Lessons from mock circulation for mechanical assistance

The interaction between the left ventricle and the LVAD

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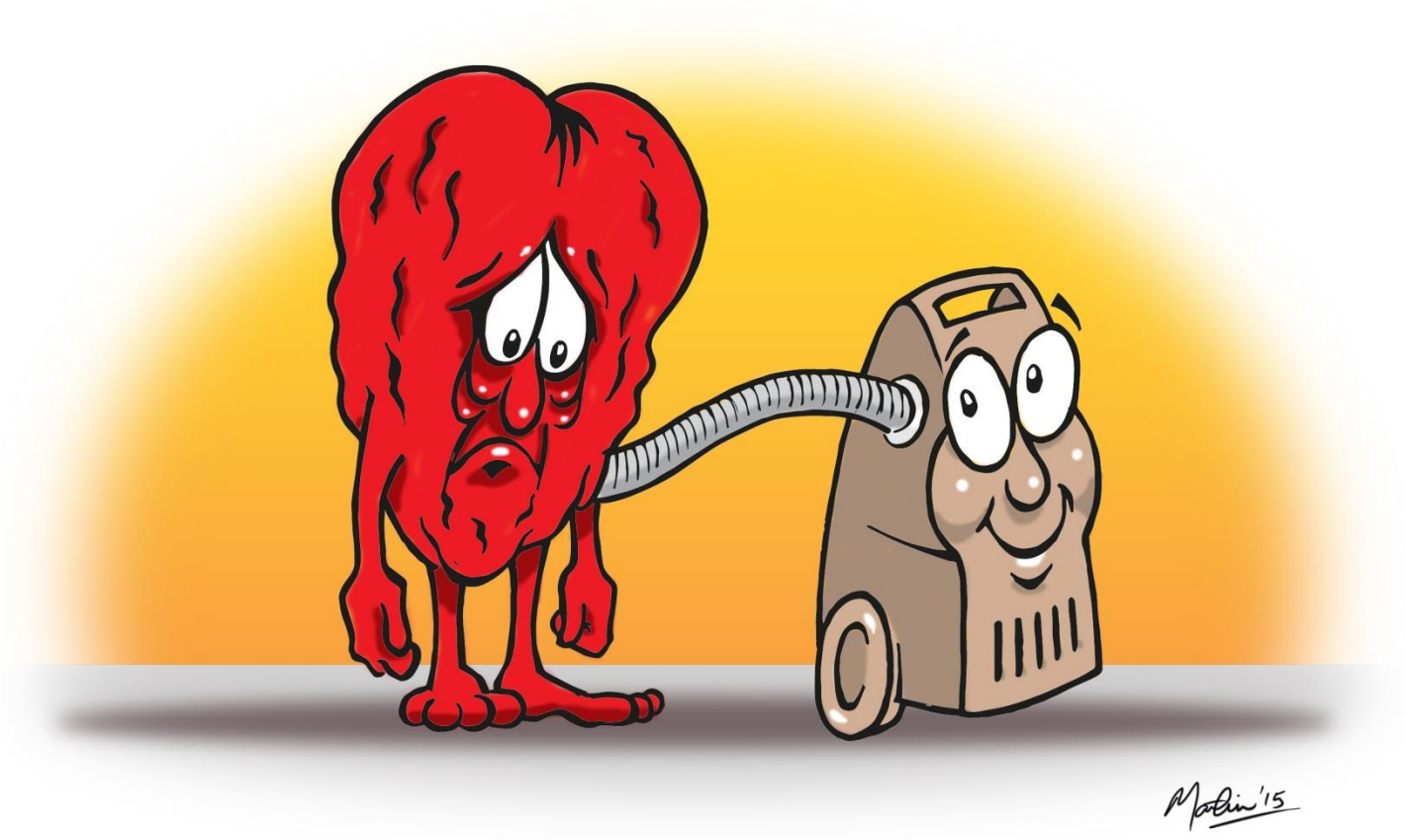
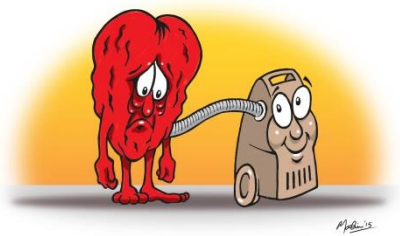
The inert heart concept

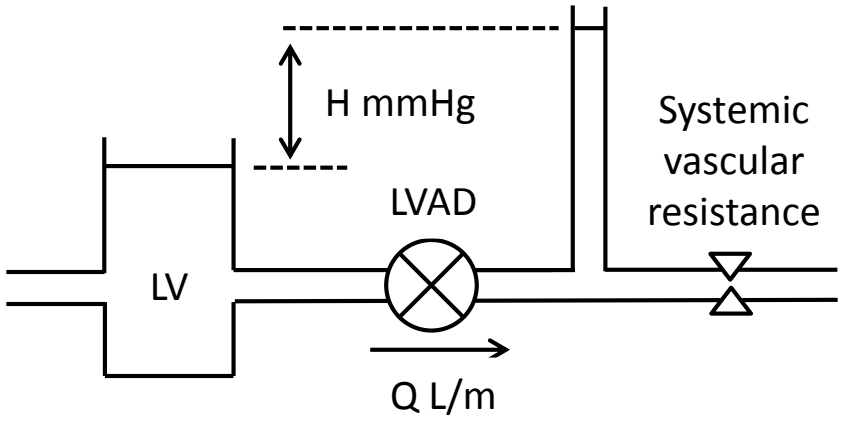


The inert heart concept

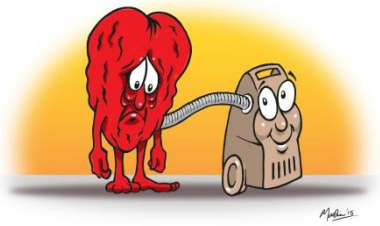


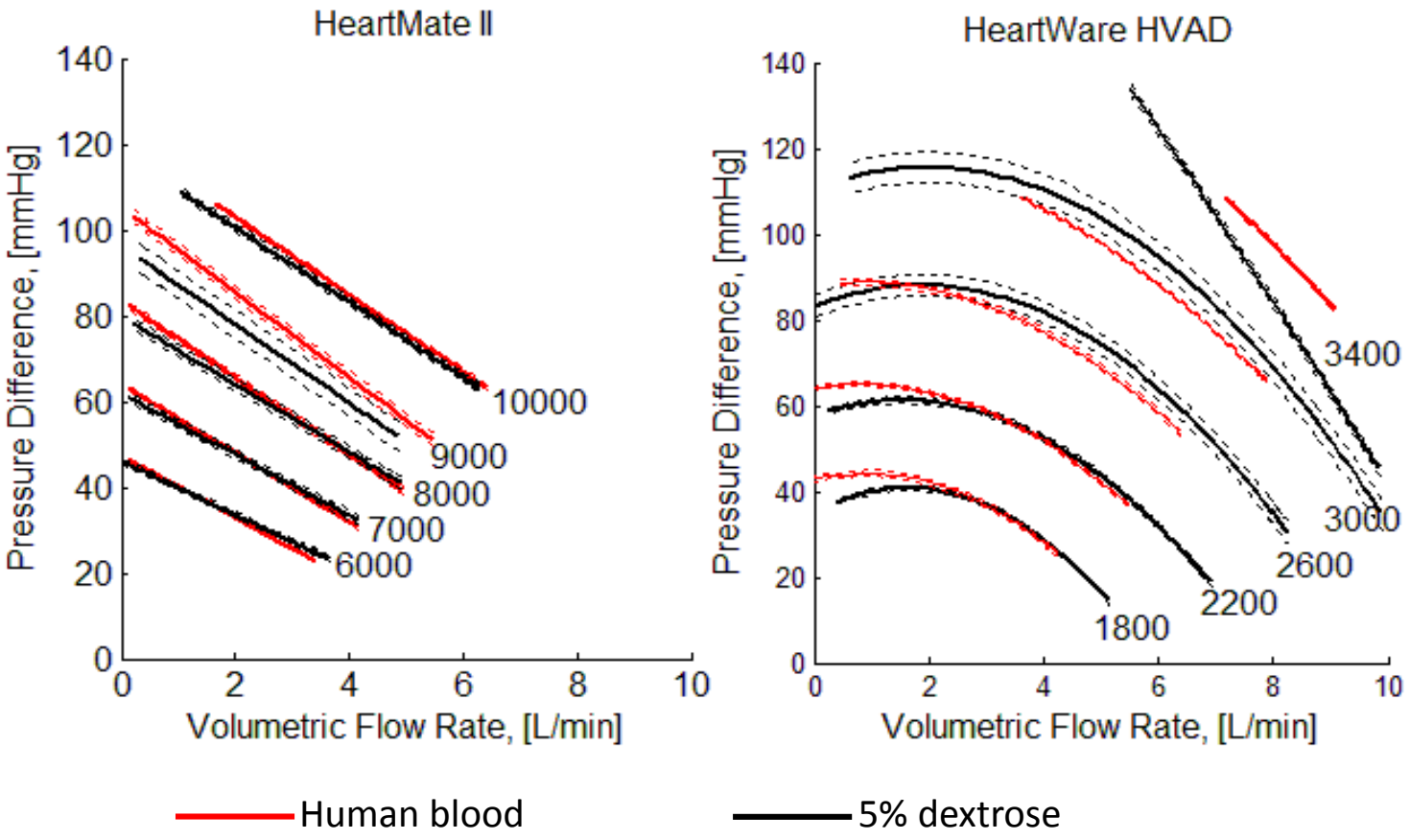
LV an inert filling chamber for LVAD

- Profound systolic heart failure (normally biventricular)
- Can occur transiently following discontinuation of CPB
- Flat arterial pressure trace, cardiac akinesia on echo
- Pressure differential across LVAD constant
- LVAD behaves as a true continuous flow pump
- Pure resistive model (arterial compliance irrelevant)



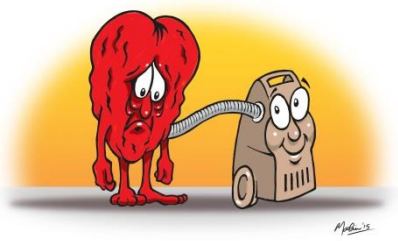
Normothermic static HQ determinations ± SD for the axial impeller Heartmate II and centrifugal HVAD





- Axial impeller: inverse linear centrifugal: inverse curvilinear
- Centrifugal: viscosity has greater effect on flow

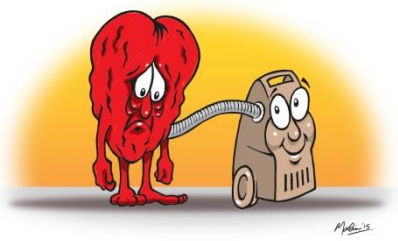
The inert heart concept



Characteristics

- Profound sustained left ventricular decompression
- Improved coronary perfusion
- Absence of systemic pulsatility
- May result in chronic dependence on biventricular support
- Extreme vulnerability of patient to accidental support cessation
- Vulnerability to acquired aortic regurgitation
    - Poor myocardial function
    - Starling’s law effect

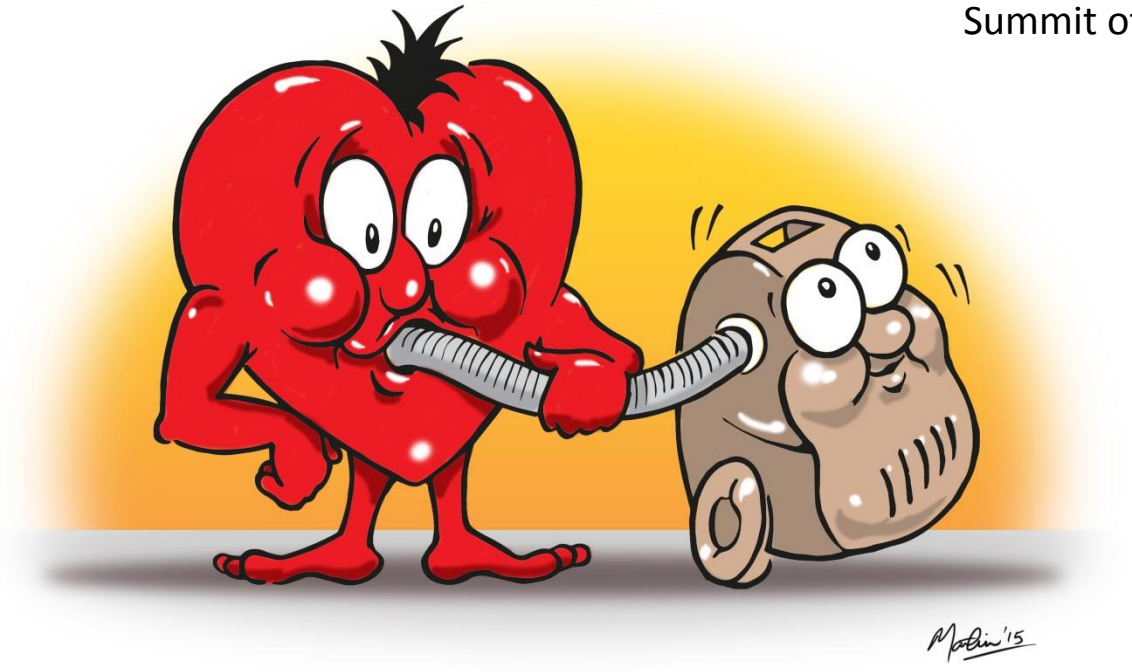
Utility and limitations of the inert heart concept



- Highlights the sensitivity of rotary blood pump flow to
  - impeller speed
  - loading conditions
- Explains why relative systemic hypotension is beneficial (higher flow)
- Explains the relative sensitivity of centrifugal pump flow to pressure differential
- However, static HQ determinations are frequently extrapolated into the dynamic physiological environment

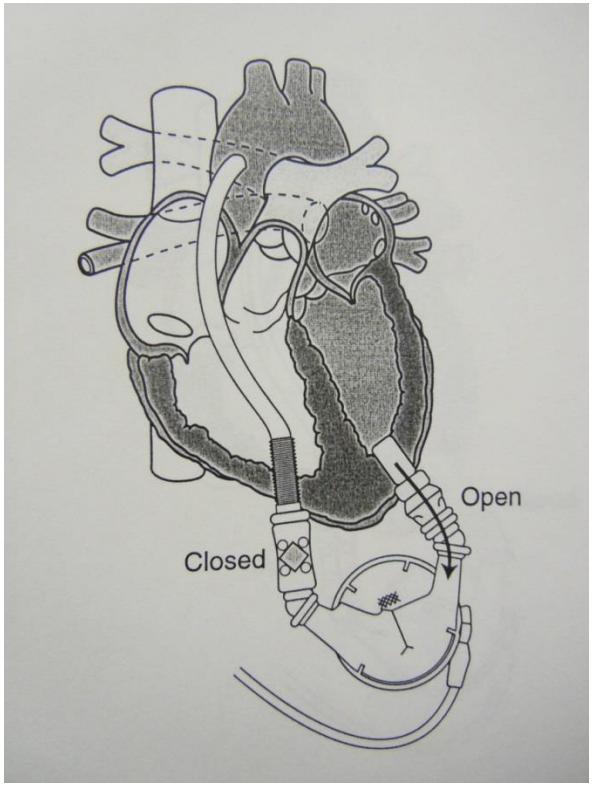
The dynamic heart concept

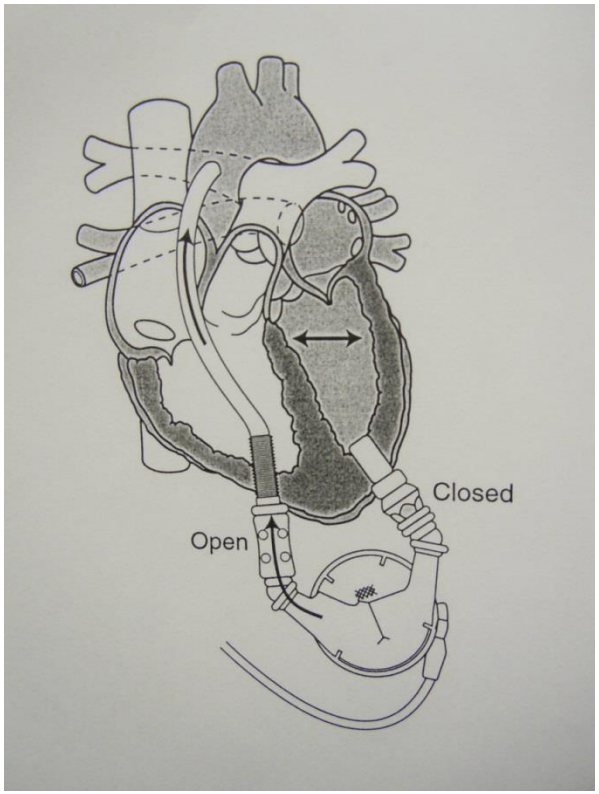
Summit of Snowdon 1085m



Pulsatile LVAD

Changing phase relationship between LV systole and LVAD ejection

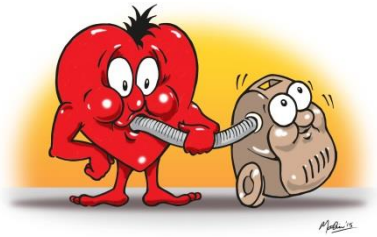




Dalby et al JHLT 2003;22:292-300

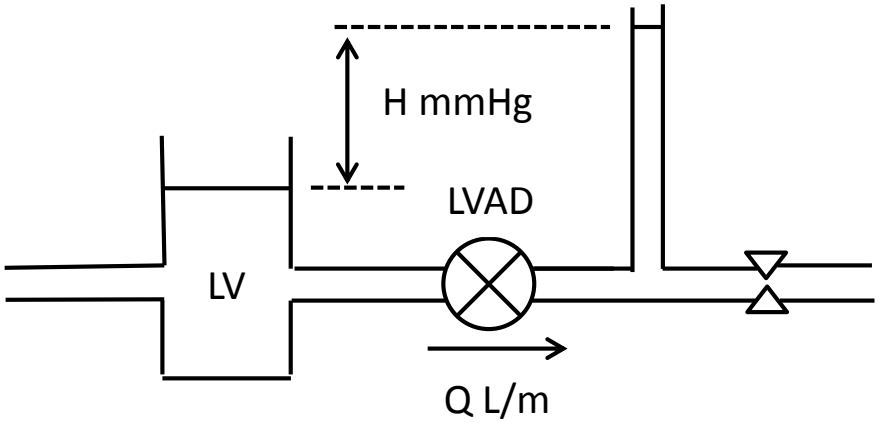
Bridge to recovery with pulsatile LVAD Birks E.J. et al. NEJM 2006; 355(18): 1873-84

The dynamic heart

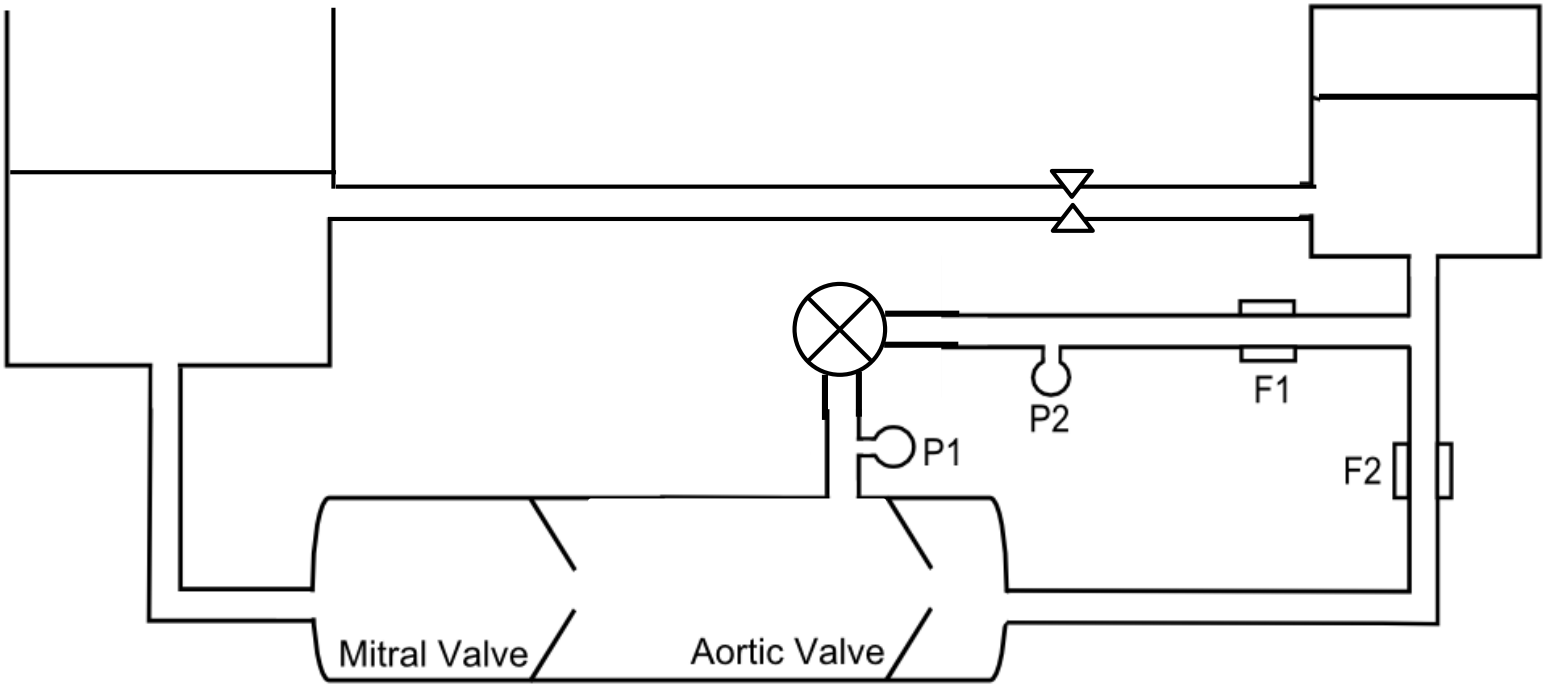


- Normally, residual LV contractility is maintained in LVAD recipients
- This contractility can change as a function of:
  - support duration
  - medication
  - possibly rehabilitation and LVAD support regime
- The changing left ventricular pressure results in a changing pressure differential across the rotary LVAD resulting in LVAD flow variation
- Important question: to what extent do rotary blood pump steady flow HQ relationships reflect clinical conditions?

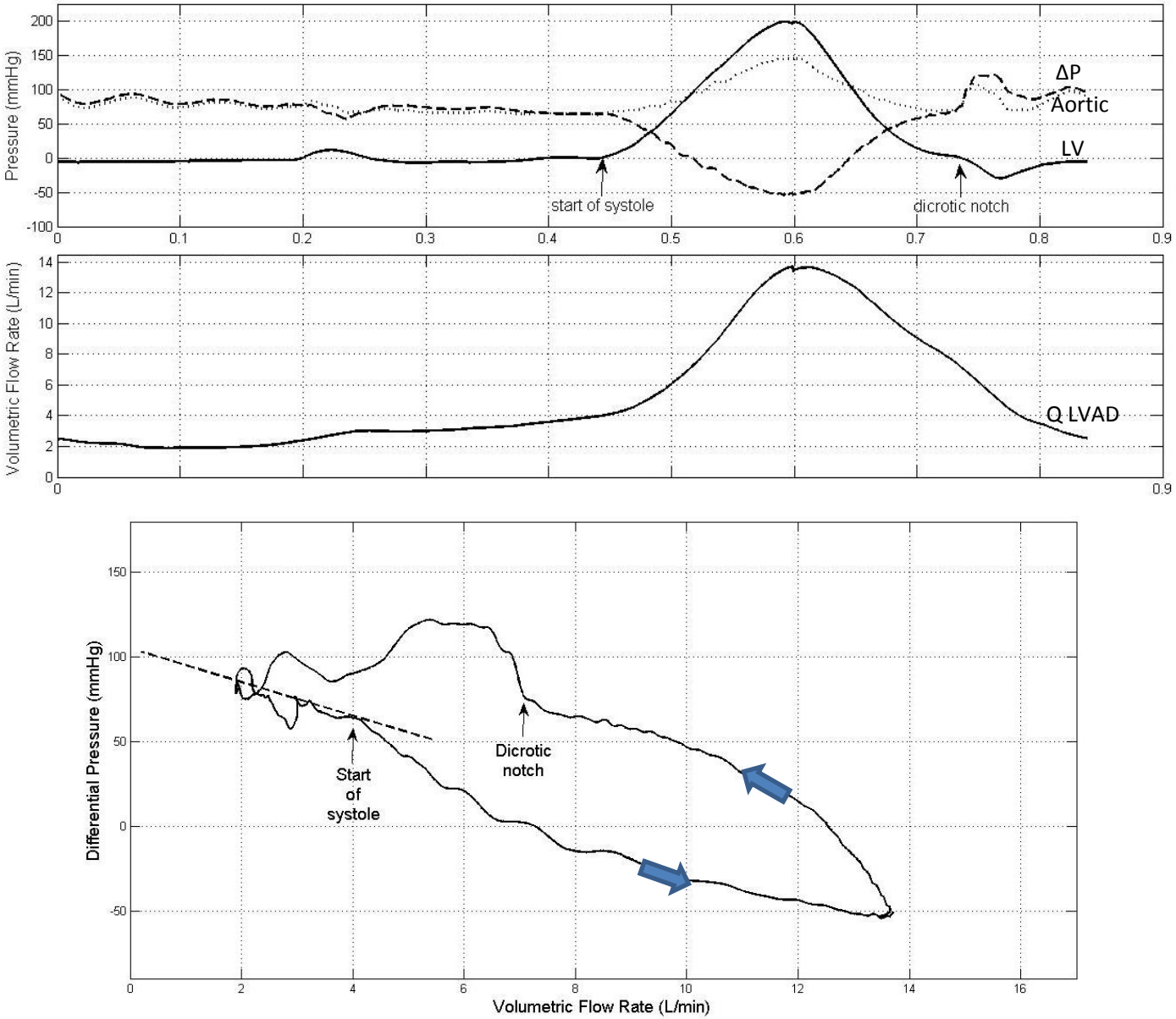
Mock circulation model selection



As there is an oscillatory component to LV pressure and thus LVAD pressure differential and LVAD flow, a pure resistive model is inappropriate

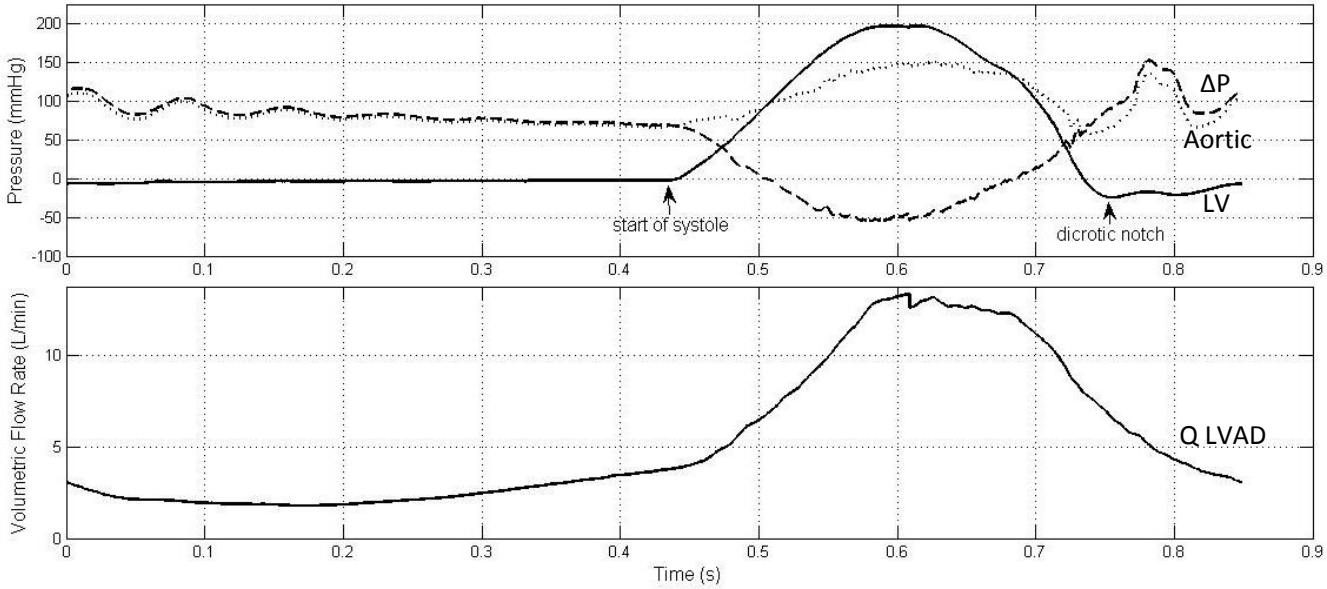


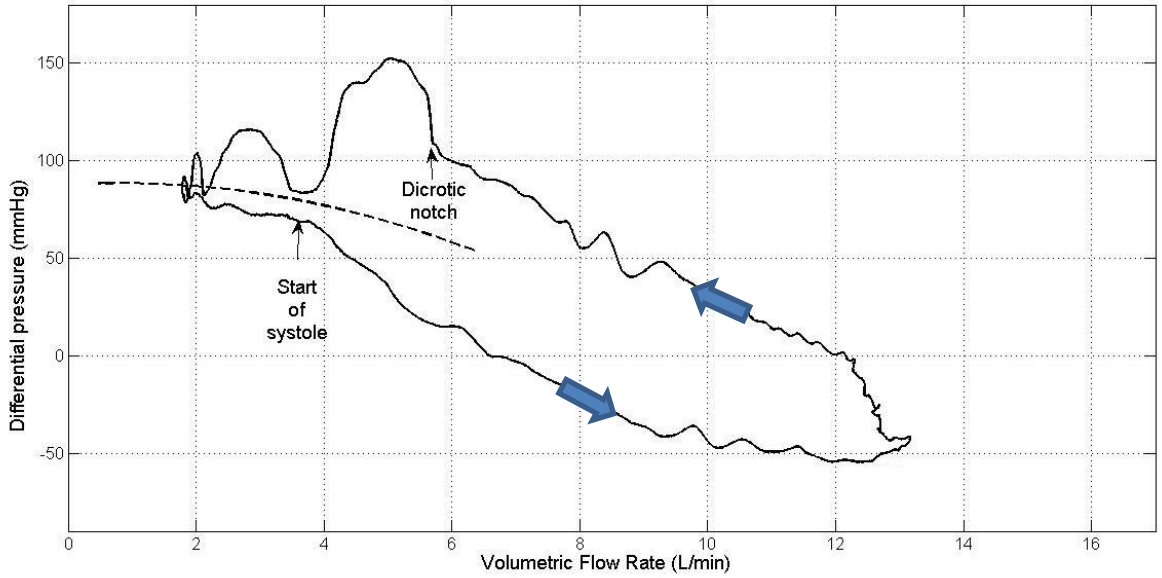
Dynamic HQ relationship for Heartmate II LVAD



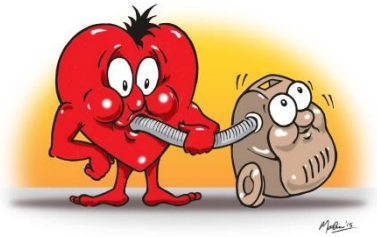
Schmidt et al. JHLT. 2011,: S213-S213

Dynamic HQ relationship for Heartware HVAD

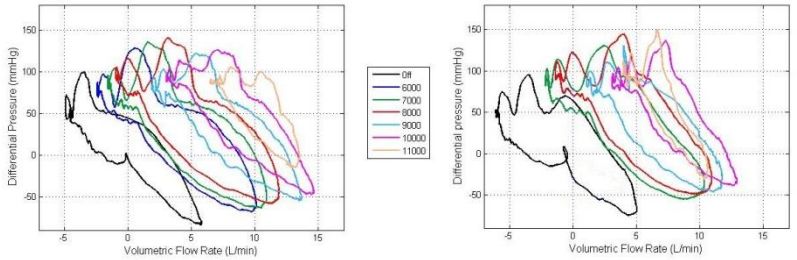
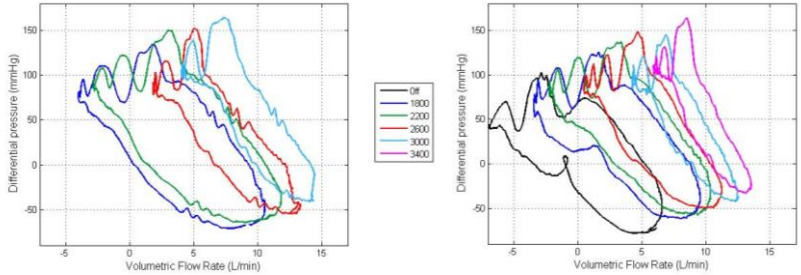
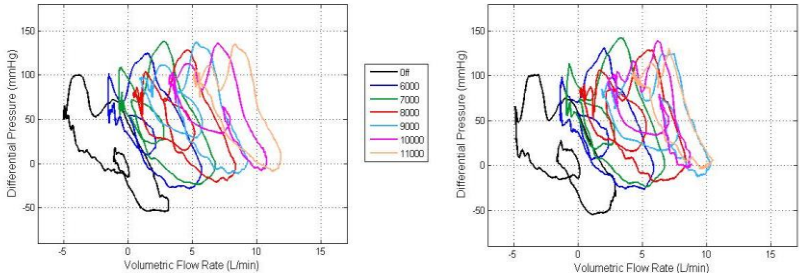
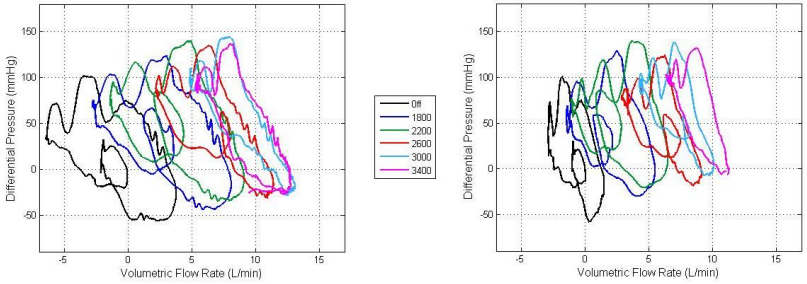


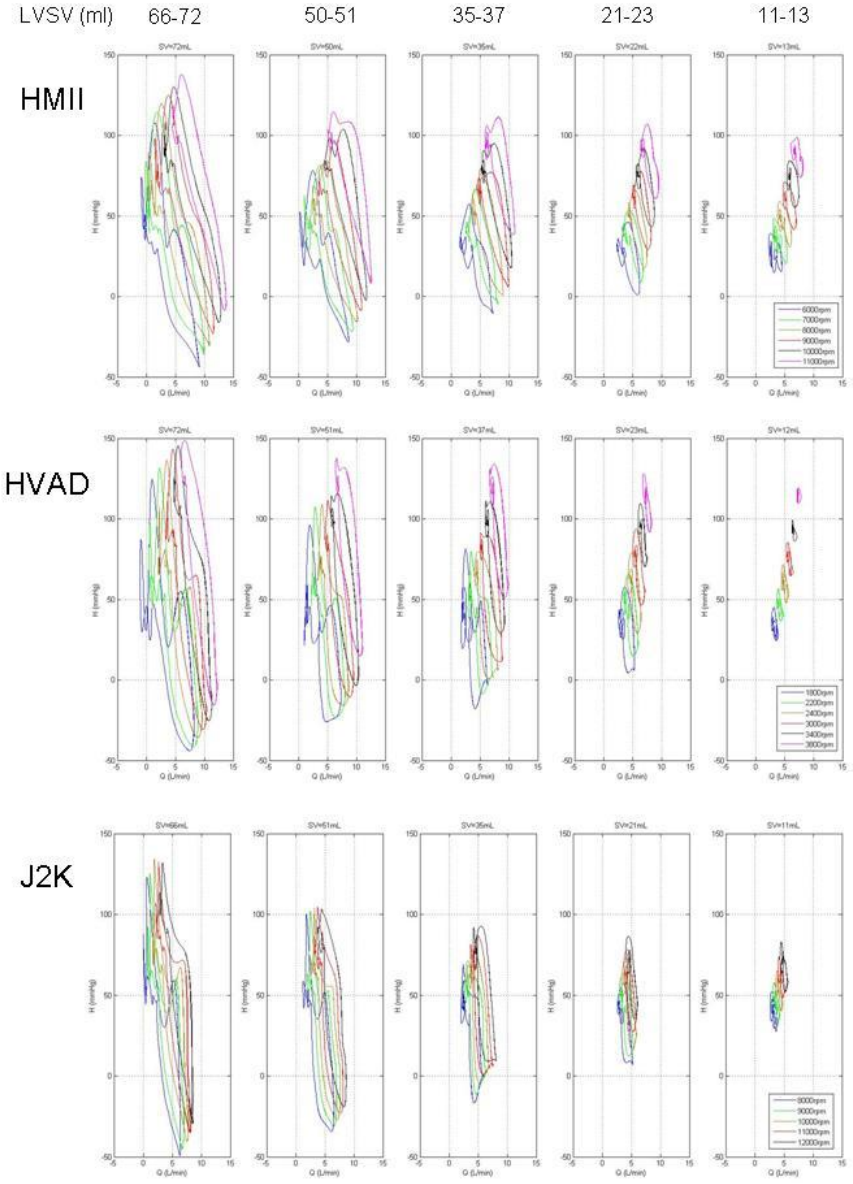


The dynamic heart concept

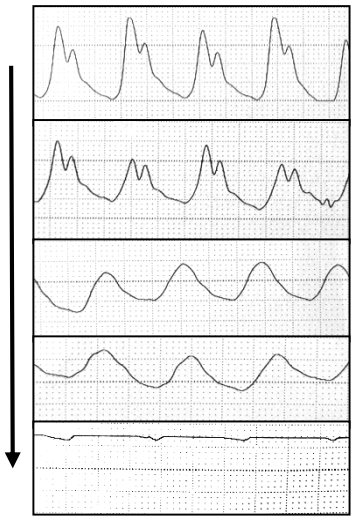


- LV systole associated with LVAD flow increase
- Varying phase relationship between LVAD pressure differential and flow
- Anticlockwise loop inscribed in HQ domain for every cardiac cycle
- Peak LVAD flows higher than predicted from static HQ determinations
- Close correspondence between static and dynamic HQ relationship during LV diastole
- Early LV systole – ΔP leads LVAD flow
- Late LV systole – LVAD flow high with respect to ΔP
- What are the effects of changing:
  - impeller speed
  - LV contractility ?

	Blood	5% dextrose	LV stroke volume (mL)
HMII			75
HVAD			75
HMII			20
HVAD			20



Speed increase



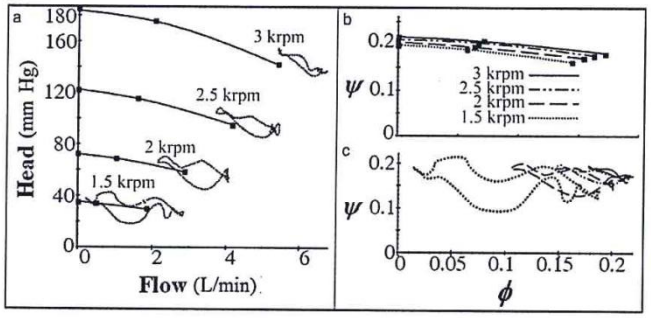
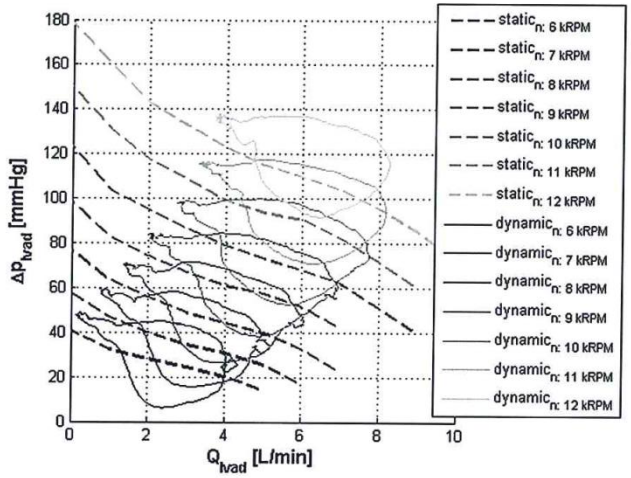


FIG. 3. *HQ* curves and loops of the rotary blood pump implanted in the sheep (a) and its corresponding nondimensional forms (b and c) (assuming density $\rho = 1060$ kg/m^3, $D = 45$ mm, $A = 71.52$ mm^2).

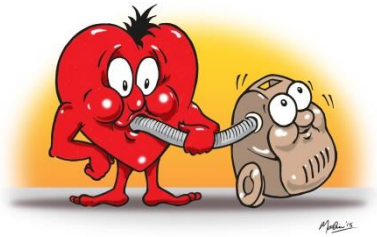
Sheep Centrimag LVAD (LV to aorta)
Pirbodaghi et al Artif Organs 2011;35:825



Mock circulation HMII
Pennings et al ASAIO J 2013;59:420

The dynamic heart concept

Assessing LV-LVAD interaction in patients



- Echocardiography
- Right heart catheter
- Pulsatility index in HMII
- Power and hence flow oscillation in HVAD
- Flow oscillation in Reliant Heart HeartAssist 5
- Contractility index determination (Schima et al.)
- Acoustic

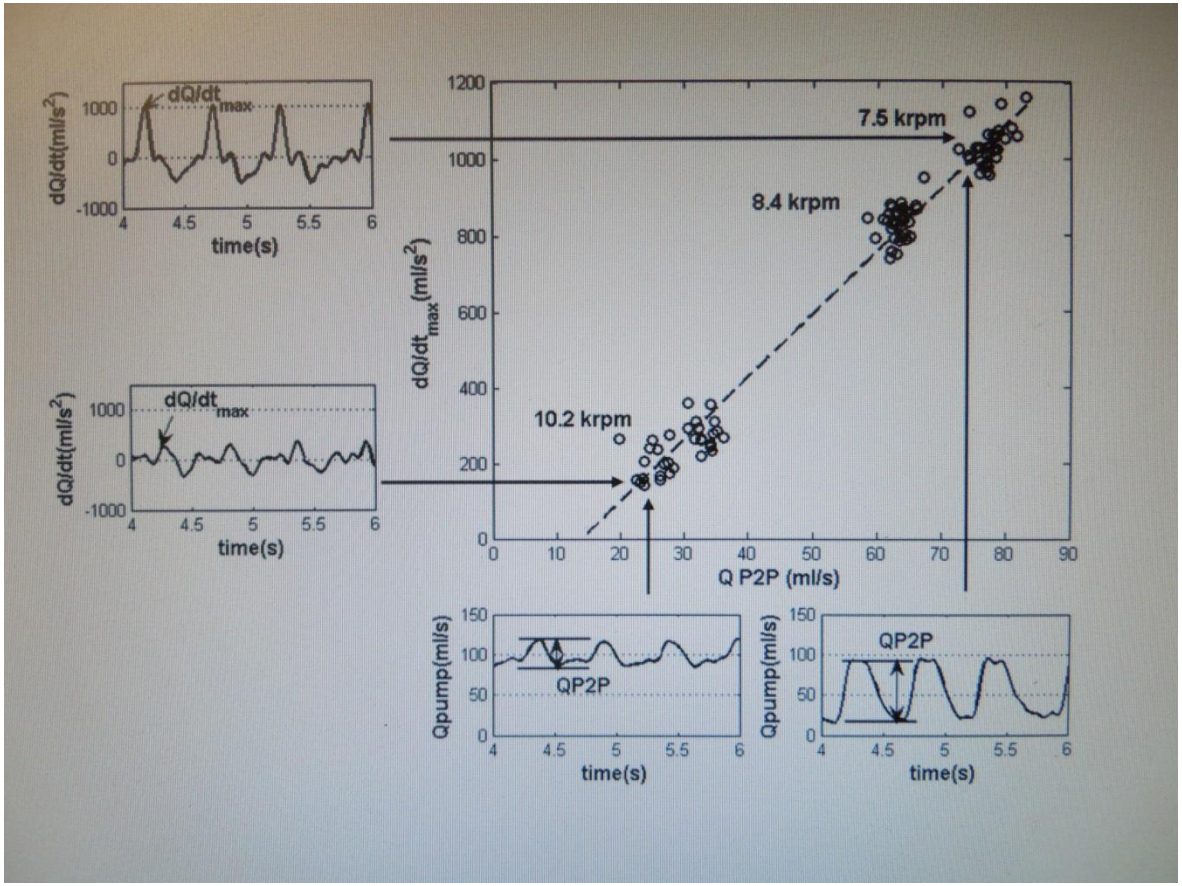
Contractility Index (IQ) determination

LVAD is an LV pressure to LVAD flow converter

dQ_{LVAD}/dt a surrogate of dP_{LV}/dt

Peak to peak flow (QP2P) a surrogate of end-diastolic volume

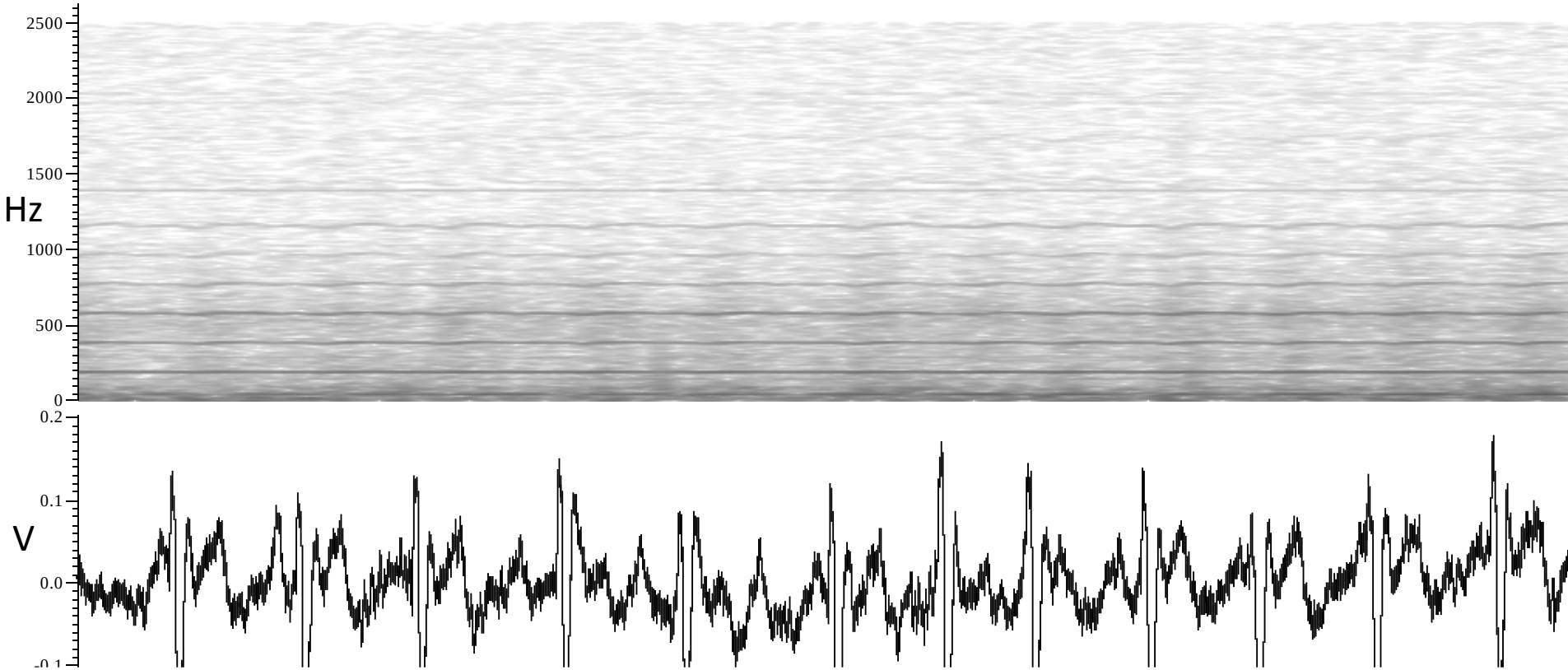
IQ the slope of the linear regression between dQ_{LVAD}/dt max and QP2P



Naiyanertr et al. JHLT 2010;29:37-44

Clinical LVAD acoustic monitoring

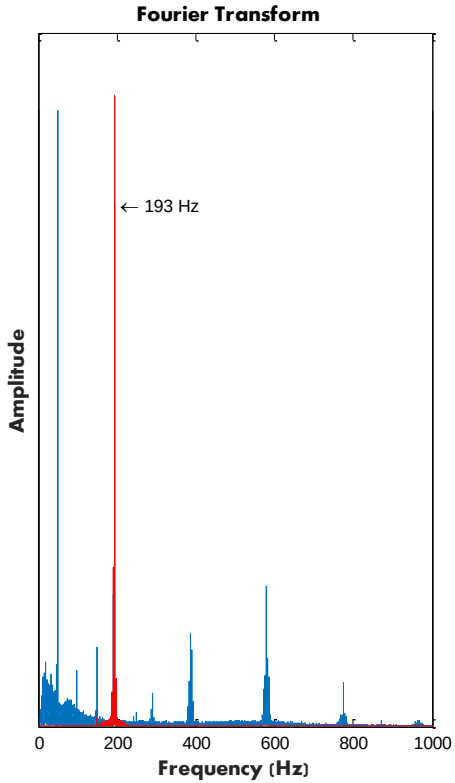
Heartware HVAD sonogram and surface ECG
2900 rpm 6.1W

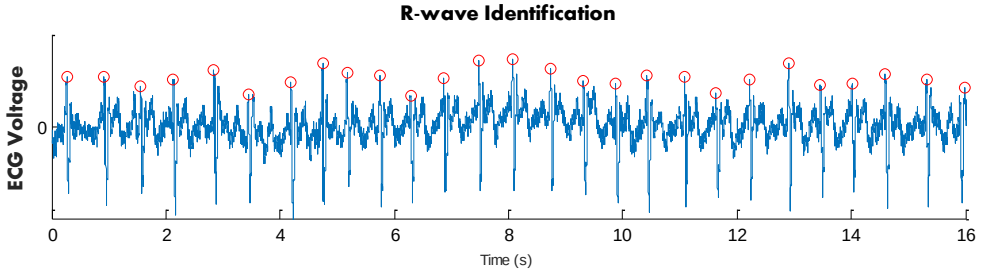


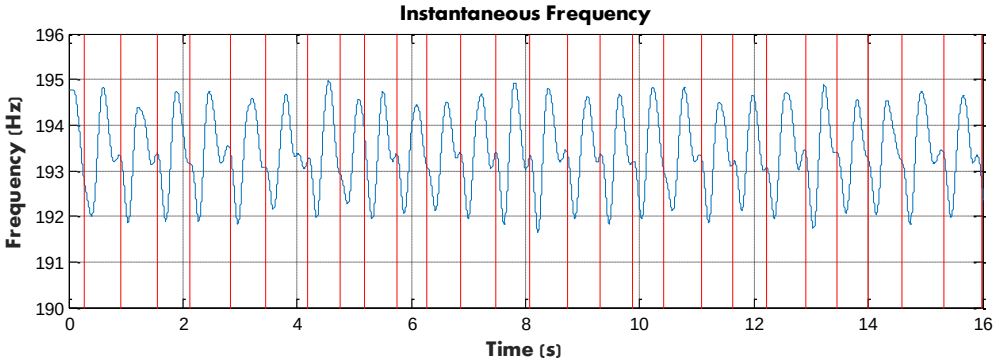
Instantaneous frequency determination

1. Empirical mode decomposition (processing power, mode hopping)
2. Hilbert transform

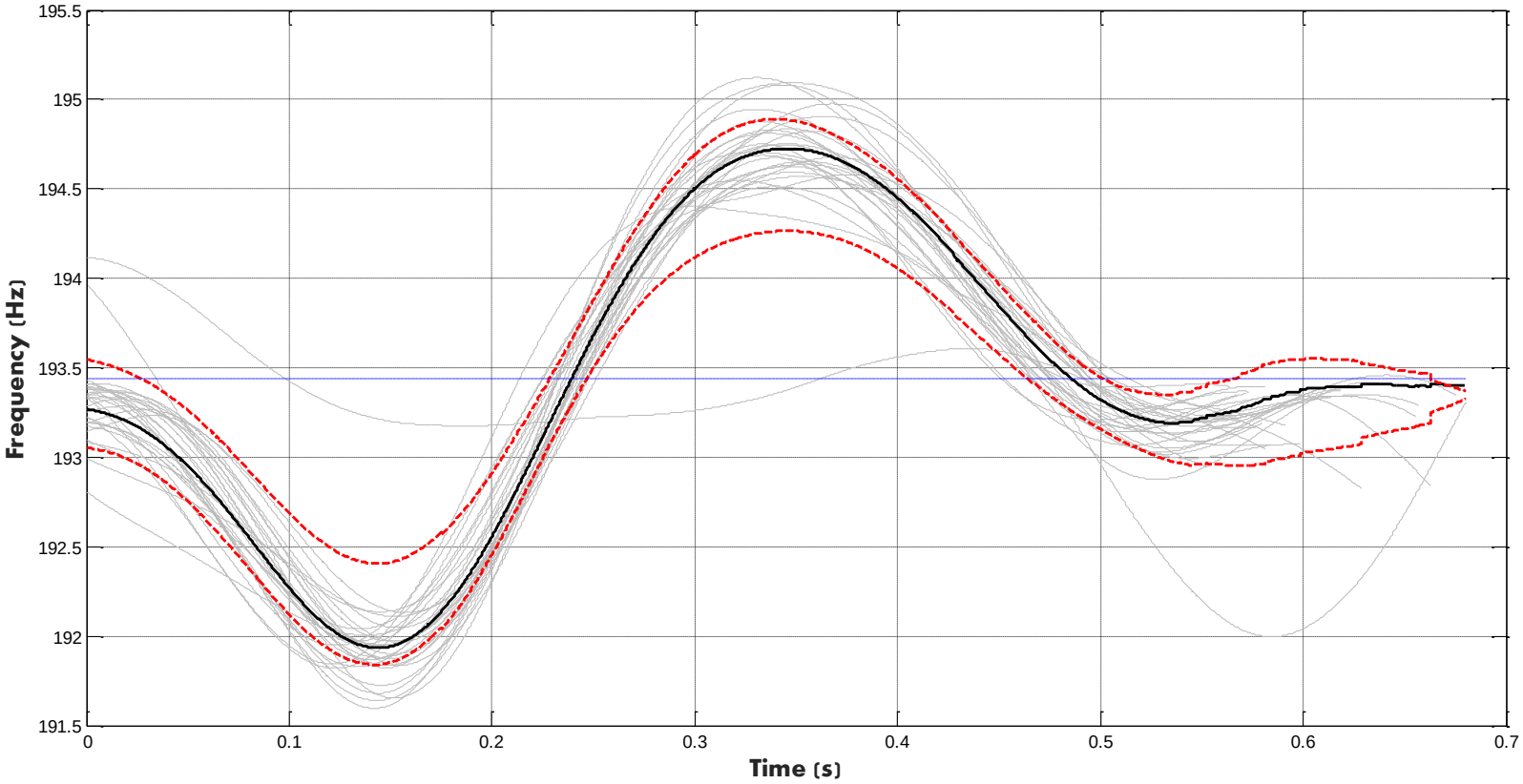
Hilbert transform methodology



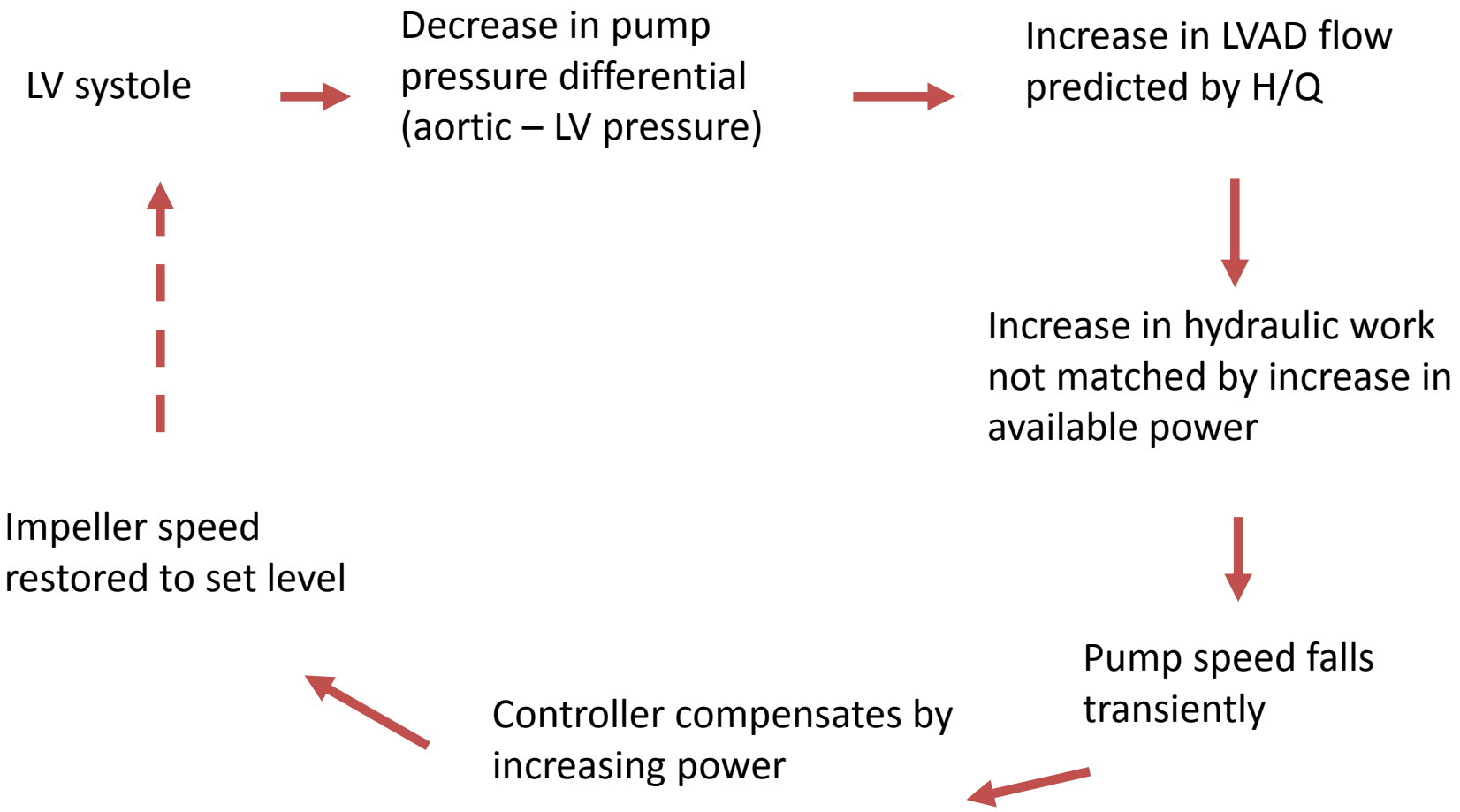




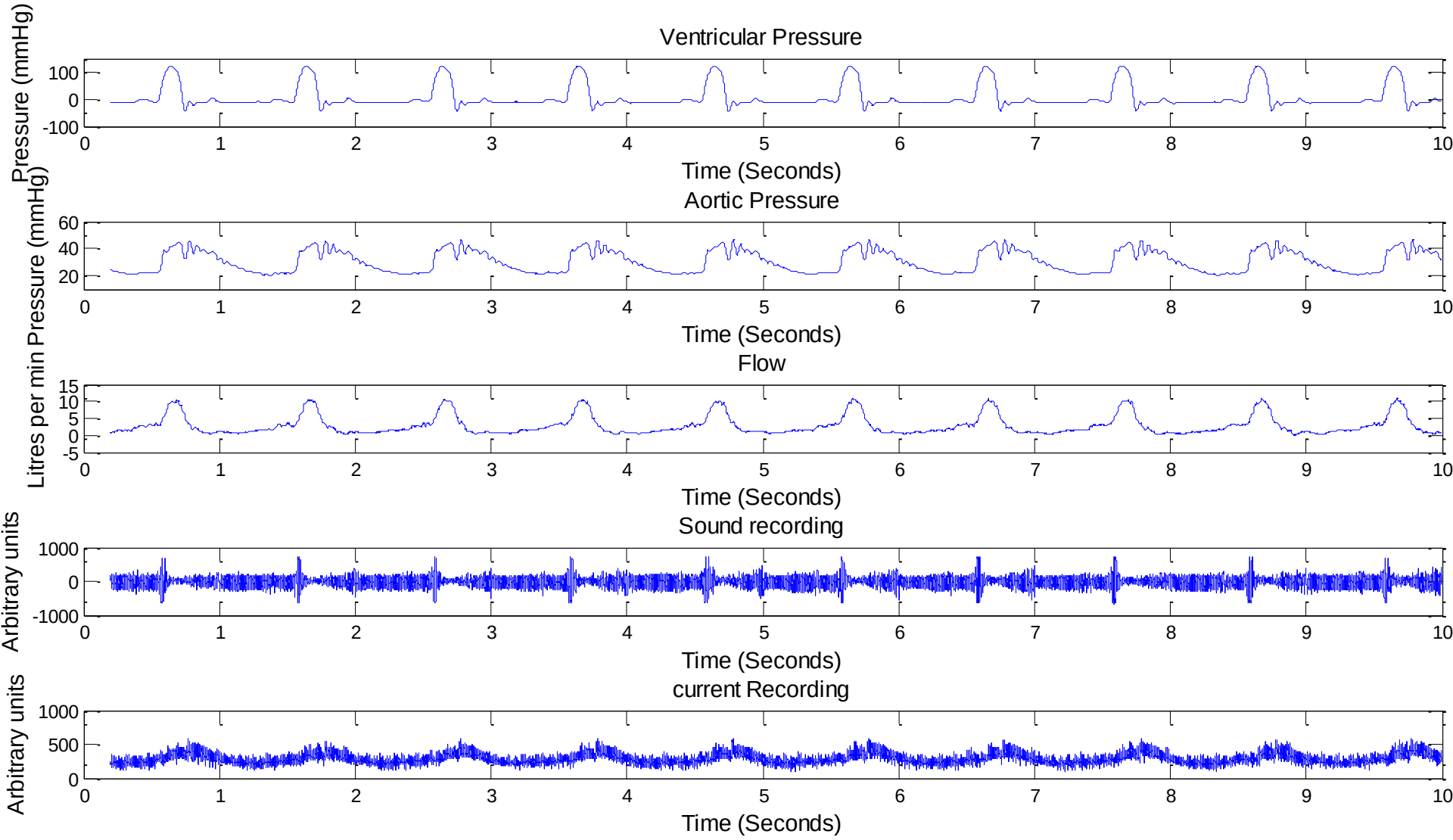
Ensemble averaged Hilbert transform



Proposed mechanism

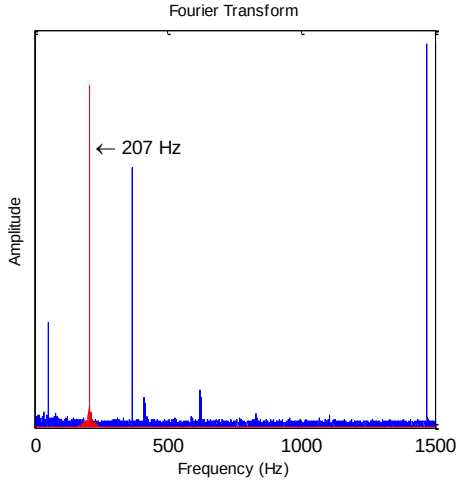


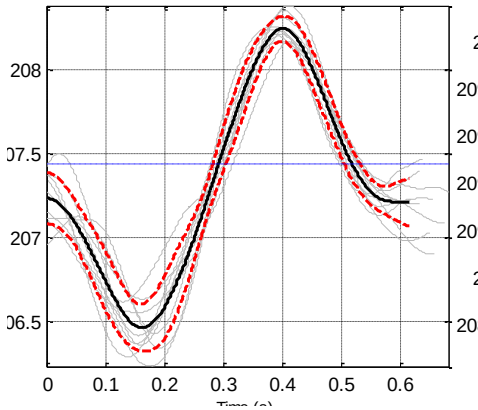
Is there a compensatory increase in the LVAD motor current in response to LV-induced frequency dip ?



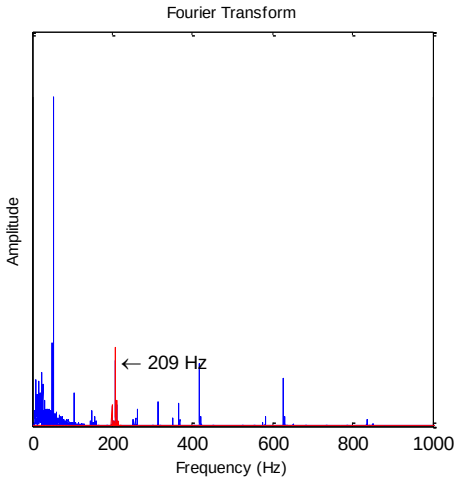
Utility of Hilbert Transform method in HVAD thrombosis/treatment episode

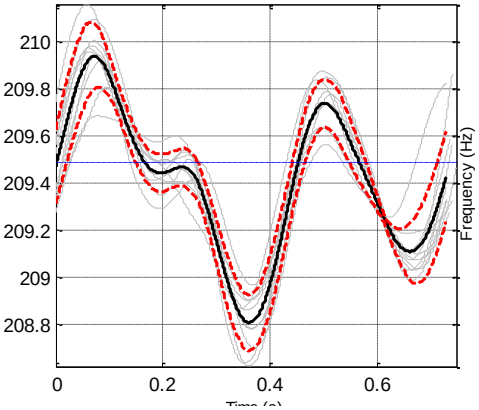
Pre-thrombus
Q6.0 6.0W



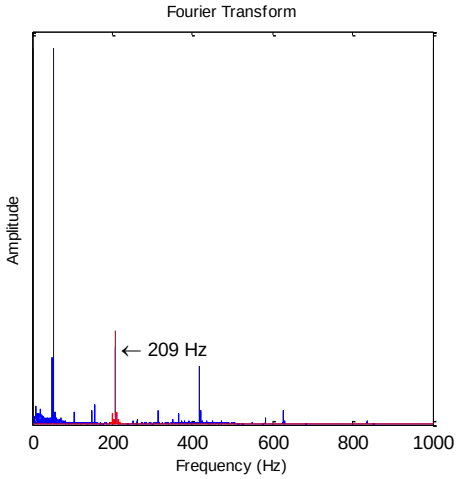


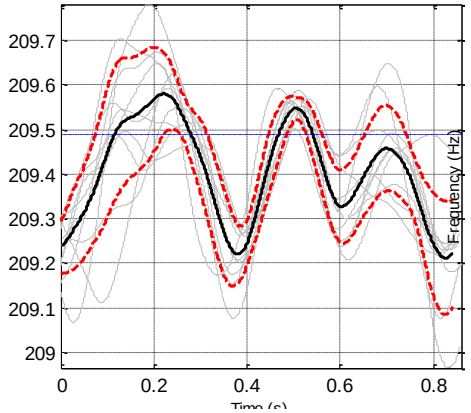
On readmission
Q1.6 3.8W



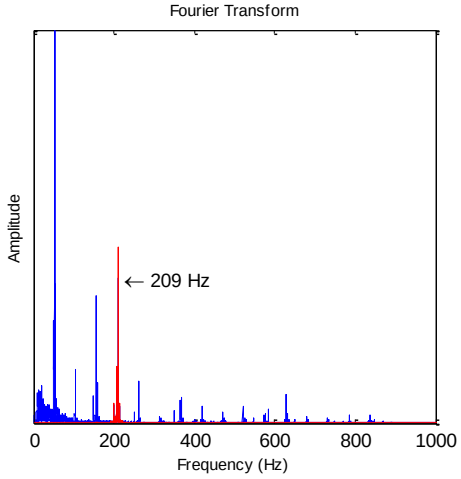


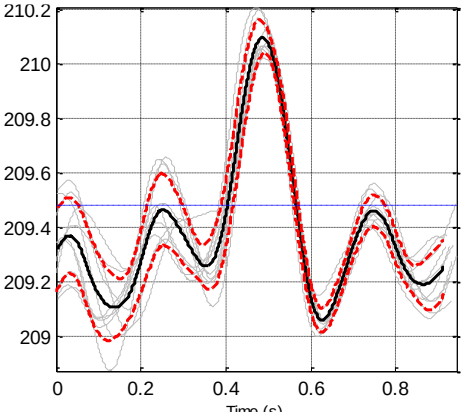
Day 2
Q2.2 4.3W





Day 3
Q3.6 5W





Summary

- Mock circulation models and acoustic analysis have contributed to understanding of LV-LVAD interaction
- This is associated with a number of potential benefits
- Selection of more clinically representative conditions in CFD
- Improvements in rotary LVAD haemocompatibility
- Enhanced propagation of pulsatility into the systemic arteries (inherent and induced)
- The development of better closed loop control pump speed algorithms to prevent left ventricular suction events
- Better management of suspected pump thrombosis episodes
- The selection of operating conditions more conducive to:
    - reverse remodelling in dilated cardiomyopathy
    - prevention of acquired aortic regurgitation

The bidirectional interaction concept

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