Published in final edited form as:

Concepts Magn Reson Part B Magn Reson Eng. 2015 August ; 45(3): 107–114. doi:10.1002/cmr.b.21287.

A novel acoustically quiet coil for neonatal MRI system

Christopher M. Ireland^{1,2}, Randy O. Giaquinto¹, Wolfgang Loew¹, Jean A. Tkach¹, Ronald G. Pratt¹, Beth M. Kline-Fath³, Stephanie L. Merhar⁴, and Charles L. Dumoulin¹

¹Imaging Research Center, Department of Radiology, Cincinnati Children's Hospital Medical Center, 3333 Burnet Ave., Cincinnati, OH 45229, USA

²Department of Biomedical, Chemical, and Environmental Engineering, 601 Engineering Research Center, University of Cincinnati, 2901 Woodside Drive, Cincinnati, OH 45220, USA

³Department of Radiology, Cincinnati Children's Hospital Medical Center, 3333 Burnet Ave., Cincinnati, OH 45229, USA

⁴Division of Neonatology and Pulmonary Biology, Perinatal Institute, Cincinnati Children's Hospital Medical Center, 3333 Burnet Ave., Cincinnati, OH 45229, USA

Abstract

MRI acoustic exposure has the potential to elicit physiological distress and impact development in preterm and term infants. To mitigate this risk, a novel acoustically quiet coil was developed to reduce the sound pressure level experienced by neonates during MR procedures. The new coil has a conventional high-pass birdcage RF design, but is built on a framework of sound abating material. We evaluated the acoustic and MR imaging performance of the quiet coil and a conventional body coil on two small footprint NICU MRI systems. Sound pressure level and frequency response measurements were made for six standard clinical MR imaging protocols. The average sound pressure level, reported for all six imaging pulse sequences, was 82.2 dBA for the acoustically quiet coil, and 91.1 dBA for the conventional body coil. The sound pressure level values measured for the acoustically quiet coil were consistently lower, 9 dBA (range 6-10 dBA) quieter on average. The acoustic frequency response of the two coils showed a similar harmonic profile for all imaging sequences. However, the amplitude was lower for the quiet coil, by as much as 20 dBA.

Keywords

Acoustic noise; Magnetic resonance imaging (MRI); Neonates

Introduction

Acoustic noise

MRI exams are known to be loud. The gradient system is the primary source of acoustic noise associated with MR procedures. The noise occurs during the rapid alterations of

current within the gradient coil, in the presence of a strong static magnetic field, producing Lorentz forces that act upon the gradient coils. The Lorentz forces generated in the gradient coil radiate audible vibrations via direct and indirect pathways into the surrounding environment. These sound waves represent a safety concern since the acoustic noise can pose a significant risk of auditory impairment.

The acoustical output of an MRI scanner can be determined by measuring sound pressure levels during exams. Sound pressure level is typically measured in decibels (dB) or in A-weighted decibels (dBA) which incorporates the frequency sensitivity of the human auditory system. Sound pressure levels of 81-117 dB are common in clinical 1.5-T MRI exams, (1) but can be as high as 131 dB for high-speed acquisitions (2). Due to potential hearing loss from noise exposure, acoustic noise is an MRI safety parameter that is regulated by the U.S. Food and Drug Administration (FDA) under Occupational Safety and Health Administration (OSHA) guidelines. For standard clinical MRI exams, regulations require that peak unweighted sound pressure levels do not exceed 140 dB and that A-weighted root mean square SPL(s) do not exceed 99 dBA with hearing protection in place. Thus, hearing protection is required for MR scanning in order to comply with regulatory practices. This is typically accomplished with earplugs or noise attenuating headphones, which provide roughly 29-32 dB and 18-32 dB attenuation to noise exposure, respectively. However, these regulations and standard practices of hearing protection do not consider the unique circumstances of the neonatal MRI population.

Acoustic noise is a critical issue in neonatal MRI because it can elicit autonomic instability and, potentially, adverse noise-induced health effects in neonates (3-7). In addition, acoustic noise and transient sounds during scanning can cause startle reflexes from the patient thereby introducing undesired motion artifact degrading overall image quality. Regulatory guidelines on safe sound pressure levels for neonates do not exist (1), although *ad hoc* limits are frequently employed. Neonatal intensive care unit (NICU) acoustic noise exposure guidelines recommend that in order to avoid physiological stress, the maximum sound level to which a patient is exposed should not exceed 65 dBA(8). Passive hearing protection is typically a part of every neonatal noise reduction strategy with the use of foam earplugs and soft-shell earmuffs (noise reduction rating = 7-12 dBA). In practice, earplugs must be cut down to size for neonates, and proper insertion is difficult. Consequently, a combination of earplugs and soft-shell earmuffs are often used to maximize hearing protection during MR scanning. While the acoustic attenuation provided by combined devices is better than individual device use, it is typically less than the combined rating of the two due to mechanical coupling and transmission pathway attenuation limits. The difficulty associated with proper device fitting, in addition to, the inability of the neonate patient to articulate the effectiveness of acoustic noise reduction creates a measure of doubt when using passive hearing protection in this population. Thus, the only guaranteed way to reduce noise exposure for an infant undergoing MRI is to perform scanning more quietly.

Neonatal MRI system

A small footprint 1.5T MRI scanner for neonatal imaging was developed at Cincinnati Children's Hospital Medical Center, Cincinnati, Ohio (9,10). The scanner, situated within

the NICU environment, eliminates the logistical challenges of moving NICU patients to the radiology department for the exam, while providing diagnostic imaging capabilities of a conventional state-of-the-art system. While vibrotactile stimulation is a concern in conventional neonatal MRI, the mechanical design of the neonatal MR scanner avoids this issue by using a cantilever patient table to suspend the patient inside the bore, thereby eliminating direct coupling of coil vibrations to the patient. Acoustical characterization of the neonatal MR scanner compared to a conventional adult-size scanner demonstrates the acoustical output is on average 11 dBA quieter (11). Although the neonatal scanner is quieter than a conventional adult-sized scanner, NICU patients still require hearing protection if their exposure to acoustic noise is to be limited to 65 dBA.

The purpose of the present study was to develop a novel RF coil to attenuate the sound pressure levels experienced by the neonate inside the bore during MRI exams even further. Gains in acoustic attenuation achieved by the novel RF body coil, together with the inherent acoustical properties of the neonatal MR system, provide even quieter imaging.

Materials and Methods

Acoustic quiet coil

A unique feature of the neonatal MR system is the ability to exchange radio frequency (RF) body coils. Single channel transmit/receive volume coils with different inner diameters (ID) are available. To accommodate the largest range of neonate sizes, an 18 cm ID coil was chosen as a benchmark. In both adult-sized MR magnets and the NICU MRI system, birdcage coils are encased in a hard shell cylinder concentrically placed inside the gradient cylinder of the magnet bore. The properties of the cylindrical shell material and structure allow audible gradient vibration propagation and radiation through the body coil with little attenuation.

To reduce the acoustic noise propagated into the patient bore space of the magnet, a novel MR imaging coil was designed, constructed, and tested. The construction of the quiet coil minimizes the presence of hard material structures which can mechanically couple the gradient cylinder to the patient bore. While a conventional RF coil shell is typically constructed from a hard plastic polymer with low acoustic transmission loss, the acoustic quiet coil was constructed from a material with high acoustic transmission loss across the dominant frequency output spectrum of MR scanner. By constructing coils with sound abating material, for identical sequence and acquisition operating conditions, we anticipated the NICU system would be quieter when using these coils compared to the conventional system body coils.

A 16-leg high-pass shielded birdcage coil with an ID of 18 cm and length 47 cm was constructed within a custom built acoustic abatement former (Fig. 1). Mass loaded vinyl (MLV) (Acoustiblok Inc., FL, USA) was used as the substrate for the birdcage coil. This material was chosen based on bench top comparison tests of several sound abating foams and padding in its performance of acoustic attenuation, MR compatibility, and safety. The material is latex-free and meets fire safety standards MIL STD1623 and MVS 302, and is self-extinguishing.

The innermost layer of MLV (i.e. the layer closest to the patient) was laid down on an 18 cm mandrill. A 16-leg (leg length = 15.5 cm), 18 cm diameter birdcage coil etched onto 4 oz. copper clad FR4 board (0.25 mm thick) was then secured to the vinyl base with multipurpose adhesive (3M, St. Paul, MN, USA). Two coaxial cables ($\lambda/2$ length) interfaced the coil to the system. The coil was tuned and matched to proton frequency at 63.8 MHz. Subsequently, mass loaded vinyl was layered around the coil to build up the former diameter to fit inside the magnet bore. Additionally, three acrylic plastic rings were distributed in the middle of the former to retain the shape of the coil by reducing compressional load from the outer vinyl layers and to serve as attachment points to secure the inner vinyl layers. A radiofrequency shield (22.85 cm in length) was constructed from copper wire cloth and was placed under the final MLV layer.

Acoustic noise evaluation of the conventional body coil and acoustic quiet coil

We performed sound pressure level measurements on the pre-clinical NICU MRI scanner using both the acoustic quiet coil and a conventional 18 cm body coil. A Bruel & Kjaer model 2250 sound level meter (Bruel & Kjaer Sound & Vibration Measurement A/S, Denmark) was used to perform the sound pressure level measurements for six standard MR scans (spin echo, gradient recalled echo, echo planar imaging, fast radiofrequency spoiled gradient echo, balanced steady state free precession, and diffusion-weighted) using acquisition parameters consistent with clinical neonatal protocols (Table 1). For both MR coils, the microphone (Type 4192, Bruel & Kjaer Sound & Vibration Measurement A/S, Denmark) was placed at the isocenter of the bore. The MR sequences, acquisition parameters, noise measurement equipment and methodology were identical for the two coils. The average sound pressure level over a twenty second interval, in units of dBA, was recorded for each of the MR acquisitions and MR coil combinations. Frequency response functions of the acoustic noise, in units of dBA, on a one-third octave band over the range of 50-20,000 Hz was also documented. The sound pressure levels measured at the isocenter of the empty bore in this study were dictated by the hardware configuration, sequence type, and acquisition parameters being evaluated. As such, the sound pressure level measured for a given sequence and coil was expected to be constant across repeated measurements within the tolerance of the measuring device. Therefore, only one set of measurements was obtained for each sequence and body coil combination evaluated.

RF heating evaluation of acoustic quiet coil

A heating test of the coil was performed using high SAR pulse sequences (Fast Spin Echo sequence, TE/TR= 10/50 ms, FOV = 18 cm, slice thickness = 3 mm, matrix size = 256×256 , number of averages = 150, avg. SAR = 3.38 W/kg) run for 15 minutes. Temperature changes on the inner surface of the quiet coil adjacent to the coil's capacitors were measured using an MR-compatible fiber optic system.

Image quality evaluation of acoustic quiet coil

After completion of the acoustic noise evaluation and heating test, image quality was examined by conducting MR scans on a DQA phantom. A spin echo axial scan (TR/TE = 800/22 ms, FOV = 20 cm, slice thickness = 3 mm, matrix size = 512×512 , receiver bandwidth = 31.25 kHz, averages = 1) was performed with each coil on the pre-clinical

NICU MRI scanner. Imaging diagnostic software on the scanner was used to compare and evaluate the phantom images from the coils based on geometric fidelity and signal to noise (S/N) ratios. A T2-weighted fast spin echo axial scan (TR/TE = 5000/113.86 ms, FOV = 18 cm, slice thickness = 3 mm, matrix size = 384×224 , echo train length = 12, number of averages = 3 receiver bandwidth = 20.83 kHz) was performed with each coil on the NICU MRI scanner on a five day old, 3.5 kg, female neonate to evaluate image quality and performance. IRB approval and parent consent were obtained for the neonatal imaging study. The neonatal MR exam was performed nonsedated, using the “feed and swaddle” method (12,13) to promote sleep during the scan. Both ear plugs and mini muffs were used for hearing protection.

Results

Acoustic noise evaluation of the conventional body coil and acoustic quiet coil

The sound pressure level values measured for the acoustic quiet coil during each of the six MR acquisitions were consistently lower than those of the conventional coil of the NICU system (Table 2). The differences in sound pressure levels measured for the two coils were statistically significant ($P = 0.03$, Paired Wilcoxon signed rank test). On average, the scanner acoustic output located at isocenter with the acoustic quiet coil was approximately 9 dBA (range 6 – 10 dBA) quieter. For the 18 cm conventional body coil, the highest sound pressure level measured was for the balanced steady-state free precession sequence at 96.5 dBA. Likewise, for the acoustic quiet coil, the balanced steady-state free precession sequence measured the highest sound pressure level at 86 dBA. The frequency response measurements performed for each of the scan sequence and coil combinations evaluated are presented in Fig. 2. The measured sound pressure level as a function of frequency showed a similar harmonic structure between the two coils for all sequences. However, the amplitude was consistently lower for the acoustic quiet coil, by as much as 20 dBA.

Image quality and heating evaluation of the quiet coil

The Magnetic Resonance signal to noise ratios measured for the quiet coil was comparable to those of the conventional body coil (S/N= 112.6 quiet coil vs. S/N= 118 Conventional body coil). Phantom spin echo axial images for the conventional system coil and quiet coil presented in Fig. 3 (top-row) demonstrate comparable S/N and geometric fidelity. Similarly, the imaging performance of the quiet coil for the neonate was found to be essentially identical to the conventional coil (Fig. 3, bottom row). The heating tests showed a temperature rise of less than 3 °C, which is well within the safety limits for exposure to human patients.

Discussion

In this study a novel MR body coil constructed with Mass Loaded Vinyl was designed and constructed to reduce the noise exposure of infants during MR scanning. The acoustic noise properties of this novel coil were investigated and the coil was shown to be on average 9 dBA quieter. MR imaging tests in phantoms and human subjects show no significant difference in imaging performance.

Neonatal hearing is sensitive and high sound levels can cause the infant physiologic distress. Consequently, to avoid putting the infant at risk, the sound pressure levels to which a neonate is exposed should be minimized. While the neonatal MR scanner acoustical output is on average 11 dBA quieter than an adult-sized scanner, the new RF body coil former further reduces the acoustic noise experienced by the patient without compromise to image quality. By exploiting the system feature of a swappable RF body coil we have been able to substantially reduce the patient exposure to acoustic noise during MRI with a novel acoustic quiet coil.

The acoustic quiet coil is a robust way of attenuating acoustic noise during MRI examinations that does not require any changes to the imaging pulse sequence. It is patient-independent and can be used in addition to passive hearing protection practices for neonates. On average an extra 9 dBA reduction of acoustic noise can be expected from using the acoustic quiet coil. Using the acoustic quiet coil reduces the risk of hearing loss and physiologic distress to the infant even if the applied passive hearing protection is not properly fitted.

A critical requirement for the acoustic quiet coil is that image quality is not compromised. Imaging tests were made to assess the performance of the coil in comparison to the conventional body coil. Evaluation of the imaging tests reveals that the coil performed nearly identical (S/N within 5%) to the conventional body coil. No geometric distortions were observed, or expected, as the coil does not include any ferromagnetic components. In addition, the mass loaded vinyl structure did not itself produce any image artifacts as the material lacks an MR signal for the echo times employed in diagnostic imaging. Finally, the coil's mass loaded vinyl structure did not compromise RF power efficiency as the transmit gain (TG) was comparable between the two coils (TG difference < 1 dB).

While this study examined a novel RF body coil for a neonatal MR scanner, this approach, in principle, can be applied to large-bore magnets and provide similar benefit. However, the exact effectiveness on a specific system must be determined experimentally, since different scanners and magnetic field strengths produce different noise levels and noise profiles. The obvious benefit from using the acoustic quiet coil is the reduced exposure to potentially dangerous levels of sound. This approach on a larger magnet can also be beneficial in other sensitive patient groups, such as older patients with anxiety, or for functional MRI studies utilizing acoustic stimuli.

Conclusion

The results of the acoustic noise evaluation demonstrate that alternative RF birdcage formers can be designed to attenuate acoustic noise inside the scanner bore without compromise to image quality. The acoustic quiet coil was found to be on average 9 dBA quieter than the conventional body coil. This lower acoustic noise not only reduces the risk of hearing loss and physiological distress, but also increases the probability that the MRI exam can be performed without sedation.

Acknowledgments

The project described was supported by the National Center for Advancing Translation Sciences of the National Institutes of Health, under Award Number UL1TR000077.

References

1. Nordell A, Lunch M, Hoesch S, Hallber B, Aden U, Blennow M. The acoustic hood: a patient-independent device improving acoustic noise protection during neonatal magnetic resonance imaging. *Acta Paediatr.* 2009; 98(8):1278–83. [PubMed: 19432831]
2. Amaro E, et al. Acoustic noise and functional magnetic resonance imaging: Current strategies and future prospects. *Journal of Magnetic Resonance Imaging.* 2002; 16(5):497–510. [PubMed: 12412026]
3. Philbin MK, Taber KH, Hayman LA. Preliminary report: changes in vital signs of term newborns during MR. *Am J Neuroradiol.* 1996; 17(6):1033–6. [PubMed: 8791911]
4. Lasky R, Williams A. The development of the auditory system from conception to term. *NeoReviews.* 2005; (6):141–152.
5. Graven SN, J B. Auditory Development in the Fetus and Infant. *Newborn and Infant Nursing Reviews.* 2008; (8):187–93.
6. Graven SN. Early neurosensory visual development of the fetus and newborn. *Clin Perinatol.* 2004; 31(2):199–216. [PubMed: 15289028]
7. Graven SN, J B. Sensory Development in the Fetus, Neonate, and Infant. *Newborn and Infant Nursing Reviews.* 2008; (8):169–72.
8. White, R. Recommended Standards for Newborn ICU Design Report of the Seventh Census of the Seventh Census Conference on Newborn ICU Design Committee to Establish Recommended Standards for Newborn ICU Design. 2007. 2007; Available from: <http://nd.edu/nicudes/stan%2023.html>
9. Tkach JA, Merhar SL, Kline-Fath BM, Pratt RG, Loew WM, Daniels BR, Giaquinti RO, Rattan MS, Kones BV, Jones BV, Taylor MD, Tiefermann JM, Murphy EC, Wolf-Severs RN, LaRuffa AA, Dumoulin CL. MRI in the neonatal ICU: initial experience using a small-footprint 1.5-T system. *Am J Roentgenol.* 2014; 202(1):W95–W105. [PubMed: 24370170]
10. Tkach J, Hillman NH, Jobe AH, Loew WM, Pratt GR, Daniels BR, Kallapur SG, Kline-Fath BM, Merhar SL, Giaquinto RO, Winter PM, Li Y, Ikegami M, Whitsett JA, Dumoulin CL. An MRI system for imaging neonates in the NICU: initial feasibility study. *Pediatric Radiology.* 2012; 42(11):1347–1356. [PubMed: 22735927]
11. Tkach JA, Li Y, Pratt RG, Baroch KA, Loew WM, Daniels BR, Giaquinto RO, Merhar SL, Kline-Fath BM, Dumoulin CL. Characterization of acoustic noise in a neonatal intensive care unit MRI system. *Pediatric Radiology.* 2014; 44(8):1011–9. [PubMed: 24595878]
12. Mathur AM, Neil JJ, McKinstry RC, Inder TE. Transport, monitoring and successful brain MR imaging in unsedated neonates. *Pediatric Radiology.* 2008; 28:260–264. [PubMed: 18175110]
13. Windram J, Grosse-Wortmann L, Shariat M, Greer ML, Crawford MW, Yoo SJ. Cardiovascular MRI without sedation or general anesthesia using a feed and sleep technique in neonates and infants. *Pediatric Radiology.* 2012; 42:183–187. [PubMed: 21861089]

Figure 1.

Acoustically quiet coil: (Top) Layer view of coil construction, (Bottom Left) RF Shield placed underneath the final MLV layer, (Bottom Middle) Oblique view of complete coil, (Bottom Right) Side view of complete coil.

Figure 2.

Frequency response of the acoustic quiet coil and conventional body coil measured for each of the standard MRI sequences tested: (a) spin echo (SE), (b) gradient recalled echo (GRE), (c) balanced steady state free precession (bSSFP), (d) echo planar imaging (EPI), (e) spoiled gradient echo (SPGR), and (f) diffusion-weighted imaging (DWI).

Figure 3. MR images acquired with the acoustic quiet coil (left column), and a conventional body coil (right column). The top row compares phantom images from each coil under identical acquisition conditions. The bottom row compares neonatal images from each coil under identical acquisition conditions. The neonatal images were acquired from an unsedated 5 day old infant.

MR protocols used for the acoustic noise evaluation of the conventional and acoustic quiet coils.

Table 1

Sequence	TR(ms)	TE(ms)	FA(°)	FOV(mm)	Matrix	Slice Thickness (mm)	# Slices	Receiver Bandwidth ($\pm$ kHz)
SE - Axial	400	10	90/180	160	256 $\times$ 256	3	20	15.63
GRE - Axial	384	13	60	160	256 $\times$ 256	3	9	15.63
hSSPF - Axial	1.5	1.6	70	180	256 $\times$ 256	3	1	125
EPI - Axial	2,000	35	90	160	256 $\times$ 256	3	30	125
SPGR - Axial	384	1.5	60	180	256 $\times$ 256	3	9	125
DWI - Axial	6,000	67.6	90/180	180	256 $\times$ 256	3	32	125

Pulse sequences: *SE* spin echo, *GRE* gradient recalled echo, *hSSFP* balanced steady state free precession, *EPI* echo planar imaging, *SPGR* spoiled gradient echo, *DWI* diffusion-weighted imaging

Imaging Parameters: *TE* echo time, *TR* repetition time, *FA* Flip angle, *FOV* field of view

Table 2

The average sound pressure level in dBA recorded for each of the MR acquisition/MR coil combinations evaluated.

Coil/Sequence	SE	GRE	bSSFP	EPI	SPGR	DWI	Average
NICU 18 cm Coil	80.2	83.1	96.4	91.9	85.7	90.9	91.1
NICU Quiet Coil	70.4	73.0	86.1	83.2	76.0	85.1	82.2

Pulse sequences: *SE* spin echo, *GRE* gradient recalled echo, *bSSFP* balanced steady state free precession, *EPI* echo planar imaging, *SPGR* spoiled gradient echo, *DWI* diffusion-weighted imaging