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Abstracts

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Ultrafast imaging and K-space

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Introduction: k-space is an elegant way to describe image formation in magnetic resonance imaging (MRI). In the realm of dynamic processes such as contrast-enhanced magnetic resonance angiography (ce-MRA), it is important to know the k-space trajectory, i.e. the temporal order in which k-space data are acquired. Specific strategies need to be applied to optimally match the imaging techniques to the physiologically controlled process of contrast transportation through the vascular system.

Basics: In ce-MRA, the use of a paramagnetic contrast agent increases the blood signal in a FLASH-type imaging sequence due to T1-shortening of blood. Following the intravenous injection of the contrast agent, it is delivered to the vessel of interest. Local blood signal is substantially enhanced. This result is optimal when data collection, in particular the center of k-space, occurs right when the contrast agent arrives at the vessels being imaged. Therefore, timing of the scan with respect to the intravenous injection is important in ce-MRA.

Methods:

- Speed. With recent improvements in gradient hardware it is possible to reduce the TR to as little as 1.6 ms. This allows the acquisition of multiple three-dimensional data sets every 2.5 s, as an example, with adequate spatial resolution to visualize emboli in the pulmonary vasculature.
- k-space trajectory. The order of k-space acquisition is synchronized with the bolus arrival. In one implementation the k-space trajectory starts in the center right during the peak arterial enhancement. The remaining k-space points are acquired in a centric elliptical fashion.
- k-space manipulations. Instead of full k-space acquisitions only parts of k-space is measured. In particular, the center of k-space can be scanned more often to increase temporal resolution, and create multiphase images during the contrast injection.

Conclusion: The major challenge in ce-MRA is related to the correct timing of the measurement sequence relative to the arrival of the contrast in the vessel of interest. Speed is of most importance, and as such, k-space needs to be scanned as quickly as possible with the shortest TR. Additional techniques with specific k-space trajectories and k-space manipulations will further help to get optimal arterial contrast with maximal spatial resolution.

Current developments in magnetic resonance contrast agents

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While the recent rapid developments in MRA were achieved using standard, non protein interacting Gd-chelates like gadopentetate dimeglumine (Gd-DTPA, Magnevist), gadodiamide (Gd-DTPA-BMA, Omniscan), gadoteridol (Gd-HP-DO3A, ProHance), gadoterate (Gd-DOTA, Dotarem) and gadoversetamide (Gd-DTPA-BMEA, OptiMARK), we have today quite a number of different agents in development or already available. In addition to the standard concentration of 0.5 M, 1.0 M concentrations have been made available such as gadobutrol (Gd-BT-DO3A, Gadovist). Two additional classes of Gd-chelates can be categorized, weak (Gd-BOPTA, MultiHance) and strong (MS-325, AngioMARK) protein binding Gd compounds. Furthermore, several different superparamagentic agents like NC100150 (Clariscan) or (Resovist C) are being evaluated for MRA, which exhibit long vascular enhancement. The 'blood pool' agents are further evaluated regarding their potential for 'first pass' imaging as

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well as 'steady state' MRA. 'Blood pool' MRA is further challenged with the arterio-venous overlay requiring segmentation techniques. This variety of different agents lead also to quite distinctive different enhancement characteristics in the first pass and delayed phases. The presentation will not offer conclusions to which agent is better or not, instead it is designed to introduce the agents and their properties for ce-MRA and give examples where those properties might be helpful and which characteristics need to be considered for optimization of MRA.

Magnetic resonance imaging/magnetic resonance angiography of the thoracic aorta

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Purpose: To review the use of MRI and MRA for the aorta in clinical practice.

Materials and Methods: Clinical experience over the last 10 years in hundreds of patients with known or suspected aortic pathology will serve as the basis for this review. Useful techniques will be discussed and applied to appropriate indications.

Results: Black blood imaging remains an essential part of evaluation of the thoracic aorta. Cardiac triggered SE black-blood imaging is the 'backbone' in the MR evaluation of the aorta. A half-Fourier single shot turbo spin-echo (HASTE) pulse sequence that uses this double inversion pulse to null the signal of blood is a particularly efficient technique. Gradient echo, flow sensitive imaging and Gd-enhanced three-dimensional MRA are useful bright blood adjuncts. Appropriate use of MR techniques in the setting of aneurysmal disease, dissection, intramural hematoma, and post-operative surveillance will be discussed. A clinical context for interpretation is essential and will be emphasized.

Conclusions: Accurate and time-efficient evaluations of known or suspected aortic pathology are possible with the use of rapid MR techniques; an understanding of the clinical context for these studies is essential for accurate interpretations.

Magnetic resonance angiography of the peripheral arteries

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'Time-of-flight' MRA has not been routinely incorporated into clinical practice for evaluating the peripheral vasculature because images are prone to artefact (over-estimation of both degree and length of stenosis) and scan times are prohibitively long for comprehensively evaluating the peripheral vasculature. Contrast-enhanced MRA has now established itself as the method of choice for evaluating the peripheral vasculature. Images of a single anatomical region of interest can be acquired, although the limitation of poor spatial coverage in the head–foot direction (< 50 cm) relative to the requirement for imaging over a long distance (> 100 cm typically) limits the usefulness of this approach. However, specific clinical issues (e.g. the state of the inflow arteries/patency of infra-popliteal arteries, etc.) can be addressed. The limitation of poor spatial coverage has now been overcome by the use of the so-called 'moving-table' technique, in which images are acquired over three or more overlapping fields of view during a single bolus of contrast agent (0.2–0.3 mmol/kg) with rapid repositioning of the patient between scans. Because of the relatively long total scan time a lower injection rate is typically used (0.5–1 cm^3/s) to reduce the risk of venous-contamination in the legs. Bolus detection and flexibility over the order of k-space mapping are essential for highest quality studies, mask subtraction offers an advantage at least in the legs. The scope of the examination can be further improved by performing dynamic two-dimensional imaging over the foot arteries (a fourth station) during injection of a second bolus of contrast agent (5 cm^3). Anticipated shortening of acquisition times without sacrificing spatial resolution, tailored scan parameters, improved coil design and more potent contrast agents will further improve the application of this already validated technique.

Embedded fluoroscopy for improved contrast-enhanced magnetic resonance angiography

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Many methods for three-dimensional ce-MRA are designed so that data acquisition is performed over the transit of the contrast bolus. Once the acquisition is initiated it is often not possible to know the actual contrast bolus dynamics, particularly if a long, high resolution three-dimensional acquisition is performed. In this work we present a means for monitoring the contrast bolus during the three-dimensional acquisition. This is done by interleaving views for a two-dimensional image sequence into the three-dimensional data acquisition, using the same field of view and pulse sequence for both the two-dimensional and three-dimensional sequences. The two-dimensional sequence redundantly samples a central line of the three-dimensional k-space. We have previously shown that this 'embedded fluoroscopy' method can provide images at a 0.5 Hz rate with good spatial resolution. In this work we demonstrate further applications including: (i) generation of parenchymal enhancment patterns simultaneously with high resolution, centrically encoded three-dimensional acquisition; (ii) modulation of the

flip angle of the three-dimensional acquisition based on real-time estimation of the contrast concentration as seen in the two-dimensional image sequence; and (iii) fluoroscopic triggering with a seamless transition from the fluoroscopic to three-dimensional phases.

Fast, comprehensive high resolution contrast-enhanced magnetic resonance angiography using undersampled three-dimensional projection imaging

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We have recently reported a general imaging sequence that produces isotropic resolution over large FOVs. Using a projection trajectory, the sequence undersamples in three k-space dimensions to reduce scan times by factors of four to twelve relative to Fourier techniques. Here we present applications for the sequence in abdominal ce-MRA.

Materials and Methods: We have implemented RF spoiling with gradient dephasing to produce a heavily T1-weighted sequence. We use non-selective RF excitation and use the coil dropoff to limit signal from outside the FOV. We acquire 1.5 mm isotropic resolution over a $38 \times 38 \times 38$ cm volume using 10 000 projections during a 35 s breath-hold. We inject 38 ml of Gd-contrast at 2 ml/s after using 2 ml for a dose timing study.

Discussion: In this implementation, scan time relative to an equivalent Fourier scan was reduced four to six times depending on whether homodyne processing was used. The large volume can quickly be centered over the abdomen to provide complete coverage of the renal, mesenteric, and spinal vessels in one breath-hold. The unsampled, high spatial frequency information aliases as a noise-like signal, compared to the streak-like artifacts seen when projection sampling is limited to two k-space dimensions.

Real-time bolus chase magnetic resonance angiography

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Two important issues for clinical ce-MRA are bolus timing and covering adequate anatomy. Fluoroscopic triggering provides reliable timing, and bolus chase acquisition allows imaging of multiple regions. This paper presents a real-time technique that achieves both reliable timing and multiple region coverage. The real-time system is developed using a workstation that communicates with the scanner data acquisition via a fast BIT3 connection (5 Mb/s). Image updating rates are 256×256 per 0.15 s. Latency on controlling data acquisition is < 1 ms. The real-time system is integrated with a fast gradient echo sequence consisting of both two- and three-dimensional pulses. Imaging starts at the aortic arch using two-dimensional, and remains there until the arch is filled with Gd. Then the sequence switches to three-dimensional. At the same time, the FOV center is shifted cranially to the carotid bifurcation for imaging the carotid arteries, or to the renal artery origin or further caudal for imaging renal arteries and abdominal aorta. The arteries in the lower extremity are imaged by stepping the table further caudally. The SFAs are imaged with two-dimensional or accelerated three-dimensional, and the tibial trifurcations are imaged with three-dimensional.

Recent advances in clinical magnetic resonance angiography at 3.0T

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Object: Last year we described our initial work to tailor a 3.0T scanner for routine clinical use. Consequently, from October 1999 to July 2000, we have imaged over 1250 patients at 3.0T. The purpose of the present work is to extend and refine the use of the 3.0T system for clinical applications.

Materials: All studies were performed on a GE VH/i 3.0T system equipped with 40 mT/m gradients. Additional coils were built either in-house, or by Ravi Srinivasan of AIRI (Cleveland, OH).

Methods: To fully exploit the advantages of a whole-body 3T scanner, coils beyond a single transmit-receive head coil are required. We have evaluated a prototype cervical coil and an improved head coil (both by AIRI), in addition to wrist and knee coils. Software development includes the use of MT at 3.0T using higher MT flip angles for the center of k-space, very short TE for pulse sequences for gadolinium bolus studies to minimize susceptibility artifacts, and methods to reduce flow artifacts.

Results: Transmit-receive coils for the cervical arteries (and other regions of the body) are feasible for clinical practice at 3.0T. The clinical applications of 3.0T imaging will continue to grow as new hardware and software is developed.

Real time imaging using sense

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SENSE (SENSitivity Encoding) uses the spatial information of phased array coil elements to reduce the imaging time. For MRA, the SENSE technique can be used to reduce the imaging time of three-dimensional

and two-dimensional (contrast enhanced) scans. For real time MRA imaging, the SENSE technique can be used to obtain a higher frame rate. This will give a better visualization of contrast bolus passage. Examples will be shown of real time MRA imaging using the SENSE technique in combination with conventional gradient echo techniques as well as SSFP and EPI techniques. Applications in the thorax and head will be shown. Currently, for most real time applications, a SENSE factor of 2 is used, resulting in a two times higher imaging speed.

Magnetic resonance angiography using steady state free precession

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Purpose: To investigate the feasibility of using steady-state free precession (SSFP) for MRA.

Materials and Methods: In SSFP the FID (S^+-signal) and spin echo (S^--signal) from a train of rf pulses are refocused in each TR interval. This increases the available image S/N. However, with standard SSFP images, signal from fat is high and does not decrease with increasing flip angles at short TR times. In addition, water signal is also bright and can obscure vascular structures. A different technique that uses a weighted S^--signal image as a mask image for effective suppression of fat and water signals for improved SSFP vascular imaging is proposed.

Results: This different approach generated high S/N vascular visualization well after the arterial phase of the administration of extra-cellular Gd-chelates as a contrast agent. The visualization of the veins, in particular, was significantly improved in the post contrast SSFP images as compared to that acquired using conventional gradient-recalled echo imaging. Furthermore, S^- mask images could be acquired at any time and not necessarily as a pre-contrast mask as in conventional contrast-enhanced MRA. The improved S/N and short acquisition times of a three-dimensional-SSFP sequence also allowed higher resolution images to be obtained.

The use of sensitivity encoding (SENSE) to reduce acquisition time in renal and outflow magnetic resonance angiography

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Using an array of receiver coils, SENSE (Syncrascan, Philips Medical Systems) undersamples k-space in the phase encoding direction(s) to decrease acquisition time. The resultant aliasing can be eliminated through a mathematical combination of data from each coil based on its different geometry/sensitivity. Applying SENSE to three-dimensional Gd-enhanced MRA, acquisition times can be reduced one-and-a-half to threefold without changing spatial resolution. SNR changes by sqrt(1/SENSE factor) × (coil geometry factor), although some of this SNR loss can be recovered by increasing Gd injection rate. In four patients (reduction factor 3), our geometry factor was approx. 0.73. We present data for both renal and moving table outflow MRA, where SENSE reduces acquisition time in the abdominal station (15 s renal, 11 s outflow). For renal MRA, this decreases breath-hold requirements, reducing chances of motion. We compare SNR and vessel sharpness in patients imaged twice (with/without SENSE). In outflow MRA, we utilize fast upper station SENSE acquisition to move rapidly to the lower stations, beginning acquisition of the third station 34 s after triggering from the aorta. This allows us to increase the Gd injection rate and achieve < 1 mm isotropic resolution in the lower station while decreasing chances of venous enhancement.

Quantitative evaluation of non-repetitive phase encoding orders for first-pass, three-dimensional contrast-enhanced magnetic resonance angiography

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The object of this study was to perform a detailed quantitative comparison of many alternative phase encoding strategies for first-pass, non-repetitive three-dimensional MRA, where each phase encode is only sampled once during the transient passage of contrast agent. The characteristics of the different phase encoding orders were tested using both a computer simulation and experimental verification using a variable flip angle scheme to precisely reproduce the contrast curve enhancement. A series of standard sequential and centric phase encoding orders including elliptical centric were used as well as two new orders defined here as elliptical sequential and a contrast curve dependent order. The characteristics to be considered included: degree of compactness, arterial and venous intensity, arterial-to-venous contrast, degree of artifact, and the blurring of the point spread function. By making use of a wide range of start times within a given contrast curve, the widely varying merits of each phase encoding order were determined and graphically portrayed. In

general, when an optimal start time is used, techniques that sample the low k-space views as compactly as possible will produce the best results; however, the same methods are more problematic when the bolus arrival time deviates substantially from that expected.

Applications of nonenhanced magnetic resonance angiography: a dual-phase acquisition, functional magnetic resonance and, and an rf subencoding acquisition

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Nonenhanced MRA, fresh blood imaging (FBI) using ECG-triggered three-dimensional half-Fourier FSE, has been presented. We report here the applications of FBI, a dual-phase scan for separation of arteries from veins, functional MRA using tagged-FBI, and an rf subencoding acquisition using multiple coils. Dual-phase FBI allows acquiring dual ECG-triggered phases in a single acquisition. Prior to three-dimensional scan, an ECG-prep scan is acquired to determine an appropriate ECG delay time for bright-blood (diastole) and black-blood arteries (systole). In three-dimensional acquisition, a single dual-phase scan with applying two different ECG delay times is acquired. After acquisition, subtraction provides artery-weighted images. The merits are reduction of two separate scans to a single dual-phase scan and less misregistration. Tagged-FBI permits studying functionality of blood vessel. A selective IR-tag pulse is applied to mark the blood vessel of interest to analyze the blood flow velocity and the blood flow function. Furthermore, an application using an rf subencoding method enables further reduction of acquisition time and T2 blurring effect, resulting improvement in image quality.

Advances in image processing techniques applied to three-dimensional magnetic resonance angiography images enhancement, segmentation and quantification — a survey and contributions

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Noise removal and contrast enhancement in vascular images require anisotropic operators. Their response either is a combination of measurements (derivatives, mean intensities...) for a set of discrete line segments, or it is computed for a single segment after estimation of local orientation. In MRM'97 we proposed a robust technique for the local orientation estimation. Now we improved the operator applied in the estimated direction. It combines a directional L-filter (truncated mean) and a Laplacian orthogonal to it. Most three-dimensional vessel segmentation techniques are based on a generalized cylinder model: centerline + surface. Usually, centerline extraction uses second derivatives. The surface is then approximated by planar contours orthogonal to the axis, obtained by edge detection. Our centerline extraction technique is based on inertia moments calculation (cf. CAR'99). We improved it to cope with strong curvatures and presence of other vessels in the vicinity. Associated with a deformable contour model it allows an automated stenosis quantification. Its maximum error is less than 5%.

Carotid artery and its centerline extracted by our algorithm.

Advanced magnetic resonance angiography image segmentation using the depth buffer (Z-buffer) segmentation algorithm

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The Z-buffer Segmentation Algorithm (ZBS) that we presented previously performed image segmentation based upon positional smoothness and continuity of objects that appear in the maximum intensity projection (MIP) of the MRA image data. The MIP Z-buffer, consisting of the original 'Z' positions of each point that projects into the MIP image, provides a two-dimensional image that is processed to look for positional smoothness around every point in the MIP image. In this presentation we will review several improvements that have been made since the initial description of the algorithm. These include improvements to the display, the segmentation algorithm, and the acquisition technique. (1) Display improvements: Working with our neurosurgery and neuroradiology collaborators we have developed a reduced dynamic range display with a rapid and intuitive user interface, and a variety of options to view the original image date (or MIP of the original data) in conjunction with the ZBS structure. (2) Segmentation algorithm improvements: We have also developed and are evaluating a multiple-MIP (multiple-direction, multiple overlapping slab) segmentation algorithm. The original algorithm operated on the Z-buffer from a single axial collapse MIP Image. The new algorithm allows multiple directions and multiple

thicknesses of the MIP algorithm to be investigated. (3) Finally, we have found the segmentation to be somewhat sensitive to ghosting artifacts related to the flow in the circle of Willis of some patients. We hypothesize that this artifact is related to the difference in timing between the phase and frequency encoding pulses. This timing difference in conjunction with the pulsatile motion of the blood results in pseudo motion of the blood vessels. The artifact is reduced by either bipolar first order gradient nulling of the phase encoding pulses or an elliptical centric acquisition, or both.

Three-dimensional magnetic resonance angiography imaging of cerebral aneurysms with volume rendering method

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Three-dimensional time-of-flight (Tof) MRA has been applied as a first choice of MRA methods in the detection of cerebral aneurysms. Also, MIP (maximum intensity projection) method has been performed as a standard image presentation of MRA. However, sometimes, it is difficult to understand the detail information from MIP images. The purpose of this study is to produce three-dimensional images of aneurysms from three-dimensional TOF MRA data, and evaluate the clinical ability of volume rendering (VR) method in comparison with MIP method. Thirty-five cases with 40 cerebral aneurysms (20 ICA, 10 MCA, and 10 ACA) were examined by three-dimensional TOF MRA. MRA was performed with two 1.5-T MRI units (Signa Horizon; GE, Gyroscan ACS-NT; Philips). MIP and VR images were generated from the same MRA data on a workstation (Advantage Workstation). VR images were reconstructed in the permitted time at clinical use. In the detection of aneurysms, MIP method has same ability as VR method. However, VR method was a useful method to know the exact relationship between aneurysms and parent arteries. The VR method should be performed when small aneurysms are suspected on MIP images.

An iterative algorithm for automated stenosis grading on magnetic resonance angiograms

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Objective: To assess an iterative algorithm for automated stenosis grading (FOS) on MR angiograms.

Method: A model with 29 different stenoses was established by ligation of six plastic hoses of 3, 4, 5, 6, 8, and 10 mm inner diameter. Stenoses were graded (1) by automated FOS algorithm, and (2) by the gold standard X-ray angiography of hoses filled with iodinated contrast media. MR imaging was conducted with isotropic voxel sizes of 1, 1.5, 2, and 4 mm^3.

Results: With the gold standard X-ray, seven stenoses were $\leqslant 50\%$, seven were 51–70%, and 15 were $> 70\%$. The grading differences between FOS and X-ray increased, as a function of (1) increasing isotropic voxel size and (2) decreasing vessel size. In hoses with 3–4 mm diameter the grading differences increased substantially, when the resolution declined from 1.5 to 2 mm^3 isotropic voxel size.

Conclusion: With isotropic voxel size of 1.5 mm^3 or smaller the FOS algorithm allows precise grading of stenoses on MR angiograms, particularly in larger vessels. With increasing voxel size and in small vessels, however, the the FOS algorithm may overestimate stenosis grade.

Arteries–veins separation by use of three-dimensional greyscale connectedness

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The complex three-dimensional structure of vascular trees images acquired with MRA is difficult to interpret using current visualization techniques. We propose a post-processing method to segment the arterial and the venous circulations, based on a generalization of the concept of connected components. Using the conventional connectedness, two objects in a binary image are connected (and then given the connectedness 1) if there is a path joining them inside the object; otherwise they are not connected (connectedness 0). The extension to a greyscale image allows the connectedness to take any numerical value between 0 and 1. The computational complexity can furthermore be reduced by only computing the connectedness in relation to regions of interest in the volume (e.g. parts of the arteries and veins, colored by the user). This will allow us to know, for each voxel, if it is connected more to the arteries or to the veins, thus providing segmentation. The original volume is then masked with the segmentation results, and rendered in two-dimensional using a maximum intensity projection algorithm. The described method has shown promise in separating arteries from veins in blood-pool agent MRA.

Real time three-dimensional volume visualization using segment tree and VolumePro

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Doctors to do surgical planning usually use two-dimensional MRI images. In order to provide more information to aid this process, three-dimensional reconstructed organ is desired, which is called volume

visualization. VolumePro is specially designed hardware card for this purpose, which is a low level volume rendering engine but can only handle image size smaller than 526 × 526 × 256. We propose a segment tree structure to manipulate volume visualization from high level. The tree node can store three-dimensional volume objects generated by VolumePro and three-dimensional graphics objects generated by surface rendering and can even hold large volume organ, which cannot be generated by VolumePro directly, complex graphics object such as the surgical tools and four-dimensional objects, which are changing from time to time to achieve real time effect. According to these ideas, we implement a system called Virtual Doctor and use the three-dimensional visual human MRI slices as the testing dataset. With this system, the doctor can do real time surgical planning with virtual animated three-dimensional organs; cutting off the tumors or tissues; flying into the human body; seeing the inside part. The original two-dimensional image slices and perspective projected images slices are also provided.

Inherent errors in measuring cross sectional area of blood vessels

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As MRA imaging continues to improve, via increases in resolution, speed and signal-to-noise, it is becoming more feasible to quantify vessel lumen. These improvements are thanks to the use of intravascular contrast agents, better gradients and higher field strengths. Usually, the question of sequence design is unlinked to that of the reconstruction method or the post processing algorithm. However, the success of one plays a significant role in the design of the other. We will show that the choice of a specific accuracy for the determination of vessel cross section leads to the selection of a specific resolution in the data acquisition. This has important ramifications for answering the question, 'What resolution is enough?' to quantify MRA data. To this end we also introduce the concept of PEP (parametric estimation plots) to convey the characteristics of performance of a given algorithm with the imaging parameters. For a large vessel of diameter 40 times the resolution, the cross section can be determined to within 90% of the correct value for an SNR of 5:1. However, as the size decreases, the required SNR increases and, at some point, no value of SNR exists to overcome the loss of resolution. Nevertheless, for a vessel of diameter only five times the resolution, and an SNR of 7.5:1 or greater, the accuracy can be maintained at 95%. Smaller objects will have significant biases in their area determinations. This material is extracted from our ISMRM talk entitled, 'Estimation of Cross Sectional Accuracy as a Function of Resolution, Signal-to-noise and Vessel Diameter' by E. M. Haacke and W. Kong, ISMRM 2000, Denver.

Three-dimensional magnetic resonance angiography of the renal arteries: volume rendering versus maximum intensity projection

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Purpose: To determine the reliability of volume rendering (VR) as a postprocessing technique of MRA data sets in accurately quantifying renal artery stenosis.

Materials and Methods: Twenty five patients with suspected renal artery stenosis underwent both ce-MRA and digital subtraction angiography (DSA) of the renal arteries. Targeted maximum intensity projection (MIP) and VR images were then reconstructed for each renal artery (main renal arteries $n = 45$, accessory renal arteries $n = 6$) in a paracoronal and paraaxial orientation. A scoring system (1–4) was used to express image quality and delineation ability of the lumen. MIP and VR images were blindly reviewed after reconstruction.

Results: The image quality obtained by VR was significantly better than that obtained by MIP ($P < 0.05$). Moreover, VR allowed a more precise delineation of the lumen of the renal artery than MIP ($P < 0.05$). In both MIP and VR as well as DSA 21 renal artery stenoses were detected in 18 patients. In the quantitative analysis of the patency of the renal arteries in ce-MRA, VR correlated with DSA better than MIP ($r = 0.96$ and $r = 0.92$ respectively).

Conclusion: Volume rendering technique of renal MRA data sets yields an overall better image quality and allows a more accurate and a more comprehensive evaluation of the renal arteries.

Improved segmentation of phase contrast angiograms using velocity field information

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In planning the treatment of intracranial aneurysms, it is desirable to know the geometry of the aneurysm, its position relative to other structures, and the pattern of filling and emptying. From MRA data, simple planar and MIP views generally cannot satisfy these requirements. The use of more advanced visualisation tools relies typically relies on a segmentation stage to detect the vessel boundary. We describe an improvement to statistical segmentation based solely on speed data by extending the background noise model to a Maxwell–Gaussian mixture distribution and including the velocity component data as prior knowledge in a Markov random field process for segmentation. In application to patient data, the proposed noise model better describes the background noise in phase contrast angiographic images than standard noise model distributions. In regions lineal

vascular structure a more complete vascular segmentation is achieved (fewer gaps). The effect of the Markov random field modelling (i.e. use of the velocity field information) is particularly noticeable in large aneurysms — a common finding is that the central region of the aneurysm fails be segmented as part of the vascular structure. The combination of slow unmixed flow, saturation, and shear lead to low signal intensity in time of flight, contrast enhanced and phase contrast studies. In three cases of giant aneurysm studied, the new technique greatly improves completeness of the intra-aneurysmal depiction over our previous work. We have not yet been able to test the new algorithm on a tight vascular loop which might be expected to produce a similar flow topology.

Maracas (magnetic resonance angiography computer assisted analysis): an interactive software for visualisation and analysis of blood vessels in three-dimensional magnetic resonance angiography providing automatic quantification of the arterial stenosis

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Maracas is an interactive software for visualisation and analysis of blood vessels in three-dimensional MRA. It constitutes an assistance tool to the diagnosis of arterial stenosis, providing a qualitative appreciation of vessel morphology and automatic measurements to determine the stenosis severity. The quantification process begins by extracting the vessel axis and boundaries in the planes locally orthogonal to it. This procedure results in a stack of two-dimensional contours along the vessel, allowing quantitative cross-section measurements and visualisation by means of triangulation-based rendering. The interaction with the software starts with the selection of a series of patient images (slices) in order to form a three-dimensional volume. Several modalities are proposed for the three-dimensional volume visualisation: MIP, MPR, MPVR and surface rendering. The software allows an easy manipulation of the volume for selecting the vessel to be quantified and a user-friendly presentation of the results. Additionally, the radiologist can carry out a virtual endoscopy of the vessel guided by its axis, automatically extracted by the software.

Future directions in magnetic resonance angiography

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This paper will discuss future prospects for MRA. This will entail discussions of the limitations to anatomic and physiologic imaging. What are the ultimate limitations to this technology? The future of MRA will depend on competing and complimenting technologies. The competing technologies include CTA, ultrasound, and optical imaging techniques. Complimenting technologies include perfusion imaging, fMRI, diffusion tensor imaging, and MRI molecular imaging. MRA has the potential to address many pathophysiologic processes that have no adequate competing imaging methods. In the future, MRA techniques will be developed to improve the imaging of neoangiogenesis. Reperfusion injury is particularly amenable to MRA imaging. With new therapeutic approaches to of free radical injury the prospects for MRA and BOLD imaging take on a renewed clinical significance. This brief presentation will attempt to access the relative priorities of MRA research designed to realize these opportunities.

Pitfalls of moving-table peripheral magnetic resonance angiography

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Object of study: One of the major challenges of peripheral MRA is the need to image a large vascular territory. Recently, moving table, bolus-chase MRA has been introduced as a method to deal with this problem by imaging the entire lower extremity arteries with a single dose of contrast material. We reviewed our recent clinical experience to identify pitfalls and limitations this technique as currently implemented.

Methods: Examinations from 58 patients with 67 symptomatic limbs who underwent moving table MRA were examined for problems that limited the diagnostic adequacy of the examination.

Results: Of the 67 symptomatic limb examinations, 39 (58%) were completely diagnostic based on moving-table MRA data alone. In the remaining 28 (42%), the examination was limited by one or more problems: 15 (22%) by inadequate vessel contrast in one or more segments, 9 (13%) by excessive venous signal, 8 (10%) by important vessel segments not included in the examined volume, 2 (3%) by artifact, and 1 (1.5%) by excessive soft tissue signal.

Conclusion: Moving table MRA has been an important advance in peripheral MRA. However, current implementations still have substantial limitations in diagnostic efficacy. These can often be overcome by the use of supplementary time-of-flight imaging.

Magnetic resonance angiography in the treatment planning of peripheral vascular disease: challenging the gold standard

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Contrast-enhanced (ce) MRA has been shown to have a high sensitivity and specificity in the evaluation

of peripheral vascular disease. If ultimately MRA is to replace digital subtraction angiography (DSA) as the first line diagnostic imaging modality in this area, it must be able to challenge successfully the status of DSA as the current gold standard. In this talk I plan to discuss the current status of ce-MRA in the therapeutic planning of peripheral vascular disease. I will discuss the areas in which ce-MRA offers positive advantages over DSA, including enhanced patient safety and comfort, and a greater facility for complex post processing. There is the potential for discrepancies between DSA and ce-MRA due to the greater sensitivity of ce-MRA to slow, chaotic and retrograde flow. I will discuss the findings of a comparative study of imaging long peripheral arterial occlusions, using both DSA and ce-MRA, in order to illustrate the possible impact of these differences on therapeutic planning. I will consider the argument that the complex issues regarding spatial resolution in ce-MRA are currently some of the most important to resolve. Overall, MRA offers many significant advantages over DSA. However, some limitations remain, which may mean it is not yet ready to be universally regarded as the new gold standard in the assessment of all aspects of peripheral vascular disease.

Use of three-dimensional high resolution magnetic resonance angiography for the surgical management of ruptured and unruptured cerebral aneurysms

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A high resolution MRA protocol has been developed at the University of Utah which significantly improves image quality over that of conventional MRA. The image data set has sufficient resolution that it can be used to construct realistic three-dimensional models of the cerebral vasculature for interactive viewing on a surgical workstation. The three-dimensional modeling is particularly helpful in working out the anatomy of complex aneurysms, and can facilitate operative planning and dissection. Up to the present time, we have utilized this technique in the evaluation and management of 18 patients with aneurysmal SAH, 9 patients with symptomatic unruptured aneurysms, and 7 patients with incidental unruptured aneurysms. Altogether, 50 aneurysms have been detected in 46 patients. Either pre- or post-operative angiography has been concordant 100% of the time, even with aneurysms as small as 2–3 mm. The three-dimensional models have always faithfully matched the operative findings in every detail. The high resolution MRA technique has sufficient sensitivity and specificity to suffice for the evaluation and surgical management of aneurysmal SAH. In three cases, the high resolution three-dimensional MRA technique detected lesions initially overlooked on conventional angiography, thus showing it to be superior in cases of small lesions.

Diffusion and perfusion-weighted magnetic resonance imaging in acute internal carotid artery occlusion

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Purpose: To evaluate diffusion- and perfusion-weighted MR imaging (DWI and PWI) of the brain in patients with cerebral symptoms secondary to acute internal carotid artery (ICA) occlusion.

Materials and Methods: Two patients have so far been included. One had been treated for a large intracavernous ICA aneurysm by balloon occlusion of the right ICA after a successful test occlusion, and the other had bilateral internal carotid occlusion due to bilateral spontaneous dissection. In a 1.5 T scanner, DWI was performed using spin echo EPI in three directions with three b values. Isotropic DW images and ADC maps were calculated. PWI was obtained using gradient echo EPI following intravenous injection of a gadolinium based contrast agent at 3 ml/s. rCBF, rCBV and MTT maps were calculated. rCBF and rCBV maps were color-coded.

Results: DWI showed small acute ischemic white matter lesions. PWI showed increased rCBV and prolonged MTT in the hemispheres of the occluded ICAs. rCBF was unchanged. After medical treatment, rCBV and MTT had normalised and there was no progression of ischemia.

Discussion: DWI and PWI may improve the diagnostic accuracy and affect the therapeutic management in patients with cerebral symptoms after ICA occlusion.

Contrast enhanced magnetic resonance angiography in dural sinus thrombosis and thrombosis of cerebral veins

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Dural sinus thrombosis (DST) is an important cause of cerebral edema, ischemia, and intracranial hemorrhage. Time of flight (TOF) and phasecontrast (PC) MRA are already accepted as valuable tools for the initial neuroradiologic diagnosis. The aim of our study was to evaluate the role of ce-MRA. Since 1997 we examined 28 patients (13 female, 11 male, 2 days to 72 years of age) with dural sinus thrombosis and thrombosis of cerebral veins. The examination protocol included a two-dimensional TOF-MRA (FLASH, TR = 27 ms, TE = 9 ms, $\alpha = 50°$, $t = 8$ min), a two-dimensional PC-MRA (FLASH, TR = 93 ms, TE = 11 ms, $\alpha = 11°$, VENC = 10 cm/s, $t = 1.5$ min), and a 3D CE – MRA (FLASH, TR = 3.2 ms, TE = 1.2 ms, = 25°, t = 20s). For CE-MRA, the three-dimensional FLASH sequence with central k-space sampling was repeated four times. The intravenous gadolinium-bolus was timed to the

second measurement. After subtraction, projective angiograms of the arterial and two venous phases were calculated. CE-MRA revealed thrombosis of the sagittal sinus ($n = 6$), straight sinus ($n = 2$), transverse sinus ($n = 16$), sigmoid sinus ($n = 5$), of cortical veins ($n = 5$), and thrombosis of an abnormal parenchymal vein in one patient. Two-dimensional TOF-angiograms failed in four occlusions of dural sinuses and veins with a methemoglobin thrombus. Thrombosis of cortical veins could not be visualized on two-dimensional PC-MRA either. Three-dimensional CE-MRA showed DST and thrombosis of cortical veins and collaterals in all patients. Although the spatial and temporal resolution of ce-MRA is inferior to catheter angiography, ce-MRA can be applied for the emergency diagnosis of DST and thrombosis of cerebral veins. Postprocessing of the MRA data was faster as compared to CT-angiography. CE-MRA can replace catheter angiography and CT-angiography for the diagnosis of cerebral vein and sinus thrombosis unless CE-MRA results are questionable.

Design issues for blinded reads of magnetic resonance angiography trials

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Objective assessment of MRA studies are of crucial importance in dose finding (phase II), efficacy (phase III) and comparative studies. While substantial efforts are undertaken to optimize the imaging and statistical part of a trial, important issues regarding blinded assessment are frequently neglected. Furthermore, blinded reader evaluations have become the standard for objective assessment of new or improved techniques also outside of sponsored clinical trials. The following components need to be addressed:

- how to narrow down and define the primary and secondary evaluation criteria,
- how to acquire, process and prepare the imaging data for a blinded read,
- how to select your blinded reader, criteria and issues of independence,
- which statistical procedures are useful for blinded read analysis,
- how to address and evaluate differences between readers,
- how to report and compare on site (unblinded) versus off site (blinded) findings.

The presentation will address these components and show how these issues can be implemented in a standard study design for MRA without straining financial resources.

Three-dimensional T2-weighted imaging for coronary angiography using the intravascular contrast agent NC100150 injection

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It has recently been shown that black blood imaging using two-dimensional T2-weighted turbo spin echo imaging can visualise the coronary arteries. This technique however relies on pre-pulses to suppress signal from flowing blood, this has also limited the technique to two-dimensional implementation. NC100150 injection will reduce the T2 in blood, the purpose of this study was therefore to test the feasibility to image the coronary arteries in patients using a navigator triggered T2-weighted three-dimensional-turbo-spin-echo acquisition. Five patients were studied using a three-dimensional-turbo-spin-echo acquisition and the intravascular contrast agent NC100150 injection at a dose of 3 mg Fe/kg b.w. 20 slices with an in-plane resolution of 1×1 mm were scanned. In all patients long segments of the left and right coronary system were visualised without signal enhancement from slow flowing blood. Respiratory triggered T2 weighted three-dimensional-turbo-spin-echo imaging using the intravascular contrast agent NC100150 injection may show clinical utility in the diagnosis of coronary artery disease as well as for vessels wall imaging since the blood signal is effectively suppressed also in areas of slow flow. If this technique is sensitive enough to also visualise pathology still remains to be seen.

A new blood pool agent: application in coronary arteries imaging

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We describe a new blood pool agent: P 792. This compound is a monomeric gadolinium molecule based on the DOTA structure. Its main physico-chemical and imaging properties are characterized by:

- A strong thermodynamic stability, thanks to the very rigid macrocyclic structure of the core of the molecule.
- A higher plasmatic concentration than the non-specific compounds, with comparable clearance. This absence of extravasation confers an optimized contrast/noise ratio for MRA. The half-life in rats is 20 min with a Vd 135 ml/kg.
- A high relaxivity which is particularly suitable for the T1 w. sequences used in MRA: $r1 = 39\ mM^{-1}\ s^{-1}$ in water and $44\ mM^{-1}\ s^{-1}$ in 4% HSA at 20 MHz. This relaxivity induces a shortening of T1 relaxation time of the blood in human to 137 ms for a dose of 26 molGd/kg, which is the crucial parameter for coronary arteries imaging for example.

- A good safety index (LD_{50} over efficient dose) > 144 compared to Gd DTPA (52) or Gd DOTA (131).

In conclusion, all these characteristics demonstrate that the new blood pool agent P792 is a good candidate for peripheral and coronary angiography.

Value of blood pool contrast agent in magnetic resonance angiography of the aorta, carotid, renal and pelvic arteries in comparison to conventional angiography in first pass and equilibrium phase

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Purpose: To determine the value of NC 100150 (blood pool agent, single iron oxide crystal stabilized with a carbohydrate–polyethylene glycolcoat, Nycomed Imaging Oslo, Norway) for evaluation of degree of stenosis or aneurysm of the abdominal aorta, carotid, renal and pelvic arteries in comparison to conventional angiography.

Methods and Materials: 17 patients with significant stenoses or aneurysm of the described vessels were evaluated with X-ray catheter intraarterial angiography and MRA after intravenous injection of NC 100150 (0.75, 1.25 and 3.0 mg Fe/kg) in the first pass and in the equilibrium phase (1.5 T Gyroscan NT Philips, Netherlands), THK: 2 mm, coronal acquisition with flipangle 40°, TR/TE 5.0/1.4 ms, breath hold for the first pass and different parameters for the different concentrations in the equilibrium phase (coils depending of the region: quad neck, synergy wrap around, body coil). For image interpretation source images were used and three-dimensional MIP pictures on an independent workstation in consensus of two radiologists.

Results: In 16 of 17 patients the first pass with 0.75 mg Fe/kg was exactly comparable with the x-ray angiography. In one patient the timing failed. In the equilibrium phase after the second and third injection the vessels were interpretable. Because of venous overlap the stenoses could only be seen on the source images. In seven patients also the source images did not show the degree of stenoses because of venous overlap.

Conclusion: NC 100150 as a blood pool contrast agent allows prolongued visualization of the arteries and may overcome some limitations of the first pass, especially if timing or breath hold fails. Evaluation of stenoses only in the equilibrium phase is not recommended.

Gd-BOPTA enhanced magnetic resonance angiography versus Gd-DTPA enhanced magnetic resonance angiography in the assessment of carotid artery stenosis

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Purpose: Contrast enhanced MRA (ce-MRA) is a well established method in the assessment of carotid artery stenosis. Gd-DTPA enhanced MRA is an accurate technique, with a slight tendency to overestimate the degree of stenosis and limitation to delineate the morphology of the plaque. Purpose was to compare ce-MRA with Gd-DTPA and Gd-BOPTA, a high relaxivity paramagnetic contrast agent.

Material and Methods: 18 patients with carotid artery stenosis were examined with MRA using a time resolved sequence. Gd-DTPA and Gd-BOPTA enhanced MRA were performed within 24 h using standard doses of respectively 15 and 10 ml at a flow rate of 2 ml/s, using the same imaging parameters. In all patients DSA was also performed and considered the gold standard.

Results: Gd-DTPA and Gd-BOPTA enhanced MRA provided an accuracy of respectively 96 and 97%. In three severe stenoses a signal loss, not seen with Gd-BOPTA, was evident with Gd-DTPA. Of the nine plaques ulcerated at DSA, seven were recognized at Gd-DTPA MRA and nine at Gd-BOPTA MRA.

Conclusion: Gd-BOPTA, due to the high relaxivity, provides better results than Gd-DTPA in the assessment of degree of stenosis and morphology of the plaque in carotid arteries. Reduced doses can be used with a cost containment.

Advances in targeted contrast agents

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Reversibly binding small gadolinium chelates to relatively abundant targets provides novel contrast and pharmacokinetics. Clinical trials for the first use of these agents for MRA are proceeding, and a better understanding of the mechanisms of contrast has led to the development of a number of novel applications as well. In this talk, we will describe recent results in imaging vessel wall, coronary imaging and myocardial perfusion imaging using MS-325, which binds reversibly to albumin. Because the gadolinium's relaxivity is dramatically enhanced while bound to albumin, the agent can be thought of as an albumin-visualizer. While the highest concentration of albumin is typically in the blood — and hence the agent's use as a blood-pool agent — the full implications of this binding are only

now beginning to be understood. For example, in preliminary cardiac perfusion studies, the transient differentiation between normal and ischemic tissue during bolus injection of contrast agent may be extended due to the albumin binding in the blood, thus making the visualization of flow defects easier with MS-325. In coronary MRA studies, even though the agent extravasates into the interstitium, the lower albumin concentration in the ECS allows reliable nulling of the myocardium, and thus improves the CNR of coronary studies. Albumin, however, is not the only target available for MRI. We will also show preliminary results demonstrating proof-of-concept imaging of clot by targeting MR contrast agents specifically to fibrin.

Gadolinium enhancement of peripheral arteries and veins

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Background: For gadolinium enhanced peripheral MRA, there is no real concensus about the optimal injection strategy of the contrast agent. Empirically, low to intermediate constant injection rates (0.3–1 ml/s) have provided excellent results. However, these injection rates differ completely from the high (3–5 ml/s) rates normally used for renal and carotid arteries. Therefore, the popular equation describing the first pass concentration of gadolinium in blood as the ratio of injection rate and cardiac output should be properly extended.

Objective: To develop a gadolinium distribution model that describes the specific enhancement of the peripheral arteries and veins.

Material and Methods: Our model is based on realistic physiological assumptions primarily taken from literature and consists of two parts. The arterial part includes delay times, first pass and equilibrium conditions, distribution over extracellular space, and renal excretion. The venous part includes relative capillary blood volume and interstitial volume of muscle tissue.

Results: In vivo measurements of the gadolinium enhancement in lower leg arteries and veins of healthy volunteers over a period of 10 min in cases of slow (0.3 ml/s) and intermediate (1 ml/s) injection rates show excellent agreement with our model predictions. This implies that our model is suitable for the optimization of the injection strategy in the interesting case of a time varying injection rate.

Predicting aorta bolus dynamics using a test bolus: theory and validation in human patients

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In three-dimensional ce-MRA, it is generally desirable to maximize injection rate while maintaining adequate and constant-contrast enhancement for approximately the duration of the scan. One can predict the patient-dependent T1 enhancement dynamics for an arbitrary injection using a test bolus. The point spread function for Gd concentration is determined from the test bolus and convolved with a larger arbitrary injection to give the predicted T1 response for the larger injection. This predicted response can then be used to tailor injection profiles prior to imaging. We have tested the accuracy of the bolus prediction method in seven patients. The aortic response of both a test bolus (1 or 2 cm^3) and a subsequent larger bolus (14–20 cm^3) are imaged using a spoiled gradient echo sequence with time resolution of approx. 1 s. Using the results from the test bolus, the response to the larger bolus is predicted. Profiles of signal intensity versus time were accurately predicted. In the patients studied, the FWHM of actual bolus ranged from 101 to 143% (9–22 s) of the injection duration (7.5–20 s). FWHM were predicted with a mean error of 2 s.

Characterizing blood oxygen saturation in the presence of Clariscan

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Introduction: At the 1999 MRA Workshop, Johannson demonstrated that Clariscan shifted the effects of blood oxygen saturation (%HbO_2) on signal decay. Differences between arterial and venous blood are still observable in the presence of Clariscan under appropriate conditions. This is a potential mechanism for separating arteries and veins in MRA with Clariscan as an intravascular agent in steady state. An obvious question is whether Clariscan can facilitate the direct characterization of blood oxygen saturation. We have explored this question through the quantitation of the relationship between blood T2 and %HbO_2 as a function of Clariscan concentration.

Methods: Using venous blood collected from five healthy volunteers with consent, the relationship between %HbO_2 and blood T2 was determined at three different concentrations of Clariscan at 1.5T.

Results and Discussion: For in vitro %HbO_2–T2 calibrations, the minimum 1/T2 value and the %HbO_2 value corresponding to minimum 1/T2 was linearly dependent on the Clariscan concentration, while the

slope of $\%HbO_2$–T2 relationship was independent of Clariscan concentration. This behaviour follows the expectation that Clariscan primarily alters only the susceptibility and T2 of the plasma in blood. In vivo, Clariscan concentration can be determined from blood T1, which is independent of $\%HbO_2$. Therefore, with the calibration, relating in vivo blood T2 to $\%HbO_2$ is feasible in the presence of Clariscan. Preliminary studies in a procine model support this conclusion.

Blood pool agent contrast-enhanced magnetic resonance angiography of the aorta and peripheral vasculature

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Due to the long intravascular half-life of MRA blood pool contrast agents, steady state imaging of the peripheral vasculature has become possible. However, venous overprojection hampers the interpretation of the arterial steady state data. A method is presented in which the strengths of the first pass and the steady state images is combined. The first pass shows only the arteriogram (at a lower spatial resolution), while the steady state data shows the arteries and veins at high resolution and contrast. First, in a MIP of the first pass data two points are placed, between which the aortoiliac vessel axis is determined. Subsequently, this axis is transferred from the first pass data to the steady state data (arteries in both images coincide), where it is used for selective display of the steady state arteries (e.g. by targeted MIP). In case of patient motion between the first pass and steady state acquisition, data are registered using maximization of the mutual information prior to warping the path obtained in the first pass to the steady state image. Results on five datasets illustrate that this procedure effectively avoids venous overprojection.

Measures to improve spatial resolution in contrast-enhanced carotid magnetic resonance angiography

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Object: To improve the spatial resolution of ce-MRA of the carotid arteries.

Materials and Methods: Elliptical centric bolus ce-MRA has been shown to reliably offer high quality images of the carotid bifurcation with lumen filling characteristics making it physiologically analogous to conventional angiography. Approx. 500 clinical studies have been performed in our practice and ce-carotid MRA has essentially replaced conventional angiography in the preoperative evaluation of patients prior to an endarterectomy. Efforts continue to improve the image quality and spatial resolution of the MRA exams and have included: shorter TR scans, dynamic reduction of the flip angle, longer scan times, spiral-in view order and high field imaging (3T). Timing methods utilized are a test bolus series and fluoroscopic triggering including embedded fluoroscopic triggering.

Results: ce-elliptical centric carotid MRA yields reliable venous suppression. Increased spatial resolution is possible with a variety of coil and pulse sequence improvements.

Aortic arch and carotid contrast enhanced magnetic resonance angiography using elliptical phase reordering

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Purpose: To evaluate the feasibility of visualizing the carotid artery from the aortic arch to the skull base with elliptical ce-MRA using increased FOV, matrix, and imaging time.

Methods: 58 patients were enrolled. Elliptical ce-MRA parameters include: 26 cm FOV, 256 × 256 matrix, 46 1.2-mm thick partitions, TR/TE/FA/BW 6.6/1.2/30°/31.2 kHz, scan time 54 s.

Results: The three-dimensional slab was correctly positioned to include the aortic arch in 55 of 58 patients. The carotid artery from aortic arch to at least the intrapetrous segment was seen in 53 of 58 patients. There was stenosis in the takeoff of great vessels in five patients. Intra-arterial contrast was graded as excellent or good in 54 patients. Moderate venous contamination occurred in three patients. Carotid bifurcation ce-MRAs were graded as equal or superior to MOTSA in 48 patients.

Conclusion: Longer acquisition 26 cm FOV elliptical ce-MRA can visualize the carotid artery from the aortic arch to the skull base in 91% patients compared with 71% success rate with 22 cm FOV, 44 s ce-MRA without significant venous contamination and maintaining similar good or excellent carotid bifurcation ce-MRA.

Measurement of internal carotid artery stenosis. A comparison between contrast-enhanced magnetic resonance angiography and conventional angiography

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Purpose: To compare ce-three-dimensional MRA, using different acquisition times, with DSA in the evaluation of carotid artery stenosis.

Material and methods: ce-three-dimensional MRA with 10 or 28 s acquisition time was performed in 17 patients with Doppler verified carotid artery stenosis. All patients underwent DSA within 48 h after the MRA. Both DSA and MRA images of 34 carotid arteries were evaluated, by two neuroradiologists, for percentage of stenosis according to measuring methods used in the NASCET and the ECST trials, length of stenosis, ulcerations, and image quality.

Results: Using the DSA as reference, the sensitivity of MRA in estimating severe stenosis (70–100%) was, depending on the observer, 75 or 92%; specificity 77 or 73% with NASCET measuring method. With the ECST method the sensitivity was 94%; specificity 88% for both observers. The inter-observer agreement was, regardless of measuring method, slightly higher in DSA than in MRA. The image quality was better with DSA than MRA irrespectively of acquisition time. The anterior intracerebral circulation was visualized in 100% of the DSA but only in 53% of the MRA. The jugular vein was enhanced in 78% of the MRA examinations with 28 s acquisition time but did not interfere with the evaluation.

Perspectives from a multi-center study of carotid imaging

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Object: In many studies, catheter-injected X-ray angiography (XRA) is used as a 'gold standard' despite substantial deficiencies in that method. This poses a problem when evaluating the true validity of MRA methods which suffer in comparison with a standard that is defined to be the truth. Our aim was evaluation of the accuracy of different imaging modalities for assessing vascular disease.

Materials: We conducted a multi-center study of the accuracy of XRA, MRA, and Doppler Ultrasound using the endarterectomy specimen excised en bloc as the standard of truth. This study recruited 300 subjects who received all imaging studies within two months of endarterectomy surgery.

Method: Routine clinical XRA (at least two views) and DUS studies were performed. The principal MRA method used was multi-slab three-dimensional TOF, although a substantial fraction of the subjects also received ce-MRA studies.

Results: A major factor in comparing across modalities is establishing what geometric parameters to use since XRA presents diameter information, MRA contains three-dimensional information, and DUS is an indirect measure of the geometric morphology. Considerations on conducting and analyzing the results from a multi-center study with multiple imaging modalities will be presented.

Magnetic resonance angiography using SyncraScan: SENSE technology in clinical practice

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SyncraScan is an exciting parallel imaging technique, based on SENSE, that allows faster scanning by skipping lines in k-space. Reconstruction of the folded data can be performed by linear algebra, using the sensitivity profile of each synergy coil. In MRA, SyncraScan allows for many protocol improvements that have not been possible with sequential sequences. One application of SyncraScan is to speed up ce-MRA acquisitions up to a factor of 3 while preserving resolution and contrast-to-noise by proportionally increasing the injection rate. Another application is to improve spatial resolution or to increase the number of slices in the same (breathhold) time. Better venous suppression is realized since k-space is traversed at higher speeds. Furthermore, higher temporal resolution can be obtained in dynamic acquisitions, enabling better visualization of changes of the contrast passage in time. Finally, better signal homogeneity is achieved since SyncraScan reconstruction includes a uniformity correction by comparing the signal of the synergy coils with that of the built-in body coil. In this work, clinically relevant examples of all mentioned applications are given and discussed. Improvements in spatial and temporal resolution, venous suppression and signal homogeneity will be shown in cerebral, thoracic, abdominal and pelvic vascular applications.

Results of a contrast-enhanced carotid magnetic resonance angiography multi-center trial

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Introduction: This work describes the results of a multi-center, carotid artery imaging trial that compares the performance of various contrast-enhanced ce-MRA methods to DSA.

Methods: Six sites, using various scanners and imaging methods, acquired three-dimensional CE MRA, 3D TOF MRA, and conventional X-ray DSA exams on 100 patients. The DSA and reformatted MRA images were filmed, and stenosis measurements were obtained from the films using a jeweler's loupe and the NASCET method. The ce-MRA measurements were compared with those obtained from three-dimensional TOF and DSA. A subset of the ce-MRA data were used to compare measurements obtained from MIP images with those obtained from the reformatted images.

Results and Discussion: The statistical analysis of the measurements is underway. Initial results indicate that ce-MRA compares very favorably with DSA in terms of demonstrating the severity of stenoses, and delineating string signs, and offers additional benefits over

non-ce-MRA methods. The striking contrast and high SNR offered by ce-MRA methods leads to improved diagnostic confidence as compare to other MRA methods. However, the limited spatial resolution of ce-MRA methods does not permit adequate delineation of some types of complex pathology.

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Functional brain magnetic resonance imaging: can we escape from microcirculation?

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BOLD fMRI has become a standard to monitor brain activation through changes in local hemodynamics. This approach remains, however, indirect. Diffusion-sensitized fMRI has been suggested as an alternative, for instance, to 'crush' signal arising from the vasculature [1]. More recently the apparent diffusion coefficients (ADC) obtained at low b values has been shown to follow hemodynamic BOLD responses, in relation to IVIM effects [2,3]. At higher b values, apparent changes in the ADC have also been seen and linked to changes in background gradients resulting from susceptibility effects from deoxyhemoglobin [4]. It remains to be seen whether actual water diffusion varies during brain activation. We have observed small, but significant clusters of decreased ADC in occipital cortex during visual stimulation. Decreases in ADC have been reported in status epilepticus induced by bicuculline [5] and cortical electroshocks [6]. Such a decrease has been tentatively explained by a transient shrinkage of the extracellular space resulting from cell swelling, as also observed in cytotoxic edema and stroke. Anterior works based on optical measurements of photon scattering during activation have suggested the existence of neuronal swelling during physiological stimulation [7]. Although this mechanism remains very putative at this stage, our preliminary results evoke a new mechanism to look at brain activation with MRI.

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Influence of carotid athrosclerosis on visibility of intracranial magnetic resonance angiography

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Introduction: We reported that the visibility of intracranial MRA was decreased in the patient with risk factor for stroke and silent lacunar infarct. The aim was to analyze the effect of carotid atherosclerosis on the visibility of intracranial MRA.

Materials and Methods: We studied 77 patients aged 61–69 years, 37 men and 40 women. All underwent MRI and extracranial carotid ultrasonography because of headache or dizziness. MRA was performed with a three-dimensional TOF. The intracranial portion of the internal carotid artery (IC) and horizontal (M1), and distal (beyond M2) middle cerebral artery segments was scored in four grade. Mean-IMT, max-IMT, and mean blood flow velocity in CCA were measured using ultrasound scanner.

Results: In subjects with good visibility of intracranial MRA for IC, M1 and distal MCA, mean-IMT of carotid artery were 0.82 ± 0.13, 0.85 ± 0.15 and 0.80 ± 0.11, respectively significantly less than in those with poor visibility of MRA. Significant correlation was seen between max-IMT and visibility of MRA in IC, M1 and distal MCA ($P < 0.001$). No relationship was found between the mean blood flow velocity in the CCA and visibility of MRA.

Conclusion: Carotid artherosclerotic change was a factor of the decrease in the visibility of intracranial MRA.

Evaluation and improvement of dynamic susceptibility-contrast magnetic resonance imaging for quantification of perfusion

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Purpose: The aim of this work was to investigate different deconvolution techniques for calculation of rCBF using DSC–MRI, and to compare rCBF values obtained with MRI and SPECT.

Method: A large group ($n = 44$) of healthy volunteers was investigated with DSC–MRI, using a modified Simultaneous Dual FLASH technique. All volunteers were examined by $^{99}Tc^{m}$ HMPAO SPECT on the same day, and a subgroup of 10 volunteers also underwent ^{133}Xe SPECT. In DSC–MRI, Gd-DTPA-BMA (0.3

mmol/kg b.w.) was used. Arterial input functions (AIFs) were registred in the carotid artery as well as in a small artery within the brain-tissue slice. Relative rCBF was calculated using Fourier Transform (FT) as well as singular value decomposition (SVD) deconvolution techniques. Relative rCBF values (DSC–MRI vs. $^{99}Tc^{m}$ HMPAO SPECT) as well as absolute rCBF values (DSC–MRI vs. ^{133}Xe SPECT) were compared.

Results: Both FT- and SVD-based deconvolution provided reasonable relative rCBF values, although the SVD technique was more robust and in better agreement with PET values from the literature. Differences between relative rCBF values obtained using a carotid-artery AIF and a small-artery AIF were practically negligible. GM-to-WM rCBF ratios obtained by DSC–MRI and SPECT showed good correlation ($r = 0.79$). After correction for partial-volume effects, a similar correlation was obtained between absolute rCBF values with DSC–MRI and SPECT ($r = 0.74$–0.83 depending on AIF location). Absolute values obtained with the SPECT technique were, however, generally lower than values obtained using DSC–MRI.

Conclusion: DSC–MRI with SVD-based deconvolution is a robust technique for measurement of relative rCBF values and a good correlation with SPECT-based results was obtained. DSC–MRI using SVD deconvolution is now routinely used at our hospital.

Quantitative measurements of cerebral blood oxygen saturation: effects of static magnetic field inhomogeneity

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We have demonstrated previously that a quantitative estimate of cerebral blood oxygen saturation can be obtained in vivo. With a region-of-interest analysis, a mean cerebral blood oxygen saturation (CBOS) of $58.4 \pm 1.8\%$ was obtained from eight normal healthy volunteers. When converting the MR measured CBOS to the oxygen extraction fraction (OEF) via the Hill equation as well as the oxygen dissociation curve, an OEF of roughly 42% was obtained, in excellent agreement with the known OEF under normal physiological conditions via PET. However, one of the major assumptions made in our study is that only deoxyhemoglobin induced susceptibility causes signal loss in MR images. Obviously, this assumption may not be valid in regions where static magnetic field is not uniform, e.g. air–tissue interface, resulting in an overestimation of the cerebral venous blood volume. In this study, in addition to the multi-echo gradient echo/spin echo sequence used to obtain an estimate of CBOS, a three-dimensional gradient echo sequence was employed to acquire images on normal volunteers ($n = 12$). The phase images collected from the three-dimensional gradient echo sequence were subsequently employed to obtain an estimate of static field variation (_B) map across the imaging volume of interest. Our results demonstrated that a substantial reduction of cerebral venous blood volume in regions of air–tissue interface can be achieved (from 12 to 3%) when effects of _B were removed. Furthermore, the whole brain cerebral venous blood volume was estimated to be within 1–4%, in accordance with the reported values in the literature. Although further validation is required, our approach may provide a unique means to obtain a quantitative measure of cerebral venous blood volume non-invasively.

Stability of cerebral aneurysms evaluated with magnetic resonance angiography and magnetic resonance velocity maps

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The origin, growth and rupture on intracranial aneurysms is dependent on arterial blood motion. The purpose of this study is to develop and apply new quantitative MRI techniques to evaluate hemodynamic stress in aneurysms. Cerebral aneurysms were studied in 11 patients, with informed consent from patients in an institutional approved protocal. The aneurysms ranged in size from 3 to 25 mm mean diameter. Three-dimensional time-of-flight MRA provided morphologic measurements used to position the velocity phase maps. Prior to MRA, intravenous injection of 20 cm^3 gadolineum-DTPA was used to increase image SNR. Velocity phase maps were acquired, gated throughout the cardiac cycle (cine), oriented parallel and perpendicular to the aneurysm neck and inflow jet. Although these velocity studies were limited to two-dimensional spatial planes, more recent pulse sequence designs 'simultaneous image refocusing' (SIR) can acquire multiple contiguous two-dimensional velocity maps simultaneously for three-dimensional spatial coverage. Analysis of data gave measurement of blood's inertial and kinetic force impinging on the aneurysm walls. These results point towards the utility of in vivo MR techniques to study mechanisms of aneurysm growth and to evaluate dynamic instabilities within cerebral aneurysms.

Hemodynamics in aneurysms

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Intracanial aneurysms present a substantial risk to patients as they are prone to rupture. Because of their geometry, transport of contrast into an aneurysm can substantially lag behind the filling of the parent vessel. This can result in poor visualization with routine ce-MRA. For example, a lateral sacular aneurysm with a narrow neck is likely to be missed using a protocol targeted for the parent artery. We have conducted a series of numerical simulations and phantom experiments to investigate flow effects for aneurysms located at the basilar artery tip. Several factors, such as, unbalanced flow resistance, asymmetry of the branch, and out-of-plane curvature, have been considered. For steady flow, both asymmetry in the branch vessels and unbalanced flow rates are shown to disrupt the stagnant vortical structure inside the aneurysm, while out-of-plane curvature has little effect. For pulsatile flow, fluid penetrates deeper into the aneurysm in systole aiding in the transport of contrast agent into that region. The motion of two pairs of vortices enhances contrast delivery, but for first pass studies, the contrast agent distribution through the aneurysm generally remains uneven. This can have an important impact on the evaluation and diagnosis of intracranial aneurysms using ce-MRA.

Intracranial time-of-flight in hyper-acute stroke

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Purpose: To investigate the role of pre- and post-contrast time-of-flight (TOF) MRA for imaging hyper-acute stroke (< 6 h from onset), particularly for detection of occlusions in the intracranial circulation.

Methods: As part of a comprehensive stroke program at our center, patients with emergent stroke are imaged on a 3T MR scanner equipped with a head coil. The imaging protocol includes anatomical imaging, diffusion weighted imaging, perfusion weighted imaging (PWI) and two MRA examinations. The first is a conventional two-slab axial acquisition covering the upper neck through to the circle of Willis (COW). Acquisition parameters are: TR/TE/tip = 24 ms/3.3 ms/15°, 256 × 192 × 42 acquisition matrix, and 240 × 144 × 46 mm imaged volume. The second TOF is acquired after a 20 ml intravenous injection of MR contrast required for PWI. An oblique single slab is centered on the COW. Parameters are: TR/TE/tip = 32 ms/3.4 ms/35°, 256 × 192 × 40 acquisition matrix, and 240 × 144 × 36 mm imaged volume.

Results: Thirty-four hyper-acute patients were imaged using both pre- and post-contrast TOF. In some cases the pre-contrast TOF was difficult to interpret and it was difficult to separate occlusion from slow or disturbed flow. Post-contrast TOF removed many of these ambiguities and had improved vessel conspicuity. By acquiring an oblique slab, overlap of confounding signal from veins, sinus and scalp was reduced. Post-contrast TOF is an effective and time-efficient method for looking at occlusions in the intracranial circulation.

Quantitative estimates of CBF: a pet and magnetic resonance study in patients with unilateral carotid occlusion

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Recently, Ostergaard et al. has shown that a quantitative measurement of CBF can be obtained with a dynamic MRI approach. However, two confounding factors have hampered the success of the SVD approach in clinical settings. First, a constant cardiac output among subjects is assumed. This assumption may not be applicable in patient populations, leading to a potential variability in the estimates of CBF among subjects. Second, the choice of the arterial input function could be contaminated by partial volume effect. In this study, normal volunteers ($n = 5$) and patients with unilateral carotid occlusion ($n = 5$) were studied. In the patient group, rCBF estimates were obtained from both PET and MR so that the validity as well as the accuracy of MR estimated rCBF could be assessed under a pathological condition. In contrast, only MR estimated rCBF was obtained in the volunteer group via the SVD approach. A correction factor was derived based on the volunteer studies. A mean rCBF of 73.6 ± 5.9 ml/100 g/min was obtained for the GM while 28.1 ± 4.8 ml/100 g/min was obtained for the WM in the volunteer group. However, when MR estimated rCBF was correlated with those obtained from PET measurements in the patient group, no clear relationships were observed. In contrast, a substantial improvement in the relationship between PET and MR estimates of CBF was obtained after the application of the correction factor obtained via the volunteer group. A slope of one and a correlation coefficient of 0.8 was obtained for the linear regression line, suggesting a highly linear relationship between the MR and PET estimates of rCBF when the correction factor derived from the volunteer studies was applied.

Three-dimensional contrast enhanced magnetic resonance angiography versus three-dimensional time of flight magnetic resonance angiography in coiled intracranial aneurysms

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Time of flight (Tof) MRA is established for the diagnosis of intracranial aneurysms larger than 3 mm, but may fail to visualize residual perfusion or reperfusion after endovascular treatment. The aim of this study was to investigate the potential role of ce-MRA for the detection of reperfusion following endovascular aneurysm treatment. Since February 1998 we examined 23 patients after endovascular aneurysm treatment with detachable coils. There were ten anterior cerebral artery, four middle cerebral artery, four basilar artery, one posterior cerebral artery), one posterior inferior cerebellar artery and one vertebral artery aneurysm. All patients were examined on 1.5 T scanner (Siemens, Germany), 3–12 months after treatment. The examination protocol included a three-dimensional TOF-MRA (FISP, TR = 35 ms, TE = 7.2 ms, $\alpha = 20°$, $t = 6.5$ min) and a three-dimensional ce-MRA (FLASH, TR = 3.2 ms, TE = 1.2 ms, = 25°, t = 20 s). For ce-MRA, the three-dimensional FLASH sequence with central k-space sampling was repeated four times. The intravenous gadolinium-bolus was timed to the second measurement. After subtraction projective angiograms of the arterial and two venous phases were calculated. Ce-MRA showed reperfusion of coiled aneurysms in seven (23) patients. The reperfusion appeared larger on three-dimensional ce-MRA as compared to catheter angiography in three (seven) patients. On three-dimensional TOF-MRA the reperfusion appeared considerably smaller in six (seven) patients. Three-dimensional TOF-MRA can fail to visualize reperfusion of coiled aneurysms due to susceptibility artefacts. On three-dimensional ce-MRA, reperfusion may be more appearent as compared to catheter angiography because of contrast agent pooling. Ce-MRA has potential for follow-up of endovascular treated aneurysms.

Assessment of border zones vasomotor reactivity before and after carotid endarterectomy by dynamic susceptibility contrast-enhanced magnetic resonance imaging

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Background and Purpose: Conflicting results have been reported on the importance of hemodynamic changes related to a high-grade internal carotid artery (ICA). The aims of this study were to investigate (1) possible hemodynamic compromises in patients who had a severe ICA stenosis, in particular within areas between the vascular territories of major cerebral arteries (border zones); and (2) the subsequent changes after carotid endarterectomy (CEA).

Materials and Methods: Perfusion series were acquired by means of dynamic susceptibility-contrast MRI using the acetazolamide test, before and after CEA. Relative regional cerebral blood volume (rrCBV) and vasomotor reactivity (VMR) were determined in 13 patients with a high-grade unilateral ICA stenosis (> 80%).

Results: Before CEA, a significant difference ($P < 0.05$) in rrCBV was found in anterior border zones between the ipsilateral and contralateral sides. Also, VMR was lower in the lesion side than in the contralateral side in anterior border zones. However this difference was not statistically significant. After CEA, the rrCBV asymmetry in anterior border zones cleared.

Conclusion: High-grade ICA stenosis with efficient primary collateral pathways may have an early limited hemodynamic impact within border zone areas. These abnormalities cleared after CEA, thus suggesting a hemodynamic impact of CEA in unilateral high-grade ICA stenosis.

Magnetic resonance angiography of spinal arterio-venous malformations

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Introduction: Non-invasive imaging of spinal arterio-venous malformations with conventional magnetic resonance imaging has been disappointing due to the large number of false positive examinations. The aim of our study was to depict arterio-venous malformations within the spinal canal using high resolution ce-MRA.

Method: Ten patients with suspected spinal arterio-venous malformations were examined on a 1.5T system (Philips Gyroscan ACS NT, PowerTrak 6000, Best, NL). All patients underwent conventional spin-echo imaging and ce-MRA (TR 4.75 ms, TE < 2 ms, flip angle 40°, FOV 400 mm × 240 × 320, scan matrix 512 × 200, slice thickness 1–2 mm, scan volume 4–8 cm). Contrast agent was delivered at a rate of 1.5 cm^3/s via an automated injector (Spectris, MEDRAD Inc.). Two acquisitions were performed, the first was initiated using fluoroscopic triggering (BOLUSTRAK).

Results: Six patients had arterio-venous malformations. Arteriographic corroboration was available in four cases only. In one patient a large pelvic feeding artery, not visualized on arteriography was confirmed. Although feeding arteries could be identified in all patients, the degree of confidence for exclusion of feeding arteries at each level was poor. In one patient

without an arterio-venous malformation, venous engorgement of the entire spinal venous plexus, thought to be related to a severe scoliosis was identified.

Conclusion: Three-dimensional ce-MRA reliably showed the presence of spinal AVMs in our study. A large feeder in one patient was missed on conventional arteriography. Exclusion of a feeding artery at a particular level can be difficult or impossible with MRA. Examination of the entire spinal vasculature may require more than one examination.

Magnetic resonance imaging and magnetic resonance angiography in pulmonary embolism

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Object of study: MRI and MRA are becoming increasingly appealing for thoracic investigations. Here, we summarize our views for the diagnosis of pulmonary embolism (PE).

Materials and Methods: Coronal MRI was performed with a free-breathing black blood single shot fast SE scan to assess the lung morphology. A volumetric MR lung perfusion scan followed to assess areas of perfusion deficit and provide contrast timing data for a high-resolution pulmonary MRA. Gd-DTPA-enhanced MRA was performed with three-dimensional FLASH (TR/TE/flip angle = 3.65/1.6 ms/25°). Two sagittal slabs were selected to cover both lungs, each acquired in a breath-hold of 15–17 s, matrix (90–106) × 512, minimum FOV 200 × 320 cm, 100–125 slab thickness, 44/100 encoded/reconstructed partitions. A variable speed dose of Gd-DTPA was used (single dose of contrast per lung). Conventional pulmonary angiography was used as the reference method on 141 patients with suspected PE and performed after the MR examination. The pulmonary MRA was evaluated with maximum intensity projections (MIP) and multi-planar reformats to inspect the vessel lumen and search for filling defects as proof for PE. Lung perfusion scans were observed qualitatively per slice or in stacks in a cine loop (20 slices, 20 time frames) and compared to the morphology scan and pulmonary MRA.

Results: MRA and pulmonary angiography were both available in 122 patients. PE was shown by catheter angiography in 37 patients, for a prevalence of 30%. MRA demonstrated emboli in 25 of 37 patients with proven PE (sensitivity 67%; 95% CI 61–73%). False positive findings were present in 6 patients (specificity 93%; 95% CI 91–95%). MRA did significantly better in central, lobar and segmental arteries than in subsegmental arteries.

Discussion: The findings of MRA are similar to helical CT. Positive aspects of MRI and MRA, such as the absence of ionizing radiation and better safety record of Gd-DTPA compared to iodine containing contrast, point to an increased acceptance of MRA as a screening test for the future.

Dynamic magnetic resonance angiography for pulmonary artery disease

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Introduction: Ultra-fast imaging sequences are important for the substantial improvements in contrast-enhanced MRA of the abdominal and thoracic vasculature. In this paper we present a faster version of the three-dimensional imaging technique which provides both high temporal and spatial resolution to create a series of images during contrast enhancement.

Methods: Dynamic, time-resolved pulmonary MRA and perfusion imaging was performed on normal volunteers and patients using a 1.5T imaging system using high-performance gradients (Gmax = 40 mT/m, SR = 200). The basic pulse sequence was a coronal gradient-echo three-dimensional acquisition (TR 1.64 ms; TE 0.6 ms; flip angle 15°). Twenty partitions were measured and interpolated to 40 slices at 2.5 mm distance. The FOV was 315 × 360 mm with a 120 × 256 imaging matrix. Each three-dimensional acquisition lasted approx. 3 s yielding voxel dimensions on the order of 2.5 × 2.6 × 1.4 mm.

Results: Rapid acquisition of data allowed dynamic imaging of the pulmonary vasculature with 3-s temporal resolution. Segmental and subsegmental arterial anatomy was routinely visualized. Pulmonary parenchymal perfusion was demonstrated for all normal subjects as a peak in the parenchymal signal over time, with well-defined wash-in and wash-out phases. Pulmonary emboli and perfusion defects were visualized in all patients, and correlated closely with the findings on conventional or CT angiography.

Conclusion: Ultra-short TR allows dynamic imaging of the pulmonary vasculature with higher temporal and spatial resolution than previously reported. It is now possible to acquire sequential three-dimensional data set in a few seconds. The combination of pulmonary MRA and perfusion imaging has the potential to improve the evaluation of embolic and non-embolic pulmonary vascular disease.

Ultrafast time-resolved magnetic resonance angiography of the pulmonary arteries

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Objective: To evaluate an ultrafast three-dimensional MRA-technique permitting the acquisition of a complete three-dimensional data set of the pulmonary vasculature in under 4 s.

Materials and Methods: MRA of the pulmonary vasculature was performed in three healthy volunteers and 20 patients referred with suspicion of PE. Imaging was performed on a 1.5T MR-scanner (Sonata, Siemens, Germany). Data was acquired in the coronal plane with the following parameters: TR: 1.6 ms, TE: 0.6 ms, flip: 15°, slab thickness:110 mm, slice thickness: 2.75 mm, 40 interpolated partitions, FOV: 360 mm, matrix: 140 × 256, partial k-space coverage. Paramagnetic contrast agent (20 ml) was administered at a flow rate of 4 ml/s with an automated injector (Medrad, Pittsburgh, PA). Data collection was commenced 8 s following initiation of the contrast injection. Scintigraphy ($n = 18$), CT ($n = 6$), transesophageal echo ($n = 6$) were used as reference standard.

Results: All three healthy volunteers but only seven of the 20 evaluated patients were able to hold their breath over the entire data acquisition period (five data sets collected over 19 s). All patients were able to hold their breath for at least 8 s, during which the first two data sets were collected. PE was demonstrated by MRA in 14 of the 20 patients. In one patient atelectasis of the right lung with an elevation of the diaphragm mimicking a perfusion defect in scintigraphy was identified. MRA diagnosis correlated with the corroborating tests in all but one patient, resulting in a positive predictive value of 100%.

Cardiopulmonary angiography and perfusion imaging in animals with a new blood pool contrast agent

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Purpose: The purpose of the study was to evaluate B-22956/1 for coronary and pulmonary angiography and perfusion imaging. B-22956/1, a novel intravascular contrast agent developed by Bracco SpA (Milan, Italy) is a stable polyaminocarboxylate Gd complex linked by means of a flexible spacer to to a deoxycholic acid moiety.

Material and Methods: Six normal domestic pigs were imaged after injection of B-22956/1, of which four were used for coronary angiography with different doses and two for pulmonary angiography/perfusion. Other five pigs with artificial pulmonary embolism (PE) were examined using ultrafast three-dimensional perfusion and angiography sequences. All studies were performed on a 1.5 T Siemens Sonata system.

Results: Injection of B-22956/1 resulted in dramatic enhancement of coronary and pulmonary arteries lasting for more than one hour. On the contrary, myocardial tissue showed only little R1 enhancement which decreased slowly in line with blood kinetics, resulting in strong vessel/muscle contrast. Prolonged enhancement using a blood pool agent also allows examination of pulmonary perfusion and pulmonary artery after a single injection. As a result, complementary information was available for the location and consequences of pulmonary emboli.

Conclusion: With this blood agent, coronary artery imaging could be performed multiple times to cover the entire heart. These results are reason to believe that ce-MRCA with B-22956/1 will efficiently detect coronary stenosis. This issue will be addressed by a study on a pig model of atherosclerotic lesions. Pulmonary perfusion imaging and angiography could be obtained in one setting for detecting PE without multiple injections.

Simultaneous assessment of ventilation and perfusion using magnetic resonance imaging

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The assessment of both pulmonary perfusion and ventilation is of crucial importance for a proper diagnosis of some lung diseases such as pulmonary embolism. Magnetic resonance perfusion imaging is usually performed using proton imaging and contrast injection. However lung proton imaging is difficult due to the low proton density and the magnetically inhomogeneous structure of lung parenchyma. In this study we show that laser-polarized 3He can be used as a non invasive probe to image, in a single MRI experiment not only the ventilation but also the perfusion state of the lungs. Blood volume maps of the lungs can be obtained based on the 3He signal depletion during the first pass of superparamagnetic contrast agent bolus. The combines and simultaneous lung ventilation and perfusion assessments are demonstrated in normal rat lung and are applied to an experimental model of pulmonary embolism.

Initial experience using direct thrombus imaging

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The T1 shortening effect of methaemoglobin (MHb) is well known but typically considered a confound rather than as a diagnostic aid. We describe our initial experience tailoring a pulse sequence to provide positive contrast for thrombus reliant on this phenomenon. Based on the method of Moody et al. used at 1.5T we found almost identical imaging parameters to be optimal at 1T. Measurements on samples of heparinized whole blood indicated T1s of 1300–1450 ms and with increased concentration of MHb a rapid reduction in T1 to < 900 ms. On the basis of a predicted optimal inversion time of ~ 950 ms for fully relaxed fluid blood, we empirically determined the combination of delay and inversion which provided best contrast between MHb amples and leg tissues using volunteers. The imaging sequence is a coronal MP-RAGE sequence (100–128 × 1–2 mm slices, TR/TE/TD/TI 10.7/4.0/1000/820 ms, FA 15°, FOV 375 × 500 mm, Mat 256 × 180–192), with water selective excitation. To date our experience is based on patients with thrombosis as assessed by conventional investigations including DVT and pulmonary thrombosis. The only source to date of uninterpretable data has been artificial joints. In all cases without prostheses, MR findings were consistent with, or showed more extensive thrombus than conventional studies at our institutions (CT for PE, U/S for DVT). Limitations include a possible blind period prior to the development of MHb in the thrombus, poor contrast with imperfect fat suppression, and incomplete coverage adjacent to prosthetic joints. Attractions of the direct thrombus approach are an acceptable scan time (~ 6 min per station), straightforward interpretation of the images and the use of MIPs for overview reading.

Reference:

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Perspectives in coronary magnetic resonance angiography

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With the development of a new group of ultrafast imaging sequences MRA of the coronary arteries has recently become possible. Coronary MRA is noninvasive, does not require iodinated contrast agents or X-ray radiation, and thus has the potential to become a very important cardiac screening tool. During the First International Workshop on Coronary MR & CT Angiography, October 1–3 2000 in Lyon, France, the latest advances in coronary MRA were discussed and compared to coronary CT angiography. A report of these latest scientific findings and new clinical applications will be provided. Most of the clinical applications of coronary MRA have been validated using first generation techniques with breathholding. It is important to know when MRI can add value to the work up of certain patients, and what our level of confidence is for obtaining a definitive clinical diagnosis and answer. Clinical applications of two-dimensional coronary MRA include coronary lesion detection, the delineation of congenital coronary artery anomalies, the characterization of previously known coronary lesions, coronary bypass graft patency, vessel patency and evaluation after coronary stent placement, coronary anatomy after heart transplantation, and coronary flow reserve quantification. However, the use of coronary MRA for blind prospective detection of coronary lesions is still being evaluated, and improved coronary MRA techniques may become an integral part of the clinical evaluation and screening of patients with ischemic heart disease. It is still premature to judge the ultimate capability of coronary MRA in screening for coronary artery disease.

Three-dimensional magnetic resonance coronary artery imaging using magnetization-prepared TrueFISP

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Introduction: TrueFISP is a fast imaging technique that gives rise to high signal-to-noise ratio and T2/T1-weighted contrast because it maintains the transverse magnetization within each TR which contributes to the signal intensity. The major problem with TrueFISP has been off-resonance artifacts secondary to field inhomogeneities. These effects can be minimized by using short TR's with a high-performance gradient system. As a result, TrueFISP has dramatically improved blood signal and contrast over conventional FLASH in cardiac cine imaging.

Objective: The goal of this work was to investigate the utility of TrueFISP for coronary artery imaging.

Materials and Methods: In each cardiac cycle, after the appropriate trigger delay, a fat saturation pulse was first applied. This was followed by a pre-pulse of $\alpha/2$ and TR/2, and 20 dummy pulses (α, TR) to prepare the magnetization to approach a steady state. A segmented TrueFISP sequence was then used to acquire data with zero net gradients in all three directions. Normal volunteers ($n = 7$) were studied to compare three-dimensional TrueFISP and FLASH for coronary artery imaging. The TR was the same for the two sequence (3.8 ms) and each scan was collected within a single breath-hold.

Results and Conclusion: Coronary artery SNR was improved by > 50% and myocardial signal was significantly suppressed in TrueFISP images, resulting in dramatic improvements in coronary artery visualization, especially in distal portions. In conclusion, TrueFISP is a very promising approach to coronary artery imaging.

Multiple flip angle subtraction for coronary artery magnetic resonance angiography

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The purpose of this work is to reduce the acquisition time for breathhold coronary angiography studies by developing a two-dimensional contrast-enhanced technique with reduced background intensity. We wish to exploit the inherent relative signal variations between different RF excitation energies on the T1s of contrast-enhanced blood and background myocardium by developing a dual-flip-angle acquisition technique with subsequent complex subtraction. The procedure includes: (i) performing two-dimensional imaging of thick (1–4 cm) obliquely oriented sections; (ii) interleaving RF repetitions at high and low flip angles to create high and low flip angle complex images; (iii) applying complex subtraction to the high and low flip angle image sets to reduce or eliminate background signal. For long T1 background, two images acquired with flip angles below and above the Ernst angle provides similar signal intensity. For the short T1 gadolinium doped material those same flip angles produce relatively low and high signal respectively. As demonstrated experimentally, subtraction of the images removes a significant portion of the background while leaving a vessel signal linear with vessel thickness. Optimal CNR of phantom images occurred at flip angles of 60 and 40°. A contrast-enhanced multiple flip angle acquisition has the potential to increase contrast while imaging a thick slab with a two-dimensional rather than a three-dimensional technique.

Preliminary correlative results of magnetic resonance myocardial perfusion reserve index imaging

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Purpose: To investigate the feasibility of practical multislice semiquantitative myocardial perfusion reserve index (MPRi) imaging of the LV myocardium at the native resolution of the MR image acquisition for the work-up of ischemic heart disease.

Methods: Six short-axis slice locations spanning the LV were acquired during the first pass of Gd-contrast antecubital-vein injection (0.05–0.1 mmol/kg, 5 ml/s) in both adenosine vasodilated 'stress', and 'rest' states (GE efgret; 2 R-R sampling). Custom software calculated MPRi images for each slice location (~ 6000 lines IDL). MPRi results of patient volunteers were compared with both contemporaneous nuclear medicine and X-ray coronary angiography studies.

Results: MPRi values within normal myocardium range from ~ 0.5–2.5, about half the expected perfusion reserve values; within perfusion defects range from 0.0 to 1.0. Patient examples and results to date from on-going clinical series will be reviewed. Patient volunteer population consists of multi-vessel disease, often with conflicting reference studies. MPRi imaging may provide quantitative objective information to reduce variability in perfusion exam interpretation, and to document perfusion exam results.

Magnetic resonance angiography of the coronary arteries in pigs using a new gadolinium-containing blood pool contrast agent (P792)

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Purpose: To evaluate the signal enhancement characteristics of a new Gd-containing blood pool contrast agent (P792) for MRA of the coronary arteries.

Material and Methods: P792 is a Gd-conatining macromolecular MR-contrast agent with renal clearance (R1 at 0.94 T: 29 l/(mmol s)). Cardiac imaging at 1.5 T was performed in a total of 5 minipigs using a pulse-triggered high-resolution three-dimensional gradient-echo sequence during first pass and for up to 30 min following intravenous injection of Gd-DTPA (0.3 mmol Gd/kg), Gd-BOPTA (0.2 mmol Gd/kg), and P792 (0.013 mmol Gd/kg, $n = 5$ each) during breathhold. The signal intensities of blood, myocardium, and noise were analyzed quantitatively. Image quality, contrast between coronary arteries and myocardium, continuity of the coronary arteries, and visualization of lateral branches were evaluated qualitatively.

Results: After administration of Gd-DTPA, Gd-BOPTA, and P792, an increase in the signal-to-noise ratio of 90, 77, and 110% in blood and of 90, 93, and 21% in myocardium was measured immediately after contrast injection ($P < 0.05$). The blood-to-myocardium signal difference-to-noise ratio was significantly higher for P792 than for the Gd compounds ($P < 0.05$) at all time points. Qualitative assessment showed that visualization of the coronary arteries and their lateral branches was significantly better after P792 compared to the Gd compounds ($P < 0.05$).

Conclusion: The blood pool contrast agent P792 significantly improves the visualization of the coronary

arteries at MRA during first pass and the equilibrium phase for up to 30 min after injection compared to low-molecular weight agents.

New applications of TrueFISP in cardiovascular magnetic resonance imaging: three-dimensional TrueFISP and inversion recovery TrueFISP

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Three-dimensional TrueFISP: The TrueFISP sequence as proposed by Oppelt et al. in 1986 offers a high contrast between myocardium and intraventricular cavity, which is desirable for accurate assessment of ventricular function. A significant drawback of TrueFISP is its sensitivity to off-resonance effects caused by an imperfect shim, chemical shifts, eddy currents, and Maxwell effects. An extension of the two-dimensional TrueFISP sequence to an ECG gated three-dimensional TrueFISP sequence is thus not straight forward and requires a very carefully designed acquisition scheme. The current implementation of our gated three-dimensional TrueFISP sequence allows to acquire the complete heart in its diastolic phase within about 20 heartbeats with a resolution of $2 \times 2 \times 3$ mm. In addition, a three-dimensional TrueFISP cine technique with a time resolution of 80 ms and a spatial resolution of $3 \times 4 \times 4$ mm was implemented.

Inversion recovery TrueFISP: Two-dimensional inversion recovery TrueFISP is a new method for T_1 quantification of the myocard within several heartbeats. The intrinsically T_1 weighted FLASH readout module was replaced by a TrueFISP readout module to continuously acquire the recovery of longitudinal magnetization after inversion or saturation. Quantitative T_1 measurements on phantoms and on humans based on FLASH and TrueFISP were compared to the gold standard of separately acquired TI measurements. Applications of IR TrueFISP may include quantitative assessment of myocard damage after CA administration.

Reference:

[1] Oppelt et al. 1986; 00: 00-00.

Update on the Flow and Motion Study Group (ISMRM) multi-centre trial of magnetic resonance flow measurement (AM PM FM)

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A multi-centre, cross-platform assessment of the methodology of phase mapping flow measurement (AM PM FM) has been undertaken under the auspices of the ISMRM Flow and Motion Study Group. A simple phantom has been specified and constructed, and a common study design prescribed which aims to gauge (1) the baseline performance of phase mapping across flow rates and velocity encoding values, (2) consistency of measurements, (3) dependency on positioning of the imaging plane relative to the scanner iso-centre and vessel axis. We are now in the midst of the site-by-site performance of the measurements. Early findings indicate overall similarities between sites in that changes in position along the magnet axis has a linear effect, though the impact of slice angulation is variable. In both cases, significant differences in flow measurements being seen. Manufacturer supplied background correction algorithms (for Maxwell terms etc.) need to be assessed. The impact of slice — vessel obliquity is however not always consistent. Some sites produce noticeably more consistent measurements than others on repeat measurements of identical flows. In part this may reflect user variability in the use of manufacturer supplied flow analysis software. All data is being submitted to centralised processing to control for this effect. Linearity of flow measurement across flow rates and velocity encoding values is generally good. We hope that these results of this trial overall will contribute to greater clinical acceptance of MR flow measurement. We anticipate needs for standards of practice and quality assurance for MR flow measurement.

Review of initial experience with three-dimensional magnetic resonance angiography of coronary arteries compared with conventional digital subtraction angiography

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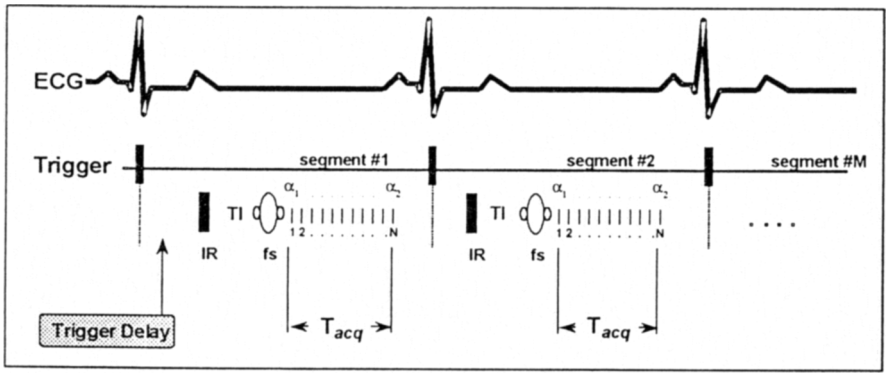
Purpose: An MR system for study of the cardiovascular system was recently introduced in our hospital. Between November 1999 and July 2000, we performed 32 MRA studies in patients who were posteriorly subjected to conventional angiographic evaluation. The purpose of the present study is to compare the results obtained with both techniques.

Methods: The underlying idea of this method is a segmented three-dimensional FLASH sequence as illustrated in Fig. 1. N lines are acquired during each heart beat, preceded by a fatsat pulse and an inversion pulse (optional). The inversion pulse is used to remove signal from the myocardium when the TI is adjusted to annul magnetization from the myocardium. Twenty-four or 32 lines are acquired per heart beat, depending on the patient heart rate. A centric reordering scheme is applied to provide optimal fat suppression. Including a

partial Fourier technique with 80% in *ky* and 50% in *kz*, a 120 × 16 × 256 matrix can be acquired in 24 heart beats (with 32 lines/beat), or in 32 heart beats (with 24 lines/beat). A thin, typically 40-mm slab is positioned along the major orientation of the right or left coronary artery. Data are acquired immediately after contrast injection, when the T1 of blood is short, to ensure quick relaxation of the blood after the inversion pulse. A test bolus procedure is used to determine the timing of the data acquisition for each patient individually. The studies were performed using a Siemens Magnetom Sonata system. Most of the patients were examined by MR on the same day of the conventional DSA study (24 subjects). The rest were subjected to conventional DSA in the course of the following week. Our protocol includes Segmented TurboFlash sequences to locate the arteries with MPR. Correct localization was verified, and the definitive sequences were acquired with gadolinium: first the right coronary artery and then the left — with another injection of contrast.



Results: The MRA study was satisfactory in 30 of our 32 patients. In the remaining two cases a lack of patient collaboration made the acquisition of diagnostic images impossible. We identified lesions in the right coronary artery ($n = 5$), in the principal left trunk ($n = 2$), in the anterior descending artery ($n = 10$), and in the circumflex artery ($n = 6$). Bypass permeability was visualized in one case. No lesions were identified in five studies. In comparison, conventional angiography revealed six right coronary lesions, two principal left trunk lesions, 15 lesions of the anterior descending artery, and 10 lesions of the circumflex artery. No significant lesions were identified in six studies.

Conclusions: The results presented are the product of an initial study without criteria for the selection of patients; nevertheless, the observations are encouraging. In our opinion, we are still unable to apply MRCA in the same way as MRA in other parts of the body. New pulse sequences with improved spatial resolution and shorter acquisition times, as well as the development of new contrasts, will allow performance to reach the standards achieved in other applications of MRA.

T2 prepared multislice D2-spiral spgr magnetic resonance angiography for detection and functional characterization of stenotic coronary arterial lesions

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Introduction: Imaging and pulse sequence parameters need to be optimized to maximize the sensitivity and specificity of anatomical detection and functional characterization of atherosclerotic stenotic coronary arterial lesions.

Methods: Non-sequential, single-phase (diastolic, ECG gated), two-dimensional-spiral SPGR pulse-sequence was used to image 13 'conventional-angiographically proved' stenotic lesions (45–70% luminal diameter) of right coronary artery. Minimum TE; 60° flip angle; 24 × 24 mm^2 FOV; 1 NEX and 12-phase × 4096-frequency spiral-matrix, were set for acquiring four to five overlapping slices (5 mm thick; 1 mm overlap; centered-around diastolic phase of cardiac cycle) during a single breath-hold.

Results: All the lesions > 45% were adequately detected as visually significant narrowing of magnetic resonance flow-luminogram. Change of signal characteristics (> 20% that of the remote upstream arterial segment) at the level of stenosis were discernible in all the six RCA-lesions which were stenosed between 60 and 70%.

Conclusion: Rationally optimized parameters of magnetic resonance coronary angiography should lead to high yield of diagnostic detection for luminal narrowing (in 45–70% stenosis) and hemodynamic compromise (in 60–70% stenosis).

Pre-liver transplant assessment with magnetic resonance imaging

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Objective: To determine the diagnostic accuracy of an all in one-MR-based-approach replacing the cur-

rently used protocol including CT, DSA and ERCP in living liver donors.

Materials and Methods: MR imaging was performed on a 1.5 T scanner (Sonata, Siemens). A phased-array torso surface coil was used for signal reception. The following image sets were collected: T1 FLASH two-dimensional axial, T2 HASTE axial fatsat, MRCP HASTE cor, FLASH three-dimensional angio (TR/TE/TA: 2.1/0.7/15), ce-T1 FLASH. The MRA data set was collected following intravenous administration of a Gd-chelate (Gd-DTPA, or Gd-BOPTA) at a dosage of 0.2 mmol/kg b.w., using an automated injector (MEDRAD) over 12 s at a volume adjusted rate ranging between 2.5 and 3.5 ml/s. A second three-dimensional data set for display of the portal and venous phase was collected after 10 s of free breathing. Thirty-six potential liver donors were assessed with MRI. Twenty patients also underwent DSA. Of these, 14 patients actually underwent liver harvesting. The MRA data sets were correlated with DSA. MRCP results were correlated with available ERCP exams and intraoperative findings.

Results: The MRI exam was completed within 25 min. Patients were excluded as potential donors based on the detection of hepatic hemangiomas ($n = 5$), as well as unfavorable hepatic morphology ($n = 10$), as documented on T1- and T2-weighted images. MRCP displayed the biliary system to the level of the first hepatic side branch. In one patient it revealed irregular widening of the pancreatic duct suggestive of chronic pancreatitis. MRA depiction of the hepatic arterial morphology correlated with catheter angiography in all 20 patients: four aberrant right hepatic arteries originating from the SMA, five left hepatic arteries originating from the left gastric artery, and one common hepatic artery originating from the SMA were correctly identified on MRA. Similarly, the portal venous system was fully assessed on MRA.

Shortened breath-hold three-dimensional contrast-enhanced magnetic resonance angiography of the renal arteries using SENSE

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Purpose: SENSE (sensitivity encoding) is an imaging technique which allows faster scanning by skipping lines in k-space while acquiring synergy data in parallel. The aim of this work is to evaluate whether SENSE allows shorter breath-hold ce-MRA of the renal arteries while maintaining image quality.

Material and Methods: Three-dimensional ce-MRA of the renal arteries using SENSE was performed in ten patients on a clinical 1.5T scanner (Philips Gyroscan ACS-NT, PowerTrak 6000). Scan time of the three-dimensional ce-MRA (TR/TE/FA: 5.1 ms/1.4 ms/40°; FOV: 400: matrix: 163 × 512; slice thickness: 1.5 mm; 50 slices in coronal plane; NEX: 1: SENSE factor: 2) was 11 s. A separate reference scan was obtained from the four-element synergy-body coil for unfolding the SENSE data. Reconstruction of the folded data can be performed by linear algebra, using the sensitivity profile of each synergy coil. For comparison all patients underwent additionally a conventional three-dimensional ce-MRA with the same imaging sequence parameter except for the SENSE factor. The scan time was 22 s. Gd-DTPA (25 ml) were applied as a bolus with a injection rate of 3 ml/s using SENSE and 1.5 ml/s with the conventional technique. The proportionally increased injection rate using SENSE is essential and was evaluated in a prior study. CNR was measured and image quality (scale from 1 to 5) of the renal arteries were assessed by two radiologists.

Results: Comparing image quality showed better images for SENSE protocol in all (ten/ten) patients. This was due to less blurring and motion artifacts. The CNR did not differ between the compared protocols. The 11 s scan time was well tolerated by all patients, while two/ten could not hold their breath for 22 s required for the conventional protocol.

Conclusions: SENSE allows for faster high quality ce-MRA of renal arteries than conventional ce-MRA. The shorter scan time is better tolerated by the patients.

Whole body magnetic resonance angiography: systemic imaging for a systemic disease

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Objective: To assess the performance of a three-dimensional MRA strategy based on a five step, single injection protocol.

Materials and Methods: Contrast enhanced three-dimensional MRA was performed in 20 patients on a 1.5T system (Sonata, Siemens, Erlangen). The imaging strategy was based on the acquisition of five three-dimensional data sets with a three-dimensional FLASH sequence. The acquisition time of each three-dimensional data set was 10–12 s. During a 3 s acquisition break the table was manually repositioned to the center of the following image volume, which was offset by 35 cm. With five successive acquisitions craniocaudal coverage extended over 175 cm, while the total scan time amounted to 72 s. Gadobenate dimeglumine (Multihance, Bracco) was administered at a dose of 0.3 mmol/kg b.w. at a rate of 1.5 ml/s for the first half and 0.7 ml/s for the second half of the contrast volume.

Results: The diagnostic performance of the outlined whole body MRA strategy allowed accurate display of

the arterial vasculature from supraaortic arteries to the lower extremity vessels. With DSA as gold standard overall sensitivity and specificity of MRA for the detection of hemodynamically significant disease was 87.6/91.3%, and 94.8/97.4% for the detection of occlusions. Short total acquisition time of 72 s and lack of invasiveness are certain to benefit patient management.

Morphologic and functional evaluation of the renovascular system using an intravascular contrast agent: experimental and clinical results

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The interrelation between the morphologic degree of renal artery stenosis and changes in parenchymal perfusion is assessed. In an invasive animal model different degrees of renal artery stenosis are created with an inflatable cuff. A dynamic T2* weighted sequence is used to measure signal–time curves in the renal artery (arterial input function = AIF) and the renal parenchyma during administration of an intravascular ultrasmall iron oxide contrast agent. After deconvolution of the calculated tissue concentration–time curves with the AIF, regional blood volume, regional blood flow (rBF) and mean transit-time are calculated. The results are compared to invasive transit-time ultrasound flow measurements and kidney weight. The morphologic degree of stenosis is measured in the steady-state using a high-resolution three-dimensional ce-MRA sequence (voxel size = $0.7 \times 0.07 \times 1$ mm). Five patients with renoparenchymal damage due to long-standing renal artery stenosis are also evaluated. In the normal canine kidney, mean cortical rBF is calculated as 424 ± 80 ml/100 g tissue per minute. These data agree with the invasive validation within 10% (377 ± 70 ml). Up to a 80% renal artery stenosis, cortical perfusion remains unchanged. With stenoses $> 80\%$ cortical perfusion drops to 190 ± 60 ml/min. In the patients, a substantial difference in the cortical perfusion of more than 200 ± 40 ml/100 g tissue per minute between the normal and the ischemic kidneys is found. The adjunct of quantitative renal perfusion measurements to three-dimensional ce-MRA in a single MR exam allows to determine the functional significance of a renal artery stenosis. Differentiation between predominately renovascular and renoparenchymal disease becomes feasible.

Rapid and robust magnetic resonance determination of aortic pulse wave velocity

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Atherosclerosis can lead to changes in aortic distensibility, increasing the mechanical impedance seen by the ejecting left ventricle, which in turn can contribute to hypertrophy and heart failure. MR measurement of pulse wave velocity provides a noninvasive technique for determining aortic distensibility.

Object: To improve the reliability and speed of MR measurements of aortic pulse wave velocity.

Methods: MR two-dimensional selective excitation pulses are used to excite a pencil in the aorta. ECG gating and Fourier velocity encoding produce a movie of aortic blood velocities over the cardiac cycle, analogous to Doppler M-mode, allowing visualization of the propagating velocity wave. Respiratory gating has been incorporated into this pulse sequence, in order to remove ghosting and improve accuracy. An analysis tool implements cross correlation to provide automated determination of pulse wave velocity from the data.

Results: Data acquired on normal volunteers showed reduced ghosting and better reproducibility with respiratory gating. The automated analysis tool yielded an order of magnitude improvement in speed and good agreement with manual fitting. Other aspects of flow are well visualized with this technique, including helical flow patterns in the descending aorta, reduced blood velocities in aneurysms, and retrograde flow in aortic insufficiency.

Cine three-dimensional MRDSA of the great vessels' value of the ultrashort TR/TE sequences for the angio of the great vessels in the chest

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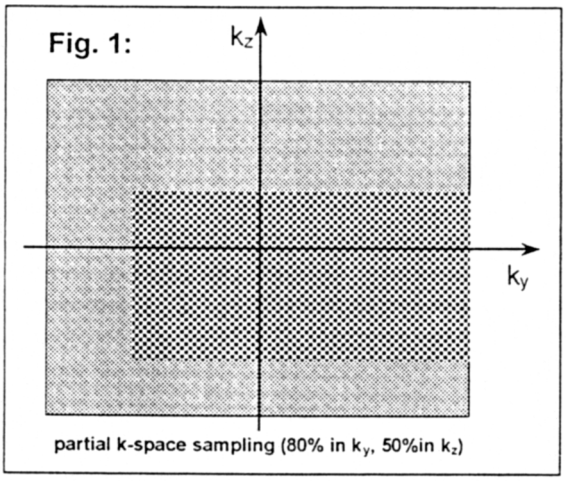
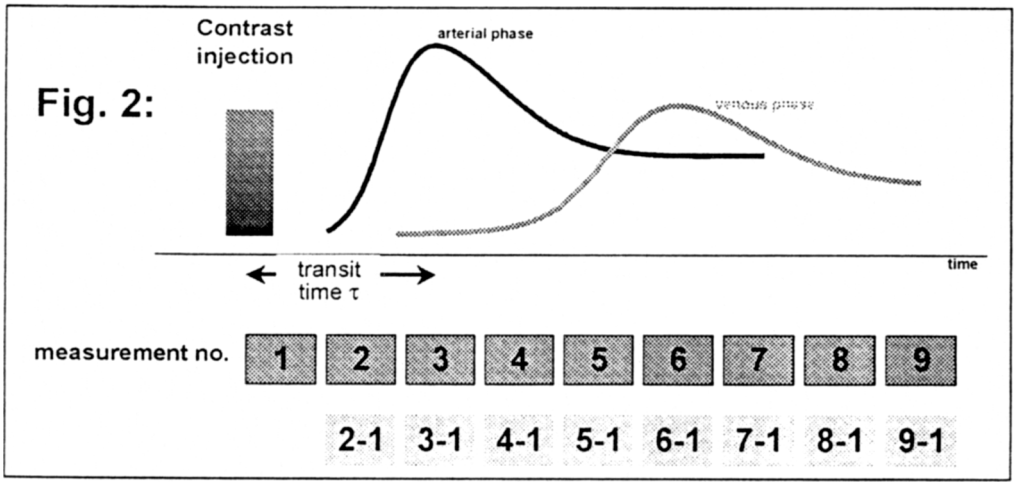
Purpose: Since the introduction of gadolinium in MRA, multiple variants have been developed with the aim of improving the spatial and temporal resolution. We report our experience in 42 patients subjected to study with a new three-dimensional ce-MRDSA sequence, acquiring a three-dimensional set every 1–2 s-thus affording a dynamic view of contrast circulation.

Methods: A total of 42 patients were explored with this new sequence with a 1.5T clinical use superconductor magnet (Siemens Magnetom Sonata).With high-power gradients (Gmax = 40 mT/m, SR200) it is possible to shorten the TR of a gradient echo sequence to as little as 1.64 ms with an echo time of 0.6 ms. The TR is short enough to allow scan times of just a few seconds, and the short TE reduces T2* signal losses significantly. The gradient echo sequence is combined with a three-dimensional FFT technique incorporating a partial Fourier acquisition as shown in Fig. 1. For a 256-matrix of 100 lines and 32 partitions, the effective scan time will be 2.1 s assuming 80% partial Fourier in the in-plane phase encode direction and 50% in the slice-select phase encode direction. A series of ultra-fast three-dimensional acquisitions is applied during contrast injection as illustrated in Fig. 2. All images are

reconstructed and a subtraction is calculated with the baseline data set of measurement number 1. All measurements are performed with a cp-body array coil for maximal signal-to-noise ratio. Acquisition involves the programming of 55 consecutive sequences. The MIP images are labeled with the time of acquisition. The three-dimensional set comprised 80–120 mm, with 24–40 partitions, a FOV of 40 cm, a 256 × 128 matrix and 1 NEX. Gadolinium was administered with a power injector at a flow rate of 2–4 ml/s. The images were evaluated in both the MIP with and without subtraction, and the source images without subtraction. Once organized, the images are viewed in dynamic (paging) mode. The images were evaluated by two radiologists distinct to the specialist who performed the study. Image quality was assessed, along with the resolution, partitions, and the novel contributions to diagnosis versus slower acquisition sequences.





Results: In our series of 42 patients we are included 22 aortic exams, five of Superior cava vein, nine of Pulmonar arteries, three of subclavian arteries and veins, and five of other (with two controls for large vessel transpositioning, two suspected cardiac tumors (one excluded and one thrombus). The best results corresponded to the aortic lesions, where dissection assessment was best. The clear delimitation of the pulmonary veins allowed their correct evaluation in cases of lung tumor infiltration.The consensus between radiologists was 95%.

Conclusions: This new sequence affords excellent time resolution in image acquisition, though occasionally at the expense of spatial resolution; in any case, clear delimitation of the different vascular phases is very important for diagnosis. This fact is of particular relevance in patients with aortic lesions.

Three-dimensional contrast enhanced magnetic resonance angiography of the spinal vessels

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The size and flow conditions of the intraspinal vessels prevent them from being consistantly visualized in TOF MRA. Three-dimensional contrast enhanced ce-MRA is a luminographic technique, that is independant from flow velocities. Our purpose was to evaluate the potential of three-dimensional ce-MRA for the diagnosis of the spinal vessels. We performed 26 ce-MRA examinations of the intraspinal vessels in 22 patients. For ce-MRA, a three-dimensional FLASH sequence (TR = 3.2 ms, TE = 1.2 ms, = 30°) was optimized for a spatial resolution of $1.5 \times 1 \times 1$ mm^3. An intravenous gadolinium-bolus (10–30 ml) was timed to arrive in the second measurement. After subtraction, angiograms of the arterial and venous phases were calculated. The radicular arteries were seen in all ce- MRA. The normal anterior and posterior spinal arteries and the leptomeningeal veins could be visualized on source images only. A tumor blush with feeding arteries were seen in multiple hemangioblastomas and a paraganglioma. In a spinal dural AV fistula, an AV shunt between a thoracal radicular artery and an elongated and dilateded leptomeningeal vein was visualized on ce- MRA. ce-MRA excluded an AV-shunt after endovascular occlusion of an AV-fistula. Three-dimensional ce-MRA can depict the radicular and intraspinal arteries, leptomeningeal veins and epidural venous plexus. Although the spatial and temporal resolution is inferior to catheter angiography, three-dimensional ce-MRA can visualize arteriovenous shunts and leptomeningeal venous drainage. This early results indicate that ce-MRA has the potential for the noninvasive diagnosis of intraspinal vascular disorders and indicate that the method is useful for the follow-up after endovascular treatment for spinal vascular malfomations and tumors.

Preliminary experience with three-dimensional projection reconstruction magnetic resonance angiography in the chest and abdomen

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Introduction: ce-MRA often requires the selection of parameters that trade-off spatial resolution and anatomic coverage. This compromise is important for clinical applications in the chest and abdomen, where the breath-hold process limits the length of the acquisition. The objective of this work is to demonstrate the merits of three-dimensional vastly undersampled isotropic projection reconstruction (VIPR) acquisition for clinical imaging of the chest and abdomen.

Methods: An undersampled three-dimensional projection acquisition was developed using a non-selective RF excitation and 10 000 projections in a single breathhold. Images were acquired during the intravenous infusion of gadolinium contrast agent for MRA, or using a steady state free precession mode for T2 contrast. Images were reconstructed at up to a $384 \times 384 \times 384$ matrix over a 38 cm FOV.

Results/Discussion: The acquisition technique provides a method for acquisition of high-resolution images over a larger FOV than Fourier techniques. The volumetric acquisition eliminates many of the issues related to scan prescription. Since the acquisition has uniform k-space weighting, the images also show relatively more venous enhancement, but are also less sensitive to timing artifacts.

Selective contrast-enhanced magnetic resonance angiography of hemodialysis access grafts and fistulae

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MR is a potentially attractive modality for evaluation of hemodialysis access anatomy and function. The wide range of flow rates encountered (0–40 ml/s), which results in a variety of flow-related artifacts near stenoses and anastomoses, however, complicates the interpretation of flow-based MRA, and to a lesser degree intravenous contrast-enhanced MRA. A method is proposed which visualizes hemodialysis access without flow artifacts. Diluted Gd-DTPA was hand-injected directly into the access, while a cuff interrupted access flow. Filling of the access was monitored at one frame per second using a two-dimensional acquisition with

complex subtraction. A three-dimensional acquisition was started, when filling was satisfactory. Four Cimino-fistulae and four PTFE grafts were examined. In four cases a complementary DSA was made. In six patients the access was completely and adequately visualized. In the first two cases, both PTFE-grafts, filling of the venous anastomosis was poor, which was remedied by lowering the cuff-pressure during the first phase of injection. An average of 3.5 ml 'pure' Gd-DTPA per patient sufficed. Filling the access and completing the three-dimensional examination required at most 92 s of cuff inflation, which was well tolerated. Images were free of flow related artifacts: all narrowings on MRA corresponded to a similar narrowing on DSA.

Paired comparison of standard three-dimensional gadolinium-enhanced renal magnetic resonance angiography versus three-dimensional gadolinium-enhanced renal magnetic resonance angiography using sensitivity encoding (SENSE) with optimized profile order and variable scan matrix

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Objectives: To compare standard three-dimensional Gd-enhanced renal MRA with a recently developed three-dimensional Gd-enhanced MRA scan technique using sensitivity encoding (SENSE) with optimized profile order and variable scan matrix.

Material and Methods: MR imaging was performed on a 1.5T MR scanner (PowerTrak 6000, release 6.2; Philips Medical Systems). Some parameters for the standard MRA technique were: FOV 512 × 302, acquisition matrix 512 × 154, acquisition slice thickness 2.2 (zero interpolated to 1.1), acquisition voxel size 4.3 mm^3, low-high profile order. Parameters for the new scan technique (using the synergy body-coil and research software proprietary of Philips Medical Systems) were FOV 410 × 410, acquisition matrix 410 × 314, acquisition slice thickness 2.2 (0 interpolated to 1.1), acquisition voxel size 2.9 mm^3, SENSE factor 2 (left–right direction), optimized low–high random profile order. Both MR protocols used 29 ml Gd at 3 ml/s, flushed with 20 ml saline. Scan duration for both breath-hold techniques: 24 s. All MR scans were judged by two radiologists based on the quality of image detail, presence of artifacts, presence of pathology, and contrast-to-noise ratio.

Results: Preliminary findings suggest the new scan technique to be superior to the standard MRA technique. The final results of the paired comparison in five volunteers and five patients with angiographically proven renal artery stenosis will be presented.

Splanchnic aneurysm and magnetic resonance angiography

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Purpose: To correlate MRA with routine exams in the diagnosis and the follow up of splanchnic aneurysms.

Materials and Methods: We retrospectively reviewed the findings of MRA of splanchnic arteries performed in 15 of 69 patients with known splanchnic aneurysms. Ten patients underwent both computed tomography (CT) and ultrasonography before MRA. Conventional angiogram has been done to confirm the diagnosis in seven cases. In three cases, MRA has been done to evaluate results of catheter embolization or surgery. Diagnosis was made first on routine exams either on ultrasonography and/or CT. MRA was performed to confirm findings of routine exam except for one patient who underwent only MRA. MRA was based on a three-dimensional spoiled gradient-echo magnetic resonance imaging with gadolinium enhancement.

Results: Patient population included seven men and eight women aged from 34 to 84 years old. Splanchnic aneurysms were localized as follow: five splenic, four hepatic, four celiac trunk and two gastro-duodenal. For 13 patients, MRA identified and localized the aneurysms as well as ultrasonography and/or CT. In one case, discrepancy between US-CT and MRA was found for the localization of the aneurysm. For this case, MRA diagnosis' was confirmed by conventional angiogram. After specific treatment, MRA demonstrated absence of gadolinium enhancement of the treated aneurysm.

Conclusion: This small series showed good correlation between CT, conventional angiogram, at a lower degree ultrasonography and MRA in order to identify and localize splanchnic aneurysms.

Imaging of thoracic aortic aneurysm and dissection with routine visualization of the proximal coronary arteries

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Purpose: Gd-enhanced MRA has recently become a routine technique used for the diagnosis, pre-operative assessment and post-operative follow-up of thoracic aortic diseases. Current Gd-enhanced techniques do not reliably depict the involvement or anatomy of the coronary arteries. The purpose of this study was to assess the usefulness of a multi-slab breath-hold Gd-enhanced MRA technique synchronized with the movement of the heart.

Methods: Fifteen patients referred for the investigation of the thoracic aorta participated in the study. All images were acquired during bolus intravenous injec-

tion of the MR contrast agent and a single 24 heartbeat breath-hold. Images were acquired in the axial plane from the origin of the aortic arch vessels to the base of the heart. Disease depiction and visibility of the proximal coronary arteries was graded on a three-point scale. These criteria were compared with unsynchronized scans.

Results: Three aneurysms and five dissections were seen. Visualization of the proximal portions of the coronary arteries and determination of involvement was possible in 14/15 cases. Coronary artery visualization was significantly improved with cardiac synchronization.

Conclusions: Synchronized imaging showed significantly better aneurysm, aortic valve leaflet and proximal coronary artery depiction. Synchronization reduced motion artifacts allowing a better visualization of the aortic root and proximal coronary arteries.

Initial experience using three-dimensional contrast enhanced magnetic resonance angiography sequences in evaluation of vascular and parenchimal findings in simultaneous kidney and pancreas transplantation

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Purpose: To determine the value of three-dimensional ce-MRA sequences in detection of vascular and parenchymal findings of kidney and pancreas in simultaneous transplantation.

Method and Materials: We evaluted 9 patients (seven male and two famale) who underwent simultaneous kidney and pancreas transplantation, using MR 1.5 T with two breathold consecutive acquisitions of 15 s each after a MultiHance injection (20 ml with flow rate of 2.0 ml/s). Images evaluation included the source images MIP and sutraction images.

Results: In all patients studied, we found high signal intensity in aorta, common iliac arteries and in main branches of transplanted vessels both arterial and venous. In all patients was possible to correctly evaluate perfusion of renal and pancreatic parenchyma.

Conclusion: Three-dimensional contrast enhanced sequence is useful and easy to perform with one contrast injection demonstrating the entire vascularization (arterial and venous) and parenchymal perfusion of transplantated kidney and pancreas.We believe that in future MRA may develop to monitorize kidney and pancreas simultaneous transplantation.

Synchronizing three-dimensional data acquisition with bolus passage down the legs for maximal bolus sharing on stepping table peripheral magnetic resonance angiography

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Purpose: Fast three-dimensional scanning was combined with reordering k-space and optimized bolus timing at three sequential stations to maximize sharing Gd contrast among stations on stepping table MRA.

Methods: Bolus passage down the legs was studied in 121 patients undergoing angiography to determine how to predict optimal bolus timing for all stations based upon a single bolus timing measurement at the ankles. Then a three-dimensional pulse sequence was developed to map k-space reverse centrically for the first station (abdomen–pelvis), sequentially for the second station (thigh) and centrically for the third station (calf) to minimize temporal separation of the three centers of k-space. The three-dimensional acquisition for the middle (thigh) station was shortened by reducing k-space in the slice direction as necessary to keep up with Gd contrast passage down the legs.

Results: Time to contrast arrival in common femoral artery = 0.7 × contrast arrival time at the ankles. Time to contrast arrival in popliteal artery = 0.8 × contrast arrival time at the ankles. This timing information combined with reordered k-space and shortening the second station to 10–15 s enabled synchronization of the centers of k-space with the peak arterial phase of the bolus at all three stations substantially improving vessel conspicuity with excellent depiction of even the infrapopliteal vessels without venous contamination.

Summary: Maximizing bolus sharing between stations improves peripheral MRA.

Multi-station peripheral magnetic resonance angiography using segmented volume acquisition ('shoot and scoot'): initial experiences

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Purpose: To test the feasibility of a segmented volume acquisition technique (three-dimensional-SNS) for Gd-enhanced peripheral MRA whereby the low-spatial-frequency k-space data (center) is acquired during the initial pass (arterial phase); and the remaining k-space data, during the second pass (delayed phase).

Materials and Methods: Thirteen healthy volunteers were imaged on a 1.5T MR scanner. In 2 subjects, multiphase single-station three-dimensional MRA was performed. Conventional single-pass three-station peripheral station three-dimensional MRA was performed in four subjects (control group). In seven subjects, a

three-station peripheral MRA was acquired over two passes using a fast station three-dimensional gradient echo pulse sequence (station three-dimensional-SNS) capable of station-specific elliptical centric view ordering and automated table motion control.

Results: Single-station MRA simulations and station three-dimensional-SNS images with at least 34% of the arterial-phase central k-space data yielded satisfactory arterial illustration. Blinded physician comparison of station three-dimensional-SNS and control group images revealed equivalence for stations one (abdomen/pelvis) and two (thigh) with preference for station three-dimensional-SNS imaging of station three (calf).

Venous signal in distal station bolus chase magnetic resonance angiography: fast arterial venous communication

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We test the hypothesis that venous signal in the distal station of bolus chase three-dimensional MRA is caused by fast arterial–venous communication by correlating bolus chase three-dimensional MRA with dynamic two-dimensional MRA. 139 consecutive patients (10/01/98–5/17/99) were included in this study. Near the tibial trifurcation in 154 legs, venous signal was measured in three-dimensional and the arterial phase (duration between the contrast bolus arrival and venous return) was measured time resolved two-dimensional images. Venous signal were observed in distal calf station in 27 of the 139 patients (19%). The arterial phase was 48.7 ± 7.8 s on 101 legs without venous signal, 34.6 ± 9.1 s on 13 legs with moderate venous signal, and 19.6 ± 4.4 s on 40 legs with substantial venous signal. The arterial phase with substantial vein is always shorter than that without vein ($P = 1.7 \times 10^{-54}$, t-test) and is shorter than that with moderate vein ($P = 5.5 \times 10^{-5}$). Short arterial phase was not related to hypertension ($P = 0.2$), diabetes ($P = 0.5$), stenoses/occlusions ($P = 0.4$), cholesterol ($r = 0.1$), or hematocrit level ($r = 0.2$). All patients with congestive heart failure ($n = 7$) and myocardial infarction ($n = 10$) had long arterial phase (no vein). The venous signal in distal calf three-dimensional station is caused by fast arterial–venous communication.

Magnetic resonance angiography of the feet

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Contrast-enhanced three-dimensional MRA of the arteries of the lower extremities is currently evolving as an appealing non-invasive alternative to digital subtraction angiography. The imaging of the tibial runoff vessels and pedal arteries, however, is still suboptimal. High quality of these images is especially important in patients who may undergo distal bypass surgery, which is the most important therapeutic option for patients suffering from severe peripheral arterial occlusive disease. In this study, we investigated the possibility of optimal imaging of the arteries of the foot on a standard clinical 1.5T MR scanner using 40 cm^3 of gadopentetate dimeglumine. Eighteen patients underwent scanning of the feet using five different techniques: feet after MobiTrak of three stacks; feet as fourth stack of MobiTrak, with a synergy body coil; feet separately from the legs with synergy body coil or head coil or Flex M coil with dynamic scan parameters. MRA of the feet after MobiTrak was not useful due to venous overprojection, caused by inaccurate timing of contrast arrival. With dynamic scan parameters optimal results were obtained. High quality images were acquired when scanning dynamically using a Flex M coil or a head coil.

High-resolution peripheral magnetic resonance angiography correlated with intra-arterial pressure measurements

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Background: Intra-arterial measurement of the pressure gradient across a stenosis is a better indicator of hemodynamic significance than estimates of diameter reduction with imaging techniques. If the unique three-dimensional imaging capabilities of MRI could be exploited to better predict which lesions are significant, a better selection of borderline stenotic lesions amenable for percutaneous therapy can be made.

Purpose: To test the ability of high resolution MRA (hr-MRA) of the iliac arteries to predict hemodynamically significant stenoses as measured with intra-arterial pressure measurements.

Subjects and Methods: Nineteen patients with intermittent claudication, underwent both DSA and free breathing hr-MRA (voxel size 2 mm^3, 35 ml Gd-DTPA, acquisition time 1 min). Luminal reduction was determined with optimized three-dimensional viewing techniques (MIP, MPR, cross-sectional measurements). Intra-arterial pressure differences across the stenosis of > 10 mmHg were considered significant.

Results: Preliminary results indicate perfect agreement between the predicted hemodynamic significance on the basis of MRA versus intra-arterial pressure measurements. Extended results of 25 patients will be presented.

Peripheral magnetic resonance angiography: high resolution acquisition with a dedicated coil

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Purpose: Practically, ce-MRA of the entire lower extremity is most difficult, since the limitation of the total dose to maximum 0.3 mmol/kg b.w. Gd has to be considered. One way of improving image quality is the implementation of a dedicated peripheral MRA (pMRA) coil. We compared such a new phased array coil with the conventional body phased array coil setting.

Materials and Methods: Ten patients with peripheral occlusive disease were included in the study. Using a three-dimensional ce-MRA, the entire peripheral circulation was visualized in three stations (pelvic, femoral and tibial region). The patients were investigated twice, first of all with a three-dimensional ce-MRA using a body phased array coil and one week later with the newly developed pMRA-coil (multiple array coil). The parameter of the sequence and the hardware were: TR/TE/FA = 0.4 ms/1.8 ms/35° (Siemens 1.5 T Symphony Magnetom), 512 matrix, (voxel size of 0.78 × 1.2 × 1–2 mm^3). The bolus arrival time was estimated at the common femoral artery by a two-dimensional time resolved GE-sequence. An individual calculation of the injection rate as a result of predefined ce-MRA image resolution and Gd dose was done for all the investigations (30 ml NaCl flush), applying 0.1 mmol/ml Gd dose for each of the three stations. The resulting three-dimensional ce-MRA images were compared based on the same anatomical partition of each coil technique. Within the proximal, middle and distal third of the femoral and tibial region including the forefoot, a region of interest was defined in order to calculate the signal-to-noise ratio (SNR).

Results: On average, the calculated increase of SNR for different vessel regions measured by pMRA compared with conventional coil set-up were for the proximal, middle and distal part of the femoral region 169.8, 38.7 and 204.4% and, and 141.5, 82.9 and 78.9% for the tibial region, respectively.

Conclusion: The visualization of the lower leg arteries at vessel diameters below 2 or 3 mm and the entire collateral circulation system in case of occlusions requires adjusted optimized ce-MRA protocols and high resolution images. The results clearly show the advantages of the new dedicated pMRA coil taking SNR into consideration. Therefore, there is a real chance of saving Gd if the pMRA coil is permitted.

Contrast-enhanced magnetic resonance angiography of the peripheral vessel tree using moving bed imaging on a 1.0T system

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Purpose: To determine the feasibility of moving bed ce-enhanced MRA on a 1.0T magnet in the diagnosis of peripheral arterial occlusive disease (PAOD).

Materials and Methods: Since the availability of the moving-bed imaging technique at our institution, 517 patients underwent MRA of the peripheral vessels. Out of these, 153 patients received ce-MRA and DSA within 14 days. MRA was performed before and after the administration of 40 ml contrast material on a 1.0T unit. Every leg was divided into 16 vascular segments and scored in four categories of disease severity. DSA served as a standard of reference.

Results: Out of the 153 patients, 3101 vessel segments were delineated by both techniques. In 2884 (93%) segments, there was full conformity in stenosis classification between MRA and DSA. In 155 segments, MRA overestimated a stenosis by one grade and in 43 by two classes. Nineteen vessel segments were not assessable due to artifacts after stent placement or bypass surgery.

Conclusion: Moving-bed MRA using a 1.0T magnet is possible, though the image quality of the calf is not always sufficient. Nevertheless, with further technical improvement moving-bed MRA will play an important role in the diagnosis and therapy control of PAOD.

Contrast-enhanced, single-injection, magnetic resonance-angiography with automated table movement (smartstep) compared to multi-injection, time-resolved contract-enhanced three-dimensional magnetic resonance angiography (TRICKS) of the run-off vessels

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Objective: Evaluation of a single-injection ce-MRA with automated table movement compared to multi-injection, time-resolved three-dimensional ce-MRA (TRICKS) of the run-off vessels in volunteers and patients.

Material and Methods: In a total of ten volunteers and ten patients, imaging of the abdominal aorta and run-off vessels was performed on a 1.5T MR system (GEMS). Individuals were imaged with both techniques. The bolus chase protocol consisted of a breath-held, contrast-triggered, GRE sequence covering the aorta, followed by an acquisition of the thigh and the calfs with automated table movement (SmartStep). A single-injection of 0.3 mmol/kg Gd-DTPA was used. The TRICKS protocol consisted of a breath-held GRE sequence and an injection of 0.1 mml/kg Gd-DTPA for imaging the aorta. Imaging of the thigh and calf was performed in two steps (0.1 mmol/kg/step), using a time-resolved sequence. Intra-individual image analysis was based on objective (vessels detected) and subjective (vessel conspicuity) points.

Results: Equal vessel segments were detected by both techniques in volunteers. Venous contamination confounded diagnosis in several patients with SmartStep, whereas no significant venous overlap was seen in TRICKS.

Conclusion: TRICKS acquires a time-series of images with improved vessel separation with less venous overlap.

Time-resolved imaging and vessel segmentation in contrast-enhanced magnetic resonance angiography of the peripheral vasculature

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Objective: We present a vessel segmentation technique based on time resolved contrast-enhanced three-dimensional ce-MRA for imaging of the peripheral vasculature. Post-processing of time-resolved images was used to produce separate arterial and venous images.

Materials and Methods: Time-resolved ce-MRA exams (TRICKS) were performed in patients and volunteers. The proximal and distal lower extremities were imaged in two acquisitions of separate contrast-agent injections (0.10, 0.12 mmol/kg b.w.). Image acquisitions of 2–5 min insured acquisition of arterial and venous phases. The time-series of three-dimensional volumes were subjected to a vessel segmentation algorithm based on the unique dynamic signature of arteries and veins (VTRAC). Temporal filtering of the time-series was performed, resulting in increased signal-to-noise (SNR) of the image.

Discussion: Bolus chase techniques are constrained by contrast transit time and may suffer from venous contamination or loss of vessels due to pathologically delayed contrast arrival. Time-resolved acquisitions are able to capture the dynamics of vessel filling and to exploit this information for the removal of unwanted anatomic structures, allowing for extended scan time for increasing SNR.

Stepping table contrast-enhanced subtraction magnetic resonance angiography of the aorta and lower extremity arteries

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Objective: The purpose of this study was to assess the diagnostic performance of MRA compared to conventional digital subtraction angiography (DSA) for identify and characterize the arterial vessels from abdominal aorta to the feet.

Materials and Methods: Twenty-six patients with suspected peripheral vascular disease underwent both DSA and stepping-table gadolinium-enhanced three-dimensional subtraction MRA; MRA images were acquired on a 1.5 T scanner in three imaging locations after a single injection of Gd-DTPA. For data analysis the arterial system was divided into eight segments. For each segment four independent observers evaluated the presence of vessel disease and classified it as normal, mildly stenosed ($< 50\%$), moderately stenosed (50–75%), severely stenosed (75–99%) or occluded. DSA was considered the gold standard.

Results: At DSA 163 segments presented occlusive vascular disease. Sensibility and specificity of MRA showed a range from 94 to 100% and from 97 to 100% depending on the grading of the stenosis. Interobserver agreement ranged from good to excellent.

Conclusion: Three steps contrast-enhanced three-dimensional subtraction ce-MRA showed to be accurate and operator-independent enough to be considered as a non-invasive alternative to DSA in patients with occlusive vascular disease.

Universal retrofitting of an magnetic resonance imaging system with SKIP™ for high resolution peripheral contrast enhanced lower extremity magnetic resonance angiography using a single biphasic intravenous injection of magnetic resonance imaging contrast and a fixed posterior and a floating anterior surface array coil

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Object: To demonstrate the quick and simple process of mounting SKIP (Stepping Kinematic Imaging Platform) onto an MRI scanner for conducting high-resolution peripheral lower extremity MRA with the existing system phased array coil and a single biphasic intravenous injection of MRI contrast.

Materials and Methods: Imaging was performed at 1.5 T (Siemens Vision ($n = 21$), GE Signa ($n = 8$), Picker Eclipse ($n = 2$)) in 12 normal volunteers and 19 patients. The existing system body array coil (Siemens) or torso array coil (GE) was mounted onto the existing MRI system table with SKIP™ (Magnetic Moments, L.L.C., Bloomfield, MI). To maximize the coil filling factor, the anterior array coil element was fixed within a saddle coil mount which allowed the anterior array coil element to float and slide over the patient surface anatomy during translation of the patient with the moving SKIP™ bed. MRA was performed at each station with a fat saturated high-resolution (512 × 192) matrix coronal three-dimensional spoiled gradient echo sequence (18–21 s/sequence measurement) and a single biphasic (15 cm^3 at 1.5 cm^3/s, followed by 23–33 cm^3 at 0.5–0.8 cm^3/s followed by a saline flush) intravenous injection of MRI contrast. Breath hold T2 TURBO STIR was performed in select cases of suspected graft infection. Fixed table increments of either 30, 40 or 48 cm were used to spatially cover 120–144 cm with an overlapping FOV and a 4–5 s scan delay for patient bed translation. The vascular S/N and vascular-to-background contrast was qualitatively graded (1 — poor, 2 — good, 3 — excellent) at each station.

Results: SKIP™ was easily implemented on various MRI scanners and allowed one to image, with MRI and MRA sequences, different spatial locations without the need of a dedicated peripheral vascular coil, software, hardware or electronic upgrades. The arterial anatomy was imaged in all cases with no venous overlap from the abdominal or thoracic aorta down to the midfoot with excellent (grade 3) vascular S/N and excellent (grade 3) vascular-to-background contrast in all cases. All patients were accurately diagnosed allowing triage of patients to percutaneous interventional treatment with or without surgical intervention without the need for diagnostic X-ray angiography. Long spatial coverages of up to 144 cm allowed one to image patients with axillary-to-femoral bypass grafts and to image associated thoracic aortic pathology.

Reconstruction of carotid bifurcation wall thickness and hemodynamics via black blood magnetic resonance imaging

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The development and progression of atherosclerosis at the carotid bifurcation is thought to be mediated by complex local hemodynamics. Using black blood MRI and computational fluid dynamics (CFD), we are now able to reconstruct three-dimensional maps of vessel wall thickness and hemodynamic parameters, making it now possible to test these hemodynamic hypotheses in a patient-specific manner.

Materials and Methods: Using a multi-slice black blood protocol, we image the carotid bifurcation over a 5–6 cm axial range at ~300 μm in-plane resolution. We have developed computer-assisted segmentation techniques to extract the three-dimensional inner- and outer-wall boundaries, from which surface maps of vessel wall thickness are extracted. The inner boundary is used as input to CFD software, which computes the subject-specific pulsatile blood flow dynamics.

Results and Discussion: Preliminary results in normal volunteers and patients with early carotid artery disease suggest no obvious relationship between hemodynamic factors and wall thickness. Such relationships may be masked by the poorer image qualities typically achieved at and distal to the level of bifurcation itself. We are currently investigating how to optimize such competing factors as outer wall-tissue contrast, in-plane and slice resolution, noise and scan time to improve the reliability of wall thickness measurements at these locations.

Carotid plaque imaging: hardware and software optimization

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The composition of atherosclerotic lesions in the carotid arteries is believed to be an important predictor of plaque vulnerability. Very high spatial resolution imaging of atherosclerotic plaque at the human carotid bifurcation may be required in order to unambiguously identify the relevant compositional elements. In addition, several MR contrasts may be necessary to discriminate between different plaque components. Our objective is to design and implement an integrated hardware and software strategy for acquiring in vivo multi-contrast MR images at very high resolution covering the plaque volume. To date, we have designed a range of custom phased array coils for in vivo carotid bifurcation imaging, and have assessed these coils with respect to signal-to-noise ratio at the common carotid artery in a series of four normal volunteers. Using the optimized coil design, we have imaged four normal volunteers as well as four patients with carotid disease using an optimized black blood pulse and results show promise in terms of identification of plaque components at very high resolution. In vitro imaging of the endarterectomy specimen has been accomplished in a limited number of cases, at much higher spatial resolution. Multi-contrast imaging followed by multi-spectral analysis has been accomplished, with pixel-by-pixel comparison to histological images of the same specimens to assess classification accuracy. Our integrated hardware/software methodology provides a framework for optimizing and assessing the accuracy of non-invasive carotid plaque characterization.

Magnetic resonance imaging for the assessment of the vulnerable plaque

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There has been increasing awareness of the importance of composition of atherosclerotic plaque as a major risk factor for acute coronary syndromes. Several invasive and non-invasive imaging techniques are available to assess atherosclerotic vessels. However, these imaging techniques are ineffective in determining the plaques that are unstable and vulnerable to thrombosis and proliferation. In vivo, high-resolution, multi-contrast MR holds great promise of non-invasively imaging vulnerable plaques and determining the different plaque components such as lipid core, fibrosis, calcifications, and thrombus in arteries. MRI is capable of discriminating plaque components on the basis of chemical composition, molecular motion, diffusion, physical state or water content. These differences may be particularly important in determining the contributing factors related to plaque rupture, such as plaque vulnerability. We will show that MRI can characterize both ex vivo and in vivo the composition of human and animal atherosclerotic plaques in the carotid, aorta, and coronary arteries. The assessment of atherosclerotic plaques by imaging techniques is essential for the identification of vulnerable plaques. MR allows serial evaluation assessment of the progression and/or regression of atherosclerosis over time. Application of MR imaging opens up whole new areas for diagnosis, prevention, and treatment (e.g. lipid lowering drug regimens) of the atherosclerotic disease.

Are intravascular magnetic resonance imaging coils necessary for high-resolution imaging of vascular wall

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Intravascular MRI coils provide high SNR and therefore enable high-resolution imaging. In this work, we show that the best surface coils cannot outperform the best intravascular MRI coils. Rather than optimizing the intravascular and surface MRI coils, we optimized the electromagnetic waves associated with these designs without knowledge of the type of coil. We could then compare the performance of these coils with no experimental bias. A computer program was written and the accuracy of the program was tested by comparing its output with the results of MRI experiments. The position of the point of interest relative to the internal coil and the size of the body has a critical importance in this calculation. We found that the size of the intravascular MRI probe is not very critical. If the point of interest is closer to the intravascular probe than to the surface of the body, using intravascular MRI probes becomes significant. The performance of the loopless antenna design is nearly optimum when the point of interest is 4–8 cm away form the intravascular probe. Other designs will be more effective when the point of interest is closer than 4 cm.

Role of contrast enhanced three-dimensional magnetic resonance imaging in atherosclerotic lesion size measurement and tissue identification

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Introduction: Atherosclerotic lesion (AS) size and its tissue characteristics may be directly linked to lesion stability. This study's aim was to determine if three-dimensional ce-fast gradient echo (FGRE) can improve the accuracy of lesion size measurement and assist in tissue characterization in AS.

Methods: Seven subjects scheduled for carotid endarterectomy (CEA) underwent a MRI scan using three-dimensional DFGRE with a custom made phase-array coil on a SIGNA scanner. Pre- and post-contrast axial images were acquired with a gadolinium agent. CEA was performed $<$ one week after MRI with plaque removed enbloc. An identical scan was conducted on the excised plaque. Histology followed. Blinded tracing of carotid artery boundaries was conducted on pre-, post- and ex vivo images by two rators and wall areas (WA) were measured. A paired t-test was conducted on matched locations ($n = 54$).

Results: There is significant difference between WA measurement (pre-ex vivo: 10.00 ± 7.79 mm^2; post-ex vivo: 6.04 ± 8.02 mm^2; $P < 0.001$), with post-contrast images provide an improved estimate of WA. The smaller ex vivo WA is expected. Post-contrast tissue changes were observed that enhanced the contrast between neovasculature, necrotic core and the surrounding tissues.

Conclusions: These results show that CE three-dimensional ce-DFGRE may be useful for AS size measurement and tissue characterization.

In vivo microimaging of abdominal aorta in transgenic mice with atherosclerotic lesions at 2T

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Purpose: The objective of this study was to develop a method for noninvasive observation of vascular disease in a transgenic mouse with a 2T MRI system.

Material and Method: In vivo and in vitro high-resolution MR images of the abdominal aorta in ApoE-deficient mice were done using a 2T system. A dedicated antenna was designed with a structure adapted to the animal size. MR images were obtained using a two-dimensional spin-echo sequence with the following parameters: 0.8 mm in slice thickness, a spatial resolution of 86 × 86 μm $T_R/T_E = 600/21$ ms for T_1 weighted images and $T_R/T_E = 1800/44$ ms for the T_2 ones.

Results: In vitro, above the renal arteries, significant lesions were observed on MR images with dark areas corresponding to cholesterol crystals as confirmed on histology. In vivo, it was possible to observe aorta lumen and also to detect arterial wall thickening with atherosclerotic lesion. Moreover, technical method permitted to follow up these modifications over several months.

Conclusion: Developments of serial and in vivo MRI using mouse model may provide an efficient way to understand the atherosclerosis evolution and could be a valuable tool to evaluate in vivo therapeutic intervention in terms of lumen and artery wall size change in mouse.

Magnetic resonance angiography of metallic vascular implants: enhanced lumen visualization

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Three-dimensional ce-MRA is currently evolving as an appealing non-invasive alternative to digital subtraction angiography. However, the imaging of vessels containing metallic vascular implants, like stents and vena cava filters, can be troublesome with this technique. Often signal void is seen at the location of a stent, rendering evaluation of the stent lumen and detection of possible restenosis inside it impossible. In our opinion radio-frequency caging of the stent lumen by the metallic cage-like construction of the implant plays an important role here. The extent to which this caging takes place is obviously different for different cage constructions, which accounts for the observed differences in signal loss inside different stents made of the same material. In this in vitro study the role of the radio-frequency and susceptibility artifacts in metallic cage-like vascular implants was studied within the context of three-dimensional ce-MRA on a clinical 1.5T MR scanner. We show that by understanding the various causes of artifacts, and by optimizing the applied RF power and pulse sequence accordingly, it is possible to deal with the caging problem and depict the lumen of a stent, which would appear dark in an ordinary three-dimensional ce-MRA scan.

Active visualization of stents in MRI: the cableless approach

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Introduction: The development of intimal hyperplasia following stent deployment can lead to restenosis or even occlusion of stents. The mechanisms of neointimal proliferation remain undetermined. Initial experiments by our group demonstrated the ability to employ stents, connected via coaxial cable, as endoluminal receive coils for intravascular MRI. In the present study, the potential of a cableless approach, using inductively coupled stents as RF signal amplifiers, was investigated.

Methods: Different prototype stents were designed from copper wire, such that the stent mesh formed an inductivity which was tuned with a ceramic capacitor to the resonance frequency of the 1.5T system. To evaluate the signal characteristics of the stents, they were immersed in 0.9% NaCl solution. Scanning was performed on a Siemens Sonata with the body coil serving as transmitter. The stent signal was picked up by a surface receive coil attached to the phantom.

Results: All different stent prototypes provided amplification of low flip angles from a fast gradient echo sequence. Signal enhancement inside and close to the surface of the stents enabled their localization with high contrast in the MRI.

Discussion: Signal enhancement inside the stents could be used to visualize the endoprothesis with high contrast. The use of these stents as inductively coupled receivers to perform high resolution intravascular imaging is currently being investigated in in vivo animal experiments. Success in this regard would provide a powerful diagnostic method for non-invasive long-term follow-up of stent patency and the understanding of the mechanisms of restenosis.

Magnetic resonance imaging guided coronary interventions

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Objective: To perform MRI-guided coronary artery catheterization in an animal model.

Materials and Methods: A 9F introducer sheath was placed through the right carotid artery cutdown from three healthy pigs and three healthy dogs. A prototype 0.032-in. MRI-guidewire, a 7F MRI-guiding catheter (Surgi-Vision, Inc.) and two flexible surface coils (GE Medical System) were connected to four different receiver channels on a GE 1.5 T CV/i scanner for simul-

taneous reception of MR signal. Surface coils were placed around the thorax. A non-gated, single-slice, fast gradient echo sequence provided three images/s during tracking of the catheters and catheterization of coronary arteries. Then, to confirm the success of a catheterization, diluted gadolinium was injected in the MRI-guiding catheter. Images were displayed in real-time on an in-room monitor.

Results: In all experiments, the MRI-guiding catheter was placed in the ascending aorta using a prescription that displays the arch, the ascending and the descending aorta, together with the carotid artery. A second view was then obtained with a 2 cm slice selection that showed the ascending aorta and the ostium of the left or right coronary artery and the MRI-guiding catheter. Multiple catheterizations of both the right and left coronary arteries were achieved, and confirmed by visualization of the coronary arteries after injection of gadolinium.

Conclusion: MRI-guided coronary catheterization in an animal model is feasible.

Comparison of two methods to localize active magnetic resonance-catheters

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The technique of active MR catheter tracking [1] makes use of the limited sensitivity profile of a small RF-coil that is attached to the tip of a catheter. Localization of the small receive coil (and therefore the device) is generally performed by acquiring at least three MR data sets in the presence of three orthogonal gradients. After Fourier transformation, the three space coordinates of the coil can be simply extracted as the peak position in the respective signal projections. However, from the MR raw data the coil position can also be calculated using an autocorrelation technique, which determines the linear phase of the raw data sets. As the autocorrelation method requires fewer multiplications and additions, it can be performed faster, which is of importance on MR systems with limited computer performance. Unfortunately, the autocorrelation method is more susceptible to errors from noise, as a sum over signal differences is computed. An analysis of the precision of the peak detection on the choice of the reconstruction algorithm and the signal-to-noise ratio will be presented.

Reference:

[1] Dumoulin et al., 1993; 00:00–00.

New developments in subsecond functional magnetic resonance angiography: dynamic catheter visualization for magnetic guided selective procedures using real time projection contrast enhanced magnetic resonance angiography. Steerability study and first in vivo results in a patient

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Introduction: The purpose of this study was to evaluate the steerability of a new method to passively visualize catheter devices under MR guidance using real time projection contrast enhanced MRA. The feasibility of this method to perform selective catheterization procedures in a patient is demonstrated.

Methods: Four different 5F catheter types were tested in a flow phantom regarding visibility of the special configuration. A 1:50 (10 mmol/l) saline solution of Gd-DTPA was used to visualize the catheter and the positioning of the tip in relation to the vascular structures. For MR imaging (1.5T, Vision, Siemens) we used a Snapshot FLASH sequence developed for projection MRA with parameters: flip 30°, TR = 4.3 ms, TE = 1.5 ms, 125 kHz bw, 50 mm thick. Temporal resolution was two image updates/s. First in vivo experiments on a patient were performed by visualizing the catheter in the hepatic artery after catheterization on DSA guidance and selective catheterization of the renal artery on MR guidance. In addition, morphologic MR images were acquired of the liver prior to transarterial chemoembolization (TACE) in a case of multilocular hepatocellular carcinoma (HCC).

Results and Discussion: Visualization of the devices was 100% in their specific end configuration. Crossing over maneuver was possible under MR guidance as well as DSA using the Hook and Sos Omniflush catheter. In the patient diagnostic relevant morphologic images could be obtained after catheterization of the hepatic artery, and selective catheterization of the renal artery was possible using the Cobra-1 catheter.

Real-time passive catheter tracking on a clinical magnetic resonance scanner

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Introduction: We present an interactive real-time system on a conventional MR scanner that passively tracks and visualizes catheters by exploiting the T1-shortening effect of Gd-based MR contrast agents and a projection dephaser in slice direction.

Materials and Methods: In vitro experiments were performed by moving commercial catheters (5–8 French) filled with dilute Gd-DTPA in a phantom. Data were acquired continuously using a variable-rate k-space imaging technique based on a two-dimensional RF-spoiled gradient-recalled echo pulse sequence running on a 1.5T clinical scanner. Typical scan parameters were TR/TE/Flip = 4.8 ms/1.6 ms/60°, FOV = 20 × 20 cm, acquisition matrix = 160 × 256, and slab thickness = 2 cm. Similar in vivo experiments were also carried out.

Results and Discussion: The real-time system successfully tracked and visualized catheters in phantoms. The system was able to reconstruct and display up to 6 frames/s using only one CPU. Images are reconstructed after every 32/64 k-space lines are acquired. The entire catheter length was identified and visualized as the catheter was moved in a tissue mimicking phantom. The real-time system may be easily implemented on conventional MR scanners with minimal additional hardware.

Magnetic resonance-guided placement of a nitinol vena cava filter in a pig

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Percutaneous placement of an inferior vena cava filter is a means for long-term prevention of pulmonary thromboembolism. In this study we investigated the feasibility of placing a nitinol vena cava filter under near real-time, high resolution MR fluoroscopy on a standard clinical 1.5T scanner. Passive tracking of the devices was performed on the basis of small susceptibility artifacts created in fluoroscopic MR images by small paramagnetic Dy_2O_3 ring-markers and by the artifacts provoked by the metallic filter itself. Dynamically acquired fluoroscopic images were subtracted from a reference image with no interventional devices in it. The resulting subtraction images were overlaid on the previously acquired two-dimensional PC road-map image by real-time image processing and displayed on an RF-shielded color display inside the MR suite. Using this technique we achieved an image refresh rate of approximately one image every 2 s. Before and after the procedure a three-dimensional PC angiogram was acquired to be able to evaluate the filter placement. The filter placement procedure, including the deployment, could well be monitored using MRI. Post-treatment three-dimensional PC angiography allowed easy evaluation of the placement procedure and revealed that the filter was placed at the desired position, just below the renal veins.

Intraarterial gadolinium-enhanced magnetic resonance angiography: in vitro injection protocol validation

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Objectives: Direct intraarterial (IA) injections of dilute Gd may be used for rapid arterial depiction during MRI-guided endovascular interventions. Using a flow phantom, we aimed to: (1) measure the optimal arterial Gd concentration ([Gd]) required for MRA; (2) validate a proposed IA Gd-enhanced MRA injection protocol.

Materials and Methods: Using an aorto-renal-iliac arterial flow phantom, we performed 36 separate catheter-based IA Gd injections. We performed two-dimensional and three-dimensional MRA using a fast spoiled gradient-recalled echo sequence. Injected [Gd], injection rates, and aortic blood flow rates were varied independently. We then measured signal-to-noise ratio (SNR) in the aorta, renal artery, and iliac artery segments.

Results: Arterial [Gd] of 2–4% produced optimal SNR for two-dimensional MRA; 3–5% Gd was best for three-dimensional MRA. Across a range of injection rates, SNR could be maintained by inversely varying the injected [Gd].

Conclusions: Successful IA Gd-enhanced MRA requires dilute Gd injections. We validated an injection protocol based on injected [Gd], injection rate, and blood flow rate.