

Influence of Geometric and Flow Complexity on Sperm Migration Dynamics

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Abstract:

Successful fertilization requires sperm to navigate complex reproductive environments shaped by fluid flow and geometric confinement. This report summarizes two studies exploring bovine sperm migration across distinct hydrodynamic and structural conditions. First, we investigated sperm rheotaxis in radial flow fields, revealing that moderate flows drive upstream migration, while higher flows induce rotational rheotaxis, where sperm follow stable curved trajectories around the flow origin. These findings enabled the development of a unidirectional navigation chip that enriches highly motile sperm with up to 98% output motility. Second, we examined sperm transport through confined obstacle lattices, demonstrating that geometric confinement regulates scattering behavior and surface interactions, with a transport model predicting enhanced effective diffusivity. Together, these studies reveal how flow and architecture independently regulate microswimmer navigation and provide principles for designing bioinspired sperm selection platforms.

Summary of Research:

This report summarizes two related studies investigating how bovine spermatozoa navigate physically structured microenvironments that reproduce key features of the female reproductive tract [1], and how the resulting behavioral insights can be translated into functional sperm-selection technology for assisted reproductive technology. For each study, a soft lithography technique was used to fabricate the microfluidic devices. The master molds were fabricated by coating SU-8 photoresist on a silicon substrate, exposing the masked wafer to UV light, and developing.

The first study, published in *Lab on a Chip*[2], combined simulations and experiments to investigate sperm rheotaxis in an outward radial flow. While moderate flow rates induced upstream migration toward the flow origin, higher flow rates produced a previously unreported behavior, rotational rheotaxis, in which sperm swirled around the flow origin while continuing to migrate inward. This behavior arises from the coupling between intrinsic helical swimming and the non-uniform shear field of radial flow.

These findings informed the design of a selection device (Fig. 1), the sperm unidirectional navigation chip, which integrates the radial flow geometry with strategically positioned constricted flow channels to reinforce unidirectional progression and exclude non-progressive cells. Evaluated on raw bovine semen, the sperm unidirectional navigation chip achieved output motility of up to 98%, recovered approximately 30% of motile sperm from the input sample, and produced a selected population swimming roughly 50% faster on average than raw semen. These results demonstrate that radial flow geometry, when appropriately tuned, can be exploited as an active selection mechanism rather than functioning merely as a passive environmental feature, offering a low-complexity, centrifugation-free alternative for assisted reproductive technology sperm preparation.

The second study, currently available as a bioRxiv preprint[3], investigated sperm navigation in confined, lattice-like environments that mimic the folded fallopian epithelium. Using microfabricated obstacle arrays (Fig. 2a-c), sperm trajectories and scattering dynamics were quantified experimentally, and the resulting data were used to develop a mathematical transport model describing sperm migration through structured environments.

The central finding was a passive adaptive sensing mechanism regulating sperm-surface interactions

as a function of local confinement. Scattering angle varied systematically with lattice spacing, and surface-interaction duration decreased under tighter confinement, indicating that cells disengage from surfaces more rapidly in more confined settings. The transport model predicted that this confinement-dependent scattering behavior could enhance effective diffusivity by up to ninefold relative to obstacle-free, free swimming (Fig. 2d).

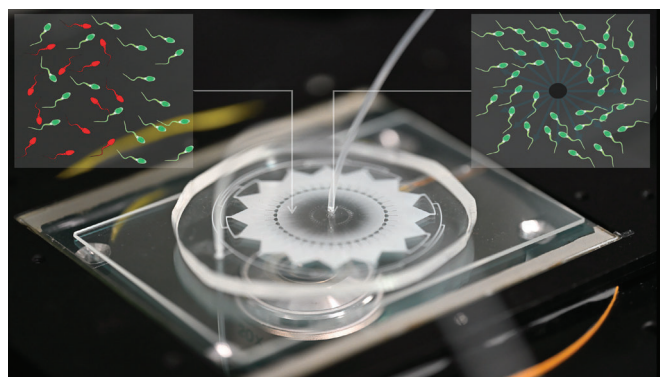


Figure 1: Microfluidic sperm unidirectional navigation chip for selective enrichment of highly motile sperm. Fluid enters through a central inlet and flows radially toward distributed outlet channels. Highly motile sperm swim upstream and become trapped near the center by rotational rheotaxis, whereas non-motile sperm, debris, and damaged cells are carried downstream and removed by the flow.

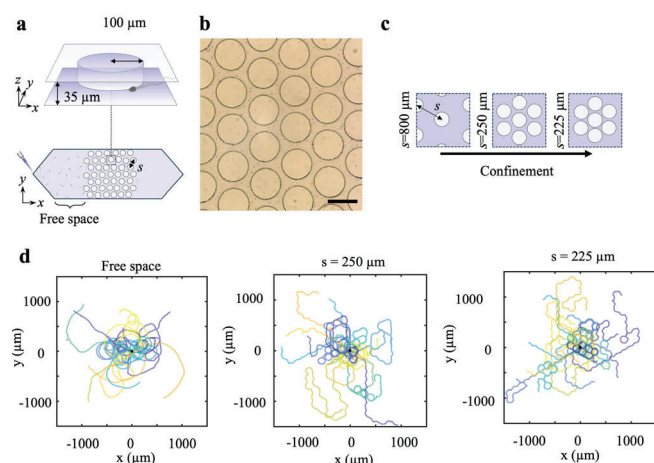


Figure 2: Microfluidic obstacle lattice for studying sperm navigation under confinement. (a) Schematic of the circular obstacle array. (b) Microscopic image of the fabricated obstacle lattice (scale bar: 200 μm). (c) Lattice confinement is systematically increased by reducing the center-to-center obstacle spacing, s . (d) Representative sperm trajectories in an obstacle-free environment and in obstacle lattices with progressively stronger confinement, illustrating the effect of lattice geometry on swimming behavior.

Conclusions and Future Steps:

Taken together, these two studies establish that both hydrodynamic and geometric features of the reproductive tract actively shape sperm transport, rather than serving as passive obstacles. The radial flow study demonstrates that flow-field structure can be engineered into a functional, quantifiably effective selection platform, while the confinement lattice study demonstrates that geometry alone modulates transport efficiency through an adaptive, passive surface-sensing mechanism robust to changes in motility state. Collectively, these findings support treating geometry and hydrodynamics as tunable design parameters for microfluidic device development.

Several directions warrant further investigation. First, the sperm unidirectional navigation chip's motile sperm recovery yield ($\sim 30\%$) leaves room for optimization; future iterations should explore alternative constriction placements and channel dimensions to improve throughput without sacrificing selection purity. Second, the mechanistic basis of rotational rheotaxis merits deeper theoretical characterization, particularly the transition between directed and rotational regimes. Third, the adaptive sensing mechanism identified in the lattice study should be examined at a molecular or biomechanical level to clarify whether it arises from flagellar mechanics alone or involves additional membrane- or surface-mediated processes. Fourth, integrating the two device paradigms, radial flow selection and confinement-based transport enhancement, into a single platform may yield synergistic gains in selection efficiency and throughput. Finally, validating these findings in human sperm samples will be essential to assess translational applicability, given that the current work was conducted exclusively in a bovine model. Addressing these questions will help move this work from proof-of-concept demonstrations toward clinically viable assisted reproductive technologies.

References:

- [1] S. S. Suarez, Mammalian sperm interactions with the female reproductive tract, *Cell Tissue Res.* 363, 185 (2016).
- [2] A. Karimi, X. Jiang, and A. Abbaspourrad, Navigation and selection of spermatozoa in a radial flow microfluidic device, *Lab. Chip* 26, 403 (2026).
- [3] A. Karimi, X. Jiang, and A. Abbaspourrad, Adaptive surface sensing enables mammalian sperm navigation in complex environments, *bioRxiv* 2025.11.16.688464 (2025).