Simulation of the Fontan circulation during rest and exercise

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Hartstichting
NO CONFLICT OF INTEREST TO DECLARE
Physiology of rest and exercise

Biventricular

Fontan

exercise

location

pressure

location

pressure

?
What limits exercise capacity in Fontan?

Limited clinical possibility to address this problem

- Inhomogeneous patient population
- Pressures, flows and volumes difficult to measure, especially during exercise

Computer modelling

- Investigate extreme situations
- Reductionistic as well as holistic approach of regulatory mechanisms
Computational model ‘CircAdapt’

• **Physical laws**
  used to describe relations on
  1. haemodynamics (pressure, flow, and volume);
  2. tissue mechanics (mechanical load, strain, stress)
  \[\rightarrow\text{reduced number of parameters}\]

• **Modular set-up and multi-level**
  Vessels, valves, contractile sheets, and peripheral resistances
  sarcomere > contractile sheet > cardiac cavity > heart > circulation

• **Dynamic simulation**
  Time dependency of volumes/pressures in cavities and vessels, flows through valves, myofiber stresses and strains
CircAdapt model for Fontan

Heart:
- single functional ventricle
- single functional atrium

Systemic circulation

Direct connection
- Systemic veins to Pulmonary arteries

Pulmonary circulation
Simulation set-up

- Dynamic pulmonary resistance (distension & recruitment)
- Systemic resistance changes proportionally to flow
- Blood pressure regulation
- Increase of cardiac output (CO)

\[ \text{CO} = \text{SV} \times \text{HR} \]

Increase stroke volume (SV)
Increase heart rate (HR)
Hemodynamics in rest

[Graph showing pressure over time vs. volume for normal aorta, Fontan aorta, normal left ventricle, Fontan ventricle, left ventricle, and right ventricle.]
HR increase preferred over SV increase with respect to Central Venous Pressure during Exercise.

**Diagram:**
- **SV increase**
  - Systolic pressure
  - Mean arterial pressure
  - Diastolic pressure
- **HR increase**
  - Central venous pressure

**Graphs:**
- Pressure vs. Cardiac output [l/min]
  - SV increase
  - HR increase

**Equations:**
- Mean arterial pressure
- Systolic pressure
- Diastolic pressure
- Central venous pressure

**Annotations:**
- Pulmonary veins
- Atrium
- Valve
- Ventricle
- Systemic veins & Pulmonary arteries
- Systemic arteries
- $R_{\text{pulm}}$
- $R_{\text{sys}}$
Background CVP increase

Lower filling pressure
Discussion

Increased systemic flow &
Increased pulmonary flow

Increased pulmonary pressure drop

Increased ventricular filling pressure
Conclusion

• Exercise in Fontan leads to increased central venous pressure (CVP)

• Increase CVP necessary for adequate pulmonary flow and ventricular filling

  Complications: Edema, decreased systemic pressure drop, etc...

• SV increase requires higher ventricular filling pressure compared to HR increase

• Clinical studies* show limited ventricular filling during exercise in Fontan patients

* Van de Bruaene et al. 2013, Robbers-Visser et al. 2008
Pulmonary vascular resistance

**Shachar et al.**

- Graph showing pressure drop versus cardiac index for different groups.
- Legend includes controls.

**Model implementation**

- Diagram illustrating model parameters and calculations.
- Notations: $Q_{\text{rest}}$, $Q_{\text{exc}}$, $R_{\text{pulm}}$, reported PVR.