Technical Note

MRI Acoustic Noise Can Harm Experimental and Companion Animals

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Purpose: To assess possible damage to the hearing of experimental and companion animal subjects of magnetic resonance imaging (MRI) scans.

Materials and Methods: Using animal hearing threshold data and sound level measurements from typical MRI pulse sequences, we estimated "equivalent loudness" experienced by several experimental and companion animals commonly subjects of MRI scans. We compared the equivalent loudness and exam duration to safe noise standards set by the National Institute for Occupational Safety and Health (NIOSH).

Results: Monkeys, dogs, cats, pigs, and rabbits are frequently exposed to equivalent loudness levels during MRI scans beyond what is considered safe for human exposure. The sensitive frequency ranges for rats and mice are shifted substantially upward and their equivalent loudness levels fall within the NIOSH safe zone.

Conclusion: MRI exposes many animals to levels of noise and duration that would exceed NIOSH human exposure limits. Researchers and veterinarians should use hearing protection for animals during MRI scans. Experimental research animals used in MRI studies are frequently kept and reimaged, and hearing loss could result in changed behavior. Damage to companion animals' hearing could make them less sensitive to commands and generally worsen interactions with family members. Much quieter MRI scanners would help decrease stress and potential harm to scanned animals, normalize physiology during MRI, and enable MRI of awake animals.

Key Words: health and safety; acoustic noise; animal MRI; companion animals; veterinary MRI
J. Magn. Reson. Imaging 2012; 36:743–747.

VERTEBRATE ANIMAL magnetic resonance imaging (MRI) is an important part of medical research, and veterinary MRI of companion animals is increasing. Human subjects are customarily provided with hearing protection against the loud, potentially damaging acoustic noise produced by MRI scanners (1); this is generally not done for animal MRI subjects. Hearing damage can interfere with physiological functions and consequent quality of life for research or companion animals (2). We investigate possible hearing damage to unprotected animals.

Pulsed gradients are basic to the MRI process, and the concomitant pulsed Lorentz forces applied to the gradient coils, gradient coil assembly, and metal cryostat situated in a static magnetic field produce vibrations that result in intense acoustic noise (1). This noise has been a problem for decades and constitutes a safety concern for patients, physicians, and health workers in the vicinity of MR imagers (3,4).

Following the introduction of clinical 1.5 T (and now 3 T) superconducting imaging magnets, increasingly powerful gradient electronics, and dense, multiplanar and multiecho pulse sequences, MRI systems now generate continuous acoustic noise with intensities in excess of 100 dB (5), well into the range of potential hearing damage as delineated by NIOSH (6). MRI acoustic noise is at levels sufficient to cause discomfort and possible damage to human hearing (5,7,8), is a cause of patient distress (9), and interferes with functional MRI (fMRI) and interventional MRI (10,11).

A lot of animal MRI is done in human clinical systems. In addition, small-bore MRI systems specifically designed for animal imaging have acoustic noise as loud as that in human systems (2), as animal MRI systems have equally powerful current pulses and often use higher static magnetic fields (leading to stronger Lorentz forces) than are the norm for human systems (12). The intense acoustic noise generated for animal MRI systems again creates a health risk for operators and researchers and, obviously, for animal imaging subjects, which often are not fitted for hearing protection (2).

Acoustic noise prevents an important area of animal MRI research, namely, MRI applied to conscious animals. While MRI is not in and of itself painful, intense acoustic noise would be painful to a conscious

Additional Supporting Information may be found in the online version of this article.

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Received August 16, 2011; Accepted March 5, 2012.
DOI 10.1002/jmri.23653
View this article online at wileyonlinelibrary.com.

animal. Thus, general anesthesia is necessary for restraint in the vast majority of animal studies. However, general anesthesia is associated with changes in many physiological parameters that we are attempting to investigate (13,14). Moreover, many of the truly sickest animal models are not good candidates for general anesthesia.

Smith (15) describes some of the needs for animal anesthesia as well as special requirements for anesthetic equipment and procedures in an MRI scanner environment. He points out that "sedation alone may be selected, however, even heavy sedation may be unpredictable in the noisy environment and a sedated patient may become stimulated unexpectedly" (page 102) (15).

MRI is used extensively in animal research and, increasingly, as a diagnostic tool in veterinary medicine (eg, 16), often with no hearing protection. Little if any consideration has been given to the effect of MRI scanner noise on animals. As with human subjects, however, loud sounds can potentially cause temporary or permanent hearing loss and stress. Effects of noise could be detrimental for research animals that will be used after scanning, or for companion animals that will be returned to owners.

Noise-induced hearing loss can impede functions that involve the auditory system, such as the ability to hear vocal communication signals and the ability to localize sound sources. Exposure of young animals, even to moderate levels of noise, can result in accelerated hearing loss later in life (17,18). High levels of acoustic noise during scanning could also affect the results of imaging studies since noise can affect metabolic, cardiovascular, and neurologic function (19). Although safe exposure standards have not been determined for most animals, it is important to consider that animals exposed to scanner noise may suffer hearing damage.

To study potential animal MRI adverse hearing effects, we measured sound levels produced by several animal scanning protocols in a commercial 3T scanner. Using hearing threshold data for several common research or companion animal species, we estimated weighted sound pressure levels and compared these to levels at which damage occurs in humans.

MATERIALS AND METHODS

Measurements

We used a Larson Davis LxT digital sound level meter (Larson Davis, Depew, NY) to measure sound pressure levels (SPLs) in dB (20) and spectra during MRI scans used for animal research imaging in a Philips Achieva 3 T clinical human scanner (Philips Healthcare, Best, Netherlands). A PCB model 375A02 (±2 dB) 1/2 inch microphone (PCB Piezoelectronics, Depew, NY) was oriented along the scanner z-axis and positioned at the scanner isocenter. The microphone was attached to the sound level meter with a 7.5-m extension cable. Overall sound pressure levels and third octave band levels (center frequencies of 20 Hz to 20 kHz) were measured using the Z frequency weighting function, which essentially applies no weighting. Sound levels were digitally logged every 1 second and later downloaded to a computer and analyzed offline.

Pulse Sequences

Here is a brief description of the five pulse sequences (PS) included in this work. More details can be found in Supporting Table S-1.

PS1. Multislice Turbo Field Echo (TFE). Survey scan (three planes) to view location of body or phantom in scanner.
PS2. 3D Fast Field Echo (FFE). Map coil sensitivity for parallel imaging or image sensitivity correction.
PS3. Multislice TFE, single plane. Imaging. Cardiac triggering set by scanner to one trigger per second.
PS4. 3D Spin Echo (SE). Imaging. Cardiac triggering set by scanner to one trigger per second.
PS5. TFE single shot. Interventional sequence running continuously to give real-time interactive imaging.

Calculating "equivalent loudness" noise levels

Hearing threshold data are available for numerous animal species. We derived threshold curves for several animal species and human subjects by curve fitting data from Heffner (21) with a second-order polynomial using Mathcad (PTC, Needham, MA).

We then calculated an estimated "equivalent loudness" (22) for each species and each pulse sequence (Table 1) by subtracting the interpolated threshold curve for the species from the measured (unweighted) spectrum for each pulse sequence. The overall equivalent loudness (*SPLeq*) for a particular pulse sequence and species was then derived by summing the spectral noise power components according to the formula:

$$SPLeq = 10 \cdot \log\left[\sum_i 10^{\left(\frac{SPL_i - Thresh_i}{10}\right)}\right] \qquad [1]$$

where SPL_i are the individual unweighted spectral SPL components in dB for a given pulse sequence and $Thresh_i$ are the interpolated threshold values for each species. In other words, the individual spectral component *SPLeqs* are converted to absolute power, summed, and the sum is converted back to dB.

This difference is technically called dB SL (dB above stimulus level) (23) and is essentially the way human acoustic weighting filters (eg, A-weighting) are derived (22).

RESULTS

MRI acoustic noise spectra typically have a broad peak, roughly centered at a few kHz (Fig. 1), which is in a sensitive region of human and animal hearing (21). Shown for comparison are the acoustic levels of a chainsaw (≈110 dB) and conversation (≈60 dB) (24).

The threshold curves for the several animal species and human subjects (Fig. 2) indicate that the pig is

Table 1
Estimated Equivalent Loudness (dB) for Human A-Weighted Hearing and Various Experimental and Companion Animals

Subject	PS1 Multislice TFE Survey, 3 planes	PS2 3D FFE	PS3 Multislice TFE, 10 sagittal slices	PS4 3D SE	PS5 3D TFE single shot, interventional
SPL, unwtd	111.5	109.5	111.5	115.9	113.9
SPL, A-wtd	112.1	109.5	111.6	116.0	113.9
Human subject	113.7	110.2	112.1	116.8	114.5
Japanese Macaque	108.5	105.5	107.4	112.3	109.8
Dog	101.4	97.2	99.0	104.9	101.8
Cat	113.6	109.6	111.5	116.8	114.1
Pig	96.8	94.2	96.2	100.8	98.5
Rabbit	100.7	96.1	97.8	103.9	100.7
Norway rat	85.2	77.2	79.6	91.2	86.4
Domestic mouse	66.5	57.3	65.4	76.4	71.6

Threshold hearing sensitivity for each species is a curve (Fig. 2, Fig. S-1) fitted to data taken from Heffner (21), including the "Human Subject" experimental data in row 3. Equivalent loudness is obtained by subtracting each threshold sensitivity spectrum from the unweighted noise spectrum for each pulse sequence (see Pulse Sequences in text and Table A-1).

the least sensitive (highest threshold curve) and humans and cats most sensitive. The most sensitive frequencies (frequencies of lowest threshold) for the pig, rabbit, dog, and cat are shifted upward relative to human hearing, which has minimum threshold at about 5 kHz. The Norway rat threshold minimum is shifted upward to about 13 kHz and the mouse minimum is ≈15 kHz. The A-weighting curve (human hearing) is somewhat flatter than the Heffner human threshold data curve (21).

The A-weighted SPLs of our five pulse sequences (Table 1, line 2) agree well with the equivalent loudness (Table 1, line 3) derived from the Heffner human threshold data (21).

SPLeqs for human subjects and all animals were above 95 dB on many scans and exceeded 100 dB for at least one scan, except for the Norway rat and the mouse. However, the SPL for the rat was above 90 dB for PS4. The dog threshold was an average from four individual dogs, one of which was about 10 dB more sensitive than the average (21). This indicates significant variations in hearing sensitivity that would be reflected in higher weighted *SPLeq* values for some dogs. These more sensitive individuals might therefore suffer more damage.

Our data were derived from a 3 T human clinical scanner. Presently, the most common clinical scanners operate at 1.5 T, for which noise levels would be 6 dB lower, still exceeding the NIOSH safety limits in many cases.

DISCUSSION

Acoustic noise produced by numerous MRI scanning protocols reach extremely high levels relative to animal hearing thresholds. The potential for noise-induced stress could have significant consequences for an animal's well-being and on research studies.

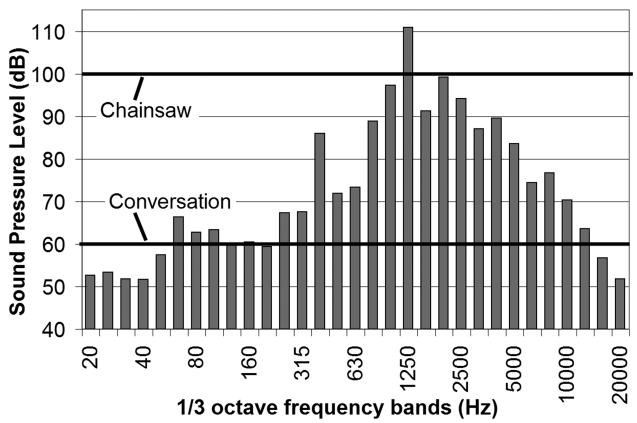

Figure 1. Unweighted MRI acoustic noise, represented as sound pressure levels (SPLs), for a range of 1/3 octave frequency bands. This spectrum was generated by a multislice TFE sequence used in an animal scan protocol. (PS1, Tables A-1 and S-1). The spectrum has a broad maximum roughly centered at about 1500 Hz.

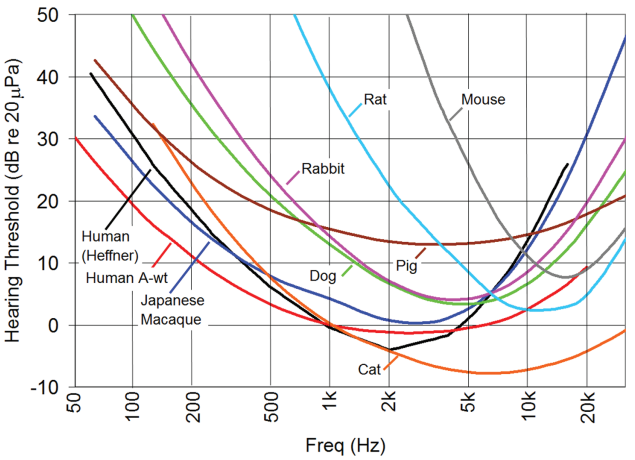

Figure 2. Hearing thresholds for humans and various animals fitted to data from Heffner (21) and A-weighting threshold function (22). Pigs are least sensitive, humans and cats most sensitive. Rat and mouse threshold curves are shifted substantially upward in frequency relative to human hearing and peak MRI acoustic noise. The threshold values in Fig. 2 are subtracted from the noise spectrum in Fig. 1 to give "equivalent loudness" (Table 1) for each species.

Thus, earplugs or ear muff sound protection should be used in all animal MRI sessions where hearing damage might result. We note that the effectiveness of earplugs, which are already used in some animal MRI studies, depends on proper fitting. Even properly inserted earplugs only provide approximately 20–30 dB of attenuation. Human subjects show altered cochlear function after MRI even when fitted with ear protection (25). Therefore, earplugs can help reduce the noise exposure levels during MR scanning, but earplugs alone may not be an adequate solution.

It is not possible to know precisely the levels of stress or damage that animals might suffer from exposure to MRI noise because safe exposure standards do not currently exist for nonhuman species. However, noise exposure has long been considered a public health risk for humans (26), and consideration of the risks to animals has also been attracting increasing attention (eg, the Acoustical Society of America Accredited Standards Committee S3 Subcommittee 1, Animal Bioacoustics (27)).

A variety of undesirable effects of noise have been demonstrated in laboratory and zoo animals, as recently reviewed by Morgan and Tromborg (28) and by LePrell (29). Noise-induced stress symptoms in animals, such as elevated heart rate, increased blood pressure, and altered metabolic rates (30) could affect the results of both acute and long-term imaging studies, particularly those investigating cardiovascular function.

The U.S. NIOSH has recommended human exposure limits for noise levels in order to avoid induced hearing loss (6). Similar effects are likely to occur in animals. NIOSH standards say that exposure time should not exceed 48, 15, 5, and 1.5 minutes for sound levels of 95, 100, 105, and 110 dB, respectively (6). It is apparent that supposedly "safe" noise levels, based on recovery from short-term hearing loss, can lead to long-term hearing degradation. If anything, such limits are set too high: there is no safety margin above them (17,18).

All animal species listed in this study except the rat and mouse may exceed some of the NIOSH standards in a 1-hour examination. Thus, it is important to use hearing protection, quieter pulse sequences, or quieter scanners for animal research or veterinary MRI.

Auditory effects of MRI acoustic noise exposure are a concern for several reasons. First, animals may experience inner ear pain or discomfort while being exposed to loud sounds, although pain thresholds for sound are difficult to obtain from animals. Animals might also experience hearing loss after exposure to loud MRI noise, depending on the level and duration of exposure. Temporary or permanent hearing loss could affect an animal's acoustic communication if their ability to detect or discriminate sounds is reduced.

For research animals that are kept for long periods (days, weeks, or months) after scanning, a compromised ability to hear other animals that are housed in a social environment could result in distress and resultant physiological alterations associated with increased circulating corticosteroids (31). Moreover, increased vocalization in animals with hearing loss is also possible.

Companion animals with cochlear damage might not respond to their owners' or family members' voices, might startle more easily and display aggressive behavior, or fail to hear warning sounds such as approaching vehicles (32). Even if cochlear damage is not permanent, exposure to loud sounds could result in tinnitus (33). Tinnitus can cause severe distress, depression, and anxiety in humans (34). Presumably, at least some animal species also experience tinnitus-related distress.

Animals are typically anesthetized to reduce noise-induced distress and pain while scanning is in progress. However, anesthesia alters bodily functions (13,14,35), which in turn can change research results. Anesthesia also reduces the auditory system's innate noise protection mechanisms, including the middle ear reflex (36,37) and the medial olivocochlear reflex (38,39). These effects may vary with the particular anesthetic, dosage, depth of anesthesia, and species.

Quieter scanning protocols, with slow gradient pulse rise and fall times (eg, 40), may also be used to reduce animals' exposure to MRI acoustic noise. However, this approach is not compatible with modern pulse sequences containing many closely spaced multiple echoes (eg, turbo spin echo (41)) that must be rapidly turned on and off to gain maximum signal-to-noise ratio and consequent high-quality data.

Much quieter MR imagers (eg, SPL $\leq$70 dB) would be a boon for animal as well as human imaging. A truly quiet animal MR imager would alleviate possible hearing damage for both animal subjects and human operators, improve validity of research results by decreasing stress on animal subjects, and might enable MRI of conscious animals.

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Table A-1
Pulse sequence description and parameters for pulse sequences used in this study

	PS Description	Function	TR (ms)	TE (ms)	FOV (mm)	Scan resolution x/y/z (mm)	Number of slices or 3D	Number of echoes	Motion synch	Rcvr coil
PS1	Multislice, Turbo Field Echo (TFE), 3 planes	Survey to view location of body or phantom in scanner	2.5	1.1	320x320x250	2.35/4/10	3 orientations 65 MS 2D	80	No	32 ch cardiac coil
PS2	3D Fast Field Echo (FFE)	Map coil sensitivity for parallel imaging or sensitivity correction.	4	0.59	600x600x405	10.71/15/15	3D	1	No	32 ch cardiac coil
PS3	Multislice, TFE, one plane, 10 sagittal slices	Imaging	2.8	1.35	240x240x60	1.5/3.12/6	10 sagital MS 2D	24	60 Hz cardiac triggered 1 heart phase	32 ch cardiac coil
PS4	3D Spin Echo (SE)	Imaging	968	31	76x38x10	0.15/0.15/0.25	3D 1.8 slice oversampling	9	60 Hz cardiac triggered 1 heart phase	6 ch cardiac coil
PS5	TFE single shot imaging	Interventional seq. run continuously, real time interactive imaging	1.99	0.96	350x241x8	2.73/2.73/8	1 slice 2D FFE	55	No	6 ch cardiac coil