SCMR
Society for Cardiovascular Magnetic Resonance

ISMRM
ONE COMMUNITY FOR CLINICIANS AND SCIENTISTS
International Society for Magnetic Resonance in Medicine

SCMR/ISMRM Jointly Sponsored Workshop

presented by Flow and Motion Quantitation and Cardiac Study Groups

Exploring New Dimensions of Cardiovascular Flow and Motion

February 1-2, 2012

Marriott World Center, Orlando, FL

www.SCMR.org

www.ISMRM.org

Exploring New Dimensions of Cardiovascular Flow and Motion

Welcome

Dear Colleagues and Friends,

On behalf of the Organizing Committee, we wish to welcome you to Orlando for this workshop presented by the SCMR in collaboration with the ISMRM Flow & Motion Quantitation and Cardiac Imaging Study Groups. This joint effort of the SCMR and ISMRM is the first of its kind, and we hope it will lead to additional efforts by both societies to combine forces where there is common interest in research and education in cardiovascular imaging. As the workshop title: "Exploring New Dimensions of Cardiovascular Flow and Motion" indicates, a program of two days of invited and proffered talks plus poster presentations has been designed to explore the current state-of-the-art in MRI measurement of flow and motion.

We expect there to be interesting topics presented for physicists and physicians alike. The program for Day One will focus on blood flow, beginning with a keynote lecture by Dr. Wilmer Nichols, author of the seminal text on hemodynamics: "McDonald's Blood Flow in Arteries: Theoretical, Experimental and Clinical Principles." The day will continue with presentations on blood flow starting with the intracranial vessels of the head, down to the peripheral vessels of the lower limbs, and everything in between. The day will conclude with a wine and cheese reception to provide attendees an opportunity to view the posters and meet with friends, old and new.

On Day Two, the program will focus on quantitative imaging of cardiac motion, myocardial tissue mechanics, and intra-cardiac flow. The day will kick-off with a keynote lecture by Dr. Philip Kilner, highly regarded for over two decades of research on the imaging and pathophysiology of congenital and valvular heart disease. The program will continue with a series of presentations on emerging methods for quantitative characterization of cardiac function and myocardial mechanics. A lunch session has been organized during which several of the vendors will provide overviews of their latest advances in cardiovascular quantitative imaging and post-processing. A number of the vendors will also have displays setup throughout the workshop and will have representatives available to discuss their latest product offerings.

We hope that these two days will provide an exciting opportunity for you to explore new aspects of quantitative imaging of flow and motion, and to engage in some fun and interesting discussion of these topics with your colleagues from around the world.

Thank you to all the presenters, organizers, sponsors and attendees for the effort and support put forth to make this meeting happen. We hope you enjoy the meeting!

Michael Markl, PhD
Program Chair

Orlando Simonetti, PhD
Program Co-Chair

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Overview

The purpose of the workshop is to educate physicians about MRI techniques with respect to characterization of tissue mechanics, non-contrast enhanced MRA and imaging of flow and motion in different regions of the human body and thereby help improving patient care. It is expected that the gained knowledge will improve the application of cardiac as well as flow and motion sensitive MRI by improving the competence and performance of physicians. In addition, the workshop will provide a forum for disseminating information related to state-of-the-art MRI techniques regarding imaging of cardiovascular function.

The interdisciplinary faculty and audience will ensure that technologies and methodologies are communicated and shared between physicists, bioengineers, physiologists, radiologists, cardiologists, vascular surgeons for the purpose of improving patient care.

Target Audience

This workshop is designed for:

- MR engineers or physicists, bioengineers, physiologists, radiologists, cardiologists, vascular surgeons;
- Medical, biological and industrial researchers with an interest in noninvasive studies of tissue mechanics, cardiovascular flow, motion, and novel MR imaging techniques
- Experienced researchers seeking to learn about the current state of the field, and actively engaged in research in this or related fields
- Less experienced researchers seeking to understand the capabilities and limitations of MRI methods, and those considering getting involved, such as clinicians considering use of these techniques in their practices
- Students are encouraged to participate

Educational Objectives

At the conclusion of the educational activity, attendees should be better able to:

- Identify methods for the acquisition of comprehensive information of flow and motion in the different parts of the human body
- Describe and select applications of flow and motion sensitive MRI techniques for the assessment of vascular hemodynamics and tissue properties in the head, neck, heart and great vessels, abdomen, and peripheral vasculature
- Discuss clinical applications and future possibilities of MR flow studies, tissue mechanics studies, and the integration of MRI and numerical modeling
- Explain, compare, and select methods used to acquire and analyze regional tissue mechanics with MRI
- Describe and explain differences of methods for non-contrast enhanced MR angiography for different vascular regions in the human body

Continuing Medical Education Credits

The International Society for Magnetic Resonance in Medicine (ISMRM) is accredited by the Accreditation Council for Continuing Medical Education (ACCME) to sponsor continuing medical education for physicians. ISMRM takes responsibility for the content, quality, and scientific integrity of this CME activity.

ISMRM designates this educational activity for a maximum of 13 AMA PRA Category 1 Credits™. Physicians should only claim credit commensurate with the extent of their participation in the activity.

SCMR and ISMRM gratefully acknowledge the support of this workshop from our industry supporters:

Philips Healthcare • Computational Engineering International (CEI) • GyroTools LLC
Siemens Healthcare • Shelley Medical Imaging Technologies • Toshiba America Medical Systems

Wednesday, February 1, 2012

Flow and Motion in the Human Body from Head to Toe: State-of-the Art and Emerging Applications

8:15 am – 8:30 am **Welcome and Introduction**
Crystal Ballroom J2

8:30 am – 9:00 am **Keynote Lecture**
Moderators: Michael Markl, PhD, Northwestern University
Orlando Simonetti, PhD, The Ohio State University

Physiology of Blood Flow and Vessel Walls
Wilmer W. Nichols, PhD, University of Florida

9:00 am – 10:30 am **Session 1 - Head**
Moderators: Noam Alperin, PhD, University of Miami
David Saloner, PhD, University of California – San Francisco

9:00 am **Intracranial Blood Flow and Aneurysms: In-vivo Flow and Analysis and CFD**
Vitaliy Rayz, PhD, University of California – San Francisco

9:25 am **CSF Flow: Acquisition Strategies and Applications**
Victor Haughton, MD, University of Wisconsin

9:50 am **W1 4D MR Imaging of Cerebrospinal Fluid Flow in Chiari I Malformation With and Without Syringomyelia and Flow Changes After Decompressive Surgery**
Jan Kröger, University Hospital of Muenster

10:02 am **W2 Characterization of Cerebral Aneurysms Using 4D FLOW MRI**
Susanne Schnell, PhD, Northwestern University

10:14 am **W3 4D Phase Contrast MRI in Intracranial Aneurysms: A Comparison with Patient-specific Computational Fluid Dynamics with Temporal and Spatial Velocity Boundary Conditions as Measured with 3D Phase Contrast MRI**
Pim van Ooij, MSc, Academic Medical Center

10:30 am **Refreshment Break**
Crystal Ballroom K-L-M

11:00 am – 12:00 pm **Session 2 - Neck**
Moderators: Tosiaki Miyati, PhD, DMSc, Kanazawa University
John Oshinski, PhD, Emory University Hospital

11:00 am **Carotid Plaques: In-vivo Characterization and Computational Fluid Dynamics**
David Saloner, PhD, University of California – San Francisco

11:25am **W4 Respiratory Effects on Phase Contrast Imaging of the Jugular Vein**
Eric Schrauben, BS, University of Wisconsin

11:37am **W5 Vectorial Wall Shear Stress Calculations in Vessel Structures Using 4D PC-MRI**
Wouter Potters, BSc, Academic Medical Center

11:49am **W6 Accuracy of MRI Wall Shear Stress Estimation**
Sven Petersson, Linköping University

12:00 pm – 1:20 pm **Lunch (on own)**

2:30 pm – 3:00 pm **Session 3 - Great Vessels**
Moderators: Debiao Li, PhD, Cedars Sinai Medical Center; Oliver Wieben, PhD, University of Wisconsin

1:20 pm **Blood Flow in the Aorta: 3D Visualization and Quantitative Analysis**
Tino Ebbers, PhD, Linköping University

1:45 pm **Flow MRI and Modeling in Congenital Heart Disease**
Mark Fogel, MD, Children's Hospital of Philadelphia

2:10 pm **W7 Flow-sensitive Four-dimensional Magnetic Resonance Imaging Facilitates the Quantitative Analysis of Systemic-to-pulmonary Collateral Flow in Patients with Univentricular Hearts**
Sarah Nordmeyer, MD, Deutsches Herzzentrum Berlin

2:22pm **W8 Quantification of Caval Contribution to Flow in the Right and Left Pulmonary Artery of Fontan Patients with 4D Flow MRI**
Pablow Bächler, Pontificia Universidad Católica de Chile

2:36 pm **W9 Assessment of Energy Loss Across Aortic Valves Using Accelerated CMR Multi-point Flow Measurements**
Christian Binter, MSc, Unversity and ETH Zurich

2:48 pm **W10 Four-dimensional Velocity Encoded MRI Improves Blood Flow Quantification in Patients with Semilunar Valve Stenosis**
Sarah Nordmeyer, MD, Deutsches Herzzentrum Berlin

3:00 pm – 3:30 pm **Refreshment Break/Exhibits/Posters**
Crystal Ballroom K-L-M

3:30 pm – 4:30 pm **Session 4 - Abdomen**

Moderators: James Carr, MD, PhD, Northwestern University;
Smita Sampath, PhD, Johns Hopkins University

3:30 pm **Comprehensive Characterization of Renal Arteries**

Oliver Wieben, PhD, University of Wisconsin

3:55 pm **W11 Quantification of Blood Flow in the Portal Circulation before and after an Intervention**

Alejandro Roldán-Alzate, PhD, University of Wisconsin

4:07 pm **W12 Lower Extremity Amputation Increases Oscillatory Flow in the Infrarenal Aorta: A New Potential Risk Factor for Abdominal Aortic Aneurysm Development**

Alexander Smolensky, MD, Emory University School of Medicine

4:19 pm **W13 Repeatability and Internal Consistency of Abdominal 2D and 4D PC MR Flow Measurements**

Andrew Wentland, University of Wisconsin - Madison

4:35 pm – 5:15 pm **Session 5 - Peripheral Vasculature**

Moderator: Christopher Macgowan, PhD, Hospital for Sick Children

4:35 pm - 5:00 pm **Flow-sensitive MRI and Non-contrast Enhanced Peripheral MRA**

James Carr, MD, Northwestern University

5:00 pm - 5:12 pm **W14 FourFlow - Open Source Code Software for Quantification and Visualization of Time-resolved Three-Directional Phase Contrast Magnetic Resonance Velocity Mapping**

Einar Heiberg, PhD, Lund University

5:15 pm – 7:00 pm **Poster & Wine and Cheese Reception**

Crystal Ballroom K-L-M

Thursday, February 2, 2012

Cardiac Tissue Mechanics & Flow

8:30 am – 9:00 am **Keynote Lecture**

Crystal J2

Moderators: Michael Jerosch-Herold, PhD, Brigham and Women's Hospital
Reza Razavi, MD, King's College London

Physiology and Clinical Importance of Cardiac Function

Philip Kilner, MD, Royal Brompton Hospital

9:00 am – 10:30 am **Session 6 - MR Techniques for the Analysis of Regional Cardiac Function**

Moderator: Amir Amini, PhD, University of Louisville;
Leon Axel, MD, PhD, NYU Langone Medical Center

9:00 am **Tagging & HARP, SENC & DENSE & Velocity Mapping: How to and What to use**

Frederick Epstein, PhD, University of Virginia

9:25 am **Emerging Applications of MR based Analysis of Myocardial Function**

Leon Axel, MD, NYU Langone Medical Center

9:50 am **W15 Polar HARP for Polar CMR Tagging**

Abbas Moghaddam, PhD, Tehran Polytechnic

10:02 am **W16 Automated Cardiac Motion Estimation from 3D Cine DENSE MRI**

Andrew Gilliam, PhD, A.D. Gilliam Consulting

10:14 am **W17 Cardiac Deformation Analysis from Orthogonal CSPAMM (OCSPAMM) Tagged MRI**

Hui Wang, University of Louisville

10:30 am – 11:00 am **Refreshment Break/ Exhibits/Posters**

Crystal Ballroom K-L-M

11:00 am – 12:30 pm **Session 7 - Novel Techniques for the Assessment of Regional Cardiac Function**

Moderators: Daniel Ennis, PhD, University of California – Los Angeles;
Frederick Epstein, PhD, University of Virginia

11:00 am **Cardiac Elastography**

Arun Kolipaka, PhD, The Ohio State University

11:25 am **Computational Analysis of Tissue Motion in CINE Images**

Gianni Pedrizetti, PhD, Universita di Trieste

11:50 am **W18 A Method to Determine Regional Mechanical Left Ventricular Dyssynchrony Based on High Temporal Resolution Short Axis SSFP Cine Images**
Jonathan Suever, Georgia Institute of Technology / Emory University

12:02 pm **W19 Mitral Valve Annular Velocity Measurements Derived from Cine MRI: Validation Against Doppler Echocardiography**
Christoph Guetter, PhD, Siemens Corporation

12:14 pm **W20 Quantitative Assessment of Myocardial Motion from Displacement Measurements Derived from Velocity Encoded MRI**
Volker Rasche, PhD, University Hospital of Ulm

12:30 pm – 2:00 pm **Vendor Presentations and Panel Discussion of Future Directions**
Vinoy/Sawgrass Rooms
Moderators: Jens Frahm, PhD, Biomed NMR; Michael Markl, PhD, Northwestern University

The 'vendor session' will provide a forum for the presentation of new developments from an industry perspective. Each 10 minute vendor presentation will be structured as scientific presentations and focus on new developments in the fields of cardiovascular flow and motion.

12:30 pm GyroTools LLC
12:40 pm GE Healthcare
12:50 pm Philips Healthcare
1:00 pm Siemens Healthcare
1:10 pm Panel discussion

Please note that the vendor session will be held during the lunch break and a box lunch will be provided to all workshop participants.

2:00 pm – 3:30 pm **Session 8 - Intra-Cardiac Blood Flow and Coronary Arteries**
Moderators: Tino Ebbers, PhD, Linköping University; Philip Kilner, MD, Royal Brompton Hospital

2:00 pm **3D Blood Flow Through the Heart and Valves**
J.J. Westenberg, PhD, Leiden University Medical Center

2:25 pm **Coronary Blood Flow**
Freddy Stahlberg, PhD, Lund University

2:50 pm **W21 Diastolic Function Imaging: A Comparison of Real-time Phase Contrast Magnetic Resonance (CMR) Imaging with Segmented Phase Contrast CMR and Doppler Echocardiography**
Paaladinesh Thavendiranathan, MD, MSc, Cleveland Clinic Foundation

3:02 pm **W22 Equal Stroke Volumes Different Costs: Left Ventricular 4D Flow in Normal and Failing Hearts**
Carl Johan Carlhall, MD, PhD, Linköping University Hospital

3:14 pm **W23 Flow Vortex Quantification in the Left Atrium**
Prasanta Pal, PhD, Yale University School of Medicine

3:30 pm – 4:00 pm **Refreshment Break/ Exhibits/Posters**
Crystal Ballroom K-L-M

4:00 pm – 5:30 pm **Session 9 - What's New: Emerging Techniques, Applications and Hot Topics**
Moderators: Michael Markl, PhD, Northwestern University; Freddy Stahlberg, PhD, Lund University

4:00 pm **CCSVI: Abnormal Venous Flow and Neurodegenerative Disease**
E. Mark Haacke, PhD, Wayne State University Research Facility

4:25 pm **Real-time Cardiovascular Magnetic Resonance**
Jens Frahm, PhD, Biomedizinische NMR Forschungs GmbH

4:50 pm **W24 Accelerated Phase Contrast Imaging Using Compressed Sensing with Complex Difference Sparsity**
Yongjun Kwak, Beth Israel Deaconess Medical Center

5:02 pm **W25 Velocity Unwrap for High Resolution Slice-selective Fourier Velocity Encoding Using Spiral SENSE**
Jennifer Steeden, PhD, UCL

5:14 pm **W26 Technique for Retrospective Respiratory and Cardiac-gated Phase Contrast Flow Measurements**
Ashley Anderson, MS, University of Wisconsin – Madison

Faculty Disclosures

Invited Speakers and Moderators:

Alperin, Noam: Financial Disclosure: Nothing to disclose

Amini, Amir: Financial Disclosure: Nothing to disclose

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Haughton, Victor: Financial Disclosure: Nothing to disclose

Jerosch-Herold, Michael : Financial Disclosure: Other: Named as inventor on pending IP protection application pertaining to diffuse fibrosis detection

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Westenberg, Jos: Financial Disclosure: Nothing to disclose

Wieben, Oliver: Financial Disclosure: Nothing to disclose

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Bächler, Pablo: Financial Disclosure: Nothing to disclose

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Carlhall, Carl Johan: Financial Disclosure: Nothing to disclose

Gilliam, Andrew: Financial Disclosure: Consultant: Siemens Healthcare

Guetter, Christoph: Financial Disclosure: Full time employee: Siemens Corporation

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Wentland, Andrew: Financial Disclosure: Nothing to disclose

Wednesday, February 1, 2012

Physiology of Blood Flow and Vessel Walls

Wilmer W Nichols, PhD

Both systolic and pulse blood pressures are stronger predictors of stroke, coronary heart disease, myocardial infarction, heart failure, end-stage renal disease and cardiovascular mortality than diastolic pressure. Furthermore, diastolic pressure is inversely related to coronary heart disease and cardiovascular mortality in older individuals. Increased stiffness (or elastance, inverse of compliance or distensibility) of the central elastic arteries is the primary cause of increased systolic and pulse pressure with advancing age and in patients with hypertension, and is due to degeneration and hyperplasia (increased collagen and decreased elastin) of the arterial wall (). Diastolic pressure decreases as arterial stiffness increases and becomes obvious after age 55-60 years and often leads to isolated systolic hypertension. As stiffness increases transmission velocity of both forward and backward (or reflected) traveling waves increase which causes the reflected wave to arrive earlier in the central aorta and augments pressure in late systole and decreases left ventricular ejection during deceleration. These changes in arterial wall properties cause an increase in left ventricular afterload and myocardial oxygen consumption and a decrease in myocardial perfusion pressure which may induce an imbalance in the supply-demand ratio, especially in hypertrophied hearts with significant coronary artery disease. Also, an increase in systolic pressure increases arterial wall circumferential stress which promotes local fatigue and development of arteriosclerosis. Vasodilator drugs have little direct active effect on large elastic arteries but can markedly reduce wave reflection amplitude and augmentation index by decreasing stiffness of the muscular arteries and reducing pulse wave velocity of the reflected wave from the periphery to the heart. This decrease in intensity (or amplitude) and increase in travel time (or delay) of the reflected wave causes a generalized decrease in systolic pressure and arterial wall stress and an increase in ascending aortic flow during the deceleration phase. The decrease in systolic pressure brought about by this mechanism is grossly underestimated when systolic pressure is measured in the brachial artery.

Intracranial Blood Flow and Aneurysms: *In-Vivo* Flow and Analysis and CFD

Vitaly Rayz, PhD

Cerebral aneurysms are localized dilatations of blood vessels, predominantly occurring in or near the circle of Willis. A growing aneurysm may impinge on the brain tissue; aneurysm rupture results in hemorrhagic stroke. The flow in cerebral aneurysms can be quite complex, with high-velocity jets, 3D vortices, and flow stagnation regions. State of the art MR Imaging and Computational Fluid Dynamics (CFD) methods can elucidate the role of hemodynamics in aneurysmal disease progression. Contrast enhanced MR angiography is the preeminent technique for acquiring aneurysmal vessel geometry, while quantitative information can be obtained with phase-contrast MR velocimetry, a technique capable of measuring time-resolved flow velocities in 3D. Due to limitations in resolution, imaging alone is limited in its ability to accurately determine some important flow descriptors, such as the hemodynamics forces acting on arterial walls. By combining MRI with patient-specific CFD modeling, it is possible to obtain this information, which can potentially help clinicians with staging treatment of cerebral aneurysms. For example, longitudinal studies of cerebral aneurysm progression have demonstrated a correlation between the areas of observed growth and the CFD-computed areas where endothelial cells are subjected to abnormally low wall shear stress. Some of the larger aneurysms were observed to develop intra-luminal thrombus. The regions of thrombus deposition were found to correlate with CFD-predicted regions characterized by flow stagnation and increased residence time. While improving PC-MRI methods will eventually enable this technique to measure flow-derived parameters with sufficient accuracy, a key benefit from computational modeling will be in predicting flow fields resulting from vascular interventions, as it is not possible to measure these flows prior to surgery. In cases when different treatment options are considered, image-based CFD can be used to model flow alterations caused in each option, and thus predict the best outcome on a patient-specific basis.

CSF Flow Imaging

Victor Haughton MD, University of Wisconsin

MR has important clinical applications in the evaluation of CSF flow. One application is the evaluation of flow in the cerebral aqueduct, to determine if the aqueduct is patent or obstructed. Another application in some institutions is to measure the velocity and volume of flow, in order to document increased flow that some clinicians believe characterizes one type of dementia called normal pressure hydrocephalus. The most common indication for CSF flow measurement is the evaluation of the Chiari I malformation. This malformation, characterized by downward displacement of the cerebellar tonsils, partially obstructs the subarachnoid space at the foramen magnum and increases CSF flow velocity in the oscillatory CSF flow related to the cardiac cycle. This application requires careful measurement of velocities and analysis of the flow patterns, to distinguish patients who require surgical treatment from those who do not.

The CSF flows in and out of the cranial vault with each heart beat, due to the expansion of the brain and cerebral vessels during systole. This oscillatory flow has characteristic flow jets, velocities, and intermittent bidirectional flow. In the Chiari I malformation, jets, velocities and bidirectional flow are exaggerated, because of the effect of the cerebellar tonsil position and other anatomic abnormalities characteristic of this malformation. The hyperdynamic flow theoretically causes the syrinx (intraspinal cyst) and other neurologic complications and symptoms associated with the malformation. Treatment of symptomatic Chiari patients is cranio-vertebral decompression, an operation that enlarges the subarachnoid space and reduces the effect of the obstructing tonsils.

The pulse sequence used clinically for the measurement of CSF flow is Phase Contrast MR. Flow can be evaluated in sagittal plane images, giving some depiction of flow at multiple levels but decreasing the accuracy of measuring because the image includes the midline slice of the subarachnoid space in which the peak velocities may not be detected. Velocity measurements in sagittal images are degraded by intravoxel dephasing. Axial images provide more accurate measurement of velocities across the entire subarachnoid space at one level. The results obtained with multiple axial images appear to be the best at the moment. A flow sensitive 3D, high resolution technique will improve CSF flow imaging when it is available. For current PC MR, parameters are: TR = 6.7–8.5 ms depending on the VENC, TE = 3.2–4.9 ms depending on the VENC, phase-encoding values = 128, FOV = 24 × 12 cm2, cardiac gating, and 14–20 cardiac phases. With the above parameters, the scanning time for both acquisitions is 34 seconds for a heart rate of 60 beats per minute. The chosen VENC depends on the expected velocity, usually in the range of 2 to 15 cm/sec.

Carotid Plaques: In-vivo Characterization and Computational Fluid Dynamics

David Saloner, PhD

Imaging evaluation of disease of the extracranial carotid arteries is of key importance in determining therapeutic options for patients with atherosclerosis. The relative proximity of the carotid bifurcation to the skin permits the use of high sensitivity coils that can be used to good effect to obtain high contrast, high resolution images of the flow lumen and of the vessel wall. The multiple contrast abilities of MR can be used to provide complementary data on the composition of the vessel wall. It has been possible to characterize the image features of the different components of the plaque on the multi-contrast data set because of the availability of histo-pathologic data from endarterectomy specimens. Since MRA can directly assess degree of stenosis, measurement of flow velocities do not serve the same role that they do in ultrasound where velocity is used as a surrogate measure of stenosis. MR velocity measurements can be used to either directly assess the velocity field (and hence related hemodynamic parameters, such as wall shear stress), or to specify the boundary conditions needed by numerical methods to compute the velocity field with high temporal and spatial resolution. Knowledge of the hemodynamic forces on the vessel wall has a potential role in determining the likelihood of atheroembolic events – either from frank plaque rupture or from adlumenal thrombus. The full power of the angiographic, composition, and velocity information that can be provided by MR is undergoing continual improvement, and the eventual impact on clinical care awaits carefully controlled prospective studies.

Blood Flow in the Aorta: 3D Visualization and Quantitative Analysis

Tino Ebbers, PhD

In recent years, 4D flow MRI is more and more used and the interest in it has been growing. Studies using this technique have already improved our physiological understanding of cardiovascular blood flow, but the technique has not reach its full potential yet. Recent advances in acquisition allow for fast measurement of high quality velocity data. In one measurement, a large amount of information is obtained, which allows for assessment of many aspects of cardiovascular hemodynamics, retrospectively. A major challenge is now to extract the relevant information for the application at hand, and to obtain reliable and accurate visualization and quantification methods for this application. It is hereby important to consider the whole imaging chain containing acquisition, post processing, visualization, quantification and data interpretation and clinical practice. Currently a wide range of 4D flow based visualization and quantitative analysis approaches are used, including angiographic visualization, vector plots, streamline and pathline visualization, feature extraction, wall shear stress analysis, pressure maps, and turbulence intensity. Visualization and quantitative analysis of blood flow has potential to improve understanding and clinical diagnosis of a range of cardiovascular diseases. Existing and new novel analysis methods have now to be tested and validated for the whole range of physiological and pathophysiological applications.

Comprehensive characterization of renal arteries

Oliver Wieben, PhD

Non-invasive assessment of the anatomy and hemodynamics of the renal vasculature provides valuable clinical information, e.g. in the diagnosis and management of renal artery stenosis (RAS) and preparation for and follow up of kidney transplantation. MR is well suited for providing anatomical and functional parameters, yet the comparatively small vessel size and significant motion during the respiratory cycle has limited its utility in daily practice.

The clinical significance of the fairly common RAS cannot be properly characterized by an anatomical stenosis measurement alone and additional parameters are needed, e.g. to monitor therapy success or to identify RAS patients who would benefit from interventional procedures. 2D flow sensitive MR imaging demonstrates flow profile changes in the presence of renal artery stenoses and has been shown to improve diagnostic accuracy in multi center trials.

Free breathing, volumetric phase contrast acquisitions can be used to provide noncontrast enhanced complex difference angiograms in patients with compromised kidney function who cannot tolerate Gadolinium-based contrast injections. Recent advances in accelerated flow imaging provide volumetric cine acquisitions with three-directional velocity encoding and high spatial and temporal resolution that generate high quality angiograms with reduced intravoxel dephasing artefacts. These '4D MR Flow' imaging schemes can provide comprehensive information that include high quality angiograms derived as complex difference images and velocity measurements at arbitrary analysis plane orientations throughout the cardiac cycle. In addition, transstenotic pressure maps can be derived via Navier Stokes equations directly from the measured velocity vector fields. Validation studies in animals have shown excellent agreement with catheter-based invasive pressure measurements, the gold standard for establishing hemodynamic significance of a stenosis.

Thursday, February 2, 2012

The Physiology and Clinical Importance of Cardiac function

Philip Kilner, MD, PhD

The heart is a valved, muscular organ whose cycles of movement maintain the circulation of blood day and night, life-long, through active as well as resting states.

The relative shapes, diameters and thicknesses of heart structures are important. The contractility of myocytes, the opening and closing of valves and the changing momentum of inflowing and out-flowing blood are each associated with phasic and directional exchanges of force. Their dynamic tensor/vector fields are structured through all four dimensions of space-time.

Through tens of millions of years of evolution, the orientations and coordinated movements of the heart's mobile, curvilinear components have arrived at a highly effectively *morphodynamic* mode of action.

Recognition of the morphodynamic elegance the healthy heart, based on combinations post mortem microscopy, in-vivo imaging and material principles, serves as a basis for recognizing the limitations as well as strengths of our current imaging approaches. Every approach is limited or selective in certain respects. However, combinations of approaches can inform our comprehension.

Pathologies such as myocardial ischaemia, hypertrophy, cavity dilatation, dys-coordination, arrhythmias and infiltrative changes can be considered as departures from the normal morphodynamic function of the heart.

Tagging and HARP, SENC and DENSE, and Velocity Mapping

Frederick H. Epstein, PhD

Cardiac magnetic resonance (CMR) is widely regarded as the gold standard modality for the noninvasive assessment of cardiac function. In addition to conventional cine imaging, CMR tissue tracking methods enable the quantitative measurement of myocardial mechanics, including tissue displacement, velocity, strain, twist, and torsion. Furthermore, CMR offers a number of different but related methods for imaging myocardial mechanics, including myocardial tagging, harmonic phase analysis (HARP), strain-encoded imaging (SENC), displacement encoding with stimulated echoes (DENSE), and velocity-encoded CMR. Myocardial tagging is the best-established method, with a 20-year history of technical development and clinical applications. While the contributions of conventional tagging have been considerable, the time-consuming nature of conventional tag analysis methods has limited its widespread use. Newer methods that build upon the original tagging concepts provide for faster image analysis, and largely overcome the limitations of conventional tagging and tag analysis techniques. For example, HARP methods greatly reduce the time required to generate displacement and strain data from tagged images. SENC imaging encodes strain information directly into the image magnitude, enabling the automatic calculation of through-plane tissue strain. In DENSE CMR, tissue displacement is encoded within the image phase, enabling the rapid calculation of tissue displacement, strain, twist, and torsion. Building on concepts originating from conventional myocardial tagging, newer methods provide for faster or automatic quantitation of metrics such as displacement and strain, and promise to be well-suited for future clinical application.

New York University

School of Medicine

Emerging Applications of MR-based Analysis of Myocardial Function

Leon Axel, PhD, MD

Introduction

- Conventional CMR is already a "gold standard" method for global function analysis
- Qualitative regional function assessment with CMR is a routine part of clinical practice
- However, there is still much room for improvement of current methods, and there are many promising new analysis methods and new application areas
- This talk will provide an overview of some evolving areas in MR-based analysis of myocardial function
- Many are represented in the talks at the meeting(s)

Evolving CMR Function Analysis and Application Areas

- Imaging methods- imaging limits function assessment capability
  - Higher speed/resolution imaging
  - More information content in images
- Analysis methods- needed to extract/analyze function data
  - More robust and rapid analysis methods
  - Integration with mechanics modeling
- Application areas
  - Development of normal function atlases
  - Assessment of diastolic function, ischemia, cardiomyopathy
  - EP: Arrhythmia imaging/dyssynchrony/CRT
  - Congenital/valvular disease
  - Aneurysms

Current Imaging Methods

- Conventional cine for wall motion
- Magnetization tagging for point correspondence
- Motion-induced phase shifts (blood/tissue motion)
  - Gradient echoes
  - Stimulated echoes (tissue)
- All limited by spatial/temporal resolution
- All affected by motion and arrhythmias

Evolving Imaging Methods

- Real-time imaging
  - Frame rate vs. frame duration
  - Radial imaging relatively robust
- Compressed sensing
  - Allows irregular k-space undersampling
  - Acquisition speed at cost of reconstruction
- 4D flow
  - Full 7D data set large
  - Need acceleration
- Elastography

Arrhythmias

- Common in cardiac disease patients
- Common indication for CMR
  - Structural correlation (sarcoid, ARVC, scar, etc.)
- Irregular rhythm leads to inconsistent timing/shape
- Resulting image artifacts in multi-cycle imaging
- Real-time imaging still relatively lower resolution
- Can we develop better beat sorting/rejection/reconstruction approaches?

Analysis Methods

- All rely to some extent on segmentation
  - Inherently hard with curved/rough heart wall
- Need robust and rapid wall tracking/motion extraction
- Method-specific tasks/difficulties
  - "Off-by-one", tag blur in tag tracking methods
  - Aliasing, integration error in phase methods
  - Elastography-specific analysis
- Displacement, rotation, strain, strain rate, shear

Evolving Analysis Methods

- More robust and rapid analysis methods needed
- Integration with suitable prior motion/shape data?
- EP modeling/guidance
  - Integrated road-mapping for procedures now (R-T?)
  - Incorporation of potential targets/response?
  - CRT selection/guidance?
- FEM mechanics modeling
  - Uncertain material properties/conduction paths
- Diffusion/fibers imaging (challenging for beating heart) and integration with modeling

Application Areas

- What is normal range of motion variables?
  - Development of standard atlases of regional structure and function
- How to classify/characterize disease?
- Assessment of diastolic function, ischemia, cardiomyopathy
- Arrhythmia imaging
  - Dyssynchrony/CRT
  - Ablation guidance/monitoring
- Congenital/valvular disease- 4D flow/function
- Aneurysms- pathophysiology/risk?

Cardiac Elastography

Arun Kolipaka, PhD

Abstract: Intrinsic mechanical properties of the tissue such as stiffness provide very important diagnostic information for treating variety of diseases in the heart. For example, diastolic dysfunction, myocardial infarction, hypertension increases myocardial stiffness. Currently, the gold standard for estimating the stiffness of the myocardium is invasive pressure-volume (P-V) model. However, P-V model requires technical precision and involves some risk factors. Therefore, there is a need for noninvasively estimating the stiffness of the myocardium. Magnetic resonance elastography (MRE) is a noninvasive phase contrast technique that synchronizes external motion in the phase of MR image to determine stiffness. However, MRE has been show to be a valuable proven tool to estimate stiffness in static soft tissues such as liver, skeletal muscle etc. Implementation of MRE on dynamic organ such as heart is challenging. This talk addresses the challenges associated with cardiac MRE and it technical limitations.

Computational Analysis of Tissue Motion in CINE Images

Gianni Pedrizzetti, PhD

Cardiac Magnetic Resonance (CMR) produces high quality images where features of the myocardial tissue can be well recognized by visual inspection. It is therefore natural to expect that an automated tracking of such features permits to follow the material elements of the myocardium and provides quantitative information on the cardiac dynamics.

This lecture introduces the basic elements of feature tracking (FT). FT derives from previous techniques developed in the field of optics and in laboratories of fluid dynamics and turbulence and its application to CMR imaging is, in principle, relatively straightforward. FT, however, is an approximate technique that is subjected to underestimation and limitations. Therefore, methods to refine the estimates are required and tailored to each specific application. Accuracy of tracking is inversely proportional to the size of the interrogation windows: good on small windows, poor on large windows. Therefore it is necessary to hierarchically detect wide motions on large windows and progressively refine within smaller windows. The use of a sequence of hierarchical strategies, in combination with the assimilation of available information, permits the optimization of FT performances to the cardiac tissue in CINE images.

Tracking, however, represents only the preliminary step toward the quantification of cardiac function. From the knowledge of myocardial motion it is possible to derive numerous quantities that describe the myocardial dynamics and, eventually, the heart function. The reliability of the different quantities derived from FT is very different for different quantities. The limitations are primarily a consequence of the spatial resolution of CINE images and the time interval between successive frames, a limitation that reflects differently on different quantities and that can be easily estimated. In additions, the evaluations are subjected to a varying degree of "repeatability". This is a key uncertainty, difficult to estimate, depending on how a small error in the measurement chain can influence the final result. Examples of how to perform technically reliable evaluations and what to avoid are shown.

In conclusion, the automated analysis of tissue motion in CINE images of is a new powerful tool that -when used with awareness of its limitations- gives quantitative and objective information to the clinician and that can become a valuable support to the diagnostic process.

3D Blood Flow through the Heart and Valves

Jos JM Westenberg, PhD

The hemodynamics of the flowing blood inside the heart and the great thoracic vessels around the heart is an important area of clinical research. Intra-cardiac flow is affected by the systolic and diastolic performance of the heart and therefore, parameters describing this intra-cardiac blood flow are representative for the systolic and diastolic functioning.

Cardiac MRI in combination with velocity-encoding or phase-contrast imaging is well-suited for the evaluation of intra-cardiac blood flow. Velocity-encoding can be performed in one (through-plane), two (in-plane) or three directions. 3D imaging in combination with three-directional velocity-encoding and time-resolved representation of the cardiac cycle results in large data sets of intra-cardiac blood flow that can be evaluated qualitatively and quantitatively.

Visualization techniques are available to provide insight in the distribution of this data; vector velocity fields, streamlines or path lines are all visualization tools that may be used to characterize the dynamic motion pattern of the blood flow inside the four chambers of the heart. Quantification of blood flow velocity, volumes or flow rate are used to describe various forms of pathology such as valve incompetence and septum defects as well as the systolic performance and diastolic filling characteristics of the ventricles.

In this presentation, the additional value of 3D blood flow imaging will be discussed over traditional one-directional through-plane velocity-encoding. Three-dimensional three-directional velocity-encoding with retrospective valve tracking will be presented for quantfying trans-valvular flow over all four heart valves within a single acquisition. This is of particular interest for assessing valve regurgitation, but also improves the assessment of diastolic filling characteristics, such as the trans-mitral flow pattern, the flow propagation velocity and pulmonary venous flow.

Coronary Blood Flow

Freddy Stahlberg, PhD

Phase contrast MR (PC-MR) has been used for clinical investigations for more than two decades. In its simplest form, PC-MR is performed in single-slice mode, using two interleaved gradient-echo sequences with different velocity sensitivity in one spatial direction. The technique has recently been expanded to encompass four-dimensional applications, allowing determination of temporally resolved velocity information in three orthogonal spatial directions, often denoted 4D PC-MR.

Although PC MR in many clinical situations is a robust and reliable quantitative method for determination of velocity and derived parameters such as flow and strain, several error sources are commonly recognized. Among these error sources are aliasing, errors in positioning and choice of region-of-interest size, object motion and residual phase background, as well as errors related to flow complexity, e.g. displacement and phase dispersion. In this context, measurement of coronary blood velocity and blood flow is one of the most challenging tasks for PC-MR, owing primarily to the combined difficulties of significant vessel motion related to cardiac pulsation as well as respiration, and to the small geometrical dimension of these vessels.

On the other hand, the technical development gives us tools to overcome at least some of these problems. As examples, breath-holding segmented gradient-echo sequences as well as sequences utilizing combined ECG triggering and respiratory gating/navigator techniques have been developed and evaluated for PC-MR in small moving vessels. Furthermore, long acquisition windows subsequent to the use of segmented techniques may be partially overcome by the use of view-sharing and under-sampling techniques such as parallel imaging, preferably in the combination with increased magnetic field strength. Finally, improved strategies for selection and positioning of ROI sizes in small vessels may also add to improved accuracy.

Owing to technical improvements, several examples of flow measurements in coronary vessels have been demonstrated. As examples, global left ventricular perfusion and perfusion reserve can be estimated by measuring coronary sinus blood flow, which is an approximation of the amount of blood that has perfused the left ventricular myocardium, divided by left ventricular mass.

Furthermore, flow velocity or flow volume and flow reserve have been successfully investigated in the left anterior descending (LAD) and right coronary artery of healthy subjects. The same types of measurements have been undertaken in the LAD artery in patient populations and have showed high agreement with intravascular ultrasound for measurement of flow and flow reserve. Potential use of the techniques can be seen in identification of patients with e.g. significant coronary artery stenosis and restenosis after stent implantation, or to evaluate the physiologic status of venous grafts.

CCSVI: Abnormal Venous Flow and Neurodegenerative Disease

E. Mark Haacke, Ph.D.
Wayne State University

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CCSVI: Abnormal Venous Flow and Neurodegenerative Disease

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Outline

1) Abnormal jugular venous flow and its links to neurological diseases
2) Introduction to measuring flow in MRI
3) Limitations of flow measurements in MRI
4) The presence of abnormal flow in multiple sclerosis
5) Flow risk factors in multiple sclerosis

Abnormal jugular venous flow (reflux) and its associations

There is a very timely review of the importance of jugular venous reflux by Chung et al*. In this paper, the authors note that without a competent jugular valve, and prolonged venous reflux, the subject may develop venous hypertension or occlusion**. Several disorders are associated with internal jugular vein (IJV) incompetence, including:

transient global ischemia***;
transient blindness+;
cough headache++; and
primary exertional headache+++.

*Chung CP, Hu HW. Jugular Venous Reflux. J Med Ultras 2008;16:210.
**Harvey W. Cardiac Classics. CV Mosby, St Louis. 1941:19.
***Lewis SL. Aetiology of transient global amnesia. Lancet. 1998:1;352:397.
+Hsu HY, Chao AC, Chen YY, et al. Reflux of jugular and retrobulbar venous flow in transient monocular blindness. Ann Neurol. 2008 Feb;63:247-253.
++Chuang YM, Hu HH. Cough headache and thoracic inlet valvular competence in uremia. Eur Neur. 2005;53:78-80.
+++Doepp F, Valdueza JM, Schreiber SJ. Incompetence of internal jugular valve in patients with primary exertional headache: a risk factor? Cephalalgia. 2008 Feb;28:182-185.

Abnormal jugular venous flow (reflux) and its associations

Valves can also tend to break down with age. In veins without valves, simply reversing the pressure gradient can produce reflux. This condition "might impede cerebral venous outflow and induce neurologic dysfunction," according to Chung and Hu*.

These conditions can occur during Valsalva-like activities such as, coughing, heavy lifting, and other strenuous activities.

In a paper on transient monocular blindness, Chung** points out that 74% of these patients had JVR compared to 20 to 40% of normals. They noticed that there was a dilation of the venules in these patients but not at all in normals.

The evidence appears to suggest that JVR affects ocular venous drainage.

*Chung CP, Hu HW. Jugular Venous Reflux. J Med Ultrasound 2008;16:210-222.
**Chung CP, Hsu HY, Chao AC, Cheng CY, Lin SJ, Hu HH. Jugular venous reflux affects ocular venous system in transient monocular blindness. Cerebrovasc Dis. Jan;29:122-129.

Reduced perfusion and tissue damage in MS

A paper by Bernie Juurlink has a nice discussion of the role of hypoperfusion in MS. He comments that the reduced perfusion can be detrimental to oligodendrocytes, preferentially affect white matter, cause demyelination, and lead to microglial activity. He notes that these can be most marked in the optic nerve and tract. He then states:

"There is now ample evidence that ischemic insults of sufficient severity can cause upregulation of cell adhesion molecules onto the endothelial cells, thus allowing infiltration of leukocytes into the brain parenchyma, resulting in an inflammatory lesion."

Can hypoxic/ischemic events, even transitory then lead to an immunological response, i.e. should we be considering the concept of "vascular immunology"?

Juurlink BH. The multiple sclerosis lesion: initiated by a localized hypoperfusion in a central nervous system where mechanisms allowing leukocyte infiltration are readily upregulated? Med Hypotheses. 1998 Oct;51:299-303.

Vascular risk factors for reduced perfusion

In a recent paper, the critical importance of certain vascular risk factors in cognitive dysfunction are discussed by Iadecola et al*.

"Aging, Alzheimer's disease and hypertension are major determinants of cognitive dysfunction associated with profound alterations in the structure and function of cerebral blood vessels."

"The brain has no energy reserves and its structural and functional integrity depend on a continuous and well regulated blood supply matched to its energetic needs."

Disruption of the auto-regulatory blood flow mechanisms whether external or with aging may lead to inadequate blood supply throughout the normal range of arterial blood pressure. The lack of response with aging or disease may "reduce cerebral perfusion, deplete cerebrovascular reserve and increase the susceptibility of the brain to vascular insufficiency and ischemic injury."

*Iadecola C, Park L, Capone C. "Threats to the mind: aging, amyloid and hypertension." Stroke 2009, 40; S40-s44.

Is MS an auto-immune generated disease?

Recently*, John Prineas published the results of a study of 26 newly forming active MS lesions in the brains of 11 patients who died shortly after the acute onset of new symptoms. Their intent was to catalogue the distribution of inflammatory cells within the lesions.

Previously,** the group reported that expanding MS lesions may exhibit prominent oligodendrocyte loss and apoptosis - hallmarks of characteristic MS pathologic changes, in the absence of infiltrating lymphocytes.

There they detailed that parenchymal T and B cells were largely absent in areas of initial oligodendrocyte loss and in areas of degenerate and dead myelin infiltrated by myelin phagocytes.

Could a reduced flow and hypoxic/ischemic events explain this?

*Henderson APD, Barnett MH, Parrat JDE, Prineas JW.
Multiple sclerosis: distribution of inflammatory cells in newly forming lesions. Ann Neurol 2009;66 739-53.

**Prineas JW. Pathology of the early lesion in multiple sclerosis. Human Pathol 1975;6: 531-54.

Is MS an auto-immune generated disease?

In contrast, in well-established trailing areas of complete demyelination packed with lipid macrophages, and, in some lesions, regenerating oligodendrocytes, showed large numbers of T and B cells.

The authors concluding interpretation stressed that :

"early loss of oligodendrocytes is a prominent feature in tissue bordering rapidly expanding MS lesions.

Macrophage activity is largely an innate scavenging response to the presence of degenerate and dead myelin.

The findings [in this paper] suggest that plaque formation has some basis other than destructive cell-mediated immunity directed against myelin or oligodendrocyte antigen."

Patients with retinal sheathing develop MS

In 1976*, Younge performed fluorescein angiographic observations in a group of patients with retinal vein sheathing and MS.

He reported "smudge-like" fluorescein staining of the vein wall 15 minutes after the dye was administered and leakage spreading into the region of sheathing at 30 minutes.

He believed the breakdown in the blood-retinal barrier to be a form of peri-vasculitis that represented a contributing factor in the sheathing process.

Hamrick and King** recounted in the ophthalmology literature that one of the early theories regarding the retinal venous phenomenon, regardless of its cause, was that:

" it might be the underlying lesion producing the clinical disease of MS" and "thus it has been postulated that a mild form of localized phlebitis may be responsible for the demyelinating process."

*Younge BR. Fluorescein angiography and retinal venous sheathing in multiple sclerosis. Can J Ophth 1976;11: 31-6.

**Hamrick LS, King MW. Retinal venous sheathing in multiple sclerosis. J Am Optom Assoc 1984;55: 135-41.

Patients with retinal sheathing develop MS

Subsequently, Lightman, et al*, in 1984 published a "systematic study" of the frequency of retinal vascular abnormalities in 50 patients presenting with acute optic neuritis.

None of the patients had a diagnosis of MS at the time of initial examination.

Abnormalities were detected in 14 of the patients with optic neuritis, including 10 cases of fluorescein leakage and 6 cases of perivenous sheathing.

After a mean follow-up of 3.5 years, MS had developed in 8 of the 14 patients with vascular abnormalities (57%).

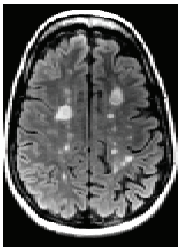
He concluded that, "The presence of perivenular abnormalities in a region free of myelin and oligodendrocytes provides evidence that the vascular changes in MS can occur independently of contiguous demyelination, and may be the primary event in the formation of new lesions."

*Lightman S, McDonald WI, Bird AC, Francis DA, Hoskins A, Batchelor JR, Halliday AM. Retinal venous sheathing in optic neuritis: its significance for the pathogenesis of multiple sclerosis. Brain 1987;110: 405-14.

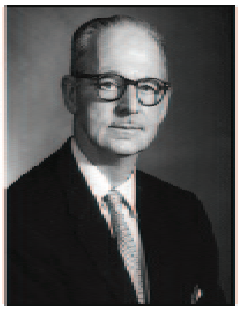
MULTIPLE SCLEROSIS

Facts about MS:

- Cause unknown…there is no cure
- 2 to 3 times more women than men
- The symptoms - mild to debilitating :
  - vision problems;
  - loss of balance and/or coordination,
  - extreme fatigue,
  - speech or memory failure;
  - muscle stiffness and paralysis.



Putnam's 1935 work on venous obstruction in a dog model



Tracey Putnam developed an experimental dog model of venous obstruction to study MS. His work supports the recent rediscovery of this concept by Dr. Paolo Zamboni of Italy.

He stated:

"The similarity between such lesions and many of those seen in cases of multiple sclerosis in man is so striking that the conclusion appears almost inevitable that venular obstruction is the essential immediate antecedent to the formation of typical sclerotic plaques."

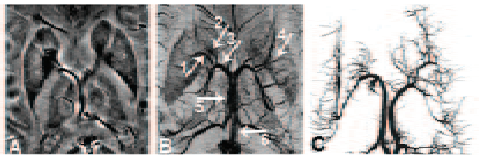
Putnam (1935). Studies in multiple sclerosis: encephalitis and sclerotic plaques produced by venular obstruction. Archives of Neurology and Psychiatry. 33: 929-940.

CCSVI

Chronic cerebro-spinal venous insufficiency

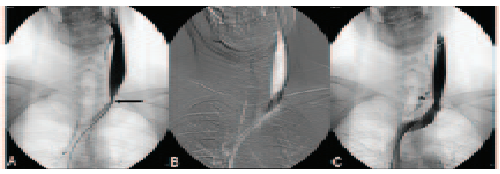
Zamboni noted narrowing of the veins at the neck or spine was restricting blood flow and dangerous levels of iron were accumulating in the brain (65 cases)

Abnormal and normal iron and venous behavior.



Haacke, E.M., Garbern, J., Miao, Y., Habib, C., Liu, M. Iron Stores and Cerebral Veins in MS Studied by Susceptibility Weighted Imaging (SWI). Int Angiol, 2010 – 29(2):149 – 57.

Paolo Zamboni and his team demonstrated that there were major venous abnormalities in MS patients both anatomically and functionally using angiograms as the gold standard.



Zamboni P et al. Chronic cerebrospinal venous insufficiency in patients with multiple sclerosis. *J Neurol Neurosurg Psychiatry* 2009;80:392-399.

The role of the caval system in venous hypertension

- The team of Aboulker et al studied the vertebral plexus network using a phlebology technique as early as 1971.
- Between 1971 and 1977, they studied 176 patients with myelopathies with an eye toward the potential role of venous hypertension and abnormal venous behavior of the vena cava system and its major trunks and feeding veins.
- They found that the most frequently occurring events from highest to lowest were as follows: stenosis of the left iliac; obstruction of the left renal vein; anomalies of the azygous vein; compression of the brachiocephalic vein; atresia of the internal jugular veins; compression of the vena cava.

Aboulker J et al. Myelopathies par hypertension veneuse intra-rachidienne. Ste De Neurochirurgie de la langue francaise. 1971.

The role of the caval system in venous hypertension

- When major vessels were re-opened some of these people with motor problems (such as development of quadriplegia) recovered and the progression of the problems not only stopped but was reversed.
- In a specific study of 50 patients, it is interesting to note that there were 17 operations that showed improvement, 17 were transitory, and 16 failed to show improvement.
- Interestingly, they also use the expression:
  "une libération poussée de la veine cave"

Aboulker J, Bar D, Marsault C, Khouadja F, Redondo A, Garel L, et al. [Intraspinal venous hypertension caused by muliple abnormalities of the caval system: a major cause of spinal cord problems]. Chirurgie. 1977;103(12):1003-15.

The re-introduction of CCSVI specifically for multiple sclerosis

In 2009, Zamboni et al [Z1] published their paper involving 65 MS patients and 235 controls in which they found anomalies in the venous pathways from the brain to the heart to be strongly associated with MS.

In a related study [Z2], Zamboni et al observed that in MS patients the cross sectional area (CSA) of the IJVs did not appreciably enlarge when subjects were supine in comparison with sitting.

Given that in healthy individuals the CSA of the IJVs when supine is approximately six times that when sitting [Z2, Z3], this suggests impairment of the flow through these veins in MS patients and extensive collateral re-routing of the blood through other venous pathways when in the supine position; something that is indicative of extracranial stenosis.

Indeed, through venography, Zamboni et al [Z4] have been able to demonstrate extensive collateral re-routing of venous blood back to the heart due to the presence of extracranial stenosis in MS patients.

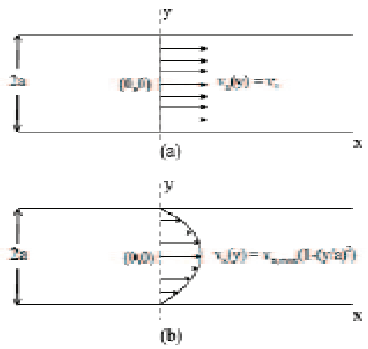
Z1. Zamboni P, Galeotti R, Menegatti E, Malagoni AM, Tacconi G, Dall'Ara S, et al. Chronic cerebrospinal venous insufficiency in patients with multiple sclerosis. J Neurol Neurosurg Psychiatry. 2009 Apr;80(4):392-9.

Z2. Zamboni P, Menegatti E, Galeotti R, Malagoni AM, Tacconi G, Dall'Ara S, et al. The value of cerebral Doppler venous haemodynamics in the assessment of multiple sclerosis. J Neurol Sci. 2009 Jul 15;282(1-2):21-7.

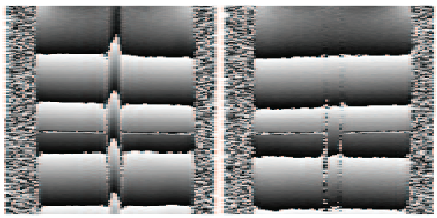
Z3. Valdueza JM, von Munster T, Hoffman O, Schreiber S, Einhaupl KM. Postural dependency of the cerebral venous outflow. Lancet. 2000 Jan 15;355(9199):200-1.

Z4. Zamboni P, Consorti G, Galeotti R, Gianesini S, Menegatti E, Tacconi G, et al. Venous Collateral Circulation Of The Extracranial Cerebrospinal Outflow Routes. Curr Neurovasc Res. 2009 Aug 1.

Plug flow and laminar flow

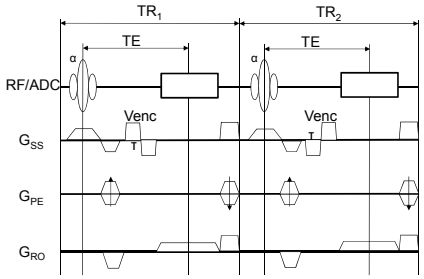


Phase as a representation of flow:
Here phase is proportional to velocity.

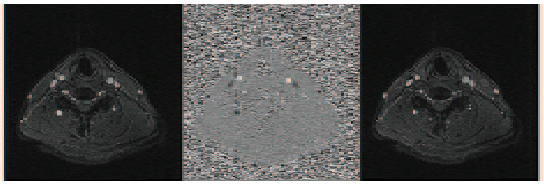


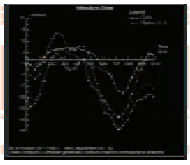
Flow encoded Compensated

Phase Contrast Imaging



VASCULAR FUNCTION: Flow Quantification

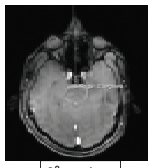




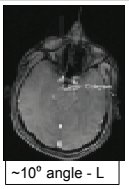
In this individual all four of the major veins in the neck showed either reflux or a reduction to nearly zero flow.

As a consequence, the speeds in the second half of the cardiac cycle had to double to get the blood out of the brain.

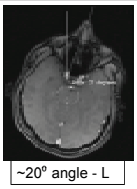
Different Head/Neck Positions



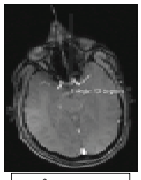
0° angle



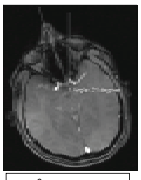
~10° angle - L



~20° angle - L

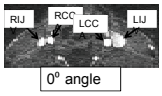


~10° angle - R

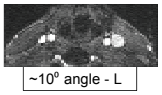


~20° angle - R

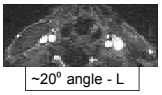
Example flow images showing the IJV vessel cross-section for different head/neck positions



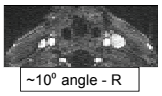
0° angle



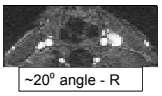
~10° angle - L



~20° angle - L



~10° angle - R

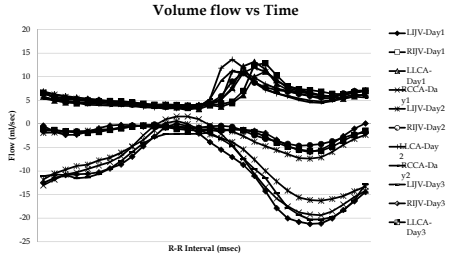


~20° angle - R

CSA Measurements (in sqmm)	RIJV	LIJV
0 deg	47	128
10 deg L	37.22	115
20 deg L	37.22	98
10 deg R	49.63	133
20 deg R	42.12	125
Standard Deviation	5.63	13.88

Note:
• This table includes the cross-section area (CSA) measurements for IJV's from the above images.

Volume Flow plots – Comparison of IJV's and CCA's – 20° Left – head/neck angle



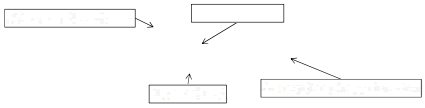
Summary of Observations

- The total flow variation measured at the C5/C6 neck level over four consecutive days produced good consistency in flow data (see table below).

Total venous flow with different head/neck angles for four days

Angle	Day1	Day2	Day3	Day4	Mean	Standard Deviation
0 degrees	-13.97	-14.24	-14.21	-14.23	-14.16	0.13
10Left	-14.06	-13.76	-11.27	-12.19	-12.82	1.32
20Left	-15.19	-11.44	-13.11	-12.88	-13.16	1.54
10Right	-14.26	-13.56	-11.84	-11.93	-12.90	1.20
20Right	-14.45	-11.37	-11.66	-11.58	-12.27	1.46

Flow Quantification

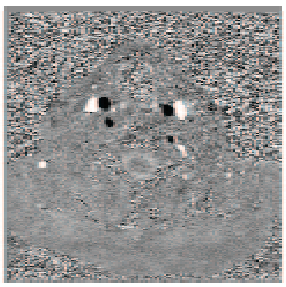


Sources of error:

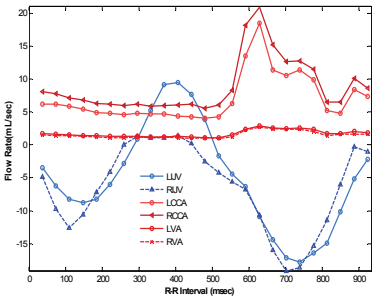
Gating pulse triggered or cardiac gated
Vessel segmentation and reproducibility
Velocity quantification and background drifts
Noise in the phase images
Physiologic reproducibility: positioning etc.

1. Firmin et al., J Comput Assist Tomogr, 11(5):751-756,1987; 2. Kraft et al., Med Phy, 19(1):79-85, 1992; 3. Frayne & Rutt, JMRI, 3(6):907-917, 1993; 4. Rebergen et al., Am Heart J, 126(6):1439-1456, 1993; 5. Lauzon et al., JMRI, 4(6):853-867, 1994; 6. McCauley et al., JMRI, 5(6):663-668, 1995; 7. Lee et al., AJR Am J Roentgenol, 169(4):1125-1131, 1997; 8. van der Geest et al., J Comput Assist Tomogr, 22(6):904-911, 1998; 9. Lotz et al., Radiographics, 22(3):651-671, 2002; 10. O'Brien et al., JMRI, 28(1):210-218, 2008; 11. Wentland et al., AJNR, 31(7):1331-1336, 2010; 12. Giese et al., MRM, Accepted 01/06/2012; 13. Haacke et al., JVIR, in print, 2012.

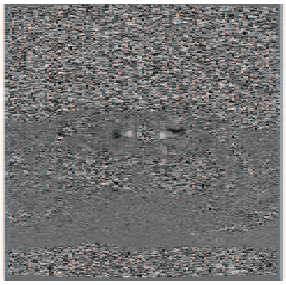
Reflux in the right IJV



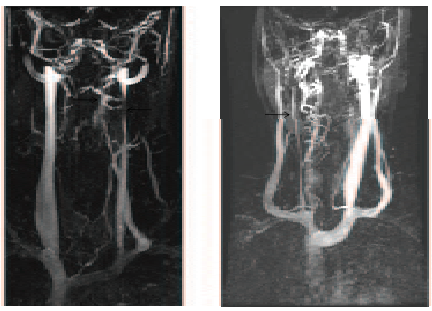
Reflux in LIJV

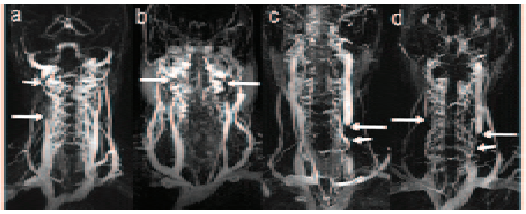


Jetting through a stuck valve?



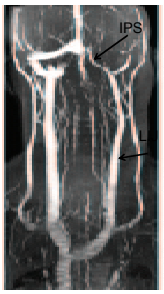
ABNORMAL VENOUS STRUCTURE:
Upper level stenosis and string stenosis





Coronal MIP demonstrating various forms of aplasia or atresia.
(a) RIJV is truncated at the mid-neck level (long arrow
(b) both IJVs are truncated at the upper neck (long arrows) level.
(c) the LIJV is obstructed at the mid-neck level (long arrow) with a thin connection with the subclavian vein (short arrow).
(d) right IJV shows a discontinuous behavior while the left IJV shows a thin connection to the jugular stump (short arrow).

18) Haacke EM et al. MS Patients With Structural Venous Abnormalities as Seen Using MRI Exhibit An Abnormal Flow Distribution of the Internal Jugular Veins. JVIR, in press.

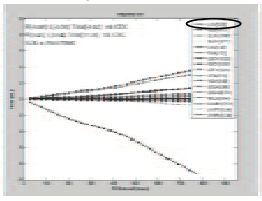


MIPed Coronal Image

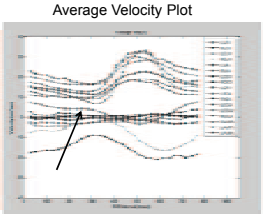
2D TOF MRV MIPed images showing the Inferior Petrosal Sinus draining into the Left IJV

Flow analysis at C2-C3 Level

Integrated Flow Plot



Average Velocity Plot

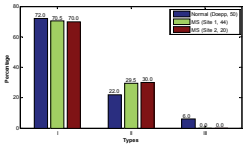


The LIJV has a reflux in its flow pattern which likely extends back to the inferior petrosal sinus.

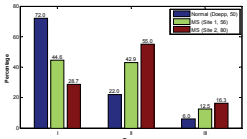
Flow Distributions (Site 1 vs. Site 2, N=125)

Flow Distribution (%)	Site 1		Site 2	
	Mean	Std	Mean	Std
LCCA/tA	39.43	3.72	40.38	4.56
RCCA/tA	40.20	4.24	41.43	4.35
LIJV/tV	27.42	17.13	27.11	18.60
RIJV/tV	42.83	18.28	39.38	20.73
tLA/tA	50.28	4.80	50.00	5.08
tRA/tA	49.72	4.80	50.00	5.08
IJV/tV	70.24	19.08	66.49	22.60
IJV/tA	-66.29	20.64	-58.64	27.47
A-V mismatch (%)	6.21	12.30	14.37	21.51
Fsd/Fd	0.51	0.25	0.52	0.25
Fd/Fsd	2.64	1.76	2.71	2.22

Dominance of IJV flow in normal controls versus two MS populations: Non-Stenotic and Stenotic Patients.



Non-Stenotic MS vs normal

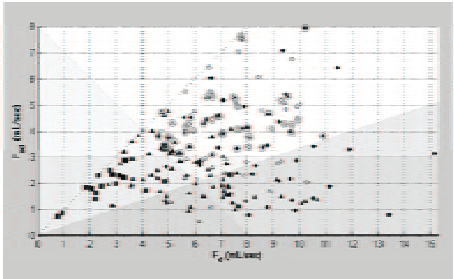


Stenotic MS vs normal

Comparison of non-stenotic MS patients out of the 200 MS patients and 50 normals using the ratio of IJV flow diivided by total arterial flow: F(IJV)/F(tA). (Doepp et al., Neuroradiology, 2004).

(Type I: F(IJV)/F(tA)>=2/3; Type II: 2/3>F(IJV)/F(tA)>=1/3; Type III: F(IJV)/F(tA)<1/3)

Results: Dominant vs. Sub-dominant Venous Flow Rates



Flow rate scatter plots of sub-dominant vein vs. dominant vein for 100 MS patients each site symbol-coded by Doepp categorization criterion. Red and blue correspond to Site 1 and Site 2. Diamonds, triangles and squares correspond to Types I, II and III. Solid symbols are stenotic MS cases (UL and LL stenosis, bilateral stenosis, diffused stenosis and TVM). Green circles represent patients with abnormal valves.

Conclusions

- We need to image as many normals as possible. Currently, the number of patients being imaged and/or treated is in the 1000s; we need age matched normal controls to compare to this patient population.
- Please visit www.ms-mri.com for updates in MR imaging protocols, publications, educational material and new quantification results.

Real-time Cardiovascular Magnetic Resonance

Jens Frahm, PhD

There is not very much doubt that CMR studies in real time would be a preferred option for patients (no breathhold), clinicians (access to arrhythmia and physiologic variations), and economists (shortened examination times, no failures), if respective techniques would offer robustness, sufficient spatiotemporal resolution and adequate contrast-to-noise. This presentation describes a recent proposal for real-time MRI that promises to meet many of these challenges. It yields serial images (i.e., movies) with acquisition times as short as 20-30 ms as well as good signal-to-noise and variable contrasts at 1.5-2.0 mm in-plane resolution.

The basic approach combines four major principles:

- a fast low-angle shot (FLASH) MRI sequence for rapid and continuous imaging using spoiled, refocused or fully balanced gradients,
- a radial trajectory for motion robustness and tolerance to data undersampling [1],
- an advanced reconstruction method for parallel imaging [2], and
- a strategy for temporal regularization [3].

The algorithm defines the image as the solution of a regularized nonlinear inverse problem, which simultaneously estimates coil sensitivities and image content [2] and – for serial imaging – exploits temporal continuity by adding a regularization term with respect to the preceding frame [3]. Taken together, the method achieves a degree of radial undersampling in an hitherto unexpected manner: typical real-time image reconstructions rely on only 7 to 15 spokes.

So far, most studies (healthy subjects) were performed on a 3 T MRI system (Tim Trio, Siemens Healthcare, Erlangen, Germany) with the use of a 32-channel cardiac coil for CMR. No hardware modification is required, but at this stage nonlinear inverse reconstructions are still performed offline using a GPU-based implementation on a by-pass computer. It automatically transfers the data during acquisition and starts the computation. Once completed (a few minutes only), the images may be re-imported into the database of the MRI system. Online control during scanning is accomplished by a sliding-window gridding reconstruction of the same data, but combining 5 successive acquisitions with complementary sets of radial spokes [1,3].

Apart from preliminary studies of joint movements or fast dynamic processes such as swallowing and speaking, current applications focus on CMR during free breathing and without ECG synchronization [4] as well as extensions to velocity-encoded phase-contrast MRI of through-plane flow in real time [5]. Most recent discoveries allow for 3D MRI movies of 1D or 2D objects at millisecond resolution [6] offering new options for monitoring MRI-guided interventions. Finally, remaining challenges for real-time CMR are the need for thorough clinical comparisons of real-time vs. cine recordings, the adaptation of the post-processing software, and full integration of the reconstruction algorithm into commercial MRI systems.

Real-time Cardiovascular Magnetic Resonance

continued...

[1] Zhang S, Block KT, Frahm J. Magnetic resonance imaging in real time: Advances using radial FLASH. J Magn Reson Imag 2010, 31:101-109.

[2] Uecker M, Hohage T, Block KT, Frahm J. Image reconstruction by regularized nonlinear inversion – Joint estimation of coil sensitivities and image content. Magn Reson Med 2008, 60:674-682.

[3] Uecker M, Zhang S, Voit D, Karaus A, Merboldt KD, Frahm J. Real-time magnetic resonance imaging at a resolution of 20 ms. NMR Biomed 2010, 23:986-994.

[4] Zhang S, Uecker M, Voit D, Merboldt KD, Frahm J. Real-time cardiovascular magnetic resonance at high temporal resolution: Radial FLASH with nonlinear inverse reconstruction. J Cardiovasc Magn Reson 2010, 12:39.

[5] Joseph AA, Merboldt KD, Voit D, Zhang S, Uecker M, Lotz J, Frahm J. Real-time phase-contrast MRI of cardiovascular blood flow using undersampled radial fast low-angle shot and nonlinear inverse reconstruction. NMR Biomed 2011, doi: 10.1002/nbm.1812.

[6] Merboldt KD, Uecker M, Voit D, Frahm J. Spatially encoded phase-contrast MRI – 3D MRI movies of 1D and 2D structures at millisecond resolution. Magn Reson Med 2011, 66:950-956.

Poster Directory

SCMR/ISMRM Jointly Sponsored Workshop - Posters

W27 Image Based Magnetic Field Background Correction for Aortic and Pulmonary Artery Flow Measurement Using Phase Contrast
Joshua Yang Cheng, St. Francis Hospital

W28 Exploring New Dimensions In Cardiovascular Flow and Motion: Application of Bloch NMR Flow Equations, Bessel and Spherical Harmonic Functions
Bamidele Awojoyogbe, Federal University of Technology Minna

W29 3d Mri Flow Analysis in an In-Vitro System Modelling Continuous Left Ventricular Support: Effect of Cannula Position in the Thoracic Aorta
Christoph Benk, University Hospital Freiburg

W30 Diastolic Vortex Ring Formation in the Human Left Ventricle: Quantitative Analysis Using Lagrangian Coherent Structures and 4D Cardiovascular Magnetic Resonance Velocity Mapping
Johannes Toger, Skåne University Hospital

W31 Spiral Readouts for 4D Flow MRI
Andreas Sigfridsson, Linköping University

W32 3D Cardiac Navigation with Rapid Multi-shot EPI
Aaron Hess, University of Oxford Centre for Clinical Magnetic Resonance Research

W33 Visualizing and Quantifying Cerebrospinal Venous Flow Using PC-VIPR
Eric Schrauben, University of Wisconsin – Madison

W34 Pressure Gradients Calculated from PC-MRI, SPIV and CFD Velocity data in a Phantom Model: Comparison with Catheter-based Pressure Measurement
Iman Khodarahmi, University of Louisville

W35 Measurement of Pulmonary Arterial Pulse Wave Reflection from Single-slice Phase-contrast and Steady-state Free Precession MRI
Peter Leimbigler, University of Toronto & Hospital for Sick Children

W36 Determination of Time-varying Pressure Field from Phase Contrast MRI Data
Lucian Itu, Siemens Corporate Research

W37 Retrogated Spiral 3-directional Myocardial Phase Velocity Mapping in a Single Breath-hold
Robin Simpson, Imperial College London

W38 Divergence-free Reconstruction for Accelerated 3D Phase-Contrast Flow Measurements
Julia Busch, University and ETH Zurich

W39 Quantitative Assessment of Myocardial Motion from Velocity Encoded MRI
Volker Rasche, University Hospital of Ulm

W40 4D-Flow Assessment of Cerebral Hemodynamic in Patients with Post EC-IC Bypass
Tetsuro Sekine, Nippon Medical School

W41 Full Tensor Registration of Diffusion Tensor Magnetic Resonance Imaging for Assessment of Cardiac Pathologies
Carla Gil, University College Dublin

W42 Quantification and Visualization of Flow in Small Vessels of the Circle of Willis: Time-resolved Three-dimensional Phase Contrast MRI at 7T Compared with 3T
Pim van Ooij, Academic Medical Center

W43 Wall Shear Stress Vectors Derived from 3D PC-MRI at Increasing Resolutions in an Intracranial Aneurysm Phantom
Pum van Ooij, Academic Medical Center

W44 Retrogated Spiral 3-directional Myocardial Phase Velocity Mapping in a Single Breath-hold
Robin Simpson, Imperial College, London

W45 A Novel Optical Flow Method for Myocardial Deformation Analysis from Tagged MRI
Mohammadreza Negahdar, University of Louisville

W46 Fast and Easy Visualization of Blood Flow Patterns in 4D Qflow MRI
Gilion Hautvast, Philips Healthcare

W47 A Dual-slice k-t Approach for Highly Accelerated Flow MRI
Daniel Giese, University and ETH Zurich, King's College London

W48 A Multi-center Inter-manufacturer Study of the Temporal Stability of Phase-contrast Velocity Mapping Background Offset Errors
Peter Gatehouse, Royal Brompton Hospital

W49 Simultaneous Wall and Blood-flow Phase-contrast Imaging Using AaSingle Low VENC
Junmin Liu, University of Western Ontario

W50 Assessment of 3D Velocity Vector Fields and Turbulent Kinetic Energy in a Realistic Aortic Phantom Using Multi-Point Variable-Density Velocity Encoding
Verena Knobloch, University and ETH Zurich

W51 Real Time Phase Encoded MR for Assessment of Acute Variability of Central Pulse Wave Velocity
Nicholas Gaddum, King's College London

W52 Hemodynamic Characterization of Aortic Valve Bypass Surgery (AVBS) Using Patient-Specific Computational Models Based on MRA and PCMR
Adrian Lam, Georgia Institute of Technology

W53 First Attempt to Motion Corrected Flow Encoding Using Free-breathing Phase-contrast CINE MRI
Christophe Meyer, Université de Lorraine

W54 Right Ventricular Strain Imaging Using 3D SPAMM Combined with Optical Flow Tracking
Hazel Rovno, University of Pennsylvania

W55 Investigation of Stenotic Jets Using 3D-PC-UTE
Karin Markenroth Bloch, Philips Healthcare

W56 Effects From RF Spoiling Disequilibrium in the Background Offsets of Phase-contrast Velocity Imaging
Peter Gatehouse, Royal Brompton Hospital

W57 Mitral Leaflet Dynamics in Ischemic Mitral Regurgitation Using High Resolution MRI
Melissa Levack, University of Pennsylvania

W58 Field-of-view Zoom during a Single-shot Short-axis Image for Cardiac Contraction Correction
Peter Gatehouse, Royal Brompton Hospital

W59 Velocity Spectrum Imaging Using Radial k-t SPIRiT
Claudio Santelli, King's College London

W60 Resolving Flow and Mass Transport in a Healthy Subject-specific Aorta Using Large Eddy Simulation
Jonas Lantz, Linköping University

W61 In-vivo Distortion of Through-plane Flow by Spiral Phase-contrast Imaging
Iain Pierce, Imperial College London

W62 Breath-held 3D Coronary Vessel Wall Imaging with Dual-density Spiral Acquisition and Parallel Imaging
Meihan Wang, University of Virginia

W63 Real Time Flow with Fast GPU Reconstruction for Continuous Assessment of Cardiac Output
Grzegorz Kowalik, Institute of Cardiovascular Science

W64 Comparison of Divergence-free Algorithms for 3D MRI with Three-directional Velocity Encoding
Michael Loecher, University of Wisconsin Madison

W65 Early Diastolic Function Observed in Canine Model of Reperfused Transmural Myocardial Infarction Using High Temporal Resolution MR Imaging
Ziheng Zhang, Yale University

W66 Normal Values of Wall Shear Stress in the Pulmonary Artery from 4D Flow Data
Julio Sotelo, Universidad de Valparaíso

W67 Flow-sensitive Four-dimensional (4D) Magnetic Resonance Imaging Reveals Abnormal Blood Flow Pattern in the Aorta and Pulmonary Trunk of Patients with Transposition of the Great Arteries Operated with Atrial Baffle Switch
Sarah Nordmeyer, Deutsches Herzzentrum Berlin

W68 Importance of k-space Trajectory on Off Resonance Artifact in Echo-planar Velocity Imaging
Jacob Bender, The Ohio State University

W69 Single Breathhold Three-dimensional Cardiac Cine MRI with Whole Ventricular Coverage and Retrospective Cardiac Gating Using kat ARC
Peng Lai, GE Healthcare

W70 A Tool for the Interactive Analysis and Exploration of In-vivo Haemodynamics from 4D PC MRI
Johann Drexl, Fraunhofer MEVIS

W71 De-noising of Dynamic Magnetic Resonance Images by the Combined Application of Wavelet Filtering and Karhunen-Loeve Transform (KLT)
Prashanth Palaniappan, The Ohio State University

W72 Towards Clinical Application of 7T TOF Angiography
Sebastian Schmitter, University of Minnesota

W73 Influence of Coronary Flow Profiles on Bolus Shape and Quantitative Myocardial Perfusion MRI
Laura Schreiber, Mainz University Medical Center

Computational Engineering International — Booth 1

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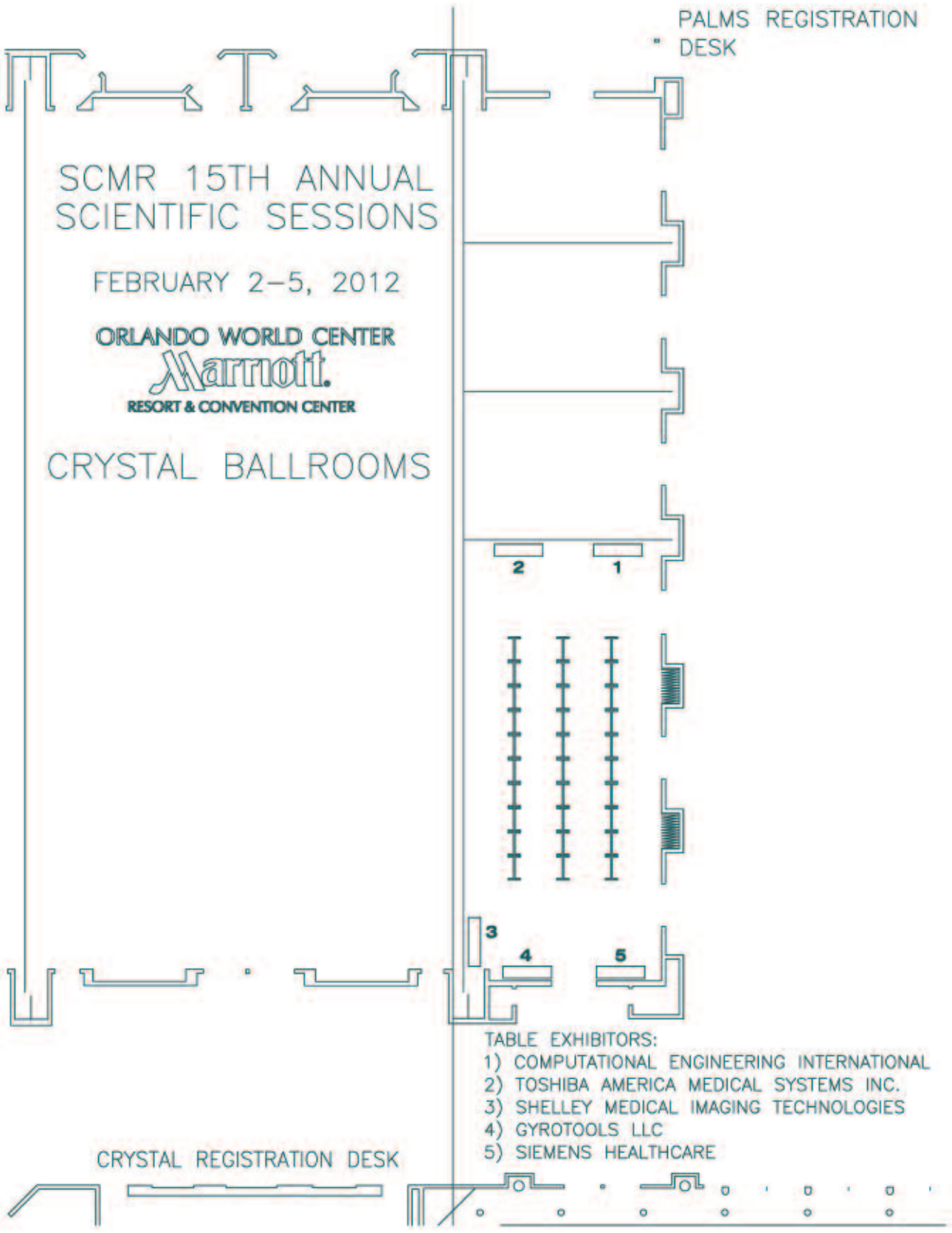

Notes

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16th Annual SCMR Scientific Sessions

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