Body imaging with parallel acquisition techniques

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Lung Imaging

MR Screening of infiltrates

Radiological lung screening is typically performed either by conventional x-ray (CXR) examination or by high-resolution computed tomography (HR-CT) of the thorax and therefore exposes patients to a considerable amount of radiation, particularly after repeated examinations. This radiation dose could be reduced by using MRI as screening modality instead of x-ray based methods. Unfortunately, MRI of the lung is still a technical challenge because of the very low proton density of the lung tissue and the strong variation of susceptibility leading to very short T2* relaxation times. Both factors together are the reason for very low MR signal intensities from lung parenchyma and hence for a low SNR. A further difficulty in lung MRI is tissue motion because of respiration and cardiac motion.

The introduction of iPAT opened new possibilities to lung imaging with T2-weighted HASTE sequences. The main disadvantage of conventional HASTE sequences is the blurring of images caused by the long echo train and the T2-related signal decay during its readout; this effect severely limited the actual maximum image resolution. By using iPAT, the echo train can be reduced to half of its original length and thus blurring artifacts are reduced. Since late echoes with low signal intensity are not acquired, SNR can even improve compared to non-iPAT sequences. Additionally, the image acquisition is accelerated such that more slices can be acquired during one breath-hold period.

To evaluate the use of iPAT HASTE sequences for lung screening, we compared HR-CT and MR images in immunosuppressed patients with symptoms of pneumonia but normal or unspecific CXR. After comparing iPAT images reconstructed with the GRAPPA and mSENSE algorithm, we decided to use the GRAPPA algorithm because of the occurrence of reconstruction artifacts in the image center of the mSENSE images. Coronal slices of the lung are acquired with a FOV of 400×400 mm^2 and a resolution of 320×320 pixels; axial slices with a FOV of 400×320 mm^2 and a 320×256 matrix. The slice thickness is 8 mm and the TE is 27 ms in both sequences. To reduce the echo train length as far as possible, a sequence with external iPAT reference scan was used; the sequence acquires the reference lines immediately before the actual image acquisition within the same breath-hold.

We found that lung MRI with iPAT HASTE sequences is nearly as good as HR-CT for the detection of pulmonary infiltrates with only few false-negative and false-positive cases such that MRI can be recommended especially as a follow-up tool after initial HR-CT diagnosis.

MR Angiography and Perfusion Imaging

Experiences on MR perfusion imaging of the lung are still limited and various approaches like conventional FLASH and HASTE sequences or flow-sensitive inversion recovery techniques are being used. However, using iPAT techniques, both temporal and spatial resolution can be significantly increased compared with conventional imaging.

Therefore, we added iPAT FLASH sequences to our protocol for 3D contrast-enhanced MR angiography (MRA) and MR perfusion imaging of patients with primary and secondary pulmonary arterial hypertension. Using GRAPPA with the dedicated 12-element iPAT coil, a temporal resolution of 1.2 seconds per phase is possible for dynamic perfusion imaging, acquiring 25 dynamic phases in 30 seconds; the image resolution is 1.5×3.0×4.0 mm^3 acquired with a 256×128 matrix in 24 slices. High resolution angiograms can be acquired with a 512 matrix (0.8×1.0×1.6 mm^3 voxel size) in 20 seconds breath-hold time. For both dynamic perfusion and high-resolution angiography, an iPAT acceleration factor of 2 is used with 24 additionally acquired reference lines (**1**-**4**).

Using the parallel acquisition technique, excellent visualization of subsegmental vessels is possible in the angiographic images. Time-resolved perfusion imaging allows a reliable detection of small segmental and subsegmental perfusion defects. Using non-iPAT methods, visualization of perfusion defects and intravascular thrombi is generally possible as well, although with lower temporal and spatial resolution than using iPAT methods. In conclusion, we could substantially improve the temporal resolution as well as the spatial resolution by using iPAT.

Functional Cardiac Imaging

Global and Regional Cardiac Function

Cardiac magnetic resonance imaging has been extensively used in assessment of global and regional myocardial function. There is no doubt that MRI represents the current standard of reference. Although dataset acquisition can be performed in virtually any plane, the calculation of functional parameters is most commonly based on a stack of slices in double oblique short axis orientation. To allow for high spatial as well as high temporal resolution, the current sequence techniques acquire a single-slice cine data set each breath-hold. Although innovations of recent years allowed for a speed up of techniques, a completion of a standardized functional study still takes about 10–15 minutes includ-

ing patient recovery periods. Real-time imaging techniques using steady-state free precession (SSFP) sequences such as TrueFISP, allow for a major speed up in data acquisition due to the completion of a short axis dataset within a single breath-hold. However, this comes along with a restriction in spatial and temporal resolution. And in terms of volumetric accuracy, temporal resolution is by far more crucial than spatial resolution as recently shown by Miller and co-workers. The current recommendation for functional cardiac imaging requests a temporal resolution of 50 ms or even better.

iPAT allows meeting this criterion when implemented in conjunction with real-time TrueFISP. Compared to previous studies performed by Barkhausen and Lee, the temporal resolution that can be achieved is in the order of 45–50 ms. And as most recently shown, this improvement in temporal resolution now leads to an accuracy of results comparable to that of segmented TrueFISP; the iPAT images are acquired with an acceleration factor of 2 and 12 reference lines. So iPAT allows for dramatic time savings in cardiac function analysis without losing accuracy of volumetric results. It even allows for a multiplanar data acquisition within a single breath-hold (**5, 6**).

Based on experiences and comparisons, the GRAPPA reconstruction shows a more robust image quality in cardiac MRI than mSENSE. Due to the higher sensitivity of SENSE-related methods to folding artifacts, these techniques seem to be less useful in cardiac imaging because of the necessary larger FOV that leads either to an additional loss of spatial resolution or to loss of acquisition time when more phase-encoding lines are acquired. Apart from the use of iPAT with real-time techniques it also allows for a further improvement of spatial or temporal resolution in segmented single-slice acquisitions compared to standard techniques. When using cine TrueFISP techniques the loss in SNR due to iPAT is almost negligible.

Myocardial Perfusion Imaging

Myocardial perfusion imaging is a promising and rapidly increasing field in cardiac MRI. The rapid development of scanner hardware allows also for an improvement in sequence technologies which has been of a major benefit in techniques that require an ultra-fast data acquisition such as myocardial perfusion imaging. MR perfusion imaging has intrinsic benefits compared to routinely used techniques of nuclear medicine such as single photon emission computed tomography (SPECT) imaging or even positron emission tomography (PET) which represents the current gold standard in clinical perfusion imaging. Besides the higher spatial resolution and lack of radiation exposure, myocardial MR perfusion imaging has no attenuation problem related to anatomical limitations.

However, with the use of magnetization-prepared TurboFLASH techniques (e.g. saturation recovery TurboFLASH) the SNR has come to a limit. Therefore a combination with iPAT techniques seems to be of less benefit, as a further loss in SNR comes along. Newly developed techniques for myocardial perfusion imaging based on SSFP techniques are currently under investigation. In comparison with TurboFLASH techniques, these sequences show a considerable higher intrinsic SNR therefore allowing for a minimal loss of SNR when combined with iPAT.

Liver Imaging

MR liver imaging is most severely restricted by respiratory movement. Therefore, image quality was considerably improved with the introduction of T2-weighted turbo spin echo (TSE) and single-shot sequences. With these techniques, breath-hold examinations of the liver became possible, which most authors consider superior to conventional spin echo sequences. Generally, a maximum breath-hold time of about 20 seconds, tolerable even for patients in bad health condition, is a limiting parameter for all sequences used for liver imaging.

Respiratory-triggered T2-weighted sequences as an alternative to the breath-hold strategy have been studied with contradictory results. An advantage of respiratory-triggered sequences is the possibility to perform high-resolution examinations with 5 mm slice thickness which has not been possible with breath-hold sequences due to the limited breath-hold time. If one attempts to overcome this limitation of breath-hold imaging by examinations with multiple breath-holds such that the liver is examined in several stacks of slices, then parts of the liver can be missed if the patient does not meet the same position of the diaphragm in all stacks.

The development of iPAT allows for a substantial reduction of acquisition time, and thus breath-hold sequences with improved spatial resolution can be used. 2D navigator-based techniques, as the Prospective Acquisition Correction (PACE) technique, known from cardiac imaging, can adapt the stacks of slices according to the respiratory position by registering the diaphragm position, so that the whole liver can be covered even if the patient does not hold his breath at the same position (**7**).

We compared four high-resolution T2-weighted sequences with 5 mm slice thickness and a 320×240–256 matrix for routine liver imaging: a breath-hold TSE sequence with and without iPAT and PACE and a respiratory-triggered TSE sequence with and without iPAT. All images were acquired with a 12-element surface coil system dedicated to iPAT applications. A respiration belt was used for respiratory triggering. The aim was to demonstrate the feasibility of iPAT and PACE for T2-weighted liver imaging and to evaluate image quality of the different sequences.

In general, imaging with iPAT reduced the acquisition time by about 40 % without visible SNR loss. Comparing breath-hold and respiratory-triggered techniques, the latter turned out to be more robust in patients whereas no difference in image quality was observed in volunteers. An explanation for this result is that patients have more difficulties with the breath-hold period of up to 20 seconds. In conclusion, iPAT liver examinations with respiratory triggering appear to be

the most robust approach for clinical routine examinations.

High-resolution renal MR angiography

Three dimensional gadolinium-enhanced magnetic resonance angiography (3D-Gd-MRA) has gained high popularity as a non-invasive imaging alternative for grading of renal artery stenosis. High accuracies of over 90 % have been reported by numerous researchers in the past five years. Nevertheless, the technique is still notoriously known for overgrading high-grade renal artery stenoses and missing low-grade lesions, thereby limiting its overall clinical acceptance. A recent Dutch multicenter trial presented less encouraging results with overall accuracies of only 85 % compared to DSA. In addition, no reliable data on grading of stenoses of the more distal main renal artery or segmental arteries exists, yet.

One major limiting factor is spatial resolution. For standard breath-hold acquisitions with bolus administration of extracellular, non-intravascular gadolinium chelates, the maximum achievable spatial resolution represents a compromise between scan time, anatomic coverage and SNR. Current imaging protocols usually obtain images with a maximum of 1.5 mm^3 isotropic resolution which still represents 5 to 7 fold less than that of digital subtraction angiography (DSA). In a renal artery with a diameter of 7–8 mm, an isotropic voxel size of at least 1 mm^3 is required for accurate depiction of a 90 % reduction in lumen diameter.

Parallel acquisition techniques allow for improvement of spatial resolution without prolonging data acquisition and are well suited for images with a high SNR such as 3D-Gd-MRA. Nearly isotropic data sets with a spatial resolution of 0.8×0.8×1 mm^3 could be acquired within 23 seconds. For data acquisition and reconstruction, the GRAPPA and SENSE algorithms were compared in terms of artifacts. To improve the contrast-to-noise ration, the one molar contrast agent gadobutrol (Gadovist®, Schering AG, Germany) was administered at a dose of 1.25 mmol/kg body weight with an injection rate of 2 ml/s.

In the iPAT images, SNR decreased by a factor of about 1.5 compared to the data without iPAT. This decrease in SNR could be visually noticed in the source images, however the intravascular signal was still acceptable. In the MIP images, the overall decrease in SNR was hardly detected.

The high-resolution renal 3D-Gd-MRA data sets were compared to selective x-ray angiography in more than 20 patients with renal artery stenosis ranging from 20 % luminal narrowing to occlusion. Image analysis of the isotropic data sets consisted of multiplanar reformats along the vessel axis to assess the degree of diameter reduction. In addition, reformats perpendicular to the vessel axis were performed to assess the degree of reduction of vessel area. Using multiplanar reformats the degree of stenosis was correctly assessed in 18 of 20 patients. In 2 cases, the degree of stenosis was overestimated. However, when reformats were performed in the isotropic data sets perpendicular to the vessel axis all stenoses could be correctly identified compared to x-ray angiography (**8-10**).

One limitation is the propagation of aliasing artifacts into the center of the image. These artifacts could be theoretically avoided by extending the FOV in the left- right direction so that no aliasing occurs at all. In clinical practice however, this would mean a substantial increase in scan time, in particular in large patients. In addition, not all patients are able to put their arms over the head. Therefore some degree of aliasing into the margins of the FOV has to be accepted. Using the GRAPPA algorithm, artifacts propagating from tissue outside the FOV into the center of the image were kept at a minimum. Only slight ring-like artifacts occurred, which did not affect the image interpretation. However, when the mSENSE technique was alternatively used, these artifacts were more severe.

In conclusion, high-resolution renal 3D-Gd-MRA using iPAT allows for substantial improvement of spatial resolution, thereby increasing diagnostic accuracy compared to digital subtraction angiography. Using the GRAPPA based algorithm, artifacts propagating into the center of the FOV can be kept at a minimum.

Whole-body Imaging/Screening

Because of the recent improvements in hardware and software and the lack of ionizing radiation, magnetic resonance imaging has become a candidate for screening imaging. We developed an MR examination which combines well established components including functional cardiac imaging together with myocardial perfusion imaging, imaging of the lung, brain, an overall view of liver, kidneys, spleen, and pancreas, as well as the arterial system.

So far, the whole-body examination was performed in two parts. In the first part, the patient is in a head first position; the spine array, two body arrays, and a head array are used as receiver coils. In the second part, the patient is in a feet first position; the spine array, the large FOV adapter, one or two body arrays (depending to the height of the patient), and the peripheral angio array are used as receiver coils. iPAT with an acceleration factor of two is applied for most scans of the examination including real-time TrueFISP imaging of the heart, high-resolution imaging of the lung as well as dynamic cardiac perfusion MRI with TrueFISP. In addition, iPAT of 3D-Gd-MRA in combination with the large FOV adapter is performed for all studies allowing a total scan time of only 62 seconds to cover the area from the thoracic aorta down to the toes at a spatial resolution of less than 1.4×1.0×1.5 mm^3.

By applying the GRAPPA algorithm with its integrated auto-calibration scan, it is possible to use flexible combinations of receiver coils with a flexible choice of iPAT directions and to move the patient table for different iPAT acquisitions. The advantage of iPAT in this kind of exam is the coverage of a large anatomic region and gain of time so that a whole-body scan can

be done within 90 minutes without loss of image quality.

In the last two months twenty individuals sent by their referring physician while participating in a manager healthcare program underwent the whole-body scan in our department. All twenty individuals tolerated the MR examination well. Compared to the conventional examination techniques like ultrasound and ECG we have established a more comprehensive exam within reasonable scan time. First results of pathologic findings (scar in lung, aortic stenosis, renal artery stenosis) show good correlation with the gold standard examinations.

In the next step, the entire protocol was implemented on a new 1.5 T whole body scanner (Magnetom Avanto, Siemens Medical Solutions, Erlangen, Germany) with a special "mode matrix" surface coil design for the entire body and a range of table movement of 2.05m. This allowed parallel imaging up to an acceleration factor of 3 for the entire body without repositioning the patient. With this system the total exam time for the entire protocol decreased to less than 50 minutes (**11, 12**).

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