ISMRM Perfusion Workshop Invited Paper

Technological Advances in MRI Measurement of Brain Perfusion

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Measurement of brain perfusion using arterial spin labeling (ASL) or dynamic susceptibility contrast (DSC) based MRI has many potential important clinical applications. However, the clinical application of perfusion MRI has been limited by a number of factors, including a relatively poor spatial resolution, limited volume coverage, and low signal-to-noise ratio (SNR). It is difficult to improve any of these aspects because both ASL and DSC methods require rapid image acquisition. In this report, recent methodological developments are discussed that alleviate some of these limitations and make perfusion MRI more suitable for clinical application. In particular, the availability of high magnetic field strength systems, increased gradient performance, the use of RF coil arrays and parallel imaging, and increasing pulse sequence efficiency allow for increased image acquisition speed and improved SNR. The use of parallel imaging facilitates the trade-off of SNR for increases in spatial resolution. As a demonstration, we obtained DSC and ASL perfusion images at 3.0 T and 7.0 T with multichannel RF coils and parallel imaging, which allowed us to obtain high-quality images with in-plane voxel sizes of 1.5×1.5 mm^2.

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MRI BASED ON PERFUSION CONTRAST has a number of potentially important clinical applications, including the assessment of myocardial viability (1), diagnosis of breast cancer (2), and diagnosis, treatment planning, and outcome prediction for brain infarction (3). One of the main factors limiting the widespread clinical application of perfusion MRI is its relatively poor spatial resolution. The spatial resolution is primarily limited due to constraints on the signal-to-noise ratio (SNR). An additional constraint is that both arterial spin labeling (ASL) (4) and bolus tracking or dynamic susceptibility contrast (DSC) MRI (5) require rapid image acquisition (i.e., high temporal resolution). In the following we will show how recent methodological developments can increase the temporal and spatial resolution of perfusion MRI of the human brain by improving the SNR and image acquisition speed.

SNR

The SNR of perfusion-based MRI is small compared to that achieved by other imaging techniques, such as T_1/T_2-weighted and proton density-weighted MRI. In ASL, this is because generally less than 1% of the spins in a given voxel are perfused per second. For an adequate SNR, therefore, ASL requires extensive signal averaging, which leads to long measurement times (typically on the order of 5–10 minutes). In DSC MRI, as a result of the enhancing effect of a contrast injection, a substantially large fraction of the spins contributes to the signal. However, because of the relatively rapid washout of contrast agent (5–10 seconds), SNR of DSC MRI is compromised due to the limited time available for signal averaging. Recent methodological and technical developments have improved the SNR of perfusion MRI in a number of ways, including increased magnetic field strength, the development of multichannel signal detectors, and the optimization of MRI pulse sequences.

In MRI the intrinsic SNR scales approximately linearly with the field strength, while at the same time the labeling efficiency of ASL and the susceptibility effects of DSC are increased at higher field strength. This increase in SNR is offset by a small but significant signal loss due to the increased transverse relaxation rate (reduced T_2 and T_2*) at higher field. With the recent advances in high-field MRI, and the increased availability of clinical systems with a field strength of 3.0 T and higher, a substantial net increase in the resolution of perfusion MRI is expected (6).

Another substantial SNR improvement can be achieved with multichannel signal detectors (7). The recent advent of parallel imaging techniques, such as simultaneous acquisition of spatial harmonics (SMASH) (8) and sensitivity encoding (SENSE) (9,10), has sparked a redesign of radiofrequency (RF) receiver

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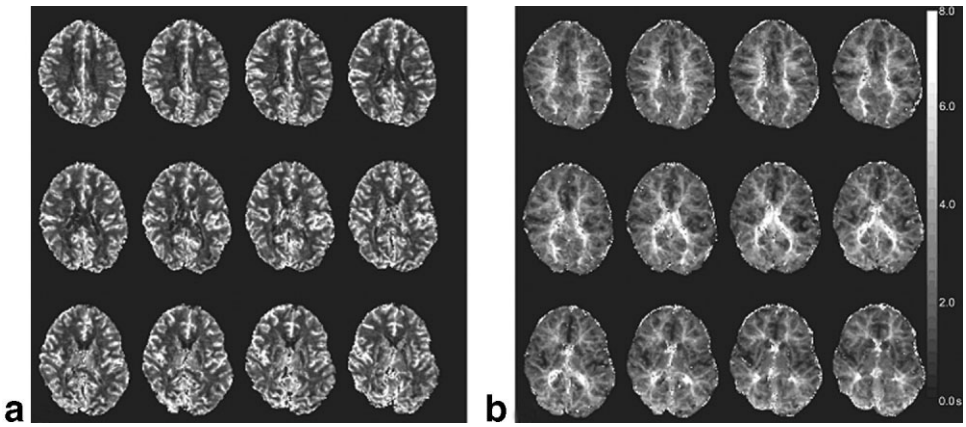

Figure 1. DSC images using high-resolution EPI at 3.0 T in a human subject. **a:** Images of relative blood volume were obtained using a 16-channel brain coil (Gd-DTPA, 0.1 mmol/kg, 0.2 mL/kg, 10 mL/second). Single-shot gradient-echo rate-2 SENSE-EPI was used with ramp sampling, TE = 40 msec, and nominal voxel size = $1.5 \times 1.5 \times 2.0$ mm^3. The relative CBV was calculated as the area under the ΔR_2* tissue response curve (see other papers in this issue). **b:** Images of bolus arrival time were obtained from the same high-resolution data as in image a. The time scale in b runs from 0 to 8 seconds.

coils. In the brain, optimally designed coils can provide a two- to fourfold increase in SNR as compared to conventional birdcage designs (11). Furthermore, combined with parallel imaging techniques, multichannel detectors allow for increased spatial resolution without sacrificing the temporal resolution, minimum echo time (TE), or volume coverage.

SNR gains are also available through pulse sequence optimization. Rapid image acquisition techniques, such as echo-planar imaging (EPI) (12), spiral imaging (13), principles of echo-shifting with a train of observations (PRESTO) (14), steady-state free precession (SSFP) (15), fast spin-echo (FSE) (16), and rapid acquisition with relaxation enhancement (RARE) (17), allow efficient sampling of the available transverse magnetization. In ASL, suppression of background signal allows a reduction of noise levels, particularly in 3D acquisitions (18). Also in ASL, some SNR improvement can be achieved by improved labeling strategies (i.e., pulse sequence modifications or the use of a separate labeling coil) (19–21).

IMAGE ACQUISITION SPEED

Both DSC- and ASL-based perfusion techniques require a high temporal resolution. For DSC this is needed to allow accurate estimation of perfusion parameters, such as bolus arrival time, time-to-peak, cerebral blood volume (CBV), mean transit time, and possibly cerebral blood flow (CBF). For ASL, a high temporal resolution reduces artifacts related to differ-

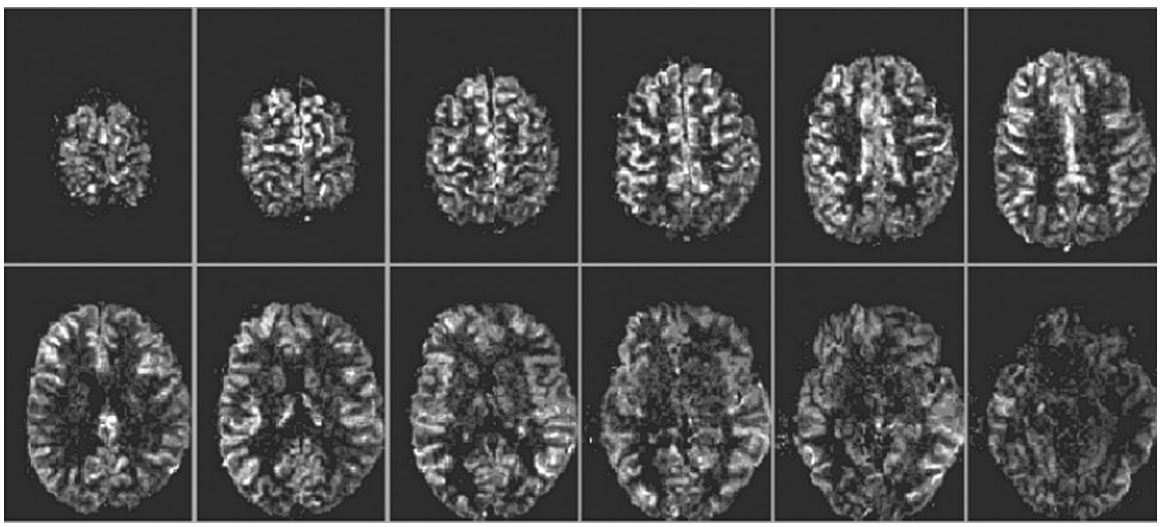

Figure 2. Perfusion images obtained with high-resolution CASL MRI at 3.0 T using a 16-channel brain coil. Single-shot rate-2 SENSE-EPI was used, with ramp sampling, a TE of 26 msec, a scan time of 10.5 minutes, and a nominal voxel size of $1.5 \times 1.5 \times 3.0$ mm^3. RF power (~1.0 W average) was applied to the labeling coil for 3 seconds at an offset of ~20 kHz in the presence of a 0.3 G/cm gradient along the S/I direction. A postlabeling delay of 1.2 seconds was allowed between the labeling and image acquisition periods (effective TR = 5 seconds). The ASL difference signal was averaged and converted to blood flow as described in other papers in this issue.

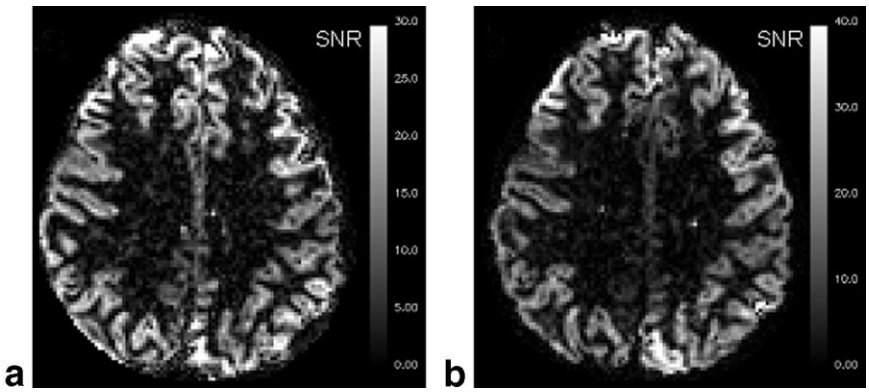

Figure 3. Example of perfusion images obtained with high-resolution flow-sensitive alternating inversion recovery (FAIR) MRI at 7.0 T using an eight-channel brain coil. Single-shot SENSE-EPI was used with ramp sampling, a labeling time of 1.5 seconds, a scan time of 5 minutes, and a nominal voxel size of $1.5 \times 1.5 \times 2.0$ mm^3. **a:** TR = 2 seconds, TE = 34 msec, and acceleration rate = 2. **b:** TR = 1 second (using the method of Ref. 19), TE = 27.5 msec, and acceleration rate = 3.

ences between label and control images (e.g., as related to motion), and facilitates its application to fMRI experiments. To achieve high temporal resolution while maintaining spatial resolution and volume coverage, rapid image acquisition techniques (such as the ones mentioned above) are needed, together with fast gradient hardware systems. In addition, recently developed parallel imaging techniques allow additional improvement in image acquisition speed. These techniques also allow shortening of the TE, which is beneficial for ASL and DSC at high field to mitigate signal loss due to background susceptibility effects.

CURRENT STATE OF THE ART

In combination, the above methods allow for substantial improvement in SNR and acquisition speed, which can be traded off for increased spatial resolution and volume coverage. In brain imaging, the combination of multichannel detectors at 3.0 T with single-shot EPI allows for acquisition of T_2*-weighted images for DSC-MRI at $1.5 \times 1.5 \times 2.0$ mm^3 resolution and high SNR (50–150), which is sufficient for calculation of the relative blood volume and bolus arrival time images (Fig. 1). With the use of multichannel detectors for ASL at 3.0 T, perfusion-weighted images can be acquired with $1.5 \times 1.5 \times 3.0$ mm^3 resolution, and perfusion images can be calculated at an SNR of 5–10 in about 11 minutes (Fig. 2). Additional SNR improvement can be achieved at 7.0 T, allowing further increases in spatial resolution and/or a reduction in overall scan time (Fig. 3). These improvements will likely make perfusion MRI more relevant for clinical application.

CONCLUSIONS

Recent technical developments, most importantly multichannel detectors and parallel imaging, allow substantial improvements of SNR and spatial resolution in ASL- and DSC-based perfusion MRI. These improvements will likely facilitate the widespread application of perfusion MRI for clinical use.

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