Understanding and measuring flow in aortic stenosis with MRI

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is entirely my own work and, except where otherwise indicated,
describes my own research.
This thesis is dedicated to my family

Strongest hand uppermost
Abstract

In patients with aortic stenosis, accurate assessment of severity with echocardiography is central to surgical decision making. But, when image quality is poor or equivocal results obtained, another robust non-invasive technique would be invaluable. Cardiac magnetic resonance (CMR) may be a useful alternative.

Phase contrast CMR can measure flow and velocity, therefore it is theoretically possible to estimate the main determinant of severity aortic valve area, using the continuity approach. However, it was found that the phase contrast estimate of stroke volume, sampled in the stenotic jet, systematically underestimated left ventricular stroke volume. This underestimation was greater with increasing aortic stenosis severity.

Critical clinical treatment decisions depend on the ability to reliably differentiate between patients with moderate and severe aortic stenosis. To achieve accurate estimation of aortic valve areas the velocity and flow data obtained in these turbulent, high velocity jets must be accurate.

In this thesis, non-stenotic and stenotic phantoms were designed and constructed to experimentally interrogate the error. It was determined that signal loss, due to intravoxel dephasing, decreased the reliability of the measured forward flow jet velocities. Extreme signal loss in the jet eventuated in salt and pepper noise, which, with a mean velocity of zero, resulted in the underestimation.

Intravoxel dephasing signal loss due to higher order motions, turbulence and spin mixing could all be mitigated by reducing the duration of the velocity sensitivity gradients and shortening the overall echo time (TE). However, improvements in an optimised PC sequence (TE 1.5ms) were not satisfactory. Flow estimates remained variable and were underestimated beyond the aortic valve.

To reduce the TE further, a new phase contrast pulse sequence based on an ultrashort TE readout trajectory and velocity dependent slice excitation with gradient inversion was designed and implemented. The new sequence’s TE is approximately 25% (0.65ms) of what is currently clinically available (TE 2.8ms). Good agreement in the phantom was maintained up to very high flow rates with improved signal characteristics shown in-vivo. This new phase contrast pulse sequence is worthy of further investigation as an accurate evaluation of patients with aortic stenosis.
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Glossary of Key Terms

**Aortic stenosis** a narrowing of the aortic valve that causes the formation of a jet during systole.

**Diastole** relaxation or dilation phase of the heart.

**Rheumatic fever** inflammatory disease due to a group A streptococcal infection that can affect the heart, joints, skin and brain.

**Systole** the ejection/contraction phase of the heart.

**Magnetic Resonance Imaging** is the creation of soft tissue images by manipulating the precessional frequency of hydrogen nuclei.

- **$T_1$ relaxation** is the time taken for the longitudinal magnetisation ($M_z$) to return to 63% of its original value $M_0$.
- **$T_2$ relaxation** time taken for the NMV’s transverse magnetisation ($M_{xy}$) to decay to 37% of its original value.
- **$T_2^*$ relaxation** is the combined loss of phase coherence due to true $T_2$ and inhomogeneities, it defines the FID envelope.

**Echo time (TE)** time between the excitation RF pulse and readout centres.

**Intravoxel Dephasing** the phase dispersal of spins within a voxel.

- **Higher order motion encoding** refers to the additional phase accrual due to acceleration, jerk and other higher order motions.
- **Iso delay time** is the effective dephasing time that results in the phase dispersion.
- **Partial excitation** occurs when a spin does not remain in the desired slice for the duration of the RF pulse.
- **Partial voluming** is where the signal from a voxel has a mixture of different tissues, or experiences bi-directional flow.
- **Spin mixing** is the mixing of fast and slow moving spins within a voxel due to the delay between excitation and readout.

**K-space** is the spatial frequency representation of a magnetic resonance image.

**Phase contrast** is a Magnetic resonance imaging technique that allows for the quantification of velocity and flow.

**Pulse sequence** an instruction set of gradient and RF pulses and ADC events that describes how the MR scanner manipulates spins.

**Repetition time (TR)** time between two successive excitation RF pulses centres.

**Ultrashort TE (UTE)** a family of pulse sequences that can achieve very short TEs for imaging of tissues with a majority of short $T_2$ components.

**V enc** is the maximal encoding velocity or aliasing velocity of a PC sequence.

**Turbulence** the random velocity fluctuations superimposed on the flow.

- **Boundary layer** is a region with steep velocity gradients, typically near surfaces or in bidirectional flow. It is characterised by large shear stresses and turbulence.
- **Reynolds number** ($Re$) the ratio of inertial and viscous forces acting on a fluid.
List of Acronyms

ADC  analogue to digital converter.
AR  aortic root.
ascAo  ascending aorta.
AV  aortic valve.
AV0cm  image plane located on the aortic valve.
AV1cm  image plane located 1cm distal to the aortic valve.
AV2.5cm  image plane located 2.5cm distal to the aortic valve.
AVA  aortic valve area.
CIM  Cardiac Image Modeller.
cineCT  cine computed tomography.
CMR  cardiac magnetic resonance.
CO  cardiac output.
DoF  degrees of freedom.
Doppler  continuous wave Doppler.
FID  free induction decay.
fMRI  Functional magnetic resonance imaging.
FOV  field of view.
LV  left ventricle.
LVOT  left ventricular outflow tract.
LVSV  left ventricular stroke volume.
MPA  main pulmonary artery.
MR  magnetic resonance.
NMR  nuclear magnetic resonance.
NMV  net magnetisation vector.
PC  phase contrast.
PCSV  PC estimate of stroke volume.
PET  positron emission tomography.
RF  radio-frequency.
ROI  region of interest.
RSI  relative signal intensity.
SI  signal intensity.
SNR  signal to noise ratio.
STJ  sino-tubular junction.
SV  stroke volume.
VTI  velocity time integral.
ZEST  New Zealand Eplerenone in Aortic Stenosis Trial.

For ease of reading, the acronyms are redefined each chapter.