening) in Figure 2, which was characterized by a direct axial discharge. The visualization indicates a high-stress concentration zone, with the maximum WSS reaching 3.28 Pa within the initial zone. In contrast, Figure 3 reveals the critical hydrodynamic flaws of the Reference Group (Circular Side-Port). The streamline analysis visualizes a recirculation zone at the closed distal end, confirming the formation of a stagnant area vulnerable to embryo retention. Furthermore, an intense stress concentration zone is observed at the edge of the circular aperture, yielding a peak Wall Shear Stress of 3.50 Pa, which significantly exceeds the safety threshold of 2.0 Pa.

The impact of geometric modification is evident in Figure 4 for Experimental Group A (Oval Side-Port). The streamline analysis reveals that the elongated aperture successfully reduces the stagnation zone and vortex formation observed in the circular model. However, despite this improvement in the flow pattern, a risk to embryo viability persists as the surface plot indicates a maximum Wall Shear Stress of 2.59 Pa, continuing to breach the critical safety threshold.

Finally, the Oval-FGIRA configuration in Figure 5 demonstrates optimized internal hydrodynamic performance. The particle trajectories confirm that the Internal Ramp Architecture successfully redirects the fluid momentum smoothly towards the exit, effectively

eliminating the stagnation zone completely. While the maximum Wall Shear Stress was minimized to 2.10 Pa, the lowest relative stress magnitude among all designs, it still marginally exceeds the 2.0 Pa threshold under this fast injection protocol (0.08 m/s). This visual evidence underscores the necessity of strictly pairing the Oval-FGIRA device with slower clinical transfer speeds to ensure absolute biomechanical safety.

5. Discussion

This study addresses the critical hydrodynamic trade-off in embryo transfer catheters: the need to minimize the risk of endometrial trauma, which favors side-port catheters, versus the need to maintain efficient embryo expulsion, which favors end-opening catheters. Previous studies by Mains and Van Voorhis (2010) identified that standard side-port catheters create a distal dead zone characterized by high vorticity and fluid stagnation, posing a significant risk of embryo retention. Our simulation of the Reference Group visually confirmed this flaw, revealing a distinct recirculation vortex and a breach of the safety threshold (WSS of 2.04 Pa) even at the intermediate speed of 0.04 m/s. A key finding of this study is the partial success of the Oval Side-Port configuration. The results demonstrated that elongating the aperture into an oval shape (maintaining a cross-sectional area equal to the Reference Group) successfully reduces

the maximum WSS to safe levels in the 0.04 *m/s* regime. However, while the oval aperture partially rectifies the flow path, it may lack the structural capability to actively guide the fluid momentum, leaving minor flow instabilities unresolved.

The Experimental Group B (Oval-FGIRA) demonstrated superior capability of addressing all hydrodynamic challenges. By integrating the internal ramp, the FGIRA design not only maintained the vortex-free flow established by the oval aperture but also significantly reduced the fluid momentum impact at the wall. Consequently, it lowered the maximum Wall Shear Stress to 1.21 Pa at the intermediate ET speed, completely eliminating the stagnation zone and mitigating the risk of vortex-induced embryo retention. This confirms that the Internal Ramp is not redundant but is an essential component that acts as a "flow conditioner," guiding the fluid smoothly to the exit without generating excessive shear forces, as compared to the maximum WSS of the Oval Side-Port catheter. While a direct numerical comparison is limited by differing velocity setups in the literature, our findings strongly align with the physiological stress trends established by Grygoruk et al. (2013). Their simulation demonstrated that conventional catheters reach the critical 2.0 Pa threshold at an injection speed of 0.1 *m/s*. Similarly, our study builds upon this by revealing that standard side-port architectures (Reference Group) actually breach this safety threshold much earlier, yielding 2.04 Pa at just 0.04 *m/s*. In contrast, the Oval-FGIRA effectively delays this critical breach, mitigating the stress to a safe 1.21 Pa at 0.04 *m/s*, demonstrating improved safety over traditional designs.

At the 0.02 and 0.04 *m/s* injection speeds, the reduction of Wall Shear Stress to 0.55 and 1.21 Pa, respectively, is biologically significant, as shear stress above 2 Pa is a potent activator of mechanotransduction pathways, such as YAP/TAZ, that can compromise cellular viability (Lin et al., 2024). Most importantly, the failure of all catheter designs to maintain safe WSS levels at 0.08 *m/s* leads to a definitive clinical implication. Therefore, we strongly recommend that the Oval-FGIRA catheter be strictly paired with "Slow" to "Intermediate" embryo transfer protocols (≤ 0.04 *m/s*). This evidence aligns with clinical findings from Nakamura et al. (2024), who demonstrated that high-velocity transfers are directly correlated with reduced pregnancy rates.

Despite these promising findings, several limitations must be acknowledged. First, the CFD simulations assumed a Newtonian culture medium

and modeled the embryo as a fluid tracer rather than a distinct particle, which may exclude potential effects of embryo size (~ 150 μm) and density on local flow patterns. Second, the catheter walls were modeled as rigid structures, whereas medical-grade TPU may exhibit slight elastic deformation during clinical use.

In summary, the Oval-FGIRA design validates that the combination of an oval aperture and an internal ramp is required to achieve both efficient delivery and optimal safety. By engineering a medical device that enhances the safety and success rate of Assisted Reproductive Technology, this research contributes to Sustainable Development Goal 3 (Good Health and Well-being), specifically Target 3.8, which calls for universal health coverage and access to quality, safe, and affordable essential health-care services (United Nations, 2015). Improving the efficiency of each IVF cycle minimizes the need for re-interventions and additional cycles, directly supporting this target by optimizing healthcare resources and reducing the financial burden on patients. Improving the efficiency of each IVF cycle minimizes the need for re-interventions and additional cycles, thereby optimizing healthcare resources. To address the mentioned limitations and advance the device toward clinical application, future work will incorporate Fluid-Structure Interaction (FSI) modeling to further validate the robustness of the FGIRA design, along with prototyping via high-precision micro-injection molding for in vitro validation using Particle Image Velocimetry to prepare the device for clinical application.

6. Conclusion

The computational investigation conducted in this study successfully characterized the hydrodynamic performance of various embryo transfer catheter designs, revealing that conventional side-port configurations suffer from fluid stagnation and elevated shear stress due to the abrupt 90-degree redirection of fluid momentum. In contrast, the proposed Oval-FGIRA (Experimental Group B) design illustrated superior efficiency by eliminating vortex formation through its integrated internal ramp architecture, which provides a smooth transition of fluid toward the lateral aperture.

Quantitative findings confirm that this optimized design achieved a Maximum Wall Shear Stress of 1.21 Pa at 0.04 *m/s* injection speed, which is significantly lower than the values observed in the Reference Group (2.04 Pa) and the Control Group (1.32 Pa), thereby ensuring transport conditions well within the physiological safety threshold of 2 Pa.

However, at higher speed of 0.08 m/s, maximum shear stress breached through the threshold at 2.10 Pa. Clinical protocols must therefore restrict the maximum injection speed to 0.04 m/s. Furthermore, the maintenance of a stable laminar flow regime, characterized by a Local Maximum Reynolds Number of 49.95 and a velocity of 0.09 m/s, validates the design's capacity to minimize potential endometrial trauma and mechanotransduction-induced cell damage.

While this study establishes a computational foundation across a spectrum of injection speeds, future research will incorporate Fluid-Structure Interaction (FSI) modeling to capture the elastic deformation of the catheter walls. Additionally, *in vitro* validation using biomimetic models and Particle Image Velocimetry (PIV) is recommended to translate these predicted hydrodynamic metrics into physical prototypes. Ultimately, the synergy between a flow-guiding internal ramp and an oval orifice establishes a safer hydrodynamic environment, offering a highly promising technical blueprint for improving IVF clinical pregnancy outcomes.

7. Acknowledgement

The authors declare that they have no personal relationships that could have appeared to influence the work reported in this paper. Furthermore, this research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

8. Abbreviations

Abbreviation	Full Term
CFD	Computational Fluid Dynamics
ET	Embryo Transfer
FGIRA	Flow-Guiding Internal Ramp Architecture
FSI	Fluid-Structure Interaction
GCI	Grid Convergence Index
IVF	<i>in vitro</i> fertilization
MAPK	Mitogen-Activated Protein Kinase
PIV	Particle Image Velocimetry
Re	Reynolds Number
SDG	Sustainable Development Goal
TPU	Thermoplastic Polyurethane
WSS	Wall Shear Stress
YAP/TAZ	Yes-Associated Protein / Transcriptional Coactivator with PDZ-binding motif

9. CRediT Statement

Abhinat Vairungroj: Conceptualization, Investigation, Data Curation, Methodology, Resources, Software, Validation, Visualization, Writing – Original Draft

Punn Pongsawasdi: Formal Analysis, Project Administration, Validation, Visualization, Writing – Original Draft, Writing – Review & Editing

10. References

- Brown, J., Buckingham, K., Buckett, W., & Abou-Setta, A. M. (2016). Ultrasound versus 'clinical touch' for catheter guidance during embryo transfer in women. *Cochrane Database of Systematic Reviews*, 3. Article CD006107. <https://doi.org/10.1002/14651858.CD006107.pub4>
- Celik, I. B., Ghia, U., Roache, P. J., & Freitas, C. J. (2008). Procedure for estimation and reporting of uncertainty due to discretization in CFD applications. *Journal of Fluids Engineering-Transactions of the ASME*, 130(7), Article 078001. <https://doi.org/10.1115/1.2960953>
- D'Angelo, A., Panayotidis, C., Alteri, A., Mcheik, S., & Veleva, Z. (2022). Evidence and consensus on technical aspects of embryo transfer. *Human Reproduction Open*, 2022(4), Article hoac038. <https://doi.org/10.1093/hropen/hoac038>
- Edwards, R. G., Steptoe, P. C., & Purdy, J. M. (1980). Establishing full-term human pregnancies using cleaving embryos grown in vitro. *BJOG: An International Journal of Obstetrics & Gynaecology*, 87(9), 737-756. <https://doi.org/10.1111/j.1471-0528.1980.tb04610.x>
- Espina, J. A., Cordeiro, M. H., Milivojevic, M., Pajić-Lijaković, I., & Barriga, E. H. (2023). Response of cells and tissues to shear stress. *Journal of Cell Science*, 136(18), Article jcs260985. <https://doi.org/10.1242/jcs.260985>
- Fontes, P. K., Milazzotto, M. P., & Ferraz, M. D. A. M. M. (2025). Mimicking the oviductal fluid viscosity improves the quality of in vitro-produced bovine embryos. *Biology of Reproduction*, 113(6), 1364-1374. <https://doi.org/10.1093/biolre/roaf202>
- Grygoruk, C., Mrugacz, G., Kolodziejczyk, M., Gagan, J., Ratomski, K., & Grusza, M. (2013). Shear stress during embryo transfer. *Progress in Health Sciences*, 3(2), 7-10.

- Guerrero-Alvarado, M. D. Á., Tejeda-Alejandre, R., Vázquez-Lepe, E., Plascencia-Martínez, D. F., Castillo-Ortega, M. M., Encinas-Encinas, J. C., & García-López, E. (2026). Micro injection molding parameters impact on thermoplastic polyurethane (TPU)'s mechanical properties. *The International Journal of Advanced Manufacturing Technology*, 142, 6037–6056.
<https://doi.org/10.1007/s00170-025-17292-y>
- IVF Co. (n.d.). *Embryo Transfer Catheter*. Retrieved from <https://ivfco.co/Catalogue/Transteb%20echotip.pdf>
- Leftwich, M. C., & Baumer, A. C. (2024). The fluid mechanics of female reproduction: A review of the biofluid mechanics of pregnancy and delivery. *Annual Review of Fluid Mechanics*, 56(1), 171-188.
<https://doi.org/10.1146/annurev-fluid-121021-033738>
- Lin, S., He, X., Wang, Y., Chen, Y., & Lin, A. (2024). Emerging role of lncRNAs as mechanical signaling molecules in mechanotransduction and their association with Hippo-YAP signaling: A review. *Journal of Zhejiang University-SCIENCE B*, 25(4), 280-292.
<https://doi.org/10.1631/jzus.B2300497>
- Mains, L., & Van Voorhis, B. J. (2010). Optimizing the technique of embryo transfer. *Fertility and Sterility*, 94(3), 785-790.
<https://doi.org/10.1016/j.fertnstert.2010.03.030>
- Mrugacz, G., Grygoruk, C., Kolodziejczyk, M., Gagan, J., Ratomski, K., & Grusza, M. (2013). Fluid velocity during embryo transfer. *Progress in Health Sciences*, 3(2), 17-20.
- Munson, B. R., Okiishi, T. H., Huebsch, W. W., & Rothmayer, A. P. (2013). *Fluid mechanics*. Singapore: Wiley.
- Nakamura, Y., Kikuchi, F., & Ezaki, K. (2024). Impact of injection speed of embryo transfer on pregnancy rate. *Journal of Mammalian Ova Research*, 41(2), 87-94.
- Owen, D. G., de Oliveira, D. C., Qian, S., Green, N. C., Shepherd, D. E., & Espino, D. M. (2020). Impact of side-hole geometry on the performance of hemodialysis catheter tips: A computational fluid dynamics assessment. *PLoS One*, 15(8), Article e0236946.
<https://doi.org/10.1371/journal.pone.0236946>
- Schoolcraft, W. B., Surrey, E. S., & Gardner, D. K. (2001). Embryo transfer: Techniques and variables affecting success. *Fertility and Sterility*, 76(5), 863-870.
[https://doi.org/10.1016/S0015-0282\(01\)02731-5](https://doi.org/10.1016/S0015-0282(01)02731-5)
- Shi, C., Sun, T. C., Meng, S. H., Wang, P., Liang, R., Duan, S. N., Han, H. J., Liu, Y. N., Shen, H., & Chen, X. (2022). Embryo density and its neutrality in day-3 embryo development: A retrospective cohort study. *International Journal of Endocrinology*, 2022, Article 6368678.
<https://doi.org/10.1155/2022/6368678>
- United Nations. (2015). *Transforming our world: The 2030 agenda for sustainable development* (A/RES/70/1). <https://sdgs.un.org/2030agenda>
- Xu, J., Yin, M. N., Chen, Z. H., Yang, L., Ye, D. S., & Sun, L. (2020). Embryo retention significantly decreases clinical pregnancy rate and live birth rate: A matched retrospective cohort study. *Fertility and Sterility*, 114(4), 787-791.
<https://doi.org/10.1016/j.fertnstert.2020.04.043>
- Yang, Y., Li, Y., Liu, C., Zhou, J., Li, T., Xiong, Y., & Zhang, L. (2022). Hemodynamic analysis of the geometric features of side holes based on GDK catheter. *Journal of Functional Biomaterials*, 13(4), Article 236.
<https://doi.org/10.3390/jfb13040236>