Simulation of circulation response to accelerational forces during spaceflight

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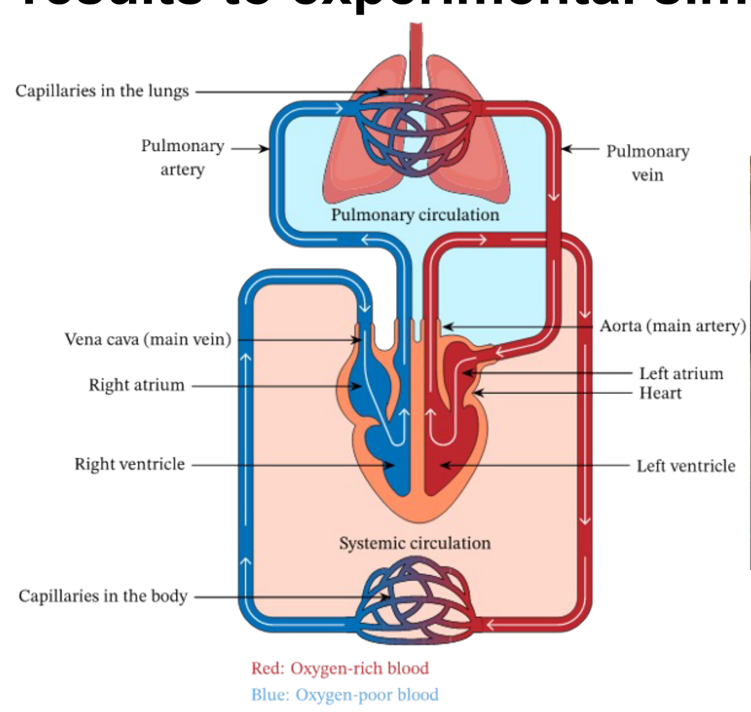
INTRODUCTION

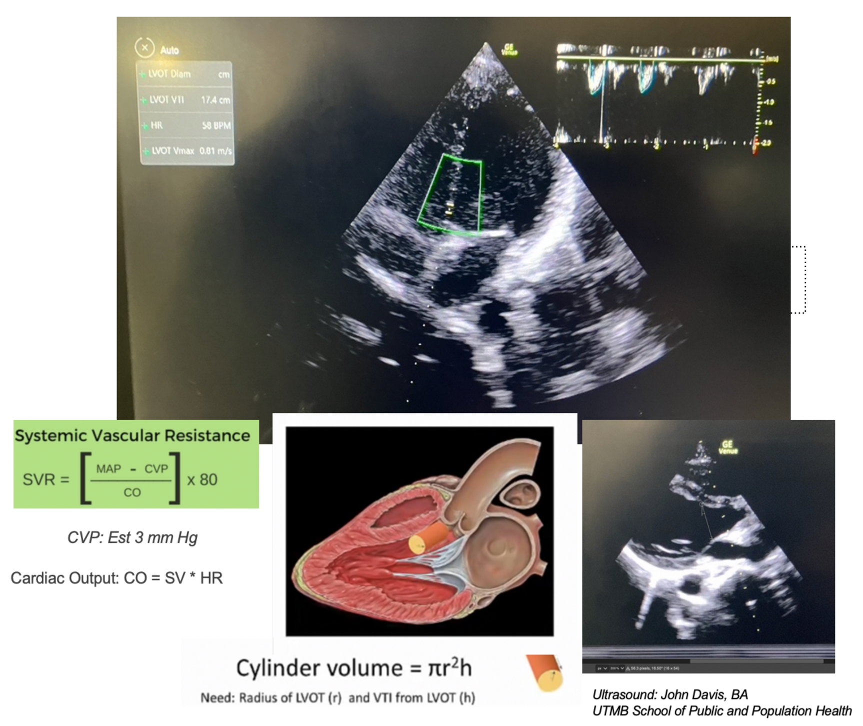
We present a model for the steady state circulation in the body, incorporating the effects of gravity. The processes underlying the control of blood flow under hyper-gravity and micro-gravity are complex and non-linear. Much has already been done to model the circulatory system under micro-gravity using partial differential equations. Few models have approached this from a prediction perspective. The simplicity and interpretability of this modeling approach enables us to predict G tolerance, and accurately parameterize a linear control model for the steady state circulation for a particular patient. We use biometric data from a centrifuge study to compare our model results to experimental simulations.



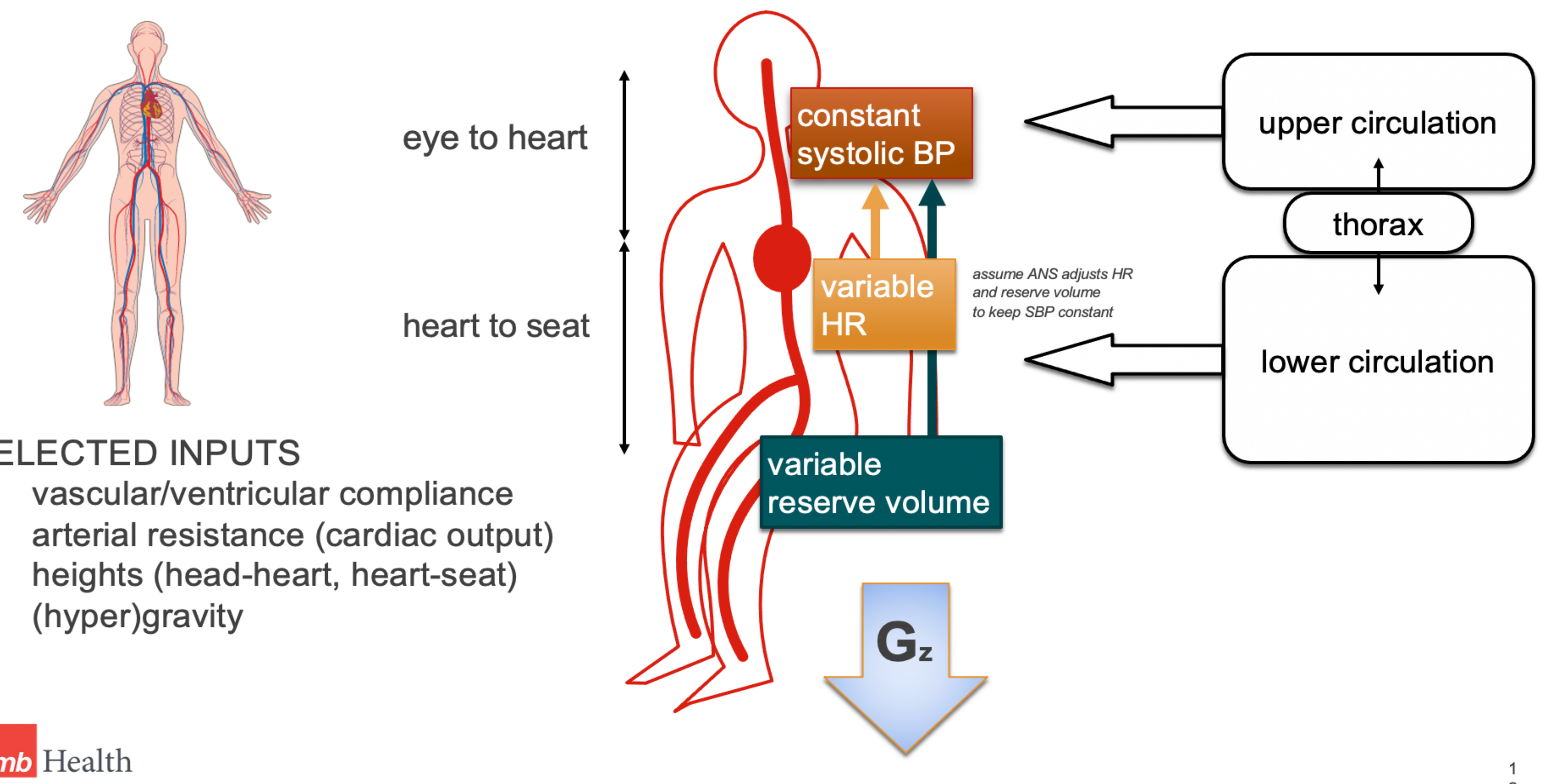
WHAT IS THE MAXIMUM G-FORCE THAT A RELAXED SUBJECT CAN TOLERATE?

ULTRASOUND
Custom Parameters
for Study Subject

height: 66 cm
eye-heart: 32 cm
heart-seat: 42 cm
BP: 108/68, **HR**: 53
MAP: 81.3
systemic arterial resistance: 16.49-20.02 mm / (L/min)
blood volume: 3.7 L +/- 10% (sweat loss)



IDEALIZED CONTROLLER: STEADY STATE



SELECTED INPUTS
- vascular/ventricular compliance
- arterial resistance (cardiac output)
- heights (head-heart, heart-seat)
- (hyper)gravity

MODEL ASSUMPTIONS

idealized controller, steady state model

→ **steady state:** no change over time (equilibrium state)

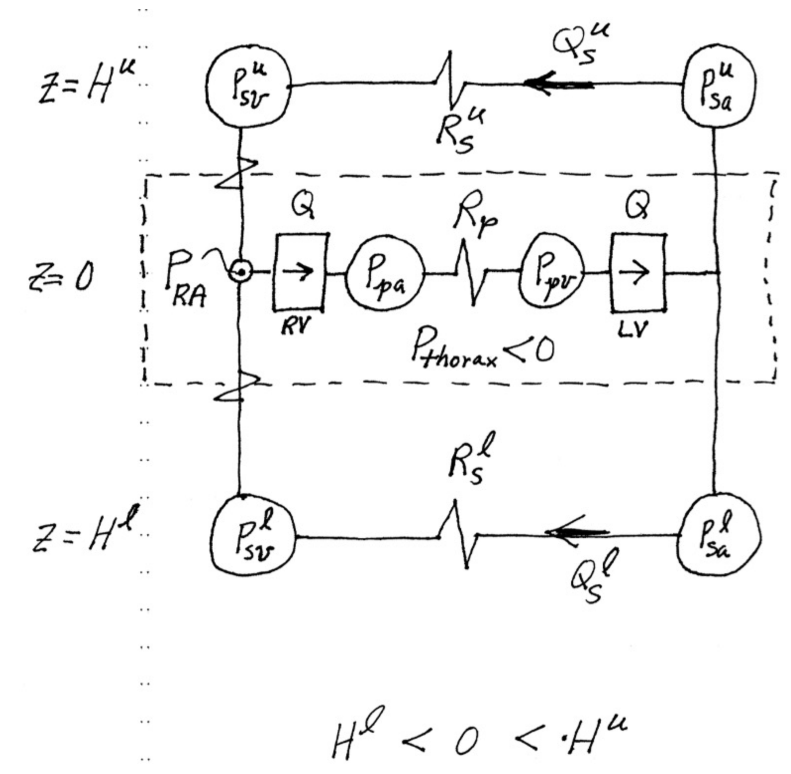
→ **idealized:** body can make <u>any</u> adjustment to the control variables (HR, reserve volume)

→ **two compartment model:** baroreceptors in *aortic arch* and *carotid artery* -> in <u>aggregate upper body</u>

→ **linear assumptions:** CVP, pressure-volume, flow-resistance, pressure-density

→ **relaxed state**: no valsalva or AGSM

<u>implicit</u> modeling of control mechanisms for HR, BP



Circulation Model

Heart Rate

$$F = \frac{\left(\frac{1}{R_s^u} + \frac{1}{R_s^l}\right)(P_{sq}^u)^* + \frac{\rho g H^u}{R_s^l}}{C_{RVD}(\Delta P_{RA})^*}$$

Cardiac Output

$$Q = \left(\frac{1}{R_s^u} + \frac{1}{R_s^\ell}\right)(P_{sa}^u)^* + \frac{\rho g H^u}{R_s^l}$$

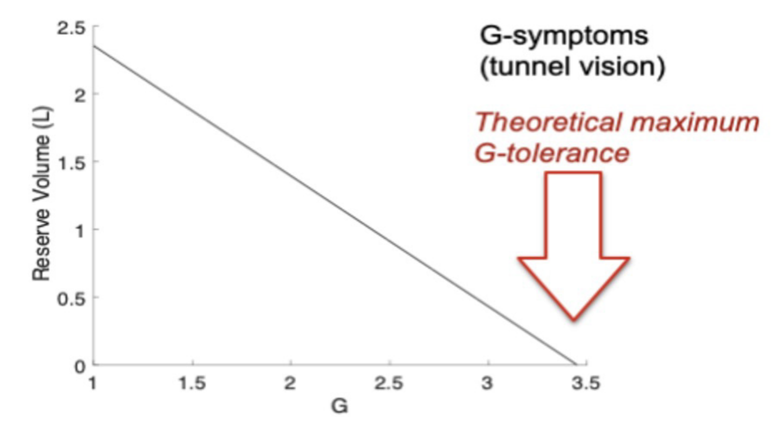
$$P_{Sa}^u = (P_{Sa}^u)^{\frac{*}{k}}$$

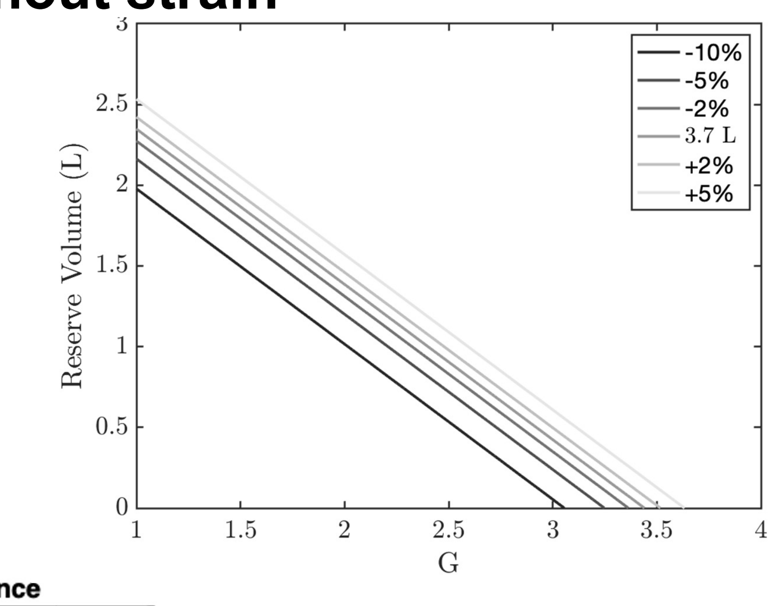
Reserve Volume

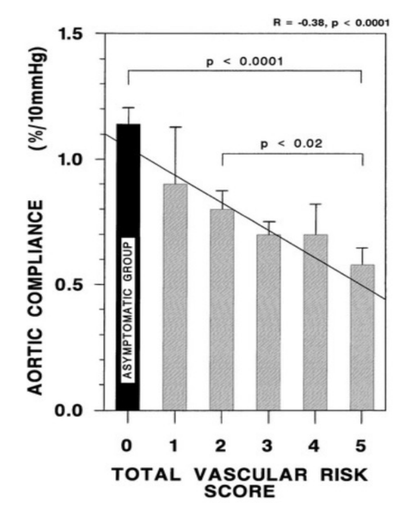
$$V_{\text{total}}^0 = V_{\text{total}} - C_p\frac{C_{RVD}}{C_{LVD}}(\Delta P_{RA})^* - (T_pG_s + C_{sa})(P_{sa}^u)^* - (T_pG_s^l + C_{sa}^l)\rho g H^u - C_s^l\rho g(-H^l)$$

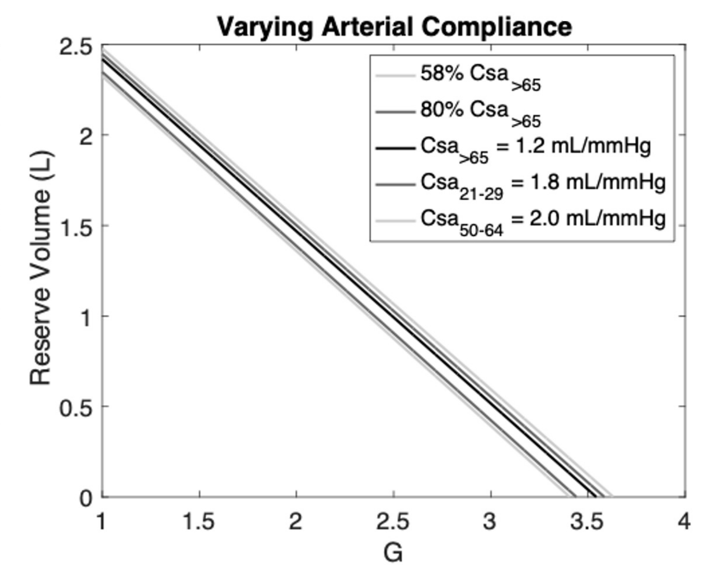
$$P_{RA} - P_{\text{thorax}} = (\Delta P_{RA})^*$$

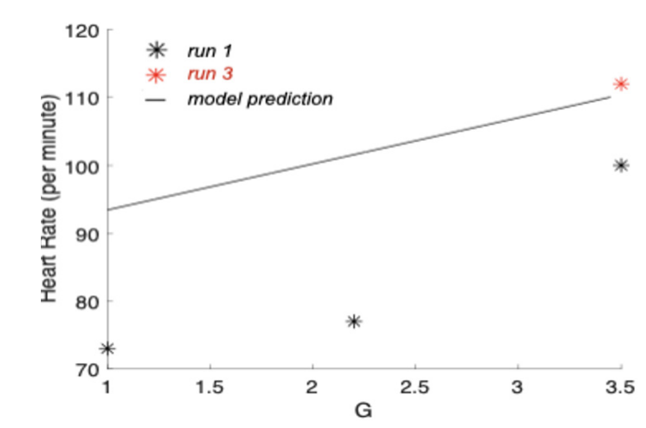
Results: Max G-Tolerance without strain



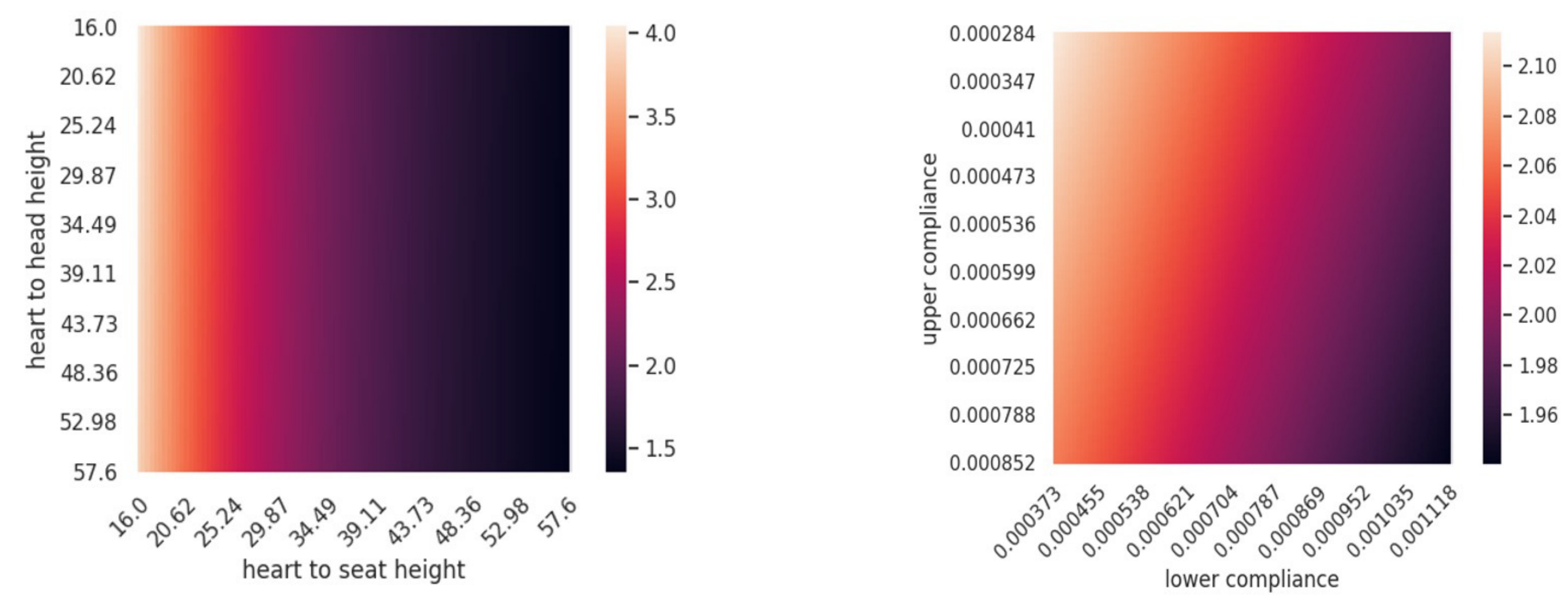








RESULTS: Predicted Max G-Tolerance with height, compliance



larger head-heart distance decreases g tolerance

lower arterial compliance has greater effect on ability to cope with change in g

Conclusion

-Model behavior is in-line with our physiological expectation

-Successful personalized prediction of G-tolerance