**Technical Note**

# Echo Planar Imaging at 4 Tesla With Minimum Acoustic Noise

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**Purpose:** To minimize the acoustic sound pressure levels of single-shot echo planar imaging (EPI) acquisitions on high magnetic field MRI scanners.

**Materials and Methods:** The resonance frequencies of gradient coil vibrations, which depend on the coil length and the elastic properties of the materials in the coil assembly, were measured using piezoelectric transducers. The frequency of the EPI-readout train was adjusted to avoid the frequency ranges of mechanical resonances.

**Results:** Our MRI system exhibited two sharp mechanical resonances (at 720 and 1220 Hz) that can increase vibrational amplitudes up to six-fold. A small adjustment of the EPI-readout frequency made it possible to reduce the sound pressure level of EPI-based perfusion and functional MRI scans by 12 dB.

**Conclusion:** Normal vibrational modes of MRI gradient coils can dramatically increase the sound pressure levels during echo planar imaging (EPI) scans. To minimize acoustic noise, the frequency of EPI-readout trains and the resonance frequencies of gradient coil vibrations need to be different.

**Key Words:** acoustic noise; MRI; EPI; vibrational resonances; sound pressure levels
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AT HIGH MAGNETIC FIELD STRENGTH, the acoustic noise produced by echo-planar imaging (EPI) techniques can be very high and has been a concern for patient safety and comfort. For these fast-imaging techniques, the sound pressure level (SPL) of acoustic noise in high-field MRI scanners can exceed 130 dB and may cause anxiety and discomfort in patients (1,2). Acoustic noise can also obscure functional magnetic resonance imaging (fMRI) studies. For instance, loud acoustic noise can produce spurious areas of activation in the auditory cortex (3,4) or alter the BOLD signal in motor and visual cortices (5,6).

Acoustic noise is a consequence of the vibrations produced in the coil assembly by the Lorentz interaction between the static magnetic field, $B_0$, and the time-dependent currents in gradient wires. Several experimental studies (1,7–9) have demonstrated a clear increase in SPL of acoustic noise for high-field systems (1), and the existence of acoustic resonances (8).

The SPL of acoustic noise in MRI scanners is commonly reduced by the use of acoustic absorbing materials (10,11) and ear protection (ear plugs and headphones). Alternatively, the SPL can be reduced by the design of quiet gradient coils (12–15), or the development of silent MRI-pulse sequences (16–19). In this work, we demonstrate that acoustic noise can be reduced dramatically by optimizing the EPI-readout frequency.

## MATERIALS AND METHODS

All studies were performed on a 4-Tesla MRI scanner that was driven by a Varian INOVA console with a shielded whole-body SONATA-Siemens gradient set (using three K2217 Siemens Cascade Gradient Power Amplifiers with 2000 V and 500 A) to produce gradient pulses with 44 mT/m peak amplitude at 0.25 msec maximum rise time. Three piezoelectric transducers (PZT) (Radio Shack, 273-073A) were placed on the inner surface of the gradient set to measure the mechanical vibrations produced by all three gradient coils. To maximize the signal-to-noise ratio, the microphones were placed at the positions where vibrational amplitudes for *x*-, *y*-, and *z*-gradient pulses are maximal: (*x*-PZT: 0.34 m, 0, 0), (*y*-PZT: 0, 0.34 m, 0), and (*z*-PZT: 0, −0.34 m, 0.60 m). Additionally, a calibrated digital sound lever meter EXTECH 407727 (Waltham, MA) was used to measure the SPL of different MRI sequences in dBA at the entrance of the scanner.

The impulse response of the coil assembly was determined using 500 μsec rectangular gradient pulses with 250 A current amplitude (22 mT/m), separately for each axis. The output voltages of the microphones were recorded with a digital oscilloscope (LECROY 9354TM, 50 msec trace, 500 kHz sampling rate, 16 bit dynamic range).

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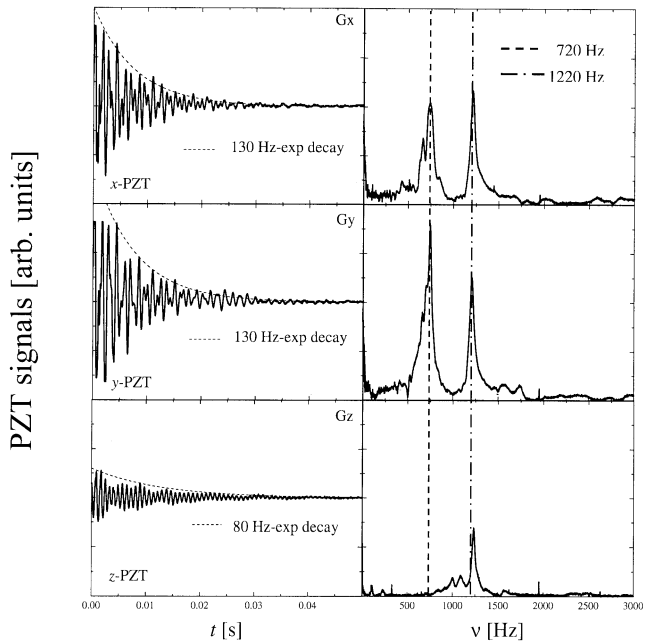


**Figure 1.** Experimental vibrations of coil assembly due to current-impulses in all three gradient coils as a function of time (left), and after Fourier-transformation (right). Gradient amplitude 22 mT/m, pulse duration 0.5 msec. Dashed lines represent the exponential decay of damped oscillations (left).

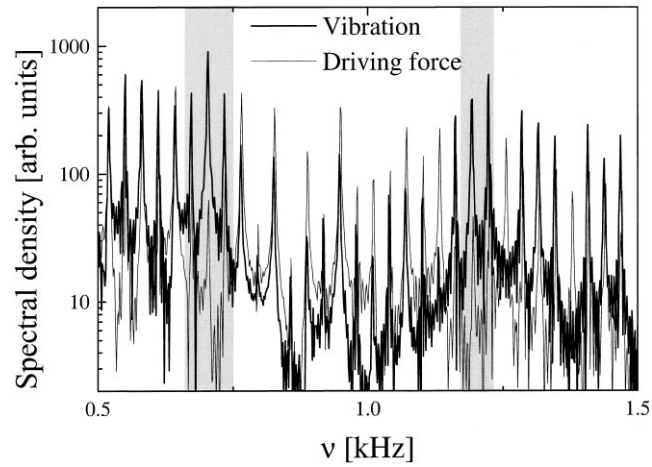


**Figure 2.** Fourier spectra of the gradient pulse train (thin line) and coil vibrations (thick line) for an MDEFT sequence. The gray vertical bars indicate the spectral positions of mechanical resonances at 720 and 1220 Hz (see Fig. 1).

## RESULTS

Figure 1 shows the damped oscillations of the *x*-, *y*- and *z*-PZT signals following the gradient impulse in the $G_x$-, $G_y$- and $G_z$-gradient coils, respectively, as well as the envelopes of the PZT signals obtained by fitting a mono-exponential decay to the signal envelopes (dashed lines). The signal decay is the result of dissipative processes in the gradient coil set, which depend on the viscosity of materials comprising the assembly. The Fourier transform of the PZT signals shows the existence of two resonance frequencies, one at 720 and one at 1220 Hz, for the transverse gradient coils $G_x$ and $G_y$, but a single resonance (at 1220 Hz) for the longitudinal gradient coil $G_z$. The resonance frequencies depend on the coil length and elastic properties (Young modulus and density) of the materials in the assembly.

Figure 2 shows the Fourier spectra of the current waveform in the $G_x$-gradient coil (thin line) and the *x*-PZT signal (thick line), as a result of acquiring a Modified Driven Equilibrium Fourier Transform (MDEFT) pulse sequence (20) (coronal, 256 × 192 × 48 matrix size, TE = 7 msec, TR = 15 msec, three-dimensional acquisition mode). Both spectra peak at the same frequencies and the relative amplitudes of the two spectra are generally very similar. However, the amplitude of vibrations with frequencies close to the gradient-coil resonances (720 and 1220 Hz; shaded areas) are magnified ten-fold or more relative to the driving current.

Figure 3 shows the time course of gradient coil vibrations produced by the $G_x$-readout gradient of an EPI-pulse sequence for three different readout frequencies (700, 920, and 1200 Hz), corresponding to receiver bandwidths of 100, 130, and 170 kHz. The amplitude of vibrations strongly depends on the readout frequency and is enhanced approximately four times when the frequency coincides with one of the resonance modes of the gradient coil (700 Hz and 1200 Hz). Consequently, the SPL was markedly reduced for a readout frequency of 920 Hz compared to resonance modes.

## DISCUSSION

Acoustic noise is a consequence of vibrations in the gradient coils and increases linearly with the strength of the magnetic and gradient fields. At high magnetic

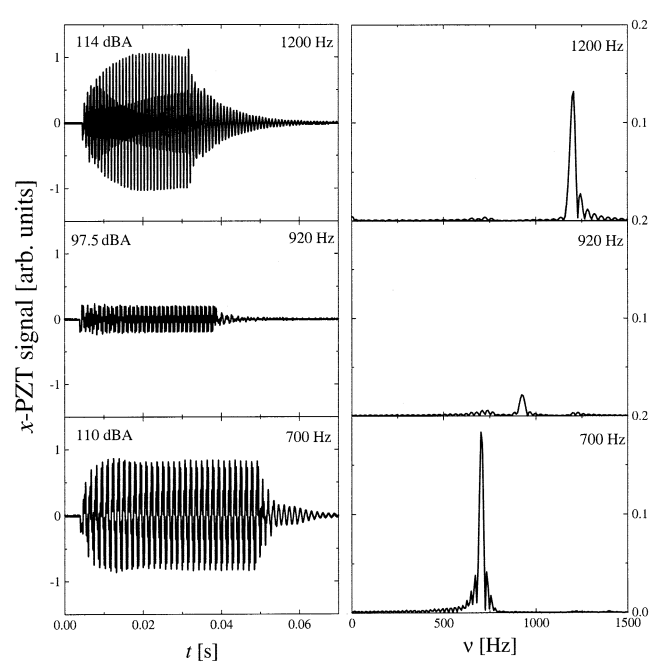


**Figure 3.** Amplitude of vibrational motion produced by EPI-readout gradients as a function of time (left) and after Fourier transformation (right), for three different readout frequencies with different SPL (in dBA).

field strengths, the acoustic noise of EPI scans can be very high and can be of concern for patient safety and comfort. In addition, acoustic noise can obscure the results of functional MRI activation studies. Due to the magnetic interaction between the main magnetic field and the gradient fields, strong magnetic forces are applied to the gradient coil assembly in MRI sequences. A fraction of this magnetic energy is transferred to the normal modes of vibration of the assembly and the remaining fraction is converted to heat.

The SPL levels of MRI-acoustic noise result from the overlap between the power spectrum of the assembly vibrations and that of the gradient waveforms. The power spectrum of gradient vibrations is a set of peaks regularly spaced in the frequency domain at multiples of the fundamental frequency, $f_0$, which for typical whole-body gradient coils ranges between 400 to 1000 Hz.

For conventional MRI pulse sequences, the power spectrum of the gradient waveform is distributed in the frequency domain because the fundamental harmonic has a low frequency (10–50 Hz), usually as a result of the slice loop. Higher-frequency components are the result of short gradient rise times during switching. For these types of pulse sequences, the SPL can be markedly reduced by smoothing the gradient waveform to minimize the overlap between the power spectrum of assembly vibrations and the apodized power spectrum of the gradient waveform. This prevents vibrational resonances of the coil assembly. For instance, it was possible to achieve a 10–20 dB reduction in SPL of acoustic noise in fast spin-echo and gradient-echo techniques by smoothing the shape of the gradient waveforms (17,18).

In contrast, the power spectrum for typical EPI sequences exhibits sharp peaks at high frequency that represent the harmonics of the readout train. In this situation, it is impossible to low-pass filter the gradient waveforms to reduce acoustic noise because the fundamental Fourier component of the waveform is close to the frequency of vibrational resonances. Thus, the readout frequencies have to be adjusted to avoid the mechanical resonances of the coil assembly.

Careful design of EPI sequences becomes more important at high magnetic fields. First, higher magnetic fields produce larger Lorentz forces, stronger vibrations, and increased SPLs compared to lower fields. Second, to minimize image distortions, higher magnetic fields generally necessitate higher EPI readout frequencies (compared to lower fields), due to increased susceptibility effects.. Thus, the readout frequency of EPI experiments performed at high fields are more likely to match vibrational resonances of the gradient coils, which further increases the MRI-acoustic noise.

On our system, perfusion scans were initially performed at 720 Hz readout frequency, which matched the fundamental mode of vibration of the gradient assembly. Consequently, the acoustic noise of perfusion scans was very high and sound-absorbing materials were used to reduce the SPL to acceptable levels. Subsequently, an additional 12 dB reduction of the acoustic SPL was achieved by changing the readout frequency to 920 Hz (see Fig. 3).

In summary, we demonstrated that vibrational resonances of the gradient coil assembly can dramatically enhance acoustic noise in EPI scans. Therefore, the EPI readout frequency needs to be chosen carefully to avoid vibrational resonances of the coil assembly. On our 4 Tesla whole-body system, this simple measure resulted in a 12 dB reduction in the SPL.

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