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A study of the position of the reference microphone of active noise control of feedforward type for MRI noise

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ABSTRACT

Magnetic resonance imaging (MRI) devices generate loud acoustical noise during operation. The sound pressure level of the MRI noise depends on the imaging sequence, but it is generally 100 dB or more. Our current study is aimed at the improvement of the acoustical environment for the MRI patient by means of an active noise control system. We propose using a feedforward system because acoustical MRI noise typically comprises unsteady pulse waves. It is important for a feedforward system that the reference microphone is located near the sound source. Here, we discuss the measurement of the sound source of MRI acoustical noise to position a reference microphone and show the effect of reference microphone position in an active noise control system by computer simulation. The apparent source of MRI acoustical noise was estimated from the delay time of the cross correlation between the signals of two microphones on the table in the MRI gantry. The result indicates that the apparent source lies between the center and edge of the gantry. Computer simulation shows that the proposed system produces substantial noise reduction when the reference microphone is attached in the vicinity of the apparent origin of the sound, such as in the wall of the scanner.

Keywords: MRI acoustical noise, Sound source, Reference microphone
I-INCE Classification of Subjects Number(s): 36.4

1. INTRODUCTION

Magnetic resonance imaging (MRI) equipment generates loud sounds when operated. This noise is generated when a pulsed current is applied to the gradient magnetic field coils in the static magnetic field. The sound pressure level depends on the imaging sequence method, but it is generally 100 dB or more [1–3]. This makes patients uncomfortable, and there is a possibility of temporary hearing loss if ear protectors are not used. Conventional ear protectors decrease the sound pressure level by approximately 20 dB, but this noise level is still unsatisfactory in terms of patient comfort, to the point where MRI diagnosis and treatment may be refused in some cases. We have studied an ear protector with an active noise control (ANC) system: the conventional protection decreases the sound pressure level for a range of high frequencies and the ANC system extends this protection effectively to low frequencies.

Using feedback control during MRI preoperative procedures to support talking between doctors and the patient has been proposed [4–6] and Resonance Technology manufactures noise reduction headphones for exclusive use in MRI inspections. Our study aims to develop an active noise control system to improve the acoustical environment for the MRI patient. MRI acoustical noise is not only periodic, it also has variations in peak level. Thus, an ANC system of the feedback type that is effective at reducing periodic noise cannot adapt to all MRI acoustical noise. We therefore developed a feedforward control system [7–9]. Previous studies have proposed using feedforward methods for controlling noise in MRI devices [4,5]. However, they evaluated the noise reduction without considering the position of the reference microphone. It is important for a feedforward ANC system that the location of the reference microphone be near the sound source.

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In this paper, a method to estimate the location of the sound source in an MRI scanner is described. The location of the sound source is estimated from the time difference between two signals on the table in the MRI gantry. Additionally, the noise reduction level is estimated by computer simulation for various locations of the reference microphone. Good performance is shown when the reference microphone is located in the vicinity of the MRI sound source.

2. ESTIMATION OF THE SOUND SOURCE LOCATION

2.1 Estimation Method

The gradient coils of MRI devices are attached in pairs around the center of the bore of the MRI gantry [10]. The combined noise from all of these coils appears to come from a source within the scanner. It is the location of this apparent source that we wish to estimate. Figure 1 shows the MRI gantry and the positions of the two microphones used for recording the noise. One microphone is located at the center of the gantry; the other is placed 900 mm from the center, near the edge of the bore of the gantry. Let the signal of the MRI acoustical noise at the center of the gantry be $x(t)$, the signal at a distance l_y from the center of the gantry be $y(t)$ and the location of the MRI acoustical noise source be $s(t)$. We estimated the location of the apparent source of the MRI acoustical noise by using the difference of arrival times as estimated from the cross correlation function [11]. The cross correlation function was analyzed by determining the leading edge of the burst wave extracted from intermittent MRI acoustical noise. The cross correlation function is

$$C_{xy}(\tau) = \sum_{t=t_1}^{t_2} x_0(t) y_0(t+\tau) . \tag{1}$$

Here, $x_0(t)$ and $y_0(t)$ are waveforms extracted from original waveforms $x(t)$ and $y(t)$:

$$x_0(t) = \begin{cases} x(t), & \text{if } t_1 \le t \le t_2; \\ 0, & \text{if } t < t_1, t_2 < t. \end{cases}$$
$$y_0(t) = \begin{cases} y(t), & \text{if } t_1 \le t \le t_2; \\ 0, & \text{if } t < t_1, t_2 < t. \end{cases} \tag{2}$$

In these expressions, t_1 and t_2 are the beginning and end times of the extraction window used for the waveform analysis. Let the time of the peak of the cross correlation function be τ_s. Then, the distance l_s to the sound source from the gantry center is given by

$$l_s = \frac{l_y - \tau_s c}{2} , \tag{3}$$

where the distance between the two microphones is l_y and the speed of sound is c.

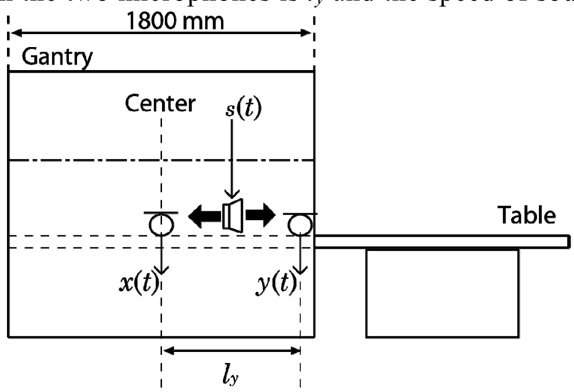

Figure 1 –The method for estimating the location of the apparent sound source.

2.2 Estimation Results

The apparent source of the MRI acoustical noise was estimated under the following conditions. The MRI equipment was a Philips Achieva 3.0-T X-series scanner, which can create a static magnetic field of 3.0 T with a maximum gradient 40 mT/m and a maximum slew rate of 200 mT/m/ms. The temperature of the room was 20.35 °C. The acoustical noise used for the estimation was an intermittent sound. Figure 2 shows an example of the enlarged waveforms of the leading edges of a burst wave recorded by the microphones. The sampling frequency was 48 kHz, the length of the time window t_2-t_1 was 840 points, and 10 cross correlation functions were averaged to determine the time lag. Figure 3 shows the cross correlation function of the signals shown in Fig. 2. The time lag between the peaks at the two microphones was 2 points, which corresponds to 0.441 ms. The estimated location of the apparent source is, therefore, 44.3 cm from the center of the MRI gantry.

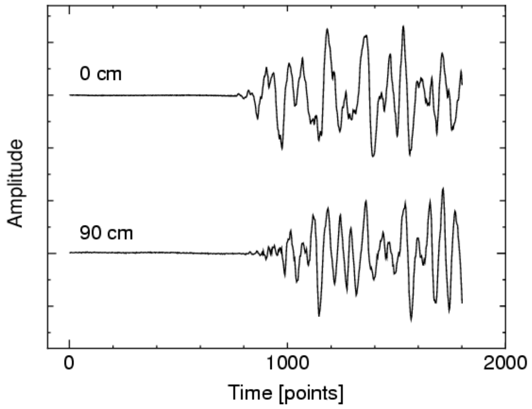

Figure 2 –Enlargement of the leading edges of the waveforms $x_0(t)$ and $y_0(t)$ of a burst wave.

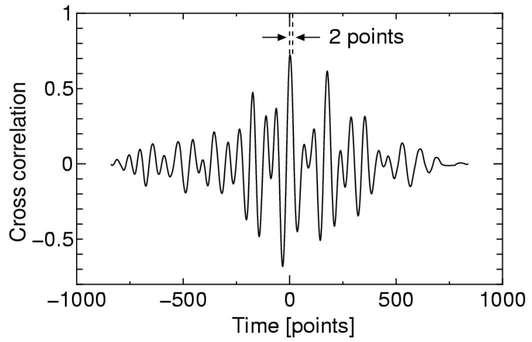

Figure 3 – Cross correlation function of the additively averaged waveforms $x_0(t)$ and $y_0(t)$.

3. COMPUTER SIMULATION OF FEEDFORWARD ACTIVE NOISE CONTROL

In the previous section, the location of the apparent source of MRI acoustical noise was estimated from the delay time of the cross correlation between the signals arriving at two microphones on the table in the MRI gantry. Here, we simulate an ANC system designed to increase the comfort of a patient undergoing an MRI knee examination. In particular, we investigate the relation between the location of the reference microphone and the noise reduction level.

3.1 Conditions of the Computer Simulation

Figure 4 shows a block diagram of a feedforward ANC system. The proposed ANC system uses the filtered-x normalized least mean square (NLMS) algorithm, which is a conventional adaptive algorithm [8,9,11,12]. This system is a feedforward control, and so the correct location of the reference microphone must be obtained to achieve satisfactory performance. The computer simulation parameters were as follows. The sampling frequency was 48 kHz, the step-size parameter α was 0.5, the FIR filter length was 8000, and the start time of active noise control was 0 s. These parameters were chosen to give the lowest possible MRI acoustical noise after the noise control algorithm converged.

Figure 5 shows the positional relation between the patient and the active noise control system. The reference microphone was placed at a distance of l_s' from the gantry center. We placed the sound source near the position of the apparent sound source in the recorded acoustical noise data. To simulate a knee examination, the control point was 1200 mm from the center of the gantry, representing the position of a patient's ear. The noise was synchronous recording data from a Philips Achieva 3.0-T X-series scanner. The non-magnetic microphones used for synchronous recording were Optacoustics Ltd. 1150 optical microphones, one of which was covered by a Trusco Nakayama EM-68N hearing guard.

The secondary path *C* was the transition path from the error microphone to the loudspeaker. In this simulation, the system used the headphone of a loudspeaker including magnetic material. Therefore, we estimated the secondary path by using a B&K 4100D Head and Torso Simulator and a Sennheiser HD280 headphone. Figure 6 shows the secondary path calculated by 512-point FFT using the cross-spectrum method with a sampling frequency of 48 kHz. The peak of the impulse response was at 2 points (0.042 ms), and other coefficients were small. This impulse response was used for the FIR filter coefficients $\boldsymbol{c}(n)$ and $\hat{\boldsymbol{c}}(n)$ in the computer simulation.

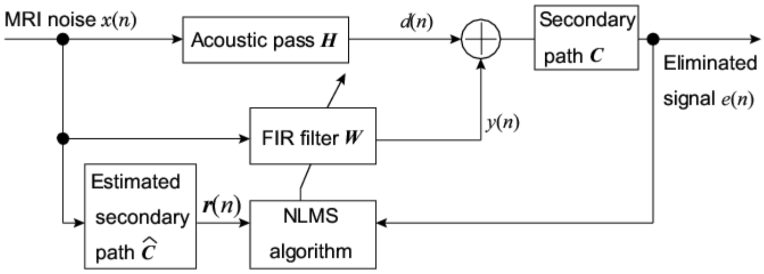

Figure 4 –Block diagram of the feedforward ANC system.

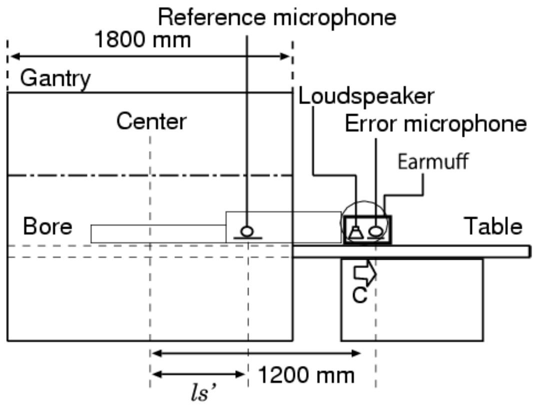

Figure 5 –The positional relation between the MRI equipment and the active noise control system in the case of a knee examination.

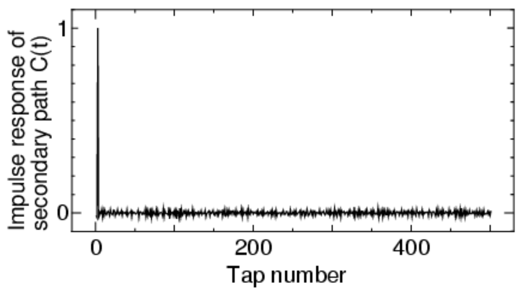

Figure 6 –Impulse response of the secondary path $C(t)$ of the active noise control.

3.2 Noise Reduction Results

The noise reduction was simulated by using the measured MRI acoustical noise of a T1W imaging sequence. Figure 7 shows the noise reduction effect of the ANC system for each position of the reference microphone. It can be seen that the maximum noise reduction was 26.1 dB at $l_s' = 450$ mm. The system was effective if the reference microphone was near the sound source, for example, in the side or ceiling of the bore [13]. We found that for a pure waveform it was necessary to collect the noise actually at the sound source to achieve good reduction of MRI acoustical noise.

Figure 8 shows the characteristics of the MRI acoustical noise reduction by the ANC system for a T1W imaging sequence and a reference microphone at l_s' = 45 cm. The short dashes indicate the time series of the MRI acoustical noise and the solid lines indicate the reduced noise. The sound pressure level was reduced from 100 dB of MRI noise to 60.7 dB by using the ANC system, and the noise reduction due only to the active noise control was 26.1 dB at 10 s. We think that the reduction time will be as fast in an actual inspection, because the change in the sound transmission path is small for a patient in a stationary position on the table.

Figure 9 shows the frequency characteristics of controlled noise for a T1W sequence with the reference microphone at l_s' = 45 cm. In this figure, short dashes indicate the sound frequency characteristics of the desired signal $d(t)$ in the earmuff, and solid lines indicate the frequency characteristics of the error signal $e(t)$ after noise reduction for approximately 10 seconds. The earmuff reduced MRI noise at high frequencies, and the proposed control system reduced MRI noise in frequency band of order of a few hundred Hertz.

These results indicate that it is possible to reduce an MRI patient's discomfort by using our proposed method.

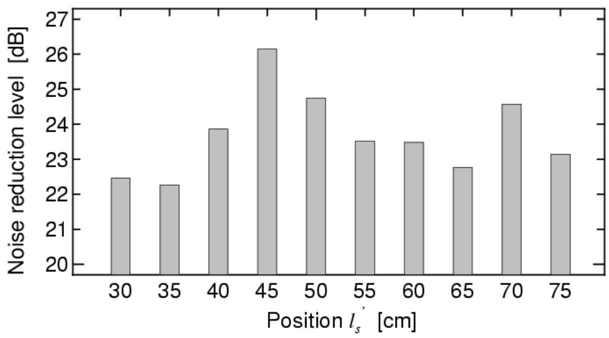

Figure 7 –Reduction level of the active noise control system for each position of the reference microphone.

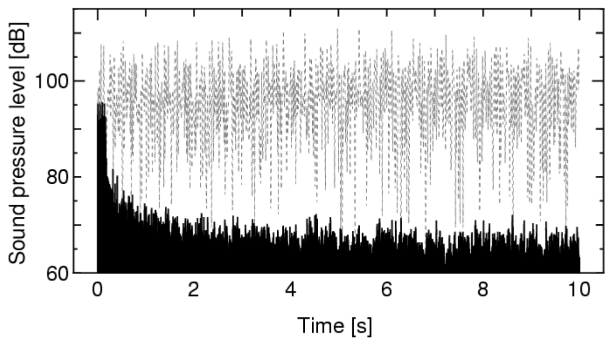

Figure 8 –Actual level of MRI acoustical noise (dashed line), and the reduced noise (solid line) (l_s' = 45 cm).

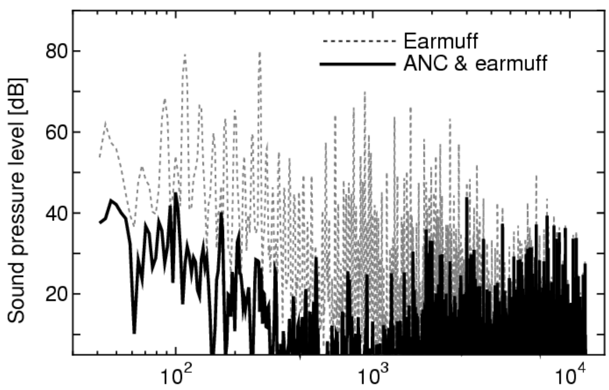

Figure 9 –Frequency characteristics of controlled noise (l_s' = 45 cm).

4. CONCLUSIONS

In this study, our aim was to produce a quieter environment for an MRI patient by using feedforward active noise control. The proposed system adopted the filtered-x NLMS algorithm for the analysis of unsteady pulsed MRI acoustical noise captured by a reference microphone located in the vicinity of the MRI sound source in order to obtain an accurate noise waveform. Computer simulation indicated that it was important for the reference microphone to be located close to the sound source in order to achieve good noise reduction. The position of the MRI acoustical noise source was estimated to be 425 mm from the center of the MRI gantry for a T1W imaging sequence.

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