Sinusoidal echo-planar imaging with parallel acquisition technique for reduced acoustic noise in auditory fMRI

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Introduction

Conventional echo-planar imaging (EPI) commonly used in functional MRI (fMRI) produces a high sound pressure level (SPL) of up to 131 dB on a 3 T MR system [1] due to fast switching of trapezoidal readout (RO) gradients. This acoustic noise may cause an unwanted BOLD signal in the auditory cortex [2] and poses a safety issue since the high SPL can provoke hearing impairment without ear protection [3]. Previously, a low noise, sinusoidally switched EPI (sEPI) sequence for auditory fMRI was proposed which reduces the SPL by 16 dB compared to a conventional trapezoidal EPI sequence on a standard clinical MR system [4]. The integration of a parallel acquisition technique (PAT) into sEPI is an enhancement of sEPI's restrictions for parameters like resolution, lower RO frequency boundary and TE. This was so far only demonstrated in part for few special cases of SPL measurements [5] and for a limited implementation of the image reconstruction using a trapezoidal reference scan [6]. In this work, we provide a comprehensive comparison of SPL measurements between sEPI and a conventional, trapezoidal EPI for their most feasible configurations with and without PAT. Furthermore, by using a sinusoidal reference scan we reduced sEPI PAT's sequence timing restrictions and improved its image reconstruction. This survey presents the benefits of sEPI and facilitates the selection of an appropriate sEPI parameter set for a given application in auditory fMRI. In addition, temporal signal-to-noise ratio (tSNR) is compared between sinusoidal and trapezoidal RO gradients.

Materials and Methods

Principle: The acoustic response s(t) of the MR system can reasonably be approximated by a linear system [7]. Thus, s(t) can be written as a convolution of an arbitrary switching g(t) of a gradient coil and the impulse response function h(t) of the system. The acoustic spectrum S(f) is given by the Fourier transform of s(t): $S(f) = G(f) \cdot H(f)$. In case of a sinusoidally switched RO gradient g(t) with frequency f_{RO}, the corresponding gradient spectrum G(f) approximates a Dirac delta function located at f_{RO}. By varying the RO bandwidth, the gradient switching frequency f_{RO} can be altered such, that the frequency response function H(f) is locally minimized for $f = f_{RO}$. *Sequence timing:* The timing scheme of the sEPI PAT sequence, which was implemented on a 3 T MR system (Magnetom Trio, Siemens Healthcare, Erlangen, Germany), is depicted in Fig.1. For optimal BOLD contrast at 3 T, a TE below 50 ms is commonly used [8], thus higher values were not considered here. *Image reconstruction:* Image reconstruction with GRAPPA [9] was implemented into the C++ based image calculation environment (ICE) of the MR system. *Setup and measurements:* We compared the SPL as a function of f_{RO} for 6 different sequences: (a) conventional EPI, matrix size = 64x64 pixels, without PAT and (b) with PAT; (c) sEPI sequence using the same parameters without PAT and (d) with PAT; (e) conventional EPI, matrix size = 128x128 pixels, with PAT and (f) sEPI using the same parameters. The parameters FOV = 220x220 mm² and slice thickness = 4 mm were identical for all the sequences. The SPL was measured using a calibrated optical microphone (MO 2000, Sennheiser electronic, Wedemark, Germany) mounted on top of a water phantom inside a 12-channel head coil. The tSNR was determined by calculating the mean signal divided by the standard deviation on a pixel-by-pixel basis from 100 measurements of a water phantom with TE = 50 ms, FA = 90° and TR = 5000 ms at the lowest RO frequency examined with the lowest possible RO bandwidth.

Results and Discussion

Over a wide frequency range, the sEPI configurations provide a reduced SPL compared to their EPI equivalent for matrix sizes of 64x64 (Fig.2) and 128x128 (Fig.3). The average SPL reduction of sEPI amounts to (5.8 ± 3.9) dB, (4.0 ± 2.4) dB and (2.1 ± 1.6) dB for 64x64 without PAT, with PAT and 128x128 with PAT, respectively. The difference in SPL ($SPL_{EPI} - SPL_{sEPI}$) for a given RO frequency amounts up to 14.6 dB, 11.1 dB and 5.1 dB for 64x64 without PAT, with PAT and 128x128 with PAT, respectively. For both matrix sizes, a general tendency of rising SPL is observed with increasing RO frequency. Integrating PAT into sEPI enables an increased resolution with a matrix size of 128x128 pixels in combination with a reduced SPL compared to conventional EPI using the same parameters, which was impossible without PAT for the given constraints. We identified a favorable RO frequency at $f_{RO} = 451$ Hz (minimum TE = 43 ms) with the lowest SPL of 77.8 dB as seen in Fig.3. In addition, PAT can be used for RO frequency reduction as visible in Fig.2. In this context, we identified favorable low RO frequencies at $f_{RO} = 225$ Hz (minimum TE = 50 ms) and at $f_{RO} = 281$ Hz (minimum TE = 40 ms) with the two lowest SPLs of 72.0 dB and 72.2 dB found for sEPI PAT, which are only about 2 dB apart from the global minimum found for sEPI at $f_{RO} = 455$ Hz (minimum TE = 44 ms). PAT also allows for shortening the minimum TE and TR of both EPI and sEPI by a factor of 1.7 and the RO train length by a factor of 2 for a given RO frequency. As shown in Fig.2, already the RO frequency at $f_{RO} = 427$ Hz achieves the third lowest SPL found for sEPI PAT with a noteworthy minimum TE = 27 ms. To reach a similar short TE for sEPI without PAT, only RO frequencies $f_{RO} \geq 714$ Hz with considerably higher SPL (> 4 dB) come into consideration. In contrast to sEPI, EPI has pronounced peaks at f_0's harmonics f_2, f_4, f_6, … as shown in Fig.4, which are caused by the trapezoidal waveform of the RO gradients. The tSNR ratio (averaged over 24 ROIs evenly distributed over the phantom) of sinusoidal to trapezoidal (sampling during flat-top time) RO gradients for the configurations 64x64 with PAT and 128x128 with PAT results in 0.96 ± 0.03 and 0.96 ± 0.02, respectively. The reduction in tSNR is expected due to the nonuniform sampling with sinusoidal RO gradients.

Conclusion

PAT enhances the parameter restrictions of the sEPI sequence in particular with (i) an increased resolution, or alternatively with (ii) an expanded RO frequency range towards lower frequencies, which is in general beneficial for SPL, or (iii) shortened TE, TR and RO train length. At the same time, sEPI PAT provides a reduction in SPL of up to 11.1 dB and 5.1 dB compared to a conventional EPI sequence having the same imaging parameters and achieves an SPL as low as 72.0 dB and 77.8 dB for matrix sizes of 64x64 and 128x128 pixels, respectively. Many research areas that are compromised by noise during fMRI could profit from our low acoustic noise imaging method as the investigation of language and music processing of the brain, tonotopy, tinnitus, and resting state networks.

References

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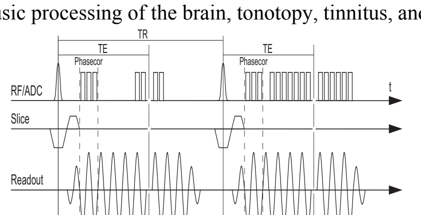

***Fig.1**: Sequence timing scheme of sEPI PAT. Both reference scan and the following undersampled sEPI acquisition operate with sinusoidal RO gradients and blipped PE gradients, have identical echo time TE and use phase correction lines.*

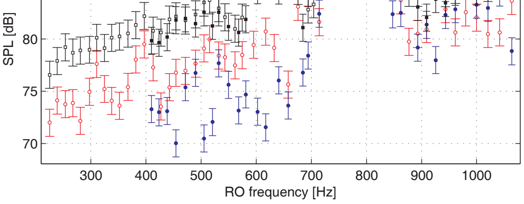

***Fig.2**: SPL of sEPI and conventional EPI with matrix sizes of 64x64 pixels without and with PAT versus RO frequency. No data is given for RO frequencies close to 785 Hz, the unfavorable acoustic resonance frequency of the gradient system.*

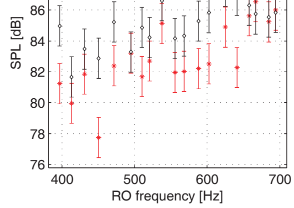

***Fig.3**: SPL of sEPI and conventional EPI with matrix sizes of 128x128 pixels with PAT versus RO frequency.*

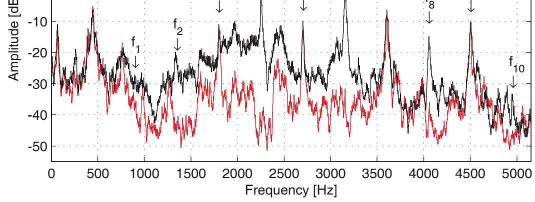

***Fig.4**: Acoustic spectrum of sEPI and conventional EPI with matrix sizes of 128x128 pixels with PAT at the RO frequency $f_{RO} = 451$ Hz. The fundamental frequency $f_0 = f_{RO}$ and its higher harmonics $f_1, f_2, \ldots, f_{10}$ are labeled.*