

Improvement of the image quality of T1-weighted anatomical brain scans

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T1-weighted anatomical brain scans are routinely used in neuroimaging studies, for example, as anatomical reference for functional data and in brain morphometry studies. Subject motion can degrade the quality of these images. An additional problem is the occurrence of signal dropouts in the case of long echo times and low receiver bandwidths. These problems are addressed in two different studies.

In the first study, it is shown that the high scalp signal, which results from the low T1 value of fat, may cause a typical ringing artefact in the presence of head motion. This problem may be enhanced if phased array coils are used for signal reception due to their increased sensitivity in the peripheral head regions. It is shown that this artefact can be avoided by combining certain fat suppression techniques that reduce the scalp signal.

In the second study, it is shown that signal dropout affects mainly the orbitofrontal cortex and the temporal lobes, and that a bandwidth of 100 Hz/pixel should be chosen for the investigation of these areas to avoid signal losses while maintaining an acceptable signal-to-noise ratio. Experimental results are based on the MDEFT sequence but can be applied to other T1-weighted sequences like FLASH and MP-RAGE. Furthermore, the presented methods for improving the image quality can be combined with other artefact reduction techniques.

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Introduction

T1-weighted anatomical magnetic resonance images are routinely acquired in neuroimaging studies alongside functional data. They can be used as an anatomical reference because they display a higher spatial resolution and a lower degree of image artefacts than the techniques used for obtaining functional data. Anatomical images can also be used in morphometric studies such as voxel-based morphometry (VBM) in which anatomical variations are

assessed on a voxel by voxel basis (Ashburner and Friston, 2000). For reliable results, images with a good spatial resolution and a high contrast between grey and white matter are required. However, the quality of anatomical brain images can be degraded due to several effects.

Spatial sensitivity variations of the coils used for RF transmission and signal reception usually result in intensity non-uniformities that can cause tissue segmentation algorithms to yield incorrect results. This problem requires the implementation of special techniques, for example, the use of compensation RF pulses for spin excitation (Deichmann et al., 2002), or postprocessing algorithms for intensity non-uniformity correction (Ashburner and Friston, 2005).

At high field strengths, RF focusing effects can aggravate RF inhomogeneities. It has been shown that the resulting signal variations can be largely suppressed by improving the imaging sequence design (Thomas et al., 2005).

Signal hyperintensity of blood vessels is a particular problem in T1-weighted anatomical sequences, which arises from the inflow of non-saturated blood into the imaging area. This is especially a problem when a head coil is used for RF transmission, because blood spins in the torso are not affected by the RF pulses of the magnetization preparation experiments. The resulting flow artefacts can be suppressed by performing spin tagging in the neck (Deichmann et al., 2004).

Two of the most common sources of artefacts are subject motion and the occurrence of image dropouts in the case of long echo times (TE) and low receiver bandwidths. In this work, these problems will be addressed.

Various techniques have been proposed to correct for the effects of within-scan subject movement. Such techniques include the acquisition of navigator echoes (Welch et al., 2002a), acquisition of an additional scan with swapped phase encoding direction (Welch et al., 2002b), autocorrection in k space (Manduca et al., 2000), application of the autofocus technique (Atkinson et al., 1999), or use of multiple receiver coils (Atkinson et al., 2004). Although these techniques are highly effective, a complete correction for subject movement is difficult to achieve, especially in areas where the image quality is considerably degraded. Thus, image features causing movement artefacts should be avoided on the acquisition

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side as far as possible. In this work, the suppression of a motion-induced ringing artefact, which is typically seen in peripheral brain areas on T1-weighted structural images, is described. The artefact arises from the high signal of lipid protons in the scalp, due to the short T1 value of fat. It may be further enhanced by the use of phased array coils, which have a higher sensitivity in the peripheral head areas. The artefact leads to an apparent loss of resolution in the affected areas and may render data useless for morphometric studies. The first study presented in this work investigates whether the use of special fat suppression techniques can reduce this motion artefact, even if no other motion correction techniques are applied.

Signal dropout is an artefact that arises in areas where the magnetic susceptibility changes abruptly, e.g., near air-tissue boundaries. It occurs due to local alterations in the static magnetic field, resulting in a rapid dephasing of the spins and consequently in very short T2* values. The problem is usually associated with T2*-weighted functional imaging sequences sensitive to the BOLD effect like EPI (Mansfield, 1977), due to their relatively long TE values. However, it is often ignored in T1-weighted anatomical imaging. It is a well-known fact that signal dropouts can be decreased by increasing the acquisition bandwidth. However, this also reduces the SNR (Li and Mirowitz, 2003). In anatomical imaging, it is common to use low bandwidths in order to increase the SNR, thus causing problems in brain areas such as the orbitofrontal cortex and the temporal lobes, which are most susceptible to dropouts (Ojemann et al., 1997). Therefore, it is necessary to find the optimum bandwidth which provides a compromise between an acceptable SNR and minimal image dropout. The aim of the second study presented in this work is to locate the brain areas that are affected by dropouts at low bandwidths and to provide guidelines for the minimum bandwidths at which these problematic areas can still be seen in T1-weighted structural scans.

Theory

MDEFT sequence

All imaging experiments presented in this work are based on the 3D MDEFT (Modified Driven Equilibrium Fourier Transform) sequence (Ugurbil et al., 1993; Lee et al., 1995; Deichmann et al., 2004). It consists of preparation–acquisition cycles with the following structure: $90^\circ - \tau_1 - 180^\circ - \tau_2 - \text{Acquisition}$.

During the preparation part, the longitudinal magnetization is saturated by the 90° pulse, relaxes partially during τ_1 , is inverted by the 180° pulse, and relaxes again during τ_2 , resulting in a T1-weighted longitudinal magnetization. τ_1 and τ_2 are given by

$$\tau_1 = \text{quot} \cdot \text{TI} \quad \tau_2 = \text{TI} - \tau_1 \quad (1)$$

where TI is the total duration of the magnetization preparation experiment. It has been shown that higher SNR values may be achieved when quot is less than 50% (Deichmann et al., 2004).

Following τ_2 , several gradient echoes are acquired with repetition time TR, echo time TE, bandwidth BW, and flip angle α .

Movement artefacts and fat suppression

In general, the shape and appearance of movement-related artefacts depend on what part of k space is being sampled when head movement occurs. If movement occurs while the center of k

space is being sampled, a major artefact results, affecting all areas of the image, often rendering the data useless. Movement during the acquisition of peripheral k space where signal power is reduced will be less problematic. However, small structures with high signal intensity still have relatively high signal contributions in peripheral k space, resulting in the movement-related ringing artefact described above. This is the case for the scalp due to the short T1 value of fat and thus the high intensity in T1-weighted images. The occurrence of this artefact is particularly evident when using a phased array coil, which has a greater peripheral sensitivity. Thus, suppression of fat signal is crucial to avoid this type of movement-related artefact.

Standard fat suppression procedures are based on fat-selective excitation followed by dephasing gradients (Bottomley et al., 1984). Here this technique will be referred to as ‘fat saturation pulse’. Although this technique effectively suppresses fat during the initial part of the read-out stage, T1 relaxation of fat continues throughout the acquisition, resulting in residual signal in peripheral k space. Thus, an additional fat suppression technique that does not suffer from relaxation effects is required. A suitable method is the use of a spectral–spatial pulse (Hardy et al., 1998) for fat insensitive spin excitation. The simplest version of this is a 1:1 binomial excitation pulse, based on the following principles: the excitation pulse is split up into two pulses, each with half the nominal flip angle, and a spacing of 2.4 ms. At a field strength of 1.5 T, the fat spins will experience a phase shift of 180° relative to the water spins, so the two excitations cancel each other. It has been shown (Deichmann, 2005) that the combination of a fat saturation pulse and a fat insensitive excitation results in a high degree of fat suppression in the scalp.

Methods and materials

General

All experiments were carried out on a 1.5 T Sonata whole body scanner (Siemens Medical Systems, Erlangen, Germany). A whole body coil was used for transmission and an eight-channel phased array head coil was used for signal reception.

For all MDEFT scans described in this work, the following image matrix was chosen: Read (head–foot): 256 pixels; 2D Phase (anterior–posterior): 224 pixels; 3D phase (left–right): 176 pixels; isotropic resolution: 1 mm.

Two versions of the sequence were used:

For ‘segmented MDEFT’, 88 gradient echoes with different 3D phase encoding were acquired after each preparation experiment, and the whole cycle was repeated 448 times. Thus, the 3D phase encoding loop was twofold segmented.

For ‘non-segmented MDEFT’, 176 gradient echoes with different 3D phase encoding were acquired after each preparation experiment, and the whole cycle was repeated 224 times. This means that the 3D phase encoding loop was not segmented.

In both cases, centric phase encoding was employed in the 3D direction, i.e., the early echoes had the lowest degree of 3D phase encoding. To avoid distortions of these echoes due to initial eddy currents, the acquisition was preceded by five dummy phase encoding steps without RF pulses (Deichmann et al., 2000).

For each version of the sequence, the imaging parameters were optimized as explained in Deichmann et al., 2004, to obtain an optimum contrast-to-noise ratio (CNR) and to avoid blurring due to

T1 relaxation. In both cases the center of k space was sampled after half the acquisition time had passed.

Fat saturation consisted of a fat-selective RF pulse followed by a gradient spoiler. Due to the duration of the spoiler pulse and the dummy scans, there was a delay of about 80 ms between fat saturation and the start of the acquisition. Thus, an excitation angle of 160° was chosen for the fat-selective RF pulse to ensure that the longitudinal magnetization of fat was minimal during the acquisition of the echoes with low phase encoding.

The fat insensitive excitation pulse was a binomial 1:1 pulse with chemical shift-selective properties (Hardy et al., 1998; Deichmann, 2005), as explained above.

All data were analyzed using MATLAB (The Mathworks Inc., Natick, MA) and SPM2 (Statistical Parameter Mapping, <http://www.fil.ion.ucl.ac.uk>).

Movement artefacts study

This study comprised 3 experiments:

Experiment 1

The purpose of this experiment was to compare the different fat suppression techniques and to assess the degrees of scalp signal suppression. Segmented MDEFT images were acquired on a healthy volunteer (36 years) who was asked to remain still during the scans. The imaging parameters were as follows: TR/TE/TI = 12.26/2.84/530 ms, BW = 123 Hz/pixel, $\alpha = 23^\circ$, $q = 42\%$. Total duration: 12 min.

Data were acquired three times with the following combinations of fat suppression techniques:

- (a) fat saturation pulse off, non-selective excitation pulse;
- (b) fat saturation pulse on, non-selective excitation pulse; and
- (c) fat saturation pulse on, fat insensitive excitation pulse.

Data were reconstructed using a standard 3D Fourier transform algorithm without applying any filters. The quality of scalp suppression was assessed by eye.

Experiment 2

The purpose of this experiment was to show that movement during the acquisition of peripheral k space causes a ringing artefact from the scalp, and that this artefact can be reduced by applying fat suppression techniques. The experiment was based on a simulated movement: the three scans described in experiment 1 were repeated, the volunteer did not move during the acquisition. Raw data were exported and modified externally to simulate a 3 mm movement in read (head–foot) direction after 8 min of acquisition, i.e., after 2/3 of k space had been sampled. Head movement was mimicked by adding to the last third of k space data a phase that increased linearly in read direction by a value of $6\pi/256$ per pixel. This procedure was performed for raw data from the three scans with different degrees of fat suppression. The resulting artefacts were visually compared.

Experiment 3

The purpose of this experiment was again to show that movement causes ringing artefacts which can be reduced by applying fat suppression techniques. In contrast to the previous experiment, this investigation was based on real head movement.

Two sequence modifications were tested on each of four healthy volunteers, aged between 23 and 40 years (average: 32 years):

- (1) fat saturation pulse on, fat insensitive excitation pulse (highest degree of fat suppression); and
- (2) fat saturation pulse off, non-selective excitation pulse (no fat suppression).

Imaging parameters were identical to those in experiment 1. The volunteers were asked to perform the same movement for each sequence modification. In a first run, the movement consisted of a single upward movement into a new position after 8 min of acquisition ('up–down motion'). In a second run, which was performed on three of the volunteers, the movement consisted of a single rightwards movement into a new position after 8 min of acquisition ('left–right motion'). A plastic device with two screws, each of which touched the subject's nose in one of the two head positions, was attached to the head coil in order to ensure motion reproducibility. Data were again reconstructed using a standard 3D Fourier transform algorithm without applying any filters. Raw data were not modified for this experiment.

In addition, a series of EPI images was acquired for each volunteer for each movement type. The volunteer was asked to perform the same movement during EPI acquisition as during the structural scan. The goal was to estimate the movement parameters and to check for reproducibility of the head movement. 40 EPI volumes were acquired per subject and movement type, during which the head remained in one position for 10 successive volumes, then moved into the other position for the next 10 volumes and so on. Imaging parameters were TR/TE/ $\alpha = 90$ ms/50 ms/ 90° . 64 slices with a thickness of 2 mm and 1 mm interslice gap were acquired with an in-plane resolution of 3 mm. Movement parameters were estimated using image realignment in SPM2.

Bandwidth study

The aims of this study were to identify brain areas where image dropouts occur at low bandwidths, to determine the minimum bandwidth for acceptable visibility of these areas, and to measure the dependence of the SNR on the bandwidth. The study consisted of three experiments.

Experiment 1

Due to the relatively long duration of the MDEFT sequence (12 min per run) it would have been impractical to compare a large number of bandwidths on the same volunteer. Thus, a 2D FLASH sequence (Haase et al., 1986) was created from the MDEFT sequence by removing the magnetization preparation part and the 3D phase encoding gradient and making the excitation pulses slice selective. The orientation, the FoV, and the spatial resolution were identical to the values chosen for the MDEFT sequence (sagittal slices, 1 mm in-plane resolution, in plane matrix 256×224 , read in head–foot direction). Thus, it could be assumed that the bandwidth-dependent dropouts for the FLASH images were the same as for MDEFT. An increased slice thickness of 2 mm was chosen, resulting in a reduced acquisition time of 5 min 35 s, thus making it possible to run several repetitions with different bandwidths. It should be noted that the increased slice thickness may give rise to further signal dropout effects. However, these are due to through-plane susceptibility gradients and will not change with the receiver bandwidth.

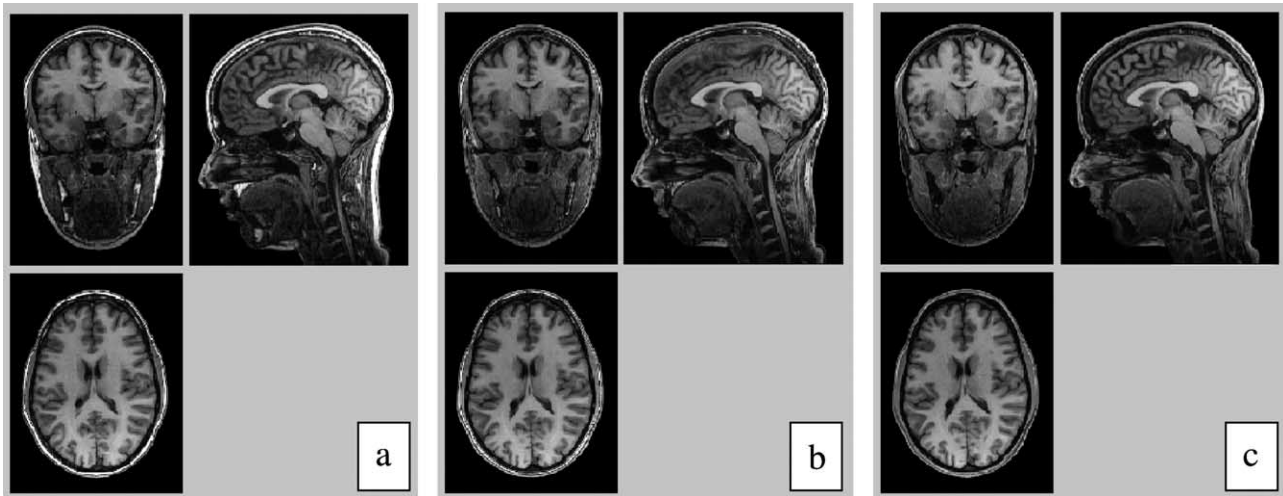


Fig. 1. Anatomical 3D MDEFT images acquired with the following: (a) fat saturation pulse off, non-selective excitation; (b) fat saturation pulse on, non-selective excitation; (c) fat saturation pulse on, fat-insensitive excitation. Note the high scalp intensity in panel a.

The sequence was tested on 4 healthy volunteers aged between 23 and 40 years (average: 32 years). For each volunteer, six scans were acquired with the following bandwidths: 50, 75, 100, 125, 150, and 391 Hz/pixel, with corresponding TE values of 8.41, 6.73, 5.90, 5.40, 5.07, and 4.04 ms. The other imaging parameters were as follows: TR = 18.68 ms, $\alpha = 60^\circ$, 80 sagittal slices covering the left and right temporal lobes and the orbitofrontal cortex. All acquired data sets were co-registered (Ashburner and Friston, 1997) using SPM2 to facilitate direct comparison. Images were assessed by eye to identify brain areas that showed signal dropouts. In addition, the SNR was calculated for each volunteer as follows: the signal intensity in white matter (WM) and grey matter (GM) was obtained from regions of interest (ROI) in the genu of the corpus callosum and in the caudate nucleus, respectively. The SNR in each tissue type was calculated from

$$\text{SNR} = 0.701 \left(\frac{\text{signal}}{\sigma} \right) \quad (2)$$

where σ is the signal standard deviation in the image background and 0.701 is the Rayleigh factor for an eight-channel phased array system (Constantinides et al., 1997).

Experiment 2

For the same volunteers, the non-segmented MDEFT sequence was run with the following imaging parameters: TR/TI = 14.97/580 ms, $\alpha = 22^\circ$, quot = 40%. Fat suppression was achieved with a standard fat saturation pulse as explained above. For each volunteer, the sequence was run twice with two different bandwidths (75 and 195 Hz/pixel) and the corresponding TE values of 4.09 and 2.48 ms, respectively. The total duration was 12 min per run. All other parameters were identical to the ones described in the movement artefacts study. SNR values were calculated as described above.

Experiment 3

For one of the volunteers, FLASH images as described in experiment 1 were acquired with the same bandwidths as chosen in experiment 2 (75 and 195 Hz/pixel) and the corresponding TE values of 6.73 and 4.68 ms, respectively. The resulting images were compared to the MDEFT images acquired in experiment 2. The purpose of this experiment was to find out if the FLASH-based results of experiment 1, especially the dependence of signal dropouts on the receiver bandwidth, can be applied to MDEFT imaging.

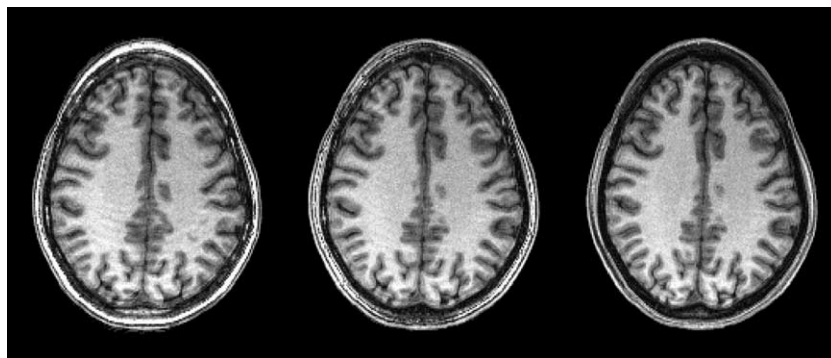


Fig. 2. Axial anatomical 3D MDEFT images with simulated movement. Data were acquired with the following: fat saturation pulse off, non-selective excitation (left); fat saturation pulse on, non-selective excitation (center); fat saturation pulse on, fat-insensitive excitation (right). In the latter case, artefacts are removed almost completely.

Results

Movement artefacts study

Experiment 1

Fig. 1 shows anatomical images acquired with the following: (a) fat saturation pulse off, non-selective excitation; (b) fat saturation pulse on, non-selective excitation; and (c) fat saturation pulse on, fat-insensitive excitation. (a) shows clearly a bright scalp signal due to the absence of any fat suppression techniques; (b) shows that images acquired with the fat saturation pulse still show some fat signal in the scalp; (c) shows that this signal is almost completely removed when combining the fat saturation pulse with the fat insensitive excitation. The results demonstrate that it is necessary to use both fat suppression techniques simultaneously in order to eliminate the strong scalp signal.

Experiment 2

Fig. 2 shows axial anatomical images with simulated movement. Data were acquired with the following: fat saturation pulse off, non-selective excitation (left); fat saturation pulse on, non-selective excitation (center); and fat saturation pulse on, fat-insensitive excitation (right). In the absence of fat suppression techniques, there are strong ringing artefacts from the bright scalp signal, both in anterior and posterior areas (left). If only the fat saturation pulse is used, artefacts are greatly reduced, but still visible in the anterior areas (center). If the fat saturation pulse is combined with the fat-insensitive excitation, artefacts are removed almost completely (right).

Experiment 3

Fig. 3 shows movement parameters for a single subject with head motion in the up–down direction (accompanied by a slight

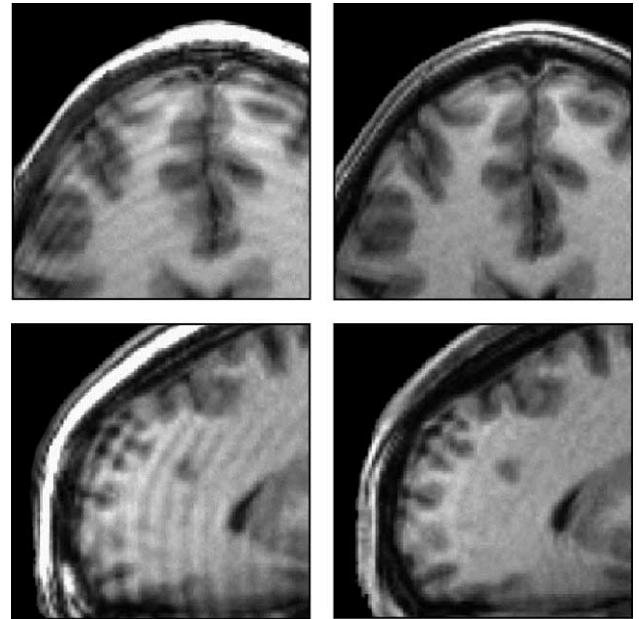


Fig. 4. Anatomical 3D MDEFT images showing motion artefact due to an up–down movement after 8 min of acquisition. Images were acquired without (left) and with (right) fat suppression. The higher intensity scalp signal and the higher amplitude ringing artefacts can be clearly seen in the images acquired without fat suppression.

rotation about the left–right axis). Typical parameters are a 2 mm shift and a rotation by 3–3.5°. The results show that the additional devices in the head coil enabled the subjects to reproduce movements quite reliably.

Fig. 4 shows images acquired on a subject who moved their head in an up–down direction after 8 min of acquisition. Images

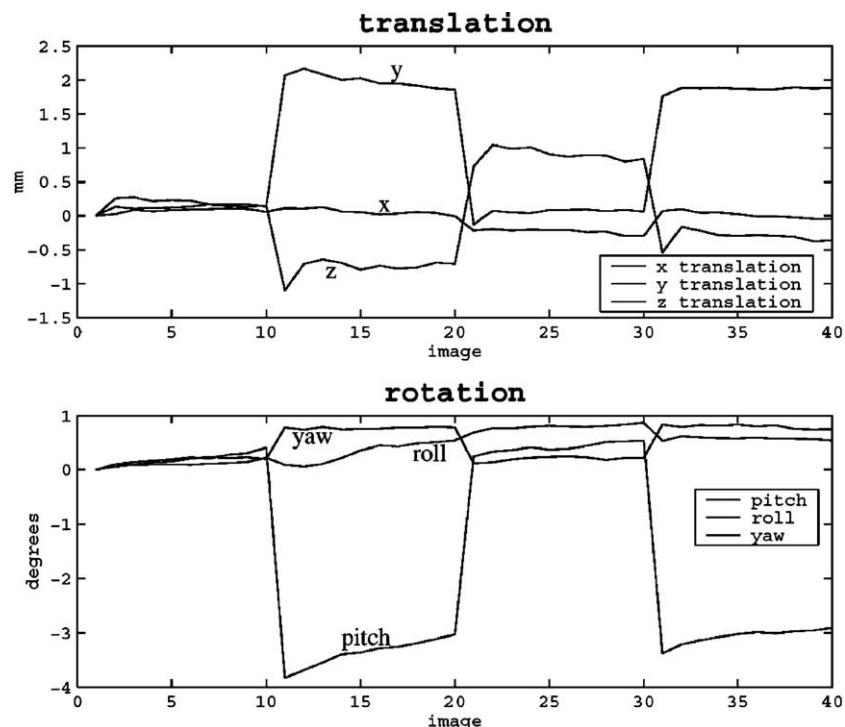


Fig. 3. Movement parameters for a single subject. Motion was in the up–down direction.

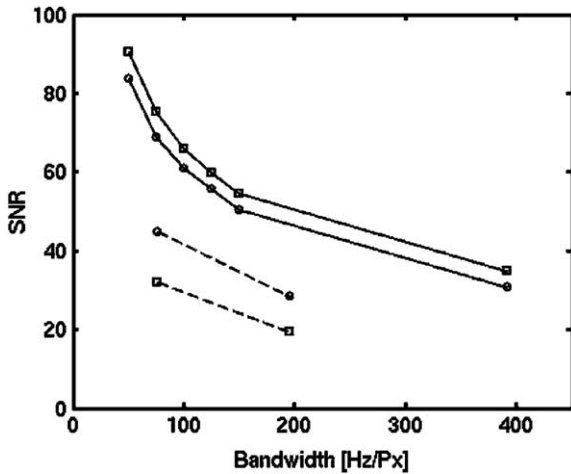


Fig. 5. Average signal-to-noise ratio (SNR) in white matter (○) and in grey matter (□) as a function of the bandwidth for the MDEFT (---) and the FLASH (—) sequence.

were acquired without any fat suppression methods (left) and with fat saturation and fat insensitive excitation (right). As in the case of the simulated data, there is a strong scalp signal with pronounced movement-related ringing artefacts in the absence of fat suppression techniques. If the fat saturation pulse in combination with the fat-insensitive excitation is used, artefacts are greatly reduced.

Bandwidth study

Experiment 1

As expected, for all volunteers the SNR in the FLASH images decreased with the bandwidth. Fig. 5 shows the SNR versus bandwidth for a single volunteer (top two plots).

Fig. 6 shows axial FLASH images from a single volunteer for the six different bandwidths. The arrows indicate areas in the orbitofrontal cortex (top) and in the temporal lobes (bottom) which are particularly affected by signal dropouts. It can be seen that for

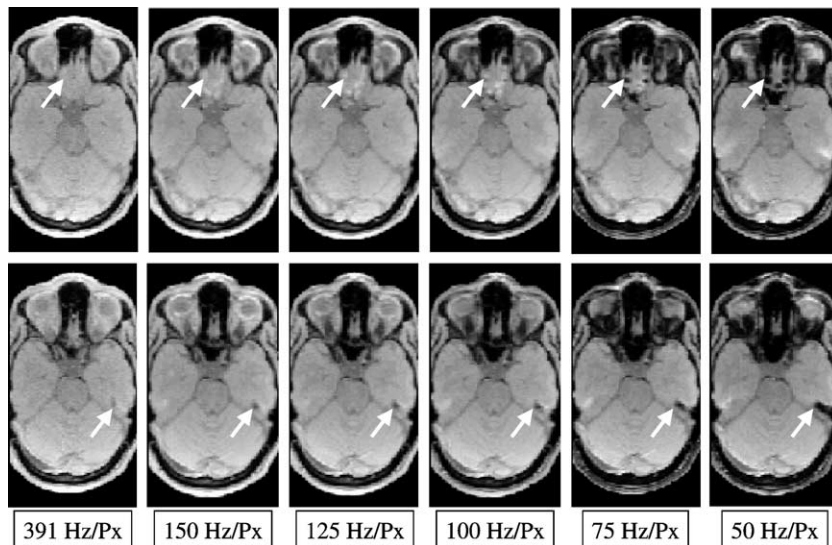


Fig. 6. Axial 2D FLASH images acquired with six different bandwidths. The arrows indicate areas in the orbitofrontal cortex (top) and in the temporal lobes (bottom) which are particularly affected by signal dropouts.

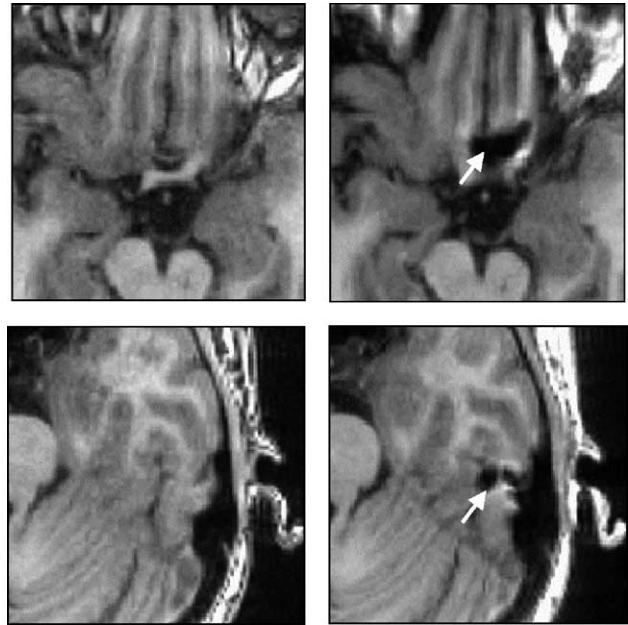


Fig. 7. Axial 3D MDEFT images acquired with a bandwidth of 195 Hz/pixel (left) and 75 Hz/pixel (right). At 75 Hz/pixel, dropouts are visible in the orbitofrontal cortex (top), and in the temporal areas (bottom). There are less signal dropouts at 195 Hz/pixel.

investigation of these areas bandwidths below 100 Hz/pixel should be avoided.

Experiment 2

Fig. 5 shows that the SNR in the MDEFT images decreases likewise with increasing bandwidth (bottom two plots).

Fig. 7 shows axial MDEFT images from a single volunteer acquired with a bandwidth of 195 Hz/pixel (left) and 75 Hz/pixel (right). At 75 Hz/pixel, dropouts are visible in the orbitofrontal cortex (top, marked by an arrow) and in the temporal areas (bottom, marked by an arrow). There are less signal dropout regions at 195 Hz/pixel.

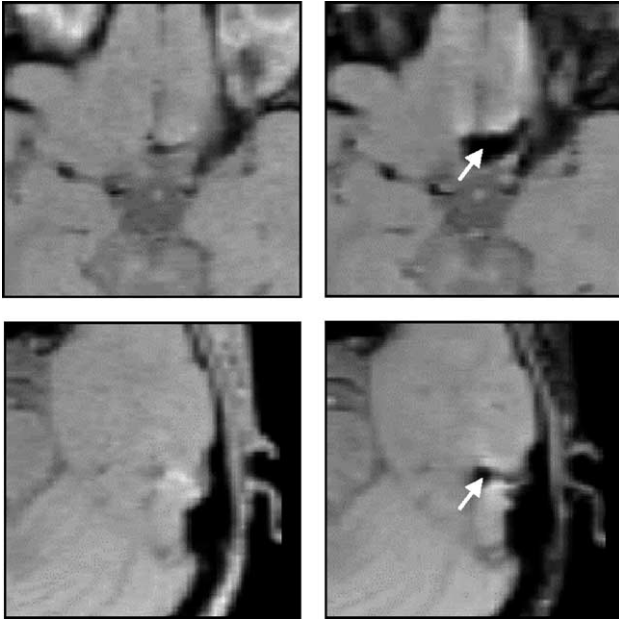


Fig. 8. Axial 2D FLASH images acquired with a bandwidth of 195 Hz/pixel (left) and 75 Hz/pixel (right). At 75 Hz/pixel, dropouts are visible in the orbitofrontal cortex (top), and in the temporal areas (bottom).

Experiment 3

Fig. 8 shows axial FLASH images acquired with a bandwidth of 195 Hz/pixel (left) and 75 Hz/pixel (right). At 75 Hz/pixel, dropouts are visible in the orbitofrontal cortex (top, marked by an arrow) and in the temporal areas (bottom, marked by an arrow). There are less signal dropout regions at 195 Hz/pixel. Comparison with Fig. 7 shows that the position and the level of dropout in both data sets are similar, with a similar improvement seen when using the higher bandwidth. This comparison shows that the conclusions based on the FLASH results can be applied to structural images acquired with the MDEFT sequence.

Based on the results of this study, it can be concluded that for structural imaging with the MDEFT sequence a minimum bandwidth of 100 Hz/pixel should be used. In this way, dropouts in the temporal and orbitofrontal areas are still negligible and an acceptable SNR is maintained.

Discussion and conclusion

The purpose of this study was to explore acquisition parameters that would reduce two types of artefacts in anatomical images: movement artefacts and signal dropouts.

The first part of the study investigates the ringing artefact caused by the interaction between high fat signal in the scalp and head motion. The bright scalp signal can be reduced using standard fat suppression techniques. The simulated motion study confirms that the ringing artefact due to head movement results from the bright scalp signal, and that it can be reduced by standard fat suppression techniques. It is almost completely removed when the fat saturation pulse is combined with the fat insensitive excitation. Furthermore, the simulation results show that strong ringing artefacts are visible even if the head motion occurs during the acquisition of peripheral lines in *k* space, in spite of the relatively low signal power. The study involving real head motion further

illustrates that motion artefacts can be greatly reduced using the combined fat suppression techniques, even if no other means of motion correction are applied.

In general, head motion during MRI studies should be avoided as much as possible, for example, using padding and cushions to immobilize the head. However, this study highlights the importance of selecting appropriate acquisition parameters in order to suppress image features that are particularly susceptible to motion such as the bright signal in the scalp. This becomes even more important when using a phased array coil which has greater sensitivity in the peripheral areas of the head. The results suggest that fat suppression techniques should be considered even when using additional methods for motion correction.

The second part of the study identified areas where image dropout occurs at low receiver bandwidths. A minimum bandwidth of 100 Hz/pixel is suggested to allow for visibility of the problematic areas without overly compromising on SNR. Although image dropout is usually a problem associated with T2*-weighted images, this work shows that when choosing low bandwidths, significant dropout can occur in the orbitofrontal and temporal areas in T1-weighted images. It is therefore important to consider the areas of interest when choosing the acquisition bandwidth. For example, when performing morphometry studies with a particular interest in orbitofrontal and temporal areas it may be necessary to use a higher bandwidths so that there is minimal signal loss. On the contrary, if there is no interest in these areas a lower bandwidth can be used, gaining the benefit of higher SNR.

The experimental results presented here are based on MDEFT sequences but can be applied to other T1-weighted sequences including 3D FLASH and MP-RAGE.

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