Measuring MRI noise
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Chapter 1

Introduction

The interaction between the strong magnetic field of a Magnetic Resonance Imaging (MRI) scanner and changing electric currents in its gradient coils turns the scanner into a giant loudspeaker. The acoustic noise produced by an MRI scanner is a serious threat for persons in the scanner, as well as for persons in the scanner room (Brummett et al. [1988]; Cho et al. [1997]; McJury et al. [1994]). Sound pressure levels of 110 dB are common and levels over 130 dB have been measured for high magnetic field scanners (Counter et al. [2000]; Foster et al. [2000]; McJury and Shellock [2000]; Price et al. [2001]; Ravicz et al. [2000]). MRI is used not only to obtain anatomical images, but also for functional brain mapping; during this functional imaging (fMRI), the produced sound is a confounding stimulus. In particular, this affects functional imaging of brain activation by auditory stimuli (Ravicz and Melcher [2001]; Talavage et al. [1999]). Furthermore, this unwanted side effect causes anxiety, distraction, results in (auditory) brain stimulation not related to the task at hand, and possibly causes hearing damage (Bandettini et al. [1998]; Brummett et al. [1988]; Cho et al. [1998a]; Elliott et al. [1999]; Mazard et al. [2002]).

Several methods have been investigated to reduce vibration at the gradient coils (Mansfield et al. [1995]; Kuijpers [1999]), to block the conduction pathway (Katsumuma et al. [2002]), and to reduce the airborne acoustic output (Moelker et al. [2003a]). Without modifications to the scanner or the scanner room, the acoustic output of the scanner can be reduced by changing the frequency content of the pulse sequences (Hedeen and Edelstein [1997]; Tomasi and Ernst [2003]). The above issues are discussed in chapter 5.

It is almost impossible to make physical modifications to an MRI scanner in a clinical setting. Modifications to the scanner for sound reducing measures are typically done by MRI manufacturers. The only property that can be altered during normal operation of a scanner is the pulse sequence that is used for scanning. A pulse sequence defines the way in which the magnetic field is changed to obtain location information. In principle, when scanning starts, the time courses of the
electric gradient currents are known (Bilecen et al. [1998]; Chapman et al. [2003]; Cho et al. [1998b]; de Zwart et al. [2002]; Hedeen and Edelstein [1997]). They depend on scanning parameters like the repetition time (TR), the echo time (TE), and the field of view (FOV). Hence, adjustments of these parameters affect the gradient currents, in time as well as in spectrum (Tomasi and Ernst [2003]). Such a pulse sequence controls the electric gradient currents. The vibrations arising from the gradient currents contain the same frequencies as the gradient currents. This methodology, together with the physical principles of MRI, are treated in chapter 2.

The amplitude of the vibrations is depending on the acoustic transfer of the scanner system. This transfer is a function of frequency, and is high at the resonance frequencies of the scanner. To reduce the sound pressure produced by a scanner, these resonance frequencies should be avoided in the gradient current. When the acoustic transfer function of the gradient system is known, it should be straightforward to calculate the acoustic noise generated by the gradient currents (Hedeen and Edelstein [1997]). However, the acoustic output is not necessarily linear with the input (Moelker et al. [2003b]), and not only the frequencies in the electric current are found in the scanner noise, e.g., the spectrum of the output may also show nonlinear components. Such components hamper a simple input-output analysis. In the theory, chapter 3, the standard definition of the transfer function is given by the division of output and input spectra. In the same chapter a proposal is given for a new transfer function, the sound pressure transfer function, that takes nonlinearities into account. This transfer function is derived with a root-mean-square method, which relates closely to the determination of sound pressure levels. Furthermore, in this chapter, additional theoretical background for the following chapters is given.

The frequency sweep signals used in chapters 6 and 7 evoke all frequencies of interest consecutively, in contrast to impulse response or noise response measurements. That makes these signals suitable for the derivation of the sound pressure transfer function. In the Materials and methods chapter (chapter 4), all variations with sweep rate and amplitude are described, as well as the settings for pulse response and noise response measurements. Further, the frequency signal response is not only analyzed with the proposed method, but also with the conventional method. The analysis methods are described in detail in this chapter.

With the proposed method for a sound pressure transfer function (section 3.5), the objective is not to find the exact sound a scanner will produce. For that, a function is needed that also calculates nonlinearities, e.g., the production of harmonic distortion or overtones. In this work, the aim is to find the sound pressure transfer function. The electric gradient current time signal convolved with this transfer function will give a time signal that predicts the sound pressure, and not so much the real sound of a scanner. With this sound pressure time signal, the sound pressure level can be calculated. This sound pressure level is subjected to standards regarding exposure levels, and exposure time.

The sweep rate of the frequency modulated signals is bounded by the use of
time-averaging in the root-mean-square method. In chapter 6, the frequency sweep signals are varied over sweep rate and amplitude. The transfer functions are both derived with Fourier transforms and root-mean-square analysis. As expected, the transfer function cannot be derived with a sensible accuracy when the sweep rate becomes too high. Further, it is shown that harmonic distortion is high in the scanner noise. The major differences between the analysis methods are found where the transfer is low. Neglecting the harmonic distortion leads to wrong predictions of the sound pressure levels at these frequencies of low transfer. From these experiments, it becomes clear that the acoustic noise does not linearly depend on the input signal amplitude.

The frequency sweep experiments described in chapter 7 make use of only one sweep rate. The analysis of these data leads to the same conclusions as in chapter 6. The results are compared with the transfer functions derived with pink noise and pulses. With such signals, no discrimination can be made between first and second-order responses. Frequency sweep signals provide a good control over frequency and amplitude, in contrast to noise signals (amplitude) and pulse signals (frequency).

Not all parts of the scanner’s surface vibrate as much as other parts. By probing the scanner with one microphone at one location, no information on this phenomenon can be extracted. With laser Doppler interferometry the surface vibrations can be measured in a noncontact manner. When the complete scanner surface responses are known, the surface responses to gradient currents can be modelled. With this information, the sound field can be calculated, as sound pressure distributions. In chapter 8, the possible difficulties with laser Doppler measurements of scanner bore vibrations are discussed. After solving all technical difficulties, time seems to be the biggest constraint of such measurements.