VURTIGO: Visualization Platform for Real-time, MRI-guided Cardiac Electroanatomic Mapping

Perry E. Radau[1], Stefan Pintilie[1], Roey Flor[1], Labonny Biswas[1], Samuel O. Oduneye[1,2], Venkat Ramanan[1], Kevan A. Anderson[1,2], and Graham A. Wright[1,2]

[1] Imaging Research, Sunnybrook Health Sciences Centre
[2] Medical Biophysics, University of Toronto

Abstract. Guidance of electrophysiological (EP) procedures by magnetic resonance imaging (MRI) has significant advantages over x-ray fluoroscopy. Display of electroanatomic mapping (EAM) during an intervention fused with a prior MR volume and DE-MRI derived tissue classification should improve the accuracy of cardiac resynchronization therapy (CRT) for ventricular arrhythmias. Improved accuracy in the spatial localization of recorded EP points will produce an EAM to constrain and customize patient-specific cardiac electroanatomic models being developed for understanding the patterns of arrhythmogenic slow conduction zones causing reentry circuits and treatment planning. The Vurtigo software presented here is a four dimensional (3D+time) real-time visualization application for guiding interventions capable of displaying prior volumes, real-time MRI scan planes, EAM (voltage or activation times), segmented models, and tracked catheters. This paper will describe the architecture and features of Vurtigo followed by the application example of guiding percutaneous cardiac electroanatomic mapping in porcine models.

1 Introduction

Magnetic resonance imaging (MRI) has been used primarily as a diagnostic tool in clinical practice and has recently been applied to the guidance of interventional procedures with the development of rapid imaging acquisition protocols. In practice, real-time MR imaging refers to the acquisition and reconstruction of images in less than one heart cycle [1]. Guidance by real-time MRI is attractive compared with x-ray fluoroscopy, because MRI has better soft tissue contrast and is capable of displaying ischemic, infarcted or arrhythmogenic tissue that impacts interventional decisions to target isthmuses of infarct tissue that form slow conduction regions[16]. Furthermore, MRI is not a source of harmful radiation which is a concern for long procedures under x-ray fluoroscopy[2]. Physiological, clinical and modelling evidence suggest that the isthmus size that generates reentry circuits is 1-2mm [18, 17, 21, 19, 20] which we hypothesize is of the order of targeting accuracy achievable for our MR-guided, real-time interventional EP platform, Vurtigo.

The Vurtigo software [22] presented in this paper is designed to enhance the use of real-time computer imaging for therapeutic interventions. The Vurtigo platform has an open-source (modified BSD) license, although it permits proprietary plugins. Frameworks for various image-guided applications such as surgery [4], and specifically for MRI-guided, percutaneous cardiovascular interventions [5] have been previously described. There are a number of 2D and 3D visualization applications for MRI such as the Slicer[6] project. However, Slicer was designed to perform a wide range of tasks from real-time tracking of interventional equipment to post-processing, segmentation, registration and analysis of data. Vurtigo is focused on features that are useful in a EP interventional setting, and designed to achieve the performance and stability for real-time updates. This project represents an attractive alternative, and is open-source, cross-platform and portable to a variety of systems outside of the original communication system.

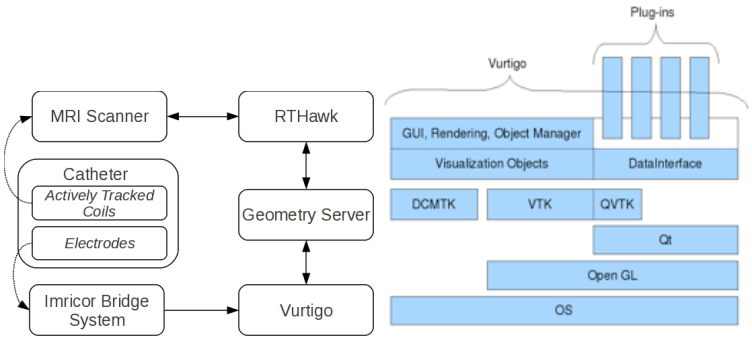
Vurtigo provides a roadmap, or 3D visual context, for the 2D real-time images using a volume acquired just before real-time scanning begins. The preoperative volume, real-time image(s) and actively tracked catheters are acquired in the same coordinate system and can be rendered together in proper spatial alignment. By comparison, using the prevalent commercial CARTO XP system (Biosense Webster, Diamond Bar, CA) an EAM is acquired under fluoroscopic (2D) guidance. This is subsequently aligned with a previously acquired MR/CT volume by manually selecting anatomical landmarks for spatial registration and then post-processing to correct for errors associated with cardiac, respiratory or patient torso motion.[14–16] Vurtigo allows importing an existing EAM dataset or composing it from tracked catheter EP recordings, and then fusing the EAM with a prior MR volume and tissue classification map. These features will be demonstrated by data from several experimental interventions with porcine models of myocardial infarct and ventricular tachycardia.

2 Architecture

This section of the paper will discuss both Vurtigo and the communication system connecting it to the MRI scanner.

2.1 Communication System Design

The communication system is composed of several pieces of software that communicate over TCP/IP sockets, (Fig. 1(a)). The central piece is the Geometry Server that serves a storage location for the most recent information, including images, image plane orientations, physiological data, and catheter information. Multiple clients can send and receive information to the server simultaneously, and all server data will remain synchronized. Between the MRI scanner and the Geometry Server is RTHawk [7]. RTHawk is both a 2D viewer and a real-time MRI scan control system, allowing customizable real-time image sequences. The communication system has been tested on GE 1.5 T Signa Excite 12.0 and



(a) Pipeline (b) Software Architecture

Fig. 1. Design. a) Communication pipeline. Vurtigo is able to passively receive information from the MRI scanner or actively prescribe the scan. EP catheter recordings are via the Imricor bridge system. b) Software components and libraries.

14.0 systems, and is theoretically compatible with all RTHawk-supported MRI systems.

Vurtigo and any other client applications connect directly to the Geometry Server and as such are independent of MRI scanner architecture. Vurtigo can passively read the scan plane orientation from the server, or drive the location of the scan plane. The latency of communication, from sending an image from RTHawk through the Geometry Server to display in Vurtigo was measured: 46 $\pm$ 11 ms (empty scene) or 64 $\pm$ 14 ms (typical EP application scene including two views, contours, and 480 EP points). Currently a work in progress, we have integrated Vurtigo into the RTHawk application and measured latencies an order of magnitude smaller: 5.6 $\pm$ 7.3 ms (empty scene) or 6.3 $\pm$ 7.7 ms (typical EP scene). The latency statistics were measured with $\geq$ 60,000 samples, by execution on a computer having an Intel®quad-core i7 2.8 GHz, 8 GB RAM, and NVIDIA®GTX 470 graphics. The unmeasured latency of communication from the scanner acquisition board to the RTHawk application (raw data client) is $\sim$3 ms.

2.2 Vurtigo Design

Vurtigo was designed and written from the beginning to provide real-time visualization for image guided interventions, and has an open-source license, (download available from www.vurtigo.ca). The architecture is illustrated in Fig. 1(b).

Vurtigo was written in C++ and uses cross-platform libraries, including Qt [9], VTK [8], DICOM Toolkit (DCMTK) [10], Insight Toolkit [11], and CUDA Toolkit [12]. CMake [13] is used as the build system. The application has been compiled on WinXP, Ubuntu Linux and MacOSX 10.6, and in principle should be compatible with most variants.

Vurtigo's plugin design provides a modular and easily extensible framework for developers, making it easy to implement desired features without advanced

knowledge of VTK. The application can be conceptually separated into the core and plug-ins. The core comprises the Graphical User Interface (GUI) as well as storage and rendering of a dynamic set of *objects*, e.g. an MRI volume, a transformation matrix, or a tracked device. Plug-ins add functionality by adding, removing, and editing these objects or enabling object interaction. Plugins can also extend Vurtigo's object framework to define new object types. Vurtigo provides developers considerable design flexibility. For example, a plug-in can provide a user interface that will be loaded dynamically. The plug-ins may be threaded, although care must be taken to track the threads internally to the plug-in. As a consequence of the modular design, plug-in developers need not be concerned with rendering updates, external objects or plug-in states, or the memory management of objects.

3 Features

3.1 Core Features

While many of Vurtigo's features are written as plug-ins, the core manages rendering and dynamic object management. Objects in the core are of two different types, those that can be rendered (e.g. 3D voxel volumes or polygonal meshes), and those that represent the state of another object (e.g. transformation matrix, colour map). There is no software-imposed limit on the number of objects that can be simultaneously loaded into Vurtigo. The software has been designed such that if an object were loaded but not rendered, then it will not have an impact on processing resources. The capacity for loaded objects, however, will be restricted by the memory (RAM) of the computer. Vurtigo on a Intel Core2 Duo laptop with 2GB RAM was able to operate normally with five volumes loaded (8 bit gray levels, matrix $512 \times 512 \times 60$). Rendering loaded objects will impact Vurtigo's execution speed depending on the object type and rendering quality.

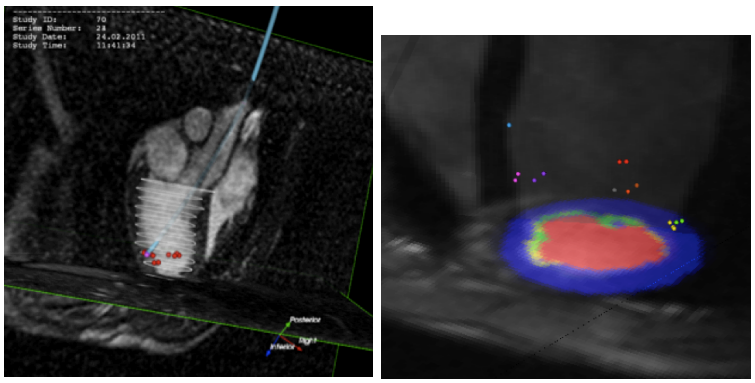
3.2 Visualization

The MRI scanner obtains real-time updates for one or two 2D planes, depending on the pulse sequence configuration. The two scan planes are completely independent and each can have a different orientation, position, and field of view (FOV). Vurtigo can display and update these real-time planes and within a prior volume visualization. If there are other real-time image sources then Vurtigo can render those images in the same 3D context. Breath-hold MRI pulse sequences can produce high-quality 3D or 4D (3D+time) datasets. After export of these files in Digital Imaging and Communications in Medicine (DICOM) format, Vurtigo can read them with accompanying meta-data describing the image and its orientation. Vurtigo has three display techniques for this content: 3-Plane, Composite, and Maximum Intensity Projection (MIP).

Rendering a set of three orthogonal planes that cut the volume and may slide along each axis or be tilted is the fastest. The 3-Plane view is texture-mapped and renders quickly even while the planes are being manipulated. A stack of

DICOM slices can also be rendered as a volume by ray tracing, and opacity is determined by voxel intensity. A Maximum Intensity Projection (MIP), a type of ray tracing that emphasizes the high intensity regions of the volume, can also be displayed. 4D volumes can be rendered and played in a loop to show cardiac motion. Hardware-accelerated rendering by CUDA compatible graphics processing units is utilized where available, increasing frame rates by a factor of 10.

All the visual objects including 2D planes, 3D volumes, 4D volumes or catheter devices that are loaded into Vurtigo are oriented and positioned in a global 3D coordinate system, and any number of these can be displayed simultaneously in their correct relative positions. The options for multiple render windows, object visibility settings, and overlay provide the means for intuitive visual comparison of MRI volumes, real-time planes, catheters, and EP mesh surfaces. An example is Fig. 2(a).



(a) Tracked catheter (b) Tissue map

Fig. 2. a)Tracked EP catheter (blue) having three microcoils fused with EP recordings (red), a prior cine MR and associated endocardial surface contours (white). b) Tissue classification map from DE-MRI fused with prior cine SSFP MR volume showing blood (red), healthy myocardium (blue), infarct (green) and heterogeneous tissue (yellow). Points are EP catheter recording locations with separate colour coding by activation time.

3.3 Interactive and Automated 2D Plane Control

Vurtigo can remotely control the MRI scan plane prescription if RTHawk is placed in read mode. Vurtigo has both a *drive mode* and a *passive mode*. In passive mode it will listen for and render new information from the scanner. In drive mode the Vurtigo interface allows the user to move the plane to a new position or orientation in the 3D view to actively change the position of the scan plane. The scanner will acquire an image at the requested position and then

pass the new image back to be rendered by Vurtigo. This way of moving scan planes is more intuitive since it has the advantage that once a prior 3D volume is loaded, or a catheter tip is located, those objects can be used as a guide to determine where the plane should be positioned. Automated prescription of real-time and/or prior roadmap planes to follow the catheter tip has also been implemented in Vurtigo.

4 Methods for EP Interventions

4.1 Active Tracking of Catheters

Catheters can be actively tracked in the MR using microcoils placed on the catheter which are sensitive to a small region in their vicinity. The location of a microcoil can be determined using a non-selective (or weakly selective) RF pulse and acquiring projections in three orthogonal directions. A centroid-based peak detection is usually used to determine the location of the microcoil in three dimensions [23].

Tracking was done with a projection (TR of 12 ms) along each direction and a tracking field of view (FOV) of 40 cm to give a true tracking rate of approximately 28 frames per second (fps) and a resolution of 1.6 mm. Active detuning of the surface coil was used to avoid coupling with the catheter coils, and requires less time ($\sim$3 ms) than the shortest TR using for imaging/tracking. The accuracy of tracking was measured in a water bath to be $\leq$2 mm, but requires further validation in-vivo.[24]

The signal in the coil is susceptible to the orientation of the catheter microcoils with respect to the main magnetic field. Additionally, tracking projections are poor when there are magnetically susceptibility differences between the catheter and tissues or materials near the microcoil. These could result in double peaks or other artifacts in the projection [25]. These are the main sources of errors in our tracking procedures. Peak offsets due to off-resonance frequencies are not an issue in practice due to the higher bandwidths (125 KHz) in our acquisition.

The tracking sequence is sensitive to off-resonance frequencies; these may be due to field inhomogeneities in the main magnetic field and variations in the local magnetic susceptibility. The field inhomogeneities were minimized by a prescan with a prescribed shim volume over the heart. We used higher bandwidths (125KHz) for the acquisition to give a 488 Hz bandwidth per pixel, so that any remaining centre frequency offset has negligible effect on positioning.

Depending on the number and location of tracked coils, Vurtigo is able to display the device's tip, the tip and direction, or a spline indicating the catheter's shape. With Vurtigo in drive mode, prior volume image planes can be attached to a tracked location on or near the catheter tip to follow its movement.

4.2 EP recordings and EAM generation

EP interventional procedures usually use two catheters. A mapping catheter is used to map the surface electrophysiological signals. A pacing catheter is

used to pace the heart slightly above its natural rate. In our EP interventions, anywhere from one to three microcoils on a mapping catheter are tracked as it is maneuvered in the LV, as well as one microcoil on the pacing catheter placed in the RV that provides programmed stimulation.[26]

EP measurements were performed using a prototype Bridge EP Recording System with two Vision MR conditional catheters (Imricor Medical Systems, Burnsville, MN). A porcine model of myocardial infarct was used for experimental EP recordings, with three of six subjects completing the entire procedure (catheter insertion, recording, removal) successfully.

MR-guided activation EP data was post-processed by Vurtigo to generate voltage amplitude maps or isochronal maps of local activation time (LAT). Each EP recording is matched to the simultaneously captured catheter position data with cardiac diastolic gating of both datasets (approximately 200ms window).

After labelling each recording point with the EP data (voltage or LAT), the data is mapped to a LV endocardial surface mesh that was automatically segmented by an in-house MATLAB®(Mathworks) post-processing algorithm [27] from the diastolic phase of the prior cine SSFP volume, (Fig. 3). Each mesh vertex is assigned the weighted average of the EP values of the recorded points (eg. voltage or LAT) located within a 10 mm (user defined) area of effect. The weightings are calculated by the inverse squared distance between the vertex and the EP recording locations, with the weight sum normalized to one. The vertices are coloured by a lookup table which maps the scalar values to RGB colours, and there is linear interpolation of colour between the vertices of each mesh triangle. This method improves upon conventional EAM by ensuring that the map has an anatomical shape rather than the best fit mesh derived from asymmetrically sampled EP recording locations that often has an irregular shape.[26]

Validation of the spatial and temporal fusion is a work in progress. For fusion of prior cine volumes with catheter locations, the catheter points were filtered to match the cardiac phase (diastole). A limiting factor is the temporal resolution (50 ms) of the prior cine volume. Therefore an estimate of the synchronization error would be approximately 65 ms, due to cine temporal resolution and variation in communication latency, assuming regular cardiac rhythm. The spatial error would correspond to the displacement of the cardiac wall over this time interval, though diastolic motion is slow. Additional spatial registration errors that require estimation and/or compensation are gross patient motion between the time of prior volume acquisition and the intervention, and the cycle-to-cycle variation due to cardiac and respiratory motion.

4.3 MR Imaging

MR imaging was performed on a 1.5 T CV/i scanner (GE Healthcare, Milwaukee, WI, USA) using a 5" surface coil. For real-time imaging, spoiled gradient echo images (128x128 pixel, 30 cm FOV, 2.3 mm resolution) were continuously acquired with a 6.8 ms TR for a true frame rate of about 9 fps. Prior volume cine SSFP parameters: 256×256 pixels, TR 3.7-4.7 ms, 20 phases, 19-23 cm FOV. During in-vivo experiments catheter tracking positions were rendered with the prior volume. Tracking was occasionally alternated with 2D real-time

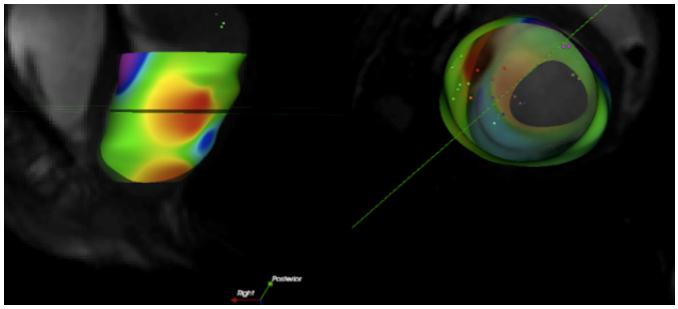


Fig. 3. Long (left) and short axis (right) views of the LV endocardial surface segmented from the prior MR volume in a fused display. Surface colour coding represents an LAT map obtained from an EP recording catheter.

scan planes to observe the current state, albeit with lower resolution and smaller FOV than the prior volume images. Rendering the volume, the real-time planes and the catheters in a fused visualization improves the interventionalist's ability to navigate with respect to the patient's anatomy.

One or more prior MR volumes were also acquired to provide detailed visualization of anatomy (cine SSFP series) or infarct. (Infarct was determined by a novel late Gadolinium enhanced (LGE) MRI series, multi-contrast delayed enhancement (MCDE)[28] with imaging parameters: SAX, 256×256 mm, 4-4.3 ms TR, 20 phases, 22-23 cm FOV.) Automatic segmentation and classification of MCDE provides maps that indicate healthy, infarcted and heterogeneous tissue. The latter has been shown to be predictive of arrhythmia events (inducibility of VT, appropriate activation of an implanted intracardiac defibrillator), and may provide an additional target for cardiac resynchronization therapy[29]. Vurtigo has the capability of fusing the tissue map with the anatomy and EP catheter information, either by same-day imaging or post-processing with landmark registration, (Fig. 2(b)).

5 Conclusions

Vurtigo is a cross-platform, freely available, open-source application, that provides advanced visualization for image-guided interventions, and has a vital role in supporting our image-guided, in-vivo EP experiments. Several new features are works in progress at this time including real-time calculation of EP data (voltage and LAT maps) from tracked EP recording catheters, and the implementation of improved signal processing and motion correction of EP data points. Further validation of the registration and synchronization accuracy, especially in-vivo, is required to assess the fusion errors of catheter locations and imaging. Work is in progress to analyse the correspondence of tissue heterogeneity from MR and slow conduction zones from electroanatomic mapping, before and after RF ablation therapy.

6 Acknowledgements

The authors would like to thank the Canadian Foundation for Innovation and Canadian Institutes of Health Research for their support.

References

1. Nayak K.S., Hu B.S.: The future of real-time cardiac magnetic resonance imaging. Curr Cardiol Rep. 2005 Jan;7(1):45-51.
2. Ladd M.E., Quick H.H., Debatin J.F.: Interventional MRA and intravascular imaging. J Magn Reson Imaging 12(4), pp. 534-46, 2000.
3. Pintilie S, Biswas L, Anderson KA, Wright GA, Radau P.: Visualization Software for Real-time Image-guided Therapeutics in Cardiovascular Interventions.MICCAI: Cardiac Interventional Imaging and Biophysical Modeling Workshop, 2009.
4. Gary K., Ibanez L., Aylward S., Gobbi D., Blake M., Cleary K.: IGSTK: An Open Source Software Toolkit for Image-Guided Surgery. IEEE Computer, 2006; pp 46-53.
5. Guttman M., et al. Real-time accelerated interactive MRI with adaptive sense and unfold. Magn Reson Med. 50,315-321, 2003.
6. 3D Slicer. `www.slicer.org/`
7. Santos J.M., Cunningham C.H., Lustig M., Hargreaves B.A., Hu B.S., Nishimura D.G., Pauly J.M.: Single Breath-Hold Whole-Heart MRA Using Variable-Density Spirals at 3T. Magn Reson Med, 55:371-379, 2006.
8. Schroeder W., Martin K., Lorensen B.: Visualization Toolkit: An Object-Oriented Approach to 3D Graphics, 4th Ed., 2006.
9. Blanchette J., Mark Summerfield M.: C++ GUI Programming with Qt 4, 2nd Ed., 2008.
10. DCMTK - DICOM Toolkit. `dicom.offis.de/dcmtk`
11. Ibanez L., Schroeder W., Ng L., Cates J.: ITK Software Guide. ITK Version 2.4. 2005.
12. CUDA Toolkit. `www.nvidia.com/object/cuda_home.html`
13. Martin K., Hoffmann B.: Mastering CMake, 4th ed., 2008.
14. Desjardins B, Crawford T, Good E, Oral H, Chugh A, Pelosi F, Morady F, Bogun F.: Infarct architecture and characteristics on delayed enhanced magnetic resonance imaging and electroanatomic mapping in patients with postinfarction ventricular arrhythmia. Heart Rhythm. 2009 May;6(5):644-51. Epub 2009 Feb 14.
15. Dickfeld T, Tian J, Ahmad G, Jimenez A, Turgeman A, Kuk R, Peters M, Saliaris A, Saba M, Shorofsky S, Jeudy J.: MRI-Guided ventricular tachycardia ablation: integration of late gadolinium-enhanced 3D scar in patients with implantable cardioverter-defibrillators.Circ Arrhythm Electrophysiol. 2011 Apr 1;4(2):172-84. Epub 2011 Jan 26.
16. Wijnmaalen AP, van der Geest RJ, van Huls van Taxis CF, Siebelink HM, Kroft LJ, Bax JJ, Reiber JH, Schalij MJ, Zeppenfeld K.: Head-to-head comparison of contrast-enhanced magnetic resonance imaging and electroanatomical voltage mapping to assess post-infarct scar characteristics in patients with ventricular tachycardias: real-time image integration and reversed registration. Eur Heart J. 2011 Jan;32(1):104-14. Epub 2010 Sep 23.

17. de Chillou C, Lacroix D, Klug D, Magnin-Poull I, Marqui C, Messier M, Andronache M, Kouakam C, Sadoul N, Chen J, Aliot E, and Kacet S: Isthmus characteristics of reentrant ventricular tachycardia after myocardial infarction. Circulation 2002 Feb 12;105(6):726-731.
18. Stevenson WG, Khan H, Sager P, Saxon LA, Middlekauff HR, Natterson PD, Wiener I.: Identification of reentry circuit sites during catheter mapping and radiofrequency ablation of ventricular tachycardia late after myocardial infarction. Circulation. 1993 Oct;88(4 Pt 1):1647-70.
19. Janse MJ, Wit AL: Electrophysiological mechanisms of ventricular arrhythmias resulting from myocardial ischemia and infarction. Physiol Rev. 1989 Oct;69(4):1049-169. Review.
20. Kleber AG and Rudy Y: Basic mechanisms of cardiac impulse propagation and associated arrhythmias, Physiol Rev. 2004 Apr;84(2):431-88. Review.
21. Bub G and Shrier A: Propagation through heterogeneous substrates in simple excitable media model. Chaos. 2002 Sep;12(3):747-753.
22. Pintilie S, Biswas L, Oduneye SO, Anderson KA, Wright GA, Radau PE.: Visualization platform for real-time, MRI-guided cardiac interventions, Proceedings 19th Scientific Meeting, ISMRM, Montreal, May 7-13, 2011, 6887.
23. Dumoulin CL, Souza SP, Darrow RD.: Real-time position monitoring of invasive devices using magnetic resonance. Magn Reson Med 1993; 29:411-15.
24. Ramanan V, Oduneye SO, Biswas L, Pintilie S, Wright GA: Accurate catheter tip tracking for MR-Guided EP procedures using realtime active detuning. Proceedings 19th Scientific Meeting, ISMRM, Montreal, May 7-13, 2011.
25. Dumoulin CL, Mallozzi RP, Darrow RD, Schmidt EJ.: Phase-field dithering for active catheter tracking. Magn Reson Med 2010;63:1398-1403.
26. Oduneye SO, Biswas L, Pintilie S, Ramanan V, Barry J, Zeidan Shwiri T, Kadmon E, Crystal E, Wright GA: MR-Guided endocardial local activation time map during programmed stimulation. Proceedings 19th Scientific Meeting, ISMRM, Montreal, May 7-13, 2011, 3888.
27. Lu Y, Radau P, Connelly KA, Dick AJ, and Wright GA.: Segmentation of left ventricle in cardiac cine MRI: an automatic image-driven Method, Functional Imaging and Modeling of the Heart 2009, Nice, France, June 3-5, 2009, In: Lecture Notes in Computer Science, 5528: 339-347.
28. Detsky JS, Paul GA, Dick AJ, Wright GA.: Reproducible classification of infarct heterogeneity using fuzzy clustering on multicontrast delayed enhancement magnetic resonance images. IEEE Trans Med Imaging. 2009 Oct;28(10):1606-14.
29. Roes SD, Borleffs CJ, van der Geest RJ, Westenberg JJ, Marsan NA, Kaandorp TA, Reiber JH, Zeppenfeld K, Lamb HJ, de Roos A, Schalij MJ, Bax JJ.: Infarct tissue heterogeneity assessed with contrast-enhanced MRI predicts spontaneous ventricular arrhythmia in patients with ischemic cardiomyopathy and implantable cardioverter-defibrillator. Circ Cardiovasc Imaging. 2009 May;2(3):183-90. Epub 2009 Mar 23.