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Transmit/receive headcoil for optimal ^{1}H MR spectroscopy of the brain in paediatric patients at 3 T

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Abstract ^{1}H magnetic resonance (MR) spectroscopy is a useful tool to obtain metabolic information from the brain in paediatric patients. To detect signals of metabolites at low concentrations or from small volumes, the signal-to-noise ratio (SNR) has to be optimized. The SNR can be increased by going to higher field strengths. However, this leads to higher spectral bandwidths, which increases the chemical shift artefact. Here we present a transmit/receive headcoil which is adapted to the dimensions of the paediatric head and enables PRESS localization with high radio-frequency (RF) bandwidths that minimize the chemical shift displacement to only 5%. In addition, since the pulse lengths are shorter with higher RF bandwidths, the echo time can be reduced to 10 ms improving SNR as well.

Keywords ^{1}H MRS · PRESS · RF coil · Paediatric · Chemical shift artefact

Introduction

In vivo ^{1}H magnetic resonance (MR) spectroscopy allows non-invasive studies of brain metabolism and can be applied safely to paediatric patients. This technique provides information on metabolite concentrations in selected volumes of a pathological region or a specific tissue type. To detect signals of metabolites at low concentrations or from small volumes, the signal-to-noise ratio (SNR) has to be optimized.

The SNR can be improved by increasing the field strength (B_0) [1,2]. Up till now clinical ^{1}H MR spectroscopy of the brain was mainly performed at 1.5 T, but the recent introduction of clinical 3-T systems makes examinations with an improved SNR feasible. In addition, the spectral resolution improves at higher fields, allowing a better distinction between signals from metabolites with small differences in chemical shifts. However, the bandwidth required to detect the metabolite signals also increases. When slice-selective radio-frequency (RF) pulses with limited bandwidth are used for volume selection, increased spatial mismatch occurs between volumes selected for metabolites with resonances with large chemical shift differences. This effect is also known as the chemical shift artefact [3].

Additionally, surface coils in a phased-array configuration can enhance the SNR, especially in regions close to the coil. These coil arrays are generally combined with a large volume transmit coil, which is less efficient in terms of RF field strength (B_1) per unit of power than a small volume transmit/receive (TxRx) coil. Since the RF power is limited, the maximum B_1 field strength will be low and thus the maximum bandwidth of the RF pulse is limited, leading to a large chemical shift artefact.

Finally, minimizing the echo time (TE) improves SNR as well, since it reduces losses due to T2 decay. At short TEs disturbing J-modulations of coupled spin systems are also minimized. Short TEs can be achieved using RF pulses with small durations, which is possible for high-bandwidth RF pulses.

Although stimulated echo acquisition mode (STEAM) localization [4] can be used to shorten TE and to reduce chemical shift artefacts, it intrinsically leads to a SNR 50% lower than that obtained by point resolved spectroscopy (PRESS) localization [5]. Since PRESS requires 180° refocusing pulses rather than 90° pulses, both the quality of the pulse profile and the bandwidths are reduced when conventional sinc pulses are used. However, numerically optimized refocusing pulses like Shinnar-le Roux [6] or MAO [7] improve the pulse profile, especially in homogeneous RF coils.

So in order to use PRESS with numerically optimized refocusing pulses at 3-T, short TE, and reduced chemical shift artefact, large B_1 field strengths are required. Therefore, we decided to use an efficient, homogeneous, TxRx headcoil allowing large RF peak powers to maximize the B_1 field strength. Compared with an adult headcoil, the size of the coil is reduced and adapted to the circumference of the paediatric head. This set-up allows spatially accurate 1-ml voxel PRESS acquisition in the brain of paediatric patients at a TE of 10 ms showing many metabolites with good SNR.

Methods

An 8-leg circularly polarized birdcage coil [8] is designed with an inner diameter and length of 19 cm (Fig. 1). The frame of the coil is made of Plexiglas in which three fixation bars can be used to prevent head movement. The coil can be manually tuned and matched for different loads (i.e., for children from 0 to 4 years old). The coil is interfaced to a clinical 3-T MR scanner (Trio, Siemens, Erlangen, Germany) using a home-built transmit-and-receiver switch with integrated preamplifier (Advanced Receiver Research, Burlington, CT, USA). Each switch has three Pi-circuits tuned to a quarter wavelength at 123.3 MHz which consist of high-power PIN diodes (M/A-COM, Lowell, MA, USA). To remain well below SAR guidelines [9], the coil is fused to prevent high average RF power deposition of more than 2 W. In addition, software restricts the power deposition to values below 1 W.

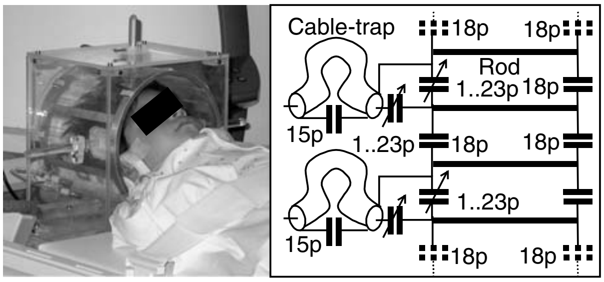

Fig. 1 A photo of the coil set-up and a part of the electric diagram are shown. The coil has been developed in high-pass mode using high-voltage capacitors (15 and 18p: American Technical Ceramics, Huntington Station, NY, USA; 1..23p: Voltronics Corporation, Denville, NJ, USA) in the end rings

The efficiency and SNR of the coil were compared with the original TxRx Siemens headcoil on one young patient. The power required for a 500-μs rectangular 90° excitation pulse was determined in both cases and the inverse ratio of the two values was used as a measure for the efficiency comparison. The relative difference in SNR should be inversely proportional to the square root of this power ratio. The SNR of the two coils was also compared with a PRESS measurement with long TE (135 ms) of a 3.4-ml voxel positioned on the same white matter region. The SNR was determined by taking the integral of the fitted Lorentzian line of *N*-acetyl aspartate (NAA) divided by the standard deviation of the spectral noise in the region between 6 and 8 ppm.

We used the full available peak power (i.e., 5 kW for local coils) so that the PRESS sequence was run at the highest available bandwidth. A two-dimensional chemical shift imaging (CSI) method was integrated into the PRESS sequence to image the quality of the localization (i.e., pulse profile and chemical shift artefact) in the excitation direction and in one of the refocusing directions (FOV = 80 mm, TR = 1 s, 32 × 32 phase encodings, 100% hamming filter, no averaging). This measurement was performed both on resonance and at a 3-ppm offset on a water phantom with saline such that the loading conditions (Q-factor) were identical to the in vivo situation. The same measurement was performed using the bodycoil.

Several paediatric patients were examined with the coil, and all patients were routinely sedated. Heart rate and oxygen level were monitored during the entire examination using a pulse-oxymeter (Nonin Medical Inc., Plymouth, MN, USA). After conventional MRI examinations were conducted, a 1-ml voxel was positioned in a region of interest. Automatic shimming of the magnetic field was performed for this region and repeated until the manually verified absolute linewidth at half height (FWHM) was about 10 Hz. For the transmitter adjustment, only a global automatic adjustment was applied. Water suppression was included using a WET procedure [10] without any further adjustments. The PRESS measurement was performed with a TE of 10 ms. A spectrum of water was acquired using the same PRESS sequence without water suppression. The quality of the spectra was evaluated using only eddy-current correction [11] and Fourier transformation.

Results

The heads of most patients who were younger than 4 years old easily fitted inside the coil. Tuning and matching of

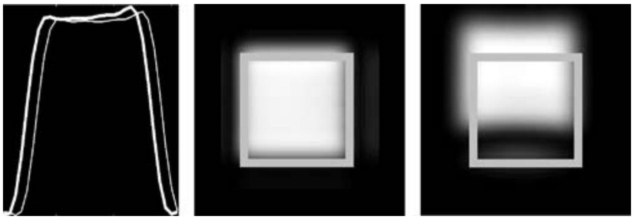

Fig. 2 The chemical shift displacement caused by a frequency offset of 3 ppm is visualized in two dimensions: the centre using the paediatric headcoil and the right using the bodycoil. The slice selective refocusing pulse is in the vertical direction and the slice selective excitation pulse in the horizontal direction. Note the reduced chemical shift artefact, especially in the refocusing direction. A 1D profile (*left*) in the refocusing direction shows both the pulse profile as well as the chemical shift artefact, acquired with the paediatric headcoil

the two coil elements was performed in less than 2 min. A 4-year-old patient was measured in both the standard Siemens headcoil and in the paediatric headcoil sequentially. The required power for a 90° excitation using a 500-μs rectangular RF pulse was 3.5 times less for the paediatric headcoil compared to the standard Siemens headcoil. This patient was also used for the SNR comparison using a PRESS measurement on a 3.4-ml voxel, which was positioned at the same region in white matter. After running the autoshim procedure twice, the absolute linewidth was 10 Hz in both coils. Figure 3 (upper spectra) presents the spectra obtained in both coils, clearly showing the improved SNR for the paediatric coil. The gain in SNR, assuming constant NAA and white noise in the region of 6–8 ppm, is 1.8.

For all patients, the B_1 field strength ($\gamma B_1/2\pi$) could be increased to more than 4 kHz using the full 5-kW RF power. This led to a bandwidth of 5 kHz using 7-lobe MAO refocusing pulses. A phantom with equal loading conditions as the patient was used to visualize the resulting chemical shift artefact. In a spectral region of 3 ppm, the chemical shift artefact is reduced to approximately ±5% (Fig. 2), i.e., measured as a relative shift in position with respect to the voxel size.

Although the RF pulses used have many lobes (7), the duration of the refocusing pulses is only 1 ms. Due to the good frequency profiles (Fig. 2, left), the length of the crusher gradients could be reduced so that a TE of 10 ms was feasible. Figure 3 shows a PRESS (TE = 10 ms) spectrum of only 1 ml from white matter of one of the patients (age = 2 years). The spectrum was acquired in 8.5 min, showing good SNR and spectral quality.

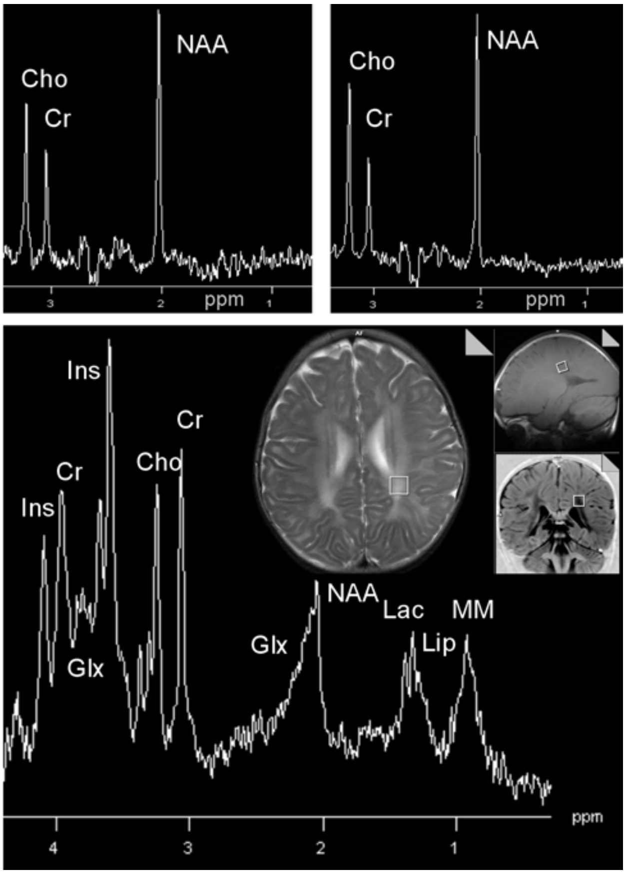

Fig. 3 *Upper* SNR difference in a 3.4-ml PRESS spectrum acquired using the standard headcoil (*left*) and the paediatric headcoil (*right*). Spectra are acquired at the same location of a 4-year-old patient (TE = 135 ms, TR = 2 s, 64 averages). *Lower* A PRESS spectrum of a small region of 1 ml in white matter of a 2-year-old patient with Sandhoff disease shows good SNR. The spectrum with a TE of 10 ms is acquired in 8.5 min (TR = 2 s). Resonances for proton spin systems of choline (*Cho*), creatine (*Cr*), *N*-acetyl aspartate (*NAA*), lactate (*Lac*), lipids (*Lip*), glutamate+glutamine (*Glx*), myo-inositol (*Ins*), and macro molecules (*MM*) are indicated

Discussion

In this study, we demonstrate that excellent MR spectra of the brain in paediatric patients can be obtained with a dedicated TxRx headcoil at 3 T. The chemical shift artefact is substantially reduced comparing the paediatric TxRx headcoil with a body transmit coil and standard head receive coil (Fig. 2). Therefore, MR spectroscopy using PRESS with accurate localization is feasible for 3-T applications in human brain.

In addition, the reduction in size of the paediatric headcoil compared to the standard adult headcoil leads to an almost doubled B_1 efficiency. As expected, the gain in SNR is about the same as the square root of the gain in power efficiency. This increased SNR can be used to detect signals of metabolites at low concentrations or to reduce the voxel size.

Vendors of MR equipment supply a large range of receiver coils for most applications in which the body coil is used for RF transmission. At 1.5 T, some vendors even no longer supply a headcoil that can be used for transmission. Also at 3 T, parallel imaging is getting increasingly popular and available, leading to a strong demand for array coils, which are normally receive-only coils. However, as the transmit coils, which are usually body volume coils, are not very efficient, this may cause certain problems such as chemical shift artefacts in slice-selective MR spectroscopy. Therefore, we developed an efficient TxRx headcoil.

Another advantage of TxRx coils is that the required RF power for a 90° excitation can be used to quantify the data, using the principle of reciprocity [12]. However, when such a method is used, one should be aware that the coil must be tuned and matched to the system impedance. A mismatch of the coil has a different effect on the transmit path vs. the receiver path due to a noise match rather than a power match of the pre-amplifier. The loading of the paediatric headcoil depends on the size of the head, which is completely different for neonates and children of 4 years old. Especially at higher RF frequencies, the tissue dominates the loading of the coil. The coil in this study is therefore for each subject matched to the system impedance of 50 ohm.

Conclusion

An efficient high-power TxRx coil was designed in order to enable the acquisition of short echo-time ^{1}H MR spectra in paediatric brain at 3T with accurate localization using PRESS. Compared with a STEAM measurement on a 1.5-T scanner with a standard headcoil, the voxel size can be reduced by almost one order of magnitude, i.e., a factor of two by switching from STEAM to PRESS, a second factor of two by increasing the field strength from 1.5 to 3 T, and another factor of almost two by replacing the standard adult headcoil for a paediatric headcoil.

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