A real-time data acquisition and control of gradient coil noise for fMRI identification of hearing disorder in children with history of ear infection

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Abstract: Early ear infection and trauma, from birth to age 12 are known to have a significant effect on sensory and cognitive development. This effect can be demonstrated through the fMRI study of children who have a history of ear infection compared to a control group. A second research question is the extent to which brain plasticity at an early age can reduce the impact of infection on hearing and cognitive development. Functional Magnetic Resonance Imaging (fMRI) provides a mapping of brain activity in cognitive and sensory regions by recording the oxygenation state of the local cerebral blood flow.

The gradient coils of fMRI scanners generate intense acoustic noise (GCN) - to which the subject is in close proximity - in the range of 90 to 140 db SPL during the imaging process. Clearly this noise will impress its signature on low level brain response patterns.

An Active Noise Canceller (ANC) system can suppress the effect of GCN on the subject's perception of a phonetic stimulus at the phoneme, word or phrase level. Due to a superimposition of the frequency and time domain components of the test signal and GCN for MR test, the ANC filtering system performs its function in real time - we must capture the brain's response to the test signal AFTER the noise has been removed. This goal is achieved through the application of field programmable gate array (FPGA) technology of NI LabVIEW.

The presentation (in the noisy fMRI environment) of test words and phrases to hearing impaired children can identify sources of distortion to their perceptual processes associated with GCN. Once this distortion has been identified, learning strategies may be introduced to replace the hearing function distorted by early infection as well as the short term effect of GCN. The study of speech cognition without the confounding effect of GCN and with the varying level of GCN for a repeated test signal at later age can be allowed to a measure of recovery through brain plasticity.

Key Words: Functional Magnetic Resonance Imaging (fMRI); gradient coil noise; active noise canceller; LabVIEW; real-time data acquisition



Submitted Jan 10, 2013. Accepted for publication Feb 14, 2013. doi: 10.3978/j.issn.2223-4292.2013.02.01 Scan to your mobile device or view this article at: http://www.amepc.org/qims/article/view/1589/2207

Introduction

Comparison of differences between fMRI data with or without activation (1-20)

A typical fMRI experiment incorporates a paradigm or

stimulus designed to localize relative differences in brain activity between active and baseline tasks. Because of the complexity of brain function, paradigms must be carefully designed to reliably modulate an isolated active or affective component. The process of analyzing fMRI data to an Quantitative Imaging in Medicine and Surgery, Vol 3, No1 February 2013



Figure 1 Approximate locations of Broca's area and Wernike's area

extent and magnitude of the brain's response to a stimulus or behavioral task can be divided into three different steps. First, data is analyzed statistically for changes in the MR signal level that are temporally correlated with the changes in the imposed paradigm. Second, a statistical threshold is used to distinguish the "inactive" regions of the brain (i.e., those demonstrating MR signal changes that are more consistent with noise) from the active brain regions responding to the conditions of the paradigm. Finally, the results of the activation analysis are registered to high-resolution structural images, which are used to more accurately determine the brain structures involved in the activation task. Hence, the quantitative differences are measured through brain activity between active and baseline tasks depending on the condition of ANC-off or -on for auditory stimulus. These changes in the MR signal level occurred in two areas of Broca's Area (Brodmann's Area 44, 45), which is the expressive speech area, activated by covert or overt word production, and Wernicke's Area (Brodmann's Area 22), which is in charge of reading texts to the patient from material that predominantly contains concrete nouns in Figure 1.

Origin and significance of gradient coil noise for phonetic perception in children during fMRI test

The acoustic noise generated by the fast and ultra-fast pulse sequences has become an important issue in fMRI through the audio stimulus. This noise stimulates the auditory nervous system, limiting the dynamic range for stimulus driven activity in functional MRI (fMRI) experiments, can influence other brain functions as well as increase patient stress (3-14), and ultimately reduce MR image quality by the detrimental effects of high acoustic levels on speech communication between patients and health care work. In particular, there are observable differences in fMRI activity on certain areas of the brain that have medical problems concerning early hearing development. For these reasons, several investigations are studied to reduce the variation of a noise level to a patient for magnetic scanning procedures (15-17). Hence, as a clinical application, this paper addresses these technical principles of ANC to research hearing in listeners. The goal of which is to optimize outcomes for hearing impaired children and to develop methods of auditory training that will be applicable to the treatment of a broad range of hearing problems, from middle ear disease to profound deafness. The acoustic noise generated by MRI systems arises from the ancillary equipment, which includes a pump for liquid helium used to supercool the image's permanent magnet, a fan for supplying ventilation to the patient, and also an air-handling equipment for the image room. The highest-level noise, however, is intermittent and is produced whenever an image is acquired. In order to generate images, MRI uses both the static field of a permanent magnet and temporally varying magnetic field gradients, which are three sets of gradient coils that produce the frequency-encoding gradient pulses, the phaseencoding gradient pulses, and the slice-selection gradient pulses. Thus, in this paper, acoustic noise generated directly or indirectly by the action of the gradient coils will be referred to as "gradient coil noise" (18). This gradient coil noise results from the rapid switching of pulsed gradient magnetic fields used to gain fast imaging. The electrical current applied to the gradient coils in the main static field induces the Lorentz forces that physically excite the structural components of the MRI scanner and surrounding structures. In other words, the structural excitation effectively turns the MRI system into a loud speaker (through structurally acoustic coupling with the surrounding air) (19,20). The magnitude of structural vibration that directly cause acoustic noise radiation depends on the magnetic field strength, gradient strength, scanner structure and geometry, spatial setting and the frequency and waveform of the switching current (21). Thus, as scanners with higher fields are introduced, problems of noise produced during scanning will increase. In particular, all of the previous fMRI studies used protocols based on echo-planar imaging (EPI) sequences, a high-speed imaging method that involves rapid (e.g., 1 KHz) gradient switching because they provide image acquisition of a volume using just a few slices, such as



Figure 2 Physical components of a single-channel feed-forward adaptive ANC controller. Where, x(t) is a noise whose wave form travels through a primary path; M(s) is a transfer function of x(t); d(t) is a sound of noise x(t) at a particular point in space; x(n) is sampled electrical signal of a reference microphone; y(n) is an output signal of an adaptive filter; d'(t) is the control sound wave that destructively interferes with the incident wave d(t); H(s) is the transfer function of the output path including the delays introduced by the propagation; e(n) is the residual sound, detected by the error microphone, to update the characteristic of adaptive filter

16 or 32. Hence, echo-planar imaging (EPI) sequences, in most cases, is the loudest sequence and then acoustic noise of gradient coil during EPI-based fMRI is recommended (22-24).

Noise control techniques of Gradient Coil Noise for phonetic perception

For the first gradient coil noise control techniques, passive noise control is considered. It means adsorption and damping of gradient coil noise by a routine use of earplugs, headphones of ear defenders, and lining the scanner bore with sound-absorbing foam. However, there are some problems such as potential temporary hearing loss, which means the hamper of verbal communication with patients during the operation of the MR system, and the sensitivity to patient movement because standard ear mufflers and plugs are uncomfortable on the ears of infant patients. Also, it has a non-uniform noise attenuation over the hearing range, that is, efficient at high-frequency over 500 Hz, but poor at low-frequency since wavelength of gradient coil noise is much greater than the thickness of typical acoustic absorbers. Low frequency sound of gradient coil is transmitted from one space to another and through different materials (25). In addition to these limitations, since such methods provide only up to 40 dB of attenuation,

the scanner noise still achieves levels of 70-120 dB SPL at the listener's ear. For more efficient decrease of gradient coil noise for fMRI, it is better to use the Active Noise Canceller (ANC). This ANC is based on an active noise cancellation ("anti-noise") technique with the existing audio system and introduces anti-phase noise to interfere destructively with the noise source when it is implemented with the adaptive filter, it makes the system minimize the error signal power, using a feed-forward noise control algorithm in order to attenuate the sound of MRI system-generated acoustic noise with a real-time data acquisition (26-28).

In *Figure 2*, the feed-forward noise control for MRI system consists of a reference microphone placed close to the noise source to gain an electrical version of noise, an advanced and filtered noise through the control loudspeaker for noise reduction, and an error microphone, which is close to the listener's ear and provides an electrical copy of the reduced noise (27). This control is more reasonable than the feed-back control for application in fMRI for two reasons. First, the availability of the advanced reference signal compensates for the delays by the distance between the control loudspeaker and the error microphone, and then extends the maximum frequency sufficiently to reduce high-frequency EPI gradient coil noise, while the upper frequency of control for feed-back system is commonly



Figure 3 STAX headphone/driver and block diagram of the fitted ANC

limited to a few hundred Hz. This limitation is significantly below that required for fMRI, as significant acoustic energy of an EPI pulse sequence is located at frequencies as high as 3-4 KHz. Second, the different microphone for reference signal from the error microphone can separate the noise sound of scanner from the stimuli of interest, while there is only one input to a feed-back control (microphone placed close to the ear). This microphone would pick up both the scanner sound and the stimuli of interest, and so the noise control system would attempt to cancel both signals. In addition, the electrical wave from applied to the MR scanner is computer generated and the same gradientdrive signal is repeated for each volume acquisition. Hence, the acoustic scanner noise is relatively stable in the time domain, in spite of slow change of the amplitude of the wave over time. According to these facts, the filter x(n) with an adaptive filter provides active noise cancellation with the required frequency and phase shaping of the reference signal. Thus it produces an output signal y(n), which becomes the control sound wave d'(t) through control loudspeaker and destructively interferes with the incident wave d(t) (28-31).

Materials and methods

ANC system requirements

The fMRI gives the means through local brain metabolic

activity to study a healing at cognitive level as well as the sensory level of a left hemisphere of the cerebral cortex (Wernicke's and Broca's area). Both active and absorptive sound cancellation must be employed to detect its effects on hearing impaired children of early childhood infection and pathology in the adult (29).

The MRI magnetic environment precludes the use of magnetic or conductive microphones or receivers in the subject's ears. So called, the headset is constructed from commercially available electrostatic headphones, which are non-metallic, combined with standard industrial Bilsom ear defenders as shown in Figure 3. Specially designed inthe-ear receiver-STAX ceramic elements are fitted to ear defender absorptive headsets. Also, gradient coil noise inside headphones is converted to electrical wave from which passes through an amplifier and error microphone to produce e(n) for updating the characteristics of the adaptive filter. Since feed-forward control of the ANC system employs a reference signal as input and relies only on the error signal in order to synthesize an input signal and the ANC system, the primary noise should be captured before reaching the error microphone and should be used as input to the ANC system (26). Also, there are two inputs to the ANC system. These input signals come from reference and error signal microphones, which are placed near gradient coil and inside the Bilsom ear defender. The reference and error microphones are omni-directional electret condenser microphones of the Parasonic product (WM-52B and WM-60A) (32) and connected to the Pre-Amplifier for the stereo electret microphone by an Op-Amplifier of NE5532.

Prototype of ANC system (32-39)

The ANC system consists of two main parts. One is the fMRI SR-003, electrostatic headphone, of the STAX with standard BILSOM ear defenders. The other is an electret microphone in the head set which will collect gradient coil noise to be actively subtracted from the desired test signal in the human subject's ear as shown in *Figure 4*.

This residual sound of gradient coil noise, detected by error microphone, is sampled by the DSP parts of the LabVIEW program to produce the error signal e(n) via amplifier and the input module of NI9215 on cDAQ-9172 or cRIO-9104 of NI chassis, which is simultaneously connected with the reference microphone placed close to the gradient coil noise source, while the analog output module of NI9263 is used for generation of anti-phase



Figure 4 Prototype of the adaptive ANC system for fMRI



Figure 5 A block diagram of the adaptive ANC system for fMRI

noise and filtered signal from the adaptive filter as shown in *Figure 5*.

Results and discussions

Analysis of GCN for ANC system

For a detailed and confirmative analysis of frequency response of gradient coil noise, both power and FFT spectrums are obtained from gradient coil noise of eight cycles on the timeand the frequency-domain using MatLab and SimuLink programs of Mathworks. The spectrogram of eight burst of gradient coil noise is represented in eight seconds over the same frequency range of the y-axis. The contour of colored bar in spectrogram varies by the level of the amplitude of gradient coil noise of the eight cycles for eight seconds. These repeated contours of eight white colored bars show a specially measured signal at a singular frequency about gradient coil noise. That is, each white colored bar stands for the peak value at the specific frequency about 1,000 Hz on FFT spectrum and 1,066 Hz on power spectrum. The line of waveform around 1,000 Hz of frequency axis becomes much thicker and stronger than another case of



Figure 6 Gradient coil noise of eight-cycle. A. Waveform in time domain; B. Spectrogram; C. Frequency spectrum; D. Power spectrum

the previous burst, due to the repetition of the gradient coil noise as shown in *Figure 6*.

Analysis of signals of ANC system using adaptive filter

An operation of ANC is tested under a simultaneous input of the recorded data of gradient coil noise and audio signal as way files. The reference microphone is placed to collect the noise source of gradient coil, and then its output signal passes through the band pass filter and digital noise filter of the FIR and is added with audio signal of the stimulus. Finally, it becomes a noisy signal and is sent to the input of the desired signal of the LMS adaptive filter after recording by the error microphone. In company with an input of desired signal, which contain gradient coil noise and audio signal, the only gradient coil noise is connected to input port of LMS filter as a reference signal. The step size, representing the value of µ, is set to 0.0002 of slow adapt in order to stabilize the LMS adaptive filter. After passing the LMS adaptive filter, the original audio signal of the stimulus, which is defined as the original signal before the LMS adaptive filter, and then including a decreased

gradient coil noise, is output as a filtered signal to speaker and m file of MatLab's workspace. The first waveform of Figure 7A represents an original signal of audio stimuli before adding with noisy source of gradient coil noise. This original signal consists of eight bursts of eight words. The secondary obtained waveform of Figure 7B is called the noisy signal after band pass and FIR filter and before the LMS adaptive filter. This signal contains gradient coil noise and audio signal, due to collection by the error microphone inside an ear defender for a real-time operation of fMRI, and is replaced with adder under the testing of ANC of the SimuLink. As like the original signal, the noisy signal is repeated and measured up to two times in a row. As a final result of ANC, the filtered signal of Figure 7C is measured as the audio signal, including a decreased gradient coil noise from output port of the LMS adaptive filter of ANC.

As shown in *Figure* 7, the amplitude of gradient coil noise is gradually decreased, depending on a passing time of operation by the LMS adaptive filter of ANC. In other words, error response of the LMS adaptive filter is getting more stable as the difference between the error of an incoming and outgoing noise to ANC becomes smaller



Figure 7 The resulting signals (in Volt) of ANC system using adaptive filter. A. Waveform of original signal; B. Waveform of noisy signal; C. Waveform of filtered signal

value. In contrast with a decreasing of noisy source of gradient coil noise, the amplitude of audio signal for stimuli is not changed during working of the LMS adaptive filter of ANC. At the second stage of repetition of the same audio signal and gradient coil noise, the decreased level of gradient coil noise becomes even larger than one of the first stage of gradient coil noise. The resulting signals of ANC is analyzed to check a performance of the LMS adaptive filter. Each signal of the LMS adaptive filter is distributed over 90 seconds of x-axis and ± 0.5 V of y-axis. According to the result from the following *Figure* 7, the amplitude of gradient coil noise is dropped from ± 0.4 to ± 0.1 V after the LMS adaptive filter of the active noise canceller (ANC). Consequently, the decreased level is about a magnitude of about 0.6 V. As the processing time of data for the LMS

adaptive filter diminishes a delay of filtering for gradient coil noise, the speed of decline of noisy source becomes faster and the reducing magnitude of the gradient coil noise grows larger over the operating time period of the ANC.

Comparison (in dB) of signals of ANC

These waveform show a magnitude of each signal in dB level after obtaining wav files from ANC. As shown in *Figure 8*, the gradient coil noise is dropped up to 10 dB at a beginning of the ANC, and then is reduced up to 17 dB of maximum level at 90 seconds after work of the LMS adaptive filter. This means that the LMS adaptive filter uses an incoming noise level, guess a noise value on output signal, and decreases a noisy source of outgoing signal.

Spectrogram and spectrum of signals of ANC system

The spectrograms are used to analyze color-based visualizations of the evaluation of the power spectrum of an audio signal as this signal is swept through time. By comparison spectrograms with spectrums, the noisy source of the filtered signal is verified to decrease in a specific frequency over period of time. *Figure 9A* and *Figure 10A* display an actual audio signal over 90 seconds before the LMS adaptive filter. *Figure 9B* and *Figure 10B* indicate the noisy signal which contains the actual audio signal between the repeated gradient coil noise before passing the LMS adaptive filter, while *Figure 9C* and *Figure 10C* are respectively a spectrogram and a spectrum of the filtered signal after passing the LMS adaptive filter. Indeed, they express the decreasing of gradient coil noise as a noisy source with a color-based visualization.

Consequently, the comparison between signals of ANC is summarized as the following.

(I)The original signal over 90 seconds

When comparing the spectrogram of *Figure 9A* with the waveform of *Figure 7A* of the original signal, the colorbased bar of the audio signal exists on the spectrogram, relying on a variation of audio signal of the waveform over the time-axis. More specifically, a succession of audio signals over time causes a production of color-based bars on the time axis of the spectrogram.

(II) The noisy signal over 90

The variation of amplitude on the waveform in *Figure 7B* conforms with the color-based visualization on the time axis of the spectrogram in *Figure 9B*. An alternation of the repeated bursts of gradient coil noise results in a same change of the shape of the color-based bar. In addition to this variation of gradient coil noise, the spectrogram shows a dark color-



Figure 8 The resulting signals (in dB) of ANC system using adaptive filter. A. original signal; B. noisy signal; C. filtered signal



Figure 9 The resulting signals (in spectrograms) of ANC system using adaptive filter. A. original signal; B. noisy signal; C. filtered signal



Figure 10 The resulting signals (in spectrums) of ANC system using adaptive filter. A. original signal; B. noisy signal; C. filtered signal

Table1 The testing condition on sequences of Figure 11					
Turning-	on/off(o/x)	on/off(o/x)			
ANC	0	0			
GCN	0	0			
Audio	х	0			
Headphone	х	х			

based band at about 1,000 Hz over frequency axis and implies an existence of a peak value of gradient coil noise around 1,000 Hz frequency over the repeated elapse of time axis.

(III)The filtered signal over 90 seconds

According to the spectrogram of the filtered signal of *Figure 9C*, the color-based visualization for the gradient coil noise becomes faint and the dark color-based band reaches around a frequency of 1,000 Hz for the peak value and disappears over the elapsed time. This outcome results from an effect of the ANC and is reliable on the short-term interval of performance of the LMS adaptive filter. Finally, it's confirmed that the LMS adaptive filter of the ANC eliminates the gradient coil noise from audio signal, which is

measured at the error microphone, selectively and effectively.

Configuration of ANC system for a real-time working of the LabVIEW

For an improvement of time delay in a performance of ANC using the SimuLink of Mathworks, the LabView program of the National Instrument is practically used to design and test for a fast operation of the real-time operation of the ANC system.

A performance of ANC system on connection-off of headphone

This is an experiment which is performed after the ANC system is turned on which is involved with the operation of connection-on and -off of the headphones, and includes waveforms of the audio signal with gradient coil noise on error and reference microphones.

As shown in *Figure 11* according to the *Table 1*, the case in which the headphones are not connected, contains an interference of gradient coil noise from the external condition for both of error and reference microphones.



Figure 11 Waveforms of audio signal with gradient coil noise before a passing of the FxLMS adaptive filter of the ANC on connection-off of headphone

In particular, the higher amplitude of gradient coil noise hinders the error microphones from catching the audio signal during a simultaneous input of audio signal and gradient coil noise, and appears on both of the microphones in spite of an operation of the active noise canceller.

The *Figure 12* is obtained after a passing of the FxLMS adaptive filter of the ANC from the error microphones. Finally, the audio signal of the error microphones, interrupted by the interference of the higher amplitude of



Figure 12 Waveforms of audio signal with gradient coil noise after a passing of the FxLMS adaptive filter of the ANC on connectionoff of headphone

gradient coil noise, is acquired after passing the FxLMS adaptive filter under the same condition of the previous testing in *Figure 11*.

This signal is defined as the filtered output signal from the FxLMS adaptive filter and is similar to the original audio signal before overlapping the gradient coil noise. As a result, in spite of the headphones being unconnected, the noise without the shielding effect of headphones due to the ear defender against the environmental noise, the amplitude of gradient coil noise from the audio signal is remarkably decreased after a passing of the FxLMS adaptive filter during a turning-on of the ANC system.

A performance of ANC system on connection-on of headphone

This case is an experiment after the operation of the ANC system under a simultaneous input of audio signal and gradient coil noise to each of the microphones, except that headphones are connected and unlike in the previous experiment.

Figure 13 Waveforms of audio signal with gradient coil noise before a passing of the FxLMS adaptive filter of the ANC system on connection-on of headphone

Table 2 The testing condition on sequences of Figure 13					
Turning-	on/off(o/x)	on/off(o/x)			
ANC	0	0			
GCN	0	0			
Audio	х	0			
Headphone	0	0			

In contrast to the previous experiment, the headphones are connected and the error microphones of *Figure 13*, obtained from the *Table 2*, display only audio signal while the reference microphones of *Figure 13* continue to show gradient coil noise. This means that the BILSOM ear defenders, covering the STAX headphones, function as the passive noise reducer and protect the high frequency component of gradient coil noise from interfering with the audio signal on the error microphones. On the other hand, the output filtered signal from the FxLMS adaptive filter of ANC differs from the previous one in which the



Figure 14 Waveforms of audio signal with gradient coil noise after a passing of the FxLMS adaptive filter of the ANC system on connection-on of headphone

headphones are unconnected and shows a complete removal of component of gradient coil noise in *Figure 14*.

Consequently, under the operation of the ANC system, the decreased low level of gradient coil noise, reduced by the BILSOM ear defenders to some extent, is dramatically eliminated from the STAX headphones for the usage in fMRI. Moreover, a combinational operation of the passive noise reduction from the ear defenders and ANC system by the FxLMS adaptive filter is effective to extract the noising source of gradient coil to interrupt the stimulus of audio signal for the fMRI.

Results of the ANC system for a real-time operating of the LabVIEW

With a configuration of ANC by data processing of FxLMS adaptive filter using the NI LabView program and cDAQ-9712, the filtered signal, which is removed the gradient coil noise of an unwanted signal, is displayed as the waveform on the front panel of the NI LabVIEW program. In addition to the output, this filtered signal is regenerated via the speaker and the analog output module of NI 9263 with a real-time. Also, it is provided that a quantitative temporal and spectral description of the raw data of a recorded gradient coil noise to be used for analysis of the specific noise sources in the fMRI environment and particular GCN in the imaging



Figure 15 The original signal and the Gradient coil noise on FPGA. A. The original audio signal; B. Gradient coil noise

Table 3 The testing condition on sequences of Figure 15					
Number of	Audio Signal	Audio Signal	Headphone		
sequence			connection		
[1]	on	off	off		
[2]	on	on	off		
[3]	on	on	on		
[4]	on	off	on		
[5]	on	on	on		
[6]	on	on	off		
[7]	on	off	off		
[8]	on	on	off		
[9]	on	off	off		
[10]	off	off	off		

pulse sequence. The describing characteristics and features of the noise that have direct implications for noise control of fMRI test, are examined by relationship between gradient coil noise and gradient noise activity to stimulating audio signal. This is essential information for understanding the mechanisms of noise generation and examining possibilities for noise reduction using the ANC system and passive noise reducer with a sealant of ear defender.

Configuration of ANC system on NI LabVIEW FPGA Module

In order to apply the ANC system to the fMRI with a realtime noise reduction, the NI CompactRIO system (NI cRIO-9004), which is powered by the National Instruments LabVIEW FPGA and LabVIEW Real-Time technologies, is considered to improve the performance and the speed of the ANC system and to secure a huge size of memory for data processing of the different values between the previous, the present, and the next data of FxLMS adaptive filter for a proper and fast operation of ANC in time-varying gradient coil noise of fMRI experiments.

The original audio signal and GCN on Error and Reference Microphones

The waveforms of *Figure 15* show the distortion of the audio signal of the error microphones depending on the providing of gradient coil noise of the reference microphones on analog input module NI9215.

The waveforms of the original audio signal and gradient coil in *Figure 15* are obtained from the FPGA target under the sequences of testing condition in the following *Table 3*.

As shown intervals of [2], [3], [5], [6] and [8] sequences of the *Figure 15*, the waveform of the original audio signal is distorted by an interference of gradient coil noise under a testing condition of both connection-on and -off of the headphones. On the other hand, the original audio signal is collected by the error microphones without damage under no gradient coil noise on certain intervals of [1], [4], [7] and [9] of the *Figure 15*.

Audio signal and GCN on the FPGA Target for connection-off and -on status of headphones

For a purpose of confirmation for a real-time application

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Figure 16 Analysis for a real-time application of ANC system by NI LabVIEW FPGA module. A. original audio signal; B. Gradient coil noise; C. regeneration of the filtered signal

Table 4 The testing condition on sequences of Figure 16					
Number of	Audio signal	Gradient coil	Headphone		
sequence	Audio Signai	noise	connection		
[1]	on	off	off		
[2]	on	on	off		
[3]	on	off	on		
[4]	on	on	on		

of the ANC system by NI LabVIEW FPGA module, the waveforms of *Figure 16* is considered during a connectionoff and -on status of headphone in the following *Table 4*. The *Figure 16A* and *B* shows the original signal with or without gradient coil noise of the error microphones and the gradient coil noise of the reference microphones on FPGA target. While both of the two waveforms are measured from the analog input module of NI 9215, the regenerated waveform of the filtered signal on FPGA target in *Figure 16C* is provided by the analog output module NI 9263. As shown in the *Figure 16*, the regenerated waveform of filtered signal is almost analogous to the original signal. These waveforms are obtained from the analog output module NI 9263 via during a real-time operation of the ANC system. In particular, when the headphones are not connected, the filtered signals of NI 9263 with gradient coil noise in the waveform of interval [2], represent some improvement of performance of the ANC system, considering an amplitude of gradient coil noise as high as 10,000 value. However, in case of this ANC system, the regenerated waveform has some kind of ripple value at specific time periods as overshoot. These unwanted phenomena should be considered and improved for a realtime application of the ANC system in fMRI experiments in the future.

Conclusions

For an analysis of Gradient Coil Noise (GCN) of Active

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Noise Canceller (ANC) system using Adaptive Filter, the echo-planar imaging (EPI) gradient coil noise pulse sequences are used to merge with audio signal in this paper. As a result, the peak value of GCN is measured around the frequency band of 1,000 Hz and confirmed with the EPI sequences, a high-speed imaging method that involves rapid (e.g., 1 KHz) gradient switching. From the analysis of signals of the ANC System, the amplitude of gradient coil noise is decreased up to 0.6 Volt and reduced up to 17 dB in filtered signal after passing the LMS adaptive filter of the ANC system. Also, the removal of the peak value of the GCN around 1 KHz is visually confirmed on the Spectrogram and spectrum of signals of the ANC system. The ANC system is configured on the NI LabVIEW FPGA Module using an NI reconfigurable I/O (RIO) hardware for a Real-Time Performance. The similarity between original audio signal and filtered signal is confirmed under connection-on status of headphones, in which the presence of gradient coil noise does not affect the signal, from the analog input/output modules (NI 9215 and NI9263). It's settled that the time delay of data processing for a realtime application of the Active Noise Canceller. In other words, the time delay of the ANC system, in the LabView program of the previous NI cDAQ-9172 and SimuLink of MathWorks, s decreased, and then real-time application of the LMS adaptive filter is fulfilled due to these advantages of LabVIEW FPGA and LabVIEW Real-Time technologies. The Real-Time working of the ANC system is used to secure a prior condition for the fMRI test inside real MRI machines.

Acknowledgements

I truly thank Dr.Chin K. Ng of the department of radiology at the university of Louisville hospital who has contributed and encouraged me to publish this paper.

Disclosure: The authors declare no conflict of interest.

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Cite this article as: Lee J, Holte J, Ritenour ER. A real-time data acquisition and control of gradient coil noise for fMRI identification of hearing disorder in children with history of ear infection. Quant Imaging Med Surg 2013;3(1):28-42. doi: 10.3978/j.issn.2223-4292.2013.02.01

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