

Evaluation of an Independent Linear Model for MRI Acoustic Noise and Implications for Acoustic Noise Reduction

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Purpose: Many attempts have been made to characterize and reduce MRI acoustic noise based on an independent linear model¹ relating gradient waveforms to the produced sound, but have shown substantial prediction error when combining sound from all three gradient axes^{1,2,3}. The purpose of this study is (1) to improve the model's prediction accuracy by synchronizing the measured acoustic impulse responses of all three gradient axes, and (2) to explore implications for acoustic noise reduction in routine imaging.

Methods and Results

Testing the Independent Linear Model: Experiments were performed on a clinical 3T scanner (EXCITE HDxt, GE Healthcare). An MR compatible sound level meter (Brüel & Kjær) was used to record audio. For each physical gradient axis, the acoustic transfer function was estimated using $H_i(f) = Y_i(f)/G_i(f)$, ($i = x, y, z$), where $Y_i(f)$ and $G_i(f)$ are the Fourier transforms of the recorded sound and input gradient waveforms, respectively. Fifteen different gradient inputs were used, including triangles, trapezoids, and low-pass filtered random noise. We observed difficulty in *precisely* synchronizing audio recordings with the MRI gradients, which resulted in small unknown time delays between the measured impulse responses for each physical gradient axis. We therefore utilized the following model for prediction $P(f) = G_x(f)H_x(f) + G_y(f)H_y(f)exp(-j2\pi f\Delta t_{yx}) + G_z(f)H_z(f)exp(-j2\pi f\Delta t_{zx})$, where Δt_{yx} and Δt_{zx} are unknown. To estimate these delays, additional recordings were obtained while gradients were played simultaneously on x- & y-axis, and then on the x- & z-axis. $|P(f)|$ was then compared with the recorded sound spectrum $|Y(f)|$ using Itakura-Saito (I-S) distance⁴ while varying Δt_{yx} and Δt_{zx} . Values corresponding to the minimum I-S distance were used.

Table 1 summarizes the results. The predicted spectra were compared to the actual recorded sound and prediction error was calculated using power spectrum difference: $(|P|^2 - |Y|^2)/|Y|^2 \times 100\%$, where P and Y are the predicted and recorded audio respectively. Fig. 1 shows a representative prediction result when different low-pass filtered random noise gradients were played on all three physical axes.

Impact of Position within the Scanner Bore: With a working prediction model, we explored the impact of precise spatial position within the bore. We measured acoustic transfer functions at ten locations within the bore with a human subject also inside. The microphone was placed at a fixed location close to the subject's left ear and then moved along physical z-axis at 5cm increments. Fig. 2 shows x-axis acoustic transfer functions measured at four positions, which vary significantly for frequencies > 1 KHz. This suggests that efforts to minimize acoustic noise prospectively will be highly sensitive to position within the magnet.

Conclusions: We have evaluated an independent linear model for gradient-induced MRI acoustic noise on a clinical scanner. By introducing a new method to synchronize the measured acoustic impulse responses of all three axes, prediction error was reduced from 32% to less than 4%. Note that previous works¹⁻³ suffered from poor accuracy when sound from all three gradient axes was combined, which we suspect was due to imperfect synchronization of the measured impulse responses. We also have shown that peaks in the acoustic transfer functions vary with precise position within the bore, which would be a weakness of any noise reduction strategy based on avoiding specific resonance peaks.

References: [1] Hedeem RA et al. MRM 1997;37(1):7-10. [2] More SR et al. JMRI 2006;23(3):388-97. [3] Sierra CVR et al. IEEE Trans. on Bio. Eng. 2008;55(9):2115-23. [4] Itakura F and Saito S. Proc. of 6th Int. Congr. on Acous. Tokyo, 1968(17):c17-c20.

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Prediction Error (%)	
G_x only	0.41 ± 0.14
G_y only	0.61 ± 0.22
G_z only	2.76 ± 1.37
$G_{x,y,z}$ (no correction)	31.90 ± 6.15
$G_{x,y,z}$ (with correction)	3.86 ± 2.49

Table 1. Prediction Error. Error is reduced in the 3-axis case from >30% to <4%.

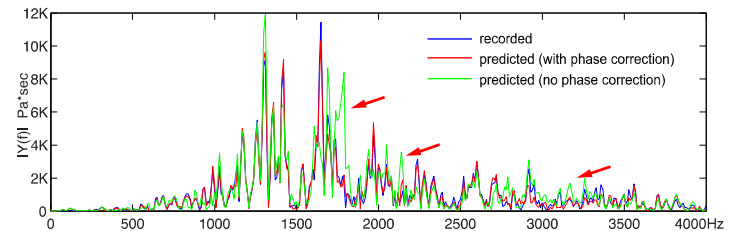


Fig 1. Representative power spectra for audio recording and model predictions. Predictions prior to correction had several spurious peaks (red arrows).

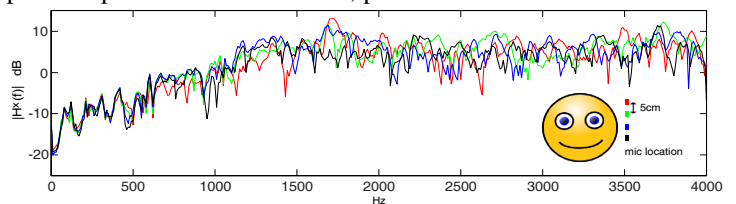


Fig 2. Measured X-axis acoustic transfer function at four locations within the scanner bore.