MAGMA (2003) 16:52–55
DOI 10.1007/s10334-003-0005-9

RESEARCH ARTICLE

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Relationship between magnetic field strength and magnetic-resonance-related acoustic noise levels

Received: 29 July 2002
Accepted: 20 September 2002
Published online: 18 February 2003

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Abstract The need for better signal-to-noise ratios and resolution has pushed magnetic resonance imaging (MRI) towards high-field MR-scanners for which only little data on MR-related acoustic noise production have been published. The purpose of this study was to validate the theoretical relationship of sound pressure level (SPL) and static magnetic field strength. This is relevant for allowing adequate comparisons of acoustic data of MR systems at various magnetic field strengths. Acoustic data were acquired during various pulse sequences at field strengths of 0.5, 1.0, 1.5 and 2.0 Tesla using the same MRI unit by means of a Helicon rampable magnet. Continuous-equivalent, i.e. time-averaged, linear SPLs and 1/3-octave band frequencies were recorded. Ramping from 0.5 to 1.0 Tesla and from 1.0 to 2.0 Tesla resulted in an SPL increase of 5.7 and 5.2 dB(L), respectively, when averaged over the various pulse sequences. Most of the acoustic energy was in the 1-kHz frequency band, irrespective of magnetic field strength. The relation between field strength and SPL was slightly non-linear, i.e. a slightly less increase at higher field strengths, presumably caused by the elastic properties of the gradient coil encasings.

Keywords Acoustic noise · Magnetic field strength · Sound pressure level

Introduction

Acoustic noise production during magnetic resonance imaging (MRI) is a well-recognized issue of concern [1]. It has been demonstrated to cause, e.g. temporary shifts in hearing thresholds and disturbance of verbal communication [2, 3, 4]. Also, acoustic noise may affect image quality in functional MRI studies [5].

Various studies have reported on acoustic noise levels and on their relation to pulse sequences and imaging parameters for clinically used MR systems of up to 1.5 Tesla [2, 3, 6, 7, 8, 9, 10, 11]. However, the current trend in MRI is towards using high-field MR systems at which acoustic noise levels are thought to be elevated. Only a few studies, to our knowledge, report on noise levels for MR systems at 3 Tesla, restricted to echo planar imaging [12, 13]. However, for adequate comparison of the properties of MR-related acoustic noise, the influence of the magnetic field strength on acoustic noise should be known. Moreover, previous data on noise levels at lower magnetic field strengths may still be valuable if the relationship is used for cautious extrapolation.

The relation between magnetic field strength and acoustic noise, which according to theory is linear [14], has not been experimentally validated yet. This was the purpose of our study.

Theoretical prediction of the relation between magnetic field strength and acoustic noise

Acoustic noise is thought to be generated by bending and buckling induced by Lorentz forces (F) acting on gradient coils during MRI. The magnitude of these forces act-

Table 1 Imaging parameters of the pulse sequences tested

Sequence	Imaging parameters				
	TR (ms)	FOV (mm)	Matrix	Slice thick-ness (mm)	Number of slices/s
FSE	22	300	256×256	4	0.48
FLASH	7	300	256×256	6	0.54
EPI	600	315	128×128	3	1.67
tFISP	3.1	160	115×128	5	0.85

ing on a wire element with length *dl* is described by Eq. 1 [14]:

$$F = B_0 \times Idl \quad (1)$$

where B_0 is the magnetic field strength and I is the gradient current. The induced mechanical waves in the gradient-supporting structures are transferred into air, described by an acoustic transfer function, [15] resulting in airborne acoustic waves with pressure P. The linear sound pressure level (SPL), expressed in decibels (dB(L)), is the logarithm of the ratio of this pressure P to an international standardized reference sound pressure (P_0) of 20 micropascals, described in Eq. 2 [16]:

$$SPL = 10 \times \log\left(\frac{P}{P_0}\right)^2 \quad (2)$$

Therefore, theoretically, doubling the magnetic field strength (or the gradient current likewise) will result in a doubling of the sound pressure, holding an increase of 6 dB(L).

Materials and methods

Acoustic data were acquired using a Siemens Magnetom Vision magnetic resonance system (Erlangen, Germany) with a gradient hardware delivering a maximum of 25 mTesla/m gradients and with 85 Tesla/m/s slew rates (rise-time 300 μs), and by using an integrated quadrature-driven transceiver body coil. A Helicon rampable magnet was ramped in successive steps of 0.5 Tesla from 0.5 to 2.0 Tesla. Acoustic data were recorded for various pulse sequences, i.e. fast spin-echo (FSE), fast low-angle shot (FLASH), echo-planar imaging (EPI) and true fast-imaging with steady state (tFISP). All imaging parameters in a given pulse sequence were kept equal at the different magnetic field strengths (Table 1) and were measured for all slice slab orientations (axial, sagittal and coronal). This made it possible to preserve the acoustic environment properties while the magnetic field strength was varied in isolation. In addition, the cold-head refrigerator system of this MR system is quiet compared to the cryogen pumping system used in most MR systems, resulting in low background or ambient noise levels.

We measured continuous-equivalent, i.e. time-averaged over a 20-speriod, linear SPLs ($L(L)_{eq}$ in dB(L)), and 1/3-octave band frequencies. The experimental set-up was in compliance with ANSI-protocol S1.13–1995 of the Acoustical Society of America [16, 17], i.e. a vertical positioning of the microphone, as the acoustic environment of the MRsuite was thought to be diffuse [4]. Although possible interference of the MR environment with the measurement set-up has been shown to be negligible [4], recordings were made at 1.5 m from the imager bore in order to completely circumvent the magnetic field affecting the microphone (type 4189, Brüel and Kjaer, Naerum, Denmark). It is of note that the relative SPL changes at the various magnetic field strengths are not affected by the distance from the MR imager. The microphone was connected to the sound analyzer equipment (Investigator 2260, Brüel and Kjaer) using a 10-m extension cable (AO-0442, Brüel and Kjaer). Ambient acoustic noise was assumed to be negligible as its SPL was >10dB lower than the SPLs of the imaging pulse sequences during the actual experiments [16]. The experimental set-up was calibrated using an appropriate sound level calibrator (pistonphone type 4231, Brüel and Kjaer). In a short pilot study, we tested the accuracy of the acoustic data elucidated by repeatedly measuring SPLs for an FSE pulse sequence at fixed magnetic field strength. As these showed variations <0.5 dB(L), all recordings were made once.

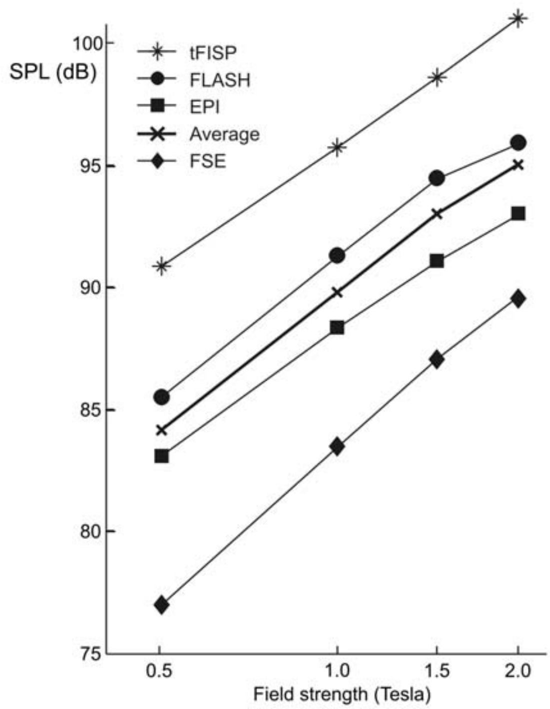

Fig. 1 Linear continuous-equivalent sound pressure levels (SPLs) at different magnetic field strengths for all imaging sequences measured and their average (*thick line*). The average curve increases 5.7 dB and 5.2 dB for magnetic fields strength increments of 0.5–1.0 Tesla and 1.0–2.0 eslaT, respectively. Magnetic field strength logarithmically scaled

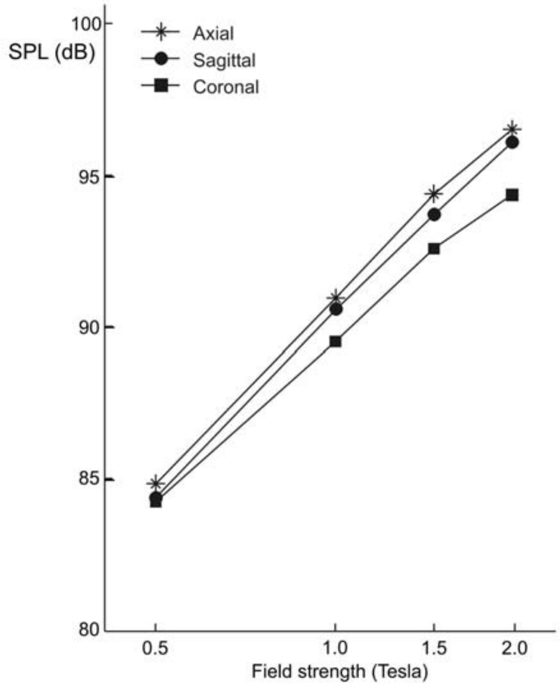

Fig. 2 Continuous-equivalent linear SPLs for sagittal, coronal and axial imaging as measured for all pulse sequences on average at different magnetic field strengths. Magnetic field strength logarithmically scaled

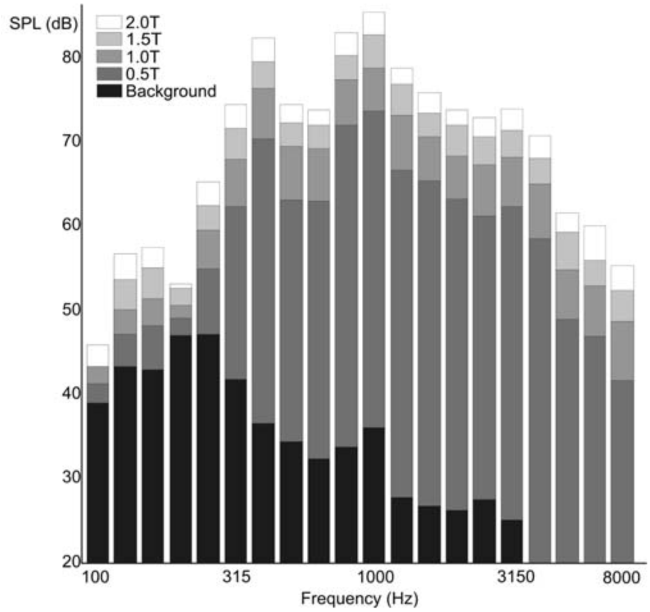

Fig. 3 Continuous-equivalent SPLs at 1/3-octave band frequencies for all pulses sequences tested (averaged). SPL differences are equal for magnetic field strength changes of 0.5–1.0 Tesla and 1.0–2.0 Tesla. Note the considerable contribution of ambient background acoustic noise to the SPL at 100 and 250 Hz

Results

The continuous-equivalent linear SPL had an almost linear relationship with the magnetic field strength on average (Fig. 1). The relation was slightly non-linear, with a smaller increase at higher field strength. Doubling magnetic field strength by ramping up from 0.5 to 1.0 Tesla and from 1.0 to 2.0 eslaT resulted in an average 5.7 and 5.2 dB(L) increase of SPL, respectively (p=0.27). This trend was similar for all but one sequence, i.e. the tFISP sequence. Moreover, an increase of about 6 dB(L) for doubling the magnetic field strength was measured for all slice orientations (Fig. 2); the average SPLs for the coronal, sagittal and axial slice orientations at 1.5 Tesla were 92.5, 93.6 and 94.2 dB(L) respectively.

Most of the acoustic energy was in the 1-kHz band, which did not substantially change with the magnetic field strength (Fig. 3). Moreover, for all 1/3-octave band frequencies, the above-described trend for the continuous-equivalent SPLs applied. At 100 and 250Hz, background acoustic noise SPLs were approximately equal to the SPLs of the actual MR sequences (about 40 and 50 dB(L) respectively), resulting seemingly in a lower increase of SPL with magnetic field strength.

Discussion

In this study, the rampable magnet of our MRI scanner (Siemens Magnetom Vision with Helicon rampable magnet) allowed us to carefully preserve the acoustic environment while changing the magnetic field strength in isolation. This is relevant for measurements of acoustic noise, as it has been demonstrated previously that the type of imager dominates the overall acoustic noise levels [9, 18], that is, the influence of the magnetic field strength on SPL might not adequately be elucidated by comparing various MR systems. The results of our experiments were in good agreement with what theory predicts, i.e. an increase of 6 dB(L) when doubling the magnetic field strength. As this was similar for all imaging protocols tested, it is likely that the trend applies in general, i.e. regardless of the pulse sequence. The small but insignificant flattening of 0.5 dB(L) may tentatively be explained by restriction of extreme movements of the gradient coils, probably caused by the elastic properties of the gradient coil encasings.

The frequency distribution of the pulse sequences tested was similar to that of previous reports [8, 9, 11, 12, 18]. Alterations of the frequency distribution were not expected a priori because of unchanged gradient current pulses and acoustic transfer function [15], which was substantiated with our results. The slightly non-linear relationship of SPL versus magnetic field strength suggests a restriction of extreme gradient coil movements which, in addition, would result in a reduction of high frequencies. However, we could not substantiate this hypothesis, because of: (1) the insignificant SPL reduction of only 0.5 dB(L), and (2) the rather coarse acoustic noise filtering in 1/3-octave bands.

It is of note that the magnitude of the Lorentz forces, producing the acoustic noise, is not dictated by the magnetic field strength solely. It can be appreciated from Eq. 1 that the gradient coil current *I* is equally important. In high-field MR systems, the gradient coil systems may encompass stronger gradients in order to circumvent, e.g. chemical shift and susceptibility artifact. Like the magnetic field strength, a two-fold increase of the gradient strength may elevate SPL by 6 dB(L). Also, simultaneous doubling of both magnetic field strength and gradient strength would result in a 12-dB(L) increase of SPL (Eq. 2). In conclusion, our results may be used for extrapolation of acoustic noise levels for more adequate comparison of MR systems at various magnetic field strengths.

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