

Experimental Mechanics of Fluids and Materials

Project leader: Tino Ebbers

Project period: 2009-2015

Summary

Traditional experimental fluid dynamics (XFD) techniques for measuring the velocity in a point (Laser Doppler Anemometry, LDA) or in a plane (Particle Image Velocimetry, PIV) are relatively time consuming and restricted to specific phantom designs. A new technique which is emerging as a valuable tool for the analysis of fluid dynamics is magnetic resonance imaging. Originally, this technique allowed for the measurement of the mean velocity in a small volume element, similar to PIV and LDA but within a shorter measurement time and with less limitation in terms of phantom design. Recently, the MRI technique has been extended to the measurement of the distribution of the velocities within the volume element, which allows for the quantification of for example turbulence intensity. Additionally, magnetic resonance imaging has the ability to measure displacement. This allows for experimental three-dimensional three-directional assessment of the deformation of soft materials. These new kinds of data open a new world with possibilities and challenges related to measurements, post processing and visualization.

Main Scientific Results

- An efficient MRI technique for time-resolved three-dimensional three-directional velocity measurements with spiral k-space sampling has successfully been implemented and evaluation.
- A generalized MRI framework for the quantification of any moment of arbitrary velocity distributions has been developed. This framework is based on the fact that moments in the function domain (velocity space) correspond to differentials in the Fourier transform domain ($k(v)$ -space). Based on this framework, we developed a technique to assess turbulent kinetic energy in the beating heart and different flow models.
- A prototype of a MRI-based industrial water tunnel has been developed and tested. The prototype allows three-dimensional assessment of velocity and turbulent kinetic of different flow phenomena.
- A semi-automatic approach for quantification and visualization of ventricular blood flow has been developed. This technique has lead to new insights into left ventricular and right ventricular blood flow in health and disease.

- An automatic registration-based assessment of 4D flow MRI data has been developed. It allows automatic analysis of 4D flow MRI data in the large vessels. The segmentation allows for automatic analysis and visualization of cardiovascular 4D flow MRI data, and in depth studies of blood flow using CFD simulations.
- A promising approach to included wall motion in CFD simulations of vascular blood has been developed. This approach circumvents all assumptions associated by fluid-structure interaction approaches by directly measuring the wall motion with MRI, and then prescribing the extracted wall motion directly in a numerical solver. Additional computational cost of this approach is only 17%, compared to a rigid wall simulation.
- A novel technique for assessment of heart muscle deformation has been developed. This technique allows for three-dimensional three-direction measurement of tissue displacement.
- We have developed a novel approach for quantification of the T1 and T2 MRI relaxation times in the heart muscle. T1 and T2 has shown to provide important information in cardiac diagnostics, but available methods generally demand a long breath hold to measure either T1 or T2 in a single 2D slice. Using an improved pulse sequence and a novel data analysis based on iterative simulation of the relaxation, we are able to map T1 and T2 simultaneously in 3D volume covering the whole left ventricular myocardium within a single breath hold of 15 heartbeats.

Degrees and promotions

2010 Tino Ebbers (PI) Associate Professor (lektor)

2011 Tino Ebbers (PI) Professor

Master projects

2009 Aidin Arbabi, “Investigating the Feasibility of Using PC-MRI Velocity Data to Estimate the Wall Shear Stress”

2012 Emre Kus “Estimation and visualization of relative pressure fields in the human heart from time resolved MRI flow data”

2014 Mattias Perkiö, “Assessment of Regional Pulse Wave Velocity in the Aorta by Using 4D Flow MRI”

2014 Catarina Tidbeck “Quantification of left ventricular blood flow using phase contrast magnetic resonance imaging”

Bachelor project work

2013 Richard Hellsberg, Simon Åkerblad, Tamara Kljajic, Tina Nikko “Development of a water tunnel system – for Implementation in MRI Scanners” LiU-IEI-RR-13/00172-SE

2013 Amanda Millinger Nylander, Mathias Brischetto, Joakim Hägglund, Jacob Bergvall, Patrik Sjögren, Elias Nilsson, Hunor Szasz, Johan Edén, “Conceptual Design of Water Tunnels for measurements in MRI scanners”, Liu-IEI-RR-13/00173-SE

Funded Staff

Initially, the seed funding has been used to cover part of the financing of the PI. When this part could be covered by other external funding, the CENIIT funding has mainly used

as seed financing for new promising projects. Therefore, during the course of this project, several persons have been partly or fully financed by this CENIIT project.

- Petter Dyverfeldt, PhD postdoc
- Jörg Schminder, MSc, PhD student
- Jonas Lantz, PhD postdoc
- Magnus Andersson, MSc PhD student

In several cases, this seed funding has resulted in promising preliminary results, which facilitated continuation of the project using funding from other external funding agencies.

Cooperation with industry

Within the course of this project, collaborations have been build up with industrial as well as clinical partners. The main industrial partners have been Philips Health Care considering development of new MRI acquisition strategies and Synthetic MRI considering T1 and T2 analysis of heart muscle tissue.

Contacts with other CENIIT projects

None

New Research Group

The PI has currently his own research group consisting of 1 research engineer, 3 PhD students, and 4 postdocs financed through external funding from the European Research council, the Swedish Research Council, and the Knut and Alice Wallenberg Foundation. The majority of the projects are direct continuations of the CENIIT project.

Publications

Refereed Journal Articles

1. Kihlberg J, Haraldsson H, Sigfridsson, A, Ebberts T, Engvall J. Clinical experience of strain imaging using DENSE for detecting infarcted cardiac segments, *J Cardiovasc Magn Reson*, 2015; 17:50.
2. Bustamante M, Petersson S, Eriksson J, Alehagen U, Dyverfeldt P, Carlhäll CJ, Ebberts T. Atlas-based Analysis of 4D flow CMR: Automated Vessel Segmentation and Flow Quantification. *J Cardiovasc Magn Reson* 2015; In Press.
3. Casas B, Lantz J, Dyverfeldt P, Ebberts T. 4D flow MRI-based pressure loss estimation in stenotic flows: evaluation using numerical simulations. *Magn Reson Med*. In press.
4. Andersson M, Lantz J, Ebberts T, Karlsson M. Quantitative Assessment of Turbulence and Flow Eccentricity in an Aortic Coarctation: Impact of Virtual Interventions. *Cardiovascular Engineering and Technology*. In press.
5. Petersson S, Dyverfeldt P, Sigfridsson A, Lantz, J, Carlhäll C-J and Ebberts T. Quantification of Turbulence and Velocity in Stenotic Flow Using Spiral 3D Phase-Contrast MRI. *Magnetic Resonance in Medicine*. In press.
6. Petersson S, Sigfridsson A, Dyverfeldt P, Carlhäll C-J and Ebberts T. Retrospectively gated intracardiac 4D flow MRI using spiral trajectories. *Magnetic Resonance in Medicine*. In press.
7. Eriksson J, Bolger AF, Carlhäll C-J, and Ebberts T. Spatial heterogeneity of four-dimensional relative pressure fields in the human left ventricle. *Magnetic Resonance in Medicine*. In press.

8. Zajac J, Eriksson J, Dyverfeldt P, Bolger AF, Ebbers T, Carlhäll C-J. Turbulent Kinetic energy in normal and myopathic left ventricles. *J Magn Reson Imaging*. In press.
9. Kvernby S, Marcel M J B, Haraldsson H, Carlhäll C-J, Engvall J and Ebbers T. Simultaneous three-dimensional myocardial T1 and T2 mapping in one breath hold with 3D-QALAS. *J Cardiovasc Magn Reson* 2014, 16:102.
10. Dyverfeldt P, Ebbers T, Länne T. Pulse Wave Velocity with 4D Flow MRI: Systematic Differences and Age-Related Regional Vascular Stiffness. *Magn Reson Imaging* 2014;32(10):1266–71.
11. Lantz J, Dyverfeldt P, Ebbers T. Improving Blood Flow Simulations by Incorporating Measured Subject-Specific Wall Motion. *Cardiovasc Eng Technol* 2014;5(3):261-9.
12. Zajac J, Eriksson J, Dyverfeldt P, Bolger AF, Ebbers T, Carlhäll C-J. Turbulent Kinetic Energy in Normal and Myopathic Left Ventricles. *J Magn Reson Imaging*; In Press
13. Lantz J, Ebbers T, Engvall J, Karlsson M. Numerical and Experimental Assessment of Turbulent Kinetic Energy in an Aortic Coarctation. *J Biomech* 2013;46(11):1851-8
14. Eriksson J, Bolger AF, Ebbers T and Carlhäll CJ. Four-Dimensional Blood Flow-Specific Markers of LV dysfunction in Dilated Cardiomyopathy. *Eur Heart J Cardiovasc Imaging*. 2013;14(5):417-424.
15. Rademakers F, Engvall J, Edvardsen T, Monaghan M, Sicari R, Nagel E, Zamorano J, Ukkonen H, Ebbers T, Di Bello V, et al. Determining Optimal Noninvasive Parameters for the Prediction of Left Ventricular Remodeling in Chronic Ischemic Patients. *Scand Cardiovasc J* 2013;47:329-334
16. Kindberg K, Haraldsson H, Sigfridsson A, Engvall J, Ingels NB, Ebbers T, Karlsson M. Myocardial Strains from 3D Displacement Encoded Magnetic Resonance Imaging. *BMC Medical Imaging*. 2012;12:9.
17. Sengupta PP, Pedrizzetti G, Kilner PJ, Kheradvar A, Ebbers T, Tonti G, Fraser AG, Narula J. Emerging Trends in CV Flow Visualization. *J Am Coll Cardiol Img*. 2012;5:305-316.
18. Kindberg K, Haraldsson H, Sigfridsson A, Sakuma H, Ebbers T, Karlsson M. Temporal 3D Lagrangian Strain from 2D Slice-Followed Cine DENSE MRI. *Clin Physiol Funct Imaging*. 2012 Mar;32(2):139-44.
19. Petersson S, Dyverfeldt P, Ebbers T. Assessment of the Accuracy of MRI Wall Shear Stress Estimation using Numerical Simulations. *J Magn Reson Imaging*. In press.
20. Sigfridsson A, Petersson S, Carlhäll CJ, Ebbers T. 4D Flow MRI using Spiral Acquisition. *Magnetic Resonance in Medicine*. In press.
21. Arzani A, Dyverfeldt P, Ebbers T, Shadden SC. In vivo Validation of Numerical Prediction for Turbulence Intensity in an Aortic Coarctation. *Annals of Biomedical Engineering*. In press.
22. Björck HM, Renner J, Shohreh Maleki S, Nilsson SFE, Kihlberg J, Folkersen L, Karlsson M, Ebbers T, Eriksson P, Länne T. Characterization of Shear-Sensitive Genes in the Normal Rat Aorta Identifies Hand2 as a Major Flow-Responsive Transcription Factor. *PLOS ONE* 2012;7(12):e52227.

23. Fredriksson AG, Zajac J, Eriksson J, Dyverfeldt P, Bolger AF, Ebbers T, Carlhäll CJ. 4-D Blood Flow in the Human Right Ventricle. *Am J Physiol Heart Circ Physiol* 2011;301:H2344-H2350.
24. Modin D, Renner J, Gårdhagen R, Ebbers T, Länne T, Karlsson M. Evaluation of Aortic Geometries created by MRI Data in Healthy Volunteers. *Clinical Physiology and Functional Imaging* 2011;31, pp485-491,
25. Eriksson J, Dyverfeldt P, Engvall J, Bolger AF, Ebbers T, Carlhäll CJ. Quantification of Pre-systolic Blood Flow Organization and Energetics in the Human Left Ventricle. *Am J Physiol Heart Circ Physiol*, 2011;300:H2135-H2141.
26. Haraldsson H, Sigfridsson A, Sakuma H, Engvall J, Ebbers T. Influence of the FID and Off-resonance Effects in DENSE MRI. *Magnetic Resonance in Medicine*, 2011;65:1104-1112.
27. Åström Aneq M, Nylander E, Ebbers T, Engvall. Determination of Right Ventricular Volume and Function using Multiple Axially Rotated MRI Slices. *Clinical Physiology and Functional Imaging*, 2011. Early view.
28. Rolf MP, Hofman MBM, Gatehouse PD, Bloch KM, Heymans MW, Ebbers T, Graves MJ, Totman JJ, Werner B, Rossum ACV, Kilner PJ, Heethaar RM. Sequence Optimization to Reduce Velocity Offsets in Cardiovascular Magnetic Resonance Volume Flow Quantification - A Multi-Vendor Study. *J Cardiovasc Magn Reson*, 2011;13:18.
29. Dyverfeldt P, Sigfridsson A, Knutsson H, Ebbers T. A Novel MRI Framework for the Quantification of Any Moment of Arbitrary Velocity Distributions. *Magnetic Resonance in Medicine*, 2011;65:725-731.
30. Dyverfeldt P, Kvitting JPE, Carlhäll CJ, Boano G, Sigfridsson A, Hermansson U, Bolger AF, Engvall J, Ebbers T. Hemodynamic Aspects of Mitral Regurgitation Assessed by Generalized Phase-Contrast Magnetic Resonance Imaging. *J Magn Reson Imaging*, 2011;33:582-588.
31. Markl M, Kilner PJ, Ebbers T. Comprehensive 4D Velocity Mapping of the Heart and Great Vessels by Cardiovascular Magnetic Resonance. *J Cardiovasc Magn Reson*, 2011;13(1):7.
32. Ebbers T. Flow Imaging: Cardiac Applications of 3D Cine Phase-Contrast MRI. *Current Cardiovascular Imaging Reports*, 2011;4(2):127-133
33. Sigfridsson A, Haraldsson H, Ebbers T, Knutsson H, Sakuma H. In-Vivo SNR in DENSE MRI; Temporal and Regional Effects of Field Strength, Receiver Coil Sensitivity and Flip Angle Strategies. *Magn Reson Imaging*, 2011;29:202-208.
34. Fredriksson AG, Zajac J, Eriksson J, Dyverfeldt P, Bolger AF, Ebbers T, Carlhäll J. 4D Blood Flow in the Human Right Ventricle. *Am J Physiol Heart Circ Physiol*. In Press.
35. Modin D, Renner J, Gårdhagen R, Ebbers T, Länne T, Karlsson M. Evaluation of Aortic Geometries created by MRI Data in Healthy Volunteers. *Clinical Physiology and Functional Imaging*. In Press.
36. Petersson S, Dyverfeldt P, Gårdhagen R, Karlsson M, Ebbers T. Simulation of Phase Contrast MRI of Turbulent Flow. *Magnetic Resonance in Medicine* 2010;64(4):1039-1046.
37. Sigfridsson A, Haraldsson H, Ebbers T, Knutsson H, Sakuma H. Single Breath Hold Multiple Slice DENSE MRI, *Magnetic Resonance in Medicine* 2010;63(5):1411-14.

38. Kvitting JPE, Dyverfeldt P, Sigfridsson A, Franzén S, Wigström L, Bolger AF, Ebbers T. In Vitro Assessment of Flow Patterns and Turbulence Intensity in Prosthetic Heart Valves Using Generalized Phase-Contrast Magnetic Resonance Imaging. *J Magn Reson Imaging* 2010;31(5):1075-80.
39. Eriksson J, Carlhäll CJ, Dyverfeldt P, Engvall J, Bolger AF, Ebbers T. Semi-automatic Quantification of 4D Left Ventricular Blood Flow. *J Cardiovasc Magn Reson* 2010;12(1):9.
40. Dyverfeldt P, Gårdhagen R, Sigfridsson A, Karlsson M, Ebbers T. On MRI Turbulence Quantification. *Magn Reson Imaging* 2009;27(7):913-922.
41. Kvitting JPE, Dyverfeldt P, Carlhäll C, Sigfridsson A, Bolger AF, Ebbers T, Engvall J. Magnetresonanstomografi ger unika möjligheter att bedöma blodflödet och dess inverkan på hjärt- och kärlsystemet [in Swedish]. *Läkartidningen* 2009;106(30-31):1901-1904.
42. Ebbers T and Farneback G. Improving computation of cardiovascular relative pressure fields from velocity MRI. *J Magn Reson Imaging* 2009;30(1):54-61.
43. Renner J, Gårdhagen R, Heiberg E, Ebbers T, Länne T, Karlsson M. Towards Subject Specific WSS Estimation in the Human Aorta - MRI and CFD Velocity Comparison, *WSEAS Transactions on Biology and Biomedicine* 2009;3(6):49-57.

Refereed Conference contribution

44. Lantz J, Carlhäll, CJ, Ebbers T. Quantification of Helical Flow Patterns in Left Ventricles of Healthy Subjects and Patients with Dilated Cardiomyopathy. 2015 Summer Biomechanics, Bioengineering and Biotransport Conference. Salt Lake City, USA; 2015
45. Loudon M, Bissell MM, Dyverfeldt P, Carlhall CJ, Ebbers T, Hess AT, Prendergast PD, Neubauer S, Myerson SG. Turbulent kinetic energy in the ascending aorta is greater in bicuspid than tricuspid aortic valve stenosis. SCMR/EuroCMR Joint Scientific Sessions. Nice; 2015.
46. Kvernby S, Warntjes M, Carlhall CJ, Engvall JE, Ebbers T. Single breath-hold 3D mapping of T1 and T2 relaxation times with 3D-QALAS-feasibility in patients. SCMR/ISMRM jointly sponsored workshop on Myocardial Tissue Characterization with MR Relaxometry: Principles and Emerging Methods. February 4-5, 2015 Nice, France.
47. Fredriksson AG, Svalbring E, Eriksson J, Dyverfeldt P, Alehagen U, Engvall JE, Ebbers T, Carlhäll C-J. 4D flow CMR can detect subtle right ventricular dysfunction in primary left ventricular disease. SCMR/EuroCMR Joint Scientific Sessions. Nice; 2015.
48. Stoll V, Hess AT, Bissell MM, Eriksson J, Dyverfeldt P, Ebbers T, Myerson SG, Carlhäll C-J, Neubauer S. Reproducibility and variability of left ventricular 4D flow in healthy volunteers. SCMR/EuroCMR Joint Scientific Sessions. Nice; 2015.
49. Bustamante M, Dyverfeldt P, Petersson S, Eriksson J, Carlhäll C-J, Ebbers T. Automatic multi-vessel volume flow calculation with 4D flow CMR. SCMR/EuroCMR Joint Scientific Sessions. Nice; 2015.
50. Eriksson J, Bolger AF, Ebbers T and Carlhäll C-J. Left ventricular hemodynamic forces are altered in patients with dilated cardiomyopathy. SCMR/EuroCMR Joint Scientific Sessions. Nice, 2015.

51. Bustamante M, Carlhäll CJ, Dyverfeldt P, Ebbers T. Automatic multi-vessel volume flow calculation from 4D flow MRI. IEEE Medical imaging Summer School. Sicily, Italy, 2014.
52. Casas Garcia B, Dyverfeldt P, Lantz J, Ebbers T. Evaluation of MRI-based irreversible pressure drop estimation in stenotic flow. Magnetic Resonance Angiography, 26th Annual International Conference. September 17-19, 2014, Rome, Italy
53. Lantz J, Ebbers T. Incorporating MRI-Measured Arterial Wall Motion in Numerical Simulations. 7th World Congress of Biomechanics (WCB 2014). July 6-11, 2014, Boston, USA
54. Eriksson J, Bolger AF, Ebbers T, Carlhäll C-J. Spatial Heterogeneity of Left Heart 4D Relative Pressures. Svensk förening för klinisk fysiologi, höstmöte. Linköping, Sweden, 2014.
55. Kvernby S, Warntjes M, Carlhäll C-J, Engvall J and Ebbers T. Myocardial T1-and T2 mapping with 3D-QALAS: comparison with MOLLI and Multi-Echo T2. Svensk förening för klinisk fysiologi, höstmöte. Linköping, Sweden, 2014.
56. Fredriksson A, Svalbring E, Eriksson J, Dyverfeldt P, Alehagen U, Engvall J, Ebbers T, Carlhäll C-J. 4D flow MRI can detect mild impairment of right ventricular function in primary left ventricular disease. Annual meeting of the Swedish Cardiovascular Association. Malmö, Sweden, 2014.
57. Kvernby S, Warntjes M, Carlhäll C-J, Engvall J and Ebbers T. Comparing 3D-QALAS with MOLLI and Multi-Echo for in-vivo myocardial T1 and T2 quantification. 23rd Int. Soc. Magn. Reson. Med. Milan, Italy. 2014.
58. Petersson S, Dyverfeldt P, Sigfridsson A, Carlhäll CJ, Ebbers T. Comparison between Cartesian and Spiral MR flow imaging of stenotic flow. 23rd Int. Soc. Magn. Reson. Med. Milan; 2014.
59. Kvernby S, Warntjes M, Carlhäll C-J, Engvall J and Ebbers T. 3D-Quantification using an interleaved Look-Locker acquisition sequence with T2-prep pulse (3D-QALAS). Soc. Cardiovascular Magn. Reson. 17th Scientific Sessions. New Orleans, LA, USA; 2014.
60. Zajac J, Eriksson J, Dyverfeldt P, Ebbers T, Carlhäll CJ. Turbulent kinetic energy from CMR identifies disturbed diastolic flow in myopathic left ventricles. Soc. Cardiovascular Magn. Reson. 16th Scientific Sessions. San Francisco, CA, USA; 2013.
61. Eriksson J, Bolger AF, Ebbers T, Carlhäll CJ. Spatial Heterogeneity of Intracardiac 4D Relative Pressure Fields During Diastole. Soc. Cardiovascular Magn. Reson. 16th Scientific Sessions. San Francisco, CA, USA; 2013.
62. Petersson S, Sigfridsson A, Carlhäll CJ, Ebbers T. Retrospectively gated intracardiac 4D flow CMR using spiral trajectories. Soc. Cardiovascular Magn. Reson. 16th Scientific Sessions. San Francisco, CA, USA; 2013.
63. Eriksson J, Bolger AF, Ebbers T, Carlhäll CJ. Equal Stroke Volumes, Different Costs: Left Ventricular 4D Flow in Normal and Failing Hearts. *Soc Cardiovascular Magn Reson*. 15th Scientific Sessions, Orlando, 2012
64. Kihlberg J, Haraldsson H, Ebbers T, Engvall J. Myocardial Deformation (Strain) Measured by DENSE Reliably Detects Myocardial Scar. *Soc Cardiovascular Magn Reson*. 15th Scientific Sessions, Orlando, 2012

65. Haraldsson H, Kihlberg J, Engvall J, Ebberts T. Segmental Variation of Myocardial Deformation in Patients with Suspected Ischemic Heart Disease. *Soc Cardiovascular Magn Reson. 15th Scientific Sessions*, Orlando, 2012
66. Petersson S, Dyverfeldt P, Ebberts T. Accuracy of MRI Wall Shear Stress Estimation. *Soc Cardiovascular Magn Reson. 15th Scientific Sessions*, Orlando, 2012
67. Arzani A, Dyverfeldt P, Ebberts T, Shadden SC. In Vivo Validation of Computational Quantification of Turbulence Intensity in an Aortic Coarctation. *Workshop on Computer Methods for Cardiovascular Devices*, 2011
68. Eriksson J, Dyverfeldt P, Engvall J, Bolger AF, Ebberts T, Carlhäll CJ. Diastolic Preparation for Left Ventricular Ejection - A Marker of Inefficiency of Failing Heart. *SCMR/EuroCMR Joint Scientific Sessions*. Nice; 2011
69. Carlhäll CJ, Fredriksson AG, Zajac J, Eriksson J, Dyverfeldt P, Engvall J, Bolger AF, Ebberts T. Visualization and Quantification of 4D Blood Flow Distribution and Energetics in the Right Ventricle. *SCMR/EuroCMR Joint Scientific Sessions*, Nice; 2011
70. Dyverfeldt P, Sigfridsson A, Knutsson H, Ebberts T. MR Flow Imaging Beyond the Mean Velocity: Estimation of the Skew and Kurtosis of Intravoxel Velocity Distributions. *19th Int. Soc. Magn. Reson. Med*, Montreal 2011
71. Haraldsson H, Sigfridsson A, Kihlberg J, Engvall E, Ebberts T. Kvantitativ bedömning av hjärtfunktion med MRI. *Medicinteknikdagarna*, Linköping 2011
72. Petersson S, Sigfridsson A, Ebberts T. 4D flödes MR mätning med spiral-insamling. *Medicinteknikdagarna*, Linköping, 2011
73. Eriksson J, Dyverfeldt P, Engvall J, Bolger AF, Ebberts T, Carlhäll CJ. Pre-Systolic Preparation for Left Ventricular Ejection - A Marker of Inefficiency of the Failing Heart. *Annual Meeting of the Swedish Cardiovascular Association*, Örebro, 2011
74. Fredriksson AG, Zajac J, Eriksson J, Dyverfeldt P, Engvall J, Bolger AF, Ebberts T, Carlhäll CJ. Assessment of Multidimensional Blood Flow Patterns and Energetics in the Right Ventricle. *Annual Meeting of the Swedish Cardiovascular Association*, Örebro,
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79. Sigfridsson A, Haraldsson H, Ebberts T, Knutsson H, Sakuma H. SNR Evaluation of 32 Channel Cardiac Coils in DENSE MRI at 1.5 and 3T. *18th Int. Soc. Magn. Reson. Med*. Stockholm; 2010

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81. Eriksson J, Dyverfeldt P, Envall J, Bolger AF, Carlhäll CJ, Ebbers T. Validation of 4D Left Ventricular Blood Flow Assessment Using Pathlines. *18th Int. Soc. Magn. Reson. Med.* Stockholm; 2010
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89. Dyverfeldt P, Kvitting JPE, Carlhäll CJ, Boano G, Sigfridsson A, Hermansson U, Bolger AF, Engvall J, Ebbers T. Potential Effects of Intraatrial Hemodynamics on the Pulmonary Venous Return in Mitral Regurgitation. *ISMRM Workshop on Cardiovascular Flow, Function and Tissue Mechanics.* Sintra; 2009
90. Sigfridsson A, Haraldsson H, Ebbers T, Knutsson H, Sakuma H. In vivo SNR in DENSE MRI; temporal and regional effects of field strength, receiver coil sensitivity, and flip angle strategies. *ISMRM Workshop on Cardiovascular Flow, Function and Tissue Mechanics.* Sintra; 2009
91. Dyverfeldt P, Kvitting JPE, Carlhäll CJ, Boano G, Sigfridsson A, Hermansson U, Bolger AF, Engvall J, Ebbers T. MRI Turbulence Measurement in Mitral Valve Regurgitation. *Röntgenveckan.* Jönköping; 2009
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