Maximum sound pressure levels at 7 Tesla – what's all this fuss about?

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Introduction

The acoustic noise during image acquisition is a well-known problem in MRI, which is especially pronounced during fast imaging with high gradient slew rates and at high field strengths. Patients can be exposed to sound pressure levels (SPL) as high as 130 dB [1] and more on clinical 3 Tesla MR systems. As the SPL increases linearly with gradient amplitude [2] the SPL of a 7T System approximates 140 dB, which is far beyond the human pain threshold.
In this work the acoustic resonances of a 7 T system were examined and the linear dependency of the sound pressure on the gradient amplitude were verified. Moreover the protocols of three different, fast imaging sequences were adjusted on the scanners resonances so that they generate a maximum SPL. The sequence's SPL values were measured and compared to a theoretical maximum value.

Methods

The sound measurements were performed on a 7T whole body system (Magnetom 7T; Siemens Medical Solutions; Germany) equipped with a 40 mT/m gradient system. To determine the acoustic noise, a calibrated optical microphone (MO2000, Sennheiser electronic, Germany) was placed inside the bore, which was connected to a electro-optical converter via a fiber-optic cable. The optical signal was digitized on a PC sound card (SoundBlaster Audigy 2 ZS, Creative Labs, Singapore).
The MR system was regarded as a linear electro-mechanical system [2]

$$p(t) = g(t) \otimes \mathrm{IRF}\cdot \qquad (1)$$

where the sound pressure $p(t)$ is a convolution of the gradient strength $g(t)$ and the inherent impulse response function IRF of a single coil. In order to determine the acoustic resonance frequencies, the Fourier transform of the coil's IRF (FRF) was measured using a gradient sweep $g(t) = g_{sw}\sin(\pi a t^2)$ from 0 to 10 kHz (g_{sw}= 3 mT/m; a = 40 Hz^2). The recorded sound pressure $p(t)$ of each sweep was Fourier-transformed and displayed in logarithmic units [dB] using

$$FRF_{dB}(f) = 20\cdot\log\left[\left|\frac{FT\left(p(t)/20\mu Pa\right)}{FT\left(g(t)/1mT/m\right)}\right|\right] + C \qquad (2)$$

where C is a constant resulting from the microphone calibration step. To determine the maximum SPL that can occur on the 7 T system, the linear dependency of the sound pressure on the gradient amplitude is assessed (cf. eq. 1). In particular, the SPL of a sinusoidal gradient waveform $g(t) = g_0\sin(2\pi f_0 t)$ should increase logarithmically with gradient amplitude g_0 according to

$$SPL(f_0) = a\cdot\log\left[\frac{g_0}{1mT/m}\right] + b. \qquad (3)$$

Here a = 20 and b = FRF$_{dB}$. This dependency is verified for 5 different frequencies with the following FRF$_{dB}$ values: 437 Hz, 519 Hz, 555 Hz, 710 Hz, 729 Hz. The plotted curves are fitted with a function equal to eq. 3.
Three different sequences with 'worst case' protocols for the SPL were examined. Here TE, TR and bandwidth is modified so that the peak component in the Fourier spectrum of the gradient waveforms coincides with the maximum of the FRF.

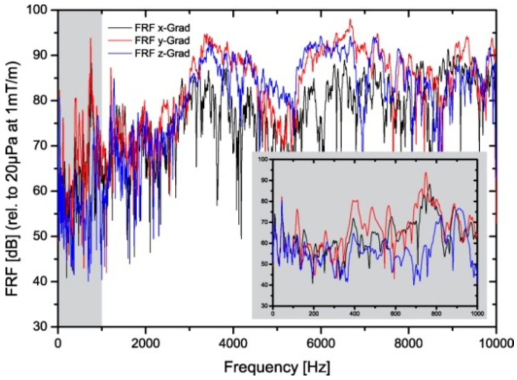

***Fig. 1:** Frequency response function (FRF) of x-, y- and z-gradient coil. The gray shaded frequency interval is shown expanded in the lower right diagram with higher spectral resolution.*

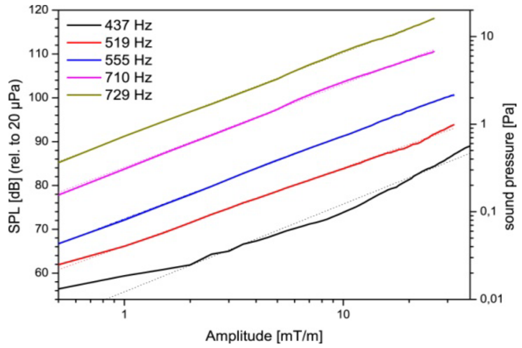

***Fig. 2:** Dependency of the sound pressure (left scale) and the sound pressure level (right scale) on the y-gradient amplitude. The gradient was switched sinusoidally with frequencyies of different intensities in the FRF.*

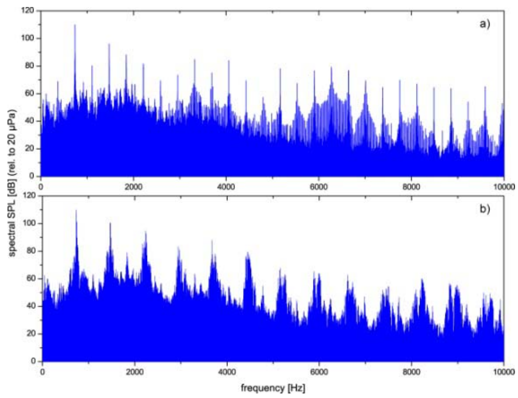

***Fig. 3:** Acoustic sound spectrum of a trueFISP sequence a) and an EPI sequence (b). Parameters: a) FOV = 228x228 mm^2, Slice = 2 mm, BW = 1953 Hz/Px, TR = 2.71 ms, TE = 1.21 ms, Matr.= 128^2; b) FOV = 228x228 mm^2, Slice = 5 mm, BW = 1860 Hz/Px, TR = 105 ms, TE = 49 ms, Res = 128.*

Results

Figure 1 shows the measured FRF$_{dB}$ of the x-, y- and z-gradient coil, the insert displaying the interval between 0 and 1000 Hz. The x- and y-gradient coils show pronounced peaks at 730-740 Hz and wider resonance intervals between 3 - 4 kHz as well as between 5.5 - 6.5 kHz. In the range between 0 and 3 kHz, the maximum FRF$_{dB}$ value amounts to 94 dB for the y gradient at 730 Hz. Figure 2 shows in a logarithmic plot the dependency of the SPL on the gradient amplitude and the corresponding fit curves (cf. eq. 3). The mean slope, determined to a = (19,0 ± 0,2) dB, only shows minor deviations from the expected value of 20. From this the maximum SPL at a sinusoidal gradient with g_{max} = 40 mT/m can be estimated to SPL$_{max}$ = FRF$_{dB}$(730Hz)+20*log(40) = 126 dB. In comparison, the maximum SPL, which could be realised with diagnostic sequences are shown in Tab. 1. Here, the maximum value of 112 dB was found for a sinusoidal EPI sequence. In all the 3 sequences the main frequency component of the readout gradient (set to y direction) or a higher order of it was adapted to 730-740 Hz. Figure 3 shows an example of the acoustic spectrum of a) the trueFISP and b) the EPI sequence. For the EPI sequence and the sinusoidal EPI sequence the echo spacing was set to 0.68 ms, so the zeroth order of the readout gradient switching equals 735 Hz. Within the trueFISP protocol TR was set to 2.71 ms, thus the first order of the readout gradient spectrum equals 738 Hz.

Sequence	Mean SPL [dB]
EPI	110 dB
Sinusoidal EPI	112 dB
trueFISP	109 dB

***Tab. 1:** Mean SPL values for three different sequences.*

Discussion

In this work the acoustic properties and the maximum SPL of a 7 T system were analyzed. As the linearity of sound pressure and gradient amplitude can be reasonably assumed, a theoretical maximum SPL of 126 dB can be given. In fact, there are frequency components beyond 6000 Hz, which have higher FRF$_{dB}$ values, but due to slew rate limitations these frequency components cannot be operated with high gradient amplitudes.
In realistic imaging pulse sequences an SPL of 126 dB could not be achieved due to limits imposed by the dB/dt-monitor of the MR system (peripheral nerve stimulation monitor), and a maximum of 112 dB was observed instead. Even this SPL is hardly present in clinical routine EPI protocols, because standard pulse sequences actively avoid echo spacings which generate acoustic resonances. The lower SPLs of this 7T MR system result from additional technical measures to reduce acoustic noise, and with worst case protocols SPLs up to 112 dB are generated, which is similar SPL values of a 1.5 T scanner. Thus, regarding acoustic safety, the same safety measures can be applied for this specific 7 T MR system as to 1.5 T systems from the same manufacturer.

References: [1] Foster et al. [2000] J Magn Reson Imaging 12:157-163; [2] Hedeen RA and Edelstein WA [1997] Magn Reson Med 37:7-10.