

Computational Modeling of Pulmonary Flow Restriction Devices for Hypoplastic Left Heart Syndrome

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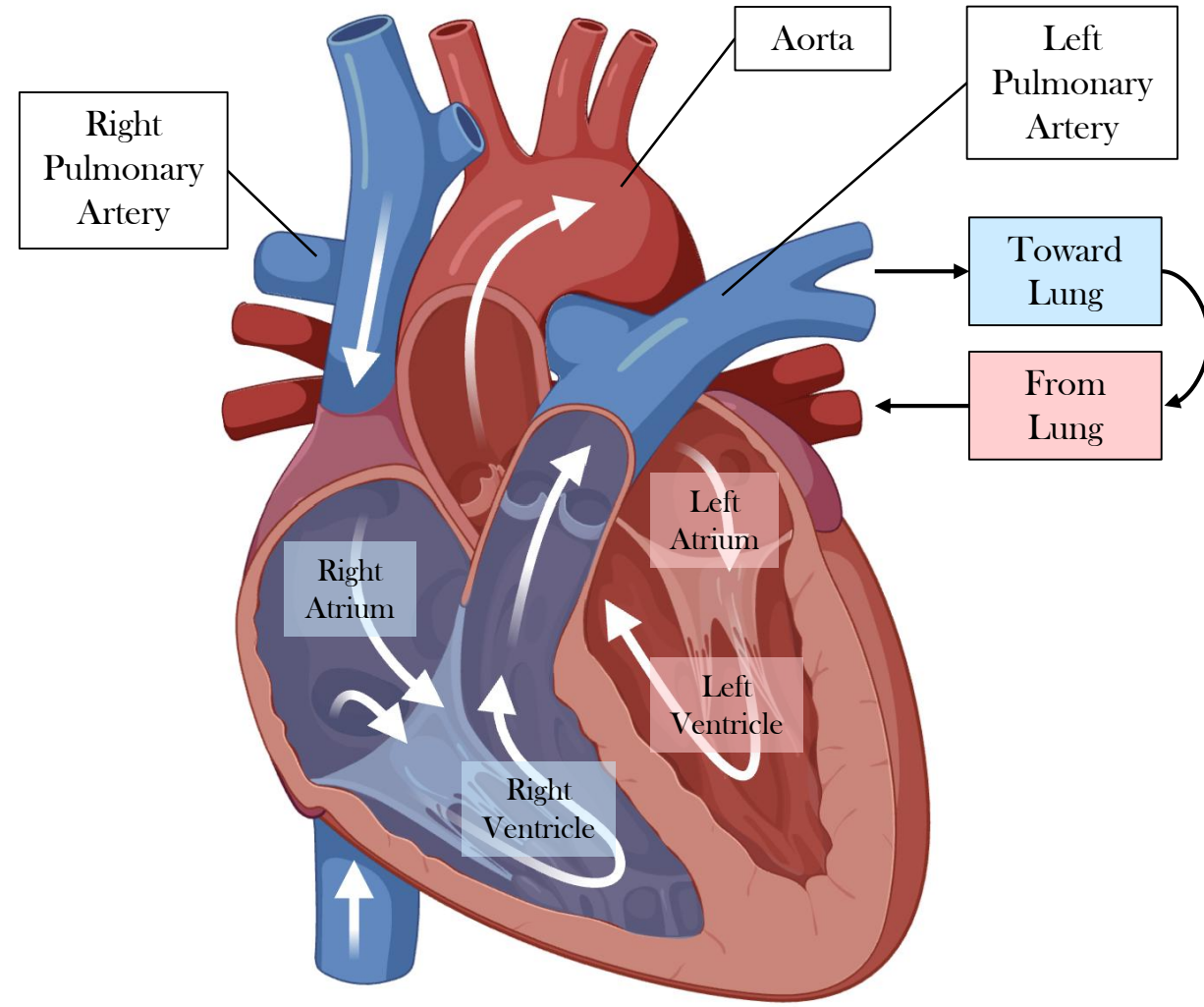
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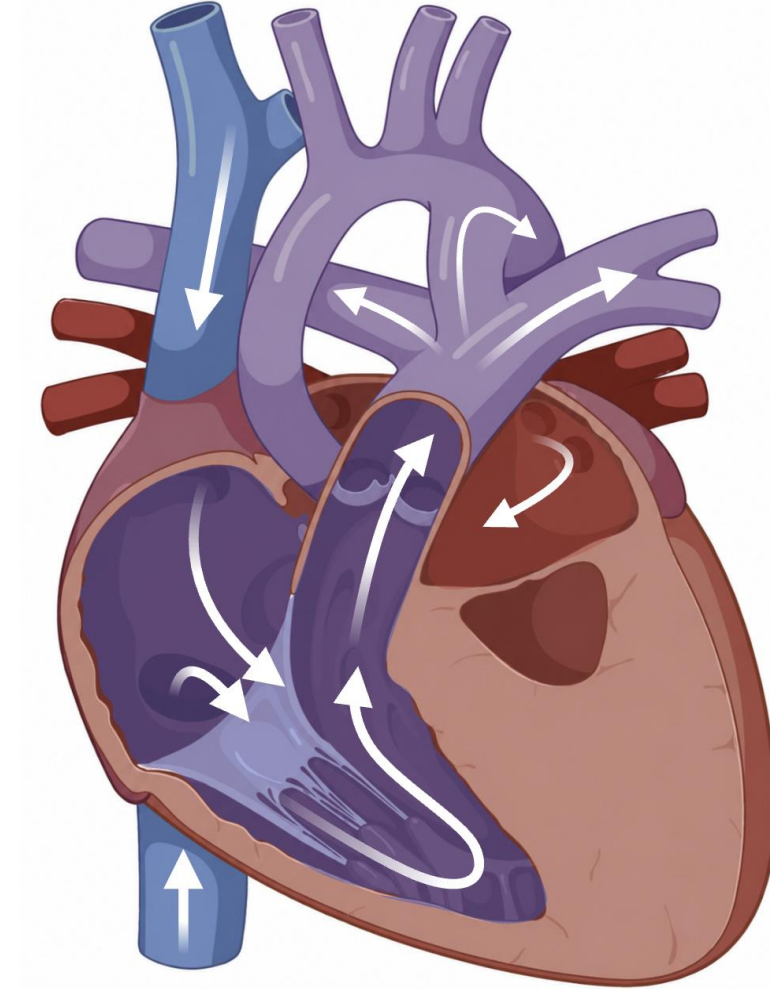
24 September 2026



Hypoplastic Left Heart Syndrome: A Severe Congenital Heart Defect



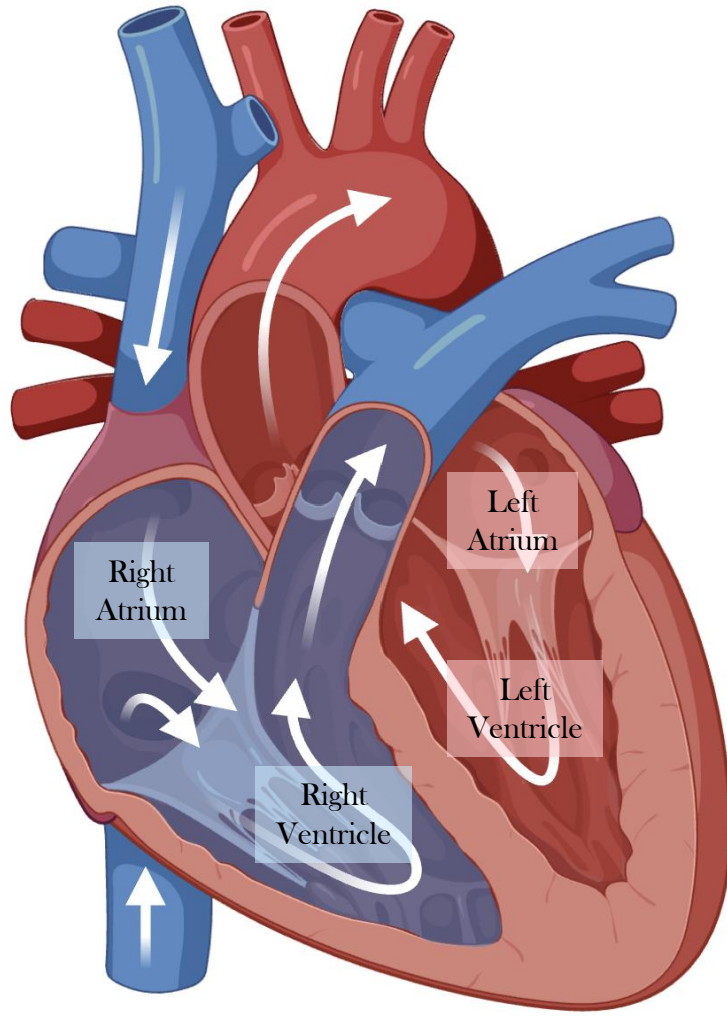
Normal Neonatal Circulation



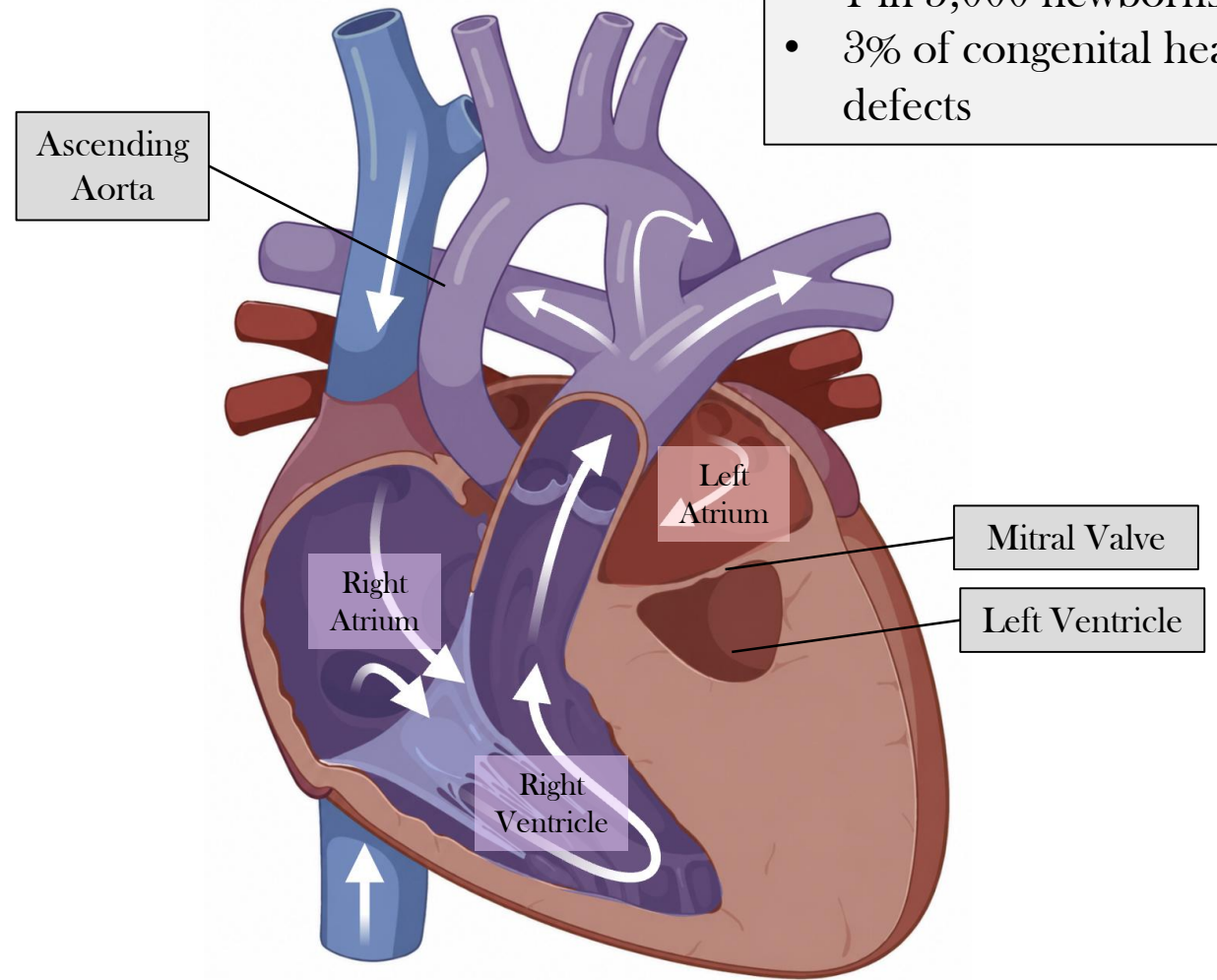
HLHS Circulation

Hypoplastic Left Heart Syndrome: A Severe Congenital Heart Defect

- 1 in 5,000 newborns
- 3% of congenital heart defects

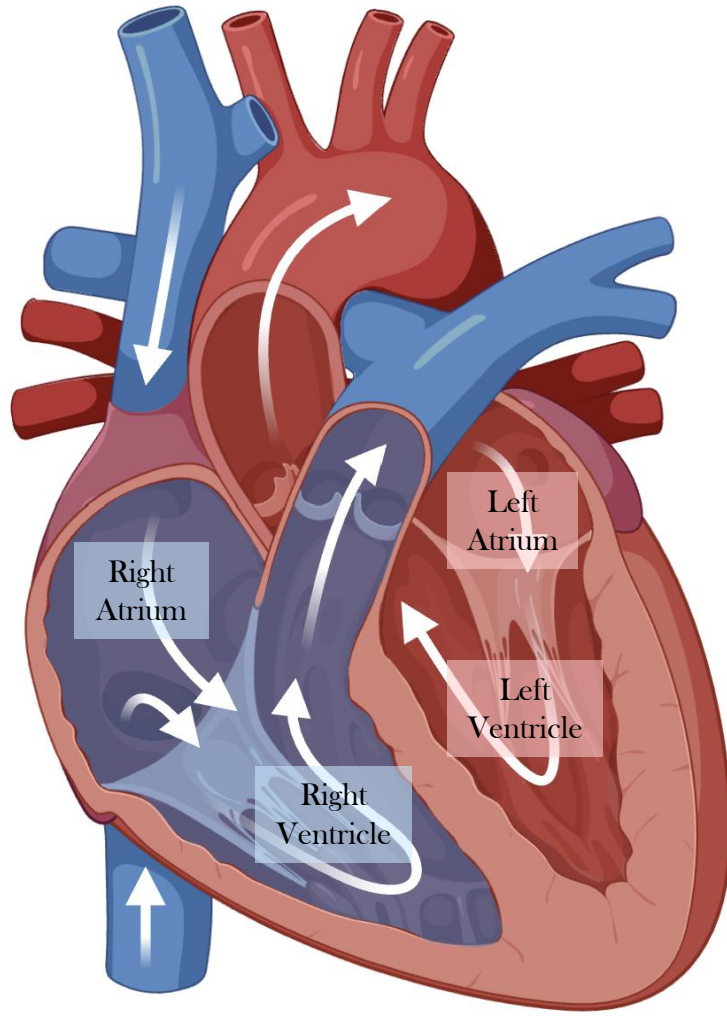


Normal Neonatal Circulation

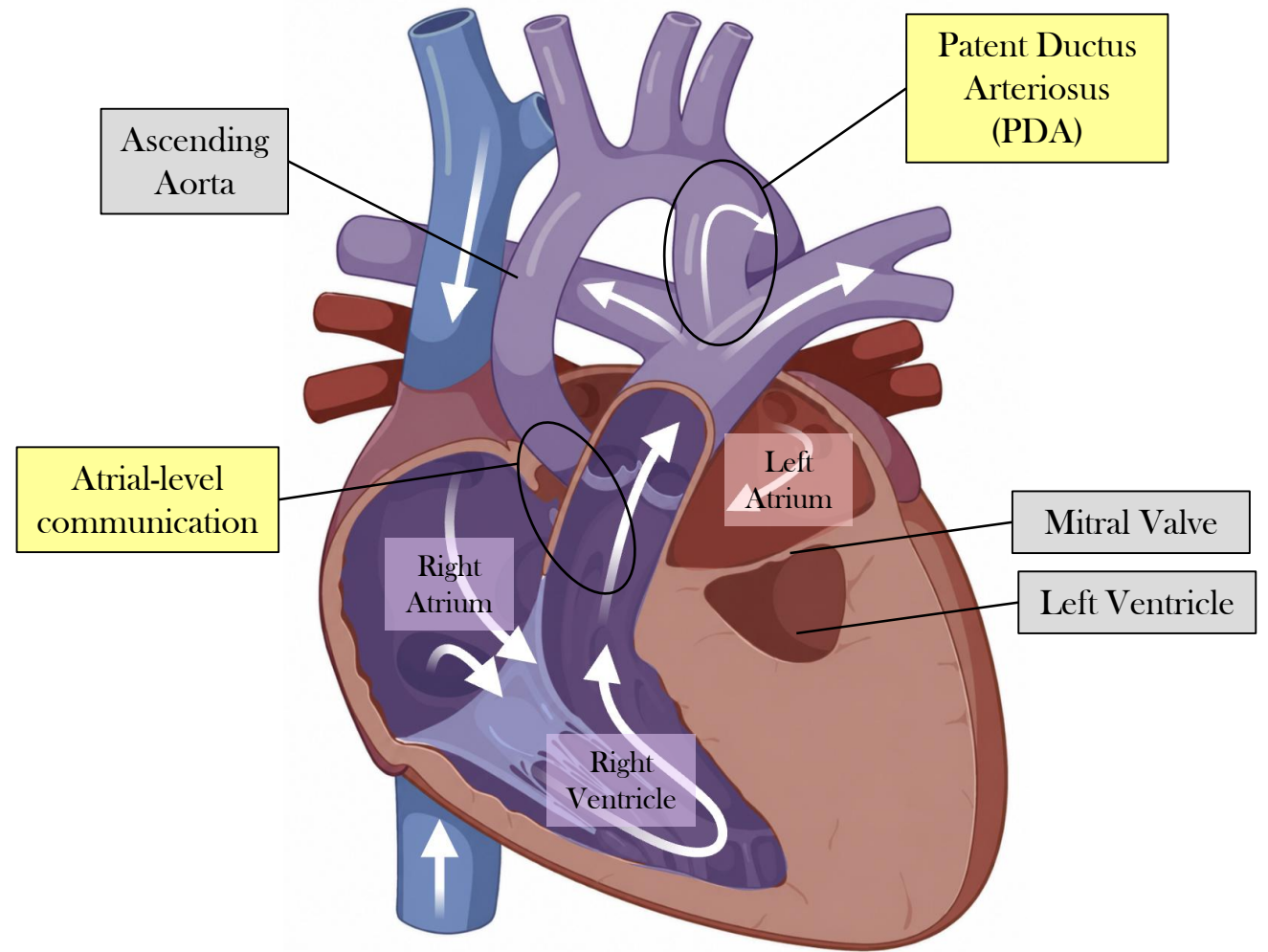


HLHS Circulation

HLHS Circulation Depends on Two Critical Pathways

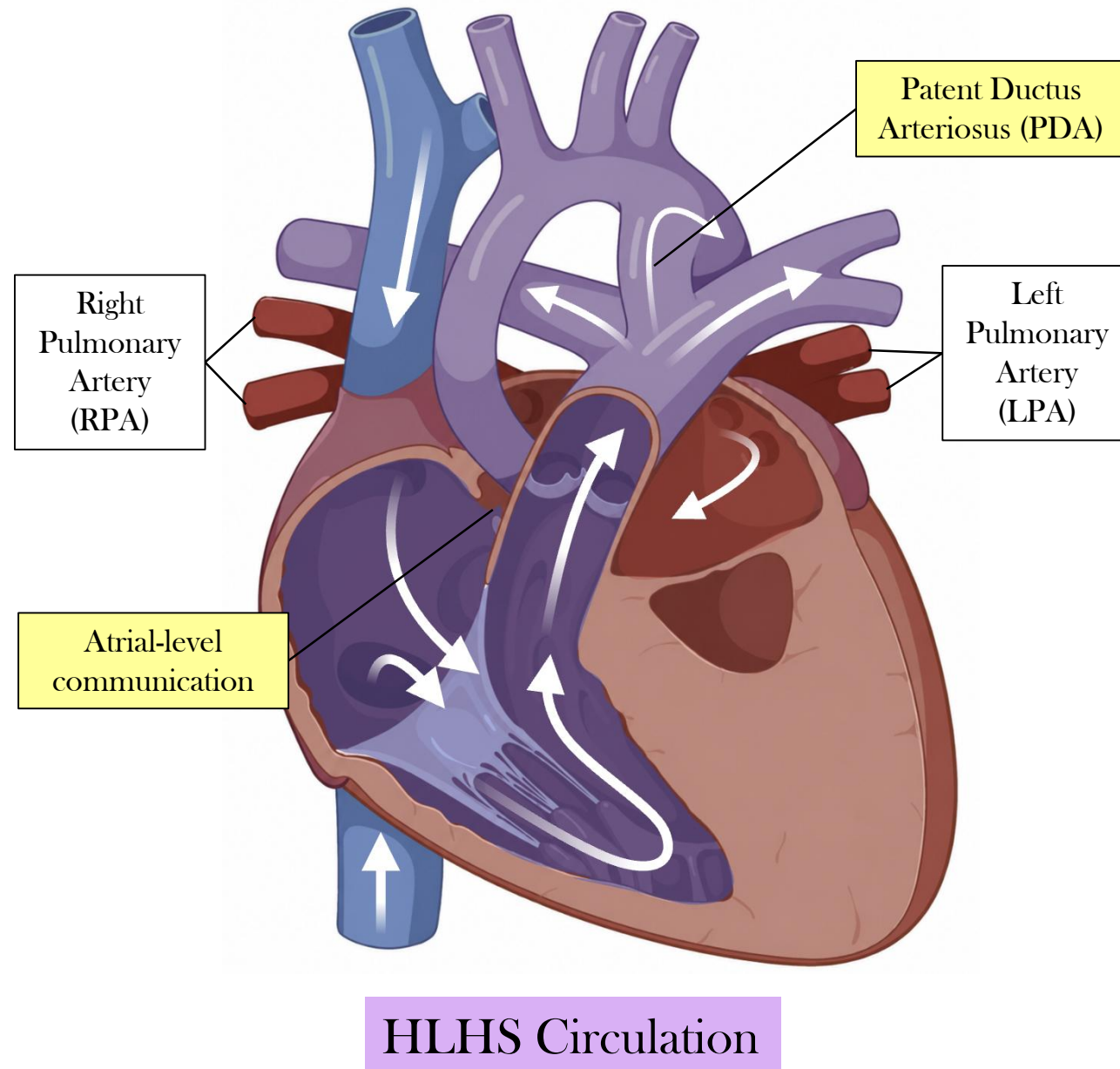


Normal Neonatal Circulation



HLHS Circulation

Hemodynamic Challenge in HLHS



Severely underdeveloped left ventricle

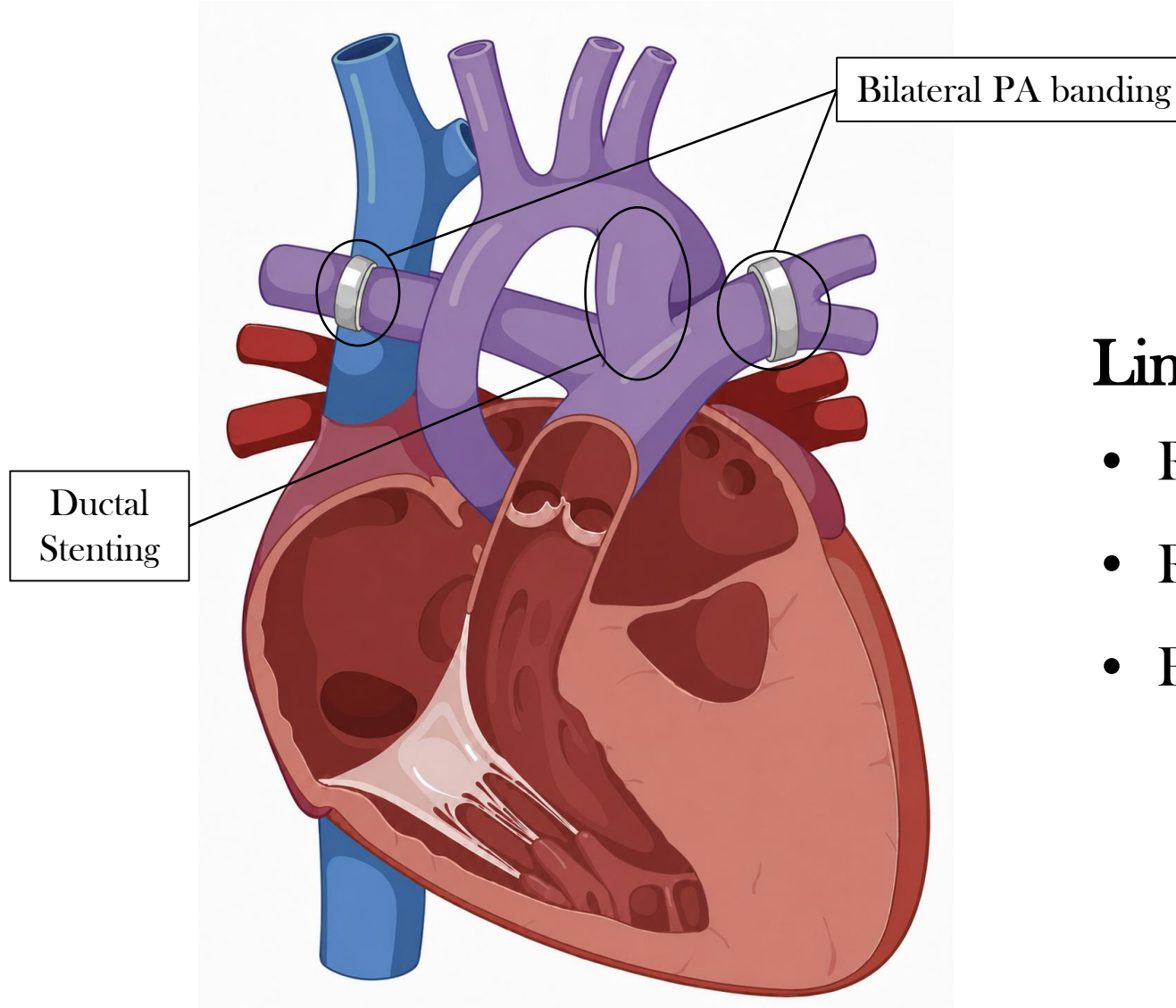
Systemic blood flow depends on PDA flow

Decreasing pulmonary vascular resistance

Pulmonary overcirculation and reduced systemic blood flow

Need to regulate pulmonary blood flow

Hybrid Approach for HLHS



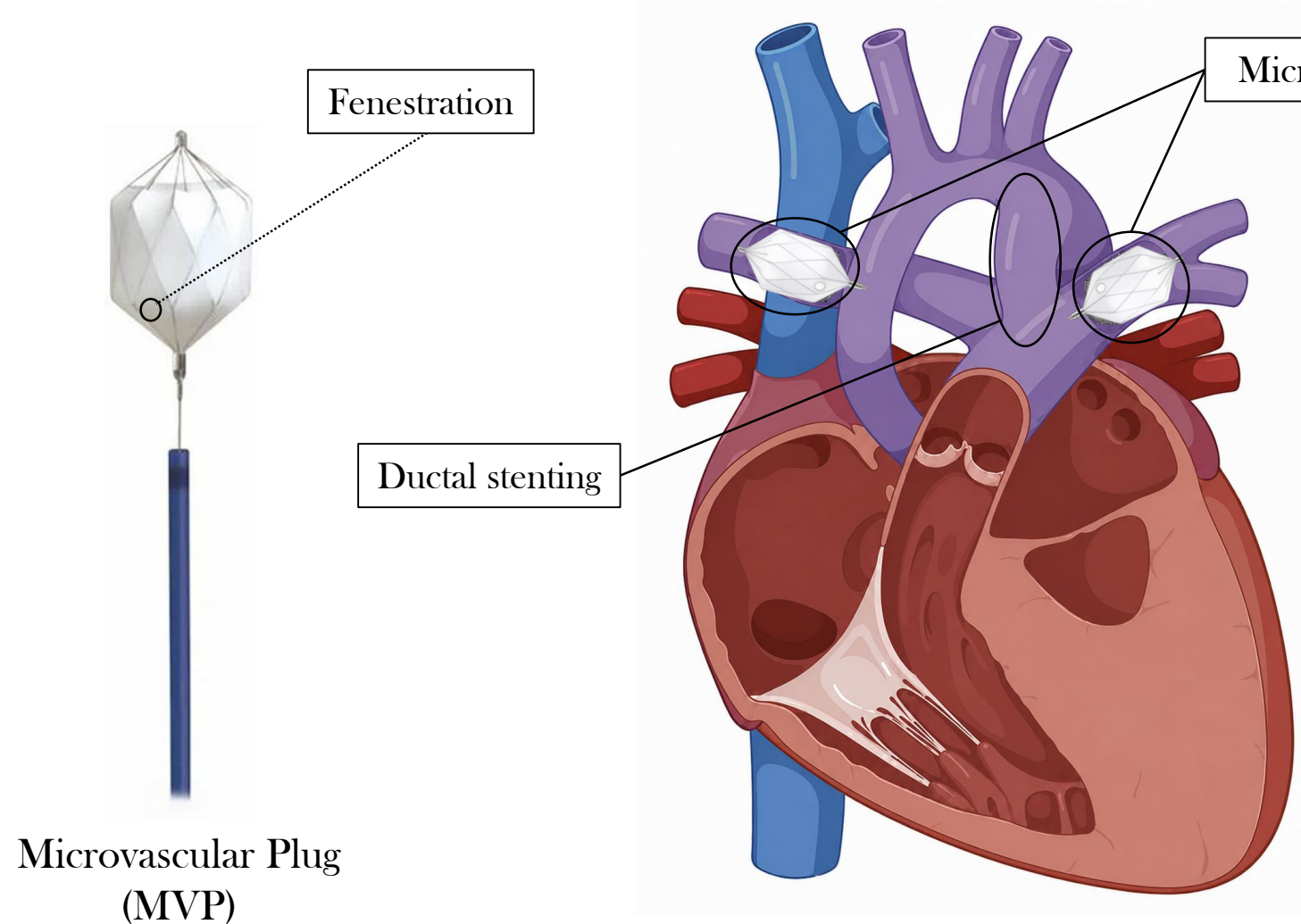
Limitations

- Requires open-chest surgery
- Risk of pulmonary artery distortion
- Precise pulmonary flow control is challenging

Hybrid Procedure

Akintürk et al., *Circulation*, 2002

Transcatheter Pulmonary Flow Restriction Using a Microvascular Plug



Microvascular Plug
(MVP)

Transcatheter procedure

Schranz et al., *Circulation*, 2020

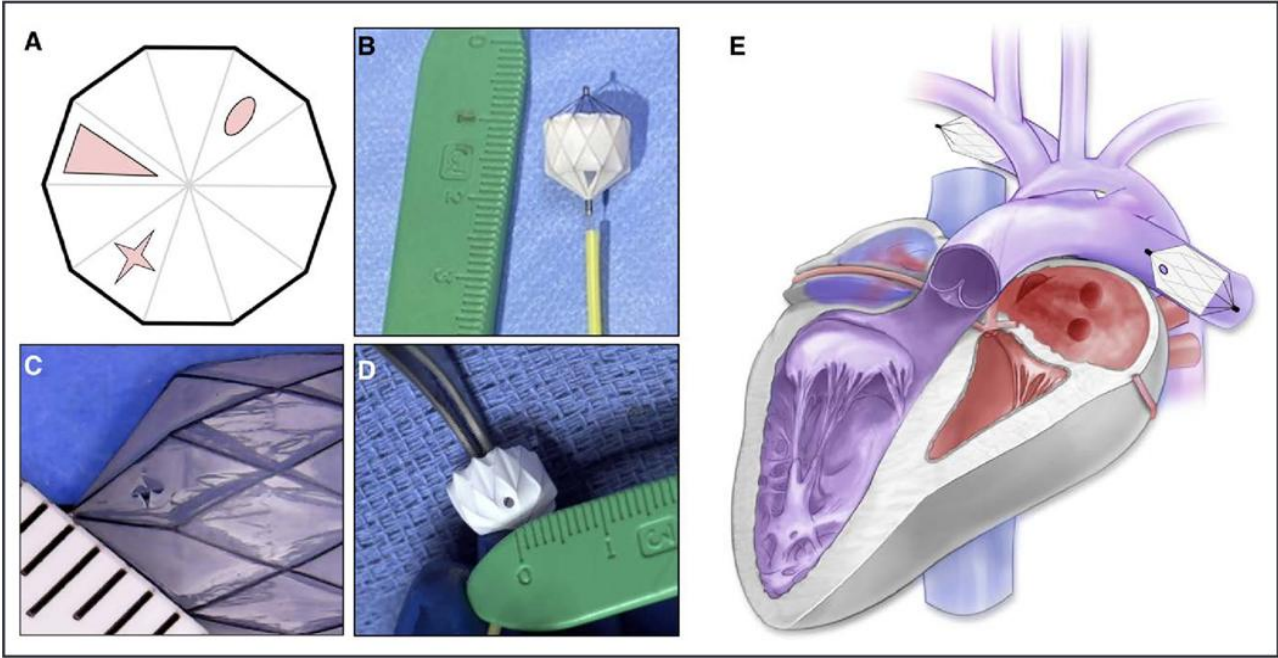
Advantages

- ✓ No surgery, bypass and scar
- ✓ Less invasive procedure
- ✓ Avoids complications associated with PA banding

Main Limitations

- ✓ Device behavior is not fully understood
- ✓ Further optimization is required

Clinical Outcomes Remain Variable



Sperotto et al., *Circulation: Cardiovascular Interventions*, 2023

Lack of fenestration design criteria

- Hole size, geometry and orientation are not standardized
- Optimal implantation position remains unknown.

Clinical Outcome	Patients (n=13)
Successful progression to second palliation	6
Required early surgical conversion	3
Death before second palliation	4

Variable Clinical Outcomes



Why do some MVP implants perform well while others fail?

Device design?

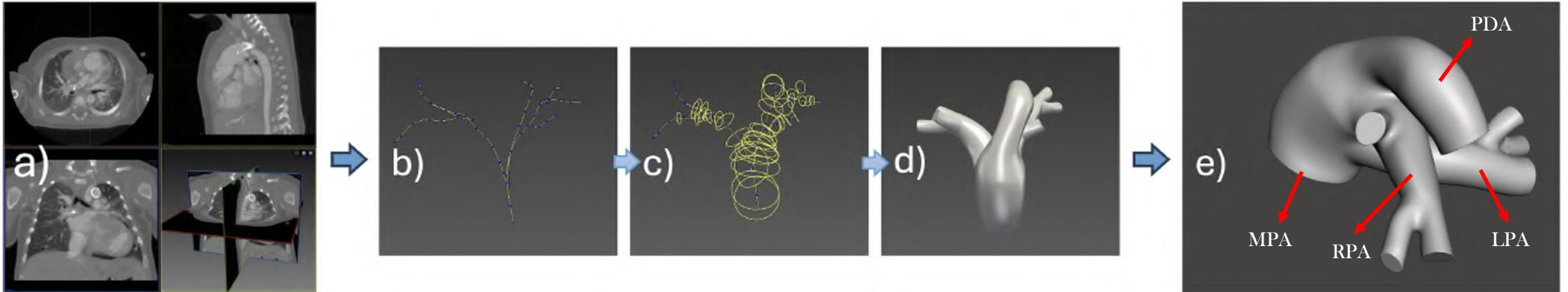
Patient anatomy?

Both?



Methods: Patient-Specific Computational Modeling

1. Patient-Specific Pulmonary Artery Geometry

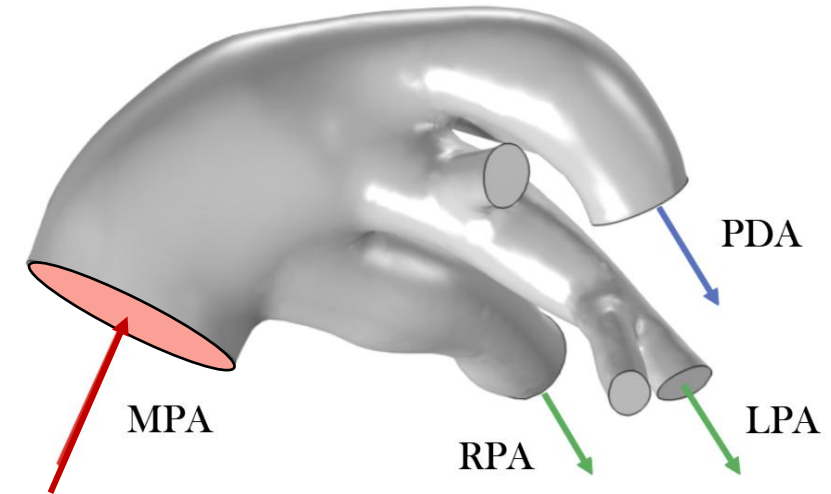
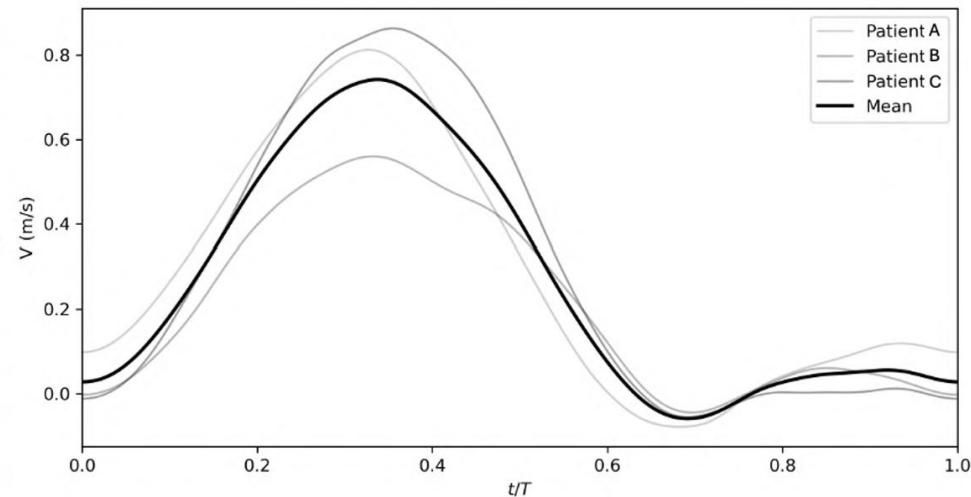
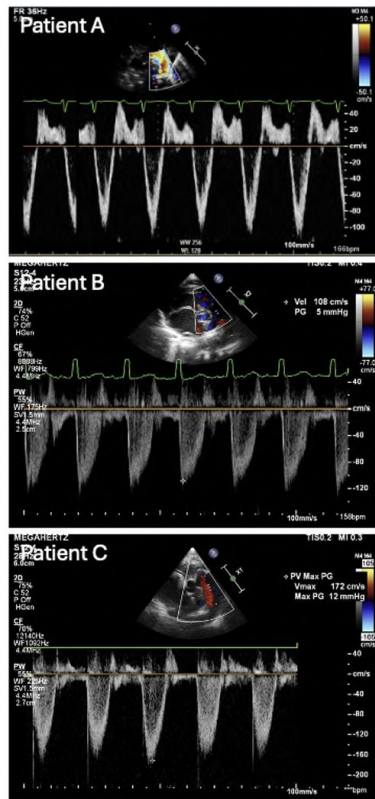


(a) CT scan (b) Centerline extraction (c) Contour generation (d) Lofting (e) Surface smoothing

Methods: Patient-Specific Computational Modeling

1. Patient-Specific Pulmonary Artery Geometry

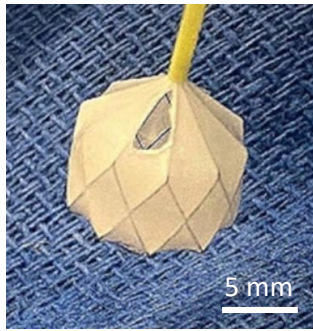
2. Patient-Specific Physiological Boundary Conditions



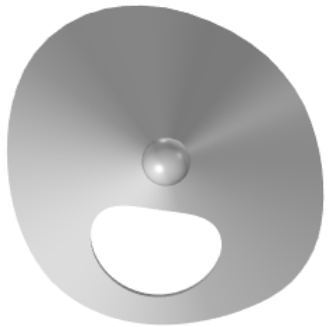
Clinical Doppler measurements $\longrightarrow$ Extract velocity waveform $\longrightarrow$ COMSOL inlet boundary condition

Methods: Patient-Specific Computational Modeling

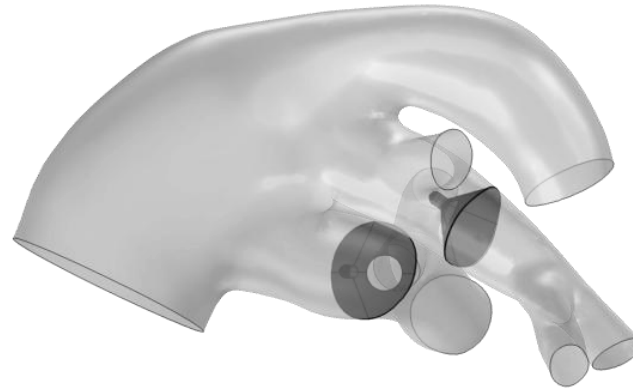
1. Patient-Specific Pulmonary Artery Geometry
2. Patient-Specific Physiological Boundary Conditions
3. Parametric Study of Device Geometry



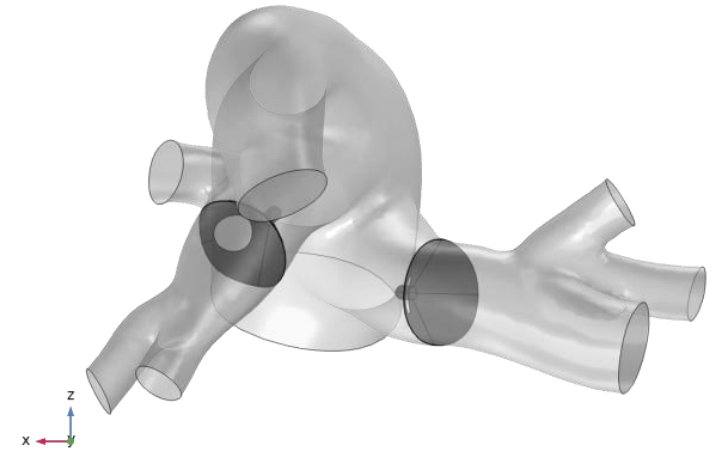
Experimental Device Prototype



Computational Device Model



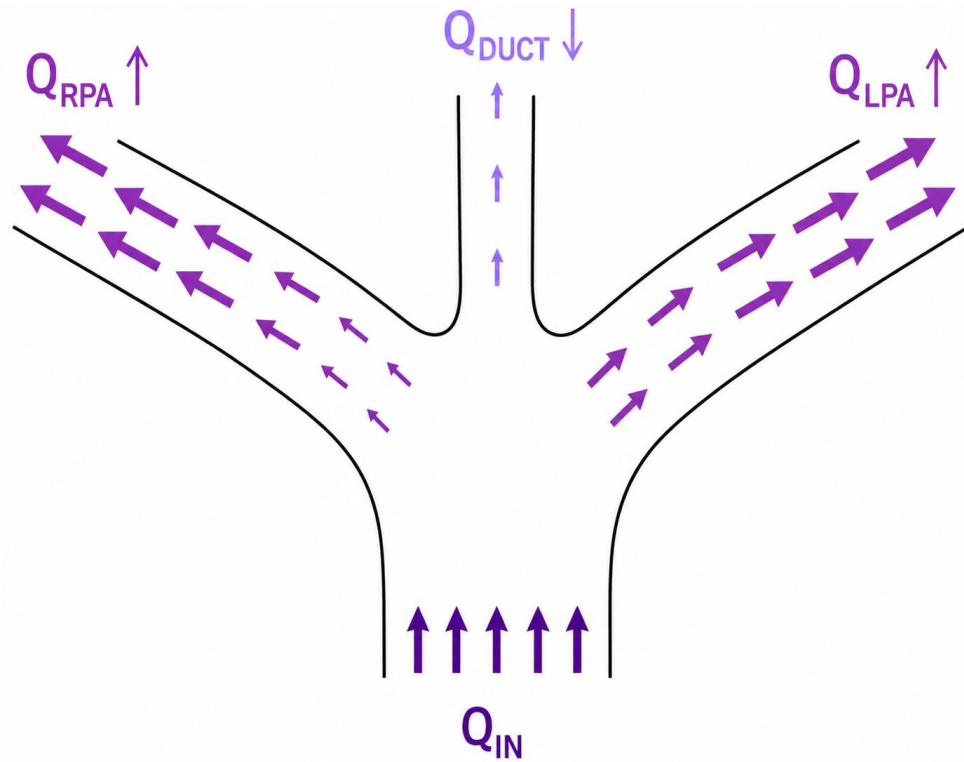
Side View



Front View

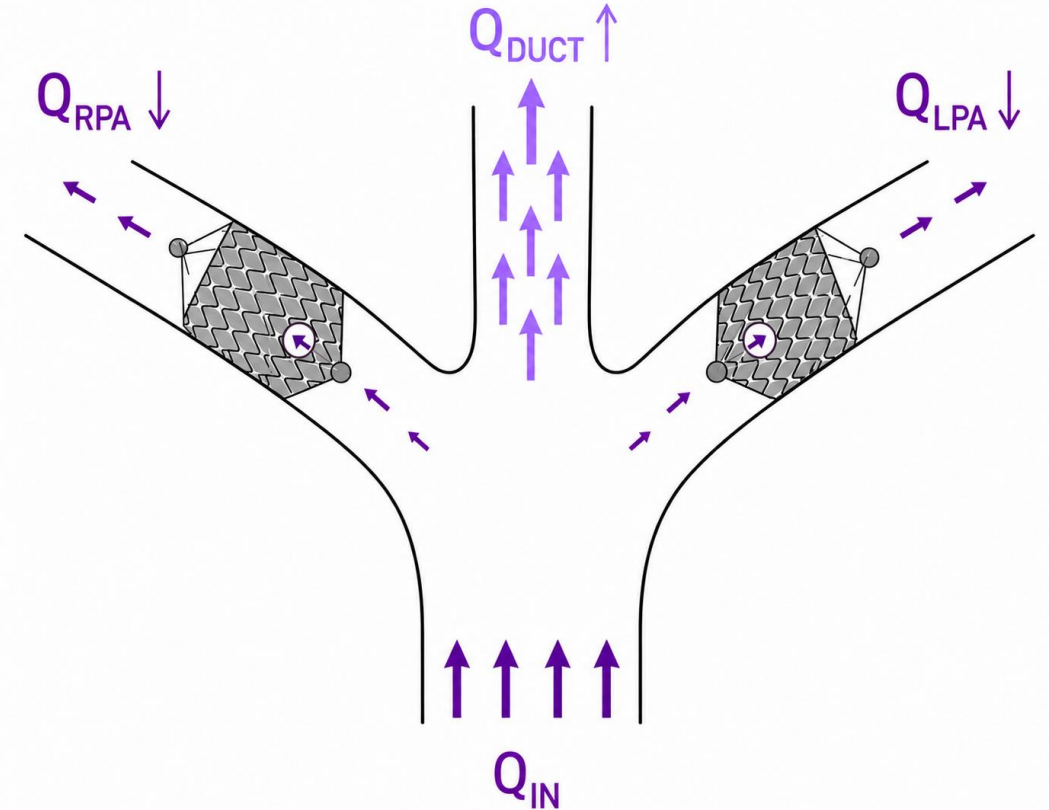
Target Pulmonary-to-Systemic Flow Balance

Pre-Intervention



$$\frac{Q_p}{Q_s} = \frac{Q_{RPA} + Q_{LPA}}{Q_{Duct}} = 4 \sim 6$$

Post-Intervention



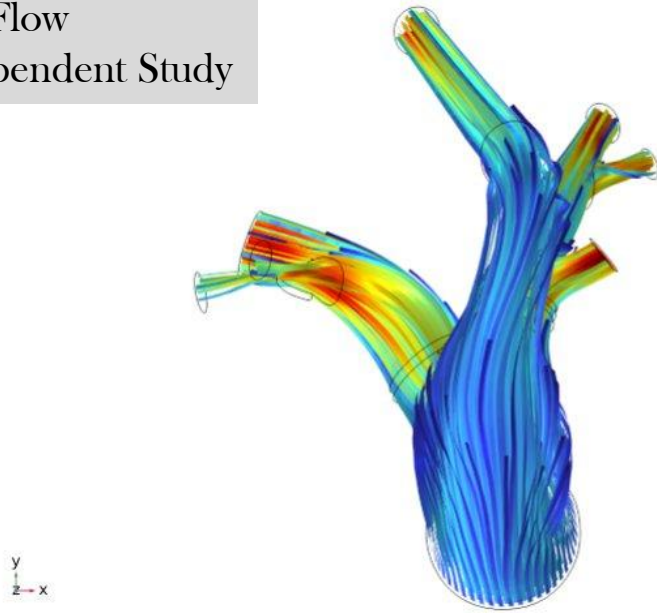
$$\frac{Q_p}{Q_s} = 1 \sim 1.2$$

Methods: Patient-Specific Computational Modeling

1. Patient-Specific Pulmonary Artery Geometry
2. Patient-Specific Physiological Boundary Conditions
3. Parametric Study of Device Geometry

4. COMSOL Multiphysics CFD Simulations

Laminar Flow
Time Dependent Study

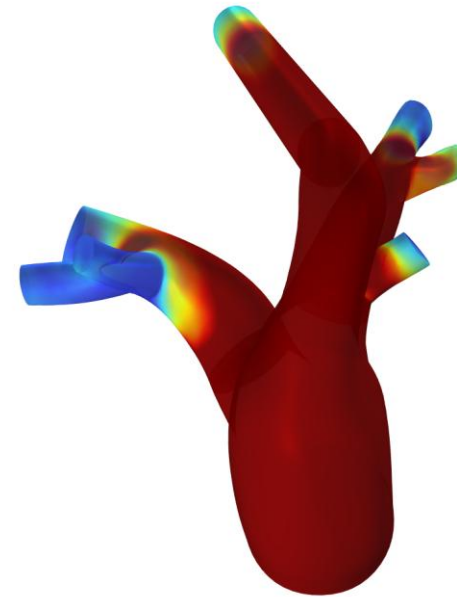


Flow Field

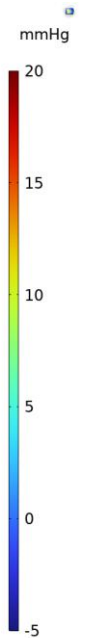
COMSOL
MULTIPHYSICS®



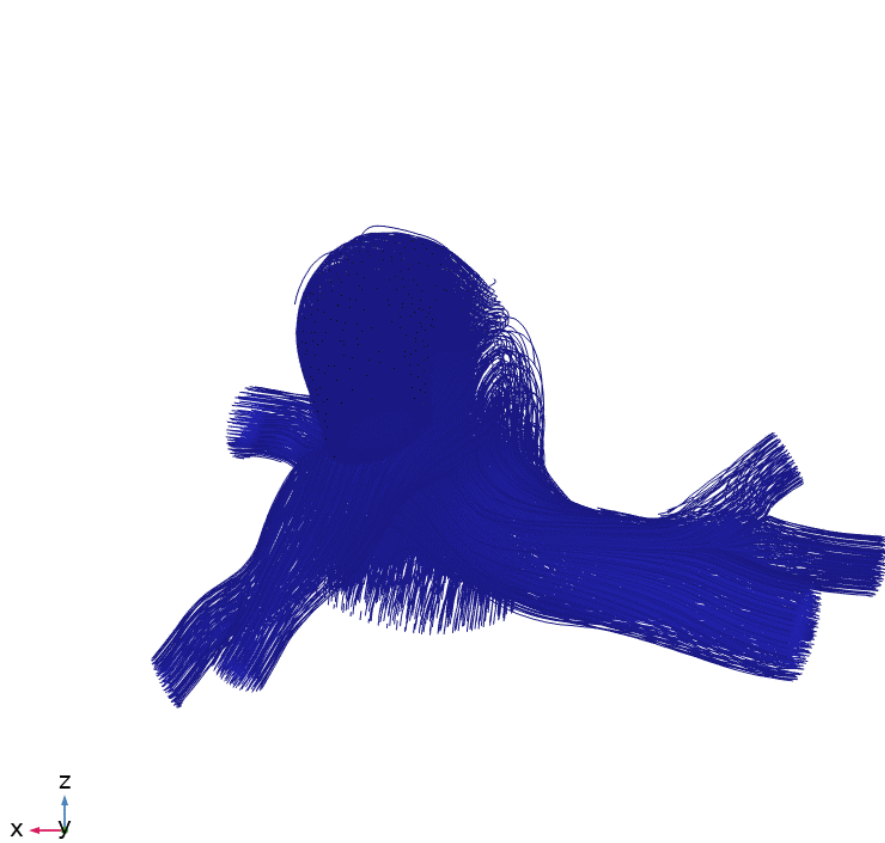
y
z → x



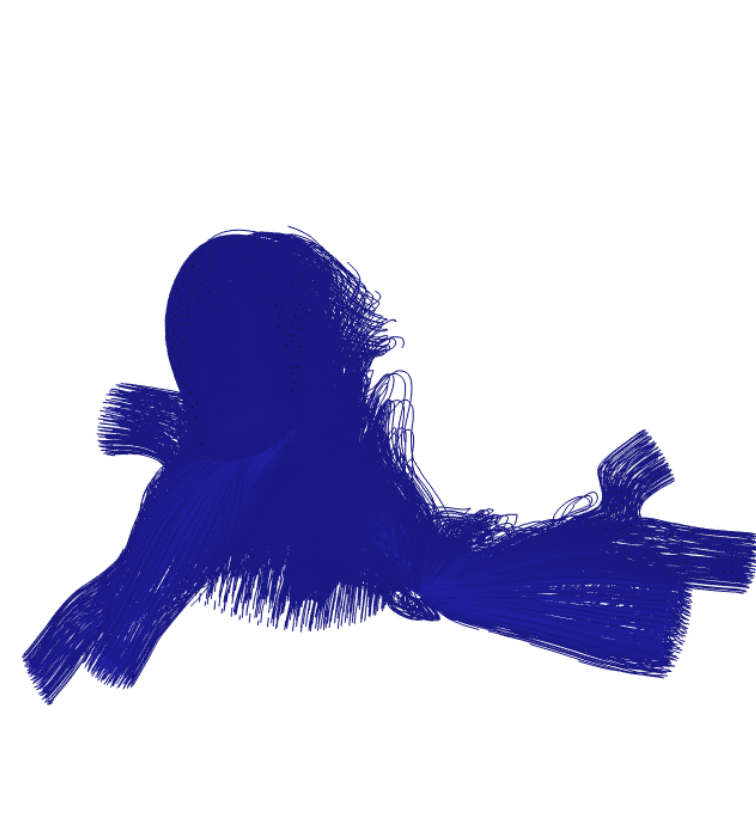
Pressure Field



Results - Pre- vs Post-intervention Hemodynamics



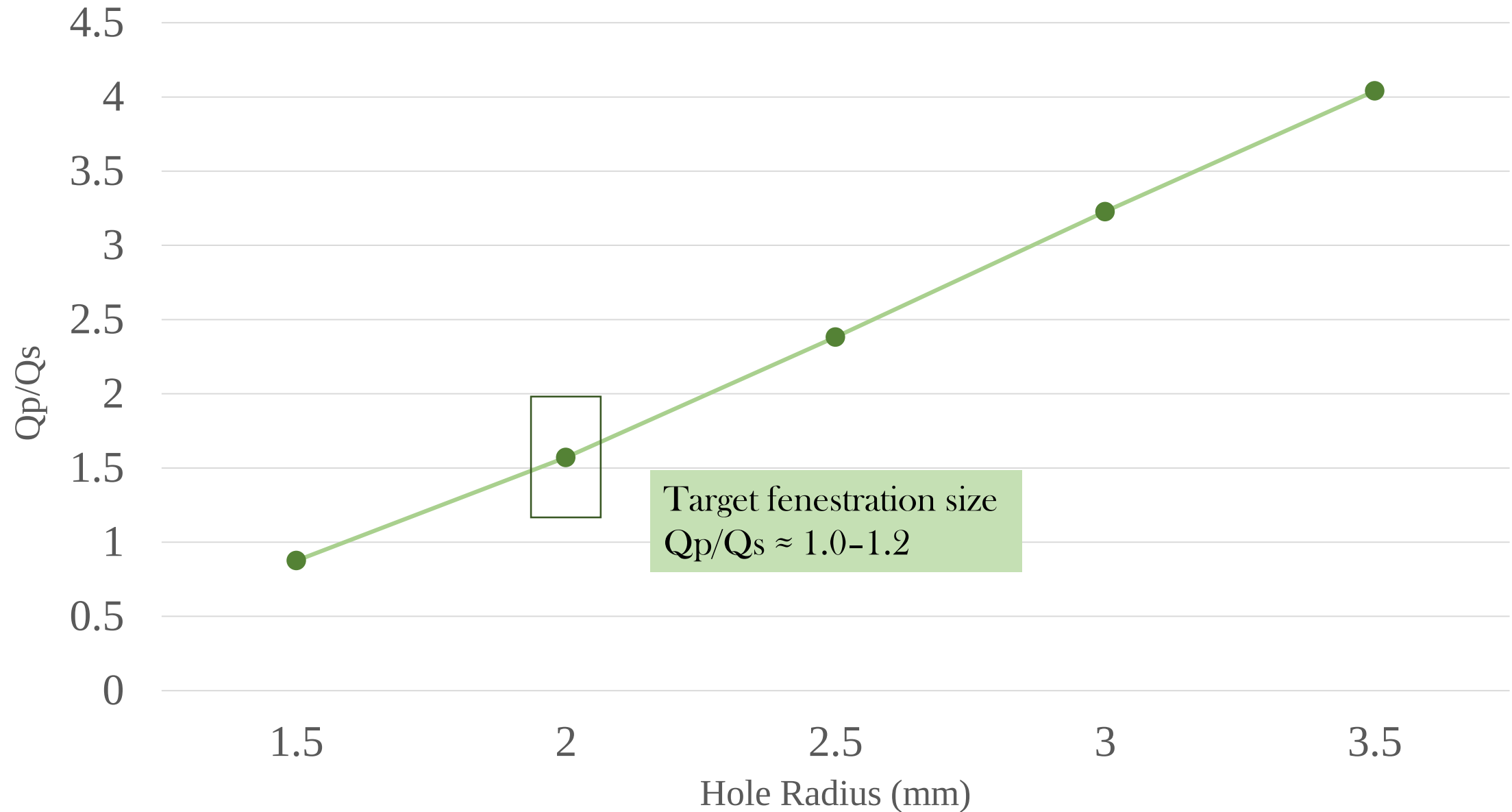
Pre-Intervention



Post-Intervention



Results - Fenestration size controls Q_p/Q_s



Results - Fenestration Shape Has Limited Effect at Constant Area

		Aspect Ratio (AR)	Q_p/Q_s
Circular Fenestration	{	1	1.57
		1.5	1.55
Elliptical Fenestration	{	2	1.57
		2.5	1.58

Conclusions

1. Patient-specific modeling captures clinically relevant flow redistribution
2. Fenestration size strongly controls pulmonary flow
3. Fenestration shape has limited effect at constant area

Thank you for your attention