Silent echoplanar imaging for auditory fMRI

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Introduction:

MRI scanners produce a loud acoustic noise during image acquisition. Especially in fast imaging sequences with high gradient slew rates patients are exposed to intense sound pressure levels (SPL) of up to 130 dBA [1]. In fMRI the acoustic noise can be particularly detrimental, as the scanner noise induces a BOLD signal in the auditory cortex [2]. This is a serious problem in auditory fMRI, because this signal interferes with the activation evoked by the auditory stimulation [3]. Thus, a low-noise fMRI technique is needed.

In this work we present a low-noise EPI sequence, which utilizes pure sinusoidal readout (RO) gradients and smooth ramps for the remaining gradients. The acoustic spectrum of the new sequence consists of only a narrow band containing a main frequency component that can be moved along the frequency axis to coincide with one of the minima of the scanner's frequency response function.

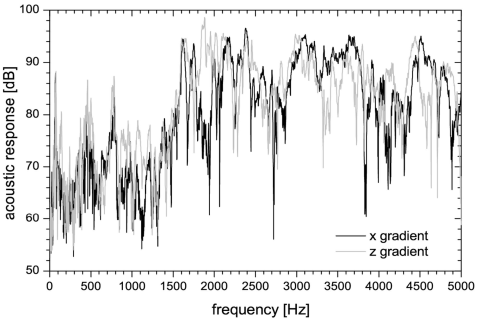

Fig. 1*: Acoustic frequency response function (FRF) of the x and z gradient coils. The y gradient coil FRF looks similar to the x gradient coil FRF.*

Methods:

The scanner system can reasonably be approximated as linear [19], which implies that the acoustic frequency response R(t) can be written as a product of the gradient's frequency response function (FRF) H(f) and the Fourier transform of the gradient switching G(f).

As the FRF generally fluctuates strongly with frequency (see Fig. 1), our approach to a low-noise sequence consists of a gradient switching g(t) which is characterized by a narrow-band input spectrum G(f) located in a frequency interval where the FRF magnitude is minimal. In this way, the transmission of acoustic energy is reduced compared to broad-band sequences. Our low-noise EPI sequence uses purely sinusoidally switched readout (RO) gradients with the switching frequency f_{RO}, which generate the requested input spectrum. Additionally the phase encoding gradient is switched constant, so that only negligible acoustic noise is generated. Fig. 2 shows the corresponding gradient switching scheme of the low-noise sequence. The constant PE gradient in combination with the sinusoidal RO gradient forms an S-shaped k-space trajectory. Thus the acquired data has to be regridded on a kartesian grid.

The sequence as well as the image reconstruction was implemented on a 3 Tesla system (Magnetom Tim Trio, Siemens Medical Solutions, Erlangen, Germany). The sound measurements were performed by an electret microphone (Panasonic MCE 2500, Matsushita Electric Industrial Co., Ltd., Osaka, Japan) which was calibrated by a gauged sound level meter (Brüel & Kjær 2235) in a sound-proof room.

In order to investigate the performance of the low-noise sequence in terms of auditory stimulation, an fMRI experiment was performed in which a sinusoidal tone was presented binaurally. The tonal frequency of the stimulus was set at 1835 Hz, a frequency which is highly pronounced in the frequency spectrum of standard EPI sequences. Five healthy volunteers (3 males, 2 females, mean age 26.3 y ± 1,3 y) underwent functional scans using both the low-noise sequence and a standard EPI sequence with same imaging parameters: FOV = 220 x 220 mm^2, 25 Slices, 5mm thickness, Matrix = 64x64, BW = 1324 Hz/Px, TE = 42 ms, TR = 79 ms (per slice), 25 slices, $\alpha = 90°$. A simple block design that included eight blocks during the presentation of the stimulus and nine blocks at rest, beginning with a rest block, was used. Data analysis was performed using SPM5 (Welcome Department of Cognitive Neurology, Institute of Neurology, University College London, London, UK) including motion correction (realignment), spatial smoothing (Gaussian-Window, FWHM = 8mm), and normalization to a standard EPI template (MNI template).

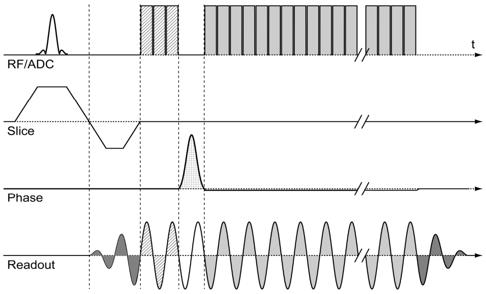

Fig. 2*: Timing scheme of the low-noise sequence. Three areas are indicated: dark gray: RO dephaser; shaded: phase correction scans, light gray: EPI RO.*

Results:

Fig. 3a demonstrates the measured acoustic spectrum of the new low-noise EPI sequence. It consists of a narrow band (bandwidth: 400 Hz) with a main frequency component located at the RO frequency of 581 Hz. The part of the spectrum above this band, which is suppressed in the low-noise sequence, is however present in standard EPI sequences, as shown in Fig. 3b. This means that stimulus frequencies above the RO frequency can be perceived well during an fMRI experiment performed with the sinusoidal EPI sequence, whereas the stimulus may be masked when a standard EPI sequence is used.

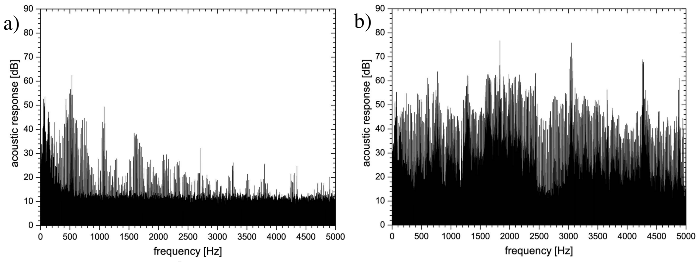

Fig. 3*: a: Measured acoustic spectrum of the low-noise sequence in the range from 0 to 5000 Hz. b: acoustic spectrum of the standard EPI Sequence.*

The measured average SPL amounts to 61.7 dBA (65.6 dB) for the low-noise sequence and 82.5 dBA (81.6 dB) for the standard EPI sequence with the same imaging paramter. Thus the resulting acoustic noise reduction counts up to 20.8 dBA (16.0 dB). The functional experiment produced significant activation of the auditory cortex in all the five volunteers when the low-noise EPI sequence was used, whereas little activation was found when the standard EPI sequence was applied. Fig. 4 shows the t-maps of one of the subjects resulting from (a) the low-noise sequence and (b) the standard sequence. The t-threshold for an FWE of $p < 0.01$ is 5.2. For the low-noise sequence, significant activation may be observed in both the left and the right auditory cortex. The maximum t-values resulting from the standard EPI sequence were below this threshold for three out of the five subjects, whereas the values from the low-noise sequence all were above the threshold: 8.83, 10.32, 12.2, 8.06, 11.68 (low-noise EPI sequence) and 3.85 5.58, 4.08, 1.96, 5.75 (standard EPI-Sequence). Both sets of t-scores were tested for a statistically significant difference using a t-test. ($t = 5.68$, dfadj = 7.84, two-tailed, $p < 0.0005$).

Discussion:

Our new low-noise EPI sequence shows essentially two fundamental improvements compared to a standard EPI sequence. Firstly, the overall SPL is reduced by more than 20 dB, whereas the imaging time for a slice with 79 ms is comparable to a standard sequence. Secondly, the acoustic frequency spectrum of the sequence only consists of a narrow band in a low frequency interval where human hearing is less sensitive. he functional experiment produced a higher level of activation of the auditory cortex with the low-noise EPI sequence than with the standard EPI sequence. Despite the small number of subjects investigated, the difference in auditory activation between the sequences in favor of the new low-noise sequence was statistically highly significant, suggesting that the low-noise sequence may be effective in reducing masking and saturation effects.

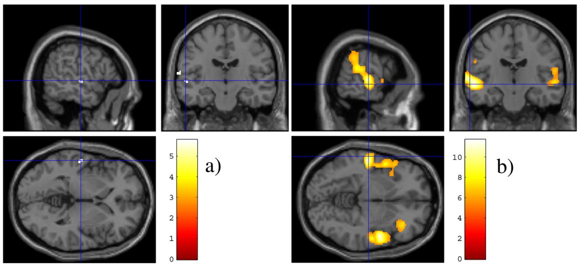

Fig. 4*: t-score statistical map (t > 5.2 , pFWE< 0.01) of one of the subjects. The images were acquired with the low-noise sequence (a) and the standard EPI sequence (b) respectively.*

References:

[1] Foster et al. [2000] J Magn Reson Imaging 12:157-163; [2]Bandettini et al. [1998] Magn. Reson. Med. 39(3):410-6; [3] Elliott MR et al. [1999] Magn Reson Med 41:1230-1235.