# Cardiac Flow Analysis Using Magnetic Resonance Imaging

by

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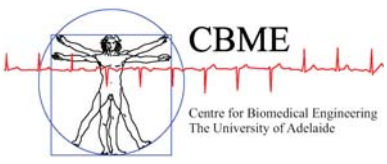




# Contents

# Abstract

Many types of cardiac abnormality have an implication on blood flow. However, most present-day diagnostic modalities analyse myocardial structures and not the cardiac flow within to detect heart defects *in vivo*. Currently, various imaging modalities, such as echocardiography, single photon emission computed tomography (SPECT), positron emission tomography (PET), X-ray computed tomography (CT), and cardiac magnetic resonance imaging (CMRI) provide a non-invasive approach for scanning humans with heart abnormalities, and are utilised in the management of cardiac patients. There is a need to develop a visualisation system for analysing flow of blood within the human heart. Motional properties of blood can be measured against normal controls and patients with cardiac abnormalities in order to discover underlying cause of these flow phenomena. This can potentially extend medical knowledge of the defects and their hemodynamic behaviour.

We characterise motion patterns of blood in the human heart and analyse the flow properties, by means of tracking, using a series of time dependent magnetic resonance images. An indication of flow vortices can be provided by numerical computation of vorticity values within the defined region of blood flow. The global estimation of parametric motion flow fields over the whole image provides useful information on the presence of vortices within the heart chamber that can be used to assess cardiac functions. In this study, the crucial strategies for this approach are implemented, and the achievable diagnostic results and quality of assessment are investigated. The developmental stages of the framework and system design of each component for cardiac diagnosis are detailed in this thesis. The key objectives of the research and development for this diagnostic system are implemented herein:

1. Realisation of a non-invasive technique to compute flow features within cardiac structures. System evaluation and velocity calibration of the flow tracker are incorporated in the study. Verification of calculated flow in time-resolved cardiac vessels is performed by error analysis using flow fields constructed by velocity-encoded magnetic resonance imaging velocimetry.

2. Measurement of cardiac vorticities in heart chambers is performed for investigation of flow phenomena. We examine the time-dependent behaviour of cardiac

flow structures in the heart. The variation of flow patterns that are associated with myocardial wall deformations and pressure changes is analysed.

3. Realisation of a statistical framework for examining variations of flow due to myocardial defects in the heart. The quantification of flow will offer the potential to complement diagnostic methods that analyse cardiac defects and evaluate patient condition after surgical intervention.

As an alternative to established medical imaging-based diagnostic techniques such as chest X-rays, and pulsed or continuous wave Doppler ultrasound scans for cardiac diagnosis, we develop a magnetic resonance imaging based approach and perform flow quantification to analyse the heart, *vis-à-vis* blood movement in chambers based on a measured flow field. This framework offers potential for non-invasive flow visualisation in cardiac structures. We validate this methodology specifically for analysing flow characteristics within a human heart case study. We also demonstrate the potential for non-invasive assessment of cardiac abnormality for a pathological case of the heart.

# Statement of Originality

This work contains no material that has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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Date

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## Commercialisation

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## Proof Reading and Discussion

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# Conventions

1. **Typesetting:** This thesis is typeset using the LaTeX2e software. TeXnicCenter 1 Beta 6.31 (Firenze) was used as an interface to LaTeX. Processed plots and images were generated using Matlab 7.0 (Mathsworks Inc.). Adobe Illustrator (Adobe Systems Incorporated) was used to produce schematic diagrams and other drawings. Medflovan medical image processing software was developed using C++ programming language—Borland C++ Builder Version 6.0 (Borland Software Corporation). The OpenGL library (Silicon Graphics, Inc) is the application programming interface for plotting colour contour and vector flow maps.

2. **Spelling:** Australian English spelling has been adopted throughout, as defined by the Macquarie English Dictionary (A. Delbridge, Ed., Macquarie Library, North Ryde, NSW, Australia, 2001).

3. **Referencing:** Harvard style is used for referencing and citation in this thesis.

# Awards

## Young Investigator Award

**Title:** Blood flow assessment in the aortic heart valve based on magnetic resonance images using optical flow analysis

**Authors:** Kelvin K. L. Wong, Pawel Kuklik, Richard M. Kelso, Stephen G. Worthley, Prashanthan Sanders, Jagannath Mazumdar & Derek Abbott

**Conference:** XVth International Conference on Mechanics in Medicine and Biology (15th ICMMB), Singapore, 6-8th Dec 2006.

**Publication:** Proceedings of the XVth International Conference on Mechanics in Medicine and Biology, ISBN 1-930746-05-9, Volume 15, pages 74-76, 2006.

## Outstanding Paper Award

**Title:** Flow imaging and validation of MR fluid motion tracking

**Authors:** Kelvin K. L. Wong, Richard M. Kelso, Stephen G. Worthley, Prashanthan Sanders, Jagannath Mazumdar & Derek Abbott

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# Publications

## Journals

WONG-K. K. L., KELSO-R. M., WORTHLEY-S. G., SANDERS-P., MAZUMDAR-J., AND ABBOTT-D. (2009). Noninvasive cardiac flow assessment using high speed magnetic resonance fluid motion tracking, *PLoS ONE*, **4**(5), Article No. e5688.

WONG-K. K. L., KELSO-R. M., WORTHLEY-S. G., SANDERS-P., MAZUMDAR-J., AND ABBOTT-D. (2009). Medical imaging and processing methods for cardiac flow reconstruction, *Journal of Mechanics in Medicine and Biology*, **9**(1), pp. 1–20.

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WONG-K. K. L., KELSO-R. M., WORTHLEY-S. G., SANDERS-P., MAZUMDAR-J., AND ABBOTT-D. (September 2009). A novel measurement system for cardiac flow analysis applied to phase contrast magnetic resonance imaging of the heart, *Proceedings of the World Congress on Medical Physics and Biomedical Engineering*, Munich, Germany.

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WONG-K. K. L., KELSO-R. M., WORTHLEY-S. G., SANDERS-P., MAZUMDAR-J., AND ABBOTT-D. (2007). Flow in left atrium using MR fluid motion estimation, *Proceedings of the SPIE Microelectronics, MEMS, and Nanotechnology (Complex Systems II),* Canberra, Australia, **6802**, Article No. 68021H.

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WONG-K. K. L., KUKLIK-P., KELSO-R. M., WORTHLEY-S. G., SANDERS-P., MAZUMDAR-J., AND ABBOTT-D. (2006). Blood flow assessment in a heart with septal defect based on optical flow analysis of magnetic resonance images, *Proceedings of the SPIE Biomedical Applications of Micro- and Nanoengineering III ,* Adelaide, Australia, **6416**, Article No. 64160L.

WONG-K. K. L., KUKLIK-P., KELSO-R. M., WORTHLEY-S. G., SANDERS-P., MAZUMDAR-J., AND ABBOTT-D. (2006). Blood flow assessment in the aortic heart valve based on magnetic resonance images using optical flow analysis, *Proceedings of the XVth International Conference on Mechanics in Medicine and Biology (15th ICMMB),* Singapore, **15**, pp. 74–76.

WONG-K. K. L., MAZUMDAR-J., AND ABBOTT-D. (2005). A study of the relationship between geometrical variation of atherosclerotic arteries and flow resistance, *Proceedings of the International Federation for Medical and Biological Engineering and the 12th International Conference on Biomedical Engineering (12th ICBME 2005),* Singapore, **12**, Article No. 3A5–01.

# List of Symbols

| Notation | Description |
|---|---|
| $B_0$ | Static magnetic field |
| $B_1$ | Magnetic field at right angles to $B_0$ |
| $M_z$ | Net magnetisation in longitudinal alignment with $B_0$ |
| $\mu_m$ | Nuclear magnetic moment in an applied magnetic field $B_0$ |
| $\Delta E$ | Energy difference between the two spin states |
| $g$ | Lande g-factor |
| $\hbar$ | Bohr magneton constant |
| $E$ | Energy of a RF photon |
| $h$ | Plank's constant |
| $\nu$ | Frequency of a RF photon |
| $x, y, z$ | Image plane coordinate system |
| $t$ | Time of first exposure |
| $\delta t$ | Exposure time delay |
| $p$ | Orientation index of image set |
| $I$ | Image intensity field of first exposure |
| $J$ | Image intensity field of second exposure |
| $\epsilon$ | Higher order terms |
| $\vec{v}$ | Motion of a point feature in space |
| $\nabla I$ | Intensity spatial gradient |
| $\Omega$ | Interrogation spatial region |
| $\tau_D$ | User specified threshold |
| $\vec{w}$ | Optical flow interrogation window size |
| $\vec{d}$ | Intensity image displacement |
| $L$ | Level number of the image pyramid |
| $n_x$ | Image width |
| $n_y$ | Image height |
| $M$ | Number of rows |
| $N$ | Number of columns |

| Notation | Description |
|---|---|
| $\omega(r)$ | Angular velocity of vortex |
| $v_\theta(r)$ | Tangential velocity of vortex |
| $\Gamma$ | Circulation of vortex |
| $a$ | Characteristic core radius |
| $r$ | Radius from vortex core |
| $\theta$ | Angle of vortex rotation |
| $W$ | Pyramidal optical flow sampling window size |
| $W_v$ | Velocity inteerogation window size |
| $E_{\text{contour}}$ | Energy function of active contour |
| $E_{\text{int}}$ | Internal energy function of active contour |
| $E_{\text{ext}}$ | External energy function of active contour |
| $F_{\text{int}}$ | Internal force of active contour |
| $F_{\text{ext}}$ | External force of active contour |
| $\alpha$ | Tension of active contour deformation |
| $\beta$ | Rigidity of active contour deformation |
| $P$ | Potential associated with the external forces |
| $X, Y, Z$ | Image plane grid system |
| $T$ | Image time grid |
| $v^{\text{Axial}}$ | Two-dimensional velocity grid in axial orientation |
| $v^{\text{Sagittal}}$ | Two-dimensional velocity grid in sagittal orientation |
| $v^{\text{Coronal}}$ | Two-dimensional velocity grid in coronal orientation |
| $V$ | Three-dimensional velocity grid system |
| $V_R$ | Resultant vector magnitude |
| $\omega$ | Vorticity of fluid |
| $\omega_{\text{Abs}}$ | Magnitude value of vorticity |
| $\omega_{\text{Dir}}$ | Polarised value of vorticity |
| $\omega_N$ | Ratio of $\omega_{\text{Dir}}$ to $\omega_{\text{Abs}}$ |
| $\Phi$ | Shear strain rate of fluid |
| $\Psi$ | Normal strain rate of fluid |
| $\mu$ | Mean of histogram |
| $m$ | Median of histogram |
| $\overline{\omega}_\mu$ | Mean of vorticity map |

| Notation | Description |
|---|---|
| $\overline{\omega}_m$ | Median of vorticity map |
| $\overline{\sigma}_\mu$ | Standard deviation from mean of vorticity map |
| $\overline{\sigma}_m$ | Standard deviation from median of vorticity map |
| $\langle\overline{\omega}_\mu\rangle$ | Temporal average of $\overline{\omega}_\mu$ values |
| $\langle\overline{\omega}_m\rangle$ | Temporal average of $\overline{\omega}_m$ values |
| $\langle\overline{\sigma}_\mu\rangle$ | Temporal average of $\overline{\sigma}_\mu$ values |
| $\langle\overline{\sigma}_m\rangle$ | Temporal average of $\overline{\sigma}_m$ values |
| $\rho$ | Reliability of measurement |
| $\gamma$ | Ratio of true vorticity grid variance to a measured one |
| $\Lambda_s$ | Vorticity grid of resolution $s$ |
| $\Delta$ | Normalised error function of two vorticity grids |
| $p_s$ | Pixel spacing |
| $t_s$ | Trigger time interval |
| $S$ | Slice thickness |
| $p_k$ | Percentage of pixels in segmented flow map |
| $A$ | Percentage area of region |
| $c_j$ | Data cluster centroid with label $j$ |
| $G_j$ | Data cluster group based on $c_j$ |
| $D$ | Discrimination of spatial separation during data clustering |
| $n_t$ | Time frame index |

# Abbreviations

| | | |
|---|---|---|
| A-P | Anterior-Posterior | 36 |
| F-H | Foot-Head | 36 |
| 2C | 2-chamber | 32 |
| 3C | 3-chamber | 32 |
| 4C | 4-chamber | 32 |
| SA | Short axis | 32 |
| LVOT | Left ventricular outflow tract view | 32 |
| HLA | Horizontal long axis | 32 |
| ROI | Region of interest | 6, 89, 288 |
| CW | Clockwise | 162, 229 |
| CCW | Counter-clockwise | 162, 229 |
| RA | Right atrium | 32, 205 |
| LA | Left atrium, Long axis | 32, 205 |
| RV | Right ventricle | 32 |
| LV | Left ventricle | 32 |
| AS | Anterior septum | 32 |
| IS | Inferior septum | 32 |
| SD | Septal defect | 11 |
| ASD | Atrial septal defect | 204, 213 |
| ASO | Atrial septal occlusion | 204, 205, 211 |
| FOV | Field of view | 59, 60 |
| OF | Optical flow | 324 |
| CFD | Computational fluid dynamics | 8 |
| ECG | Electrocardiogram | 6, 31, 56, 148, 161 |
| CT | Computed tomography | xi, 10, 204, 210 |
| PET | Positron emission tomography | xi, 204 |
| SPECT | Single photon emission computed tomography | xi, 204 |
| NMR | Nuclear magnetic resonance | 24, 26 |
| MRI | Magnetic resonance imaging | 38, 238, 255 |
| CMRI | Cardiac magnetic resonance imaging | xi, 204 |
| PCMRI | Phase contrast magnetic resonance imaging | 3 |

| | | |
|---|---|---|
| MRIV | Magnetic resonance image velocimetry | 5, 13, 15 |
| MRV | Magnetic resonance velocimetry | 5 |
| MRA | Magnetic resonance angiography | 245 |
| FID | Free induction decay | 28 |
| T1W | $T_1$ weighted | 29 |
| T2W | $T_2$ weighted | 29 |
| TE | Echo time | 29 |
| TR | Repetition time | 29 |
| PDW | Proton density weighted | 29 |
| SSFP | Steady state free precession | 29, 219, 245, 284 |
| GCFP | Global coherent free precession | 245 |
| SNR | Signal-to-noise ratio | 6 |
| RF | Radio frequency | 24, 26 |
| VENC | Velocity encoding | 5, 35, 219 |
| PIV | Particle image velocimetry | 5, 15, 243, 323 |
| API | Application Programming Interface | 252 |
| MIP | Medical image processing | 251 |
| IIL | Intel imaging library | 252 |
| IPP | Intel integrated performance primitives | 252 |
| DICOM | Digital imaging and communications in medicine | 60, 190 |
| True FISP | Fast imaging with steady-state free precession | 29, 284 |
| MEDFLOVAN | Medical flow visualisation and analysis | 255 |

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