bSSFP fMRI Study of Sound Amplitude Modulation in Inferior Colliculus
Jevin W. Zhang1,2, Condon Lau1, Patrick P. Gao1,2, Joe S. Cheng1,2, Gehua Tong1, Iris Y. Zhou1,2, and Ed X. Wu1,2

1Laboratory of Biomedical Imaging and Signal Processing, The University of Hong Kong, Hong Kong, Hong Kong SAR, China, 2Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong, Hong Kong SAR, China

Introduction – Amplitude modulation (AM) is an essential feature of most natural acoustic signals and it is important in various sound perceptual tasks. By spatial shifts of excitation, brain neuronal maps optimize information processing. The periodotopic map in inferior colliculus (IC) is based on the temporal analysis of periodic stimuli. The balanced steady state free precession (bSSFP) sequence is a fast MRI acquisition sequence free of image distortion, susceptibility-induced signal loss, and sporadic scanner noise. Our previous work demonstrated that sparse temporal sampling is not a prerequisite in auditory fMRI studies of the IC [3, 4]. Here we employed the bSSFP and continuous imaging instead of echo planar imaging (EPI) and sparse temporal sampling to investigate the spatial representation of AM encoding in IC.

**Fig. 1:** Acoustic stimulation paradigm for the AM study consisted of three different stimuli. Each stimulus was presented by two continuous blocks in one fMRI session and was in random and interleaved order.

**Fig. 2:** Power spectrum of the unmodulated broadband noise used in the experiment. It was later modulated by 1, 16 or 80 Hz sinusoidal waveform as the stimulation.

**Methods** – Animal preparation: Sprague-Dawley rats (250 – 300g, N = 5) were examined. Animals were anesthetized with 3% isoflurane for induction and maintained at 1% Animal stimulation: Monaural broadband noise stimuli were produced by a free-field magnetic loudspeaker (TDT MF1) and driven by an amplifier (TDT SA1). Sound was generated by the computer with a high soundcard and was delivered to the left ear canal via a 165 cm long custom built tube. (i) Animals were stimulated in a block design paradigm of 40s sound off then six blocks of 20s on and 40s off. In one fMRI session each stimulus was performed by two continuous blocks and randomly interleaved (Fig. 1). The fMRI session was repeated for three to six times each animal. The stimuli were broadband noise (Fig. 2) sinusoidally modulated by 1, 16 or 80 Hz and the modulation depth was 80%. The modulation equation was

\[ A(t) = \frac{1}{2} \left[ 1 + \sin(2\pi fm t) \right] N(t) \]

where \( A(t) \) was the AM sound, \( m \) the AM depth, \( f_m \) the modulation frequency and \( N(t) \) the broadband noise. (ii) For comparison we also performed the tonotopic mapping experiment using sweeping paradigm in one animal [4].

**Results** – Fig. 4A&B show the beta-value maps corresponding to three different modulation frequencies \( f_m \) from one representative animal and averaged maps from five animals. Beta-value represents the activation strength from the GLM shift from dorso-medial to vento-lateral IC with increasing \( f_m \). This spatial shift can be clearly seen in the subtraction map (Fig. 4B&D). The positive subtraction beta-value means that voxel responded to high \( f_m \) more and the negative value means that it responded more to low \( f_m \). Fig 5A shows the coherence map which represents the activation strength in the tonotopic mapping experiment using sweeping paradigm. Fig. 5B shows the tonotopic (i.e., spatially specific frequency encoding) map. The yellow arrows in Fig. 4B&D and 5B show the general spatial encoding gradient for the AM frequency and tonotopy gradient. The orthogonal representation of the two different gradients can be observed in the same animal.

**Discussion** – In this study we demonstrated the detection of spatial encoding of amplitude modulation (AM) sound frequency using continuous bSSFP fMRI. Furthermore, the AM frequency encoding gradient was observed to be orthogonal to the sound spectrum frequency encoding or tonotopy gradient. Our in vivo findings here paralleled by the electrophysical recording studies by others. Recordings in the central nucleus of IC show a simple gradient orthogonal to the main tonotopic gradient [5]. Rees and Moller also showed that in anesthetized rat IC the most effective modulation frequency was below 100 Hz [6]. Their data also showed that the neuron firing rate increased monotonically with increasing modulation depth and some saturated or decreased after the depth reached 80%. Our findings can help us understand more about the auditory processing and hearing disorders.

**Fig. 4:** (A&C) The beta-value maps overlaid on the smoothed bSSFP images from a representative animal and the averaged maps from five animals. Beta-value represents the activation strength from the GLM shift from dorso-medial to vento-lateral IC with increasing \( f_m \). This spatial shift can be clearly seen in the subtraction map (Fig. 4B&D). The positive subtraction beta-value means that voxel responded to high \( f_m \) more and the negative value means that it responded more to low \( f_m \). Fig 5A shows the coherence map which represents the activation strength in the tonotopic mapping experiment using sweeping paradigm. Fig. 5B shows the tonotopic (i.e., spatially specific frequency encoding) map. The yellow arrows in Fig. 4B&D and 5B show the general spatial encoding gradient for the AM frequency and tonotopy gradient. The orthogonal representation of the two different gradients can be observed in the same animal.