# Avoiding Electromagnetic Artifacts When Recording Auditory Steady-State Responses

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**Abstract**

Electromagnetic artifacts can occur when recording multiple auditory steady-state responses evoked by sinusoidally amplitude modulated (SAM) stimuli. High-intensity air-conducted stimuli evoked responses even when hearing was prevented by masking. Additionally, high-intensity bone-conducted stimuli evoked responses that were completely different from those evoked by air-conducted stimuli of similar sensory level. These artifacts were caused by aliasing since they did not occur when recordings used high analog-digital (AD) conversion rates or when high frequencies in the electroencephalographic (EEG) signal were attenuated by steep-slope low-pass filtering. Two possible techniques can displace aliased energy away from the response frequencies: (1) using an AD rate that is not an integer submultiple of the carrier frequencies and (2) using stimuli with frequency spectra that do not alias back to the response frequencies, such as beats or "alternating SAM" tones. Alternating SAM tones evoke responses similar to conventional SAM tones, whereas beats produce significantly smaller responses.

**Key Words:** Aliasing, auditory steady-state responses, electromagnetic artifacts, sinusoidal amplitude modulation

**Abbreviations:** AC = air conduction; AD = analog-digital; AM = amplitude modulation; ASSR = auditory steady-state response; BC = bone conduction; EEG = electroencephalogram; $f_a$ = aliasing frequency; $f_c$ = carrier frequency; $f_m$ = modulation frequency; $f_N$ = Nyquist frequency; $f_s$ = sampling frequency; MASTER = multiple auditory steady-state response; SAL = sensorineural acuity level; SAM = sinusoidal amplitude modulation

**Sumario**

Cuando se realizan registros múltiples de respuestas auditivas de estado estable, evocadas por medio de estímulos sinusoidales de amplitud modulada (SAM), se pueden generar artefactos electromagnéticos. Los estímulos por v[ia aérea de alta intensidad evocan estas respuestas aún cuando se enmascare la audición. Además, los estímulos de alta intensidad conducidos por vía ósea también evocaron respuestas que fueron completamente diferentes de aquellas por vía aérea, a niveles sensoriales similares. Estos artefactos fueron causados por relación, dado que no se presentaron cuando los registros se hicieron utilizando tasas altas de conversión analógico-digital (AD), o cuando las frecuencias en la señal electroencefalográfica (EEG) fueron atenuadas por filtros. Existen dos posibles técnicas para desplazar esta energía relacionada de las frecuencias de respuesta: (1) usando una tasa AD que no sea sub-múltiplo entero de las frecuencias portadoras, y (2) usando estímu-

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los con un espectro de frecuencia que no esté relacionado con las frecuencias de la respuesta, tales como las pulsaciones o los tonos SAM alternantes. Los tonos SAM alternantes evocan respuestas similares a los tonos SAM convencionales, mientras que las pulsaciones producen respuestas significativamente menores.

**Palabras Clave:** Aliasing, respuestas auditivas de estado estable, artefactos electromagnéticos, modulación sinusoidal de la amplitud

**Abreviaturas:** AC = conducción aérea; AD = analógico-digital; AM = modulación de la amplitud; ASSR = respuestas auditivas de estado estable; BC = conducción ósea; EEG = electroencefalograma; $f_a$ = frecuencia relacionada; $f_c$ = frecuencia portadora; $f_m$ = frecuencia de modulación; $f_N$ = frecuencia Nyquist; $f_s$ = frecuencia de muestreo; MASTER = respuesta auditiva múltiple de estado estable; SAL = nivel sensorineural de agudeza auditiva; SAM = modulación sinusoidal de la amplitud

Human auditory steady-state responses (ASSRs) can provide a rapid and objective assessment of auditory thresholds (Picton et al, 2003). These responses can be evoked by stimuli that have good frequency-specificity, such as sinusoidally amplitude-modulated (SAM) tones. These stimuli can be presented using both air-conduction (AC) and bone-conduction (BC) transducers.

Since ASSRs are elicited by the envelope of the sound rather than by the carrier, there should be little problem with electromagnetic artifacts. A sinusoidally amplitude-modulated (SAM) tone has energy only at the carrier frequency ($f_c$) and at two side bands separated from the carrier by the modulation frequency ($f_m$). Provided the stimulus-transduction is linear, there is no energy at the modulation frequency in the stimulus or in the electromagnetic fields associated with its transduction.

Artifacts may occur, however, with high-intensity AC stimuli or moderate-intensity BC stimuli. Dimitrijevic et al (2002) considered the possibility of artifacts in the responses to BC stimuli by seeing whether these responses could be altered by simultaneously presented AC masking. Physiological responses are eliminated by masking, but electromagnetic artifacts are not. We generally found that masking eliminated the responses, but we did not use BC intensities of more than 30 dB SL (and even at this level a few responses were not eliminated). Small and Stapells (in press) recorded significant responses to BC stimuli at intensities of 40 dB HL and higher from subjects who were unable to hear the sounds due to severe sensorineural hearing loss. In addition, Gorga et al (in press) described artifactual responses for AC stimuli of 95 dB HL and higher in subjects who could not hear the sounds due to severe or profound hearing loss.

Small and Stapells (in press) found that the artifacts with BC stimuli could be inverted in polarity by inverting the stimulus. This result was difficult to understand since inverting the stimulus does not change the envelope but only flips the polarity of the carrier. After modeling the stimuli in order to understand how this could happen, we discovered that the artifacts were likely related to "aliasing." Aliasing occurs when a signal is sampled at a rate lower than twice its frequency. The signal is then seen at a frequency equal to the absolute difference between its frequency and the closest integer multiple of the sampling rate (Figure 1). The analog-digital (AD) conversion rates used in recording ASSRs were designed for the efficient analysis of the responses at the frequencies of modulation. These rates did not fully consider the problem of the stimulus

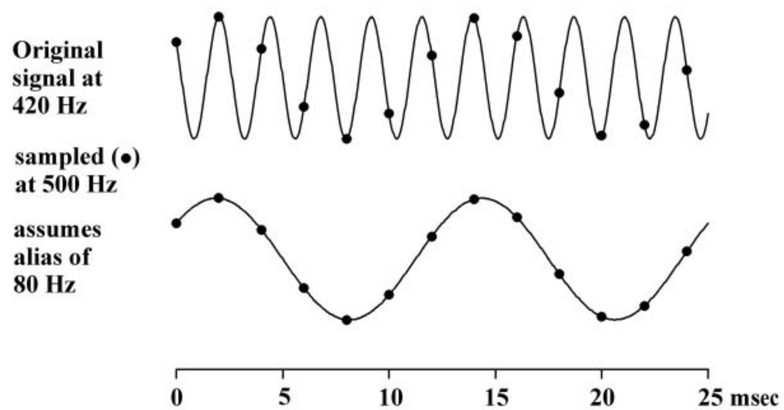


**Figure 1.** Aliasing. The figure shows how aliasing occurs using a simple example. In the upper tracing a signal of 420 Hz is sampled (dots) at a rate of 500 Hz. One half the sampling rate (the Nyquist frequency) is lower than the frequency of the signal. As shown in the lower tracing, the sampled activity is interpreted as 80 Hz (the absolute difference between the frequency of the stimulus and the sampling frequency).

artifact at the carrier frequencies, which can become very large with bone conduction at moderate intensities or air conduction at high intensities and overwhelm typical anti-aliasing filters.

Upon contacting David Stapells, we learned that he had already figured this out and had tested some solutions. Small and Stapells (in press) propose using AD conversion rates that alias any possible artifacts to regions of the spectrum distant from the responses. Our present paper confirms the presence of electromagnetic artifacts when recording ASSRs to both AC and BC stimuli. Furthermore, we replicate the Small and Stapells approach to eliminating the problem by changing the AD rate. Lastly, we evaluate another solution using different stimuli: beats or alternating SAM tones.

## METHODS

### Subjects

Twelve subjects (mean age 25 years, range 21-29, six male) participated in these experiments. All had thresholds less than 20 dB HL at the frequencies 500, 1000, 2000, and 4000 Hz. Subjects slept or drowsed in a reclining chair, located within a darkened sound-attenuated chamber during the recordings. Experiments 1 and 2 were done in one recording session, while experiments 3 and 4 required two separate recording sessions. Each recording session lasted about two hours. Five or six subjects participated in Experiments 1, 2, and 3 where the effects were large and obvious. All 12 subjects participated in Experiment 4 where the effects were smaller.

### Stimuli

Stimuli were constructed using MATLAB (Mathworks) and presented to the subjects using a specially modified version of the MASTER (multiple auditory steady-state response) software (John and Picton, 2000), which is capable of reading stimuli from text files. Four different stimuli, with carrier frequencies 500, 1000, 2000, and 4000 Hz, were simultaneously presented. Each carrier had its own signature modulation frequency (80, 88, 96, and 104 Hz) to allow us to recognize four different ASSRs. The digital-analog (DA) conversion rate was 32 kHz. Stimuli were routed to the tape input of a Grason-Stadler 16 audiometer, which was used to adjust the stimuli to the desired intensity for presentation to the subject.

AC stimuli were presented at 115 dB HL through the right earphone of a set of TDH 50P earphones. The earphones were located on the neck just below the ear and were cushioned with a towel (which also reduced the perceived intensity). The ear canals were occluded with Etymotic ER-3A insert phones (which could be used for presenting masking noise). Due to both the neck location of the earphone and the occluded ear canals, the perceived intensity of the stimuli was between 40 and 50 dB HL. These stimuli became inaudible if white noise at 50 dB equivalent masking level was presented binaurally through the insert phones.

BC stimuli were presented using a Radioear B71 transducer held on the mastoid process of the temporal bone behind the right ear using an elastic headband exerting a force of approximately 500 g. During BC stimulation, both ear canals were occluded. Stimuli were calibrated in dB HL. Because of the occlusion of the ear canals (as discussed in Dimitrijevic et al, 2002), the BC stimuli at 500 and 1000 Hz had thresholds that were 15 dB lower than the HL (calibrated for unoccluded ears).

Four different types of stimuli were used. The first was a simple SAM tone with 100% depth of modulation. The second was the same stimulus inverted in polarity. The third was an "alternating SAM tone." This is a SAM tone that alternates the polarity of the carrier at every cycle of the modulation. Basically the SAM tone is multiplied by the sign of the modulation signal shifted by 90 degrees. The transition in polarity occurs in the null section between "bursts" of the amplitude modulation (AM) stimulus, when the amplitude of the signal is functionally zero, in order to prevent an acoustic artifact at the modulation frequency. This alternating SAM tone requires the depth of modulation to be 100% and the number of modulation cycles within the DA buffer to be even. The fourth stimulus was composed of two tones separated by the required envelope frequency to form beats. The left side of Figure 2 shows the stimuli in both time and frequency domains. (The right side of the figure illustrates the aliasing problem.)

## Recordings

The electroencephalographic (EEG) signal was recorded between the vertex and posterior neck using a Grass P55 amplifier with a bandpass of 1–300 Hz (-6 dB points,

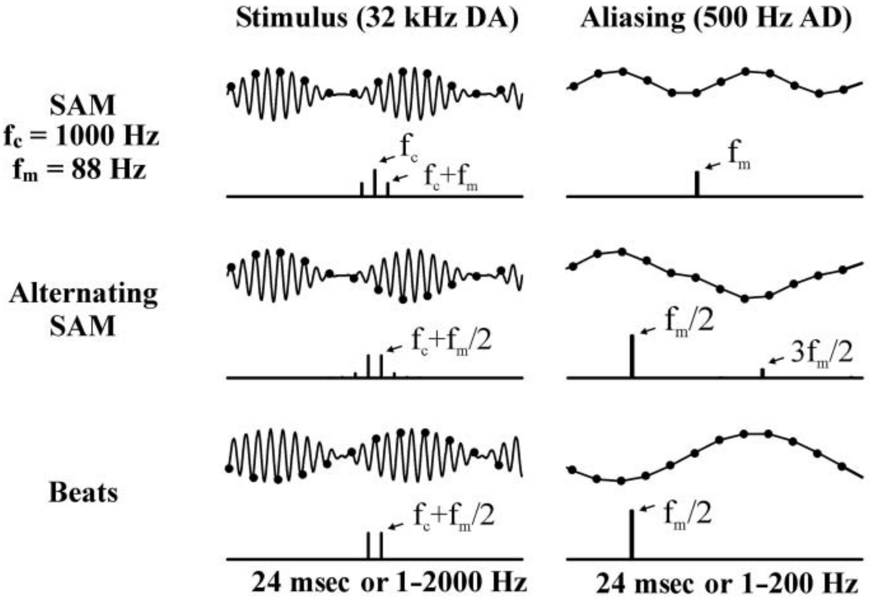


**Figure 2.** Aliasing of stimuli. The figure shows six time-domain signals each paired with its amplitude spectrum. The left side of the figure represents acoustic stimuli, and the right side of the figure represents how these might be represented in the EEG recording. The top row illustrates how a sinusoidally amplitude-modulated (SAM) signal can be aliased down to give artifacts at the modulation frequency ($f_m$) if the analog-digital (AD) conversion rate is too slow to follow the carrier frequency ($f_c$). In this case the acoustic signal was created using a 32 kHz digital-analog (DA) conversion rate, and the EEG recording was obtained using a 500 Hz AD rate. (Though not shown in this figure, the amplitude of the aliased signal recorded at $f_m$ varies with the relative timing between the AD and DA rates. For the purpose of this figure the relative timing has been adjusted so that the amplitude of the aliased signal is about the same as that of the original signal.) An alternating SAM signal has a different amplitude spectrum, and the aliasing occurs at one half of $f_m$ (and at 3/2 of $f_m$). For beats, all of the aliased signal is at one half of $f_m$. None of the acoustic stimuli have energy at the frequency of modulation. The spectrum of alternating SAM stimuli is similar to that of the beats but contains several additional low-amplitude side bands. The x-axis for the time waveforms spans 24 msec. Due to the difference between the DA and AD conversion rates, the x-axis for the spectra spans 2000 Hz (stimulus) and 200 Hz (aliasing).

6 dB/octave slope). The MASTER system converted this activity to digital form using AD rates of 500, 1280, or 8000 Hz. AD rates were chosen as a submultiple of the 20 MHz clock on our input/output board. For the two slower rates, 20 sweeps each lasting exactly 16 seconds were averaged together prior to analysis. When the AD rate was 8000 Hz, a one second sweep was averaged 160 times. (The shorter sweep-time was used to facilitate the online Fourier transform, the speed of which varies with the number of points in the sweep). Weighted averaging was used to attenuate the effect of intermittent noise, which occurred in the EEG signal due to nonbrain sources such as EMG (John et al, 2001). In some recordings, additional low-pass filtering at 200 Hz was performed using a Krohn-Hite 3750 filter with a 24 dB/octave slope. The MASTER system calculated a Discrete Fourier Transform of the averaged sweep to obtain the amplitudes and phases of the responses at the modulation frequency and the probability that the response was different from the activity at adjacent frequencies.

## Experimental Design

Experiment 1 served both to demonstrate the presence of artifacts and to examine their relationship to aliasing. Responses to SAM stimuli were digitized at rates of 500, 1280, and 8000 Hz. The stimuli were AC tones presented at approximately 115 dB above threshold through earphones on the neck. In one condition, white-noise masking at a level of 50 dB effective masking was presented binaurally via inserts to prevent any hearing of the auditory steady-state stimuli. In the other condition, no noise was presented, and the subjects were able to hear the stimuli presented through the occluded earphones. When masking was present, only artifacts would be recognized. With no masking, the recorded responses would contain both physiological responses and artifacts. Five subjects participated in this experiment.

Experiment 2 looked at artifacts caused by different AC stimuli when the AD conversation rate was 500 Hz. Four types of stimuli were used: SAM, inverted SAM, alternating SAM, and beats. The stimuli were presented at 50 dB HL. As in the first experiment, stimuli were presented, in two conditions, either with or without masking (at a 50 dB equivalent masking level). We hypothesized that artifactual "responses" would be present in the SAM recordings and that these would be unaffected by noise because they were due to electromagnetic induction rather than to physiological processes associated with hearing. We further hypothesized that the responses to the alternating SAM stimuli or beats would be eliminated by the masking noise, since these would be physiological, rather than artifactual, in origin. This experiment involved the same five subjects as the first.

Experiment 3 compared the responses to AC and BC stimuli for stimulus intensities 50, 40, 30, and 20 dB HL. Three different types of stimuli were used: SAM tones, inverted SAM tones, and alternating SAM tones. In addition to examining the responses to the SAM and the inverted SAM tones, we averaged these together as "SAM+/-." The main hypothesis was that the responses to high-intensity BC stimuli would be artifact-contaminated, as shown by larger responses than expected from the AC stimuli of equivalent intensity and would demonstrate inverted polarities for the inverted stimuli. A subsidiary hypothesis was that the beat stimuli and the alternating SAM stimuli would not show these artifacts. Six subjects participated in this experiment.

Experiment 4 compared the responses to SAM tones with the responses to alternating SAM tones and beats at intensities of 50, 40, 30, and 20 dB HL using only AC stimuli. Based on the results of Experiment 2, the hypothesis was that the responses to beats would be smaller than the other responses. Twelve subjects participated in this experiment (six from Experiment 3).

## Statistical Evaluations

Amplitudes and phases were evaluated for the responses to each amplitude-modulated carrier frequency. The F-test was used to assess whether a response was present or not (John et al, 2000). When averaging measurements across subjects, the amplitudes of responses that were not significantly different from the background activity were arbitrarily set to zero and their phases omitted from the calculations. Amplitudes were averaged arithmetically and phases combined using unit-vector averaging. In order to simplify the graphical

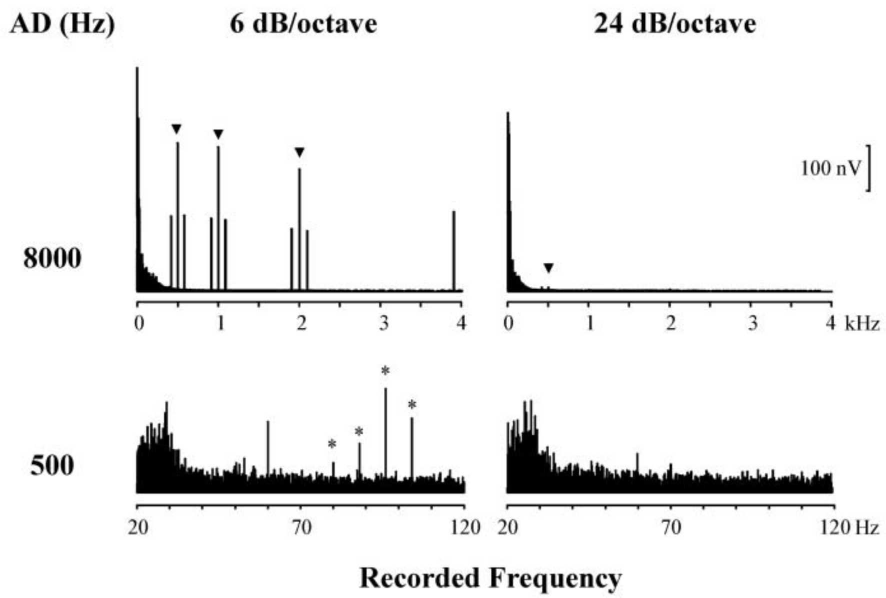


**Figure 3.** Effects of AD rate and filtering. This figure shows data from one particular subject. For all these recordings masking noise was used to eliminate physiological responses. The upper row shows the results with an AD rate of 8000 Hz. When the filter has a slope of 6 dB/octave (300 Hz low-pass setting), stimulus artifacts are clearly visible at the frequencies of the carriers (triangles) and the side bands. The amplitude decreases with increasing frequency of the carriers, but the measured fall-off in amplitude is less than 6 dB/octave. This might relate to changes in phase between the artifact and the AD converter. When the AD rate is 500 Hz (lower left), the side bands are aliased to give artifacts at the modulation frequencies (asterisks). When the filter has a slope of 24 dB/octave (250 Hz low-pass setting), the stimulus artifacts are attenuated (only 500 Hz remains visible—see filled inverted triangle on upper right graph), and there are no recognizable artifacts when the AD rate is 500 Hz (lower right). The energy from the 500 Hz SAM tones (closest to the filter cutoff) may have aliased into the EEG, but this was not significantly different from the residual noise levels.

demonstration of the results, the response measurements were generally combined across the different carrier frequencies. The phases of the responses varied with the carrier frequencies of the different stimuli, but this did not significantly affect the larger changes due to intensity or stimulus type. The amplitudes of the different responses were compared using a 3-way ANOVA (carrier frequency, intensity, stimulus type). Results were considered significant at $p < 0.01$ using Geisser-Greenhouse corrections.

## RESULTS

### Experiment 1: AD Rates and Filtering

The data recorded using AD rates of 8000 Hz showed large artifacts representing the stimuli with peaks at the carrier frequencies (indicated by the triangles in Figure 3) and at the side bands. These peaks were not affected by the masking noise (the figure representing only the responses recorded with noise). However, using the additional 24 dB/octave filter (low-pass set at 250 Hz), in addition to the 6 dB/octave filter (low-pass set at 300 Hz), severely attenuated these artifacts, effectively eliminating them at frequencies above 500 Hz (upper right of Figure 3). The data also included responses at the modulation frequencies, which were eliminated by the masking noise (and therefore represented physiological responses to the stimuli that were heard when there was no masking). When the AD rate was 500 Hz, there were large responses at the modulation frequencies (asterisks in the lower left of Figure 3). These were attenuated but not eliminated by the masking noise (the figure only shows the masked responses) but were completely eliminated by the increased filtering (lower right of Figure 3).

The upper 3 rows of Figure 4 show the effects of the different AD rates. Artifactual contamination was demonstrated when peaks (asterisks) in the spectra were not eliminated by the presence of masking (right columns). These occurred at the frequencies of modulation for the SAM tones when the AD rate was 500 Hz. The unmasked responses (open triangles) were substantially larger than those recorded when the AD rate was

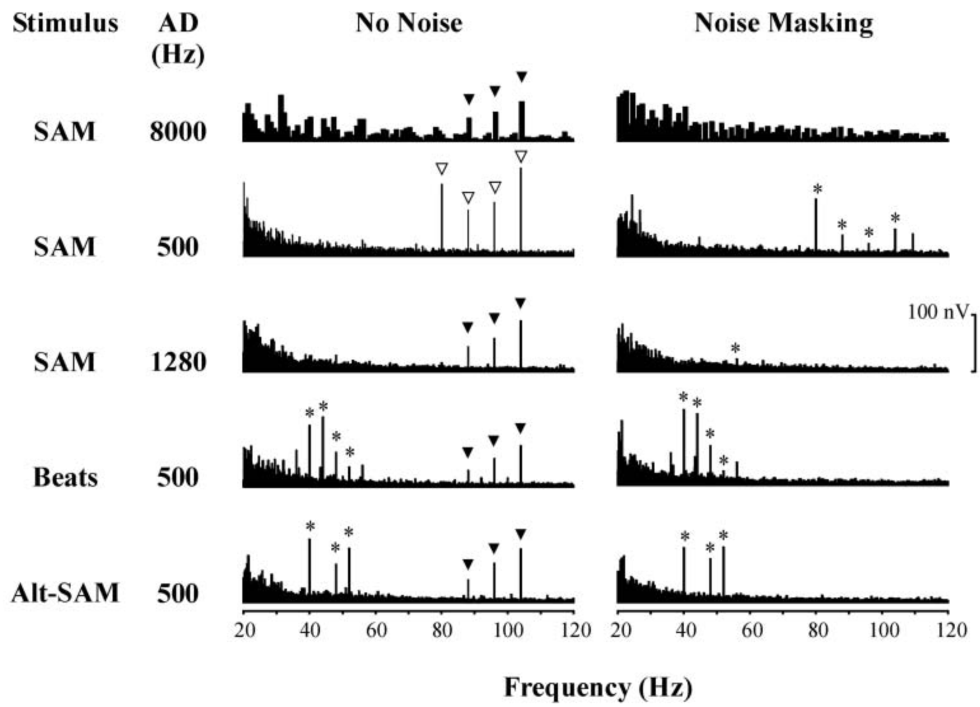


**Figure 4.** Noise masking. This figure shows the effects of masking (right side) on the recorded responses averaged over the five subjects examined in this experiment. If the responses are physiologically based, any response on the left side of the figure (no masking) should disappear on the right side of the figure because physiological responses are inhibited by masking noise. The data in the first row of the figure show responses recorded with an AD rate of 8000 Hz. Responses (filled triangles) are shown at the modulation frequencies of the 1000, 2000, and 4000 Hz tone. The responses for the 500 Hz tones were small and variable between subjects and did not show on the grand mean data. When the AD rate is 500 Hz (second row), the responses at the modulation frequencies (open triangles) are a combination of both physiological responses and the aliased stimulus artifacts. Masking noise (right side of figure) eliminates the physiological responses but leaves the stimulus artifacts (asterisks). When the AD rate is 1280 Hz (third row), no artifacts contaminate the physiological responses indicated by filled triangles, although there is a tiny artifact at 56 Hz (asterisk) that is only visible in the masked recording. When the stimuli were beats or alternating SAM tones, artifacts (asterisks) occurred at half the modulation frequencies and did not contaminate the physiological responses (filled triangles). The spectra of the first row have a lower resolution (thicker lines) than the other spectra because the frequency transform was based on 1 rather than 16 seconds.

8000 or 1280 Hz. At these rates the small responses at the modulation frequencies (filled triangles) were eliminated by masking noise. When the AD rate was 1280 Hz, there were large responses outside the 20-120 Hz region (shown in Figure 4) that were not eliminated by masking. The full spectrum out to 640 Hz showed clear peaks at 160 and 192 Hz, and very large responses at 280, 500, and 560 Hz. (The genesis of these artifacts will be examined mathematically in the discussion.) Beats and alternating SAM tones caused artifacts at frequencies equal to half the modulation frequencies (asterisks in the lower two responses on the right) as well as physiological responses (eliminated by masking) indicated by the filled triangles in the lower two responses on the left.

### Experiment 2: Choice of Stimuli

The effects of the different stimuli are shown in rows 2, 4, and 5 of Figure 4. Using an AD conversion rate of 500 Hz, the beats and the alternating SAM stimuli did not elicit artifacts at the frequencies of modulation; that is, any responses in the region of 80 to 104 Hz were eliminated by masking noise indicating their physiological origin. However, there were clear artifacts at frequencies equal to one-half the modulation frequencies of the stimuli, since these remained in the presence of a masking noise (asterisks). The alternating SAM stimuli also showed artifacts at frequencies equal to 1.5 times the modulation frequencies (not within the range of the spectra plotted in Figure 4).

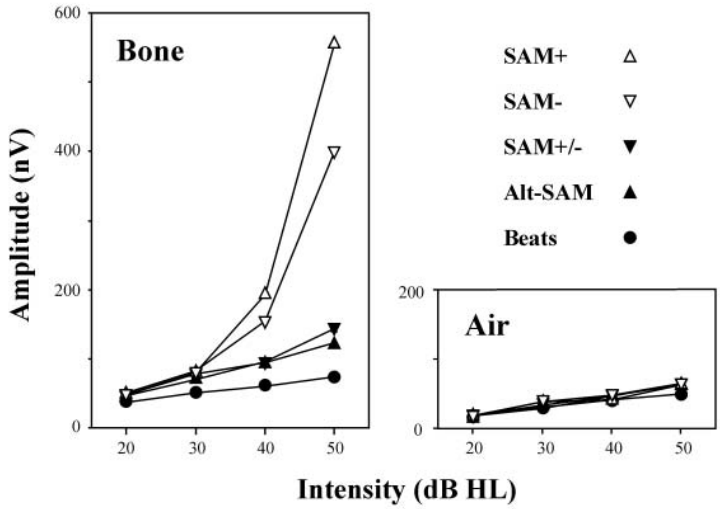


**Figure 5.** Responses to air- and bone-conducted stimuli-amplitudes. This figure shows the mean amplitudes from six subjects. The AC responses are about half the amplitude of the uncontaminated BC responses. One would expect the BC responses to be about twice the size of the monaural AC responses because the BC stimuli activate both ears. Responses are shown separately for the SAM stimuli (SAM+), the inverted SAM stimuli (SAM-), and the average of these two responses (SAM+/-). The responses to BC SAM+ and SAM- stimuli are much larger than expected from the AC stimuli at 50 dB HL (and significantly larger at 40 dB).

### Experiment 3: Bone-Conduction Stimuli

The mean data for this experiment are presented in Figures 5 and 6. At 50 dB HL the amplitudes of the responses to the SAM and the inverted SAM tones were about 10 times larger for the BC stimuli than for the AC stimuli (Figure 5). In addition, the phases of the BC responses at 50 dB HL differed by almost 180 degrees (Figure 6). Lesser differences were also noted at 40 dB HL. The BC responses to the beats and alternating SAM stimuli and the average of the responses to the SAM- and SAM+ stimuli were similar to those of the AC responses although about one-half the amplitude. Figure 7 presents data from one subject at 40 dB for the BC stimuli.

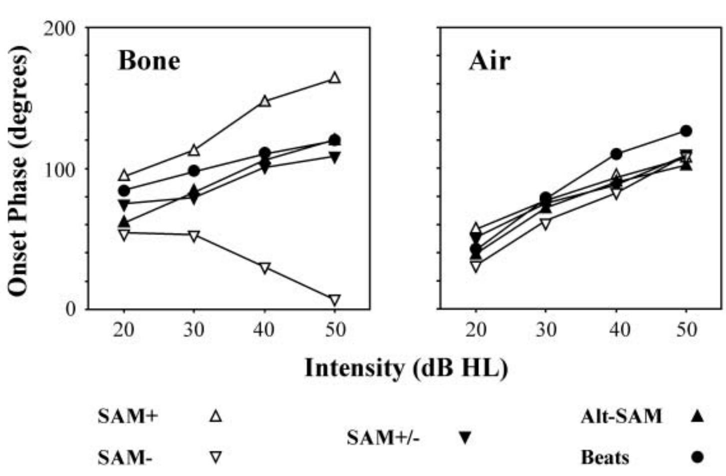


**Figure 6.** Responses to air- and bone-conducted stimuli-phases. This figure plots the onset-phases of the responses vector averaged over six subjects. Phase delay increases as the onset phase decreases (i.e., as the intensity decreases). The phases of the SAM+ and SAM- responses to BC stimuli are almost 180 degrees different at 50 dB HL and significantly different from the AC responses at 40 dB HL.

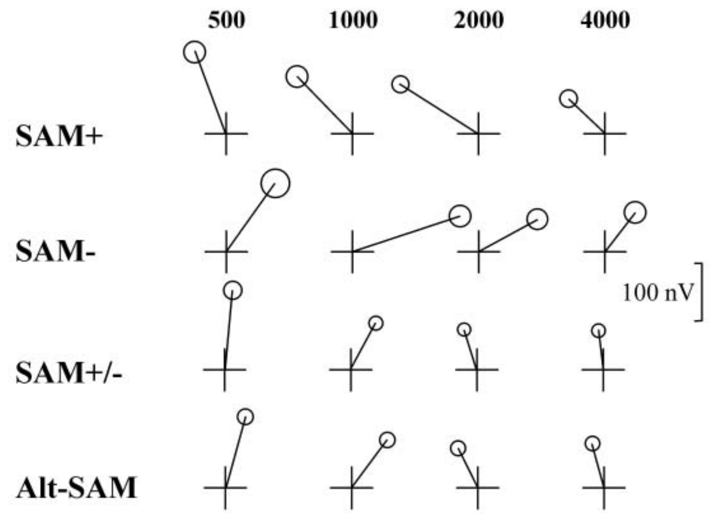


**Figure 7.** Reponses to bone-conducted stimuli. This figure plots the responses at each of the carrier frequencies for one subject to three of the types of stimuli used in Experiment 3. Also shown are the average responses for the SAM+ and SAM- stimuli. The intensity of the stimuli was 40 dB HL (responses would have been too large to display easily at 50 dB HL). The responses are represented as polar plots, showing the amplitude as the length of the vector, the onset phase as the counterclockwise angle from the x-axis, and the noise limits as the radius of the circle. The responses to the SAM+ and SAM- stimuli represent a combination of the responses (shown in the SAM+/- response) with an artifact, which is 180 degrees out of phase for the two stimuli (close to 0 degrees for the SAM- stimulus and close to 180 degrees for the SAM+ stimulus).

### Experiment 4: Choice of Stimuli (Air Conduction)

The mean amplitudes for this experiment are shown in Figure 8. The ANOVA showed a main effect of stimulus intensity ($F = 68.3$, $df = 3,33$, $p < 0.001$), a main effect of stimulus type ($F = 14.0$, $df = 2,22$, $p < 0.001$), and an interaction between these two factors ($F = 6.3$, $df = 6,66$, $p < 0.01$). Other main effects and interactions did not reach significance. Post hoc testing showed that the responses to the conventional SAM and to the alternating SAM tones were significantly larger than the responses to the beats, and not significantly different from each other. The interaction was caused by the differences between stimuli being less at lower intensities.

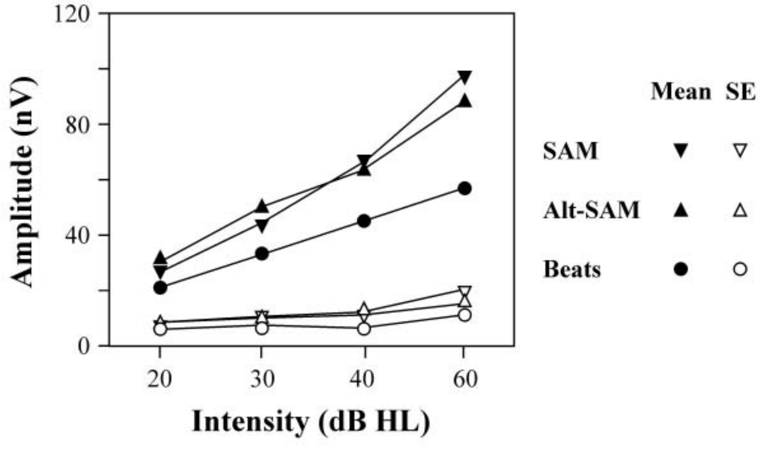


**Figure 8.** Choice of stimuli. This figure graphs the effects of intensity and stimulus type on the amplitude of the responses. Both means (over 12 subjects) and standard errors of the means are plotted. The responses to the beats are significantly smaller than to the other stimuli.

## DISCUSSION

### Electromagnetic Artifacts

When currents are converted into sound by an acoustic transducer, electromagnetic fields are generated. These fields can be picked up as artifacts by the electrodes that record the EEG. The size of the artifacts will vary with the transducers. BC transducers will cause more artifact than AC transducers, and earphones more than insert phones. The size of the artifact will also vary with intensity of the stimulus, the distance between the transducer and the recording circuits, and the geometry of both the electromagnetic field and the recording circuits. The common practice of braiding the electrode wires reduces the artifact by reducing the area through which the magnetic field passes when inducing currents in the circuit made up by the electrode wires and the scalp. The artifact will also vary with different electrode montages, with electrodes that are farther apart resulting in greater artifact (again, because the circuit area is likely larger).

If the transducer is linear, the electromagnetic field will contain only those frequencies present in the signal. There should be no artifact at the modulation frequency of SAM tones. This is shown in the upper part of Figure 3 where the artifacts are present at the carrier frequencies with two side bands separated from each carrier by the modulation frequency. Energy is not present at the frequencies of modulation.

### Aliasing

When sampling at a rate of $f_s$, the amplitude or power spectrum only contains frequencies up to the Nyquist frequency, which is equivalent to $f_s/2$. Frequencies of $Kf_s \pm f_a$ (where K is an integer) are aliased into the spectrum at frequency $f_a$ (Lyons, 1997, especially section 2.10, "Aliasing"). This is illustrated in Figure 1, where a 420 Hz signal sampled at 500 Hz is aliased to 80 Hz. This process is often considered as a "folding" of the spectrum back onto itself with the folds occurring at integer multiples of the Nyquist frequency (Figure 9). The typical

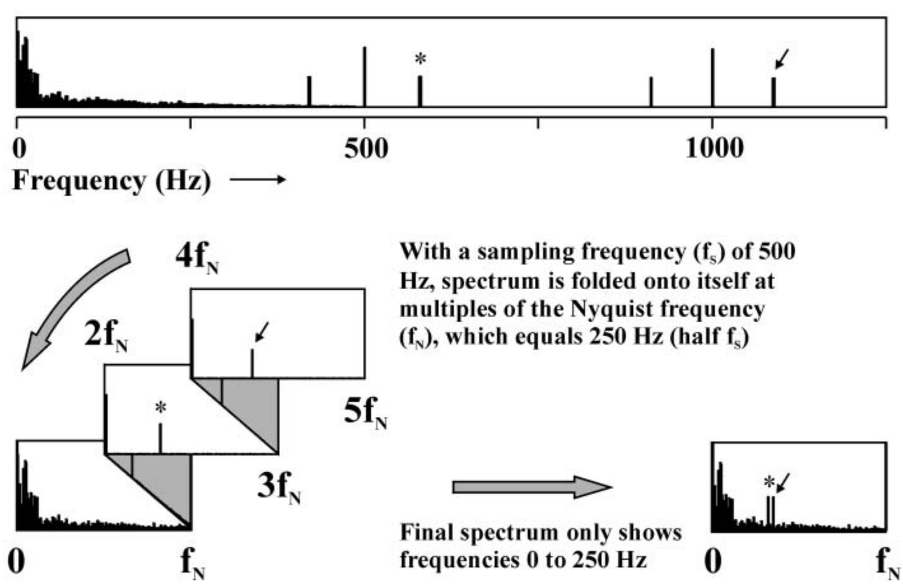


**Figure 9.** Process of aliasing. This figure illustrates the process of aliasing using part of the spectrum recorded at an AD rate of 8000 Hz shown in the upper left of Figure 3. The spectrum is plotted at the top of the present figure within the limits of 0 and 1250 Hz (the rest of the spectrum is not shown to simplify the presentation). Aliasing can be considered as a "folding" of the frequencies above the Nyquist frequencies back into the spectrum. The lower left of the figure shows the folding that would occur if the activity had been recorded with an AD rate (or sampling frequency) of 500 Hz. The folding occurs at multiples of the Nyquist frequency (250 Hz). The upper side band activity of the 500 Hz SAM tone, occurring at 580 Hz (asterisk), is folded back into the spectrum at 80 Hz (i.e., 580 - 500 = 80). In the gray fold, the lower side band, occurring at 420 Hz, is also aliased at 80 Hz (i.e., 500 - 420 = 80). (The process for this particular frequency is also illustrated in Figure 1). The energy at 500 Hz is aliased into the first bin of the spectrum, since it occurs at the fold. The upper side band of the 1000 Hz SAM tone, occurring at 1088 Hz (arrow), is aliased into the spectrum at 88 Hz together with the lower side band at 912 Hz (in the gray folded region). The final spectrum (lower right) only contains frequencies between 0 and 250 Hz. There are artifacts at 80 and 88 Hz. This diagram does not show the aliasing of frequencies above 1250 Hz, which would result in additional artifacts at 96 and 104 Hz (as shown in the lower left of Figure 3).

case occurs when we have artifacts using an AD rate of 500 Hz and multiple SAM stimuli with carrier frequencies ($f_c$) equal to integer multiples of this AD rate (e.g., 500, 1000, 2000, and 4000 Hz). The spectra of the SAM tones contain energy at $f_c$ and at two side bands ($f_c \pm f_m$). The energy at the carrier frequencies is aliased into the spectrum at 0 Hz. The side bands, which are separate from the carriers by the modulation frequency, are aliased back into the spectrum at the modulation frequency. This contaminates the recording of any physiological responses that follow the modulation frequency, since the artifact-related energy occurs in the same frequency bins as the responses. In Figure 8, the side bands at 420 and 580 Hz (asterisk) are folded back into the spectrum at 80 Hz, and side bands at 912 and 1088 Hz (arrow) are folded back at 88 Hz.

The amount of activity picked up in the spectrum will vary with the phase of the signals and the relative phase between the AD conversion and the artifactual signals (Figure 1). Because of the phase changes occurring during the electromagnetic induction and in the amplification of the signals, the amount of aliased artifact (and its phase) is not simply predictable.

If a physiological response is present, the aliased artifact will be vector-added to this response. The responses indicated with open triangles in the second row of Figure 4 combine physiological responses (similar to those recorded with the 8000 Hz AD rate in the first line) and artifacts (shown on the right after masking removes the physiological responses). With the BC stimuli, we recorded responses to both SAM tones and inverted SAM tones. The artifact was 180 degrees different in phase for these two stimuli (Figure 6). At 50 dB HL the artifact was much larger than the physiological response (Figure 5), and the vector combination of the two was effectively the same as the artifact. The responses to the SAM+ and SAM- tones were 180 degrees out of phase. At 40 dB HL the artifact was smaller—a change of -10 dB is equivalent to dividing the amplitude by 3.2. It then becomes of similar magnitude to the physiological response. Vector addition results in a response that is bigger than the physiological response and has a phase somewhere between the phase of the physiological response and the artifact. This can be seen in the vector plots of Figure 7.

The usual way to prevent aliasing is to filter the signal prior to AD conversion. Anti-aliasing filters reduce the energy in the signal at frequencies above the Nyquist frequency. Our low-pass filter was set at 300 Hz, which was close to the Nyquist frequency (250 Hz) when using an AD conversion rate of 500 Hz (and below the Nyquist frequency for our more usual AD rate of 1000 Hz). The fall-off of the filter (6 dB/octave) was not very steep. The intensity of acoustic signals are changed in logarithmic fashion (i.e., in dB), and at high intensities the stimulus artifact is very large. The size of the recorded stimulus artifact could therefore have been quite large despite the filtering (upper left of Figure 3). The addition of a filter with a steeper cut-off (24 dB/octave) and lower low-pass setting of 250 Hz significantly attenuated the stimulus artifacts (upper right of Figure 3) and eliminated the problem caused by aliasing them back to the modulation frequencies.

The stimulus artifact is likely due to the electromagnetic induction of currents in the electrode circuits prior to amplification. The artifact may also have been picked up after the amplification but prior to AD conversion (e.g., as crosstalk between the DA and AD channels). However, the fact that the extra filtering eliminated the artifacts (Figure 3) showed that the artifact occurred before or during the amplification. If there were some contamination with stimulus artifact after the amplification of the EEG, the anti-aliasing filter would not have helped.

Changing the AD rate so that it is not a submultiple of the carrier frequencies, or their side bands, can deflect the aliased artifact to locations in the spectrum other than the region where one is evaluating responses (Small and Stapells, in press). Aliasing occurs at frequencies equal to the absolute difference between an integer-multiple of the sampling rate and the recorded frequency. When the AD rate is a submultiple of the carrier frequencies, the carrier frequencies are all aliased at 0 Hz, and each pair of side bands is aliased to the modulation frequency. When the AD rate is set to 1280 Hz, the carrier frequencies (above 640 Hz) are aliased back as 160 (4000 - 3x1280), 280 (1280 - 1000), and 560 (2x1280 - 2000) Hz. Close to the region of the responses, the side bands would give artifacts at 56 (3896 - 3x1280) and 192 (1280 - 1088) Hz. The 56 Hz component was only occasionally visible in our recordings (Figure 4, right), but the others were larger (though not shown in the limited spectrum displayed in Figure 4). Since the carriers and the side bands are all aliased separately, one has to check to make sure that none of these are contaminating the recordings at the modulation frequencies. It is also important to ensure that artifacts do not occur in frequency bins adjacent to the responses, since these are used to create a noise estimate (John and Picton, 2000). Artifactual contamination of these frequencies would increase the size of the noise estimate and therefore make it harder for the evoked response to reach significance.

### Stimulus Approaches to the Aliasing Artifact

The aliased artifact can also be deflected away from the region of the modulation frequencies by using different stimuli. The carrier frequencies can be changed so that these are not multiples of the AD rate. For example, using an AD conversion rate of 1000 Hz and a SAM tone with $f_c$ of 1060 Hz and $f_m$ of 88 Hz (i.e., side bands at 972 and 1148 Hz) will alias stimulus artifact at 28 (1000 - 972), 60 (1060 - 1000), and 148 (1148 - 1000) Hz. We did not formally evaluate this approach, but it is a feasible solution to the artifact problem.

The spectrum of beats and alternating SAM tones contain frequencies at $f_c \pm f_m/2$. These are aliased at $f_m/2$ and do not interfere with assessing the responses at $f_m$. The alternating SAM tones also contain energy that is aliased at $3f_m/2$ (Figure 2). (The spectrum of the stimulus contains energy separated from the envelope frequency by $f_m/2$ and $3f_m/2$). While the spectra of the two stimuli are similar, the alternating SAM tone evokes responses that are significantly larger than those evoked by the beats (Figure 8). This is probably due to the larger "gaps" between the "bursts" of the AM stimuli, and the steeper slopes, which exist in the alternating SAM tones compared to the beats (John, Dimitrijevic et al, 2002). Alternating SAM tones are preferable to beats for threshold-evaluation, since the larger responses increase the speed of detecting responses.

### Other Sources of Stimulus Artifact

In addition to the induction of currents in the electrode wires by electromagnetic fields, artifacts can be introduced into the recording circuits through leakage currents that occur after the amplification of the EEG signals. These are generally very small. As for the acoustic transduction, the energy should not be at the envelope frequency. However, nonlinearities may occur during the leakage process, and aliasing can occur if the leakage happens after the amplification/filtering and before the AD conversion (e.g., through crosstalk between the DA and AD channels). If one short-circuits the input electrodes and makes a recording, small signals may still be recorded at the stimulus modulation frequencies. Since there is no background noise in the recording, these tiny signals will be significantly different from the level of activity at adjacent frequencies. In our research MASTER system this leakage signal is measured as about 1 nV when the pre-amplifier is set at 10,000X. The leakage is actually causing a signal of 10 mV in the circuit after the amplification. This is far below the normal level of background activity when recording the ASSRs. Accordingly, when a subject is attached to the system, these small artifacts are lost in the residual EEG noise. After averaging for 5 minutes, the noise levels are generally 10–20 nV (see discussion in John, Purcell et al, 2002). However, one should be careful to amplify the EEG signal sufficiently so that the leakage is indeed smaller than the background EEG (i.e., "noise"). If the pre-amplifier is set at 1,000X, the leakage could be measured as about 10 nV, since the relative magnitude of the amplified signal is smaller with respect to the artifact added to this signal as it travels through the postamplification circuitry. Accordingly, using a lower amplification setting can lead to an increased chance of detecting artifacts as responses. Using alternating SAM stimuli or beat stimuli deflects the leakage artifacts away from the modulation frequencies to one-half these frequencies (and also to 1.5 times these frequencies for the alternating SAM stimuli), leaving virtually no leakage artifact at the modulation frequencies. The recorded amplitudes at the frequencies of modulation are then below the system noise levels, equivalent to about 0.05 nV when using a pre-amplification of 10,000X. Using AD conversion rates that are not integer submultiples of the carrier frequencies also eliminates these artifacts. Anti-aliasing filters will not affect these leakage artifacts that occur after the filtering and before the AD conversion.

**Bone-Conducted Stimuli**

BC stimuli elicit clear artifacts at intensities of 40 dB HL and above. It is likely that there is artifact contamination also at 30 dB HL in some subjects. This may vary with the placement of the vibrator and the electrodes. The responses to BC stimuli were about twice the amplitude of the responses to AC stimuli of similar intensity relative to threshold (Figure 5). This is due to the BC stimuli evoking responses from both ears (see discussion in Lins et al, 1996). Stimulus artifacts are less of a problem if one uses the sensorineural acuity level (SAL) procedure (e.g., Cone-Wesson et al, 2002). In this technique, unmodulated narrowband noise is presented through the BC transducer while responses are recorded to modulated AC stimuli. At typical levels, the BC noise will likely cause artifact. However, since it is not related to the modulation frequencies of the stimuli, such artifact will not affect the responses, though it might raise the level of the background EEG noise and make it more difficult to recognize the responses. The modulated AC stimuli are usually presented at levels below those at which artifact might be expected. Nevertheless, the SAL technique requires more recording time (both masked and un-masked thresholds must be estimated) and is limited by the levels that can be tested, and by the accuracy of calibrating the normal BC masking effect.

**Physiological Artifacts**

Small and Stapells (in press) discuss possible physiological artifacts. Some stimuli may evoke responses from regions of the brain not related to auditory processing or from physiological generators other than the brain. In terms of the objective assessment of hearing, these can be considered physiological artifacts. For example, reflex responses in the postauricular (O'Beirne and Patuzzi, 1999) or sternocleidomastoid (Welgampola and Colebatch, 2001; Welgampola et al, 2003) can be evoked by high-intensity sounds. These might be mediated through the cochlear or vestibular end-organs. Vestibular brain responses might also occur (e.g., de Waele et al, 2001) although these are difficult to dissociate from muscle reflexes in the scalp or extra-ocular muscles. Vestibular-mediated responses are larger for lower frequency stimuli (Todd et al, 2000; Welgampola et al, 2003). From the point of view of using MASTER, one should be aware that responses to high-intensity (e.g., above 60 dB SPL) and low-frequency (e.g., less than 1000 Hz) sounds may be mediated through the vestibular end-organ. Whether or not the vestibular activation that initiates these muscle responses can also mediate "hearing" (i.e., be interpreted as sound rather than changes in equilibrium) remains an open question.

**Prevalence of Artifacts**

This paper describes the artifacts that can be recorded when recording ASSRs due to the aliasing that can occur with particular settings of the stimulation and recording systems. These problems have been corrected in the MASTER system that is commercially produced by Bio-logic Systems Corporation. We have not determined whether such artifacts are recorded in other commercial systems for recording the ASSRs since we do not have access to these instruments. The occurrence of artifacts depends on the stimulus intensity, the AD conversion rates, the carrier frequencies, the anti-aliasing filters, and other aspects of the system design. A simple test for whether such artifacts are possible is to perform a recording with the sound on and the input electrodes short-circuited or resting in a saline solution. A more formal test is to record responses in profoundly deaf subjects (Gorga et al, 2004; Small and Stapells, in press).

## CONCLUSIONS

Artifacts from stimuli may interfere with recording auditory steady-state responses. They occur with bone conduction at intensities of 40 dB HL or more and with air conduction at intensities of 90 dB HL or more. Artifacts are most prominently caused by aliasing. They may be prevented by using anti-aliasing filters with steep filter slopes and/or procedures to deflect the artifact into regions of the spectrum distant from the frequencies of the steady-state responses.

Artifact deflection can be accomplished by ensuring that the AD rate is not an integer submultiple of the carrier frequencies or by using beats or alternating SAM tones. Choosing AD and DA conversion rates, modulation frequencies, carrier frequencies, and stimulus types for recording ASSRs requires care.

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