A Cardiac Cycle Resolved CFD Simulation of CSF Flow in a CKCS

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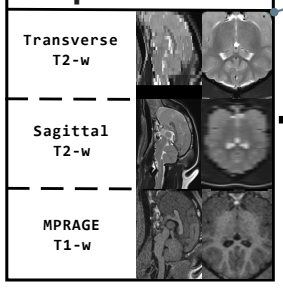
Introduction:

Cavalier King Charles Spaniels (CKCS) are highly predisposed to Chiari-like malformation (~95%) and syringomyelia (~45%)[1], conditions affecting cerebrospinal fluid (CSF) circultion. These disorders cause pain and neurological dysfunction, yet their underlying mechanisms remain unclear. Understanding normal CSF dynamics is a critical first step in treating these conditions. CSF flow is recognised as pulsatile and cardiac-driven, shaped by craniospinal compliance. Phase-contrast MRI can capture velocities at limited locations, but cannot resolve pressures or 3D flow patterns. Computational Fluid Dynamics (CFD) overcomes these limitations by reconstructing the entire flow field from MRI-derived anatomy, enabling visualization of velocities, pressures, and pressure gradients.

Here, we present the first cardiac cycle-resolved CFD simulation of CSF flow in a CKCS, offering new insights into the CSF dynamics of a healthy dog.

3D Modelling:

Input: MRI



- **Field Strength:** 1.5 Tesla
- **Coverage:**
  - Whole Brain
  - Entire spinal subarachnoid space

!! Scans must include the full extent of the SAS from cranial to lumbar regions to enable complete CSF pathway reconstruction !!

Image Processing

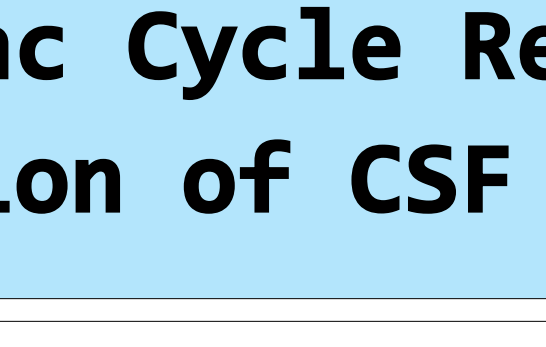
Segmentation

Image Processing: Raw MRIs upscaled and combined to maximise contrast between CSF, brain tissue, and bone

Segmentation: Ventricles and cranial subarachnoid space (SAS) extracted; spinal SAS traced slice-by-slice; central canal approximated along the spinal axis

Post-processing: Surfaces smoothed, hollowed, and cleaned

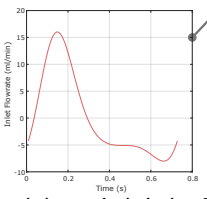
Final step: Re-meshed into a 4.5 million cell polyhedral CFD mesh



Boundary Conditions:

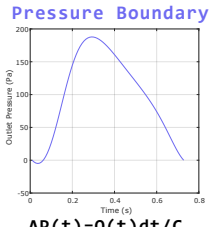
Velocity Inlet Condition
- Rationale: CSF motion in the cranial vault i driven by arterial expansion of the brain during each heartbeat
- Implementation: Applied a sinusoidal velocity to the ventricular system and inner cranial SAS
- Frequency = 82.4 bpm (period = 0.73 s)
- Boundary assumptions: Ventilatory effects excluded to isolate purely cardiac-driven flow

Flow Boundary



$Q(t)=a\ sin(sin(2\pi ft+\psi)+2\pi ft)+b$

Pressure Boundary

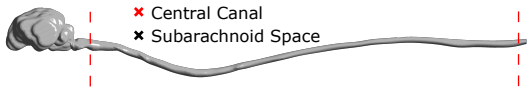


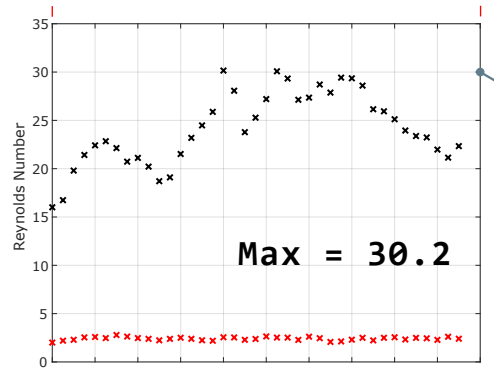
$\Delta P(t)=Q(t)dt/C$

CFD Setup
- Solver: SIMPLEC with skewness correction = 2
- Timestep: dt = T / 80 (s)
- Fluid Properties:
  - Density, ρ = 998.2 kg/m³
  - Viscosity, μ = 0.001003 Pa·s
- Simulation length: 3 cardiac cycles
- Mesh and timestep sensitivity analyses performed

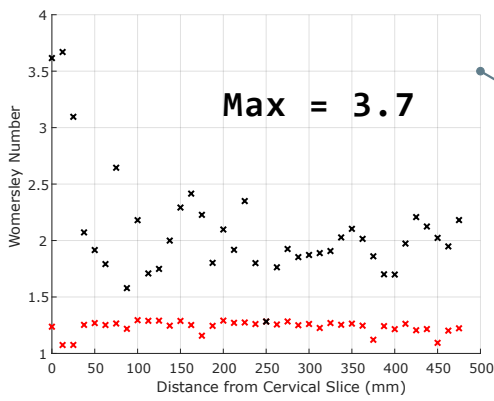
Pressure Outlet Condition
- Rationale: CSF outflow at the distal spine is buffered by tissue and venous compliance
- Implementation: Applied a presure outlet scaled by an effective compliance model
- Comliance = 2.1e-10 F
- Function: Reproduces the physiological pressure variations expected due to the cardiac cycle

Results:





Reynolds Number
- Definition: Ratio of convective inertial to viscous forces
- Finding: Values remain below criitcal throughout the cardiac cycle
- Interpretation: CSF flow is firmly laminar
  - Disturbed patterns seen on MRI are no true turbulence



Womersley Number
- Definition: Ratio of transient inertial to viscous forces
- Finding: Values remain above one, confirming CSF is pulsatile and inertially driven
- Interpretation: Consistent with cardiac-cycle forcing, but lower than in humans[2] suggesting less inertial dominance in CKCS

- Less than 1% of CSF leaving the 4th ventricle enters the central canal
- The first estimate of the fraction of flow that may drive syrinx formation

	Flow Volume [µl]				Fraction of CSF Volume [%]	
	Systolic	Diastolic	Net	Stroke	Systolic	Diastolic
Central Canal	0.24	0.33	-0.05	0.57	0.59	0.80
Subarachnoid Space	39.99	40.23	0.67	80.22	99.41	99.20

Qualitative Results:

- Jet-like flows observed, producing localised high velocities
- Flow appears disturbed but not turbulent
- Pressure-Velocity phase shifts indicate flow is driven by pressure
- Bidirectional pulsatile motion

Future Directions:

- Simulate the healthy flow in CKCS
- Compare unaffected and affected flow
- Identify CM/SM biomarkers
- Simulate surgical intervention

Flow Animations:

Please Scan This To See Flow Visuals!!

https://sites.google.com/view/vetschoolsymposium

Conclusions:

In this work we present the first cardiac cycle-resolved CFD simulation of cerebrospinal fluid flow in a Cavalier King Charles Spaniel. The simulations show that Reynolds numbers never exceeded 30, confirming that the flow remains firmly laminar. By contrast, human studies often report higher Reynolds numbers, which help explain the more complex flow patterns described clinically. The Womersley numbers were consistently greater than one, indicating that CSF motion in the CKCS is pulsatile and inertia-driven, as expected under cardiac cycle forcing. However, these values were significantly lower than those reported in humans, suggesting that the flow in dogs is less inertially dominated. Together, these findings highlight important species-specific differences in CSF dynamics. Most importantly, they demonstrate how CFD can provide access to pressures and gradients that cannot be measured with MRI alone, offering a new window into the mechanisms that may contribute to Chiari-like malformation and syringomyelia.

[1]. Jones, R., Cirovic, S. & Rusbridge, C. A review of cerebrospinal fluid circulation with respect to Chiari-like malformation and syringomyelia in brachycephalic dogs. Fluids Barriers CNS 22, 25 (2025). https://doi.org/10.1186/s12987-025-00636-x

[2]. Loth F, Yardimci MA, Alperin N. Hydrodynamic modeling of cerebrospinal fluid motion within the spinal cavity. J Biomech Eng. 2001 Feb;123(1):71-9. doi: 10.1115/1.1336144. PMID: 11277305.