In vitro analysis of aortic fluid dynamics through 4D-flow MRI using a pulsatile MRI-compatible mock circulation loop

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Abstract

4D Flow MRI enables the evaluation of in vivo hemodynamics and the identification of fluid dynamic biomarkers potentially involved in the onset and progression of cardiovascular diseases. However, high variability in vivo, both among patients and in animal models, combined with prolonged acquisition times, limits the isolation of relevant parameters and hinders rigorous comparative analyses. MRI-compatible in vitro platforms offer a robust and ethical alternative, enabling the study of cardiovascular hemodynamics under controlled and repeatable conditions.

This study aimed to develop and validate an MRI-compatible pulsatile mock loop to assess local hemodynamics in patient-specific aortic phantoms using 4D Flow MRI. Two aortic anatomies, previously examined in vivo, were selected for comparison.

To replicate realistic aortic mechanical properties, uniaxial tensile tests were conducted on various silicones. Aortic phantoms were manufactured via injection molding from CT-based segmentations. The mock loop included a pulse duplicator connected, via an ad hoc dimensioned hydraulic line, to the phantom placed inside the MRI scanner. The phantom, including supra-aortic branches, was connected to a Windkessel-based afterload replicating systemic input impedance. 4D Flow MRI acquisitions were performed under pulsatile conditions at 60 and 90 bpm, mimicking rest and mild exercise.

Sorta Clear 18 was identified as the most appropriate silicone, with an elastic modulus of 0.71 MPa and compliance per unit length of 0.000153 $L \cdot s \cdot mm^{-1} \cdot mmHg^{-1} \cdot min^{-1}$, closely matching physiological values. In vitro results demonstrated the feasibility of replicating realistic pressure and flow waveforms, as well as local flow patterns consistent with in vivo data.

In conclusion, this platform enables accurate, non-invasive reproduction of patient-specific aortic hemodynamics, offering a reproducible and ethical alternative to animal testing and lengthy clinical acquisition protocols.

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