A Dual-Field Inertial–Acoustic Microfluidic Chip for Label-Free Circulating Tumor Cell Isolation

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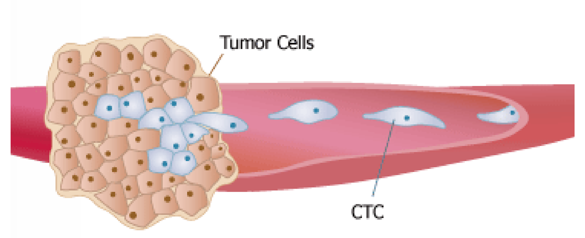
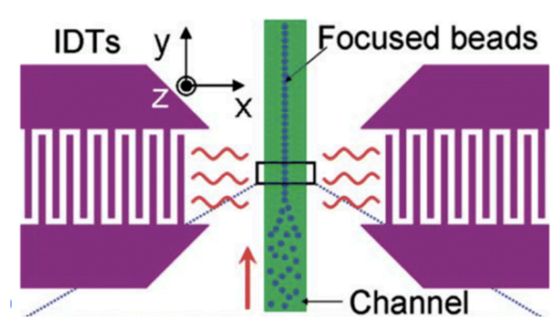
Engineering Problem & Project Objectives

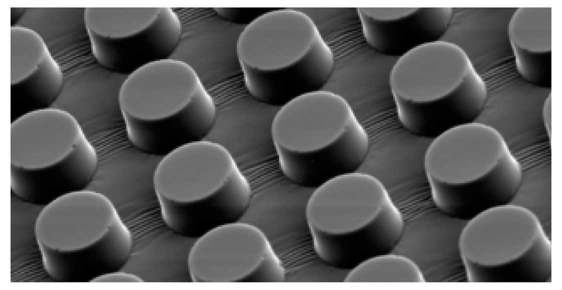
Engineering Problem:

Circulating tumor cells (CTCs) are extremely rare (<10 cells/mL) yet clinically critical for early cancer detection and monitoring.

Region / Provider	Typical Cost (approx.)
United States	**≈ $2,689**
Bangkok medical centre	**≈ $1,450 USD**
Hong Kong clinic (CTC test)	**≈ HK$10,000–20,000 (~$1,280–**



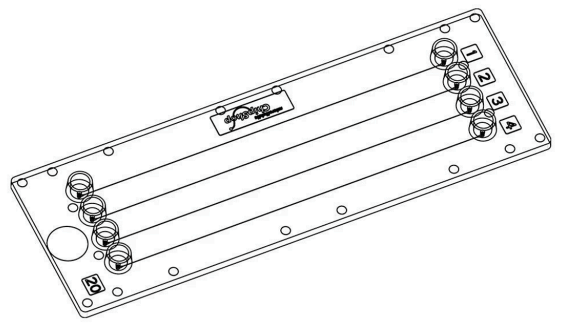




Engineering Question :

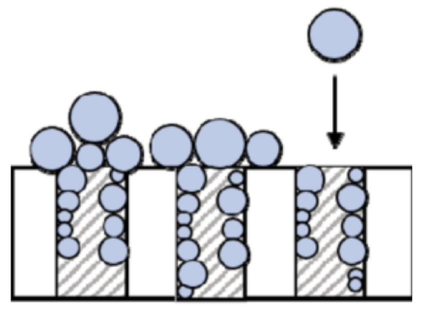
Can a microfluidic chip achieve:

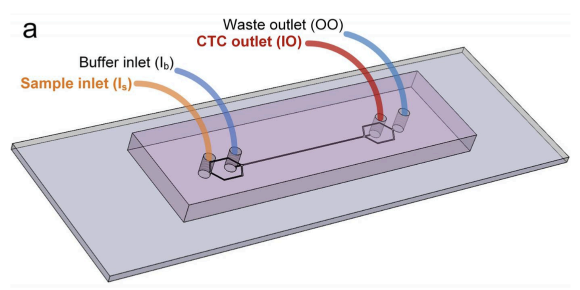
- **High-efficiency**
- **Label-free separation**
- **High throughput**
- **Stable, low-adhesion continuous operation?**



Limitations with Current Approaches:

- **CellSearch (FDA-approved) → EpCAM-based capture → Misses CTCs undergoing EMT (loss of EpCAM expression)**
- **Size-based filtration → clogging during continuous flow**
- **Single-field microfluidics → tradeoff between efficiency, purity, throughput**
- **Wall adhesion & fouling → instability during long-term operation**





Engineering Objectives:

Goal 1 – Dual-Field Label-Free Separation
- **Inertial focusing + acoustic manipulation**
- **95% enrichment efficiency**
- **3× throughput improvement**

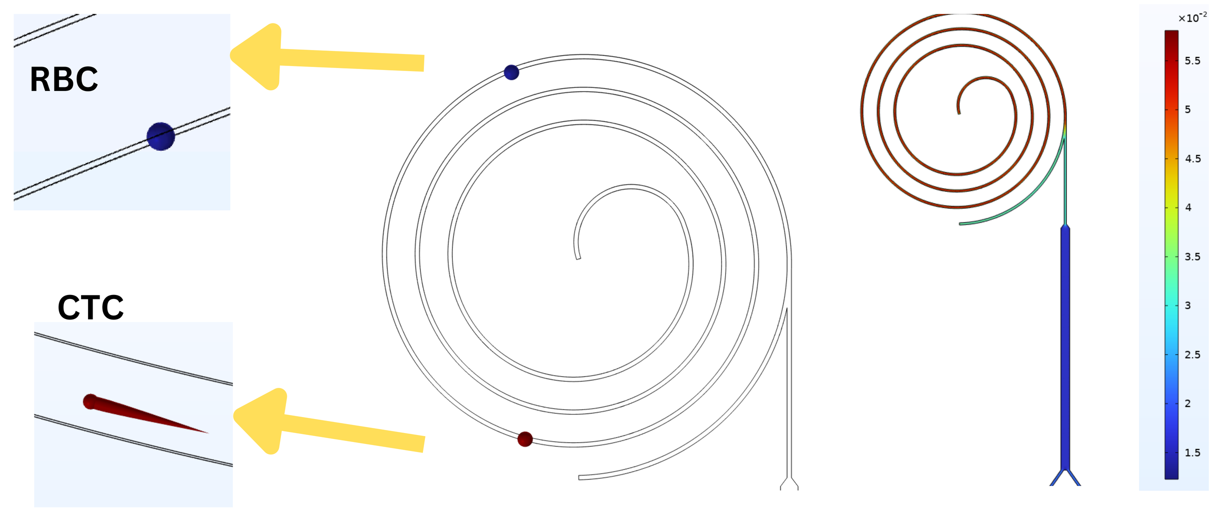
Goal 2 – Anti-Adhesion Stability
- **SiO_2 micropillar textures**
- **Surface chemical modification (PEG / zwitterionic)**
- **72-hour continuous operation target**

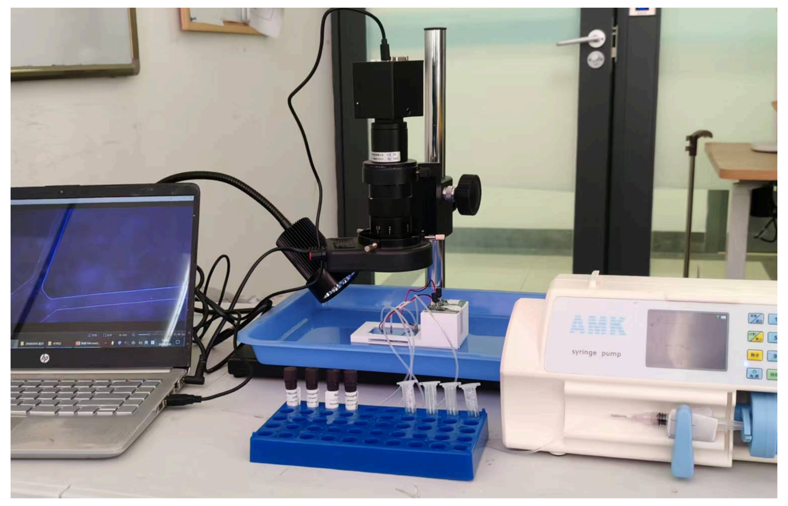
Data Analysis & Results

COMSOL Simulation:

- **Laminar Flow + Particle Tracing**
- **Particle sizes: 20 µm (CTC), 10 µm (WBC), 6–7 µm**
- **Bounce wall interaction**
- **Geometry matched fabricated chip**

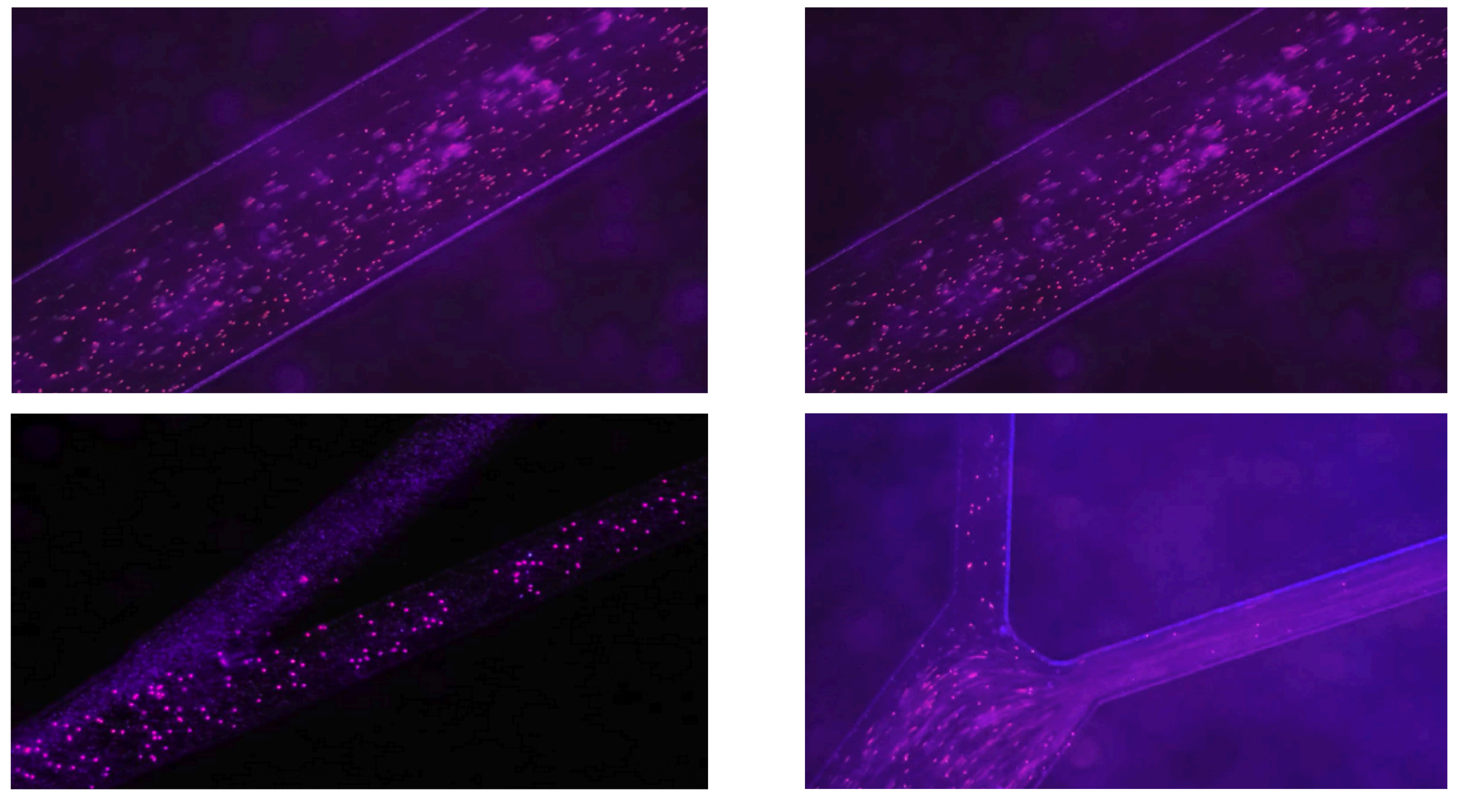
Result:
Size-dependent equilibrium focusing observed
Large particles migrate to distinct lateral positions





Microfluidic Experiments:

- **PDMS–glass fabricated chip**
- **1 inlet + 3 outlets**
- **Syringe pump driven**
- **Flow rate: 0.8–2.5 mL/h**
- **Optimal inertial separation: ~1.5–2.0 mL/h**
- **Test beads: 2, 7, 10, 20 µm**



>96% CTC enrichment efficiency

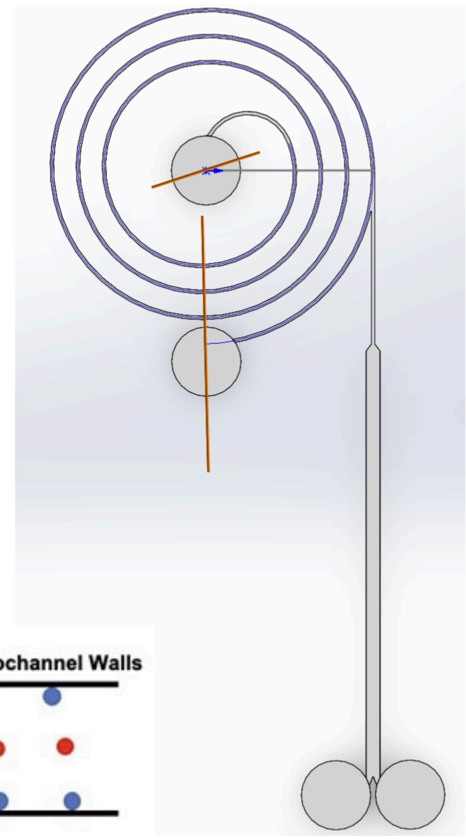
Project Overview

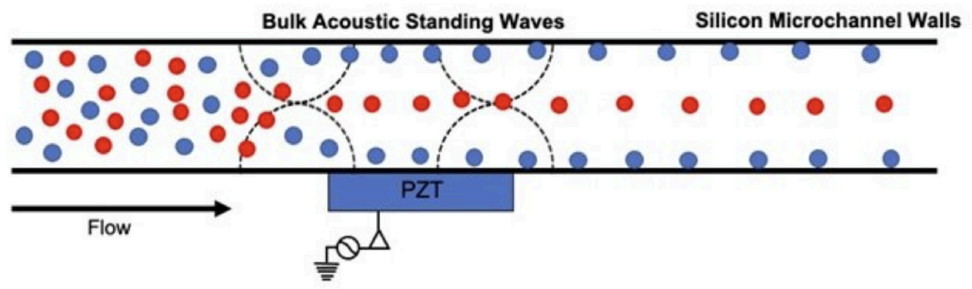
Dual-Field Separation Architecture:

Stage 1 – Spiral Inertial Channel

- **Diameter: 20 mm**
- **3.3 turns**
- **200 × 100 µm cross-section**
- **Reynolds number controlled (laminar flow maintained)**
- **Dean flow + inertial lift force**
- **Size-dependent lateral focusing**

$$Re = \frac{\rho U D_h}{\mu} \qquad F_L \propto \rho U^2 a^4 / D_h^2$$

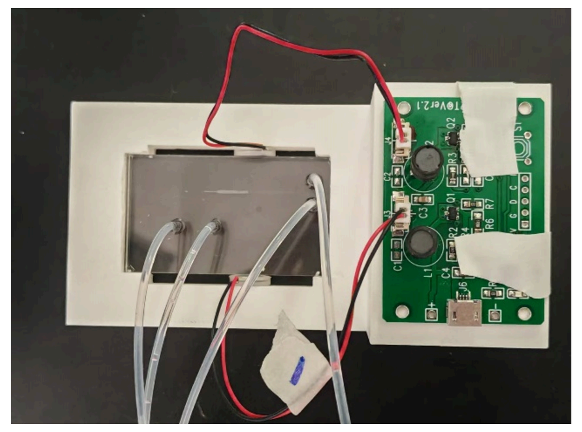




Stage 2 – Acoustic Straight Channel

- **800 × 100 µm**
- **Length: 25 mm**
- **Piezoelectric transducer (PZT)**
- **Standing wave field**

$$F_{rad} \propto a^3 \nabla E_{ac}$$



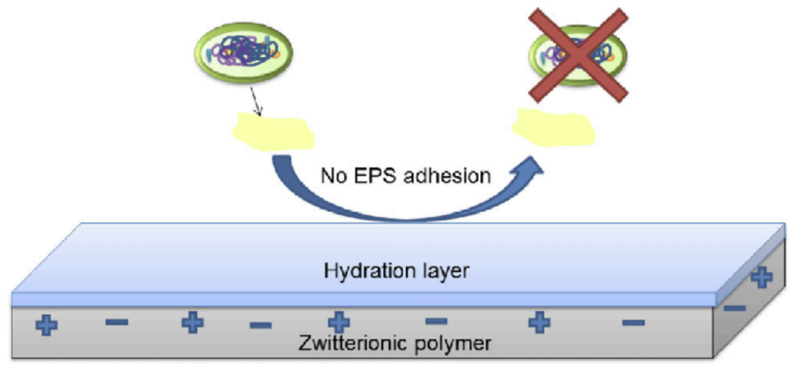
Anti-Adhesion Strategy:

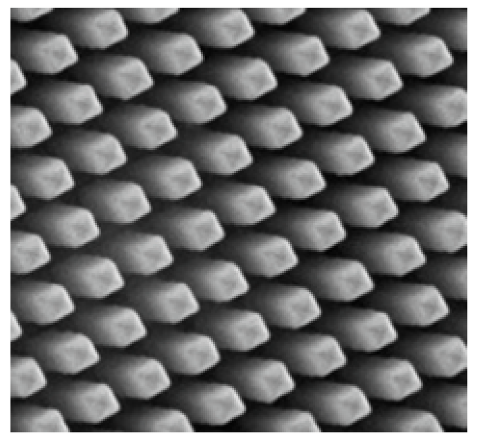
Micropillar Arrays

- **Reduce effective contact area**
- **Maintain near-wall shear**
- **Suppress stagnation zones**

Surface Chemistry

- **PEG → simple, hydrophilic, moderate durability**
- **Zwitterionic → stronger hydration shell, better long-term stability**

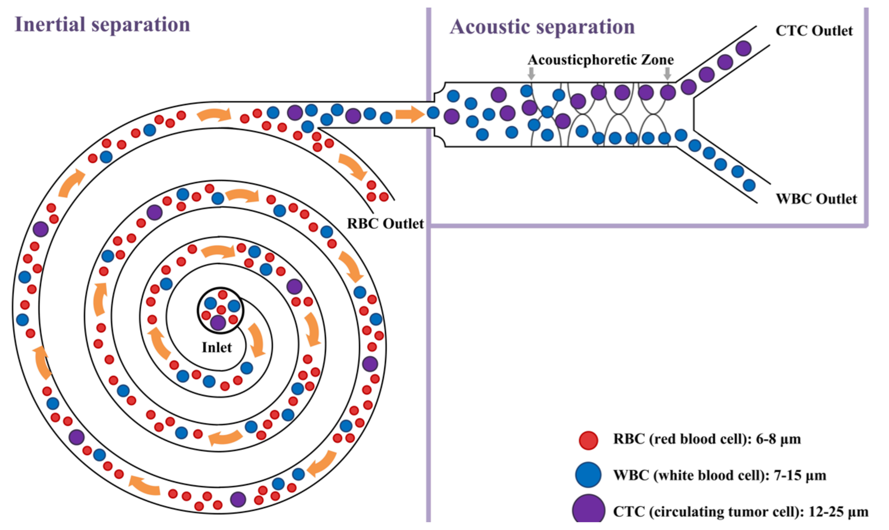




Conclusion

Interpretation:

- **Inertial channel provides high-throughput pre-alignment**
- **Acoustic stage refines separation without physical contact**
- **Dual-field reduces dispersion and improves outlet purity**
- **Micropillar + surface chemistry addresses fouling limitations**



Future Work:

- **Integrated portable lab-on-chip system**
- **On-chip cleaning & antifouling control**
- **AI-based automated image analysis**
- **Clinical sample validation**

Novelty:

- **Dual-field integration (inertial + acoustic)**
- **Hybrid anti-adhesion design**
- **Sequential staged separation logic**