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(54) SYSTEM AND METHODS FOR OBJECTIVE EVALUATION OF HEARING USING AUDITORY STEADY-STATE RESPONSES

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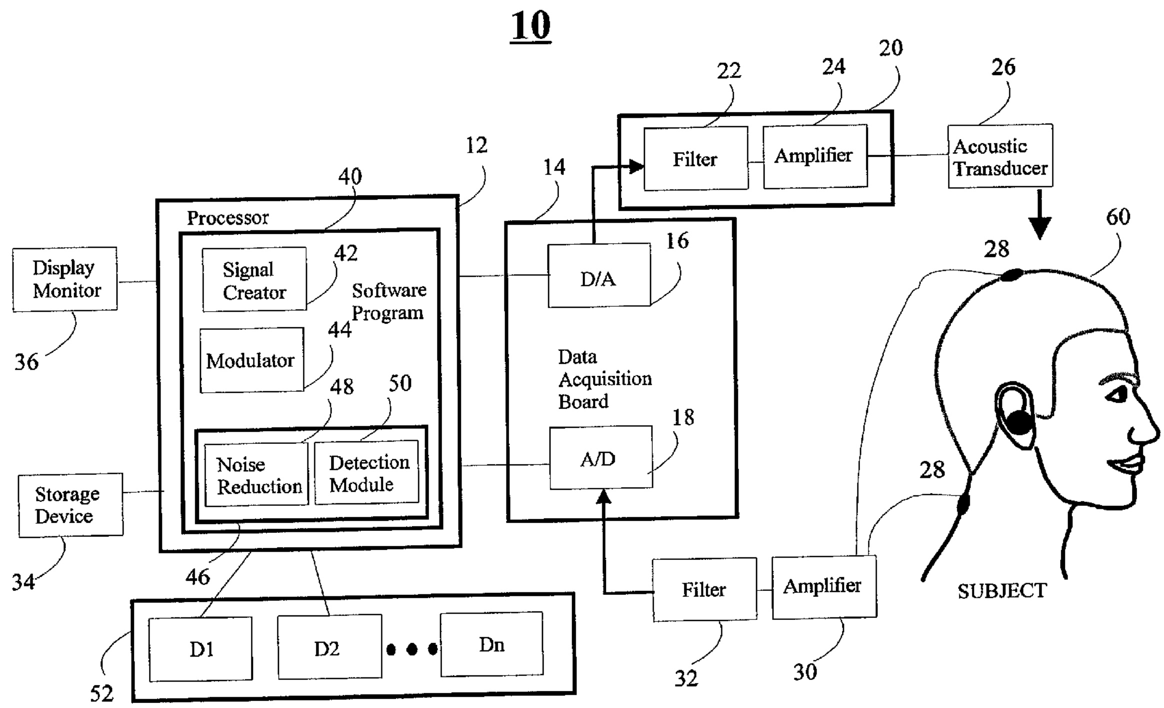
(57) **ABSTRACT**

This invention relates to an apparatus and method for assessing a subject's hearing by recording steady-state auditory evoked responses. The apparatus generates a steady-state auditory evoked potential stimulus, presents the stimulus to the subject, senses potentials while simultaneously presenting the stimulus and determines whether the sensed potentials contain responses to the stimulus. The stimulus may include an optimum vector combined amplitude modulation and frequency modulation signal adjusted to evoke responses with increased amplitudes, an independent amplitude modulation and frequency modulation signal and a signal whose envelope is modulated by an exponential modulation signal. The apparatus is also adapted to reduce noise in the sensed potentials by employing sample weighted averaging. The apparatus is also adapted to detect responses in the sensed potentials via the Phase weighted T-test or Phase zone technique. The apparatus may further perform a number of objective audiological tests including latency tests, AM/FM discrimination tests, rate sensitivity tests, aided hearing tests, depth sensitivity tests, suprathreshold tests and auditory threshold tests. The apparatus is further adapted to perform multi-modality testing in which more than one sensory modality of the subject is tested simultaneously.



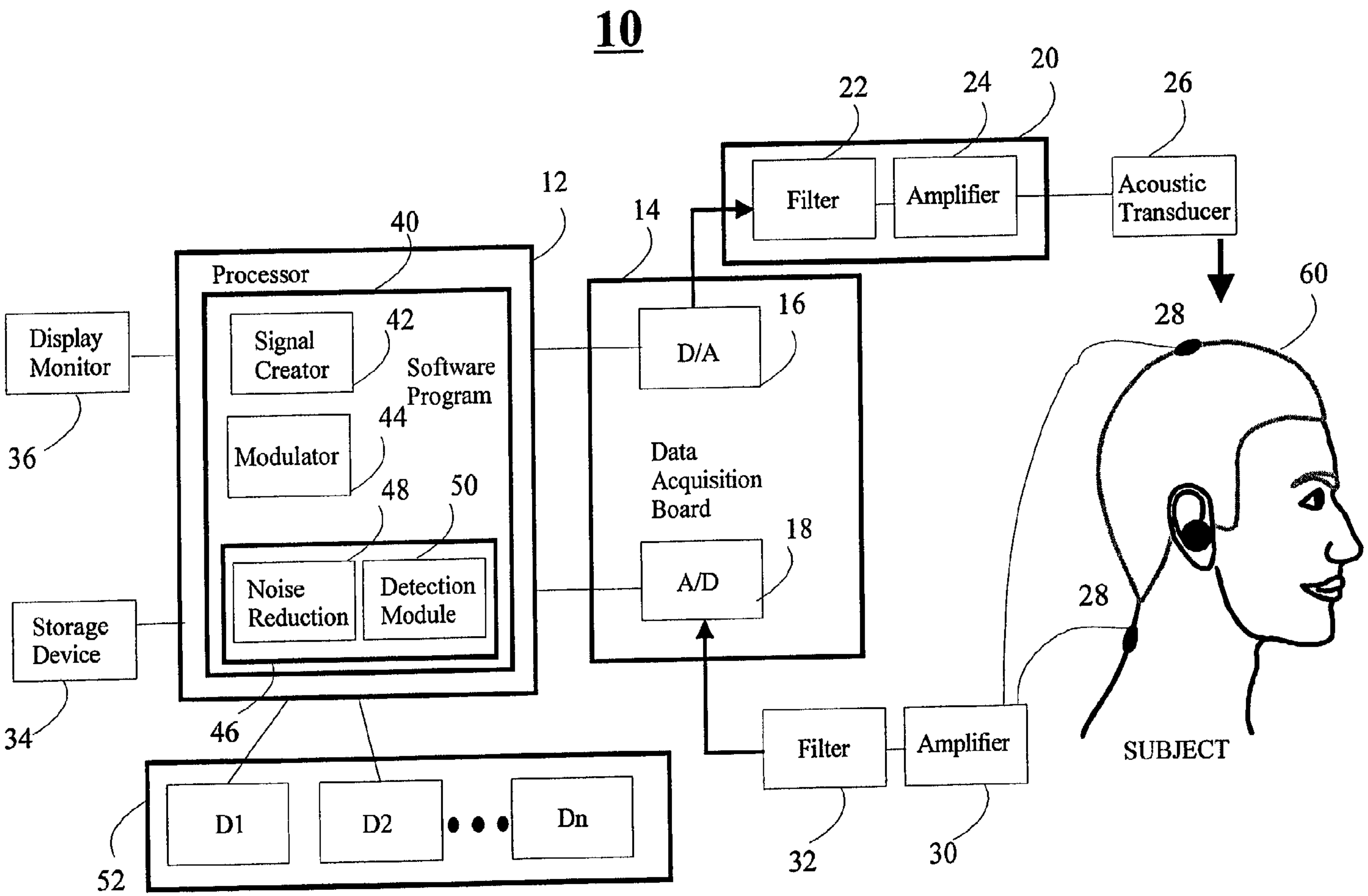

10
Processor
Software Program
Signal Creator
Modulator
Noise Reduction
Detection Module
Display Monitor
Storage Device
Data Acquisition Board
D/A
A/D
Filter
Amplifier
Acoustic Transducer
Filter
Amplifier
SUBJECT
D1
D2
Dn
12
14
16
18
20
22
24
26
28
28
30
32
34
36
40
42
44
46
48
50
52
60

FIGURE 1a

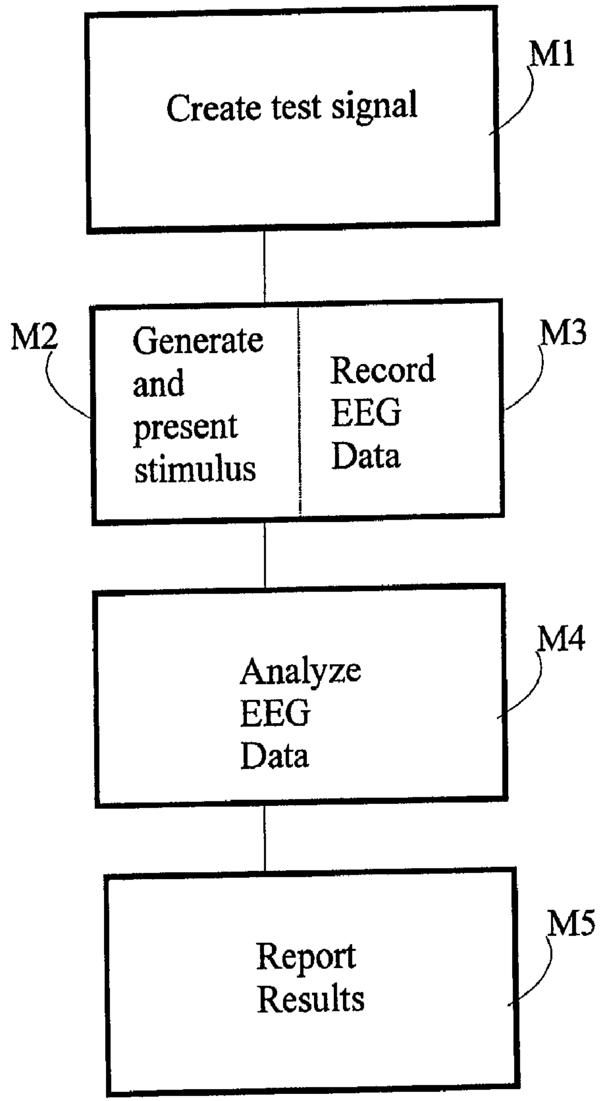

Create test signal
M1
M2
Generate and present stimulus
Record EEG Data
M3
Analyze EEG Data
M4
Report Results
M5

FIGURE 1b

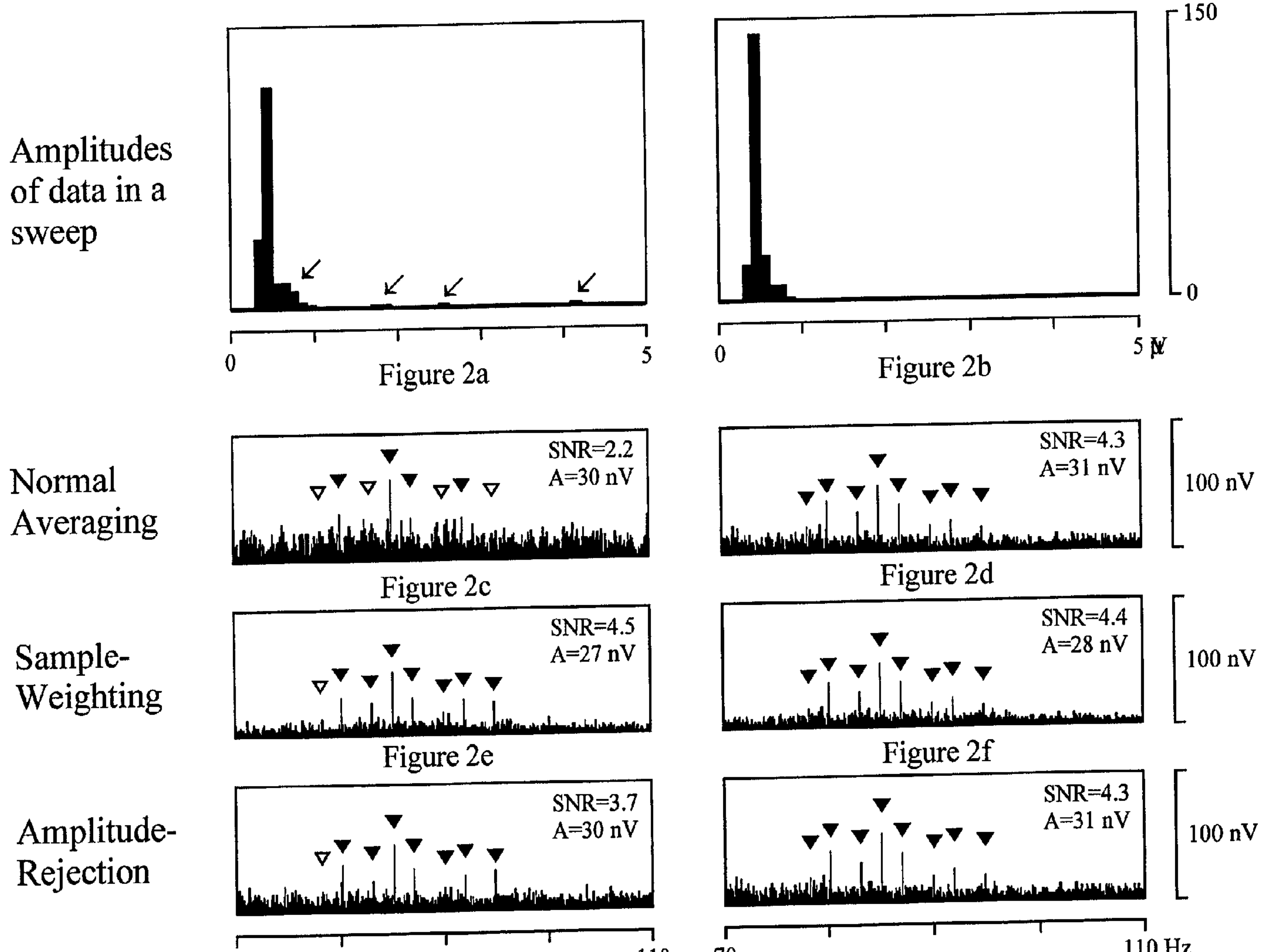


Figure 2a

Figure 2b

Figure 2c

Figure 2d

Figure 2e

Figure 2f

Figure 2g

Figure 2h

F=2.19; df 2,32; p=0.13
actual phase = 87 degrees

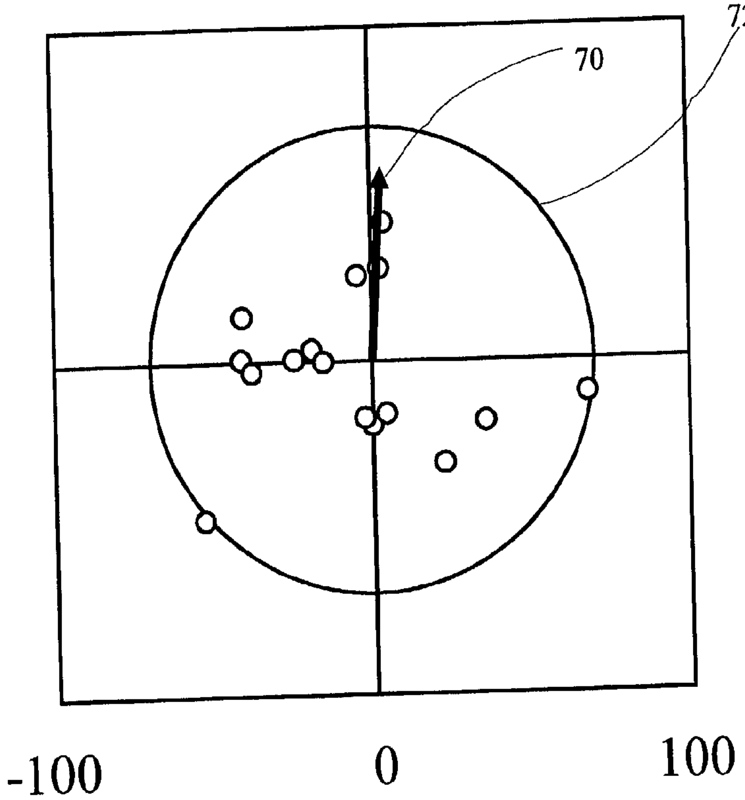


FIG 3a

t=2.29; df 15; p=0.02
expected phase = 104 degrees

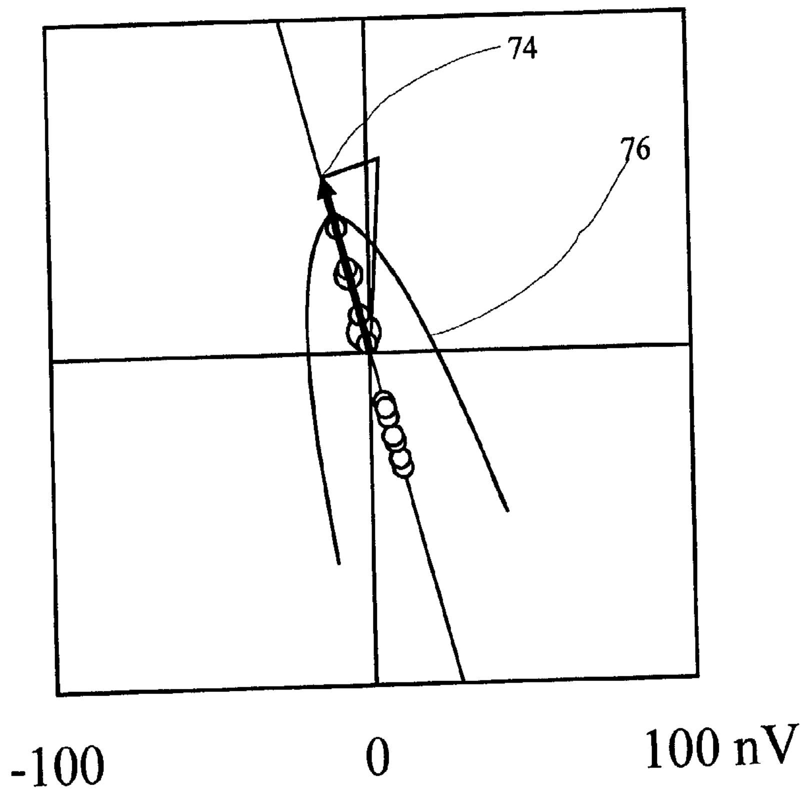


FIG 3b

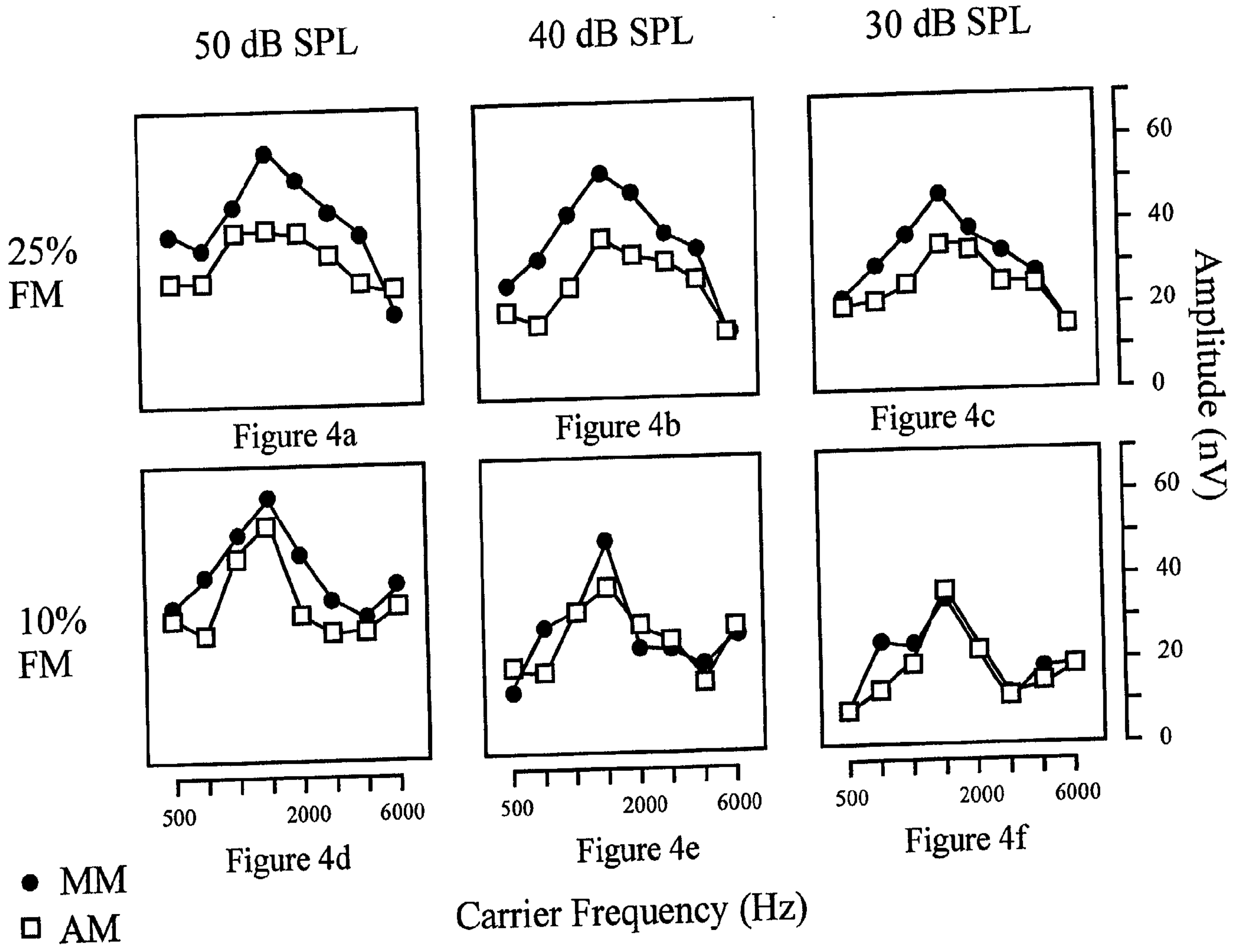


Figure 4a

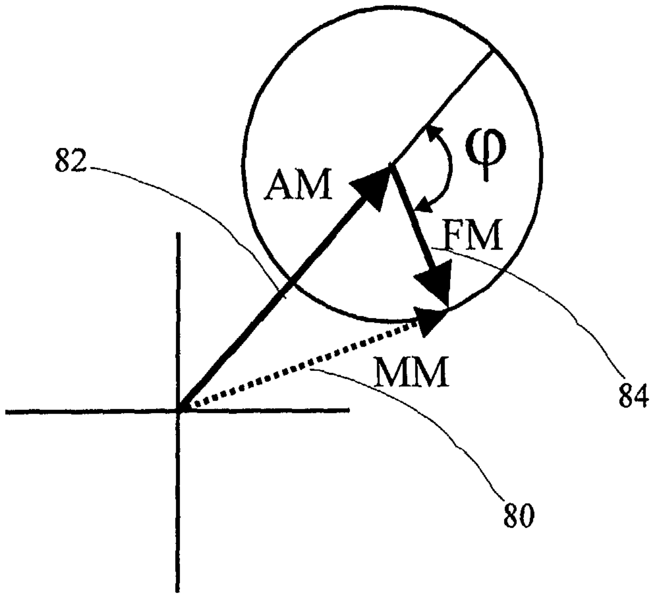
Figure 4b

Figure 4c

Figure 4d

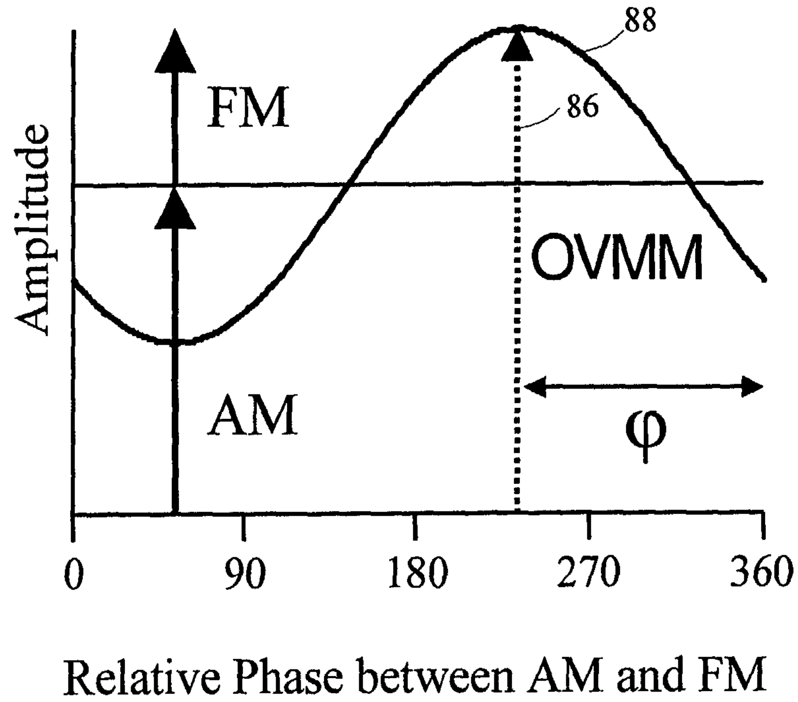
Figure 4e

Figure 4f



82
AM
φ
FM
MM
84
80

FIG 5a



88
86
FM
Amplitude
OVMM
AM
φ
0
90
180
270
360
Relative Phase between AM and FM

FIG 5b

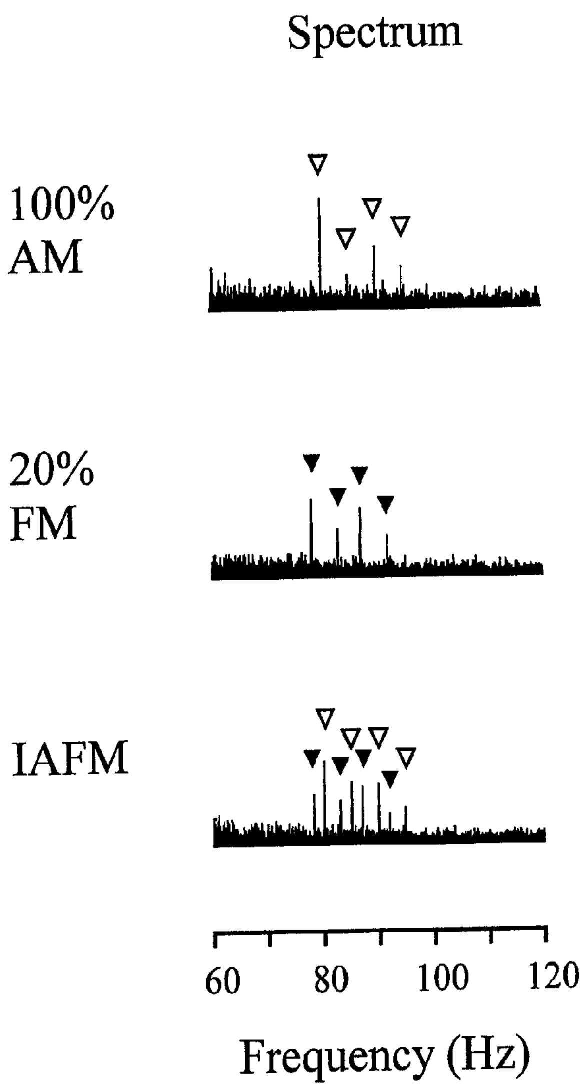

Spectrum
100% AM
20% FM
IAFM
60
80
100
120
Frequency (Hz)

FIG 6a

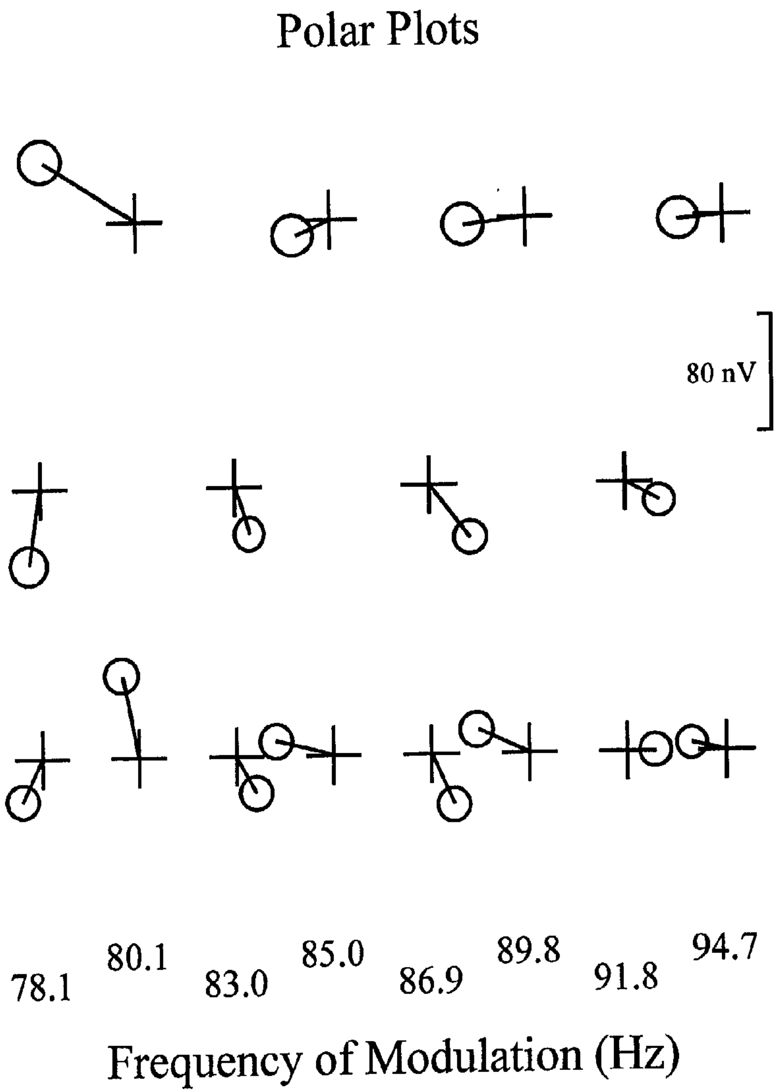
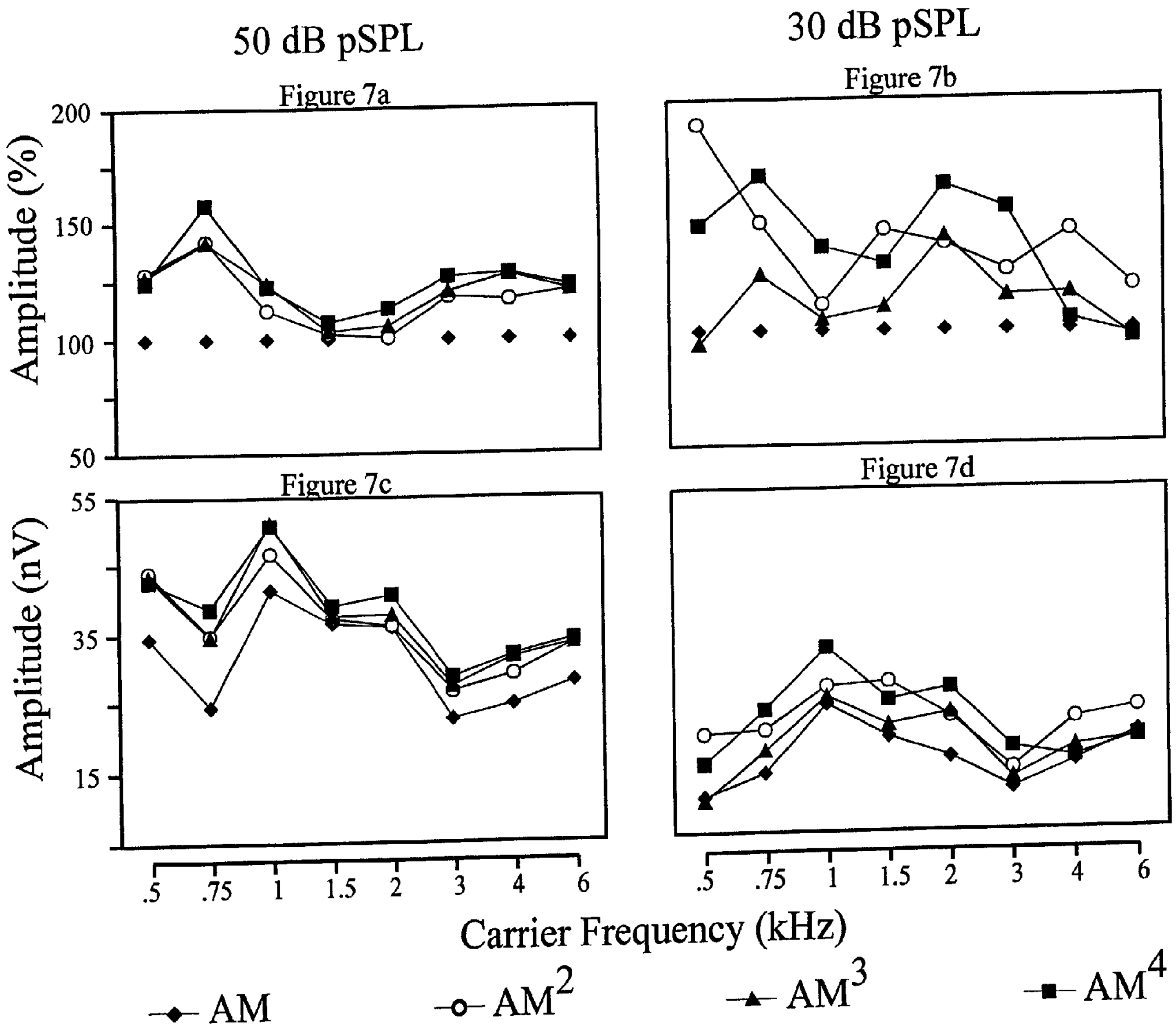

Polar Plots
80 nV
78.1
80.1
83.0
85.0
86.9
89.8
91.8
94.7
Frequency of Modulation (Hz)

FIG 6b


50 dB pSPL
30 dB pSPL
Figure 7a
Figure 7b
Figure 7c
Figure 7d
Amplitude (%)
200
150
100
50
Amplitude (nV)
55
35
15
.5
.75
1
1.5
2
3
4
6
Carrier Frequency (kHz)
AM
AM2
AM3
AM4

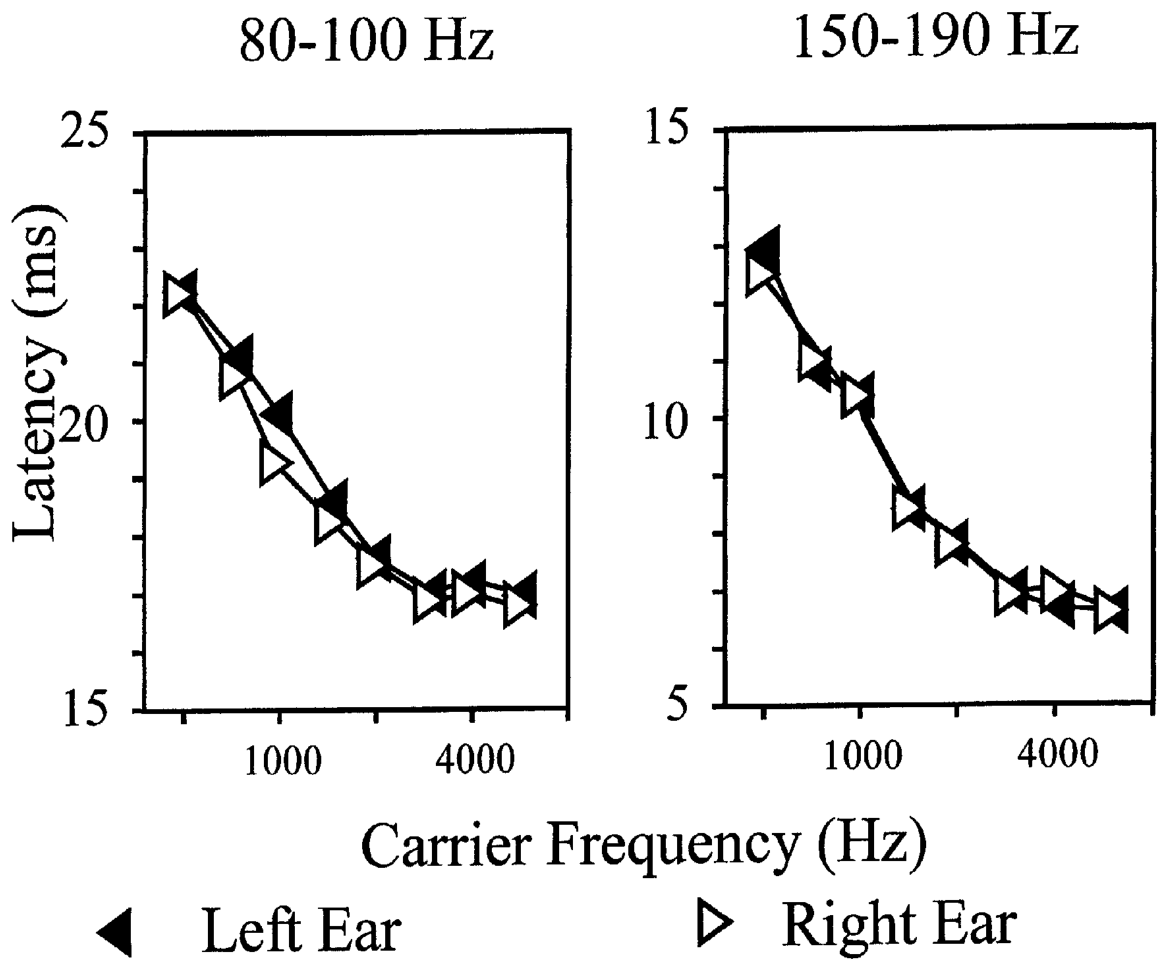

80-100 Hz
150-190 Hz
Latency (ms)
25
20
15
15
10
5
1000
4000
1000
4000
Carrier Frequency (Hz)
Left Ear
Right Ear

FIG 8

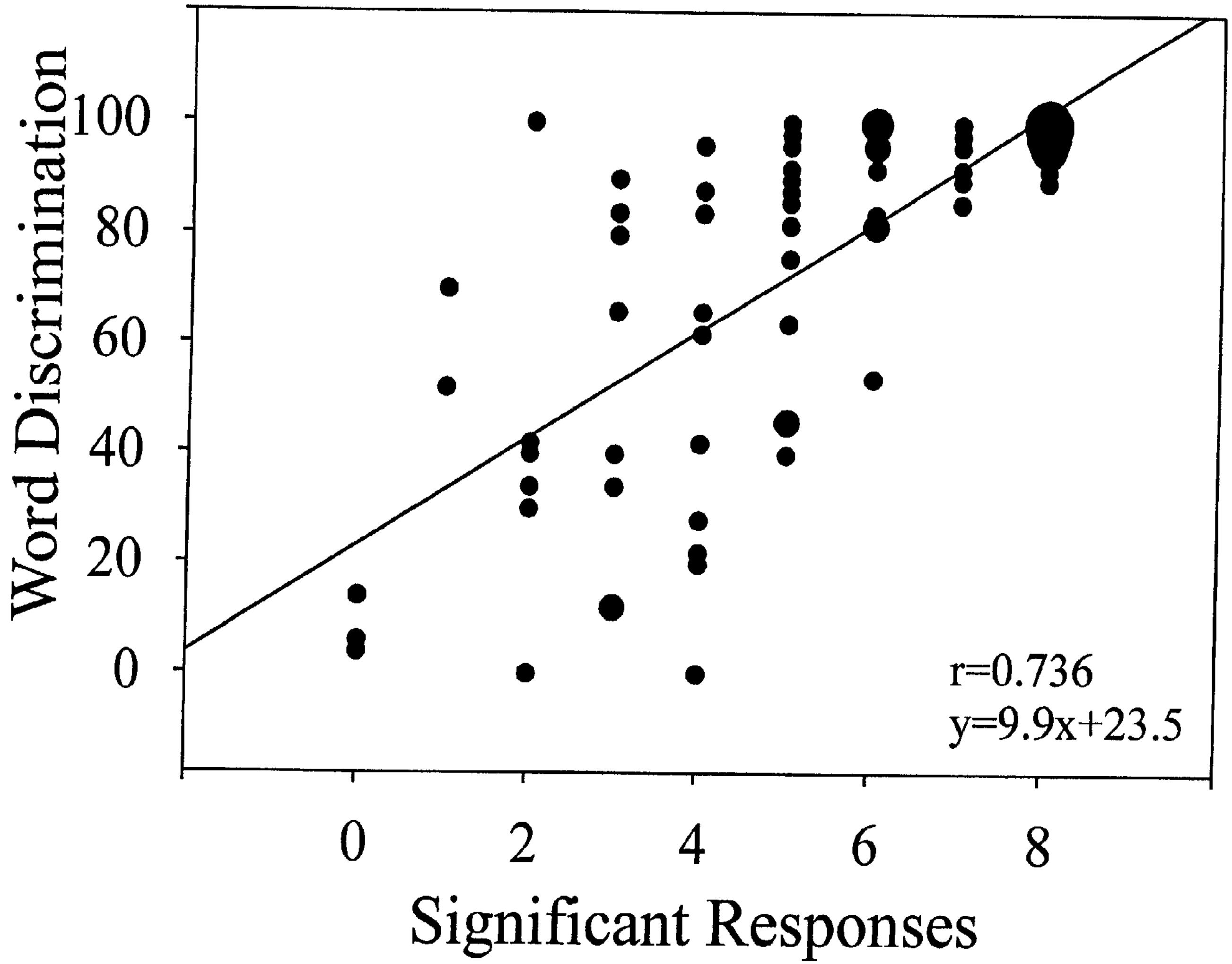
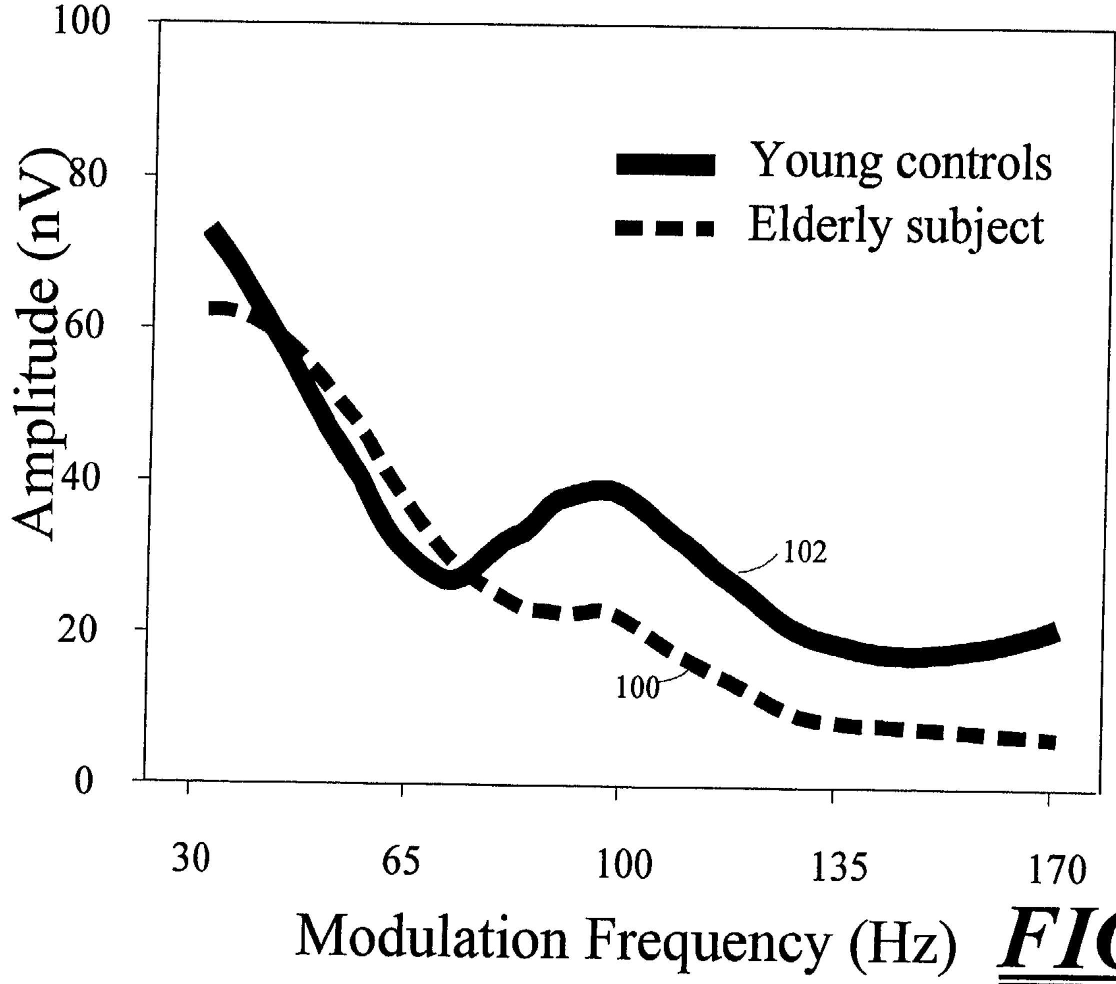

Word Discrimination
100
80
60
40
20
0
0
2
4
6
8
Significant Responses
r=0.736
y=9.9x+23.5

FIG 9



Amplitude (nV)
100
80
60
40
20
0
Young controls
Elderly subject
102
100
30
65
100
135
170
Modulation Frequency (Hz)

FIG 10

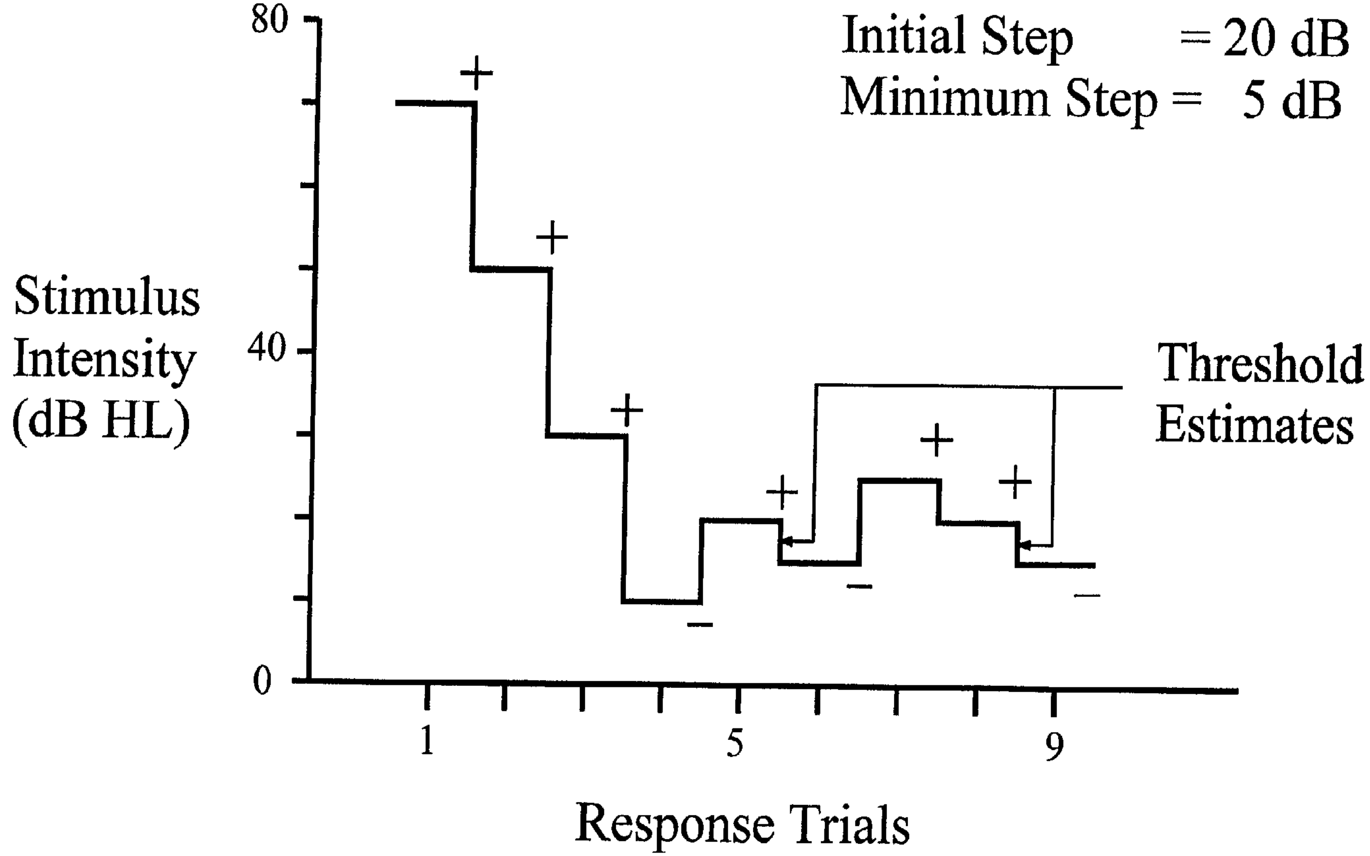
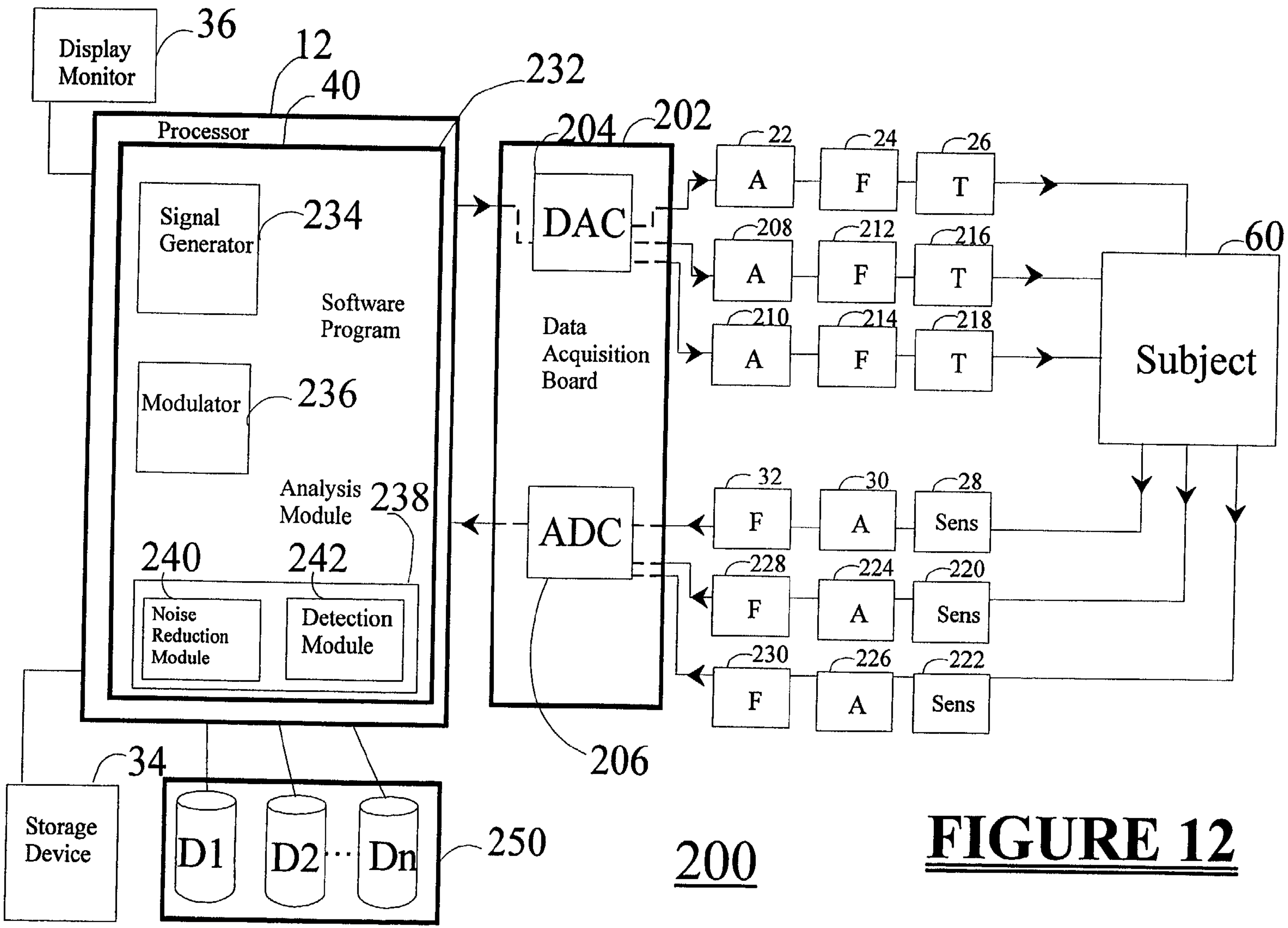

Initial Step = 20 dB
Minimum Step = 5 dB
Stimulus Intensity (dB HL)
80
40
0
Threshold Estimates
1
5
9
Response Trials

FIG 11



200

FIGURE 12

300

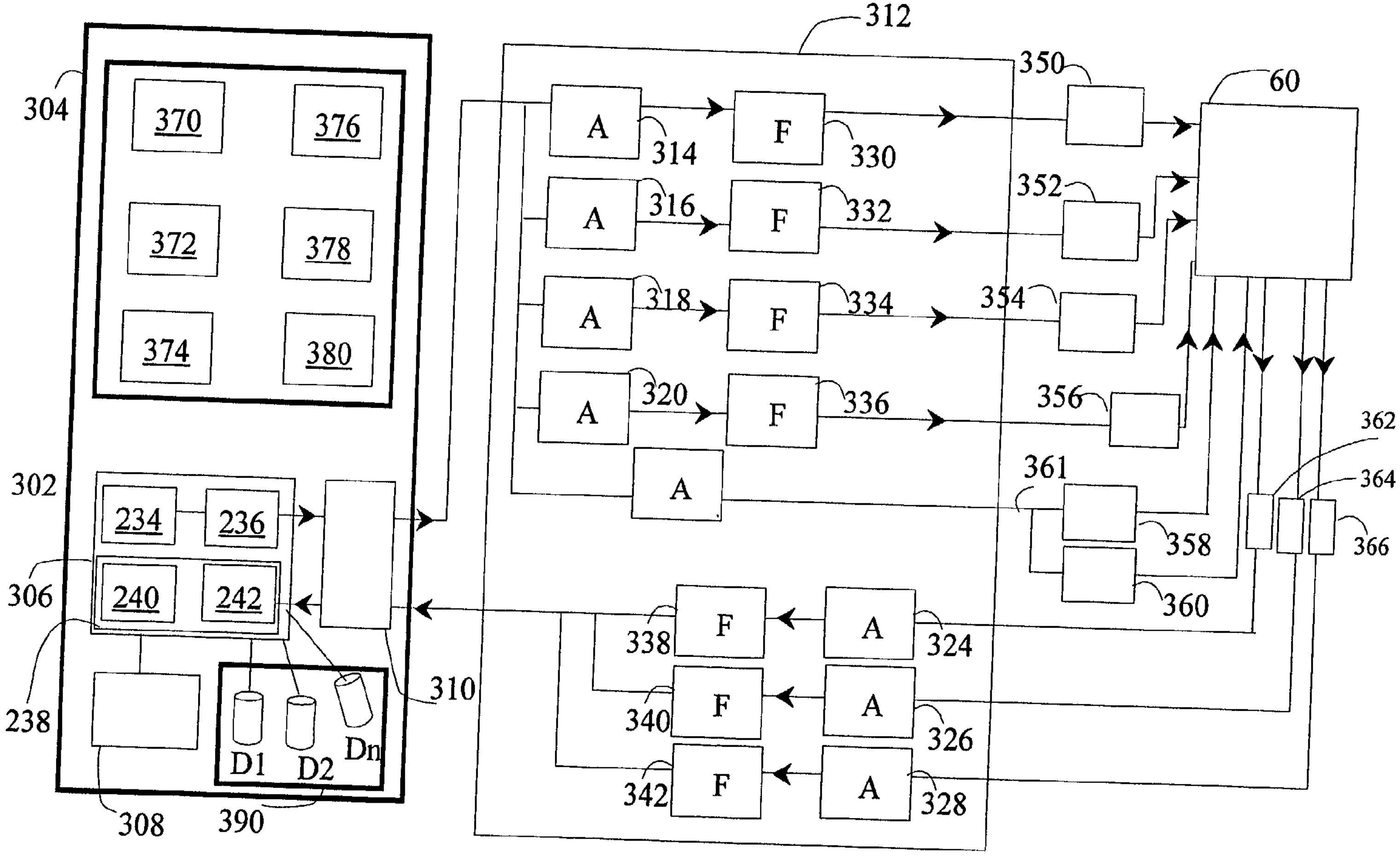


FIGURE 13

SYSTEM AND METHODS FOR OBJECTIVE EVALUATION OF HEARING USING AUDITORY STEADY-STATE RESPONSES

[0001] This application claims the benefit of Provisional Applications Serial No. 60/205,469, filed May 19, 2000, Ser. No. 60/247,999, filed Nov. 14, 2000 and Ser. No. 60/287,387, filed May 1, 2001.

FIELD OF THE INVENTION

[0002] This invention is in the field of auditory assessment and relates to the identification and evaluation of hearing impairment. More particularly, the invention describes a system and method for objectively evaluating an individual's hearing abilities by recording auditory steady-state responses.

BACKGROUND OF THE INVENTION

[0003] Hearing-impairment is a significant health problem, particularly at the two ends of the human life span. Approximately one in a thousand newborn infants and more than a quarter of adults over the age of 65 have a significant hearing loss. In the case of infants, early detection of hearing loss is necessary to ensure that appropriate treatment is provided at an early stage and that the infant can develop normal speech and language. The detection of a hearing-impairment requires a measurement of how well someone can hear sound (i.e. audiometry).

[0004] Conventional audiometry is performed by having a subject respond to acoustic stimuli by pressing a button, saying "yes", or repeating words that may be presented in the stimulus. These tests are subjective in nature. Audiometry allows an audiologist to determine the auditory threshold of the subject, which is defined as the lowest intensity at which a sound can be heard. The audiologist evaluates the auditory threshold of a subject by using a stimulus that most commonly consists of a pure tone. The stimulus is presented via earphones, headphones, free field speakers or bone conduction transducers. The results are presented as an audiogram which shows auditory thresholds for tones of different frequencies. The audiogram is helpful for diagnosing the type of hearing loss a subject may have. The audiogram can also be used to fit a hearing aid and adjust the level of amplification of the hearing aid for subjects who require hearing aids.

[0005] Audiometry may also involve subjective testing at supra-threshold intensities to determine how well the subject's auditory system discriminates between different sounds (such as speech) presented at intensities at which they normally occur. The audiologist will therefore determine how many simple words a subject can accurately recognize at different intensities with and without different amounts of background noise. The audiologist may also conduct tests which measure how well the subject can discriminate changes in the intensity or frequency of a sound or how rapidly these changes occur.

[0006] Conventional audiometry cannot be performed if the subject is an infant, young child or cognitively impaired adult. In these cases, objective tests of hearing are necessary in which the subject does not have to make a conscious response. Objective audiometry is essential for detecting hearing impairment in infants or elderly patients as well as for evaluating functional hearing losses. Furthermore, few objective tests have been developed for supra-threshold tests of speech, frequency, or intensity discrimination.

[0007] One form of objective audiometry uses auditory evoked potentials. Auditory evoked potential testing consists of presenting the subject with an acoustic stimulus and simultaneously or concurrently sensing (i.e. recording) potentials from the subject. The sensed potentials are the subject's electroencephalogram (EEG) which contain the subject's response to the stimulus if the subject's auditory system has processed the stimulus. These potentials are analyzed to determine whether they contain a response to the acoustic stimulus or not. Auditory evoked potentials have been used to determine auditory thresholds and hearing at specific frequencies.

[0008] One particular class of auditory evoked potentials is steady-state evoked potentials (SSAEPs). The stimulus for the SSAEP consists of a carrier signal, which is usually a sinusoid, that is amplitude modulated by a modulation signal which is also usually a sinusoid. The SSAEP stimulus is presented to the subject while simultaneously recording the subject's EEG. If the auditory system of the subject responded to the SSAEP stimulus, then a corresponding steady-state sinusoidal signal should exist in the recorded EEG. The signal should have a frequency that is the same as the frequency of the modulation signal (i.e. modulation frequency). The presence of such a corresponding signal in the EEG is indicative of a response to the SSAEP stimulus. Alternatively, the phase of the carrier signal may be frequency modulated instead of or in addition to amplitude modulation to create the SSAEP stimulus.

[0009] The SSAEP stimulus is sufficiently frequency-specific to allow a particular part of the auditory system to be tested. Furthermore, the SSAEP stimulus is less liable to be affected by distortion in free-field speakers or hearing aids. Typical modulation frequencies which are used in SSAEP stimuli are between 30 to 50 Hz or 75 to 110 Hz. The latter range may be particularly useful for audiometry because at these rates, the SSAEP responses are not significantly affected by sleep and can be reliably recorded in infants. Furthermore, SSAEP responses at these rates result in audiometric threshold estimates that are well correlated with behavioral thresholds to pure tone stimuli. In SSAEP testing, the presence or absence of an SSAEP response to an SSAEP stimulus can be determined using several statistical techniques.

[0010] However, objective audiometry employing SSAEP testing is time-consuming because the amplitude of the SSAEP response is quite small compared to the background noise which is the subject's ongoing brain activity (i.e. EEG) while the test is being conducted. The SSAEP response thus has a small signal-to-noise ratio (SNR) which makes it difficult to detect the SSAEP response in a short time period. One technique to reduce SSAEP testing time is to use a multiple SSAEP stimulus which combines several SSAEP test signals (i.e. where a test signal is meant to mean one SSAEP stimulus). The potentials sensed from the subject during the presentation of the multiple SSAEP stimulus contains a linear superposition of SSAEP responses to each SSAEP test signal in the multiple SSAEP stimulus. This makes it possible to record the SSAEP responses to multiple (e.g., four or eight) stimuli in the same time that it takes to record the response to a single stimulus. Therefore, this technique results in a reduction of test time since the SSAEP responses to several SSAEP test signals may be detected concurrently. However, the SNR for each SSAEP response is still small and the testing time for recording the response to a single SSAEP stimulus has not been reduced. To reduce the SSAEP test time techniques are required to either increase the amplitude of the SSAEP response and/or decrease the amplitude of the noise that is recorded along with the SSAEP response. A more sensitive statistical method that can detect SSAEP responses with small SNRs would also be useful.

[0011] While objective testing identifies that a subject has a hearing loss, the next step is usually to treat the subject by providing them with a hearing aid. However, if the subject is an infant, a method is required to objectively adjust the hearing aid since this cannot be done with conventional subjective methods. Some objective methods have been developed such as determining the real-ear insertion gain when a hearing aid is in place. w However, this method is only useful if one knows the actual unaided audiometric thresholds of the subject so that the hearing aid can be adjusted to match prescriptive targets. Furthermore, placement of a probe-tube in an infant can be challenging. There have also been methods based on click evoked auditory evoked potentials (i.e. wave V of the click-evoked ABR) but the stimuli used in these methods are restricted to certain frequency ranges and do not test the ability of the hearing aid to process continuous signals like speech. Accordingly, there still remains a need for an objective method to measure the benefits of a hearing aid in patients where behavioral thresholds and real-ear measurements are difficult to obtain.

SUMMARY OF THE INVENTION

[0012] The present invention is an apparatus for recording SSAEP responses and a set of methods for using the apparatus to test various aspects of a subject's auditory system. The apparatus comprises hardware to present SSAEP stimuli, to acquire EEG data while simultaneously presenting the SSAEP stimuli, and to analyze the EEG data to detect the presence of SSAEP responses. The apparatus further comprises software to enable the creation and presentation of the SSAEP stimuli, the acquisition of the EEG data (i.e. electrophysiological potentials) and the analysis of the EEG data. The software further enables displaying the results of ongoing testing and the final results of the test as well as the storage of the test results for subsequent viewing and/or analysis.

[0013] The present invention also includes software adapted to effect noise reduction algorithms which may include sample weighted averaging. The software is also adapted to effect statistical tests that are used to detect the SSAEP responses to the SSAEP stimuli. These statistical tests may include the phase weighted t-test, the phase zone technique and the modified Rayleigh test of circular uniformity (MRC).

[0014] The present invention also uses particular types of SSAEP stimuli to increase the amplitude of the resulting SSAEP responses. These SSAEP stimuli may include a combined amplitude modulation and frequency modulation signal in which the phase of the frequency modulated signal is adjusted relative to the phase of the amplitude modulated. These SSAEP stimuli may also include using an exponential modulation signal. The present invention also uses an SSAEP stimulus consisting of an independent amplitude modulation signal and frequency modulation signal wherein the AM modulation rate is different than the FM modulation rate. This stimulus evokes two SSAEP responses that can be independently analyzed.

[0015] In another aspect of the invention, these SSAEP stimuli can be used for a variety of objective tests such as determining audiometric thresholds and testing the aided and unaided hearing of a subject. The present invention further comprises several other audiometric protocols including latency tests, AM/FM discrimination tests, rate sensitivity tests, aided hearing tests, depth sensitivity tests and supra-threshold tests.

[0016] The present invention further comprises databases of normative data which can be used to construct SSAEP stimuli, detect SSAEP responses and determine whether detected SSAEP responses are indicative of normal or abnormal hearing. The databases contain data which are grouped by subject characteristics such as age, sex and state over a variety of stimulus characteristics such as type of SSAEP stimulus, the type of modulation (amplitude versus frequency), the modulation rates and modulation depth. The database also preferably contains data about SSAEP response characteristics such as latency and ratio of amplitudes of SSAEP responses to amplitude modulated and frequency modulated SSAEP stimuli.

[0017] In an alternative embodiment, the apparatus is adapted to perform multi-modality testing in which more than one sensory modality (i.e. vision and audition) of the subject is tested simultaneously.

[0018] The invention comprises a method of testing the hearing of a subject comprising the steps of:

[0019] (a) selecting at least one test signal;

[0020] (b) modulating at least one of the amplitude and frequency of the at least one test signal by an exponential modulation signal to produce at least one modulated test signal;

[0021] (c) transducing the at least one modulated test signal to create an acoustic stimulus and presenting the acoustic stimulus to the subject;

[0022] (d) sensing potentials from the subject while substantially simultaneously presenting the acoustic stimulus to the subject; and,

[0023] (e) analyzing the potentials to determine whether the potentials comprise data indicative of the presence of at least one steady-state response to the acoustic stimulus.

[0024] The invention further comprises testing the hearing of a subject comprising the steps of:

[0025] (a) creating an optimum-vector mixed modulation test signal comprising at least one signal having an amplitude modulated component with a first phase and a frequency modulated component with a second phase wherein the second phase is adjusted relative to the first phase to evoke an increased response from the subject;

[0026] (b) transducing the test signal to create an acoustic stimulus and presenting the acoustic stimulus to the subject;

[0027] (c) sensing potentials from the subject while substantially simultaneously presenting the acoustic stimulus to the subject; and,

[0028] (d) analyzing the potentials to determine whether the potentials comprise data indicative of the presence of at least one steady-state response to the acoustic stimulus.

[0029] In another aspect, the invention comprises a method for testing the hearing of a subject comprising the steps of:

[0030] (a) creating a test signal comprising at least one independent amplitude modulated and frequency modulated signal having an amplitude modulated component and a frequency modulated component, wherein the amplitude modulated component comprises a first modulation frequency and a first carrier frequency and the frequency modulated component comprises a second modulation frequency and a second carrier frequency wherein the first modulation frequency is substantially different from the second modulation frequency and the first carrier frequency is substantially similar to the second carrier frequency;

[0031] (b) transducing the test signal to create an acoustic stimulus and presenting the acoustic stimulus to the subject;

[0032] (c) sensing potentials from the subject while substantially simultaneously presenting the acoustic stimulus to the subject; and,

[0033] (d) analyzing the potentials to determine whether the potentials comprise data indicative of a steady-state response to each amplitude modulated component and a steady-state response to each frequency modulated component.

[0034] In another aspect, the invention comprises an apparatus for testing the hearing of a subject, wherein the apparatus comprises:

[0035] (a) a signal creator adapted to create a test signal comprising at least one combined amplitude modulated and frequency modulated signal having an amplitude modulated component with a first phase and a frequency modulated component with a second phase wherein the signal creator comprises means for adjusting the second phase relative to the first phase;

[0036] (b) a transducer electrically coupled to the processor and adapted to transduce the test signal to create an acoustic stimulus and present the acoustic stimulus to the subject;

[0037] (c) a sensor adapted to sense potentials from the subject while the acoustic stimulus is substantially simultaneously presented to the subject; and,

[0038] (d) a processor electrically coupled to the sensor and adapted to receive the potentials and analyze the potentials to determine if the potentials comprise data indicative of at least one response to the acoustic stimulus.

[0039] In another aspect, the invention comprises a method of analyzing potentials to determine whether the potentials comprise data indicative of the presence of at least one steady-state response to a steady-state evoked potential stimulus. The method comprises the steps of:

[0040] (a) presenting an evoked potential stimulus to a subject;

[0041] (b) sensing potentials from the subject while substantially simultaneously presenting the stimulus to the subject to obtain a plurality of data points;

[0042] (c) transforming the plurality of data points into a second plurality of data points;

[0043] (d) biasing the second plurality of data points with an expected phase value to obtain a plurality of biased data points; and,

[0044] (e) applying a statistical test to the plurality of biased data points to detect the response.

[0045] The invention further comprises a method of detecting a response to an evoked potential stimulus comprising the steps of:

[0046] (a) presenting an evoked potential stimulus to a subject;

[0047] (b) sensing potentials from the subject while substantially simultaneously presenting the stimulus to the subject to obtain a plurality of data points; and,

[0048] (c) calculating phase values for the plurality of data points,

[0049] wherein, a response is detected if an adequate number of the calculated phase values fall within a predetermined phase value range.

[0050] The invention further comprises an apparatus for testing the hearing of a subject, wherein the apparatus comprises:

[0051] (a) a signal creator adapted to create a test signal;

[0052] (b) a transducer electrically coupled to the signal creator and adapted to transduce the test signal to create an acoustic stimulus and present the acoustic stimulus to the subject;

[0053] (c) a sensor adapted to sense potentials from the subject while the acoustic stimulus is substantially simultaneously presented to the subject; and,

[0054] (d) a processor electrically coupled to the sensor and adapted to receive the potentials and analyze the potentials to determine if the potentials comprise data indicative of at least one response to the acoustic stimulus;

[0055] wherein the analysis involves biasing the potentials based on an expected phase value. The apparatus further comprises a database of expected phase value data correlated to subject characteristics and stimulus characteristics.

[0056] In yet another aspect, the invention comprises a method of noise reduction for a plurality of data points which are obtained during steady-state evoked potential testing, wherein the plurality of data points comprise at least one signal and noise and wherein said method comprises the steps of:

[0057] (a) obtaining said plurality of data points;

[0058] (b) separating said plurality of data points into a plurality of epochs; and,

[0059] (c) applying an adaptive noise reduction method to each epoch.

[0060] In another aspect, the invention comprises a method of objectively testing the hearing of a subject comprising the steps of:

[0061] (a) selecting an auditory test;

[0062] (b) creating an appropriate test signal comprising at least one component for the auditory test;

[0063] (c) transducing the test signal to create a stimulus and presenting said stimulus to the subject;

[0064] (d) sensing potentials from the subject while substantially simultaneously presenting the stimulus to the subject; and,

[0065] (e) analyzing the potentials to detect at least one response.

[0066] In another aspect, the invention further comprises an apparatus for objectively testing the hearing of a subject, wherein the apparatus comprises:

[0067] (a) a selector adapted for selecting an auditory test to perform on the subject;

[0068] (b) a signal creator electrically coupled to the selector and adapted to create an appropriate test signal comprising at least one component for the test;

[0069] (c) a transducer electrically coupled to the signal creator and adapted to transduce the test signal to create an acoustic stimulus and present the acoustic stimulus to the subject;

[0070] (d) a sensor adapted to sense potentials from the subject while the acoustic stimulus is substantially simultaneously presented to the subject;

[0071] (e) a processor electrically coupled to the sensor and adapted to receive the potentials and analyze the potentials to determine if the potentials comprise data indicative of at least one response to the acoustic stimulus; and,

[0072] (f) a programmable hearing aid coupled to said processor, wherein, the programmable hearing aid comprises a plurality of programmable gain factors for different frequency regions and at least one programmable filter slope.

[0073] In an alternative embodiment, the invention comprises a method of testing at least two senses of a subject, wherein the method comprises the steps of:

[0074] (a) selecting a first steady-state test signal to test a first sensory modality;

[0075] (b) transducing the first steady-state test signal to create a first stimulus and presenting the first stimulus to the subject;

[0076] (c) selecting a second steady-state test signal to test a second sensory modality;

[0077] (d) transducing the second steady-state test signal to create a second stimulus and presenting the second stimulus to the subject;

[0078] (e) sensing potentials while substantially simultaneously presenting both stimuli to the subject; and,

[0079] (f) analyzing the potentials to determine whether the potentials comprise data indicative of at least one steady-state response to the stimuli.

[0080] In an alternative embodiment, the invention further comprises an apparatus for testing at least two senses of a subject, wherein the apparatus comprises:

[0081] (a) a signal creator adapted to create a first steady-state test signal and a second steady-state test signal;

[0082] (b) a first transducer electrically coupled to the selector and adapted to transduce the first test signal to create a first stimulus and present the first stimulus to the subject;

[0083] (c) a second transducer electrically coupled to the selector and adapted to transduce the second test signal to create a second stimulus and present the second stimulus to the subject;

[0084] (d) a first sensor adapted to sense first potentials from the subject while the first stimulus is substantially simultaneously presented to the subject;

[0085] (e) a second sensor adapted to sense second potentials from the subject while the second stimulus is substantially simultaneously presented to the subject;

[0086] (f) a processor electrically coupled to the first sensor and adapted to receive the first potentials and analyze the first potentials to determine if the first potentials comprise data indicative of at least one response to the first stimulus; and,

[0087] (g) the processor, electrically coupled to the second sensor and adapted to receive the second potentials and analyze the second potentials to determine if the second potentials comprise data indicative of at least one response to the second stimulus,

[0088] wherein, each stimulus is presented substantially simultaneously.

[0089] Further objects and advantages of the invention will appear from the following description, taken together with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0090] For a better understanding of the present invention and to show more clearly how it may be carried into effect, reference will now be made, by way of example, to the accompanying drawings which show a preferred embodiment of the present invention and in which:

[0091] **FIG. 1***a* is a schematic of an embodiment of the apparatus of the present invention;

[0092] **FIG. 1***b* is a flow diagram illustrating the general objective auditory test methodology;

[0093] **FIG. 2***a* is a histogram of EEG amplitudes during a noisy recording session;

[0094] **FIG. 2***b* is a histogram of EEG amplitudes during a quiet recording session;

[0095] **FIG. 2***c* is the amplitude spectrum of the result of performing normal time averaging on the EEG data shown in **FIG. 2***a*;

[0096] **FIG. 2***d* is the amplitude spectrum of the result of performing normal time averaging on the EEG data shown in **FIG. 2***b;*

[0097] **FIG. 2***e* is the amplitude spectrum of the result of performing sample weighted averaging on the EEG data shown in **FIG. 2***a;*

[0098] **FIG. 2***f* is the amplitude spectrum of the result of performing sample weighted averaging on the EEG data shown in **FIG. 2***b;*

[0099] **FIG. 2***g* is the amplitude spectrum of the result of performing amplitude rejection on the EEG data shown in **FIG. 2***a* and then performing normal time averaging;

[0100] **FIG. 2***h* is the amplitude spectrum of the result of performing amplitude rejection on the EEG data shown in **FIG. 2***b* and then performing normal time averaging;

[0101] **FIG. 3***a* is a plot of the results of the F-test on an averaged sweep of EEG data points containing an SSAEP response;

[0102] **FIG. 3***b* is a plot of the results of the phase weighted t-test for the same set of data shown in **FIG. 3***a;*

[0103] **FIG. 4***a* is a graph of SSAEP response amplitudes to an MM SSAEP stimulus and an AM SSAEP stimulus for a 50 dB SPL stimulus intensity and a frequency modulation depth of 25%;

[0104] **FIG. 4***b* is a graph of SSAEP response amplitudes to an MM SSAEP stimulus and an AM SSAEP stimulus for a 40 dB SPL stimulus intensity and a frequency modulation depth of 25%;

[0105] **FIG. 4***c* is a graph of SSAEP response amplitudes to an MM SSAEP stimulus and an AM SSAEP stimulus for a 30 dB SPL stimulus intensity and a frequency modulation depth of 25%;

[0106] **FIG. 4***d* is a graph of SSAEP response amplitudes to an MM SSAEP stimulus and an AM SSAEP stimulus for a 50 dB SPL stimulus intensity and a frequency modulation depth of 10%;

[0107] **FIG. 4***e* is a graph of SSAEP response amplitudes to an MM SSAEP stimulus and an AM SSAEP stimulus for a 40 dB SPL stimulus intensity and a frequency modulation depth of 10%;

[0108] **FIG. 4***f* is a graph of SSAEP response amplitudes to a MM SSAEP stimulus and an AM SSAEP stimulus for a 30 dB SPL stimulus intensity and a frequency modulation depth of 10%;

[0109] **FIG. 5***a* is a plot illustrating how the response to an SSAEP stimulus containing amplitude modulated and frequency modulated components can be modeled as the vector addition of the SSAEP response to the amplitude modulated component of the SSAEP stimulus and the SSAEP response to the frequency modulated component of the SSAEP stimulus;

[0110] **FIG. 5***b* is a graph illustrating how the response to an SSAEP stimulus containing amplitude modulated and frequency modulated components can be modeled as a sinusoid when the phase of the frequency modulated component of the SSAEP stimulus is varied with respect to the phase of the amplitude modulated component of the SSAEP stimulus;

[0111] **FIG. 6***a* is the amplitude spectrum of the SSAEP response to an AM SSAEP stimulus, an FM SSAEP stimulus and an IAFM SSAEP stimulus;

[0112] **FIG. 6***b* is a group of polar plots showing the detection of the SSAEP responses shown in **FIG. 6***a;*

[0113] **FIG. 7***a* is a graph of test results showing percent increase in SSAEP responses when using an exponential modulation signal in the SSAEP stimulus as compared to an AM SSAEP stimulus for a stimulus intensity of 50 dB pSPL;

[0114] **FIG. 7***b* is a graph of test results showing percent increase in SSAEP responses when using an exponential modulation signal in the SSAEP stimulus as compared to an AM SSAEP stimulus for a stimulus intensity of 30 dB pSPL;

[0115] **FIG. 7***c* is a graph of test results showing amplitudes of SSAEP responses when using an exponential modulation signal in the SSAEP stimulus as compared to an AM SSAEP stimulus for a stimulus intensity of 50 dB pSPL;

[0116] **FIG. 7***d* is a graph of test results showing amplitudes of SSAEP responses when using an exponential modulation signal in the SSAEP stimulus as compared to an AM SSAEP stimulus for a stimulus intensity of 30 dB pSPL;

[0117] **FIG. 8** is a pair of graphs of the latencies calculated for 80 and 160 Hz modulation rates for SSAEP responses in response to SSAEP stimuli presented to the right and left ears of a group of subjects;

[0118] **FIG. 9** is a plot of word discrimination as a function of the number of significant responses to IAFM SSAEP stimuli for various subjects;

[0119] **FIG. 10** is a graph of amplitude of SSAEP responses as a function of SSAEP stimulus modulation rate for a group of young control subjects and for an older subject with minor hearing loss;

[0120] **FIG. 11** is a schematic diagram of how an audiometric threshold can be estimated using an algorithm that automatically adjusts sound intensity on the basis of whether an SSAEP response is detected;

[0121] **FIG. 12** is a schematic of an objective multimodality test apparatus; and,

[0122] **FIG. 13** is a schematic of a portable version of the objective audiometric test apparatus which is also adapted to perform multi-modality testing.

DETAILED DESCRIPTION OF THE INVENTION

[0123] The present invention provides an apparatus for recording steady-state evoked potentials and a set of methods for using the apparatus to test various aspects of a subject's hearing. The basic hardware and software components of the apparatus will be discussed first. Noise reduction methods will be discussed next followed by response detection. Test signals which can be used for SSAEPs will then be discussed. Finally, protocols for objective audiometric testing based on SSAEP stimuli will be discussed.

[0124] Hardware and Software Components of the Invention

[0125] Referring to **FIG. 1***a*, the objective audiometric test apparatus **10** includes a processor **12**, a data acquisition board **14** having a digital to analog converter (DAC) **16** and an analog to digital converter (ADC) **18**, an audiometer **20** having a filter **22** and an amplifier **24**, a transducer **26**, a sensor **28**, a second amplifier **30**, a second filter **32**, a master database **52** having a plurality of databases D1, D2, to Dn, a storage device **34** and a display monitor **36**. The processor **12** is suitably programmed with a software program **40** comprising a signal creator module **42**, a modulator module **44** and an analysis module **46** having a noise reduction module **48** and a detection module **50**.

[0126] A personal computer, for example a Pentium **750** running Windows **98**, may provide the processor **12**, storage device **34** and display monitor **36**. The software program **40** is run on the personal computer and the master database **52** along with the plurality of databases D1 to Dn can be stored in the memory of the personal computer and can communicate with the software program. Alternatively, these components may be effected on a laptop, a handheld computing device, such as a palmtop, or a dedicated electronics device.

[0127] The objective audiometric test apparatus **10** can be used to assess the auditory system of a subject **60** by presenting SSAEP stimuli to the subject **60**. While the stimulus is being presented, the objective audiometric test apparatus **10** records sensed potentials (i.e. EEG data) and amplifies the EEG data. This is done while substantially simultaneously presenting the SSAEP stimuli to the subject **60**. The EEG data is then processed and statistically evaluated to determine if the recorded EEG data contains SSAEP responses. For example, data processing may show the responses that are statistically significantly different than the background EEG noise levels. The design of the objective audiometric test apparatus **10** follows clear principles concerning the generation of the acoustic stimuli, the acquisition of artifact-free data, the analysis of EEG data in the frequency-domain and the objective detection of SSAEP responses in noise.

[0128] The processor **12** may be any modern processor such as a Pentium **750**. The data acquisition board **14** is a commercial data acquisition board (AT-MIO-16E-10) available from National Instruments. Alternatively, another data acquisition board with a suitable number of input and output channels may be used. The data acquisition board **14** allows for the output of data via the DAC **16** as well as the input of data via the ADC **18**.

[0129] The output from the DAC **16** is sent to the audiometer **20** which may also be under the control of the processor **12**. The audiometer **20** acts to condition the stimulus which is presented to the subject **60** via the filter **22** and the amplifier **24**. Rather than using the audiometer **20**, functionally similar amplifying/attenuating and filtering hardware can be incorporated into the audiometric test apparatus **10** to control the intensity and frequency content of the stimulus that will be presented to the subject **60**.

[0130] The SSAEP stimulus is presented to the subject **60** via the transducer **26** which may be a pair of speakers, headphones or at least one insert earphone. The insert earphones may be earphones designed by Etymotics Research. The transducer **26** allows the SSAEP stimulus to be presented to the left and/or right ears of the subject **60**. The stimuli may also be presented using free-field speakers, bone conduction vibrators or other acoustic transducers.

[0131] While the stimulus is being presented to the subject **60**, the EEG is substantially simultaneously sensed from the subject **60** using the sensor **28** which is typically electrodes. The electrodes generally include one active electrode placed at the vertex of the subject **60**, one reference electrode placed on the neck of the subject **60** and a ground electrode placed at the clavicle of the subject **60**. Other configurations for the electrodes are possible. It may also be possible to use more electrodes.

[0132] The sensed EEG data is then sent to the amplifier **30** which amplifies the sensed EEG data to a level that is appropriate for the input range of the ADC **18**. The amplifier **30** may use a gain of 10,000. The amplified sensed EEG data is then sent to the filter **32** which filters the amplified sensed EEG data such that sampling can be done without aliasing by the ADC **18**. The filter **32** may have a lowpass setting of 300 Hz and a highpass setting of 1 Hz. The ADC **18** receives the filtered amplified EEG data and samples this data at a rate of approximately 1000 Hz. The sampling rate depends on the settings of the filter **32**. Other sampling rates may also be used, however, provided that the Nyquist rate is not violated as is well understood by those skilled in the art.

[0133] The objective audiometric test apparatus **10** shown in **FIG. 1 a** may be extended to comprise other circuitry such as attenuation circuits which may be used in the calibration of the apparatus. Other circuitry may be added to the objective audiometric test apparatus **10**, to effect other audiometric tests such as performing an aided hearing test in which the subject **60** has at least one hearing aid and the objective audiometric test apparatus **10** is adapted to alter the gain of the hearing aid so that the subject **60** can hear the SSAEP stimuli which are presented to the subject **60** via free-field speakers.

[0134] The objective audiometric test apparatus **10** can clearly be embodied in various ways. For example, many different types of computers may be used. In addition, the data-acquisition board **14** may have both multiple inputs (ADCs) and multiple outputs (DACs). Multiple inputs may be used when SSAEP responses are recorded at multiple electrode sites on the subject **60** and the EEG data obtained from these electrode sites are used to increase the SNR of the SSAEP responses. Furthermore, principal component analysis, or source analysis, may be used, where the variance of the EEG data points are projected onto at least one dipole source and data not related to the dipole source are removed from the EEG data, thereby separating signal from noise. Multiple outputs may also be used (e.g. 8 DACs) to create the acoustic stimuli that are presented to each ear of the subject **60**. This would allow some components of the SSAEP stimulus to be manipulated independently from the others. For example, multiple DACs may allow a band-limited noise-masker to be increased in intensity when the SSAEP response to a particular SSAEP stimulus, presented through one of the DAC channels, becomes significant.

[0135] The software program **40**, also known as the MASTER (Multiple Auditory Steady-State Response) program allows a user to select a particular auditory test to perform on the subject **60**. The software program **40** is preferably programmed using the LabVIEW™ software package available from National Instruments, but could be instantiated with other software packages. The software program **40** comprises a plurality of modules which are not all shown in **FIG. 1***a* to prevent cluttering the Figure. The software program **40** controls test signal generation via the signal creator module **42** and the modulator module **44**. The software program **40** also allows the operator to select from a number of objective audiometric tests which will be discussed later in more detail. The signal creator module **42** creates data series for the carrier signals that are used in the SSAEP stimulus. The signal creator module **42** will typically employ the modulator module **44** to amplitude modulate and/or frequency modulate these carrier signals. The software program **40** then controls analog to digital conversion and digital to analog conversion according to the protocol of the auditory test that is being performed.

[0136] The software program **40** then analyzes the sensed EEG data via the analysis module **46** which includes the noise reduction module **48** and the response detection module **50**. As previously described, the SNR of the SSAEP response is quite small. Therefore, the sensed EEG data must be processed to reduce background noise. Accordingly, the noise reduction module **48** may employ sample weighted averaging, time averaging and/or adaptive artifact rejection (which will all be described later in more detail). The reduced noise signal is then sent to the detection module **50** to determine whether at least one SSAEP response is present within the data. The detection module **50** may employ the phase weighted t-test, the phase zone technique or the MRC method which will later be described in more detail.

[0137] The software program **40** can also display test results in the frequency domain on the display monitor **36**. The software program **40** can also save the test results on the storage device **34** which may be a hard drive or the like for further extensive analysis by other programs. The software program **40** also allows the test results to be printed by a printer (not shown).

[0138] The software program **40** also communicates with the master database **52** which comprises a plurality of databases D1 to Dn. Only a few of these databases have been shown in **FIG. 1** for reasons of clarity. The databases contain normative data from sample populations of subjects relating to a variety of parameters for SSAEP testing. For instance, the databases include normative phase data which can be used to create an optimal vector SSAEP stimuli having amplitude and frequency modulated components which are adjusted to evoke SSAEP responses with increased amplitudes. The databases further contain information about the amplitude of SSAEP responses to various SSARP stimuli.

[0139] The software program **40** implements a graphical user interface which consists of a series of interactive screens. These interactive screens allow a user to control the software program **40**, perform a desired auditory test and analyze test results. The interactive screens comprise a Main screen, a Stimulus Set-Up screen, a View Stimulus screen, a Recording Parameters screen, a Record Data screen, a Process Data screen and several Test Result summary screens.

[0140] The Main screen permits the user to select a particular audiometric test to perform. The Main screen also allows the user to navigate through the various other screens that are available.

[0141] The Stimulus Set-Up screen permits the user to define up to 8 SSAEP test signals which can be combined in a multiple SSAEP stimulus that can be presented to both ears of the subject **60**. Other embodiments of the invention will allow more than eight stimuli to be presented. For example, eight stimuli may be presented to each of the two ears of the subject **60** for a total of 16 stimuli. The user can define the frequency of the carrier signal (i.e. carrier frequency), the frequency of the modulation signal (i.e. modulation frequency), the amplitude modulation depth, the frequency modulation depth, the stimulus intensity, and the phase of the frequency modulation component relative to the phase of the amplitude modulation component for a particular type of SSAEP stimulus. The Stimulus Setup-Up screen therefore allows the user to choose the SSAEP stimulus to comprise an amplitude modulation test signal (AM), a frequency modulation test signal (FM), a combined amplitude modulation and frequency modulation test signal (referred to as mixed modulation or MM), an optimum vector combined amplitude modulation and frequency modulation test signal (OVMM) and an independent amplitude modulation and frequency modulation test signal (IAFM). Furthermore, the user can also define the envelope of the carrier signal by choosing a particular modulation signal. In particular, the user can choose a sinusoidal signal as the modulation signal or an exponential modulation signal as the modulation signal. Some exemplary exponential modulation signals include a sinusoid that has an exponent of 2, 3, 4 or 5. Alternatively, fractional exponents may be used.

[0142] Once, the carrier frequency and modulation frequency are chosen, the signal creator **42** automatically adjusts these frequencies to ensure that an integer number of cycles of the carrier signal and modulation signal can fit in the output buffer of the DAC **16** and the input buffer of the ADC **18** This is important to avoid spectral spreading in the generated acoustic stimulus as well as to avoid spectral spreading in the sensed EEG data which are digitized by the ADC **18**. The signal creator **42** may also be used to present test signals to the subject **60** with constant peak-to-peak amplitudes or constant RMS amplitudes, whereby the amplitude of the envelope of the test signal is increased to compensate for the modulation depth.

[0143] The signal creator **42** can also generate stimuli consisting of tones, broad-band noise, high-pass noise, low-pass noise, or band-pass noise all of which can be either modulated or unmodulated. In the case of noise, the signal creator **42** may allow the user to adjust the band-pass and band-stop characteristics of the noise including the roll-off of the transition region that is between the band-pass and band-stop regions. Currently the objective audiometric test apparatus **10** uses a circular buffer in the DAC **16**. However, in the case of noise stimuli, the incorporation of a double buffering technique may be used where data is read from one half of the buffer and written to the other half of the buffer. The data that was just written to the buffer is then shifted to the half of the buffer where data is read from.

[0144] The Recording Parameters screen enables the user to define the rate of the ADC **18**, the rate of the DAC **16** (which must be a multiple of the A/D rate) and the epoch duration (i.e. the size of the input buffer contained in the ADC **18**). The user may also define an artifact rejection level, calibration coefficients, phase adjustment coefficients and whether on-line computations are made upon weighted or un-weighted (i.e. raw) data. The user may also choose amplification values for data acquisition boards which provide amplification such as the AT-MIO-16e-10 board. The artifact rejection level may be based on an absolute threshold value or upon the average amplitude of the high frequency range of the sensed EEG data.

[0145] The View Stimulus screen enables the user to view the SSAEP stimuli that will be presented to the subject **60**. The View Stimulus screen also allows the user to view the amplitude spectra of the SSAEP stimuli.

[0146] The Record Data screen allows the user to view the sensed EEG data for the current epoch that is being sampled. The user can also view the amplitude spectra of the average sweep (a sweep is a concatenation of epochs and the average sweep is the result from averaging a plurality of sweeps). When the average sweep is displayed, the frequencies of the SSAEP responses in the EEG data are highlighted for easy comparison with background EEG activity (i.e. background noise). The Record Data screen also allows the user to control the acquisition of the EEG data. In addition, the Record Data screen allows the user to view both the numerical and graphical results of statistical analyses that are conducted on the EEG data to detect the presence of at least one SSAEP response to the SSAEP stimulus.

[0147] The Process Data screen enables the user to choose different methods of viewing, storing, combining and analyzing data sets, which either contain sweeps or SSAEP responses from a single subject or from a plurality of subjects. The data sets may be combined so that each sweep that goes into a final average is weighted by the amount of data from which it is created or by the number of separate data sets combined. The data sets may also be subtracted, in order to enable the user to calculate, for example, derived-band responses.

[0148] The software program **40** has options for collecting and displaying data. For example, as is commonly incorporated into clinical audiometric devices, the parameters for several clinical protocols can be stored in several parameter files to enable several tests to be run automatically, for example, each with different stimulus intensities or different SSAEP stimuli. The results for tests incorporating different SSAEP stimuli and different stimulus intensity levels can be displayed in several Test Summary screens where all of the audiometric test results of the subject **60** are presented, for example, in traditional audiogram format.

[0149] In another embodiment of the objective audiometric test apparatus **10**, the hearing tests may be performed partly automatically or fully automatically and may be used to adjust a hearing aid. In the case of a hearing aid, the gain of the hearing aid may be adjusted by the objective audiometric test apparatus **10** according to the outcome of aided hearing tests that are conducted. For example, during the calibration of the hearing aid, the gain of the hearing aid for a specific frequency region may be automatically increased if an SSAEP response to a given SSAEP stimulus in that specific frequency region was not detected. In this embodiment, the objective audiometric test apparatus **10** can communicate with the hearing aid device using a physical connection, such as a ribbon cable, or via RF telemetry as is used to adjust other biomedical devices (such as implanted stimulators).

[0150] **FIG. 1*b*** illustrates the general steps undertaken by the objective audiometric test apparatus **10**. The objective audiometric test apparatus **10** first generates a test signal in step **M1** which is appropriate in testing an aspect of the auditory system of the subject **60**. The test signal comprises a wide variety of signals including tones, noise, amplitude modulated signals, frequency modulated signals, optimum vector amplitude and frequency modulated signals, independent amplitude and frequency modulated signals, signals which have envelopes that are modulated by an exponential modulation signal, and the like. Accordingly, this step may comprise selecting a test signal and then modulating the test signal to obtain a modulated test signal. This procedure may also be done on more than one test signal so that the test signal comprises at least one modulated test signal. The next step M2 is to transduce the test signal to create a stimulus and present this stimulus to the subject **60**. The next step M3 is to record the EEG data of the subject **60** simultaneously with presentation of the stimulus. The presentation of the stimulus and the acquisition of the EEG data must be synchronized with the objective audiometric test apparatus **10** to accurately represent signals of interest. The next step **M4** consists of analyzing the recorded EEG data to determine whether there are any responses present in the EEG data. This step will typically involve performing a noise reduction method on the EEG data and then applying a detection method to the noise reduced data. The next step **M5** may be to report test results. The steps outlined in **FIG. 1*b*** may be part of a larger audiometric test that will involve performing each of the steps several times. These particular audiometric tests and the steps which are involved are discussed in more detail below.

[0151] SSAEP Detection

[0152] The EEG data that is sensed during the presentation of a multiple SSAEP stimulus contain superimposed responses to the multiple components of the SSAEP stimulus as well as background noise. Accordingly, it is difficult to distinguish the SSAEP responses in the time domain. However, if the EEG data is converted into the frequency domain, using a Fast Fourier Transform (FFT) for example, the amplitude and phase of each SSAEP response can be measured at the specific frequency of each modulation signal in the multiple SSAEP stimulus.

[0153] As previously stated, the SNR of the SSAEP response is very small. Accordingly, a large amount of EEG data needs to be collected to increase the SNR of the SSAEP data. Conventional approaches to increase the SNR of the SSAEP response include artifact rejection and time averaging. These conventional approaches are implemented by the analysis module **46** since these techniques are still fairly popular with clinicians and research scientists in the field of audiometry.

[0154] As previously mentioned, epochs of EEG data are acquired during SSAEP testing. Artifacts may contaminate the data and introduce large noise spikes that are due to non-cerebral potentials such as movement of facial muscles or the like. Accordingly, artifact rejection involves analyzing each epoch to determine if the epoch contains data points that are higher than a threshold level such as 80 μV. Artifact rejection is useful in removing spurious noise components to noise reduction techniques such as time averaging to be more effective. The noise reduction module **48** is adapted to effect artifact rejection on the epochs which are recorded. If an epoch is rejected, the next epoch that does not exceed the artifact rejection threshold is concatenated to the last acceptable epoch. This concatenation procedure does not cause discontinuities in the data because the SSAEP stimulus which evokes the SSAEP response is constructed so that each epoch contains an integer number of periods of the SSAEP response.

[0155] Time averaging comprises concatenating epochs to form sweeps. A plurality of sweeps are then averaged in time to yield an average sweep. Time averaging reduces the level of background noise activity that are not time-locked to the stimuli. After the average sweep is obtained, it is converted into the frequency domain via the FFT. In this case, the sweep duration is an issue since increasing the sweep duration distributes the background noise power across more FFT bins without affecting the amplitude of the SSAEP response which is confined to a single FFT bin since the SSAEP response occurs at a single frequency and the noise is broadband. Thus increasing the duration of the sweep increases the frequency-resolution of the FFT. The specific frequencies available from the FFT are integer multiples of the resolution of the FFT which is 1/(Nt), where N is the number of data points and t is the sampling rate. One possible implementation uses a sampling rate of 1000 Hz, an epoch length of 1024 points and sweeps that are 16 epochs long (16,384 points). Accordingly, the resulting frequency resolution is 0.61 Hz (1/(16*1.024*0.001)) and the frequency region in the FFT spans DC (0 Hz) to 500 Hz. Alternatively, sweeps may also be 8 epochs long or 12 epochs long.

[0156] The detection module **50** may provide a noise estimate which is derived from neighboring frequencies in the amplitude spectrum (i.e. FFT) at which no SSAEP response occurs. If there were no SSAEP response in the recorded data then the power at the modulation frequency, where the response should occur, would be within the range of the noise power at the neighboring frequencies. An F-ratio may then be used to estimate the probability that the amplitude at the modulation frequency in the resulting FFT is not statistically different from the noise estimate. When this probability is less than 0.05 ($p<0.05$), the SSAEP response may be considered significantly different from noise, and the subject **60** is considered to have heard the SSAEP stimulus. A more stringent criteria of $p<0.01$ can also be chosen. Currently, the objective audiometric test apparatus **10** provides an F-Ratio where each SSAEP response in the amplitude spectrum associated with a frequency of modulation is compared to the FFT data in 60 noise bins above and 60 noise bins below the FFT bin that contains the SSAEP response. Accordingly, this ratio is evaluated as an F-statistic with **2** and **240** degrees of freedom.

[0157] The objective audiometric test apparatus **10** further comprises the noise reduction module **48** which may be adapted to employ artifact rejection in which epochs are rejected based on high frequency activity. Artifact rejection which simply chooses a threshold based on the sensed potentials may not be optimally efficient because low-frequency high-amplitude EEG activity (e.g. less than 20 Hz) dominates the amplitude of the sensed EEG data. Thus the noise in the vicinity of the SSAEP response, which may be in the frequency range of 70 to 200 Hz, is not appropriately represented by the recorded EEG data. Accordingly, rejecting epochs based upon the mean amplitude of the high frequency EEG noise may be more appropriate.

[0158] In addition, the noise reduction module **48** may employ an adaptive artifact rejection method in which an adaptive threshold value is calculated which depends on a statistical property of the data points in an epoch. This method comprises calculating the standard deviation of the data points in the epoch and setting the threshold value to be two times the calculated standard deviation value. If the epoch contains data which is over this threshold limit, then the epoch is rejected. This rejection method may be performed offline, after the sensed EEG data has been recorded from the subject **60** or the method may be performed online while the sensed EEG data is being recorded from the subject **60**. The online artifact rejection method may provide an idea of how much EEG data needs to be recorded from the subject **60** based on the number of epochs which are rejected. Alternatively, this adaptive artifact rejection method can be done after the epoch is filtered by a bandpass filter having a passband which is substantially similar to the frequency region in which the SSAEP response may occur (i.e. 70 to 110 Hz or the frequency range of 120 to 250 Hz). Alternatively, other statistical measures may be used to adaptively set the artifact rejection threshold.

[0159] The noise reduction module **48** may further employ sample weighted averaging to reduce the noise in the sensed EEG data. Under the sample weighted averaging method, epochs are concatenated into sweeps of sufficient duration. A plurality of sweeps are formed and aligned such that a matrix is formed where the sweeps are the rows of the matrix and the epochs are the columns of the matrix. Each sweep is filtered and the epochs along each column are then weighted by an estimate of the noise variance that is local to the frequency region in which the SSAEP response resides. The noise variance estimate is local to the frequency region in which the SSAEP response resides because the bandpass filtering of the sweeps is done such that the passband of the filter is substantially similar to the frequency region in which the SSAEP response should occur. For example, the passband of the bandpass filter may be from 70 to 110 Hz. The epochs are then weighted by the inverse of this noise variance after the noise variance has been normalized. The weighted epochs along each column of the matrix is then summed to yield a resulting sweep which has a reduced noise component compared to the case of simply performing time averaging on the plurality of sweeps. Alternatively, noise weighted averaging may be used where the amplitudes of the steady-state responses are removed from the noise estimate.

[0160] In pseudo-code format, sample weighted averaging is effected according to the steps of:

[0161] a) obtaining a plurality of epochs while sensing EEG data from the subject **60** while simultaneously presenting the SSAEP stimulus;

[0162] b) forming a plurality of sweeps by concatenating the epochs together;

[0163] c) filtering each sweep to obtain a plurality of filtered sweeps;

[0164] d) aligning each sweep to form a first matrix in which the sweeps are the rows of the matrix and the epochs within the plurality of sweeps are the columns of the matrix and aligning each filtered sweep in a similar fashion to form a filtered matrix which is used to calculate weights;

[0165] e) calculating the variance of each epoch in the filtered matrix to obtain a noise variance estimate for each epoch in the filtered matrix;

[0166] f) normalizing the noise variance estimate for each epoch in the filtered matrix by dividing the noise variance estimate for each epoch in the filtered matrix by the sum of all noise variance estimates for the epochs along the column of the filtered matrix which contains the epoch to obtain a normalized noise variance estimate for each epoch;

[0167] g) inverting each normalized noise variance estimate to obtain a weight for each epoch and multiplying each corresponding epoch in the first matrix by its respective weight to obtain a plurality of weighted epochs; and,

[0168] h) summing all of the weighted epochs in the first matrix along the columns of the first matrix to obtain a signal estimate.

[0169] Referring to **FIGS. 2***a*-**2***h*, sample weighted averaging and artifact rejection (based on the mean amplitudes of higher frequency regions) are compared to normal averaging. The results show that sample weighted averaging results in SSAEP responses with the higher SNR. **FIG. 2***a* shows a histogram for amplitudes of recorded EEG data points for a noisy recording (i.e. there were many artifacts during the recording, the amplitudes of which are identified by arrows in **FIG. 2***a*). **FIG. 2***b* also shows a histogram for amplitudes of the recorded EEG data for a quiet recording (i.e. there were not many artifacts during the recording). The data points in **FIGS. 2***a* and **2***b* were obtained from the same subject who was presented a multiple SSAEP stimulus comprising eight test signals at 50 dB SPL. **FIGS. 2***c* and **2***d* show the results from analyzing the data using normal averaging. The SSAEP responses that have been detected are denoted by the filled arrowheads. In **FIG. 2***c*, only four of the eight SSAEP responses have been detected meanwhile in **FIG. 2***d*, all eight of the SSAEP responses have been detected. **FIGS. 2***e* and **2***f* show the results from analyzing the EEG data using sample weighted averaging. In **FIG. 2***e*, seven SSAEP responses have been detected and in **FIG. 2***f*, eight SSAEP responses have been detected. Furthermore, comparing **FIG. 2***e* with **FIG. 2***c* shows that sample weighted averaging has detected 3 more SSAEP responses as well as increased the average SNR of the SSAEP responses by a factor of over 2. **FIGS. 2***g* and **2***h* show the results from analyzing the EEG data using amplitude rejection in which rejection was based on the mean amplitude of the EEG data in the higher frequency region. **FIG. 2***g* shows that this form of artifact rejection resulted in seven SSAEP responses being detected while **FIG. 2***h* shows that all eight SSAEP responses were detected.

[0170] Referring now to the detection module **50**, a phase weighted t-test is used to detect the presence of SSAEP responses in the recorded EEG data. The phase weighted t-test employs data biasing to detect the SSAEP response based on a priori knowledge about the SSAEP response. In particular, if the phase of the SSAEP response is known, then the EEG data can be biased so that statistical analysis (i.e. the detection method) is more likely to recognize an SSAEP response with a phase that is similar to the expected phase than noise data with a completely different phase. The biasing of the data points is done by employing a weighting function that provides larger weights for SSAEP responses that have a phase which is close to the expected phase value. The phase weighted t-test allows phase-weighting without the need for empirical compensation of the probability level at which the SSAEP response is detected.

[0171] Since the recorded EEG data is processed by the FFT, the resulting data points are two-dimensional and have real and imaginary components. The FFT bins which represent the SSAEP response and the surrounding noise can be projected onto a single dimension oriented at the expected phase by using the equation:

$$p_i = a_i * \cos(\theta_i - \theta_e) \quad (1)$$

[0172] where

[0173] p_i is the projected value;

[0174] a_i is the amplitude of an FFT component (i.e bin);

[0175] θ_i is the phase of the FFT component; and,

[0176] θ_e is the expected phase of the response.

[0177] An upper confidence limit, based on the amplitude of the projected FFT components that contain noise can then be estimated using a one-tailed Student t-test with $p<0.05$ (to reduce the number of false positives, $p<0.01$ can be used). An SSAEP response can then be recognized as being statistically significantly greater than noise (i.e. detected) if the projected value of the FFT component whose frequency is the same as that of the SSAEP responses which is being detected is larger than the upper confidence limit.

[0178] The steps to employ the phase weighted t-test on the EEG data points include the following steps:

[0179] a) forming a plurality of sweeps from the EEG data points;

[0180] b) averaging the plurality of sweeps to obtain a plurality of averaged data points;

[0181] c) calculating a plurality of Fourier components for the plurality of averaged data points wherein the Fourier components are calculated for the frequency region where the response should occur and adjacent frequencies thereof (for noise estimation);

[0182] d) calculating the amplitude (a_i) and phase (θ_i) for the plurality of Fourier components which were calculated in step (c);

[0183] e) biasing the amplitudes (a_i) to obtain biased data points (p_i) according to the formula:

$$p_i = a_i * \cos(\theta_I - \theta_e)$$

[0184] where θ_e is the expected phase value (this is done for the Fourier component at which the response should occur as well as for adjacent Fourier components which represent noise);

[0185] f) calculating upper confidence limits using a one tailed Student t-test on the biased amplitudes which represent noise in the vicinity of Fourier components where the response should occur; and

[0186] g) comparing biased amplitudes of Fourier components where the response should occur to the upper confidence limits to determine if the biased amplitudes are larger than the upper confidence limit.

[0187] If the biased amplitudes for the response is larger than the upper confidence limit, then the response is detected; otherwise no response is detected. Note that in the above method, some preprocessing techniques can be used on the plurality of data points to reduce the background EEG noise amplitude in the plurality of data points by the noise reduction module **48**. These preprocessing techniques may include artifact rejection, adaptive artifact rejection, time averaging and sample weighted averaging.

[0188] Referring to **FIGS. 3***a* and **3***b*, the use of a phase weighted t-test is illustrated on some sample data. **FIG. 3***a* shows that the response **70** is within the upper confidence limits which are defined by the circle **72**. The upper confidence limits **72** were obtained according to the procedure previously described using two-dimensional F-statistics. The SSAEP response **70** is therefore not statistically significant (i.e. not detected) since the magnitude of the SSAEP response **70** is not larger than the upper confidence limit **72**. However, knowing that the expected phase of the SSAEP response should be 104 degrees, in this example, allows for the use of the phase weighted t-test which is shown in **FIG. 3***b*. Biasing the FFT components that represent noise results (i.e. the open circles in **FIG. 3***b*) results in upper confidence limits **76** that are now shown by a parabola (the actual upper confidence limit is the single point where the parabola intersects the line of the expected phase). Notice that the apex of the parabola **76** has a smaller excursion from the origin as compared to the circle **72** which makes it easier to detect an SSAEP response if its phase is similar to that which is expected. The SSAEP response is now biased by projecting it on the expected phase of 104 degrees. The SSAEP response **74** now extends beyond the confidence limits **76** of the projected noise measurements. The SSAEP response is considered to be statistically significant and therefore detected with the same number of noise data points shown in **FIG. 3***a*.

[0189] In the case of the multiple SSAEP stimulus which contains multiple signals that evoke multiple SSAEP responses, the phase weighted t-test is repeated for each of the expected SSAEP responses, with each response having a different expected phase since they were evoked by test signals having various carrier frequencies.

[0190] The formula in equation (1) for biasing the amplitudes based on the difference between the measured phase and the expected phase can be made broader or tighter depending on the weighting function that is used. For instance, the cosine weighting in equation 1 can be replaced with a cosine squared function in order to more strongly punish values that deviate from the expected phase. Alternatively, the 'tightness' of the weight function can be adjusted according to the normative inter-subject or intra-subject variance of expected phase values. For example, the standard deviation for the measured phase values in a normative database, contained within the master database **52** can be normalized and used to weight the difference between the expected and observed phases in equation 1.

[0191] Furthermore, phase coherence measurements can be biased toward an expected phase in exactly the same way as was done for the phase weighted t-test, whereby the phase coherence estimate is biased by the difference between the expected and observed phases. Additionally, these methods of biasing the data can be used to evaluate responses in average sweeps, single sweeps, or even across individual epochs.

[0192] Alternatively, the average sweep is not always calculated and the presence of a response can be statistically assessed by assessing the SSAEP responses for each sweep or even for each epoch.

[0193] Several approaches can be used to define the expected phase. First and foremost, a database of normative expected phase values are collected and stored in the master database **52**. These normative expected phase values can be obtained by collecting the average phases of SSAEP responses obtained from a group of normal subjects (who may be matched for age and gender) who were presented with similar stimuli. Another approach is to estimate the expected phase from previously recorded data on the particular subject who is currently being tested. For example, if an SSAEP response at 60 dB SPL has a phase of 80 degrees then one may use this value or a slightly smaller phase as the expected phase for the SSAEP response that is recorded during a test with a similar SSAEP stimulus that is at 50 dB SPL. Alternatively, the phase measured from several earlier sweeps of a recording period may be used to obtain an estimate of the phase for the sweeps which are taken later in the recording period. Another alternative would be in the case of the multiple SSAEP stimulus which contains individual SSAEP stimuli at different carrier frequencies. In this case, the phases of the SSAEP responses that have reached statistical significance (i.e. been detected) during a given testing period can be used to estimate what the phase should be for SSAEP responses that have not yet reached significance. For example, if the phase of a response to an SSAEP stimulus with a carrier signal comprising a 1000 Hz tone that is amplitude modulated at 80 Hz is 45 degrees and the phase of a response to an SSAEP stimulus with a carrier signal comprising a 4000 Hz tone that is amplitude modulated at 90 Hz is 90 degrees then the predicted phase for an SSAEP response to an SSAEP stimulus that with a carrier signal comprising a 2000 Hz tone that is amplitude modulated at 85

Hz that has not reached significance may be interpolated as being 60 degrees. Other interpolation methods may be used.

[0194] The detection module **50** may be further adapted to perform a phase zone method to detect the presence of SSAEP responses in recorded EEG data. While the statistical detection methods of the prior art, rely on the probability of phases randomly occurring, a statistical detection method may be made stronger if the distribution of phases is expected to lie within a given number of degrees (i.e. the target phase range) from an expected phase value. For example, if the expected phase of a given response is 90 degrees, then the chance of the phase value landing within N degrees of the expected phase is (N/360). Accordingly, if N is set at 90 and the expected phase is 70 degrees, then there is a 1 in 4 chance that each calculated phase value of a recording without an SSAEP response will occur between 25 and 115 degrees (i.e. the target phase range). The number of phases that fall within the target phase range can be compared to the number of phases which fall outside of the target phase range using binomial analysis, with a probability of 0.25 (i.e., 1 in 4) for this example. However, if the variance of the calculated phases is small, then the target phase range may also be made smaller (i.e. a target phase range less than 90 degrees). This will allow the SSAEP response to become statistically significant (i.e. detected) with a smaller amount of EEG data points since the binomial probability index will get smaller as the target phase range gets smaller

[0195] In terms of SSAEPs, the phase zone method is effected by analyzing each sweep of data rather than using the average sweep as is done in the F-test. The method consists of the steps of:

[0196] a) presenting the SSAEP stimulus to the subject **60**;

[0197] b) sensing the EEG from the subject **60** while substantially simultaneously presenting the stimulus to the subject **60** to obtain a plurality of data points;

[0198] c) separating the plurality of data points into sweeps;

[0199] d) calculating a Fourier component for the frequency at which the response should occur for each sweep;

[0200] e) calculating a phase value for each Fourier component;

[0201] f) calculating a phase target range;

[0202] g) calculating the number of phases (Na) from step (e) that are within the target phase range; and,

[0203] h) using binomial analysis to analyze Na to determine whether said plurality of data points contains a response.

[0204] The phase target range can be calculated based on a database of normative expected phases, stored within the master database **52**, that are correlated to the subject and the SSAEP stimulus characteristics.

[0205] The detection module **50** may be further adapted to perform another statistical method for detection referred to as the MRC method. The use of an expected phase angle has been incorporated as a variant of the Rayleigh test for circular uniformity (RC) termed the modified Rayleigh test (MRC). The RC method can be made more statistically powerful if an expected phase angle is known. Hence the MRC is developed which weights the RC value with a weighting function that incorporates the expected phase according to the following equation:

$$MRC=RC^{*}\cos(\theta_a-\theta_e) \qquad (2)$$

[0206] where θ_a is the vector-averaged angle of the data set and ^{o}e is the expected angle.

[0207] In addition to detecting responses at the modulation frequencies used in the SSAEP stimulus, the detection module **50** may be adapted to detect the SSAEP responses that occur at the carrier frequency. In this case, the sampling rate of the ADC **18** would have to be increased so that EEG data with frequency content in the range of the carrier frequency could be properly sampled. However, this EEG data may be difficult to interpret because stimulus artifacts, which are created by electromagnetic inductance, will add to the sensed EEG data and distort the data. These artifacts can be minimized by various techniques such as shielding the transducer **26** and separating it from the recording instrumentation (i.e. the sensors **28**, the amplifier **30** and the filter **32**). In addition, the use of insert earphones with a greatly extended air-tube can aid in overcoming stimulus artifacts (provided that the transfer function of the transducer is adapted to compensate for the filtering effect of the lengthened tube). Another technique to remove the stimulus artifact may be based on the fact that the stimulus artifact changes its amplitude linearly with changes in the intensity of the SSAEP stimulus while the latency of the stimulus artifact does not change, whereas an SSAEP response will show non-linearities in its intensity relationship and will change latency. Thus, if EEG data is recorded at more than one stimulus intensity, algorithms may be constructed to remove the stimulus artifacts based on its linearity with respect to stimulus intensity.

[0208] SSAEP Stimuli

[0209] The objective audiometric test apparatus **10**, via signal creator **42** is adapted to construct a variety of test signals which can be used in the SSAEP stimulus. These test signals include tones, amplitude modulated signals (AM), frequency modulated signals (FM), an optimum vector combined amplitude modulated and frequency modulated signals (optimum vector mixed modulation or OVMM) and independent amplitude modulated and frequency modulated signals (IAFM). The modulator **44** may also be used with the signal creator **42** to provide envelope modulation with an exponential modulation signal. The signal creator **42** can also generate test signals consisting of broad-band noise, high-pass noise, low-pass noise, or band-pass noise all of which can be either modulated or unmodulated.

[0210] The signal creator **42** generates the optimum vector combined amplitude modulation and frequency modulation (OVMM) test signal such that the amplitude modulation rate is the same as the frequency modulation rate. Furthermore, the phase of the frequency-modulated component of the OVMM test signal is adjusted with respect to the phase of the amplitude modulated component of the OVMM test signal such that the SSAEP response evoked from the subject has an increased amplitude.

[0211] Referring to **FIGS. 4*a*-4*f***, the amplitudes of SSAEP responses to an SSAEP stimulus consisting of an AM test signal (open square data points) and an SSAEP stimulus consisting of an MM test signal (filled in circular data points). The data was collected from eight test subjects. The SSAEP responses were obtained for a variety of carrier frequencies, stimulus intensities and frequency modulation depths. **FIGS. 4**a-**4**f show that the MM SSAEP stimulus evoked SSAEP responses with larger amplitudes than the AM SSAEP stimulus for a variety of stimulus intensities and carrier frequencies. The frequency modulation depth for the MM SSAEP stimulus was 25% for **FIGS. 4**a-**4**c and 10% for **FIGS. 4**d-**4**f (the frequency modulation depth indicates the frequency deviation from the carrier frequency in the SSAEP stimulus). The amplitude modulation depth was 100% for the AM SSAEP test results shown all Figures. In **FIGS. 4**a-**4**c, at 50, 40 and 30 dB SPL, the amplitudes of the SSAEP response were 30%, 49%, and 28% larger for responses evoked by the MM SSAEP stimulus as compared to those evoked by the AM SSAEP stimulus. **FIGS. 4**d-**4**f show results from a different group of eight subjects in which the SSAEP response amplitudes were 20%, 7%, and 8% larger when using MM SSAEP stimuli. These Figures also show that it is possible to obtain enhanced response amplitudes near threshold using frequency modulation depths near 25%.

[0212] For the test results shown in **FIGS. 4**a-**4**h, the MM SSAEP stimuli were not adjusted to evoke SSAEP responses with optimal amplitudes. When an optimum vector mixed modulation signal is used, the SSAEP response amplitudes are larger for the higher frequency test results (i.e. 4000 to 6000 Hz). It should also be noted that the use of an FM depth of 10% in the MM SSAEP stimulus is not sufficient to increase the SSAEP response amplitudes as compared to the response amplitudes obtained when using the AM SSAEP stimulus. Rather, an FM depth of 25% is needed to evoke larger amplitude SSAEP responses as is shown in **FIGS. 4**b and **4**c.

[0213] Referring to **FIG. 5**a, adjusting the phase of the FM component of the MM SSAEP stimulus relative to the phase of the AM component results in SSAEP responses with different amplitudes. At one particular phase the response will be larger than at other phases. This is the basis of the optimum-vector mixed modulation stimulus. This adjustment is based on the principle that the SSAEP response **80** to an MM SSAEP stimulus is the vector sum of the response to the AM component **82** of the SSAEP stimulus and the FM component **84** of the SSAEP stimulus, in which the components are independent or only interact to a small degree. The SSAEP response to the AM component **82** is shown as the vector originating at the origin. Added to the SSAEP response to the AM component **82** is the response to the FM component **84** of the SSAEP stimulus which has a different phase than the SSAEP response to the AM component **82**. These SSAEP responses were evoked by an SSAEP stimulus in which the FM component had the same phase as the AM component so that the relative phase between the AM and the FM components of the SSAEP stimulus was zero. As is evident from **FIG. 5**a, this results in an SSAEP response to the MM stimulus that is smaller than the response to the AM stimulus alone.

[0214] Referring to **FIG. 5**b, if the phase of the FM component of the SSAEP stimulus was adjusted relative to the phase of the AM component of the SSAEP stimulus in a range from 0 to 360 degrees there would be a variation in the amplitude of the response **86** which could be modeled as a sinusoid. Increases in the phase of the FM component of the SSAEP stimulus will rotate the FM response vector **84** clockwise. The SSAEP response to the MM SSAEP stimulus for any phase value of the FM component relative to the AM component of the SSAEP stimulus can then be obtained by drawing a vector straight up from the x-axis to the response curve **88**. This line would be drawn at the point on the x-axis which is the value of the phase of the FM component with respect to the AM component for the SSAEP stimulus. One example of a possible response is shown as the dotted-line vector **86** which also happens to be the largest response amplitude. In this case, the SSAEP response **84** to the FM component of the SSAEP stimulus and the response **82** to the AM component of the SSAEP stimulus will line up to produce an optimum vector mixed-modulation (OVMM) stimulus, which should produce the largest MM response when the relative phase between the phase of the FM component and the AM components of the SSAEP stimulus is ϕ. **FIG. 5**b thus indicates how the angle (p can be derived using several MM response amplitudes obtained as the relative phase between the FM and AM components of the SSAEP stimulus is varied. The resulting SSAEP response amplitudes can be fit with a sine wave having a baseline-offset (as shown in **FIG. 5**b). The size of the baseline-offset is equivalent to the amplitude of response to the AM component of the SSAEP stimulus and the amplitude of the sine wave is equivalent to the amplitude of the response to the FM component of the SSAEP stimulus.

[0215] These stimuli are called optimum-vector mixed modulation (OVMM) stimuli to distinguish then from other MM stimuli where the relative phases of the AM and FM components are arbitrarily set. OVMM SSAEP stimuli can therefore be used to evoke SSAEP responses with larger amplitudes. This is beneficial since SSAEP responses with larger amplitudes have larger SNR which should allow for SSAEP response detection in a smaller amount of time.

[0216] The process to test with OVMM SSAEP stimulus follows the following steps:

[0217] a) create a test signal which contains at least one combined amplitude modulation and frequency modulation signal in which the phase of the FM component of the test signal is adjusted relative to the phase of the AM component of the test signal such that an increased response can be evoked from a subject;

[0218] b) creating the test signal further comprises choosing the carrier frequency of the AM component to be substantially similar to the carrier frequency of the FM component and the modulation frequency of the AM component to be substantially similar to the modulation frequency of the FM component;

[0219] c) transducing the test signal to create an acoustic stimulus and presenting the acoustic stimulus to the subject;

[0220] d) sensing potentials from the subject while substantially simultaneously presenting the acoustic stimulus to the subject; and,

[0221] e) analyzing the sensed potentials to determine whether they contain data indicative of at least one steady-state response to the acoustic stimulus.

[0222] Testing with OVMM SSAEP stimuli preferably utilizes a database of normative optimal phase values, stored within the master database **52**, that may be used to adjust the phase of the FM component of the OVMM SSAEP stimulus relative to the AM component of the OVMM SSAEP stimulus. This basically entails creating a database of normative values. The database is stored in the master database **52**. The database of normative values can contain phase difference data (i.e. difference between the phases of the FM and AM components of the OVMM SSAEP stimulus) which is correlated to subject characteristics and stimulus characteristics. Subject characteristics typically include the age of the subject, the sex of the subject and the like. Stimulus characteristics include the carrier frequency of the FM or AM component, the intensity of the stimulus, the AM modulation depth, the FM modulation depth and the like.

[0223] The following steps may be followed to create the database of normative phase difference data:

[0224] a) Select a sample population to test which is correlated to a group of subjects who will be examined; i.e., if testing will be performed on newborn infants then a sample of 100 subjects may be tested, who may be appropriately matched for age and for sex;

[0225] b) Record EEG data from the sample population that contain responses to SSAEP stimuli which contain AM components only and responses to SSAEP stimuli which contain FM components only; this testing should be done for each of the stimuli which will be used when examining the group of subjects from step (a);

[0226] c) Detect the SSAEP responses in the recorded EEG data and measure the phase of each SSAEP response;

[0227] d) Calculate the differences in the phases measured in step (c) between the SSAEP responses to the AM component only SSAEP stimuli and the FM component only SSAEP stimuli and plot the resulting SSAEP response amplitudes (which is the vector summation of the responses to the AM component only SSAEP stimuli and the FM component only SSAEP stimuli) to obtain a waveform as shown in **FIG. 5***b*; and,

[0228] e) Find the phase difference for which the resulting vector summation of the response amplitudes for the AM and FM components result in a maximum amplitude; this phase value is then used in the OVMM SSAEP stimulus to evoke increased responses from test subjects.

[0229] The signal creator **42** can also generate another test signal comprising an AM component and an FM component wherein these two components are independent from each other in that they evoke SSAEP responses that are independent from each other. This property holds true for a multiple SSAEP stimulus that contains multiple independent AM and FM components. Accordingly, the test signal is referred to as an independent amplitude and frequency modulation signal (IAFM). The IAFM signal has an AM modulation frequency that is different from the FM modulation frequency.

[0230] Referring to **FIG. 6***a*, a partial view of the amplitude spectrum of the SSAEP responses for a multiple SSAEP stimulus that contains AM test signals having 100% amplitude modulation depth is shown in the top panel. The middle panel shows a partial view of the amplitude spectrum of the SSAEP responses for a multiple SSAEP stimulus that contains FM test signals having 20% frequency modulation depth and the bottom panel shows the SSAEP responses for a multiple SSAEP stimulus that contains IAFM test signals. The frequencies of the SSAEP responses are indicated by inverted triangles. **FIG. 6***b* shows the corresponding polar plots for each of the SSAEP responses. The circles represent the confidence limits of each SSAEP response. If the circle does not contain the origin, then the SSAEP response can be considered to be statistically significantly ($p<0.05$) different from the background noise and therefore detected. The SSAEP responses in the bottom panel tend to be slightly smaller in amplitude than those obtained when only one type of modulation was used in the SSAEP stimulus. However, the phases between the SSAEP responses in the bottom panel and the corresponding responses in the top and middle panels are quite similar. Thus, IAFM stimuli allow for the independent testing of the parts of the auditory system that respond to amplitude modulation and the part of the auditory system that responds to frequency modulation. The separate SSAEP responses (i.e. in response to either an AM or FM SSAEP stimulus) can be used to evaluate hearing for a particular frequency region by incorporating both of these SSAEP responses to evaluate if a SSAEP response is present using the Stouffer method.

[0231] Experimental results have also shown that FM SSAEP stimuli can evoke SSAEP responses when the frequency modulation depths as little as 2% are used. Furthermore, SSAEP responses can be evoked when using faster FM modulation rates. Experimental data has also shown that SSAEP responses to FM stimuli could be elicited at these rapid rates and low modulation depths while producing a different phase as compared to the SSAEP response to an AM SSAEP stimulus. This suggests that the FM SSAEP stimulus was being processed differently than the AM SSAEP stimulus. This is important for testing paradigms that will rely on these faster rates. Furthermore, experimental data has shown that the use of AM and FM stimuli presented at supra-threshold intensities with depths of modulation less than 100% and rates of modulation over 70 Hz evoke SSAEP responses whose amplitudes have a correspondence to behavioral thresholds.

[0232] The signal creator **42** is also adapted to create a test signal comprising a carrier signal that is modulated by two modulation signals that modulate in the same manner but at different modulation rates. This test signal may be called a dual modulation signal. For instance, there may be 2 modulation signals which amplitude modulate a carrier signal at different modulation rates. An SSAEP stimulus based on this type of test signal may be useful in certain situations. For instance, the two SSAEP responses that are evoked by the dual modulation SSAEP stimulus can be evaluated using the Stouffer Method. Additionally, it may be useful to set the lower modulation rate in the 30-40 Hz range while the higher modulation rate is in the 70-90 Hz range. Accordingly, by using the Stouffer method, responses for both the 30-40 Hz and 70-90 Hz ranges can be simultaneously assessed. If a subject is alert, the SSAEP responses to lower modulation rates will become significant faster, while a subject that begins to doze off may cause the SSAEP responses to the faster stimuli to become significant faster.

[0233] The Stouffer method statistically compensates for trying to detect 2 rather than 1 response, however, a potential drawback may occur when an SSAEP response that is highly significant when evaluated independently fails to reach significance when assessed in concert with another SSAEP response. For example, an 80 Hz SSAEP response that is highly significant should not be assessed as being not significant if it is combined with a 40 Hz SSAEP response that is far from being significant. The software program **40** can compensate for this by using Bonferroni corrections or by allowing the user to choose different criteria for detecting an SSAEP response (i.e. choosing the $p<0.01$ or $p<0.001$ criteria instead of the $p<0.05$ criteria).

[0234] One possible use of the dual modulation test signal may be to monitor the level of arousal for a patient who is subjected to anesthesia. The use of anesthesia will reduce the amplitude of the 40 Hz SSAEP response but not the amplitudes of the higher frequency SSAEP responses. Thus, to ensure that the measurement of data is not contaminated by some peripheral dysfunction, such as the earphone not working correctly or the ear developing a conductive hearing loss, it would be beneficial to monitor both the 40 Hz and 80 Hz SSAEP responses simultaneously. The 80 Hz SSAEP response could be used to demonstrate that the peripheral auditory function of the subject 60 patient is normal. Another use for the dual modulation test signal is in the assessment of the ability of the subject **60** to process temporal modulation functions (as is discussed in greater detail below).

[0235] The signal creator **34** creates the various test signals which are used in the SSAEP stimulus according to Equation 2. Accordingly, Equation 2 can be used to create AM, FM, MM, OVMM and IAFM test signals.

$$s(i)=a[1+m_a \sin(2\pi f_{am}ti)]\sin(2\pi f_c ti+F(i))/(1+m_a^2/2)^{1/2} \tag{2}$$

where:

$$F(i)=(m_f f_c/(2f_{fm}))\sin(2\pi f_{fm}ti+\theta\pi/180) \tag{3}$$

[0236] i is an address in the DAC output buffer

[0237] t is the DAC rate;

[0238] θ is the phase difference in degrees between the AM and FM components of the test signal s(t);

[0239] f_{am} is the modulation frequency for amplitude modulation; and,

[0240] f_{fm} is the modulation frequency for frequency modulation.

[0241] The test signal s(t), consists of sinusoidal tones having a carrier frequency of f_c. The AM is performed by the terms within the square brackets. The AM test signals are created by modulating the amplitude (a) of the carrier signal. The amplitude modulation depth is (m_a) controls the influence of the modulation signal on the envelope of the carrier signal.

[0242] The FM test signal is formed by modulating the phase of the carrier waveform according to the function F(i) shown in equation 3. The frequency modulation depth (m_f) is defined as the ratio of the difference between the maximum and minimum frequencies in the frequency modulated signal compared to the carrier frequency. For example, when a 1000 Hz carrier tone is frequency modulated with a depth of 25%, the frequency varies from 875 Hz to 1125 Hz which is a deviation ±12.5% from the carrier frequency of 1000 Hz. The term $m_f f_c/(2f_{fm})$ represents the frequency modulation index (often denoted by β). The final divisor in equation 2 is used to maintain a constant root-mean-square amplitude for various amounts of amplitude-modulation.

[0243] If m_f equals zero, then the test signal s(i) becomes an AM sinusoid. If m_a equals zero, then the test signal s(i) becomes an FM sinusoid. If f_{am} and f_{fm} are equal and if both m_a and m_f are greater than zero, then the test signal s(i) becomes an MM test signal. If f_{am} and f_{fm} are not equal and if both m_a and m_f are greater than zero, the test signal s(i) becomes an IAFM test signal.

[0244] The signal creator **42** can also create a test signal in which the envelope of the signal is modulated by an exponential modulation signal. In order to use exponential amplitude modulation, the formula for AM (in the square brackets) of Equation 3 becomes:

$$\lfloor 2m_a((((1+\sin(2\pi f_m ti))/2)^{eam}-0.5)+1)\rfloor \tag{4}$$

[0245] where eam is the exponent. In this equation, the test signal is adjusted to maintain the same root-mean-square value for the intensity of the resulting SSAEP stimulus regardless of the exponent used in the exponential modulation signal. In order to form an FM test signal with an exponential envelope, a running integral of the envelope equation must be maintained. The running integral sums all the envelope values up to the present address in the buffer according to:

$$\varsigma_i = \sum_1^i x_i \tag{5}$$

[0246] and the envelope that is being integrated is:

$$x_i=(2\pi m_f f_c t)(((1+\sin(2\pi f_{fm} ti))/2)^{efm}-0.5) \tag{6}$$

[0247] where efm is the exponent for the exponential modulation signal. The integrated value is then inserted into Equation 3 instead of the value F(i). In addition, changes in the phase of the envelope may be made by shifting the function in time.

[0248] Referring to **FIGS. 7***a***-7***d*, the usage of exponential envelope modulation for both AM and FM SSAEP stimuli produce larger responses than AM SSAEP stimuli. **FIGS. 7***a* and **7***b* show the percent increase in response amplitude when using AM SSAEP stimuli with exponential envelopes compared to AM SSAEP stimuli without exponential envelopes for a 50 dB pSPL and 30 dB pSPL stimulus intensity. **FIGS. 7***c* and **7***d* show response amplitudes in nV corresponding to the data shown in **FIGS. 7***a* and **7***b*. At 50 dB pSPL the exponential envelope modulation increases the SSAEP response amplitude in the lower and higher frequency ranges. At 35 dB pSPL, the exponential envelope modulation increases the SSAEP response amplitude especially for the lower frequencies.

[0249] An informal analysis of the results shown in **FIGS. 7***a***-7***d* indicates that using a sinusoidal signal to the power of 2 or 3 at stimulus intensities of 30 and 50 dB pSPL provides the larger SSAEP response amplitudes. Alternatively, fractional exponents may also be used. It should be noted that an increase in SSAEP response amplitude by 40% will enable the test time to be reduced by a factor of 2 when detecting the SSAEP response since the EEG noise decreases with the square root of the data (i.e. $1.4142=(2)^{1/2}$). Thus, modulating the envelope of the SSAEP stimulus with an exponential signal may result in a reduction of test time.

[0250] Exponential envelopes may also be created using AM depths below 100%, such as 80%, in order to more closely maintain the steady-state nature of the SSAEP stimulus. Additionally, the use of exponential envelopes tends to increase the amplitude of the SSAEP responses at harmonic of the modulation frequency. Accordingly, hearing tests may be utilized where envelopes are modulated by an exponential sinusoid in the 40 Hz range and the SSAEP responses are evaluated at the second harmonics of the modulation frequency. A detection method may also be devised in which the sensed EEG data is evaluated at both the modulation frequency and the second harmonic of the modulation frequency using the Stouffer method or a Stouffer method which defaults to the evaluation of a single harmonic when one of the two harmonics meets some criteria (i.e. $p<0.01$ or $p<0.001$).

[0251] Audiometric Testing Using Steady-state Evoked Potentials

[0252] The objective audiometric test apparatus **10** is also adapted to perform various audiometric tests in an objective manner using SSAEP stimuli without any necessary user control other than the selection and initiation of a particular audiometric test. Testing is objective in the sense that the subject does not have to subjectively respond to the stimuli used in the test and the individual conducting the test does not have to subjectively interpret the recorded data since statistical methods are used to analyze the recorded data. Thus, the "completely objective auditory testing system" (i.e. COATS) performs these tasks objectively. The objective audiometric test apparatus **10** may be used to evaluate hearing in subjects with normal hearing, cochlear hearing loss or abnormal auditory nervous systems, and in subjects who use hearing aids.

[0253] In general, the objective audiometric test apparatus **10** presents SSAEP stimuli, records EEG data and determines whether SSAEP responses are present in the EEG data. The objective audiometric test apparatus **10** then presents further SSAEP stimuli to obtain more precise information. However, the individual performing the audiometric tests can make decisions about which SSAEP stimuli to present and the duration of each test.

[0254] The objective audiometric test apparatus **10** is further adapted to obtain multiple audiometric thresholds concurrently. In addition, the objective audiometric test apparatus **10** is adapted to perform audiometric testing on subjects with aided and unaided hearing. With respect to aided hearing tests, the objective audiometric test apparatus **10** can be used to adjust the various parameters of a hearing aid. The objective audiometric test apparatus **10** can also perform latency tests, AM/FM discrimination tests, rate sensitivity tests, aided hearing tests, depth sensitivity tests and supra-threshold tests.

[0255] The objective audiometric test apparatus **10** also utilizes one of the databases of normative data, stored in the master database **52**, to construct SSAEP stimuli, detect SSAEP responses and determine whether detected SSAEP responses are indicative or normal or abnormal hearing. The databases contain data which is correlated by subject characteristics such as age, sex and state over a variety of stimulus characteristics such as type of modulation, type of modulation envelope, modulation rate and modulation depth, etc. The database also contains data about SASEP responses such as latency, the ratio of amplitudes of SSAEP responses to AM and FM SSAEP stimuli, etc.

[0256] The objective audiometric test apparatus **10** can perform audiometric tests to assess the supra-threshold hearing of a subject. The supra-threshold tests comprise assessing the threshold of a subject's auditory system in detecting changes in the frequency or intensity of a stimulus at supra-threshold stimulus intensities. Accordingly, the supra-threshold test comprises an intensity limen and a frequency limen. The intensity limen test protocol involves varying the intensity of a stimulus by varying the AM depth. In particular, the intensity limen involves estimating the threshold for detecting a change in the amplitude modulation depth of the stimulus. The frequency limen involves varying the frequency content of the SSAEP stimulus by varying frequency modulation depth. In particular, the frequency limen involves estimating the threshold for detecting a change in the FM depth of an SSAEP stimulus. The intensity and frequency limens correlate with the subject's **60** ability to discriminate supra-threshold sounds of various intensities and frequencies.

[0257] The procedure for determining the intensity limen preferably involves the following steps:

[0258] a) Constructing an SSAEP stimulus with an AM component having an AM depth of 100%;

[0259] b) Recording the EEG data while presenting the SSAEP stimulus to the subject **60**;

[0260] c) Analyzing the EEG data to determine if there was a response to the SSAEP stimulus;

[0261] d) If there is a response, then decreasing the AM depth of the AM component by half and repeating steps (b) and (c); and,

[0262] e) if no response is detected then the intensity limen is determined as the lowest AM depth which resulted in an SSAEP response being detected.

[0263] Likewise, the frequency limen can be conducted according to the following steps:

[0264] a) Constructing an SSAEP stimulus having an FM component with an FM modulation depth of 40%;

[0265] b) Recording the EEG data while presenting the SSAEP stimulus to the subject;

[0266] c) Analyzing the EEG data to determine if there was an SSAEP response to the SSAEP stimulus;

[0267] d) If there is a response, then decreasing the FM depth of the FM component by half and performing steps (b) and (c); and,

[0268] e) if no response is detected then the frequency limen is determined as the lowest FM depth which resulted in an SSAEP response being detected.

[0269] The supra-threshold hearing test may further involve varying the modulation depths in an SSAEP stimulus and examining the size of the resulting SSAEP responses compared to population normative values.

[0270] The supra-threshold hearing test may further comprise a method which should be less prone to inter-subject differences. The method comprises measuring the amplitude of the SSAEP response when presenting the subject with an AM SSAEP stimulus that has an AM depth of 100%. This response amplitude may then be compared to SSAEP response amplitudes that are obtained when presenting the subject with an AM SSAEP stimulus that has smaller AM depths. Accordingly, a demonstrative measure may be the ratio of the amplitude of an SSAEP response which is recorded while presenting a subject with an AM SSAEP having a 50% AM depth to the amplitude of an SSAEP response obtained while presenting a subject with an AM SSAEP having a 100% AM depth. As in the case of absolute amplitudes, normative values can be obtained for these ratios using appropriate age and sex matched control populations that were exposed to similar stimuli. These normative values can be obtained from one of the databases in the master database **52**.

[0271] The objective audiometric test apparatus **10** may also perform latency tests on the subject to determine if the subject has normal or abnormal hearing. Through the use of a "preceding cycles technique", experiments have shown that SSAEP responses have reliable and repeatable latency values in normal healthy ears. The latency values are obtained from the phases of the detected SSAEP responses. The latency of an SSAEP response is important for diagnosing various kinds of sensorineural hearing loss. An abnormally long latency value may indicate that an acoustic neuroma is present. Alternatively an abnormally short latency value may indicate that the subject has Meniere's disorder.

[0272] Referring to **FIG. 8**, the results of a set of experiments using dichotic stimulation are shown. A multiple SSAEP stimulus with four carrier signals having carrier frequencies that were separated by an octave were presented to one ear and four stimuli at intervening carrier frequencies were presented to the other ear for a group of subjects. The SSAEP stimuli were then reversed and applied to the opposite ear. The data shown in **FIG. 9** are the latencies derived by modeling the vector-averaged phase delays measured across eight subjects in the subject group. These phase delays were measured as having occurred after 1 preceding cycle in the stimulus waveform. Phase delay was found to be similar for SSAEP responses evoked by SSAEP stimuli having one test signal component or SSAEP stimuli having more than one test signal component, as long as adjacent carrier frequencies in the SSAEP stimulus were separated by at least 1 octave. The experimental results showed that phase (and hence latency) are stable over time and change as expected with the intensity level of the stimulus. Phase delay was also the same for monaural and binaural presentation.

[0273] Since phase delay was found to be consistent, a normative database, stored within the master database **52**, containing appropriate age and sex matched normative phase delay or latency values for various stimuli may be constructed. This normative database of phase delay values may then be used as a reference to detect abnormalities in subjects by measuring their phase delay or latency. In addition to absolute latency values, normative values for the differences between the latencies for responses to pairs of stimuli may be useful in the detection of abnormal hearing. For instance, the difference between the latency estimate for SSAEP stimuli with 2000 and 4000 Hz carrier frequencies may be used.

[0274] The procedure for measuring latency uses the following steps:

[0275] a) Record the steady-state response to an SSAEP stimulus and measure the onset phase of the response in degrees;

[0276] b) Convert the onset phase to a phase delay (P) by subtracting it from 360° (it may be necessary to make the phase delays 'rational' across different carrier frequencies, i.e. an extra 360 degrees may be added to the phase delay (i.e. phase unwrapping) so that the phase delay for a carrier frequency with a lower frequency is longer than the phase delay for a carrier frequency with a higher frequency, (a situation which makes sense since higher frequencies are transduced near the basal end of the cochlea)); and,

[0277] c) Convert the phase delay to a latency (L) value in milliseconds according to the formula:

$$L=1000^*(P+N^*360)/(360^*f_m) \tag{7}$$

[0278] where f_m is the modulation frequency for the SSAEP stimulus that evoked the SSAEP response and N is chosen as the number of preceding cycles. For modulation frequencies in the range of approximately 75-100 Hz, N can be chosen to be 1. The value of N can be determined from normative studies using different modulation frequencies. N is set for each response in order to bring the latency values calculated for a subject as close as possible to normative latency values.

[0279] Another way of determining the latency value is to present an SSAEP stimulus at a given carrier frequency and vary the modulation frequency. The phase of the response to each different modulation frequency is then measured and plotted versus modulation frequency. The latency value is then estimated from the slope of the phase versus modulation frequency plot.

[0280] The objective audiometric test apparatus **10** can also perform AM/FM discrimination tests using SSAEP stimuli. The AM/FM discrimination tests correlates with speech discrimination tests. One test involves using the number of responses to multiple IAFM SSAEP stimuli as an estimate of the ability of a subject's auditory system to discriminate the frequencies and intensities necessary for speech perception. If the SSAEP responses suggest that the auditory system of the subject cannot make these discriminations then the subject will not be able to discriminate all of the words. Accordingly, the intensity of the SSAEP stimulus would be similar to the intensity at which words would be presented during a subjective speech discrimination test in terms of root mean square SPL.

[0281] Referring to **FIG. 9**, the percentage of words that were correctly discriminated by a subject versus the number of significant SSAEP responses that were detected when a multiple IAFM SSAEP stimulus was presented to the subject is shown. The multiple IAFM SSAEP stimulus comprised

AM and FM signals with carrier frequencies of 500, 1000, 2000 and 4000 Hz. The areas of the plotted circles are related to the number of data points, with the largest circle representing 7 data points. This scattergram shows a correlation between the number of detected (i.e. significant) SSAEP responses and the word discrimination. The IAFM stimulus may be a good stimulus for looking at word discrimination since it presents multiple AM and FM stimuli simultaneously. Other multiple stimuli may also be used. For example, eight separate carrier signals may be presented with four of these amplitude-modulated and the other four frequency-modulated. The idea is to evaluate both amplitude and frequency discrimination at multiple frequencies.

[0282] Accordingly, a test protocol that could be used to indicate the speech processing ability of the subject may consist of determining the number of SSAEP responses that were evoked by a multiple IAFM SSAEP stimulus. The test period may persist for a certain amount of time, for example 12 minutes, or until the residual noise background reached a minimal limit. The testing may be done both in the absence and presence of noise masking as is conventionally done in subjective speech discrimination tests. The use of noise masking is important in testing subjects who have difficulty listening to speech with background noise. The word recognition score is then be estimated from a function that correlates the number of detected SSAEP responses which were evoked by the multiple IAFM SSAEP stimulus to the word recognition score. The actual function may be determined from studies on a normative sample population of subjects. Control recordings need to be included to ensure that responses can be reliably recorded (and that the noise levels are not too high). These control tests may employ SSAEP response to single tones (i.e. sinusoids) with 100% amplitude modulation.

[0283] The AM/FM discrimination test could further comprise testing the ability of the subject to discriminate frequency changes from amplitude changes. The amplitude of the SSAEP response to an FM component of an IAFM SSAEP stimulus could be compared to the amplitude of the SSAEP response to an AM component of an IAFM SSAEP stimulus in the form of a response amplitude ratio (denoted by FM/AM). Alternatively individual FM SSAEP and AM SSAEP stimuli may be used. This FM/AM ratio can then be compared to normative FM/AM ratios that may be computed for all age groups and stored in a database within the master database **52**. Initial studies suggest that FM/AM ratios for 500 to 6000 Hz carrier frequencies are between approximately 1 and 2 for younger subjects and below approximately 1 for older subjects. Deviations from this range may be used to indicate a problem in the part of the auditory system that processes AM signals or the part of the auditory system that processes FM signals.

[0284] The objective audiometric test apparatus **10** can also perform rate sensitivity tests in which the amplitude of the SSAEP response to an SSAEP stimulus with increasing modulation frequencies may be measured. The various SSAEP stimuli that have been discussed (i.e. AM, FM, OVMM, MM, IAFM) and the use of exponential envelope modulation can be presented with modulation rates that vary from a few Hz to several hundred Hz. In general, as the modulation frequency (or modulation rate) increases, the amplitude of the SSAEP response to the SSAEP stimulus decreases with the exception of local maxima that can occur in the 40, 80, and 160 Hz ranges. However, this rate of response amplitude decrease can vary for different subjects, particularly if the different subjects include individuals with normal hearing and abnormal hearing.

[0285] Referring to **FIG. 10**, the SSAEP response amplitudes of an older subject **100** measured in response to SSAEP stimuli having a range of modulation frequencies is compared to the average SSAEP response amplitudes obtained from a group of normal control subjects **102**. The data shows that the decrease in SSAEP response amplitude with increasing modulation rate occurs more rapidly for the older subject **100** who also had a minor hearing loss. Although the older subject **100** could hear the SSAEP stimuli with higher modulation frequencies, the SSAEP response amplitudes for the SSAEP stimuli with higher modulation frequencies did not produce large amplitude SSAEP responses. Therefore, by comparing the rate of decrease in the SSAEP response amplitude (i.e. the rate sensitivity) that occurs with increasing SSAEP stimuli with increasing modulation rates to those obtained from an appropriate normative population, subjects with abnormal hearing can be detected. Alternatively, instead of using the absolute value of the SSAEP response amplitude (which is shown in **FIG. 10**), a ratio of SSAEP response amplitudes may be used such as the ratio of the SSAEP response amplitude for an SSAEP stimulus with a low modulation frequency to the SSAEP response amplitude for an SSAEP stimulus with a high modulation frequency.

[0286] The larger decay in SSAEP response amplitude that occurs with increasing modulation frequency in the older subject (with a minor hearing loss) is similar to the decay that would be predicted by studies on older adults who display large gap detection thresholds and more rapid decay in their temporal modulation transfer functions. Since an AM SSAEP stimulus with a carrier frequency of 100 Hz can be considered similar to a stimulus which is on for half a cycle and off for half a cycle then a 100 Hz AM SSAEP stimulus may be considered similar to having a stimulus on time of 5 msec and a gap duration of 5 msec. Additionally, an AM SSAEP stimulus with a 200 Hz carrier frequency is similar to having a stimulus "on" time of 2.5 msec, with a gap duration of 2.5 msec. Accordingly, the SSAEP responses which are recorded in response to SSAEP stimuli with modulation frequencies in the range of 100 to 200 Hz may be used to provide a physiological correlate of the modulation transfer function or the gap function of an individual for gaps ranging from 5 msec to 2.5 msec. The period of the gap of the SSAEP stimulus may be functionally increased by decreasing the modulation frequency or by increasing the exponent when using an exponential modulation signal with the SSAEP stimulus. Alternatively, both of these operations may be applied to the SSAEP stimulus.

[0287] The rate sensitivity test may further comprise using a multiple SSAEP stimulus comprising 4 AM test signals. The modulation frequencies of the 4 AM test signals can initially be chosen to be 40, 44, 48, and 52 Hz for example. If the two ears of a subject have been shown to have similar hearing ability, then the other ear of the subject may be presented with a multiple SSAEP stimulus that comprises 4 AM test signals with modulation frequencies of 42, 46, 50, and 54 Hz. After each recording is done, the modulation frequency of each AM test signal may be increased by 10 Hz. In this manner, estimates of SSAEP response amplitude may be measured in 10 Hz steps from approximately the 40 to 190 Hz range. A plot of SSAEP response amplitude versus modulation frequency may then be generated for each of the AM test signals or for a combination of the SSAEP responses to the 4 AM test signals such as the mean SSAEP response amplitude at each modulation frequency. If the mean values at each of the modulation frequencies are found to be more useful than using information obtained for each of the 4 AM tones separately, then single rather than multiple stimuli may be used in this test. Alternatively, the carrier waveform could be band-limited noise that is modulated at a single modulation rate. Since broadband noise can evoke a larger SSAEP response than that evoked by a single AM tone, the duration of this test should be shorter.

[0288] The objective audiometric test apparatus **10** may further estimate a threshold above which the auditory system of a subject no longer responds to the modulation frequency used in the SSAEP stimulus. This test yields a "cutoff" modulation frequency threshold at which the auditory system of the subject no longer recognizes SSAEP stimuli with higher modulation frequencies.

[0289] The objective audiometric test apparatus **10** may also be used with subjects who have hearing aids. In this case the objective audiometric test apparatus **10** may be used to adjust the settings (e.g. gain) of the hearing aid so that the subject can hear sounds near his/her threshold. The adjustment protocol comprises presenting the subject with an SSAEP stimulus while recording the EEG of the subject. The EEG is then analyzed to determine if an SSAEP response to the SSAEP stimulus occurred. If an SSAEP response did not occur, then the gain of the hearing aid may be increased in step changes until an SSAEP response to the SSAEP stimulus can be detected (or until some maximum level of gain is reached which is necessary to prevent the use of any gain levels which may damage the ear). Typically, this protocol would use SSAEP stimuli with an intensity level similar to that of conversational speech which may be approximately 50-60 dB HL. The SSAEP stimuli would also use modulation depths that are typical of speech sounds such as FM test signals having an FM depth of approximately 20% and AM test signals having an AM depth of approximately 50%.

[0290] Depending on the parameters that can be adjusted in the hearing aid, the adjustment protocol can be made more or less specific in its operations. For example, the gain of the hearing aid may be adjusted separately for different frequency regions. Therefore, these gains may be separately and concurrently adjusted. Alternatively, if only the gain and the filter slope of the hearing aid can be adjusted then a different adjustment protocol may be used to adjust these parameters on the basis of the recognized SSAEP responses when presenting SSAEP stimuli at different frequencies to the subject.

[0291] The objective audiometric test apparatus **10** may further include another hearing aid adjustment protocol known as the Seek and Adjust Single-Multiple (SASM) technique. In this case, the gain of the hearing aid is automatically increased, by the objective audiometric test apparatus **10**, until an SSAEP response to an SSAEP stimulus is detected. After this has been done for all the SSAEP stimuli, several paired SSAEP stimuli may then be presented to the subject. Alternatively, rather than pairs, four or more AM test signal may be used in the multiple SSAEP stimulus. This is done because it has been shown that the thresholds for a multiple SSAEP stimulus (which may be more similar to natural sounds such as speech) may be higher than the thresholds for SSAEP stimuli having comprising single test signals. For example, in the case of a high frequency hearing loss that is steeply sloping near 4 kHz, both a 2 kHz and a 4 kHz AM sinusoid may be presented together in a multiple SSAEP stimulus. If a 60 dB SPL stimulus needed to be amplified by 20 dB in order for the auditory system of the subject to detect the 2 and 4 kHz AM test signals, then the multiple AM SSAEP stimulus may first be presented to the subject using a 20 dB gain. If a significant SSAEP response is not obtained for either component of the multiple SSAEP stimuli, the gain for this frequency region in the hearing aid may be increased a maximum of 3 times in +5 dB SPL steps for example. If, on the other hand, a significant SSAEP response is not obtained for either component of the multiple SSAEP stimulus, then the gain of the hearing aid corresponding to the frequency region of either the first component of the multiple SSAEP stimulus, or the second component of the SSAEP stimulus, or both components of the SSAEP stimulus may be increased a maximum of 3 times in +5 dB SPL steps (for example). In this manner, interactions can be evaluated, and the gain parameters that result in the lowest overall gain will be automatically chosen for the hearing aid.

[0292] The objective audiometric test apparatus **10** may also be used to objectively measure the audiometric thresholds of a subject by presenting multiple SSAEP stimuli at multiple stimulus intensities to the subject and recording the SSAEP responses. The objective audiometric test apparatus **10** may then adjust the intensity levels of the SSAEP stimuli based on the detection of SSAEP responses and the amplitude of the SSAEP responses. Since a multiple SSAEP stimulus may be used, multiple audiometric thresholds may be estimated simultaneously. Experimental results have shown that audiometric threshold estimated with SSAEP stimuli are correlated with behavioral audiometric thresholds.

[0293] The objective audiometric threshold assessment method involves using a multiple SSAEP stimulus comprising 4 or more AM SSAEP test signals having an amplitude modulation depth of 100% and carrier frequencies that are separated by at least one-half octave. Alternatively, the multiple SSAEP stimulus may comprise FM test signals each having an FM modulation depth in the range of 20%. The use of these modulation depths for the AM and FM components of the multiple SSAEP stimulus permit the audiometric testing to be frequency specific. The SSAEP stimulus may also comprise MM or OVMM SSAEP test signals having similar modulation depths. Furthermore, the SSAEP stimulus could also have an envelope that is modulated by an exponential modulation signal with the modulation being done such that the resulting SSAEP stimulus is predominantly frequency specific.

[0294] The objective audiometric threshold assessment method may further involve adjusting the intensity of each component of the multiple SSAEP stimulus either independently or simultaneously. In the independent case, the intensity of a component of the multiple SSAEP stimulus is reduced when the corresponding SSAEP response has been detected in the recorded EEG data. This independent intensity adjustment can be achieved if each component of the multiple SSAEP stimulus is sent to a separate DAC that can be adjusted in real time. Alternatively, the components of the multiple SSAEP stimulus may be combined digitally and then presented through 2 DACs (1 for each ear of the subject). In this case, the intensity of a given component of the multiple SSAEP stimulus may be digitally adjusted independently of the other components and combined in the multiple SSAEP stimulus. This may be done provided that the DAC has sufficient resolution (e.g. 16 or more bits) to allow for the accurate presentation of less intense components in the presence of higher intensity components.

[0295] To illustrate this principle, a multiple SSAEP stimulus may comprise 4 AM test signals with carrier frequencies of 0.5, 1, 2, and 4 kHz presented at 50 dB SPL. Each of the 4 test signals are represented in a 16 bit buffer with about 16,384 bits each (this of course depends on the particular data acquisition board that is used in the test apparatus). If the SSAEP response to the AM test signal with a carrier frequency of 1 kHz becomes significant first, in order to present this AM test signal at 40 dB SPL while the other test signal components are presented at 50 dB SPL, the test signal must be decreased by 10 dB SPL. Since the multiple SSAEP stimulus is stored in the RAM of the processor **12**, a new multiple SSAEP stimulus may be created by adding together the test signal components (now with a reduced intensity AM test signal component having a 1 kHz carrier frequency), and sent to the output buffer of the DAC **16**. In this case, a dual buffer technique can be used in which the output buffer can be originally defined as being twice as long as an SSAEP stimulus. The multiple SSAEP stimulus is then loaded into the first half of the buffer. When a new multiple SSAEP stimulus is created, it can be loaded into the second half of the output buffer, such that when the end of the first buffer is reached, the new multiple SSAEP stimulus can be seamlessly presented to the subject by simply changing the memory address where the DAC **16** looks for data to convert into analog data.

[0296] Alternatively, rather than recreating the entire multiple SSAEP stimulus, the intensity of a single component within the multiple SSAEP stimulus may be adjusted using the Stimulus Flux method. The Stimulus Flux method involves changing the intensity of a single component within the multiple SSAEP stimulus by creating and separately storing a waveform for each component of the multiple SSAEP stimulus. When the intensity of a particular component of the multiple SSAEP stimulus must be adjusted, the amplitude of the corresponding waveform is multiplied by the required amplitude factor such that when this waveform is subtracted from the multiple SSAEP stimulus, the intensity of the desired component will be adjusted to the desired value. The new multiple SSAEP stimulus may then loaded into the output buffer of the DAC **16** and subsequently presented to the subject **60**.

[0297] An algorithm to carry out the objective audiometric threshold assessment method may involve an adaptive staircase method. The adaptive staircase method is designed to bracket the audiometric threshold as efficiently as possible by adjusting the value of a step size. The step size is used to increase or decrease the intensity of components within the multiple SSAEP stimulus during subsequent presentations of the multiple SSAEP stimulus to the subject. The step size may be adjusted on the basis of SSAEP response detection at a given stimulus intensity and the sequential replication of the audiometric threshold estimates. One possible definition of the audiometric threshold may be the intensity of a particular component (for which the audiometric threshold is being determined) of the multiple SSAEP stimulus between the last two stimulus intensities which resulted in detected and not detected SSAEP responses when using a minimum step size. The audiometric thresholds may be then confirmed based on replicated audiometric threshold estimates using the staircase procedures shown in **FIG. 11**.

[0298] The objective audiometric threshold assessment method also includes the selection of initial stimulus intensity, initial step-size and minimum step-size. Maximum and minimum limits for the stimulus intensities must also be set above and below which the method will not look for audiometric thresholds. The rules for step size changes may also be defined. Furthermore, the step-size itself may decrease with time or vary with the remaining range of stimulus intensities that are to be tested (e.g. the step size can be defined as half of the distance between the present stimulus intensity and the minimum or maximum stimulus intensity which will be tested). There must also be a minimum step size that will determine the precision whereby the audiometric threshold is estimated (e.g this may be 5 or 10 dB SPL). Other parameters that need to be set are the criteria whereby an SSAEP response is judged to be present or absent. The Phase weighted t-test or the phase zone method may be used to detect the response. Alternatively, any detection method known in the art may be used. The criterion for judging that an SSAEP response to an SSAEP stimulus is absent may be adjusted based on a minimum level of residual background noise in the processed EEG data. This criterion may also include a time limit for which the test expires. Alternatively, both of these criteria may be used.

[0299] The objective audiometric threshold assessment method may be implemented as follows. Several test signals components are combined in a multiple SSAEP stimulus which is presented at a given intensity level. Alternatively, a single test signal component may be used in the SSAEP stimulus. EEG data is simultaneously recorded, while the SSAEP stimulus is presented to the subject. The recorded EEG data is subsequently analyzed for SSAEP response detection. As soon as one SSAEP response is detected, the intensity of the test signal component (denoted as TS1) which evoked this SSAEP response is reduced by a step-size equal to half the dB SPL distance between the current intensity level for the test signal component TS1 and the minimum intensity level which will be tested in the audiometric threshold test. Accordingly, a new multiple SSAEP stimulus will be constructed based on this new test signal component TS1. The method now involves the same steps as before: presenting the multiple SSAEP stimulus, recording EEG data and analyzing the data for any SSAEP responses. The protocol also involves halving the step size for the component in the multiple SSAEP stimulus that evoked a detected SSAEP response. Therefore, if an SSAEP response is detected for the test signal component TS1, then the stimulus intensity for the test signal component TS1 is reduced by the new step size. Alternatively, if a response was not detected for the test signal component TS1, then the intensity level for the test signal component TS1 is increased by the new step size. An estimate of noise level of the recorded EEG data may also be made to ensure that a lack of SSAEP response detection is not due to excessive noise in the recorded EEG data. The noise estimate may also be used as a multiplicative factor to increase the test time when presenting a given multiple SSAEP stimulus. Thus, the test time may be extended as a function of the amount of noise in the recorded EEG data.

[0300] The objective audiometric threshold assessment method further comprises obtaining threshold crossings until thresholds for all test signal components in the multiple SSAEP stimulus have been obtained. Alternatively, when a sufficient number of threshold crossings have been obtained for some test signal components in the multiple SSAEP stimulus but not for other test signal components, a new multiple SSAEP stimulus could be constructed comprising the test signal components for which thresholds have not been obtained. Testing would then continue with this new multiple SSAEP stimulus.

[0301] The objective audiometric threshold assessment method may further comprise adjusting the intensities of all of the test signal components in the multiple SSAEP stimulus simultaneously. Some test signal components of the multiple SSAEP stimulus may then be removed after a specified duration of time if SSAEP responses have been detected for these test signal components. The remaining test signal components in the multiple SSAEP stimulus are then presented for another duration of time such as 90 seconds for example. Since the detection of an SSAEP response to a single SSAEP stimulus may require about 90 seconds, this audiometric threshold detection procedure will be approximately 2 times as fast as testing with an SSAEP stimulus which has single test signal components. Additionally, since SSAEP stimuli comprising AM, FM, OVMM or MM test signals can be presented binaurally to a subject (i.e. to both ears of the subject), the objective audiometric threshold assessment method may be 4 times as fast as testing with an SSAEP stimulus comprising single test signals presented separately to each ear.

[0302] The objective audiometric threshold assessment method may alternatively present test signal components in the multiple SSAEP stimulus at different intensities. Since SSAEP responses to test signals having carrier frequencies of 500 Hz and 4000 Hz typically require more time to be detected compared to SSAEP responses to test signals having carrier frequencies of 1000 and 2000 Hz, the stimulus intensity of the former test signal components may be increased relative to the later test signal components. Accordingly, the intensity of the test signal components having 500 Hz and 4000 Hz carrier frequencies may be presented at 10 dB SPL above the intensity level for the test signal components having carrier frequencies of 1000 Hz and 2000 Hz (note that these exact frequencies do not have to be used and are shown for illustrative purposes; it is the frequency region in which they reside that is important). In this fashion, the SSAEP responses to the test signal components may all be detected at approximately the same time. Alternatively, the multiple SSAEP stimulus may comprise only 2 test signal components, such as test signal components having 500 Hz and 4000 Hz carrier frequencies since these test signals will be transduced by separate, fairly spaced apart regions of the basilar membrane and SSAEP responses to these particular stimuli will both require long times to detected.

[0303] When the objective audiometric threshold assessment method has been completed, the results can be presented in a standard audiometric format as is commonly known to those skilled in the art. The presentation of the test results may include highlighting whether SSAEP responses to test signal components were detected when the test signal components were presented alone or in combination with other test signal components. For example, these SSAEP responses may be circled or highlighted with a particular color. In addition to the actual audiometric thresholds that were obtained from testing, estimates of audiometric thresholds may also be made which are extrapolated from detected SSAEP responses for test signal components which were presented at higher stimulus intensities. For example, by taking the decrease in the amplitude of the SSAEP responses obtained for a test signal component presented at 60, 50, and 40 dB SPL, an estimate of when an SSAEP response will not be detected may be made by projecting a line connecting the amplitude of these detected SSAEP responses to the level of the average background EEG noise.

[0304] Multi-modality Testing

[0305] Referring to **FIG. 12**, an alternate embodiment of the objective audiometric test apparatus **10** comprises an objective multi-modality test apparatus **200**. Please note that in **FIG. 12**, like numerals were used to represent elements that are similar to the elements of the objective audiometric test apparatus **10** shown in **FIG. 1***a*. The objective multi-modality test apparatus **200** may be used to concurrently test other modalities while the auditory system of the subject **60** is being tested. In this embodiment, the visual and somatosensory modalities are concurrently tested with the auditory modality. In other embodiments, other sensory modalities may be concurrently tested with the auditory system. The testing of multiple modalities may allow for the determination of whether an auditory abnormality is part of a more widespread disorder of the nervous system such as multiple sclerosis for example. In addition, multi-modality testing may be used to investigate neurological disorders.

[0306] The objective multi-modality test apparatus **200** comprises the processor **12**, a data acquisition board **202** having at least one DAC **204** and at least one ADC **206**, amplifiers **22**, **208** and **210**, filters **24**, **212** and **214**, transducers **26**, **216** and **218**, sensors **28**, **220** and **224**, amplifiers **30**, **224** and **226** and filters **32**, **228** and **230**. The processor **12** further comprises a software program **232** that encodes the functionality of the objective multi-modality test apparatus **200**. The software program **232** comprises a signal creator **234**, a modulator **236** and an analysis module **238** having a noise reduction module **240** and a detection module **242**. The software program **232** is also coupled to a plurality of a master database **250** which comprises a plurality of databases D1 to Dn. The processor **12** is also coupled to the storage device **34** and the computer display **36**.

[0307] In use, the signal creator **234** generates test signals that are appropriate as stimuli for evoking auditory, visual and somatosensory response potentials. The modulator **236** may be employed in the creation of the test signals. The test signals are then sent to the DAC **204** which may comprise a plurality of output channels or may be a plurality of single channel DACs. The DAC **204** sends the test signals to the amplifiers **22**, **208** and **210**. The amplifiers **22**, **208** and **210** amplify the test signals to adjust the intensity level of the test signals to levels that are suitable for testing. The amplified test signals are then sent to filters **24**, **212** and **214** to remove any noise from the digital to analog conversion process and the amplifying process.

[**0308**] The filtered, amplified test signals are then sent to the transducers **26**, **216** and **218** so that the test signals may be transduced by and simultaneously presented to the subject **60**. The transducer **26** may be an auditory transducer that transduces the appropriate test signal into an auditory stimulus. Accordingly, the transducer **26** may be a pair of headphones or at least one insert earphone. The particular test signals used for the auditory stimulus can be any of the stimuli that were previously discussed for the objective audiometric test apparatus **10**. For instance the auditory stimulus may be two AM sinusoids (i.e. tones) at different carrier frequencies, having modulation frequencies of 87 and 93 Hz.

[**0309**] The transducer **216** may be a visual transducer that transduces the appropriate test signal into a visual stimulus. Accordingly, the transducer **216** may be a strobe light which can produce a pulsating flash or the transducer **216** may be a grid of light emitting diodes. The visual stimuli may be presented at modulation rates of 16 and 18 Hz, for example, to the left and right eyes of the subject **60**. Alternatively, the visual stimuli may be presented to only one eye of the subject **60**. As in the case of the auditory stimuli, multiple modulated visual stimuli may be presented to a single eye.

[**0310**] The transducer **218** may be a tactile transducer that transduces the appropriate test signal into a tactile stimulus. Accordingly, the transducer **218** may be a vibrotactile stimulator or the like. The vibrotactile stimulator may be applied to at least one finger of the subject **60**. For instance, the vibrotactile stimulator may be applied to the left and right index fingers of the subject **60**. The tactile stimuli may be presented at rates of 23 and 25 Hz although other presentation rates may be used.

[**0311**] When presenting the multi-modality stimulus to the subject **60**, the test signals which are used must be chosen such that the frequencies of the responses to each of the auditory, visual and tactile stimuli are not equal to each other, are not integer multiples of each other and share a minimum of common factors. This must be ensured so that the responses and their harmonics do not interfere with one another.

[**0312**] EEG data is recorded while the multi-modality stimulus is presented to the subject **60**. The EEG data of the subject **60** is recorded using sensors **28**, **220** and **222** that are typically electrodes. These electrodes are placed on certain regions of the subject **60** to obtain EEG data with better signal to noise ratios. The sensors **220** that measure the response to the visual stimulus may be placed over the occipital regions of the brain of the subject **60**. The sensors **222** that measure the response to the tactile stimulus may be placed over the central scalp which is contralateral to the presentation of the tactile stimulus. The sensors **28** that measure the response to the auditory stimulus may be placed on the vertex of the subject **60**. In each of these cases alternative placements of the electrodes is possible. For instance, the placement of these sensors may also involve using a plurality of electrodes placed at numerous (i.e. 32 or 64) locations on the scalp of the subject **60**.

[**0313**] Each of the sensed potentials (i.e the EEG data which is also understood to be a time series data) may then be amplified by amplifiers **30**, **224** and **226** to an amplitude level that is sufficient for digitization. The amplified EEG data may then be filtered by filters **32**, **228** and **230**. The amplified, filtered EEG data is then sent to the ADC **206** for digitization at a sampling rate that is sufficient to sample the EEG data without aliasing.

[**0314**] The sampled data is then analyzed by the analysis module **242**. The data is first preprocessed by the noise reduction module **240** to reduce the amount of noise in the sampled data and produce noise reduced EEG data. The noise reduction module **242** may use the sample weighted averaging method to reduce noise. The noise reduction module **242** may also use adaptive artifact rejection. Alternatively, the noise reduction module **242** may use any noise reduction algorithm that is known in the art.

[**0315**] The noise reduced EEG data is then analyzed by the detection module **242** to determine whether there are any responses present in the noise reduced EEG data. The detection module **242** may implement the phase weighted t-test, the phase zone technique or the MRC method. Alternatively, the detection module **242** may use other detection algorithms that are known in the art. The detection module **242** may also provide a probability estimate that a detected response is truly a signal and not noise. The detected responses may then be compared to normative data on other subjects which is contained in the master database **250**. This comparison may provide an indication of whether the subject **60** has a widespread disorder of the neural system.

[**0316**] Based on the objective multi-modality test apparatus **200**, a procedure for multi-modality testing would comprise the following steps:

[**0317**] (i) Attach electrodes to the subject **60**;

[**0318**] (ii) Set up or attach transducers to present the multi-modality stimuli to the subject **60**;

[**0319**] (iii) Present the multi-modality stimuli to the subject **60** wherein the stimulus for each modality is synchronized with the objective multi-modality test apparatus **200** so that the multiple responses can be recognized by their signature modulation frequencies;

[**0320**] (iv) Record the EEG data at each electrode location to obtain three EEG data time series;

[**0321**] (iv) Reduce the noise in each EEG data time series to produce a set of noise reduced EEG data time series;

[**0322**] (v) Detect the steady-state responses in each noise-reduced EEG data time series wherein a steady-state response is recognized at the modulation frequency specific to the modality stimulus that evoked the response; and,

[**0323**] (vi) Compare the amplitudes of the detected responses to normative values matched for age and sex (alternatively the comparison can be done within the subject **60** if modality stimuli are presented to both the left and right sides of the body of the subject **60**).

[0324] Portable Objective Multi-modality Test Apparatus

[0325] The present invention further comprises a portable objective multi-modality test apparatus **300** as shown in **FIG. 13**. The portable objective multi-modality test apparatus **300** is similar to the objective multi-modality test apparatus **200** that was shown in **FIG. 12** and therefore comprises many of the same components. The portable objective multi-modality test apparatus **300** comprises a laptop computer **302** which has a screen **304**, a software program **306**, a storage device **308**, a master database **390** comprising a plurality of databases D1 to Dn and a PCMCIA data communication card **310**. The software program **306** comprises the signal creator **234**, the modulator **236** and the analysis module **238** including the noise reduction module **240** and the detection module **242**. The objective multi-modality test apparatus **300** further comprises a control box **312** having amplifiers **314, 316, 318, 320, 322, 324, 326** and **328**, filters **330, 332, 334, 336, 338, 340** and **342**, transducers **350, 352, 354, 356, 358** and **360** and sensors **362, 364** and **366**.

[0326] The portable objective multi-modality test apparatus **300** operates in much the same manner as the objective multi-modality test apparatus **200** except that the apparatus is based on the laptop **302** and the control box **312**. Alternatively, a palmtop or other portable computing device may be used. On the screen **304** there are various graphical user interfaces (GUI) windows that are implemented by the software program **306**. There is a Load protocol window **370**, a View Stimuli window **372**, a View EEG window **374**, a data acquisition window **376**, a continue acquisition window **378** and a process data window **380**. These GUI windows allow a user to operate the portable objective multi-modality test apparatus **300** and perform various tests on the subject **60**.

[0327] The PCMCIA data communication card **310**, which may be a National Instrument DAQCard-6062e card, enables functional communication and data transfer between the laptop **302** and the control box **312**. The PCMCIA data communication card **310** provides test signals to the control box **312** and receives the recorded EEG data. Other communication systems may also be used to support data transfer between the components of the system provided that they can support the necessary data transfer rates.

[0328] The control box **312** contains two audio amplifiers **314** and **316** which amplify the test signals, provided by the PCMCIA data communication card **310**, and provide the test signals to two transducers **350** and **352** which transduce the test signals into acoustic stimuli and present the acoustic stimuli to the subject **60**. The laptop **302** controls the intensity of the acoustic stimulus via the gain of the audio amplifiers **314** and **316**. Alternatively, eight or more audio amplifiers may be contained in the control box **312** in order to permit separate intensity control of test signals contained within a multiple SSAEP stimulus that may be presented to the subject **60**. The output of the audio amplifiers **314** and **316** are then sent to filters **330** and **332** to remove any digitization noise or artifacts in the test signals. The filters **330** and **332** may also be used to introduce pass band masking signals into the test signals. In a like manner, the control box **312** further comprises other amplifiers **318** and **320** and filters **334** and **336** that manipulate the test signals before they are transduced into visual and tactile stimuli.

[0329] The various test signals are then transduced by the transducers **350, 352, 354** and **356**. The transducers **352** and **354** may be headphones or insert earphones. The transducers **352** and **354** may also be speakers if the ears are not to be tested separately. The transducer **354** provides the visual stimuli to the subject **60** and may be a strobing light source or goggles that can be placed over the eyes of the subject **60**. The transducer **356** provides the tactile stimuli to the subject **60** and may be at least one vibration transducer that is attached to at least one finger of the subject **60**. Each stimulus in each modality is modulated at a unique frequency. Each stimulus must also be synchronously initiated and locked to the portable objective multi-modality test apparatus **300** so that the steady-state responses to the multi-modality stimulus can be recognized by their signature modulation frequencies (the steady-state responses occur at the modulation frequency used in the modality stimulus).

[0330] To record the steady-state responses to each of the modality stimuli, groups of electrodes **362, 364** and **366** are placed on the scalp of the subject **60** as was previously described for the objective multi-modality test apparatus **200**. Multi-modality steady-state testing could also be achieved by using multiple scalp recordings (e.g. using 32 electrode locations over the scalp) or by recording the EEG data with a small number of input data channels (e.g., 3) with specifically located electrodes.

[0331] The electrodes **362, 364** and **366** provide sets of EEG time series data to the control box **312**. These sets of EEG time series data are then amplified by the amplifiers **324, 326** and **328** and filtered by the filters **338, 340** and **342**. Alternatively only one amplifier and one filter may be used. The amplifiers **324, 326** and **328** have gain settings which are under the control of the laptop **302**. The filters **338, 340** and **342** may be programmable analog filters for lowpass, highpass, and notch filtering the sets of EEG time series data. These filters **338, 340** and **342** may also be controlled by the laptop **30** (the laptop may also control the other amplifiers and filters within the control box **312**). The filtered and amplified sets of EEG time series data are then sent to the PCMCIA data communications card **310** where the sets of EEG time series data are digitized and sent to the analysis module **238**. The sets of EEG time series data can then be processed to remove noise, via the noise reduction module **240** and then analyzed for response detection via the detection module **242** as was previously described for the objective multi-modality test apparatus **200**.

[0332] The portable objective multi-modality test apparatus **300** may further comprise means to enable the adjustment of hearing aid devices which may be worn by the subject **60**. In particular, the control box **312** may be adapted to communicate with hearing aid devices **358** and **360**. The communication may be via a physical connection such as a ribbon cable **361**. Alternatively, in the case of implanted hearing aid devices, the communication may occur via RF telemetry as is used to adjust other implanted biomedical devices (such as implanted stimulators). The portable objective multi-modality test apparatus **300** may then be used to adjust the frequency specific gain settings, the filter slope setting or other relevant settings of the hearing aid devices **358** and **360** as described previously in the method of adjusting hear aids using SSAEP stimuli. The adjustment of the hearing aid devices **358** and **360** may be done by a trained medical professional or may be adjusted automatically by the laptop **302** based upon the pass/fail results of the SSAEP testing procedure.

[**0333**] It should be understood that various modifications can be made to the preferred embodiments described and illustrated herein, without departing from the present invention, the scope of which is defined in the appended claims.

1. A method of testing the hearing of a subject, said method comprising the steps of:

(a) selecting at least one test signal;

(b) modulating at least one of the amplitude and frequency of said at least one test signal by an exponential modulation signal to produce at least one modulated test signal;

(c) transducing said at least one modulated test signal to create an acoustic stimulus and presenting said acoustic stimulus to said subject;

(d) sensing potentials from said subject while substantially simultaneously presenting said acoustic stimulus to said subject; and,

(e) analyzing said potentials to determine whether said potentials comprise data indicative of the presence of at least one steady-state response to said acoustic stimulus.

2. The method of claim 1, wherein said exponential modulation signal comprises a sinusoidal signal having an exponent which is greater than 1 and less than or approximately equal to 4.

3. The method of claim 1, wherein said exponential modulation signal is defined by the formula:

$$y[n]=2*m_a*[(((1+\sin(2*\pi*f_{am}*t*n))/2)^{eam}-0.5)+1]$$

in which:

y[n] is a time series of data points representing said exponential modulation signal;

m_a is the AM modulation depth;

f_{am} is the AM modulation frequency;

t is the time spacing between said data points;

n is a given data point; and,

eam is the exponent of said exponential modulation signal.

4. The method of claim 1, wherein steps (b) and (e) of said method are effected by a software program.

5. A method of testing the hearing of a subject, wherein said method comprises the steps of:

(a) creating an optimum-vector mixed modulation test signal comprising at least one signal having an amplitude modulated component with a first phase and a frequency modulated component with a second phase wherein said second phase is adjusted relative to said first phase to evoke an increased response from said subject;

(b) transducing said test signal to create an acoustic stimulus and presenting said acoustic stimulus to said subject;

(c) sensing potentials from said subject while substantially simultaneously presenting said acoustic stimulus to said subject; and,

(d) analyzing said potentials to determine whether said potentials comprise data indicative of the presence of at least one steady-state response to said acoustic stimulus.

6. The method of claim 5, wherein said method further comprises creating a database of normative optimal phase difference data correlated to subject characteristics and stimulus characteristics.

7. The method of claim 5, wherein the method further comprising using said database of normative phase difference data to adjust said second phase relative to said first phase.

8. A method of testing the hearing of a subject, wherein said method comprises the steps of:

(a) creating a test signal comprising at least one independent amplitude modulated and frequency modulated signal having an amplitude modulated component and a frequency modulated component, wherein said amplitude modulated component comprises a first modulation frequency and a first carrier frequency and said frequency modulated component comprises a second modulation frequency and a second carrier frequency wherein said first modulation frequency is substantially different from said second modulation frequency and said first carrier frequency is substantially similar to said second carrier frequency;

(b) transducing said test signal to create an acoustic stimulus and presenting said acoustic stimulus to said subject;

(c) sensing potentials from said subject while substantially simultaneously presenting said acoustic stimulus to said subject; and,

(d) analyzing said potentials to determine whether said potentials comprise data indicative of a steady-state response to each amplitude modulated component and a steady-state response to each frequency modulated component.

9. An apparatus for testing the hearing of a subject, wherein said apparatus comprises:

(a) a signal creator adapted to create a test signal comprising at least one combined amplitude modulated and frequency modulated signal having an amplitude modulated component with a first phase and a frequency modulated component with a second phase wherein said signal creator comprises means for adjusting said second phase relative to said first phase;

(b) a transducer electrically coupled to said processor and adapted to transduce said test signal to create an acoustic stimulus and present said acoustic stimulus to said subject;

(c) a sensor adapted to sense potentials from said subject while said acoustic stimulus is substantially simultaneously presented to said subject; and,

(d) a processor electrically coupled to said sensor and adapted to receive said potentials and analyze said potentials to determine if said potentials comprise data indicative of at least one response to said acoustic stimulus.

10. The apparatus of claim 9, wherein said apparatus further comprises a database of normative phase differences data correlated to subject characteristics and stimulus characteristics.

11. The apparatus of claim 9, wherein said processor is further adapted to create a second test signal comprising at least one independent amplitude modulated and frequency modulated signal.

12. A method of analyzing potentials to determine whether said potentials comprise data indicative of the presence of at least one steady-state response to a steady-state evoked potential stimulus, wherein said method comprises the steps of:

(a) presenting an evoked potential stimulus to a subject;

(b) sensing potentials from said subject while substantially simultaneously presenting said stimulus to said subject to obtain a plurality of data points;

(c) transforming said plurality of data points into a second plurality of data points;

(d) biasing said second plurality of data points with an expected phase value to obtain a plurality of biased data points; and,

(e) applying a statistical test to said plurality of biased data points to detect said response.

13. The method of claim 12, wherein effecting steps (c) and (d) comprises the steps of:

(f) forming a plurality of sweeps from said plurality of data points;

(g) averaging said plurality of sweeps to obtain a plurality of averaged data points;

(h) calculating a plurality of Fourier components for said plurality of averaged data points;

(i) calculating the amplitude (a_i) and phase (θ_I) for said plurality of Fourier components;

(j) biasing said amplitudes (a_i) to obtain biased data points (p_i) according to the formula:

$$p_i = a_i * \cos(\theta_I - \theta_e)$$

wherein θ_e is said expected phase value.

14. The method of claim 12, wherein effecting step (e) comprises the steps of:

(k) calculating upper confidence limits using a one tailed Student t-test on biased amplitudes which represent noise in the vicinity of Fourier components where said response should occur; and,

(l) comparing biased amplitudes of Fourier components where said response should occur to said upper confidence limits to determine if said biased amplitudes are larger than said upper confidence limit.

15. The method of claim 12, wherein said expected phase value is obtained from a database of normative expected phase values correlated to subject characteristics and stimulus characteristics.

16. The method of claim 12, wherein said expected phase value is obtained from previous testing on said subject using stimuli having a higher intensity.

17. The method of claim 12, wherein said stimulus contains other components for which responses have been detected and said expected phase value is obtained from extrapolation of said phase values for said responses which have already been detected.

18. A method of detecting a response to an evoked potential stimulus, wherein said method comprises the steps of:

(a) presenting an evoked potential stimulus to a subject;

(b) sensing potentials from said subject while substantially simultaneously presenting said stimulus to said subject to obtain a plurality of data points; and,

(c) calculating phase values for said plurality of data points, wherein, a response is detected if an adequate number of said calculated phase values fall within a predetermined phase value range.

19. The method of claim 18, wherein said effecting step (c) further comprises the steps of:

(d) separating said plurality of data points into epochs;

(e) calculating a Fourier component for the frequency at which said response should occur for each epoch; and,

(f) calculating the phase of each Fourier component calculated in step (e).

20. The method of claim 19, wherein said method further comprises the steps of:

(g) calculating a target phase range;

(h) calculating the number of said Fourier components that have a phase that is within the target phase range (N); and,

(i) using binomial analysis with N to determine whether said plurality of data points contain a response.

21. The method of claim 20, wherein said target phase range is calculated based on a database of normative expected phases correlated to subject characteristics and stimulus characteristics.

22. An apparatus for testing the hearing of a subject, wherein said apparatus comprises:

(a) a signal creator adapted to create a test signal;

(b) a transducer electrically coupled to said signal creator and adapted to transduce said test signal to create an acoustic stimulus and present said acoustic stimulus to said subject;

(c) a sensor adapted to sense potentials from said subject while said acoustic stimulus is substantially simultaneously presented to said subject; and,

(d) a processor electrically coupled to said sensor and adapted to receive said potentials and analyze said potentials to determine if said potentials comprise data indicative of at least one response to said acoustic stimulus;

wherein said analysis involves biasing said potentials based on an expected phase value.

23. The apparatus of claim 22, wherein said apparatus further comprises a database of expected phase value data correlated to subject characteristics and stimulus characteristics.

24. A method of noise reduction for a plurality of data points which are obtained during steady-state evoked potential testing, wherein said plurality of data points comprise at least one signal and noise and wherein said method comprises the steps of:

(a) obtaining said plurality of data points;

(b) separating said plurality of data points into a plurality of epochs; and,

(c) applying an adaptive noise reduction method to each epoch.

25. The method of claim 24, wherein said adaptive noise reduction method comprises effecting sample weighted averaging wherein weights are calculated based on the variance of noise, wherein the frequency of the noise is in close proximity to the frequency of the signal.

26. The method of claim 25, wherein said sample weighted averaging is effected according to the steps of:

(d) forming a plurality of sweeps by concatenating the epochs together;

(e) filtering each sweep to obtain a plurality of filtered sweeps;

(f) aligning each sweep to form a first matrix in which the sweeps are the rows of the matrix and the epochs within the plurality of sweeps are the columns of the matrix and aligning each filtered sweep in a similar fashion to form a filtered matrix which is used to calculate weights;

(g) calculating the variance of each epoch in the filtered matrix to obtain a noise variance estimate for each epoch in the filtered matrix;

(h) normalizing the noise variance estimate for each epoch in the filtered matrix by dividing the noise variance estimate for each epoch in the filtered matrix by the sum of all noise variance estimates for the epochs along the column of the filtered matrix which contains the epoch to obtain a normalized noise variance estimate for each epoch;

(i) inverting each normalized noise variance estimate to obtain a weight for each epoch and multiplying each corresponding epoch in the first matrix by its respective weight to obtain a plurality of weighted epochs; and,

(j) summing all of the weighted epochs in the first matrix along the columns of the first matrix to obtain a signal estimate.

27. The method of claim 26, wherein filtering comprises using a bandpass filter having a passband region which is local to the frequency region where the at least one signal resides such that the calculated weights are based on the frequency region local to the frequency region where the at least one signal resides.

28. A method of objectively testing the hearing of a subject, wherein said method comprises the steps of:

(a) selecting an auditory test;

(b) creating an appropriate test signal comprising at least one component for said auditory test;

(c) transducing said test signal to create a stimulus and presenting said stimulus to said subject;

(d) sensing potentials from said subject while substantially simultaneously presenting said stimulus to said subject; and,

(e) analyzing said potentials to detect at least one response.

29. The method of claim 28, wherein said auditory test is a latency test which comprises calculating a latency value for a detected response and comparing said latency value to a database of normative latency values to obtain an indication of the normal/abnormal status of the auditory system of said subject.

30. The method of claim 29, wherein said latency test comprises the steps of:

(f) calculating an onset phase for each detected response in said sensed potentials;

(g) calculating a phase delay (P) for each detected response by subtracting each onset phase from 360 degrees.

(h) calculating a latency value (L) for each detected response according to the following formula:

$$L=1000*(P+N*360)/(360*f_m)$$

where N is the number of cycles that have occurred in the stimulus before each detected response to a respective component of said stimulus occurs and f_m is the frequency of said detected response; and,

(i) comparing each latency value to a database of normative latency values to obtain an indication of the normal/abnormal status of the auditory system of said subject.

31. The method of claim 30, wherein N is approximately 1 and fm is in the range of approximately 75 to 100 Hz or in the range of approximately 150 to 190 Hz.

32. The method of claim 29, wherein said latency test further comprises the steps of:

(j) calculating a first latency value for a first detected response and calculating a second latency value for a second detected response;

(k) finding the difference between said first latency value and said second latency value to obtain a differential latency value; and,

(l) comparing said differential latency value to a database of normative differential latency values to obtain an indication of the status of the auditory system of said subject.

33. The method of claim 28, wherein said auditory test is an aided hearing test which comprises the following steps:

(m) fitting said subject with a hearing aid;

(n) performing steps (b) to (e);

(o) adjusting the hearing aid if an inadequate number of responses are detected in step (e); and,

(p) performing steps (n) and (o) until an adequate number of responses have been detected in said potentials.

34. The method of claim 33, wherein said method further comprises effecting step (o) by adjusting the gain of said hearing aid for a frequency region which is substantially similar to the frequency region of a component in said test signal for which a response was not detected.

35. The method of claim 28, wherein said auditory test is an AM/FM discrimination test and said test signal comprises at least one independent amplitude modulation and frequency modulation signal, wherein, said AM/FM discrimination test comprises the steps of:

(q) performing steps (b) to (e);

(r) calculating a response ratio according to the number of detected responses divided by the total number of responses which could have occurred in response to said stimulus; and,

(s) estimating a word recognition score correlated to said response ratio.

36. The method of claim 35, wherein said test signal further comprises noise masking.

37. The method of claim 28, wherein said auditory test is an AM/FM discrimination test and said test signal comprises an amplitude modulated component and a frequency modulated component, wherein, said AM/FM discrimination test comprises the steps of:

(t) performing steps (b) to (e);

(u) calculating a first amplitude of a response to said frequency modulated component;

(v) calculating a second amplitude of a response to said amplitude modulated component;

(x) calculating an amplitude ratio by dividing said first amplitude by said second amplitude; and,

(y) comparing said amplitude ratio to a database of normative amplitude ratios to obtain an indication of the status of the auditory system of said subject.

38. The method of claim 37, wherein said test signal comprises a plurality of pairs of amplitude modulated components and frequency modulated components and the method further comprises carrying out steps (u) to (y) for each of said pairs.

39. The method of claim 28, wherein said auditory test is a depth sensitivity test and said test signal comprises one or more amplitude modulated components having a modulation depth or one or more frequency modulated components having a modulation depth, wherein, said depth sensitivity test comprises the steps of:

(z) carrying out steps (b) to (e);

(aa) obtaining an estimate of response amplitude for each detected response; and,

(bb) comparing each estimated response amplitude with a database of normative response amplitudes to obtain an indication of the status of the auditory system of said subject.

40. The method of claim 39, wherein said depth sensitivity test further comprises the steps of:

(cc) detecting responses to test signals comprising a first modulated component having a first modulation depth and a second modulated component having a second modulation depth, wherein said modulation depths are different;

(dd) analyzing said detected responses to obtain an estimate of a first response amplitude for a detected response to said first modulated component and a second response amplitude for a detected response to said second modulated component;

(ee) calculating a response amplitude ratio from said first response amplitude and said second response amplitude; and,

(ff) comparing said response amplitude ratio with a database of normative response amplitude ratios to obtain an indication of the status of the auditory system of said subject.

41. The method of claim 28, wherein said auditory test is a rate sensitivity test which comprises the following steps:

(gg) creating a set of modulation frequencies comprising at least two modulation frequencies;

(hh) creating a set of test signals wherein each test signal comprises at least one amplitude modulated component having a unique modulation frequency chosen from said set of modulation frequencies;

(ii) carrying out steps (c) and (d) for each test signal in said set of test signals;

(jj) analyzing said set of potentials to detect a response for each amplitude modulated component in said set of test signals and estimating a response amplitude for each detected response;

(kk) calculating a rate sensitivity value based on said estimated response amplitudes; and,

(ll) comparing said rate sensitivity value to a database of normative rate sensitivity values to obtain an indication of the status of the auditory system of said subject.

42. The method of claim 41, wherein said rate sensitivity value is the slope of the line resulting from a plot of estimated response amplitude for each amplitude modulated component versus modulation frequency for each amplitude modulated component.

43. The method of claim 28, wherein said auditory test is a supra-threshold test comprising an intensity limen test and said test signal comprises an amplitude modulated component having a modulation depth of approximately 100%, wherein said intensity limen test comprises the steps of:

(mm) performing steady state evoked potential testing while minimizing the modulation depth of the test signal upon each detected response to determine a minimum modulation depth at which a response is detected; and,

(nn) comparing said minimum modulation depth with a database of normative minimum modulation depths to obtain an indication of the status of the auditory system of said subject.

44. The method of claim 43, wherein said supra-threshold test further comprises a frequency limen test and said test signal comprises an amplitude modulated component having a frequency modulation depth, wherein, said frequency limen test comprises the steps of:

(oo) determining a minimum modulation depth at which a response is detected; and,

(pp) comparing said minimum modulation depth with a database of normative minimum modulation depths to obtain an indication of the status of the auditory system of said subject.

45. The method of claim 28, wherein said auditory test is an auditory threshold test and said test signal comprises two or more combined amplitude modulation and frequency modulation signals having carrier frequencies which are separated by more than one-half octave, wherein, each combined amplitude modulation and frequency modulation signal has a frequency modulated component and an amplitude modulated component and the phase of the frequency modulated component is adjusted relative to the phase of the amplitude modulated component, wherein said auditory threshold test comprises the step of:

(qq) carrying out steps (c) to (e) to determine a minimal stimulus intensity for which a response is detected for each combined amplitude modulation and frequency modulation signal.

46. The method of claim 45, wherein the envelope of each combined amplitude modulation and frequency modulation signal is modulated by an exponential modulation signal.

47. The method of claim 45, wherein said auditory threshold test is conducted for a maximum time limit which is adjusted depending on the amount of noise in said potentials.

48. The method of claim 45, wherein said auditory threshold test comprises upwardly adjusting the intensities of components in said stimulus which tend to evoke responses having smaller amplitudes, so that all components in said stimulus evoke responses having similar amplitudes.

49. The method of claim 45, wherein step (e) comprises the step of:

(rr) reducing noise in said potentials to obtain reduced noise potentials by employing sample weighted averaging.

50. The method of claim 45, wherein step (e) comprises the step of:

(ss) performing a phase weighted t-test on said potentials to determine whether said potentials comprise data indicative of at least one response to said stimulus.

51. The method of claim 45, wherein step (e) comprises the step of:

(tt) performing a modified Rayleigh test of circular uniformity (MRC) on said potentials to determine whether said potentials comprise data indicative of at least one response to said stimulus.

52. The method of claim 45, wherein adjusting said intensity of one of said components comprises using the Stimulus Flux method which comprises creating another waveform of appropriate phase and amplitude, which when added to said test signal, results in the desired adjustment of said intensity of one of said components.

53. An apparatus for objectively testing the hearing of a subject, wherein said apparatus comprises:

(a) a selector adapted for selecting an auditory test to perform on said subject;

(b) a signal creator electrically coupled to said selector and adapted to create an appropriate test signal comprising at least one component for said test;

(c) a transducer electrically coupled to said signal creator and adapted to transduce said test signal to create an acoustic stimulus and present said acoustic stimulus to said subject;

(d) a sensor adapted to sense potentials from said subject while said acoustic stimulus is substantially simultaneously presented to said subject;

(e) a processor electrically coupled to said sensor and adapted to receive said potentials and analyze said potentials to determine if said potentials comprise data indicative of at least one response to said acoustic stimulus; and,

(f) a programmable hearing aid coupled to said processor, wherein, said programmable hearing aid comprises a plurality of programmable gain factors for different frequency regions and at least one programmable filter slope.

54. A method of testing at least two senses of a subject, wherein said method comprises the steps of:

(a) selecting a first steady-state test signal to test a first sensory modality;

(b) transducing said first steady-state test signal to create a first stimulus and presenting said first stimulus to said subject;

(c) selecting a second steady-state test signal to test a second sensory modality;

(d) transducing said second steady-state test signal to create a second stimulus and presenting said second stimulus to said subject;

(e) sensing potentials while substantially simultaneously presenting both stimuli to said subject; and,

(f) analyzing said potentials to determine whether said potentials comprise data indicative of at least one steady-state response to said stimuli.

55. The method of claim 54, wherein said steady-state test signals comprise an auditory signal, a visual signal and a tactile signal.

56. The method of claim 54, wherein said method further comprises ensuring that all modulation frequencies in the stimuli are not integer multiples of one another.

57. An apparatus for testing at least two senses of a subject, wherein said apparatus comprises:

(a) a signal creator adapted to create a first steady-state test signal and a second steady-state test signal;

(b) a first transducer electrically coupled to said selector and adapted to transduce said first test signal to create a first stimulus and present said first stimulus to said subject;

(c) a second transducer electrically coupled to said selector and adapted to transduce said second test signal to create a second stimulus and present said second stimulus to said subject;

(d) a first sensor adapted to sense first potentials from said subject while said first stimulus is substantially simultaneously presented to said subject;

(e) a second sensor adapted to sense second potentials from said subject while said second stimulus is substantially simultaneously presented to said subject;

(f) a processor electrically coupled to said first sensor and adapted to receive said first potentials and analyze said first potentials to determine if said first potentials comprise data indicative of at least one response to said first stimulus; and,

(g) the processor, electrically coupled to said second sensor and adapted to receive said second potentials and analyze said second potentials to determine if said second potentials comprise data indicative of at least one response to said second stimulus, wherein, each stimulus is presented substantially simultaneously.

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(54) Title: STEADY STATE MEASUREMENT AND ANALYSIS APPROACH TO PROFILING AUDITORY EVOKED POTENTIALS FROM SHORT-LATENCY TO LONG-LATENCY

(57) Abstract: The present invention relates to methods and systems for profiling evoked potentials in brain electrical activity which apply steady state response concepts to analysis of longer latency responses reflective of activity of brain regions beyond the brainstem, up to an including the cortex. The use of repeated stimuli within a single analysis window produces a quasi steady-state response and permits a high-resolution spectral analysis. Response amplitudes were measured at repetition rates from 80 to below 1 Hz, using trains of repeated tone-burst stimuli. An amplitude measure introduced and defined as the harmonic sum was incorporated into the spectral power of the response carried by both the fundamental frequency, and the harmonics thereof. Additionally, time ensemble averaging can be employed to improve signal to noise ratio.

STEADY STATE MEASUREMENT AND ANALYSIS APPROACH TO PROFILING AUDITORY EVOKED POTENTIALS FROM SHORT-LATENCY TO LONG-LATENCY

of which the following is a

SPECIFICATION

PRIORITY CLAIM

This application claims priority to United States Provisional Application Serial No. 61/183,826, filed June 3, 2009, the contents of which is hereby incorporated by reference in its entirety.

1. INTRODUCTION

The present invention relates to auditory evoked potentials which serve to assess central nervous system function by evaluating peripheral and central auditory function, and which provide a global view of the integrity of the auditory pathway. Particularly, the present invention provides a method to profile auditory steady-state response amplitudes over a wide range of stimulus repetition rates (or modulation frequencies), including those that were expected to represent the general ranges of traditional transient (obligatory) auditory evoked potentials. Additionally, the present invention utilizes the harmonic structure of the response to provide a more comprehensive analysis.

2. BACKGROUND OF THE INVENTION

The brain is well-known to be highly electrically active at all times, as evidenced by measurements on a subject's scalp in an electroencephalogram reading. This electrical activity can be synchronized with an event such as the occurrence of a discrete sound, as well as more elaborate stimuli such as a semantic change in a spoken phrase. This synchronization can be defined as an evoked potential, or evoked response, and recorded from the nervous system of a subject as an electrical potential following presentation of a stimulus. These evoked potentials are distinct from spontaneous potentials as detected by electroencephalography or electromyography.

Traditionally, transient response stimulus and analysis methods are employed to analyze auditory evoked potentials and provide a tool by which to monitor peripheral and central auditory function, assess its maturation, and overall obtain a global view of the integrity of the auditory pathway. However, there is a fundamental shortcoming of this conventional approach by virtue of the way the auditory evoked potentials are traditionally analyzed.

Conventional transient auditory evoked potentials are analyzed via signal averaging, which is performed in an effort to improve the signal-to-noise measurement embodied in a given response. However, the stimulus-related portion of the response is only known in general form from the examiner's subjective reference. Even after substantial signal-to-noise improvement, the putative response must be judged in a background of residual noise from which it can be difficult to distinguish some, if not all, of the component waves which make up the auditory evoked potential. In short, transient evoked potentials do not allow for the evoked response to be predicted, with a sufficient degree of accuracy, by the stimulus administered. Consequently, auditory evoked potential response analysis can be strongly based on examiner judgment, thus introducing the element of subjectivity to any analysis and conclusions drawn.

Furthermore, a particular challenge for researchers and clinicians alike are the potential ambiguities of wave identification over the course of maturation. In other words, the time it takes for transient auditory evoked potentials to reach well-defined adult waveforms is dependent upon structural and functional development, maturational effects of myelination, synaptic density and neuro-plasticity of the neural pathways specific to individual auditory evoked potential components. For lower sites along the auditory pathway (i.e., namely pontine-ward) development is relatively short, for example, the auditory brainstem response reach maturity by approximately two years of age. Conversely, for higher sites along the auditory pathway (i.e., namely cortical-ward) development is relatively long (which reflect middle latency response) and reach maturity by 12 years of age. Similarly, late-cortical components (which reflect long latency response) reach maturity by 17 years of age. Of particular concern is the potentially confounding maturational and pathological changes present in auditory evoked potentials, and thus potential hazards of using age-corrected norms. Moreover, even in adults, pathological changes via central nervous system disorders and trauma differentially affect auditory evoked potentials further, if not confound precise wave identification, especially with the diversity of focal injuries that can occur.

Accordingly, there is a need for a shift toward a more analytical approach to the auditory evoked response, such as the steady-state response provided in the present invention. Additionally, such an approach can further provide an alternative view of the brain's responses to auditory stimulation and can serve such interests as tracking maturational changes and/or effects of brain disease or injury, when extended to incorporate a more comprehensive representation of the auditory evoked potential component waves, namely to cover the latency range of traditional auditory evoked potentials accessed via a transient stimulus-response analysis.

3. SUMMARY OF THE INVENTION

The purpose and advantages of the present invention will be set forth in and apparent from the description that follows, as well as will be learned by practice of the present invention. Additional advantages of the present invention will be realized and attained by the methods and systems particularly pointed out in the written description and claims hereof, as well as from the appended drawings.

To achieve these and other advantages and in accordance with the purpose of the present invention, as embodied and broadly described, the present invention provides techniques for evaluating auditory steady state responses. An exemplary method includes administering an auditory stimulus to a subject over a comprehensive range of predetermined repetition rates (or modulation frequencies), with the auditory stimulus generating an electrical activity in the subject; synchronizing the electrical activity in the subject with the auditory stimulus to define an auditory evoked potential; monitoring the auditory evoked potential; identifying a plurality of spectral components of the auditory evoked potential; calculating the harmonic sum of the plurality of spectral components; determining the combined or overall magnitude of the auditory evoked potential, wherein the overall amplitude includes the plurality of spectral components.

In accordance with another aspect of the present invention the overall amplitude includes a fundamental frequency of the stimulus. Furthermore, another feature of the present invention is the identification of the fundamental and measurable harmonics to calculate a harmonic sum which includes the square root of the sum of squares of select spectral components, wherein the select spectral components have a magnitude which is greater than an estimated noise value. In some embodiments, the stimulus is administered at rates of less than about 10 Hz, for example, less than about 1 Hz. The stimulus can be administered at a progressively decreasing rate from about 80 Hz to about 0.75 Hz. Additionally, the stimulus can be a sinusoidal pulse administered at about 70 decibels to subjects that are awake or in a condition of light sleep. Further, the subjects can be adults of at least 18 years of age, or children less than 9 years of age. In accordance with another aspect of the invention the auditory evoked potential in the subject reflects the cortical activity of the brain.

Additionally, the present invention includes a system for evaluating evoked potentials in brain electrical activity using auditory steady state profiling comprising a device for administering an auditory stimulus to a subject over a range of frequencies from about 80 Hz to about 0.75 Hz, the auditory stimulus generating an auditory evoked potential in the subject indicative of the cortical activity of the brain; a sensor for detecting the auditory evoked potential; a processor for identifying a plurality of spectral components of the auditory evoked potential, the processor configured to calculate the harmonic sum of the plurality of spectral components; and an output for displaying the overall amplitude of the auditory evoked potentials, wherein the overall magnitude includes the plurality of spectral components. The harmonic sum can include the square root of the sum of squares of select spectral components, wherein the select spectral components have a magnitude which is greater than an estimated noise value, and the overall amplitude includes a fundamental frequency of the stimulus.

It is to be understood that both the foregoing general description and the following detailed description are exemplary and are intended to provide further explanation of the present invention. The accompanying drawings, which are incorporated in and constitute part of this specification, are included to illustrate and provide a further understanding of the method and system of the present invention. Together with the description, the drawings serve to explain the principles of the present invention.

4. BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 is a graphical representation of an conventional auditory evoked potential using transient stimulus.

FIGURE 2 is a graphical representation of auditory evoked potentials generated by repeated stimulus over a predetermined window to define a quasi-steady-state response.

FIGURE 3 is a series of graphical representations of grand averages of the auditory steady-state response power spectra at each repetition rate.

FIGURE 4 is a graphical representation comparing the response profile obtained by the steady-state response technique of the present invention to the conventional transient analysis.

FIGURE 5A-B are a graphical representations illustrating spectral analysis of an auditory evoked potential in accordance with the present invention.

FIGURE 6 is a graphical representation of an auditory evoked potential amplitude spectrum and noise floor in accordance with the present invention.

FIGURES 7A-B are a graphical representations of an auditory evoked potential amplitude spectrum of awake subjects and subjects in a state of light-sleep in accordance with the present invention.

FIGURES 8A-B are a graphical representations of auditory evoked potentials in children for a transient response and an amplitude spectrum in accordance with the present invention.

FIGURE 9 is a graphical representation of auditory evoked potential profiles for children and adults in accordance with the present invention.

FIGURE 10 is a graphical representation of transient auditory evoked potential profiles for children and adults in accordance with the present invention.

FIGURE 11 is a graphical representation of auditory evoked potential profiles for children and split-half adults, including standard error bars, in accordance with the present invention.

FIGURE 12 is a graphical representation of an auditory evoked potential profile of awake subjects and subjects in a state of light-sleep in accordance with the present invention.

5. DETAILED DESCRIPTION OF THE INVENTION

Reference will now be made in detail to the exemplary embodiments of the present invention, which are illustrated in the accompanying drawings. The system and corresponding method of the present invention will be described in conjunction with the detailed description of the system.

The methods and systems presented herein may be used for profiling auditory evoked potentials in brain electrical activity which apply steady state response concepts to analysis of longer latency responses reflective of activity of brain regions beyond the brainstem, up to an including the cortex.

Conventional auditory evoked potential techniques employ transient stimuli which evoke a multi-phasic transient response that does not reflect or relate directly to the stimulus spectrum. An example of an auditory evoked potential obtained via the traditional approach is illustrated in Figure 1 in which a brief 1 kHz sinusoidal pulse was administered at less than 1/s at 70 db SPL, which is a moderate intensity level representative of conversational levels of speech. The wave form illustrated includes a first peak (P1), a first minimum (N1), and a second peak (P2), which is indicative of a neurologically intact adult. Such conventional transient techniques derive from time ensemble averaging of multiple stimulus presentations, which are effectively overlaid in time to extract the desired response signal(s) from the noise background. Typically, the signal extracted from the noise background (also referred to herein as noise floor) can range from about 10 micovolts, down to fractional microvolts for the shortest-latency responses. In effect, the response potential is treated as a single event under this transient technique such that for each stimulus administered to a subject there is a corresponding and discrete response evoked. However, in conventional practice the response is estimated via long-term averaging over all stimulus repetitions.

As discussed above, the transient auditory evoked potential reflects essentially the impulse response of the system and is not directly representative of, the spectrum of the input signal. Further, the analysis of the transient auditory evoked potential suffers from "picking" and interpreting peaks of the response waveform. This can be problematic due to the inherent variability of the waveform, e.g., across and even within subjects, or due to residual noise. These variations or fluctuations in the waveform of transient responses can be further compounded by factors of sleep, maturation level of the subject, and/or sensory deficits of the subjects. This leads to difficulty and uncertainty in transient analysis and interpretation as changes are not easily quantified and/or isolated in an unambiguous manner. This is particularly problematic in attempting to separate the influence of background electroencephalogram and other components of the noise floor.

Therefore, and in accordance with an aspect of the present invention, a steady-state response approach is employed in analyzing auditory evoked potentials in order to take advantage of the inherently deterministic aspects of this technique. As illustrated in Figure 2, repeated stimuli are administered within an analysis window having a latency of a 10,000 milliseconds, in which the P1-N1-P2, i.e. the vertex potential, complexes are repeated to permit a quasi-steady-state response and high resolution spectral analysis, while still allowing for time ensemble averaging. This technique is applicable even for evoked potentials corresponding to the auditory long-latency response which can be evoked at a stimulus repetition rate (also referred to as a modulation frequency (Fm)) to below 1 Hz. Further, and in accordance with the present invention, the steady-state response technique eliminates the disadvantages of time-domain peak-picking, and allows for a complete spectral analysis. As discussed herein the spectral analysis of the present invention can include measurement of overall response power, detailed harmonic structure analysis, magnitude-vs-phase comparison, and other analyses of components of the evoked response, as so desired.

5.1 METHODS

5.1.1 Subjects

The adult cohort comprised twenty-five subjects, 18 to 35 years of age, and the pediatric cohort comprised twelve children 6-9 years of age. In an effort to minimize gender effects, the subjects were all females. No subject had a personal history of otological or neurological disorders. Each subject demonstrated normal middle ear function in both ears as defined by unremarkable otoscopic and tympanometric results (peak pressure within ±100 daPa). All subjects had normal hearing sensitivity in both ears, thereby corroborating the assumption of an overall intact auditory nervous system. Hearing sensitivity was measured using the modified Hughson-Westlake procedure, as known in the art. Pure-tone thresholds were determined to within 5 dB, per standard clinical procedure (ANSI, 1996). Hearing with normal limits was defined more rigorously than by clinical practice, namely by thresholds of 15 dB HL or better for pure-tone octave frequencies between 0.25 and 8 kHz. In addition, all subjects demonstrated the main component waves of transient auditory evoked potential response measurements in the three major latency groups.

5.1.2 Stimuli

The stimuli for transient and steady-state recordings were generated using Intelligent Hearing Systems (Miami, FL) SmartASSR evoked potential (EP) software. The routinely distributed auditory steady-state response software provides stimulus control and analysis for testing using at repetition rates of 40 Hz and above. To permit testing lower rates, e.g., 20 Hz and below, alternative versions of control modules were provided to set the repetition rate and corresponding response windowing, thereby over-riding initialization. The use of manufacturer-supplied modifications assured operation without significant degradation of the performance of the instrumentation and/or substantive deviations from the FDA approved use of this instrumentation. Other adaptations needed to accomplish the specific aims of the study were accomplished via SmartEP utilities and external software used to analyze ASCII downloads of the data. Similarly, conventional transient response testing was accomplished using the standard SmartEP software (i.e. implemented on the same instrumentation platform). Indeed, the parameters chosen for the lowest stimulus repetition rate were chosen to provide essentially overlapping paradigms, yielding essentially identical time-domain responses via either paradigm.

The stimuli for the auditory brainstem response (ABR), middle latency response (MLR) and long-latency response (LLR) all were 1 kHz tone bursts (TBs). This stimulus was chosen for purposes of a uniform comparison across latency ranges, although adjusted by other parameters (e.g., rise-fall time and duration) to be a mutually effective stimulus across repetition rates. Because the transient auditory evoked response literature provides limited guidance for systematically choosing TB parameters over the breadth of range used in this study, a rule-based approach was sought by which to systematically vary rise and fall, and overall duration as a function of repetition rate. The envelope parameters were adjusted so as to be increased by 1.414X with each decrease in repetition rate. The envelope itself was the extended cosine, to ensure an adequately abrupt on-set (for excellent neural synchrony) while, again, maintaining reasonable frequency specificity. Repeated TBs was first used for the 40-Hz steady-state responses ASSR (Galambos et al., 1981). Repetition rates were at octave or nearly octave intervals from 80 Hz down. The envelope parameters for both transient auditory evoked potentials (AEP) and auditory steady-state responses (ASSR) are outlined in Table 1.

Table 1 Envelope parameters for transient auditory evoked potentials (AEP) and auditory steady-state responses (ASSR)

	Rate	Rise/Fall	Duration
ABR	20	1	4
MLR	10	2.8	11
LLR	0.75	11	45
ASSR	80	1	4
	40	1.4	5.6
	20	2	8
	10	2.8	11
	5	4	16
	2.5	5.6	23
	1.25	8	32
	0.75	11	45

5.1.3 Recordings

Silver-silver chloride electrodes were affixed at vertex (shared across channels, non-inverting input), ipsilateral and contralateral mastoid (inverting inputs) and nasion (ground of the recording amplifiers). Inter-electrode impedances of less than 5 kilohms at 30 Hz (Grass Instruments EC2) were achieved in all subjects. The same two-channel electrode montage and type of recording electrodes were used for both transient and steady-state AEP testing. For the auditory steady-state response, an entire sweep (1024 points) was rejected if it contained any potential with voltage amplitudes greater than ±50 microvolts within 50 millisecond window. For repetition rates of 40 and 80 Hz, the evoked response test system used an analog-to-digital conversation rate of 20 kHz, which was down-sampled to 1 kHz for a final spectral resolution of 0.9765 Hz. For lower repetition rates, progressively lower sampling rates (SR) and longer acquisition windows (AW) were required as repetition rate was decreased below 40 Hz. Time-ensemble averaging was incorporated to enhance the signal-to-noise prior to spectrum analysis. The maximum number of sweeps averaged was proportionally varied such that the total acquisition time for each repetition rate was approximately four minutes. Separate parameters chosen to enable the recordings of transient AEPs and ASSRs are outlined in Table 2.

Table 2 Recording parameters for transient auditory evoked potentials (AEP) and auditory steady-state responses (ASSR)

	Sampling	Acquisition	Number of	Gain	B-pass	Sweeps
ABR	-	11/ms		100	100-3000	4096
MLR	-	100		100	10-1500	2048
LLR	-	500		50	0.4-30	512
ASSR	1000	1.024/s	80	100	100-3000	160
	1000	1.024	40	100	100-3000	160
	800	1.28	22	100	0.4-100	160
	400	2.56	22	100	0.4-100	80
	200	5.12	22	100	0.4-100	40
	100	10.24	13	100	0.4-100	20
	100	10.24	10	100	0.4-100	20
	100	10.24	7	100	0.4-100	20

5.1.4 Procedure

Subjects were tested in 2 recording sessions (approximately 1.5 hours each), on average 12 days apart. Pure-tone behavioral threshold and auditory steady-state response testing was completed with subjects comfortably semi-reclined in a double-walled sound treated booth. Steady-state responses were recorded with the subject alert and awake. In order to limit recording sessions to a reasonable time period, only the right ear from each subject was tested. This constraint was imposed, as well, to avoid the removal or replacement of the transducer within recording sessions, for optimal signal stability within and across tests. Pure–tone behavioral thresholds for octave frequencies between 0.25–8 kHz and a screening ABR, MLR and LLR were obtained in the initial recording session. Auditory steady-state responses were obtained in the second recording session at the eight repetition rates, as well as one within-test session recording. Additionally, and in order to avoid a false impression of a reproducible peak component, two no-stimulus control trials were carried out to serve as a baseline from which to judge the amplitude of the noise in the auditory steady-state response stimulus evoked response.

Subjects were seated in a lighted sound treated room and were instructed to remain awake and alert during LLR and MLR testing. To assure alertness, the subject's were required to count the number of tones during each recording. During recording, electroencephalography (EEG) and eye tracking was monitored continuously to ensure no hallmarks of drowsiness or sleep were observed during testing (e.g., decrease or disappearance in electrical activity recorded from the scalp surface, very slow eye movement or cease of eye blinking). During ABR testing the light in the sound treated room was turned off and all subjects were encouraged to sleep. The insert earphone was kept in place without removal or repositioning throughout the recording session.

5.2 SPECTRAL ANALYSIS FOR QUASI-STEADY-STATE

Conventional approaches to auditory evoked responses focus on the spectral power at the fundamental frequency, which is the lowest frequency in a harmonic series, in order to analyze the amplitudes of the responses (defined below). However, and in accordance with the present invention, the power at the fundamental frequency accurately account for the power in the overall spectrum of all responses. This is particularly relevant at the lowest repetition rate, where the fundamental can be difficult to detect and/or is not the dominant spectral component. Accordingly, the present invention provides an overall amplitude measure of the response. A conventional measure from acoustics is that of percent total harmonic distortion (THD). For instance, THD is specified in the performance analysis of stereo hi-fidelity amplifiers. This measure is calculated as follows:

$$\mathrm{THD} = 100 \times \sqrt{\frac{p2^2 + p3^2 + p4^2 \cdots}{p1^2 + p2^2 + p3^2 \cdots}} \qquad \text{[Eq. 1]}$$

where p^1, p^2, p^3...are the observed sound pressures or voltages observed at frequencies F_1, F_2, F_3, etc., namely the fundamental frequency (F1) and its harmonics, wherein subscript 1 is the fundamental frequency and successive integers ≥ 2 denote the harmonics. However, in the present invention, an alternative equation was derived utilizing the term appearing in the denominator of Eq. 1, i.e. the sum of the voltages squared, including both the fundamental and all measureable harmonics. Thus, Eq. 1 was modified to define the measure used, dubbed herein as the "harmonic sum" (HS) and computed as follows:

$$HS = \sqrt{p1^2 + p2^2 + p3^2 \cdots} \qquad \text{[Eq. 2]}$$

For spectral analyses and to compute the HS from the data generated by the software employed herein, two spectral analyses were made: the first was that of the 'response' estimate which was the average of the rarefaction and condensation sweeps of the two buffers (apropos the "split" or double-buffering employed in the signal acquisition protocol of the test system employed); the second was that of the "noise" estimated, computed as the difference between the two buffers. Knowing the integer values from the power spectrum analysis, representing the voltage squared of the amplitudes, the HS can be computed by taking simply the square root of the sum of these values for the spectral components identified to significantly exceed the noise floor, as described in further detail below.

In accordance with an aspect of the present invention, and in order to analyze the individual responses, the total response at each repetition rate is examined for spectral components that are identified to be integer multiples of the fundamental frequency (F1). Contralateral recordings are analyzed for responses at repetition rates ≤ 40 Hz, while ipsilateral recordings are analyzed for responses at 80 Hz, in order to investigate the crossed ascending auditory pathway and levels of response generation (as discussed in above). In deference to inherent limits of frequency resolution via digital analyses (e.g., binary rounding), the frequency component was scored and its amplitude taken as the peak falling ± 5% of the target frequency. The estimated background noise spectrum was then superimposed on the response spectrum to identify the components at the fundamental frequency (F1) and its harmonics, in order to determine which components were greater than the noise floor, i.e., having a signal-to-noise greater than 0. For purposes of presenting and characterizing the grand averaged response and noise spectra, as discussed in more detail below, each spectrum was normalized relative to the maximum power at each repetition rate. Additionally, and as presented herein, graphical plots with the response/amplitude spectra and noise spectra superimposed permit direct comparison, facilitate comparisons across components of differing harmonic number, and simplify comparisons across repetition rate.

For purpose of illustration and explanation, grand averages of the auditory steady-state response power (or amplitude) spectra at each repetition rate are displayed in Figure 3. The total response and the estimated background noise are superimposed in each of the representative plots, with the noise depicted by the line of greater weight. At 0.75 and 1.25 Hz, the averaged steady-state response is represented by a series of spectral components at integer multiples of the fundamental frequency (F1). Of these spectral components, the greatest amount of power occurs at several harmonics of the fundamental frequency. For example, at 0.75 Hz, the maximal amplitude was at the sixth harmonic (4.5 Hz), while at 1.25 Hz, the greatest power moved to the fourth harmonic (5 Hz), that is, slightly closer to the fundamental frequency (F1) of 1.25 Hz. At 2.5 Hz, 5 Hz and 10 Hz, the averaged response is represented by fewer spectral harmonic components at or above the fundamental frequency (F1). Of these harmonic components, the greatest amount of power occurred either at the fundamental frequency or primarily the second harmonic. At 20, 40 and 80 Hz, the averaged steady-state response was represented by only a small number of spectral components at integer multiples of the fundamental frequency. Of these spectral components, the greatest amount of power occurred at the fundamental, with diminishingly small powers at the second and third harmonics by 40 Hz.

Figure 4 illustrates the significance of the harmonic sum of the response in accordance with the present invention. Particularly, Figure 4 depicts that the overall amplitude of the response decreased as repetition rate increased from 0.75 to 80 Hz. To demonstrate the use of harmonic structure in response measurement, the harmonic sum of the response and the analysis based on the fundamental frequency have been superimposed in Figure 4. The analysis based on the harmonic sum (shown in solid line) revealed that amplitude was largest at 0.75 Hz and smallest at 80 Hz, while the analysis based on the fundamental frequency alone (shown in broken line) revealed that amplitude remained largest at 2.5 through 80 Hz and was smallest at 0.75 Hz. Accordingly, the detailed analysis of the various spectral components of the evoked response provided by the harmonic sum and steady-state response technique of the present invention allows for a more accurate and informative presentation of the evoked response.

5.3 EXAMPLES AND DISCUSSION

As discussed above, the steady-state response technique of the present invention allows for a spectral analysis of the evoked response, particularly for long-latency responses. In the example illustrated in Figures 5A-B, the modulation frequency employed was low enough to also produce essentially the same long-latency response as recorded via conventional transient techniques (as illustrated in Figure 1) and indeed demonstrate quasi-discrete spectra with components at the modulation frequency (Fm) and its harmonics, as described above. Figure 5A depicts a steady-state response simulated from long-latency response data obtained by duplicating the epoch to emulate repeated stimuli (also referred to as "response train") within the analysis window. Comparisons are provided between the spectrum of an individual epoch (also referred to as "single response") versus the quasi-steady-state response ("response train"). The repeated stimuli ("response train") is shown to approximate a discrete spectrum and the spectral envelope follows that of the individual (transient) response. Frequency and amplitude scales are relative in this representation. Similarly, Figure 5B depicts a comparison of the simulated steady-state response using actual long-latency response data (referred to as "real" in the plot) versus a long-latency-like waveform which is synthesized using haversines of progressively longer period from P1-P2 (referred to as "synthesized" in the plot). The overall spectral results depicted demonstrate spectral features that are valid (i.e. rather than noise or other artifact). For long-latency auditory evoked potentials, wherein duty-cycle of the response is quite low, the response spectrum is inherently complex and may not necessarily show the highest power to occur at the fundamental frequency (Fm), as discussed with reference to Figure 3 above.

Figure 6 provides the grand average of the amplitude spectrum of the evoked response at a repetition (or frequency modulation), of 0.75 Hz. Particularly, Figure 6 illustrates the relative amplitude spectrum from steady-state response stimulus in accordance with the present invention, which is normalized to largest spectral peak. Further, Figure 6 depicts both the evoked potential (also referred to as "Response" in the plot) as well as the estimated noise floor (also referred to as "Est. Noise" in the plot) which is derived by taking the difference between the two-buffers of the dual-buffered response acquisition process, as described above. As illustrated, the noise has a maximum amplitude, which is approximately equal to the response, at about 0.75 Hz.

In accordance with an aspect of the present invention, the observed grand average spectrum of the steady-state response using the approach described herein achieves the level of predictability sought of the deterministic approach to response-stimulus analysis. Further, the approach disclosed herein is particularly advantageous as modulation frequency is lowered, which results in the spectral power being less concentrated at the modulation frequency, and more dispersed about the harmonic structure of the response, as described above. Additionally, the effective rise-time of the stimulus envelope at lower modulation frequencies can prove too long to robustly stimulate auditory evoked potentials utilizing conventional techniques. Thus the steady-state approach of the present invention is applicable to a broad latency range of auditory evoked potentials, particularly the obligatory sensory evoked potentials defined as long, middle, and short latency responses.

In accordance with another aspect of the invention, a comparison between states of awake and light sleep (dozing) in the same subjects was conducted. Similar to the previously described methods, stimuli were repeated tone bursts at 1 kHz. Spectral analyses of the steady-state responses demonstrated responses that remained relatively robust for all repetition rates. Results for Fm = 0.75 Hz are shown in Figures 7A-B. As illustrated, the steady-state response/long-latency response exhibits sensitivity to level of arousal, yet is robust in dozing subjects. It is difficult, if even possible, to examine this effect via traditional transient response due to the uncertainty in distinguishing the response versus residual noise. Consequently, it errors can occur in attempting to unambiguously quantify the auditory evoked potential. As discussed above regarding the interpretive aspect of conventional time analysis of the response, both background electroencephalogram and the response are sleep-level dependent. Therefore, it is advantageous to have a means to objectively separate response and background noise components, as provided by the present invention.

Figure 7A represents the grand average amplitude spectrum of responses in which the subjects are awake, while Figure 7B depicts the amplitude spectrum of subjects under light-sleep (dozing) conditions. While sleep analysis was not performed, all subjects reported dozing off during this phase of testing, in contrast to the awake phase, wherein they were watching a movie (absent any audio that may interfere with the stimulus). For sake of comparison, spectral power has been normalized to the awake relative amplitude scale. As illustrated, the spectral envelope varies between the two conditions. For example, the maximum amplitude under light-sleep conditions is more than double the value of the maximum amplitude under awake conditions. Furthermore, although a similar center of gravity is depicted between both conditions, differences in the noise floor are exhibited in the two conditions. For example, the estimated noise floor under light-sleep conditions exhibits an amplitude of approximately 0.6 at a frequency of 7.5 Hz and 9.75 Hz, whereas the amplitude under awake conditions remains substantially constant from a frequency of approximately 6 Hz. Unlike the conventional transient response, the effects of sleep response and background noise can be readily separated in the steady-state response of the present invention.

In accordance with another aspect of the invention, the steady-state response disclosed herein was applied to a cohort of children wherein the sample size was 12, and the ages of the subjects ranged from 6-9 years of age. The results of which are illustrated in Figures 8A-B show equal efficacy for steady-state response assessment of the long-latency responses. Particularly, Figure 8A depicts the grand average transient response, while Figure 8B depicts the steady-state response amplitude spectrum of the present invention. Upon comparison of the transient responses of pediatric subjects (Figure 8A) to adult subjects (Figure 2) it is evident that although the P1 components share a common behavior, the pediatric long-latency response shows immaturity of the N1-P2 complex as compared to adults. Consequently, this discrepancy can further confound correct wave interpretation in traditional transient techniques. For purposes of comparison, spectral power is normalized to adult sample average. Upon comparison of the steady-state responses of pediatric subjects (Figure 8B) to adult subjects (Figure 6) it is evident that there are fewer spectral peaks, a lower center of gravity of the spectral power, and the nearly doubling of the amplitude scale in the pediatric response.

Figures 9-12 illustrate findings of profiling relative spectral power across modulation frequency for a number of comparisons. It is to be understood that the applications illustrated herein are for explanation and illustration purposes, and do not encompass or limit the applications of the present invention. The results illustrated are from the grand-average spectra for the respective subject groups or conditions, wherein a single magnitude value per modulation frequency (Fm) was sought to represent the overall response. This value was computed for the total number of spectral components that were greater than the noise estimate at all multiples (i.e. harmonics, nFm) of the modulation frequency, starting with the frequency module itself. This value, referred to as the overall spectral sum, is computed based on the total harmonic distortion, as discussed herein. This approach is based on the observation that limiting analysis to the modulation frequency Fm would grossly under-estimate the overall response magnitude for 20 Hz and below, and dramatically so below 5 Hz.

Figure 9 illustrates a further comparison of the pediatric and adult steady-state response, wherein the pediatric response is substantially larger than in adults at low modulation frequencies. However, this trend is reversed at modulation frequencies above 20 Hz.

Figure 10 illustrates a comparison of transient response data for different stimulus repetition rates. The pediatric response depicted in Figure 10, which reflects the traditional transient approach, exhibits lower amplitude than that of the adults. This is in contrast to the findings illustrated in Figure 9, which illustrate pediatric vs. adult results obtained via the steady-state response approach. However, an explanation for this discrepancy is that the steady-state response of the present invention captures the entire response power, and as discussed above, and not merely the N1-P2 magnitude, which is the typical amplitude measurement of the transient response technique. Further, it is noteworthy that the subject sample size for the transient data was 12 whereas the subject sample size for the steady-state response data was 25.

Figure 11 illustrates a comparison between the pediatric profile and sub-groups, or "split-half", profiles from the adult sample. To conduct this measurement, the subjects were randomly assigned to two sub-groups. Standard-error bars are included for the various profiles and represent a greater variability than the difference between the two split-half groups. This relatively large standard-error of the pediatric profile can be attributed to, among other things, the maturational variance even within the 3-year age constraints of the pediatric group, i.e. ages 6-9 years (with a sample size of 12).

Figure 12 illustrates the effects of light sleep on the profile. As expected for the spectra, the evoked response under sleep condition is more robust with a greater amplitude, however this enhancement diminishes at 5 Hz-10 Hz. The 40-Hz auditory steady-state response is known to be somewhat vulnerable to sleep, as appears to be the 20-Hz response. The auditory steady-state response at 80 Hz and above, which is comparable to the auditory brain-stem response to a brief transient signal, is shown to be independent of the level of arousal.

Accordingly, and as discussed above, the steady-state response technique disclosed herein allows for quantitative analysis, for example, identifying spectral peaks above the noise floor, and thereby reducing possible confounds that depend upon developmentally related differences in the stimulus-related response itself, as well as any background noise. This is particularly advantageous for equating the traditional peaks of the time-domain response, over a decreasing age of the examinee. While the time-domain components of a response are of interest with respect to their individual generators, the steady-state approach of the present invention provides a means by which to gain additional information and/or measurements in a format that can be consistently implemented and/or more attractive for certain applications, such as to profile the responses over broad ranges of stimulus repetition rates. Particularly, the spectra of responses at the lower stimulation rates are necessarily complex, yet valid estimates of the response's magnitude. By employing the steady-state response approach, the spectra are essentially discrete and thus readily accessible to further quantitative analyses, e.g. starting with overall spectral power as expressed by the harmonic sum.

Further, the present invention allows for the identification and evaluation of the function of spectral power of the response as compared to the repetition rate. This includes analyzing the response magnitude across traditional latency domains. This is an improvement over traditional transient techniques which do not adequately provide or allow for this function due to the problem of wave identification/interpretation. Considering the neuroanatomical bases of the behavior of the steady-state responses over modulation frequency, as discussed herein, this profile can provide a useful technique for a broad variety of neurological and/or audiological interests.

For example, in particular non-limiting embodiments, the present invention provides for a method of evaluating central nervous system function in a test subject, comprising:

(i) administering an auditory stimulus to the test subject over a range of predetermined frequencies, the auditory stimulus generating an electrical activity in the test subject;

(ii) synchronizing the electrical activity in the test subject with the auditory stimulus to define an auditory evoked potential;

(iii) identifying a plurality of spectral components of the auditory evoked potential of the test subject;

(iv) calculating the harmonic sum of the plurality of spectral components of the test subject;

(v) determining the overall amplitude of the auditory evoked potential in the test subject, wherein the overall amplitude includes the plurality of spectral components; and

(vi) comparing the overall amplitude of the auditory evoked potential in the test subject with the overall amplitude of the auditory evoked potential in a control subject,

where a difference between overall amplitude of the auditory evoked potential in the test subject relative to the control subject indicates that there is a defect in the central nervous system function of the test subject. In some embodiments, a decrease in the amplitude of the auditory evoked potential in the test subject relative to the control subject will reveal that the defect can be the result of a developmental disorder, a degenerative condition, or an injury that may be traumatic, metabolic, ischemic or toxic.

Accordingly, the steady-state response technique described herein thus permits profiling maturation and state effects in a manner that avoids issues of wave interpretation and minimizes complications of concomitant differences in background noise. Furthermore, this technique is readily amenable to objective analyses and data recordation including computer scoring or tracking of responses. Additionally the present invention can be employed in a myriad of diverse applications including brain-damaged subjects (e.g. head injury, stroke, etc.); electric response audiometry (both threshold prediction and "hearing screening"), namely to work with the longer-latency (more cortical-ward generated) potentials which may be indicative of auditory function closer to the level of conscious behavior. Furthermore, while the present invention relates to overall response independent of conventional wave (peak) identification, individual spectral features are reasonably expected to be associated with conventionally identified peaks (e.g. P1 of the long-latency response P1-N1-P2 complex), if not isolatable using spectral analysis with repetition rate(s) that may facilitate the elicitation of targeted waves.

While the present invention is described herein in terms of certain preferred embodiments and/or applications, those skilled in the art will recognize that various modifications and improvements may be made to the present invention without departing from the scope thereof. Moreover, although individual features of one embodiment of the present invention may be discussed herein or shown in the drawings of the one embodiment and not in other embodiments, it should be apparent that individual features of one embodiment may be combined with one or more features of another embodiment or features from a plurality of embodiments.

In addition to the specific embodiments claimed below, the present invention is also directed to other embodiments having any other possible combination of the dependent features claimed below and those disclosed above. As such, the particular features presented in the dependent claims and disclosed above can be combined with each other in other manners within the scope of the present invention such that the present invention should be recognized as also specifically directed to other embodiments having any other possible combinations.

Thus, the foregoing description of specific embodiments of the disclosed subject matter has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the disclosed subject matter to those embodiments disclosed. It will be apparent to those skilled in the art that various modifications and variations can be made in the method and system of the present invention without departing from the spirit or scope of the present invention. Thus, it is intended that the present invention include modifications and variations that are within the scope of the appended claims and their equivalents.

CLAIMS

WHAT IS CLAIMED IS:

1. A method of evaluating auditory steady state responses comprising:

administering an auditory stimulus to a subject over a range of predetermined frequencies, the auditory stimulus generating an electrical activity in the subject;

synchronizing the electrical activity in the subject with the auditory stimulus to define an auditory evoked potential;

monitoring the auditory evoked potential;

identifying a plurality of spectral components of the auditory evoked potential;

calculating the harmonic sum of the plurality of spectral components;

determining the overall amplitude of the auditory evoked potential, wherein the overall amplitude includes the plurality of spectral components.

2. The method of claim 1, wherein the overall amplitude includes a fundamental frequency of the stimulus.

3. The method of claim 1, wherein the harmonic sum includes the square root of the sum of squares of select spectral components.

4. The method of claim 3, wherein the select spectral components have a magnitude which is greater than an estimated noise value.

5. The method of claim 1, wherein the stimulus is administered at a rate of less than about 10 Hz.

6. The method of claim 1, wherein the stimulus is administered at a rate of less than about 1 Hz.

7. The method of claim 1, wherein the stimulus is administered at a progressively decreasing rate from about 80 Hz to about 0.75 Hz.

8. The method of claim 1, wherein the stimulus is administered at about 70 decibels.

9. The method of claim 1, wherein the stimulus is a sinusoidal pulse.

10. The method of claim 1, wherein the stimulus is administered to awake subjects.

11. The method of claim 1, wherein the stimulus is administered to subjects in a state of light sleep.

12. The method of claim 1, wherein the subjects are adults of at least 18 years of age.

13. The method of claim 1, wherein the subjects are children less than 9 years of age.

14. The method of claim 1, wherein the auditory evoked potential in the subject reflects the cortical activity of the brain.

15. A system for evaluating evoked potentials in brain electrical activity using auditory steady state profiling comprising:

a device for administering an auditory stimulus to a subject over a range of frequencies from about 80 Hz to about 0.75 Hz, the auditory stimulus generating an auditory evoked potential in the subject indicative of the cortical activity of the brain;

a sensor for detecting the auditory evoked potential;

a processor coupled to the sensor and receiving the detected potential therefrom, the processor configured to identify a plurality of spectral components of the auditory evoked potential, the processor configured to calculate the harmonic sum of the plurality of spectral components;

an output coupled to the processor and receiving the calculated harmonic sum therefrom, the output displaying the overall amplitude of the auditory evoked potentials, wherein the overall amplitude includes the plurality of spectral components.

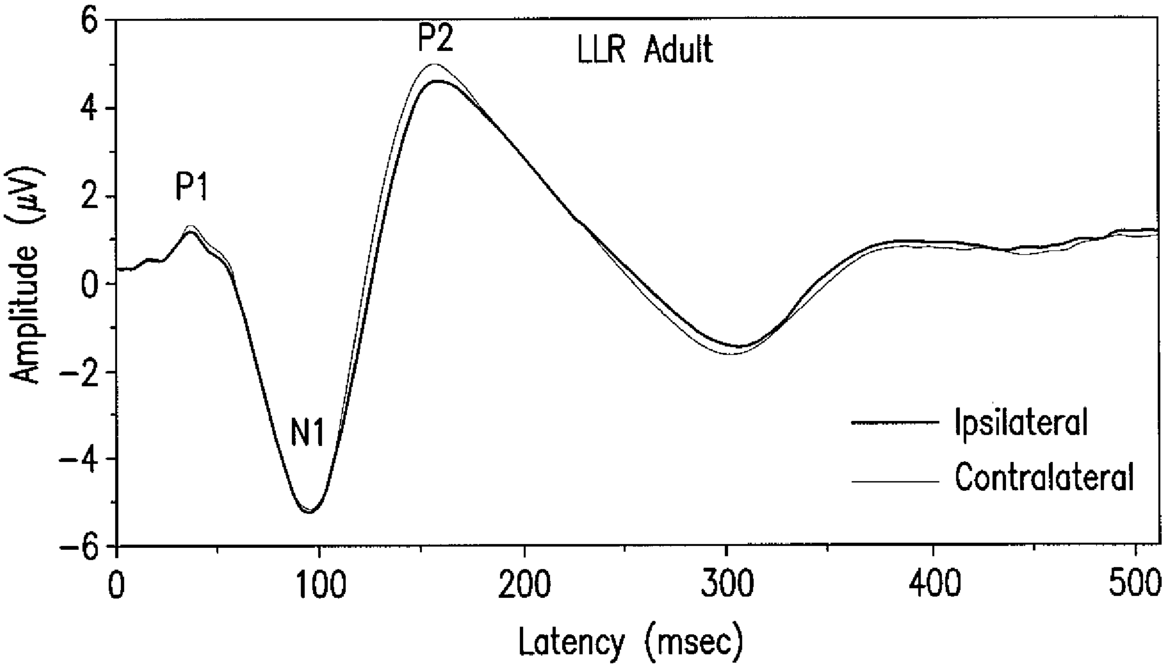
16. The system of claim 14, wherein the harmonic sum includes the square root of the sum of squares of select spectral components.

17. The system of claim 15, wherein the select spectral components have a magnitude which is greater than an estimated noise value.

18. The system of claim 14, wherein the stimulus is administered at a rate of less than 10 Hz.

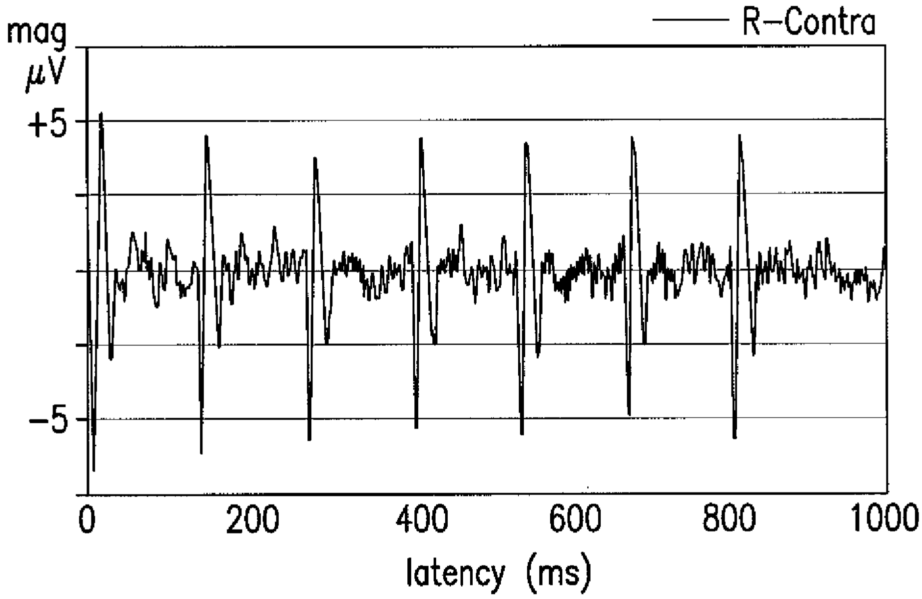
19. The system of claim 14, wherein the overall amplitude includes a fundamental frequency of the stimulus.

20. The system of claim 14, wherein the stimulus is a sinusoidal pulse administered at about 70 decibels.



P2
LLR Adult
P1
N1
Amplitude (μV)
6
4
2
0
−2
−4
−6
0
100
200
300
400
500
Latency (msec)
Ipsilateral
Contralateral

FIG.1



mag
μV
R−Contra
+5
−5
0
200
400
600
800
1000
latency (ms)

FIG.2

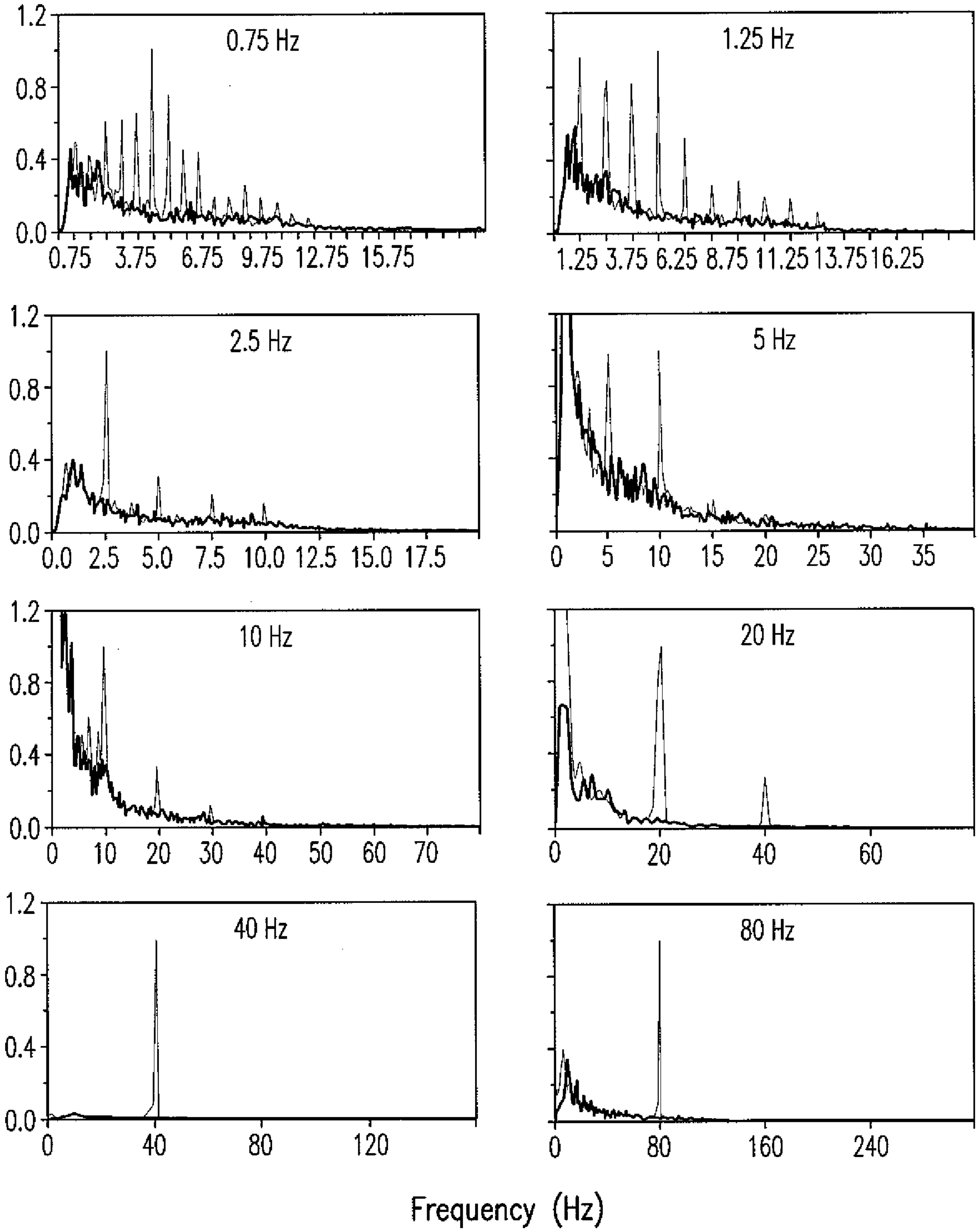

0.75 Hz
1.25 Hz
2.5 Hz
5 Hz
10 Hz
20 Hz
40 Hz
80 Hz
1.2
0.8
0.4
0.0
0.75 3.75 6.75 9.75 12.75 15.75
1.25 3.75 6.25 8.75 11.25 13.75 16.25
0.0 2.5 5.0 7.5 10.0 12.5 15.0 17.5
0 5 10 15 20 25 30 35
0 10 20 30 40 50 60 70
0 20 40 60
0 40 80 120
0 80 160 240
Frequency (Hz)

FIG.3

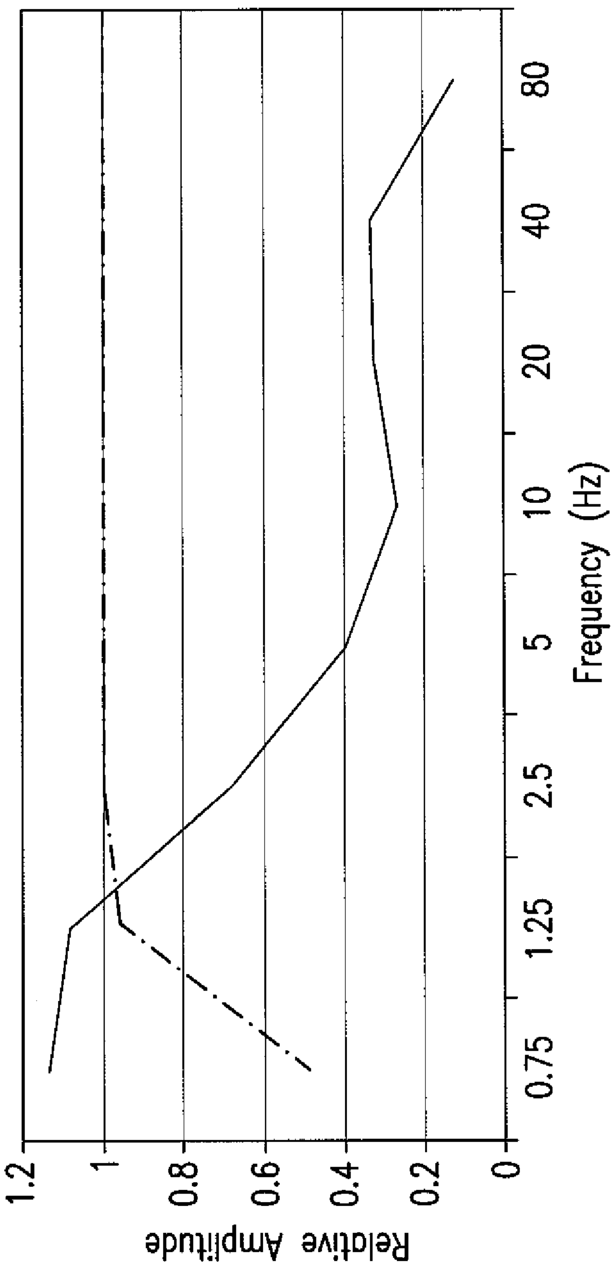

Relative Amplitude
1.2
1
0.8
0.6
0.4
0.2
0
0.75
1.25
2.5
5
10
20
40
80
Frequency (Hz)

FIG.4

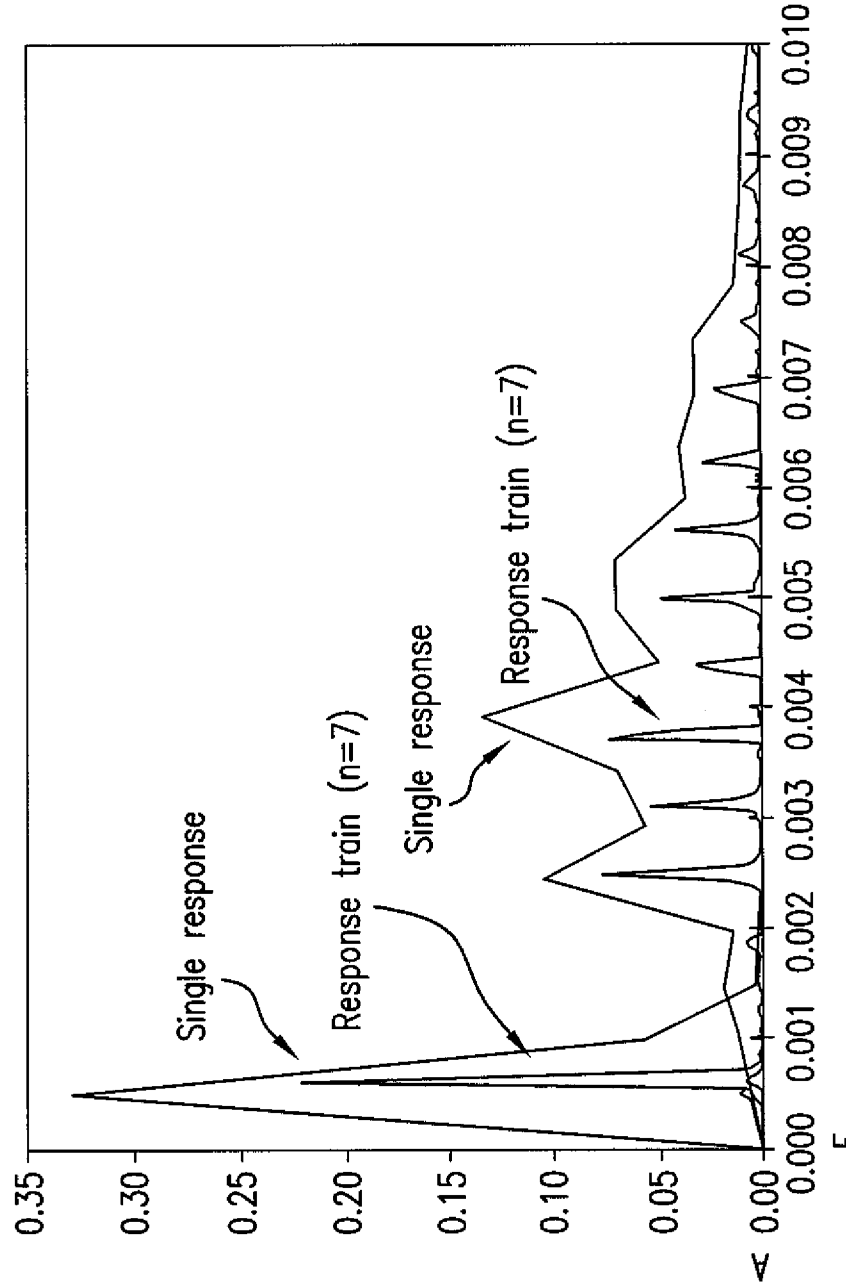

Single response
Response train (n=7)
Single response
Response train (n=7)
A
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
F
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009
0.010

FIG.5A

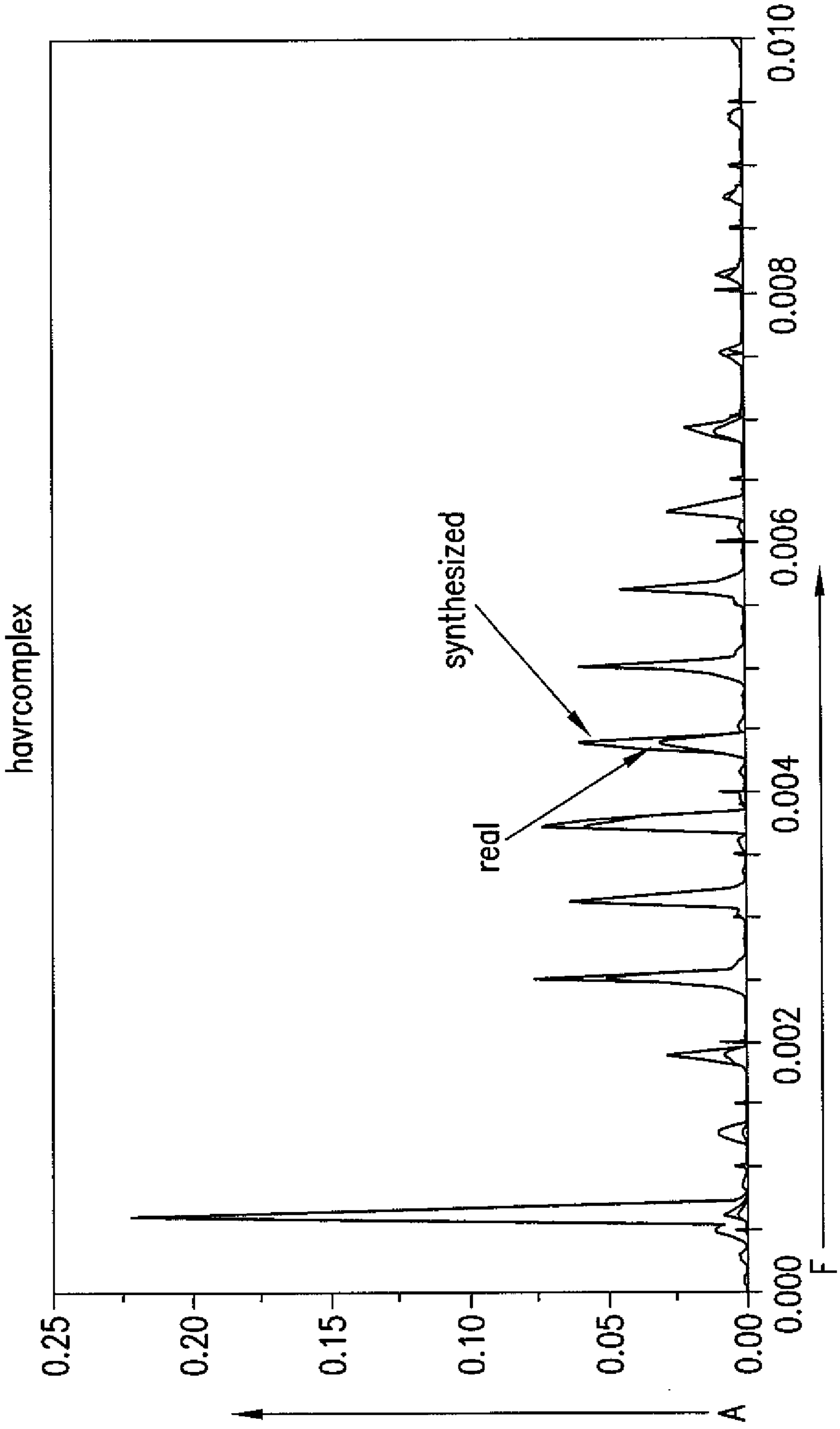
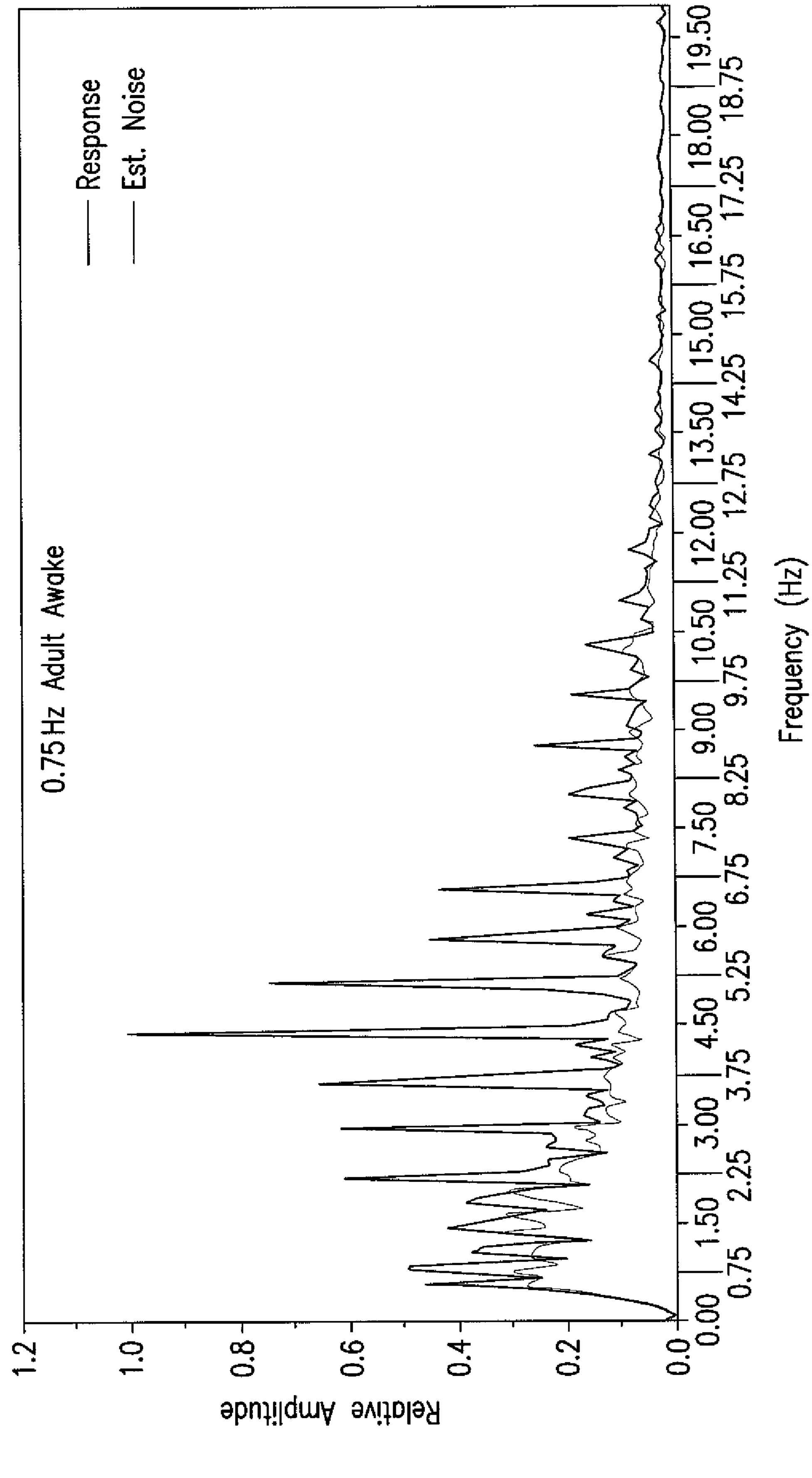
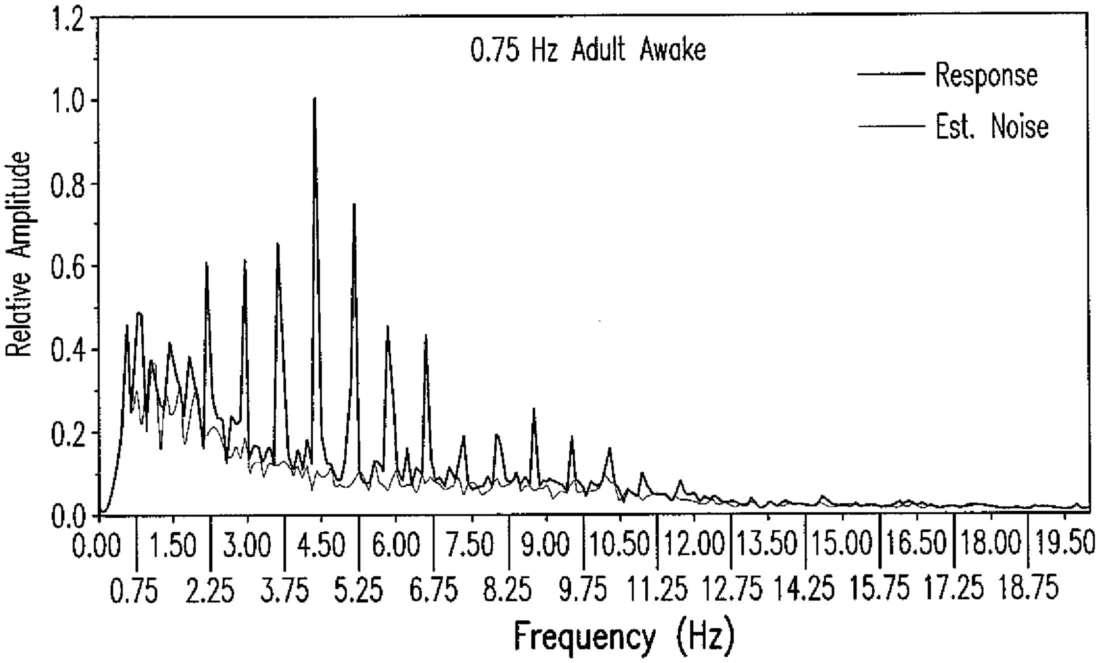

havrcomplex
synthesized
real
0.25
0.20
0.15
0.10
0.05
0.00
A
0.000
0.002
0.004
0.006
0.008
0.010
F

FIG.5B



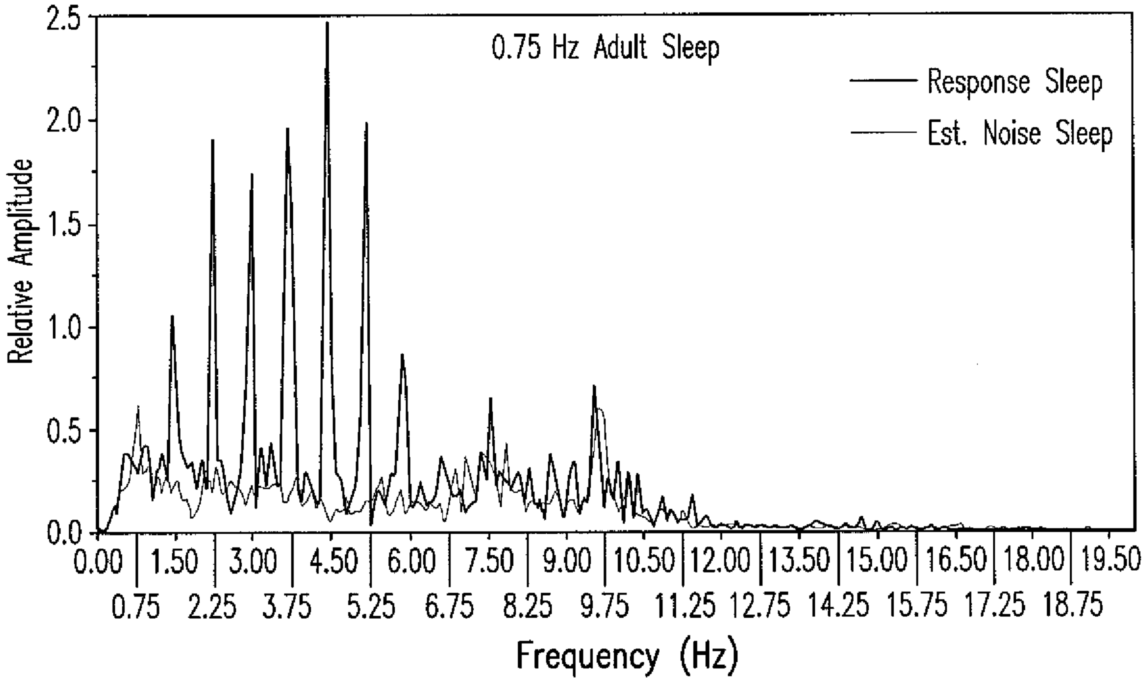
0.75 Hz Adult Awake
Response
Est. Noise
Relative Amplitude
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.00
0.75
1.50
2.25
3.00
3.75
4.50
5.25
6.00
6.75
7.50
8.25
9.00
9.75
10.50
11.25
12.00
12.75
13.50
14.25
15.00
15.75
16.50
17.25
18.00
18.75
19.50
Frequency (Hz)

FIG.6



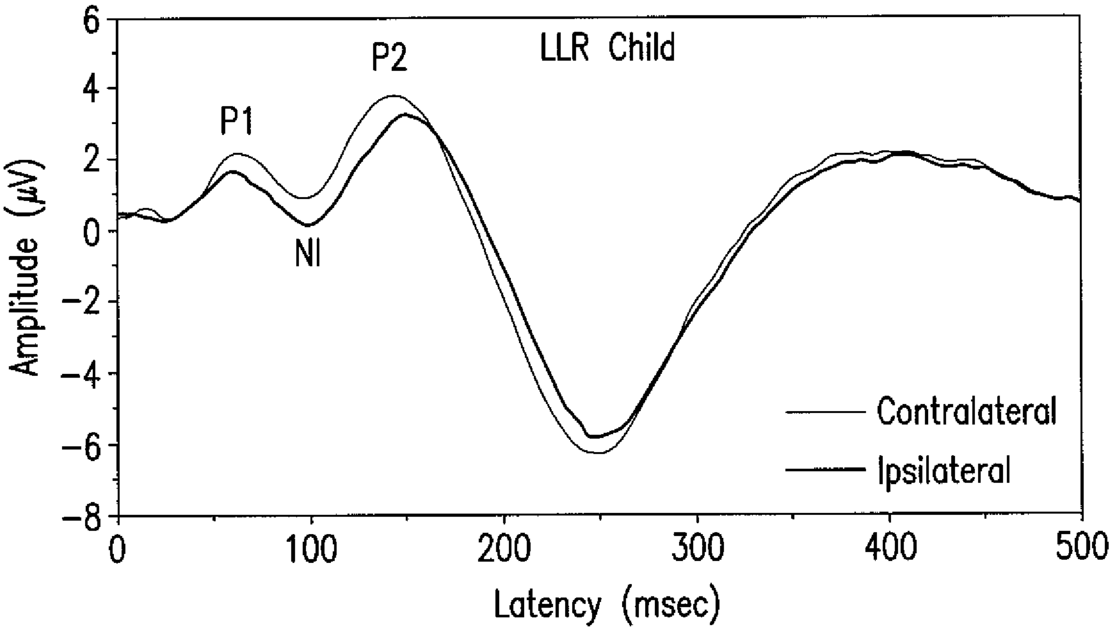
0.75 Hz Adult Awake
Response
Est. Noise
Relative Amplitude
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.00
1.50
3.00
4.50
6.00
7.50
9.00
10.50
12.00
13.50
15.00
16.50
18.00
19.50
0.75
2.25
3.75
5.25
6.75
8.25
9.75
11.25
12.75
14.25
15.75
17.25
18.75
Frequency (Hz)

FIG.7A



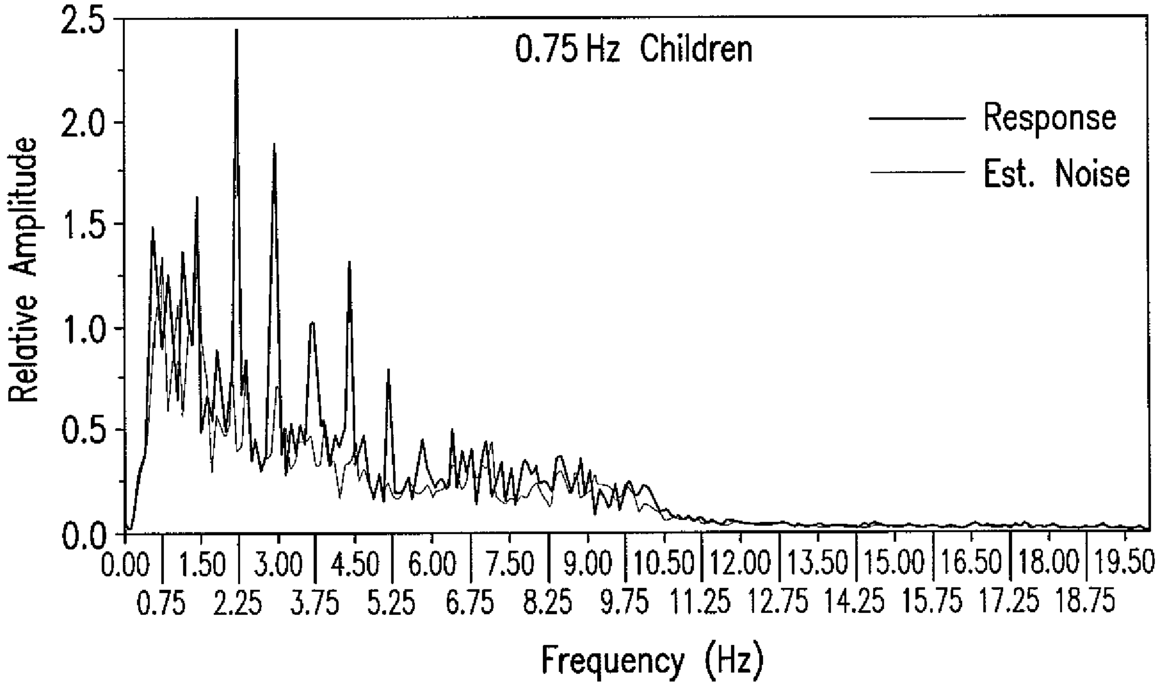
0.75 Hz Adult Sleep
Response Sleep
Est. Noise Sleep
Relative Amplitude
2.5
2.0
1.5
1.0
0.5
0.0
0.00
1.50
3.00
4.50
6.00
7.50
9.00
10.50
12.00
13.50
15.00
16.50
18.00
19.50
0.75
2.25
3.75
5.25
6.75
8.25
9.75
11.25
12.75
14.25
15.75
17.25
18.75
Frequency (Hz)

FIG.7B



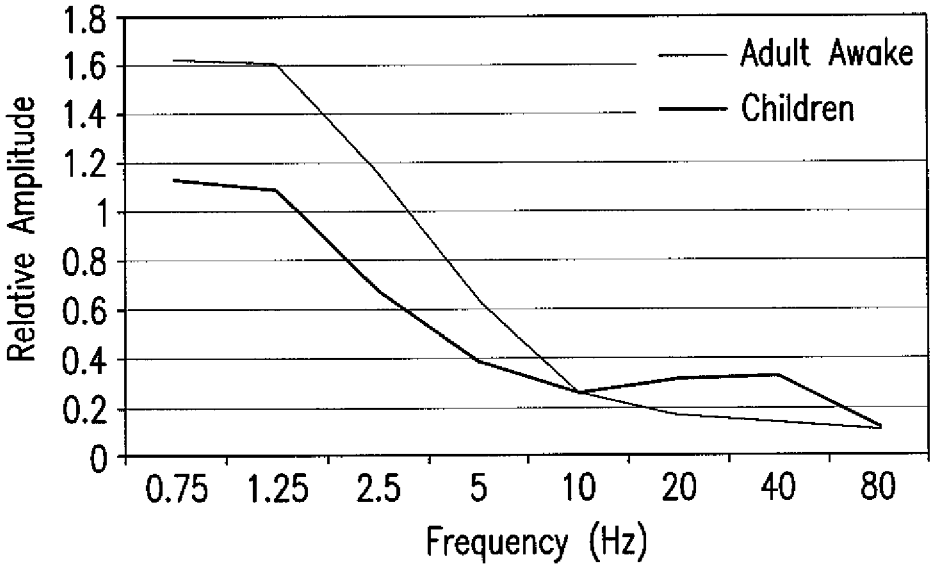
LLR Child
P1
P2
NI
Amplitude (μV)
6
4
2
0
−2
−4
−6
−8
0
100
200
300
400
500
Latency (msec)
Contralateral
Ipsilateral

FIG.8A



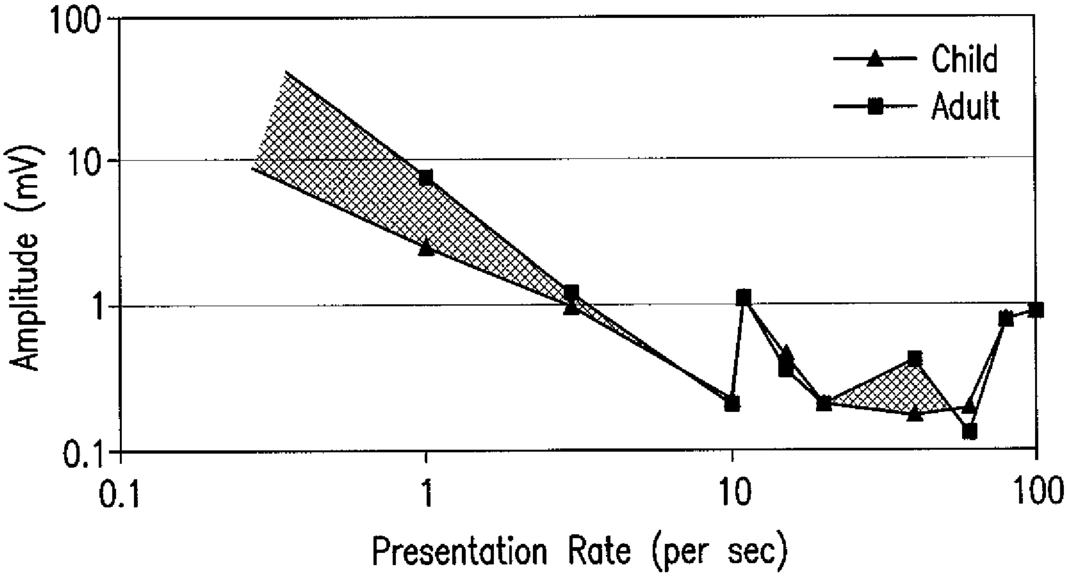
0.75 Hz Children
Response
Est. Noise
Relative Amplitude
2.5
2.0
1.5
1.0
0.5
0.0
0.00 1.50 3.00 4.50 6.00 7.50 9.00 10.50 12.00 13.50 15.00 16.50 18.00 19.50
0.75 2.25 3.75 5.25 6.75 8.25 9.75 11.25 12.75 14.25 15.75 17.25 18.75
Frequency (Hz)

FIG.8B



1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Relative Amplitude
Adult Awake
Children
0.75
1.25
2.5
5
10
20
40
80
Frequency (Hz)

FIG.9



100
10
1
0.1
Amplitude (mV)
Child
Adult
0.1
1
10
100
Presentation Rate (per sec)

FIG.10

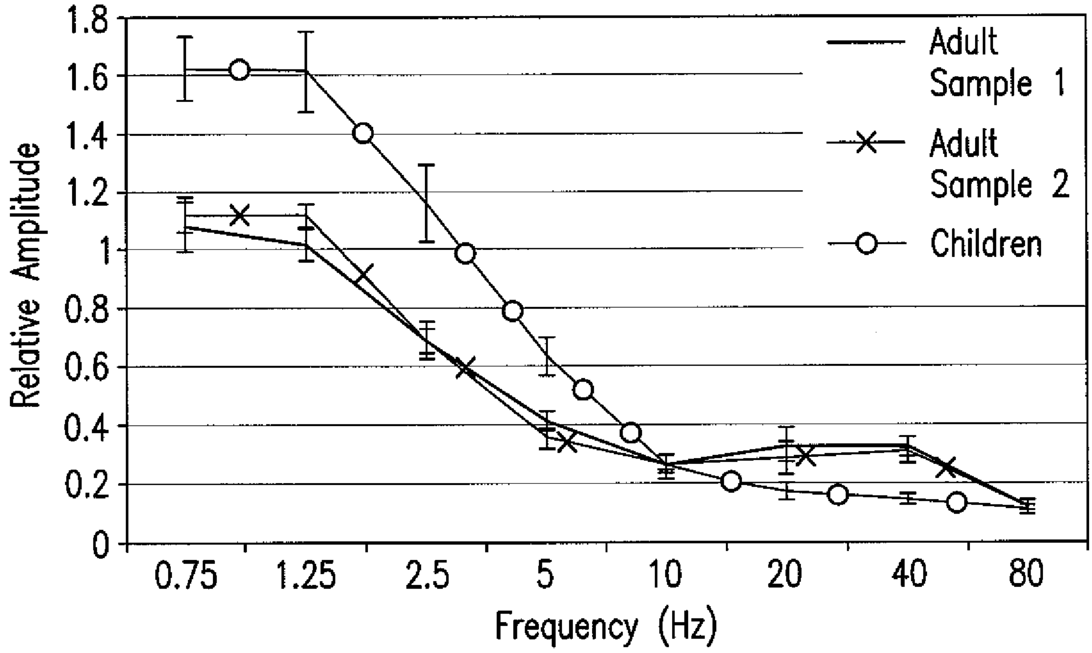

Relative Amplitude
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.75
1.25
2.5
5
10
20
40
80
Frequency (Hz)
Adult Sample 1
Adult Sample 2
Children

FIG.11

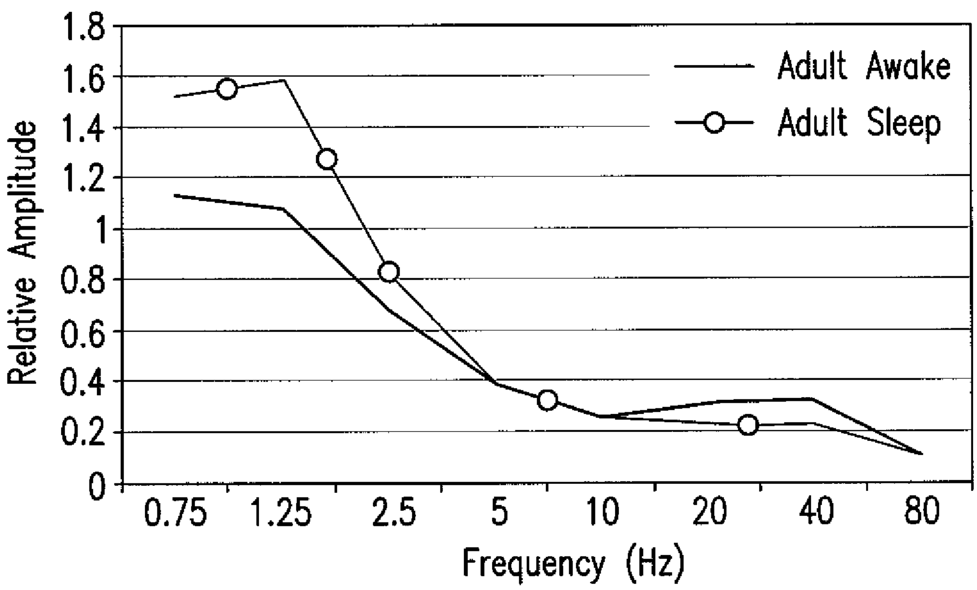

Relative Amplitude
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.75
1.25
2.5
5
10
20
40
80
Frequency (Hz)
Adult Awake
Adult Sleep

FIG.12

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(54) **METHOD TO DESIGN ACOUSTIC STIMULI IN THE SPECTRAL DOMAIN FOR THE RECORDING OF AUDITORY STEADY-STATE RESPONSES (ASSR)**

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(57) **ABSTRACT**

The invention relates to a method to design and generate frequency-specific electrical or acoustical stimuli for the recording of auditory steady-state responses, ASSR, from human individuals, where the stimuli are generated as a combination of a series of three or more spectral components (i.e. pure tones), each having a specified frequency, amplitude and phase and where the frequency difference between the successive pure tones in the series preferably is constant=f_s. The invention further relates to a device for detection of ASSR and to a software program for use in such device.

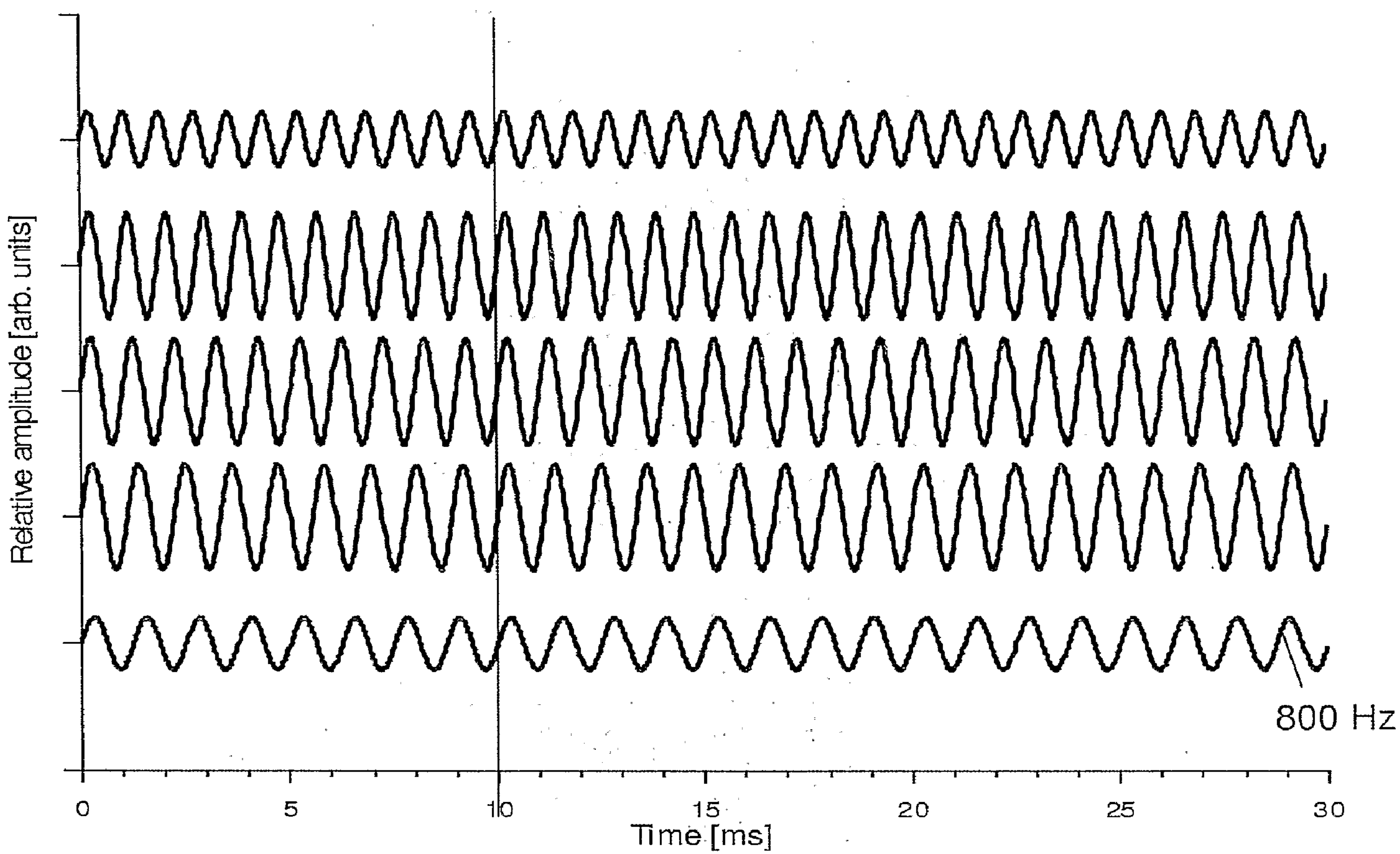


Figure 1

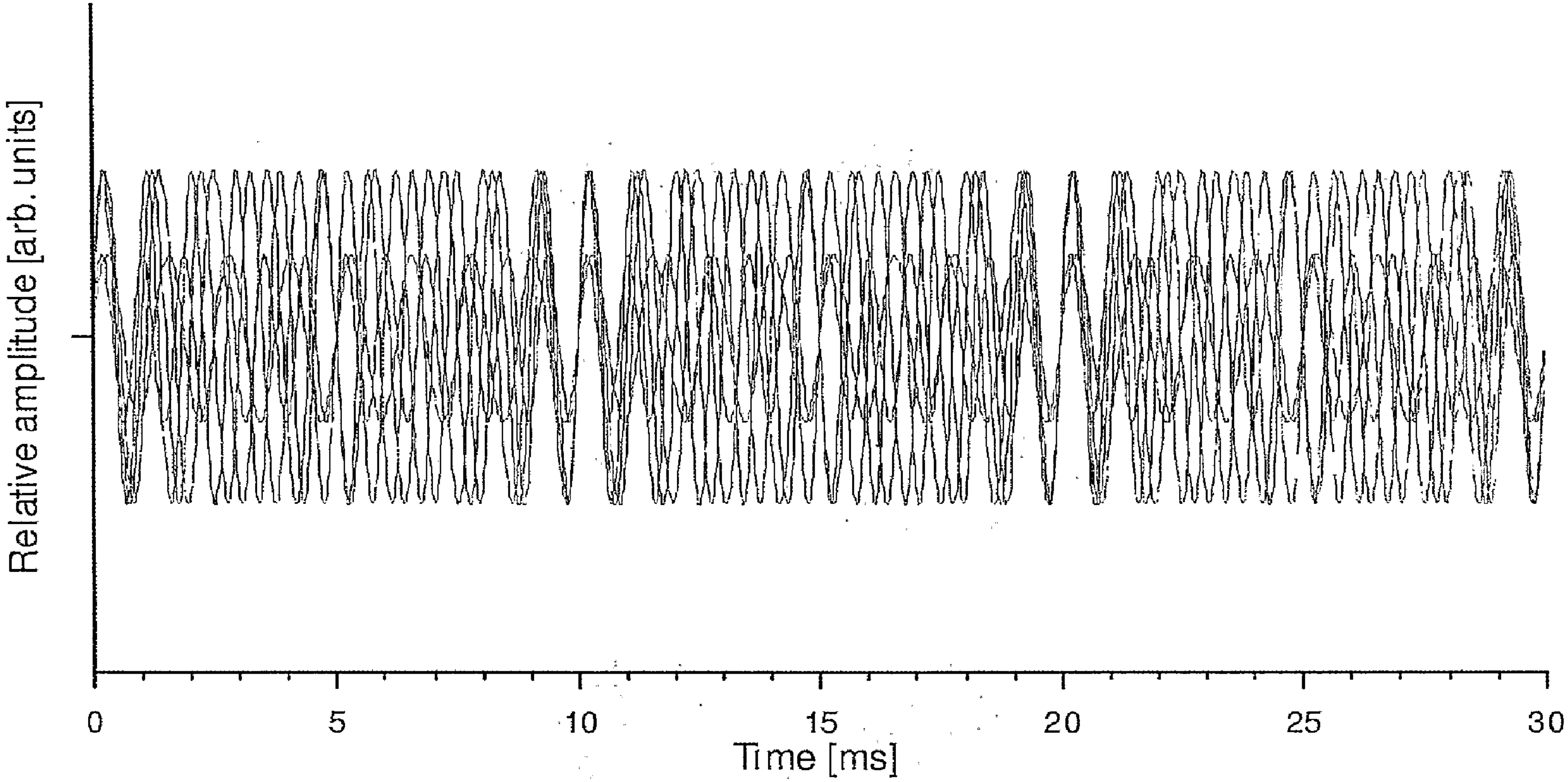


Figure 2

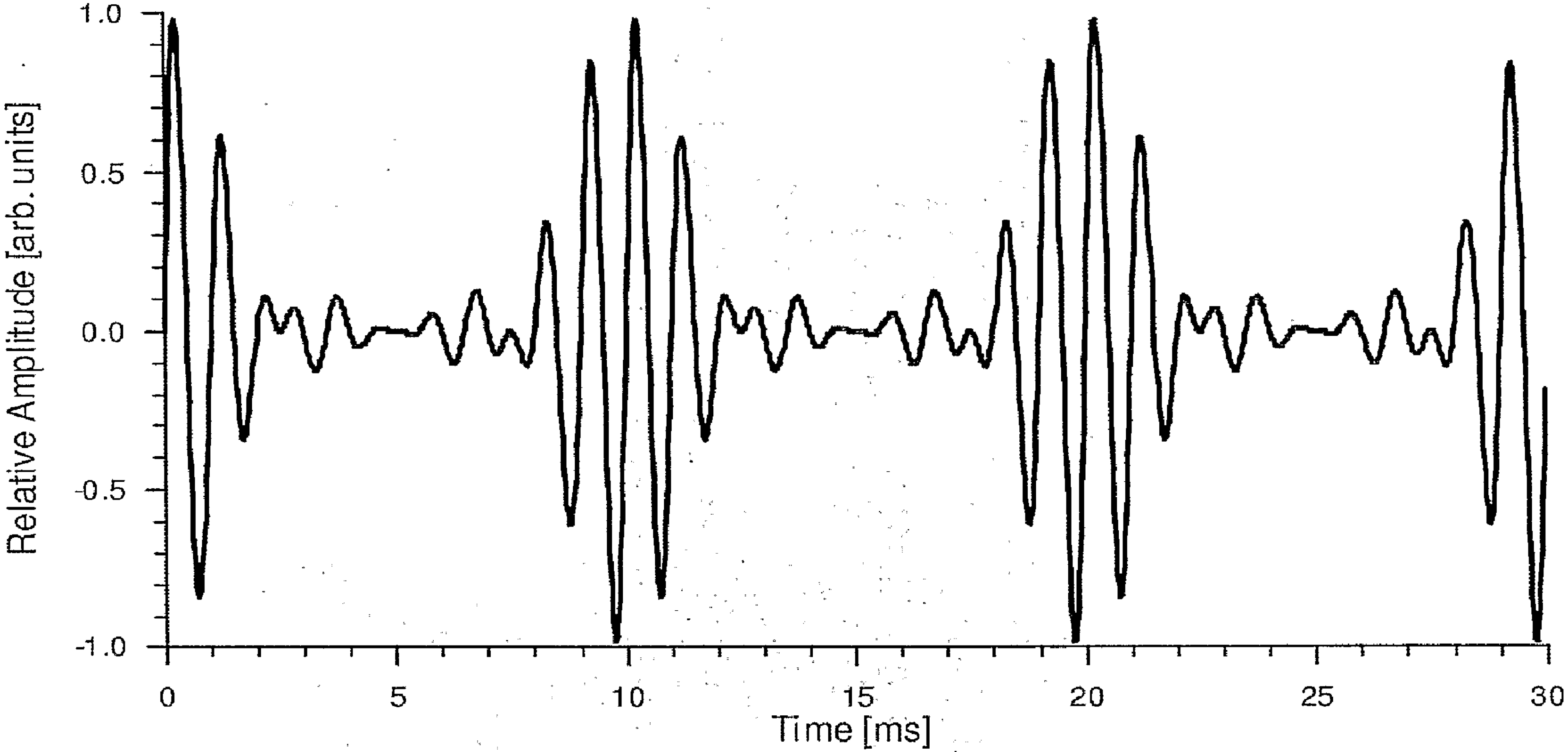

1.0
0.5
0.0
-0.5
-1.0
Relative Amplitude [arb. units]
0
5
10
15
20
25
30
Time [ms]

Figure 3

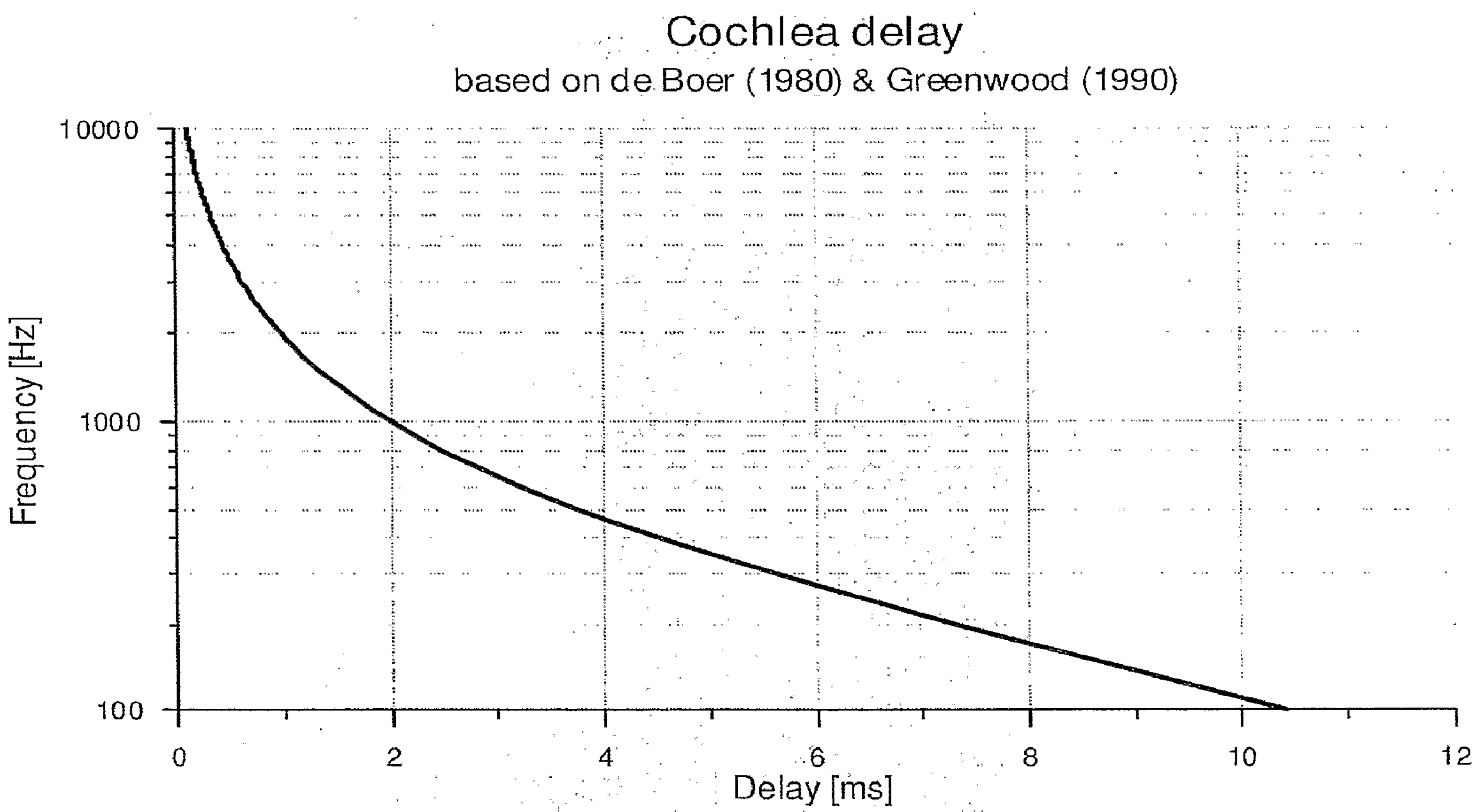

Cochlea delay
based on de Boer (1980) & Greenwood (1990)
Frequency [Hz]
10000
1000
100
0
2
4
6
8
10
12
Delay [ms]

Figure 4

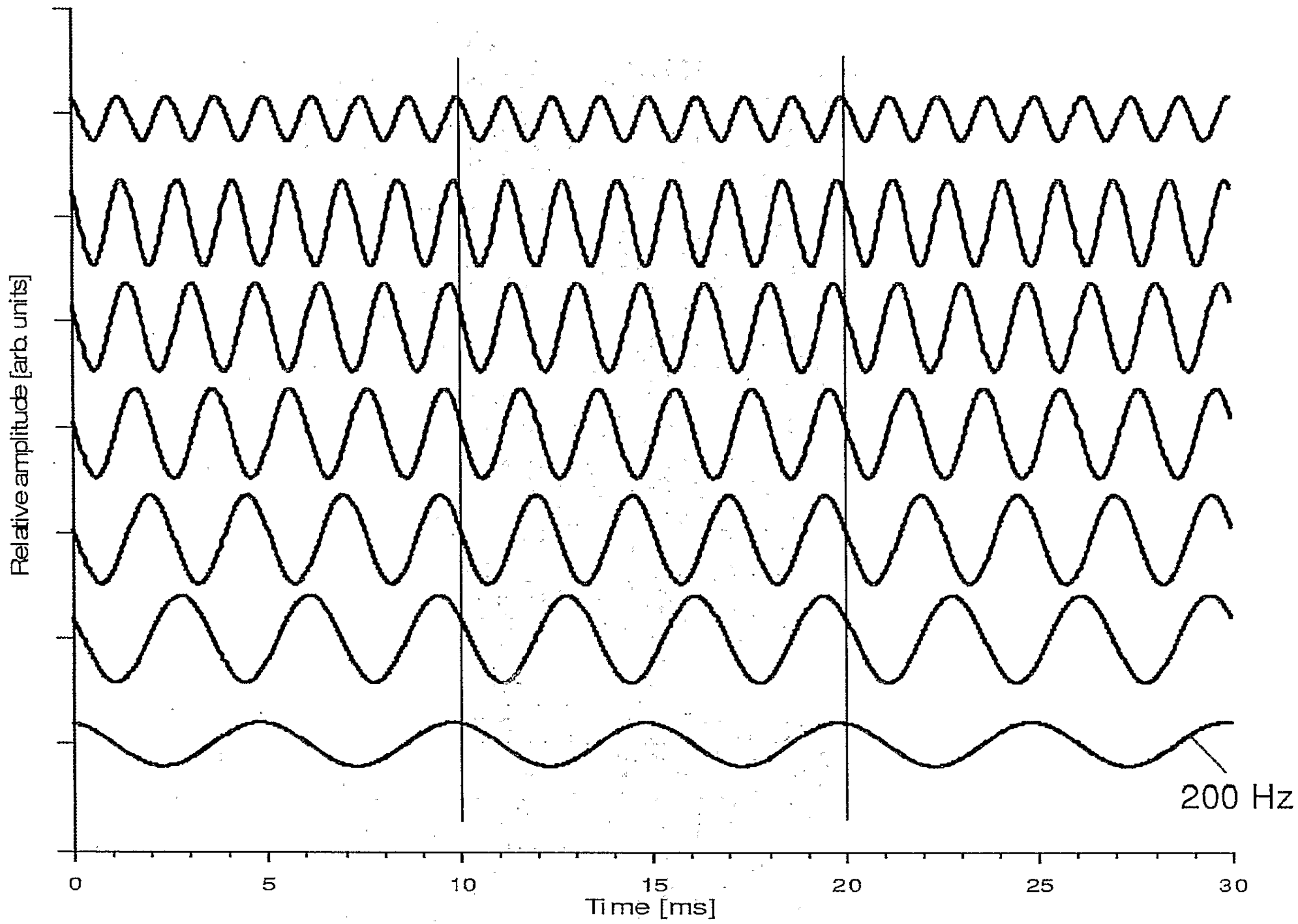


Figure 5

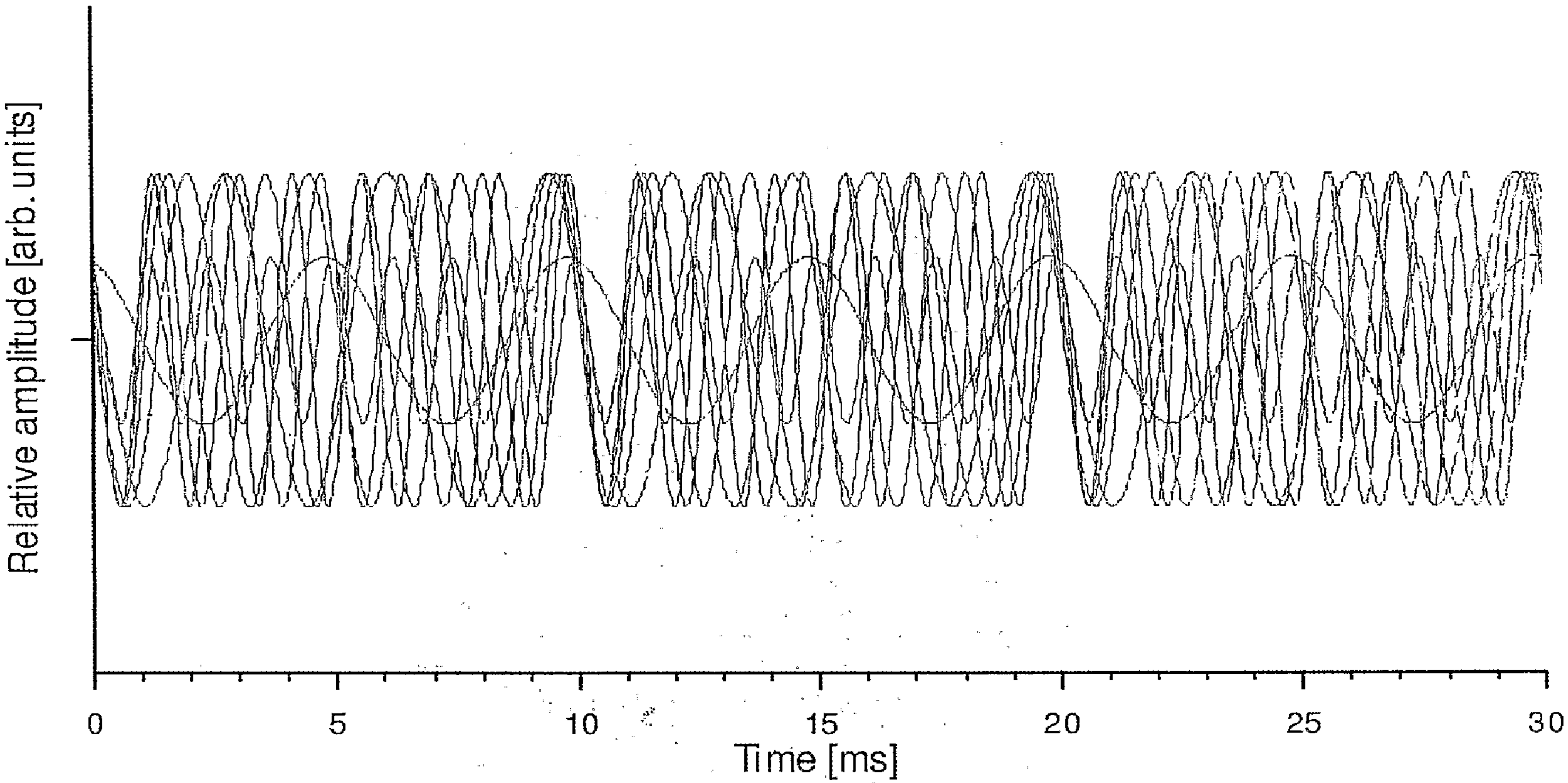


Figure 6

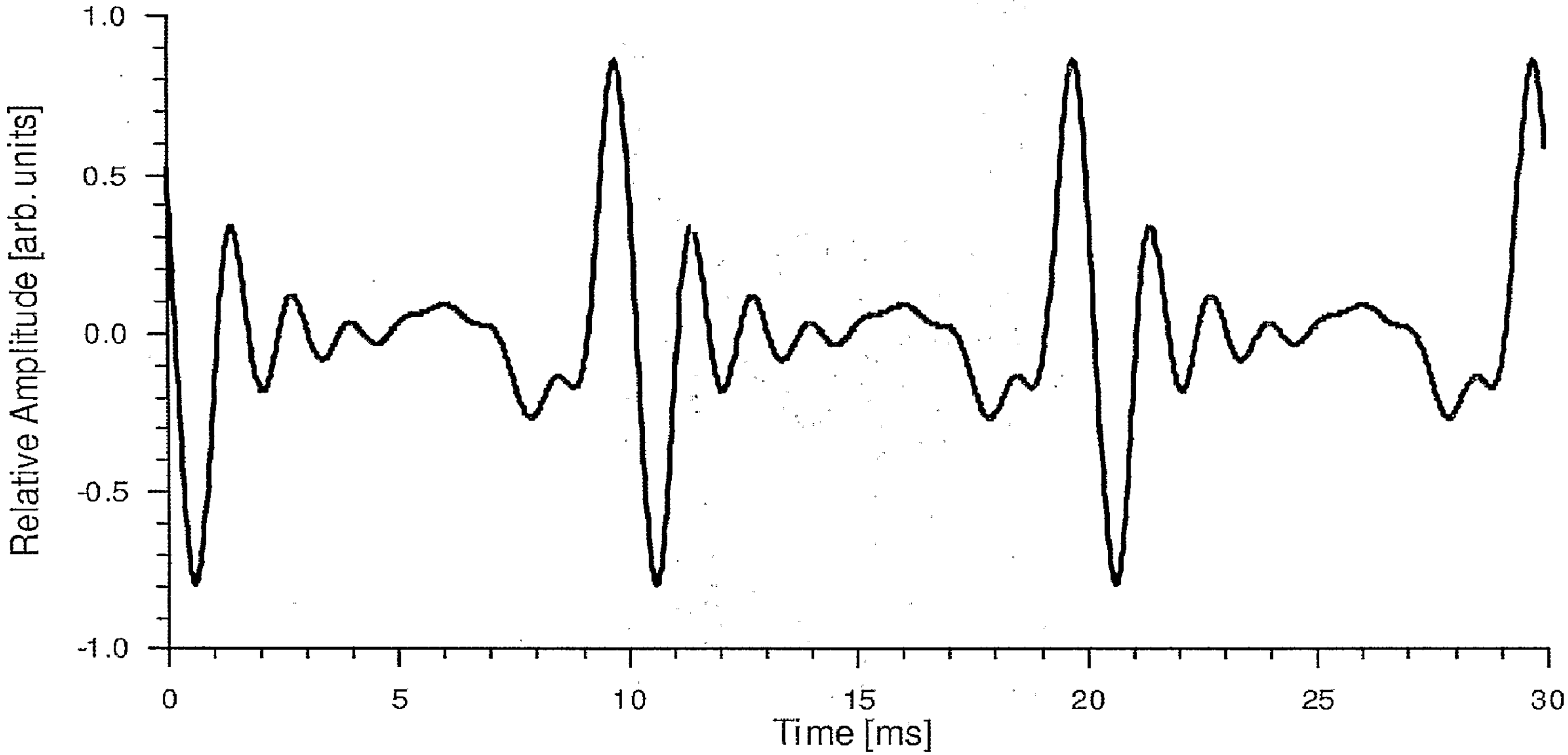

Relative Amplitude [arb. units]
1.0
0.5
0.0
-0.5
-1.0
0
5
10
15
20
25
30
Time [ms]

Figure 7

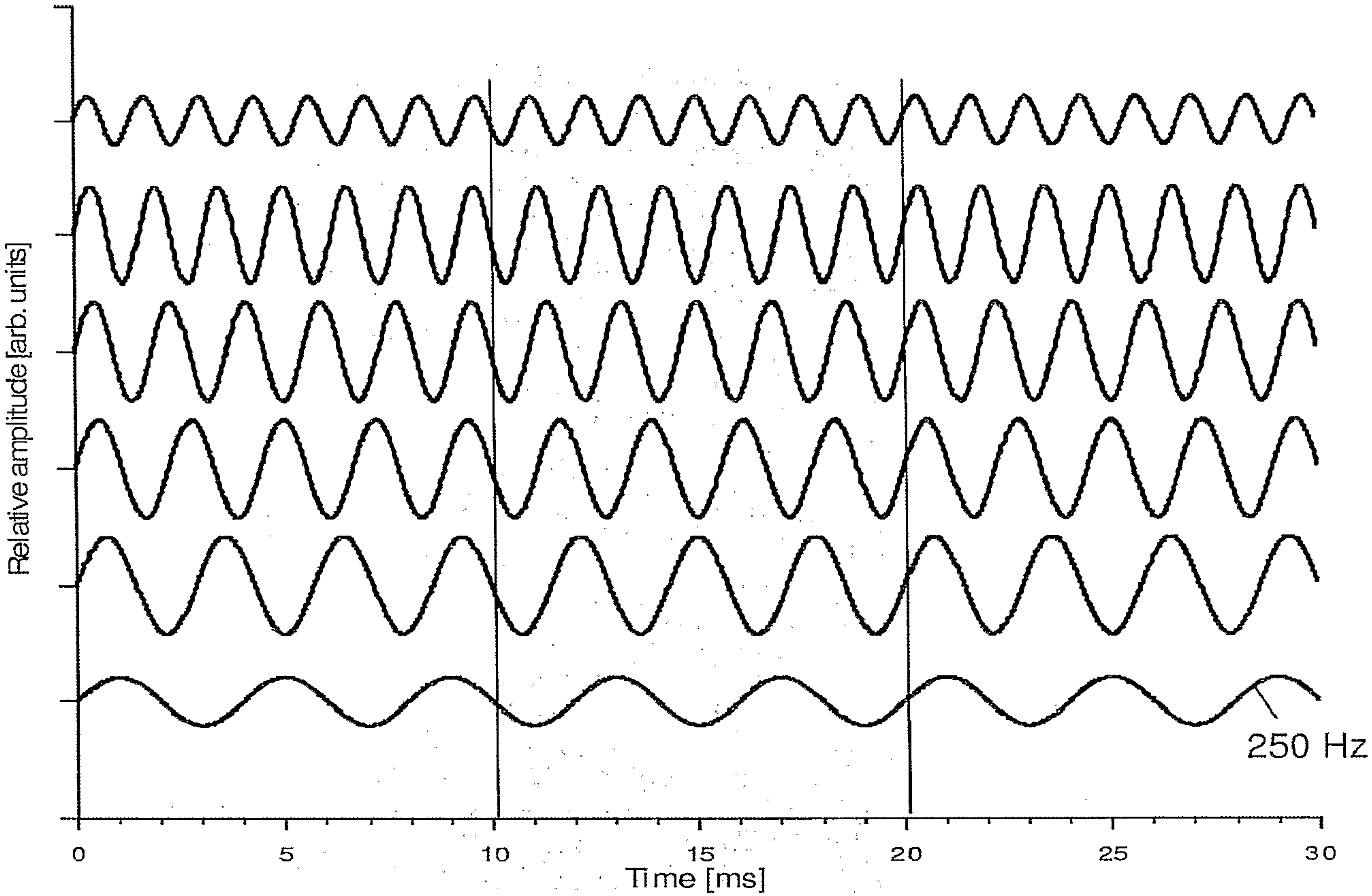


Figure 8

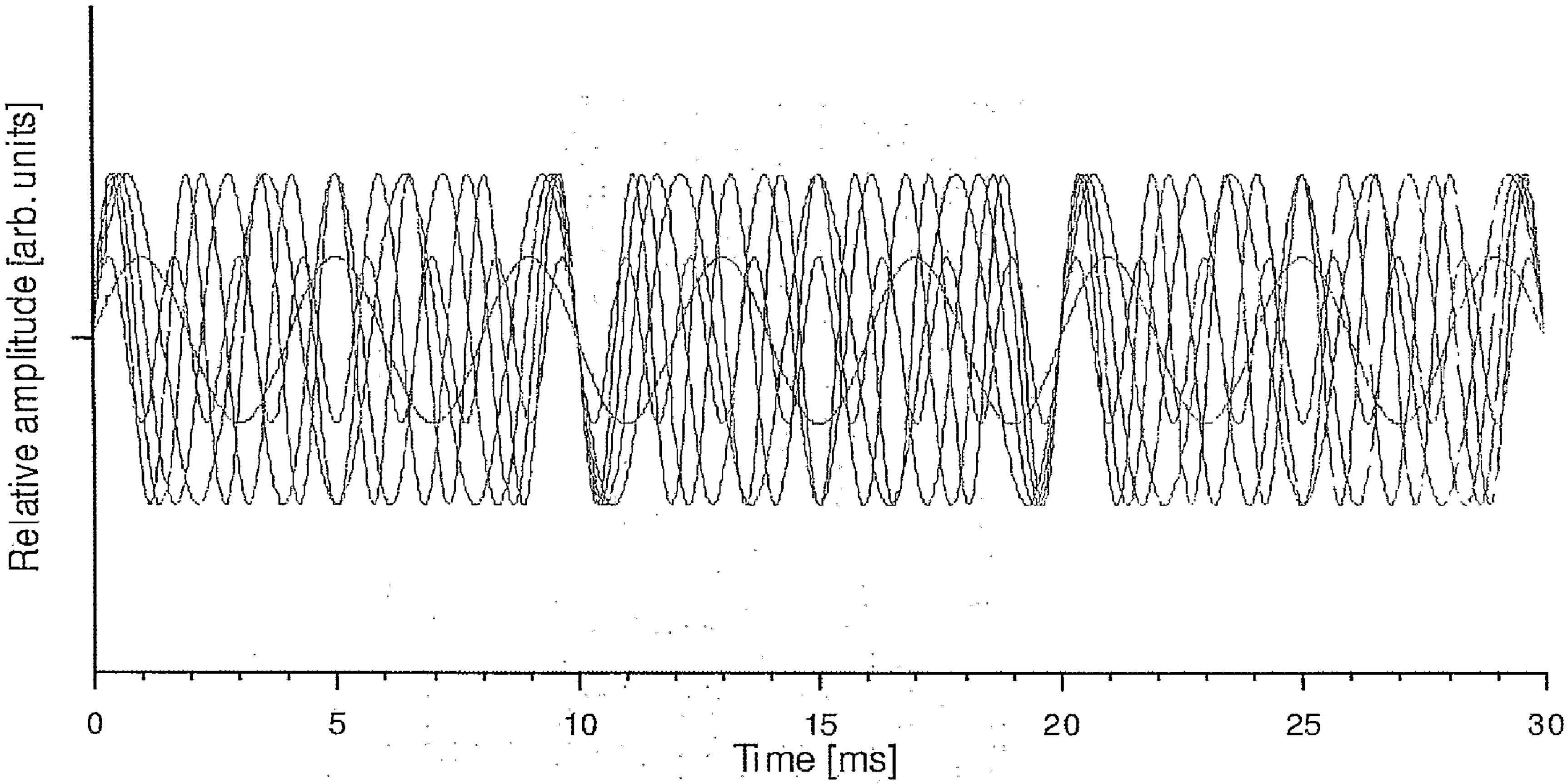
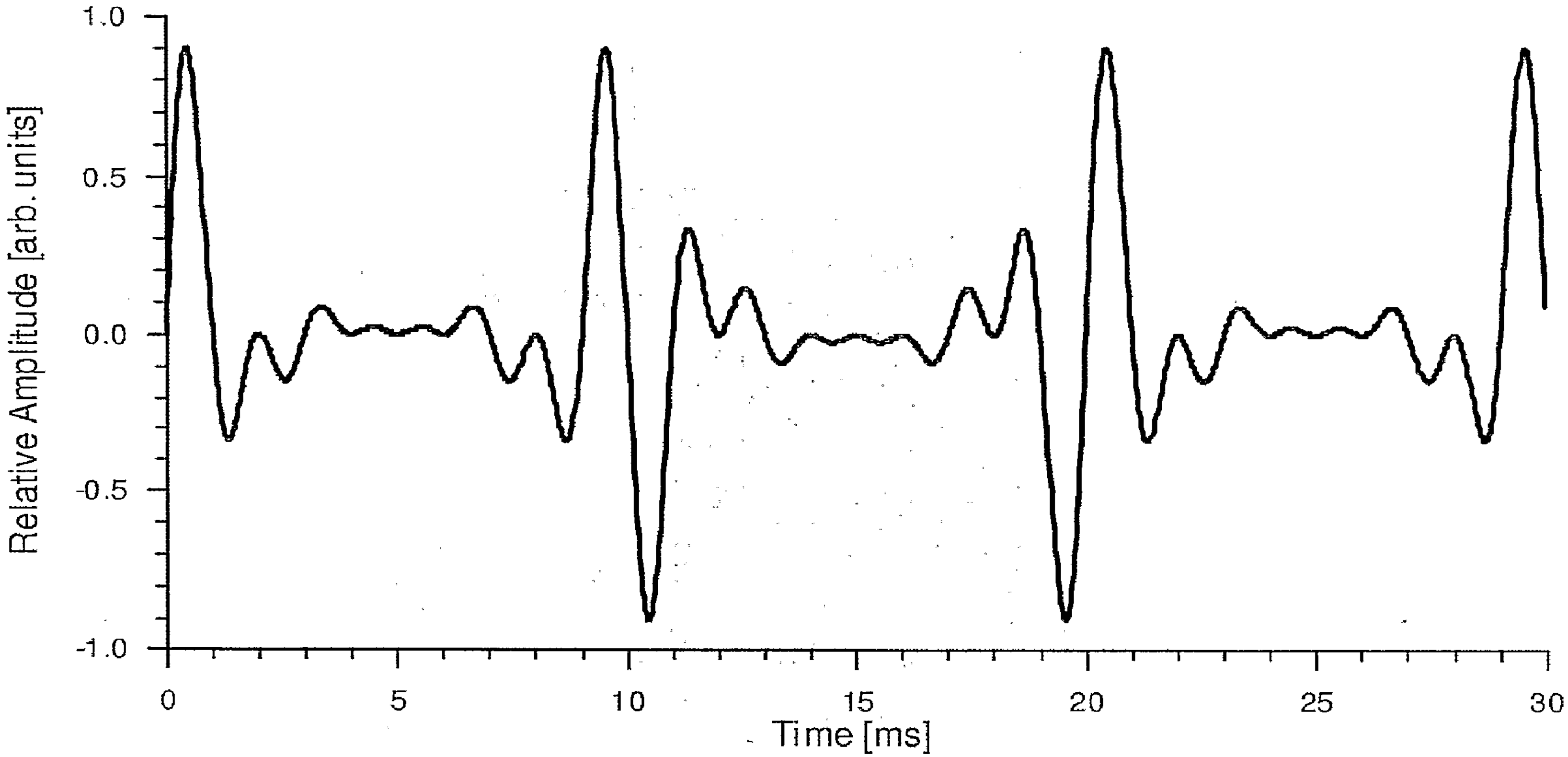


Figure 9



Relative Amplitude [arb. units]
1.0
0.5
0.0
-0.5
-1.0
0
5
10
15
20
25
30
Time [ms]

Figure 10

METHOD TO DESIGN ACOUSTIC STIMULI IN THE SPECTRAL DOMAIN FOR THE RECORDING OF AUDITORY STEADY-STATE RESPONSES (ASSR)

AREA OF THE INVENTION

[0001] The present invention relates to the field of recording Auditory Evoked Responses (AER) from human test subjects and especially of obtaining evoked responses that originate from specific places or frequency areas along the auditory pathway. The invention concerns a spectral domain design of acoustic stimuli especially for the recording of Auditory Steady-State Responses (ASSR).

BACKGROUND OF THE INVENTION

[0002] A series of AER-tests relate to the field of objective hearing tests which particularly are used with infants and small children, since early in life standard pure-tone audiometry, which demands active participation of the individual test subject, is not yet possible.

[0003] Several of the known test methods that record evoked responses from the auditory pathway make use of broad band click stimuli. Since a click stimulus excites a relatively broad frequency area, it is difficult to obtain frequency specific information by such stimulus. Never-the-less, click stimuli are employed in many clinical test setups especially for oto-neurological evaluations or when it is the purpose of the testing to obtain a general impression about the hearing acuity of the individual. This latter applies for instance to new born hearing screening programs. However, for a more detailed analysis of the individual hearing acuity, like for instance in audiological diagnostic evaluations, frequency specific information is in demand, especially to establish a basis for an appropriate (re)habilitation by hearing aids, cochlear implants or the like.

[0004] To this end, a series of relatively new test methods have matured. These methods are referred to as Auditory Steady-State Responses (ASSR) or by other acronyms. For a review of the ASSR—the reader is referred to e.g. Picton et al. 2003. ASSR-procedures make use of a sustained stimulus often produced as a continuous carrier waveform consisting of a single or a plurality of pure tones, a broad band or a band limited noise or the like, which is modulated either in amplitude, in frequency or in both, by specific modulation signals.

[0005] Most of the electrophysiological activity which underlies the generation of auditory evoked responses (AER) is caused by non-linear processes in individual nerve fibers, neurons or other neural units, and the AER are therefore related to the envelope of the acoustic stimulus. This is especially true for the ASSR, which consequently is composed of a combination of the fundamental frequency and its harmonics of the modulation signal. Thus, the ASSR is most readily detected and analyzed in the spectral domain rather than in the temporal domain, (Picton et al. 2003).

[0006] ASSR-stimuli have hitherto been described and defined in the temporal domain, as modulation (in amplitude, frequency or in both) of one or multiple carriers. However, several ways of designing an appropriate stimulus for an ASSR-test are described in the literature (e.g. Sturzebecher et al. 2001, John et al. 2003, Picton et al. 2003) and several patents apply to this problem. In the experimental animal 'beat' stimuli generated by pairs of pure tones have also been used—e.g. Dolphin, 1997.

[0007] One patent by Sturtzebecher et al. 2000 (U.S. Pat. No. 6,524,258) deals with the use of several amplitude modulated carriers having a frequency that is offset by a specific frequency difference, and where all carriers are modulated with the same modulation signal.

[0008] Another patent by John et al. 2001 deals with a broad spectrum of problems related to the recording of ASSR. Relevant to the problem described herein, the John et al. patent especially concerns the use of stimuli that may be modulated independently in amplitude and in frequency or a signal whose envelope is modulated by an exponential modulation signal—see also John et al. 2002.

[0009] It is a basic characteristic of an auditory evoked response that the magnitude of the response depends on the number of auditory units that are activated synchronously by the stimulus. This is part of the reason why a click stimulus, which simultaneously activates a broad band of frequencies, provides evoked responses that in general are larger than those obtained by narrow band or frequency specific stimuli (Eggermont, 1977).

[0010] However, in the peripheral part of the auditory pathway, the Cochlea, all frequency areas along the cochlear partition do not get excited simultaneously because of the travel time through the cochlea—from the base (high frequency area) to the apex (low frequency area) (Elberling, 1974). This has lead to the design of so-called chirp stimulus (e.g. Dau et al. 2000) where the individual frequency components of the click are time-adjusted to compensate for the cochlea travel time, so the responses from nerve fibers from different parts of the cochlear partition get time-aligned or synchronized. It was demonstrated that the chirp-stimulus generates Auditory Brainstem Responses (ABR) with larger amplitudes than those generated by the corresponding standard click stimulus.

[0011] A similar approach was used by Don et al. 1997 who demonstrated that if prior to summation, narrow-band Auditory Brainstem Responses, (ABR)—that originate from different frequency regions along the cochlear partition—are time-aligned to compensate for the individual cochlea delay, this would create a much larger stacked ABR than the broad band ABR.

[0012] In the clinic, it is important to keep test time at a minimum for the detection of an auditory response or to obtain a specific response quality. Larger response amplitudes will in general result in shorter test time, and the compensation for cochlear travel time could therefore be one way of increasing response amplitude and thereby shortening the test time.

[0013] A general problem in the recording of auditory evoked responses is how to avoid that stimulus related artifacts (being either electromagnetic or acoustic) are introduced in the recording path and here cause an interaction with the physiological response. Traditionally these problems have been minimized or eliminated by careful considerations and counter measures in the recording set-up and the proper use of shielded acoustical transducers. However, at high stimulus levels it is not always possible to get rid of the artifact.

[0014] For auditory evoked responses that are recorded using brief acoustic stimuli it is possible to use the time lag between the stimulus and the generation of the evoked response and to introduce a recording time window which only incorporates the evoked response and leaves out the stimulus artifact.

[0015] Another way which traditionally has been used is to change the polarity of every other stimulus; a method which eliminates the artifact through the averaging process which most often is applied as a means to improve the signal-to-noise ratio in order to recognize the tiny evoked responses that are buried in the physiological background noise.

[0016] For the ASSR where both stimulus and response are continuous temporal separation between stimulus artifact and response is not possible. As described above, the ASSR is readily analyzed in the frequency domain, since the response energy is located only at the fundamental frequency of the stimulus envelope (the repetition or modulation frequency) and its harmonics. Most of the ASSR energy is contained within the first six harmonics or so (Cebeulla et al. 2004), which for a repetition frequency of 100 Hz will cover the frequency range up to about 600 Hz. For an ASSR stimulus that for instance consists of a single pure tone carrier which is amplitude modulated with a low frequency pure tone the stimulus energy (and that of the artifact) will be located around the carrier frequency. For lower modulation frequencies (Gower than e.g. 100 Hz) and higher stimulus carrier frequencies (larger than e.g. 1000 Hz) the energy of the response and artifact will be spectrally separated unless frequency-aliasing occurs—like that described by e.g. Picton & John, 2004. However, for lower stimulus frequencies (e.g. 500 Hz) possible interaction between response and artifact may occur—not only covering the same spectral area but actually sharing the same frequency bins in the response spectrum.

SUMMARY OF THE INVENTION

[0017] It is the objective of the present invention to provide a new way of designing and generating an appropriate ASSR-stimulus that enhances the response from the test subject.

[0018] According to the invention this is done by using a spectral domain approach, which is proposed in claim **1**. This design enables the stimulus—and the frequency area it effectively stimulates—to be spectrally precisely defined. Through the spectral domain approach the stimulus is generated—not by modulation—but by combination, e.g. summation, of a number of continuous pure tones, each having individual amplitude and phase and a frequency precisely defined at the frequency axis. The frequency region that gets stimulated—corresponding to a narrower or wider response area—can be accurately defined through this design method.

[0019] According to claim **2** the frequency difference between the successive pure tones in the series is constant= f_s.

[0020] According to claim **3** the individual pure tone has a frequency that is an integer multiple of the constant frequency difference, f_s.

[0021] According to claim **4** the individual pure tone has a frequency that corresponds to a half-integer multiple of the constant frequency.

[0022] According to claim **5** the individual pure tone has a phase (i.e. time-lag), that compensates for the corresponding cochlear delay or any other phase or temporal deviations in the stimulus system, the recording system and/or in the auditory pathway. Hereby the response from the test subject is enhanced.

[0023] According to claim **6** the combination is formed as the sum, the average or the like of the three or more spectral components.

[0024] According to claim **7** the electrical or acoustical stimuli is generated in software or in hardware.

[0025] The invention further relates to a device for detecting ASSR. Such device does according to the invention comprise means for generating stimuli in accordance with any of the claims **1-6**, means for providing the stimuli to a test subject and means for detecting responses to the stimuli from the test subject. The device may, except for the means for generating stimuli, be of a type known in the art.

[0026] Preferably the device comprises a software program for providing the stimuli.

[0027] The invention also relates to a software program for use in a device as described above. The program comprises program code for generating components in accordance with any of the claims **1-5**, program code for combining the components in accordance with claim **6** and program code for providing a combined output to be supplied to a test subject as a stimuli.

[0028] Preferably the program comprises code for giving the individual pure tone a phase (i.e. time-lag), that compensates for the corresponding cochlear delay or any other phase or temporal deviations in the stimulus system, the recording system and/or in the auditory pathway. Hereby the response from the test subject is enhanced.

[0029] The program is preferably stored on a readable storage media, such as a diskette, a CD-ROM, a DVD, a disk drive, a flash memory or a similar memory.

[0030] The invention will be described in more detail in the following description of preferred embodiments, with reference to the drawings.

DESCRIPTION OF THE DRAWINGS

[0031] FIG. **1** Shows an example with five pure tones having the frequencies 800, 900, 1000, 1100 and 1200 Hz. The frequency difference is 100 Hz and each frequency corresponds to an integer multiple of this difference. The tones with the lowest and highest frequency have half the amplitude than that of the other three pure tones and all the pure tones (sinusoidal waveforms) have the same starting phase.

[0032] FIG. **2** Shows the pure tones in FIG. **1** plotted on top of each other and demonstrates that with a repetition frequency that corresponds to the frequency difference, f_s=100 Hz, all five pure tones become in-phase (viz. every 10 ms).

[0033] FIG. **3** Shows the final stimulus comprised by the pure tones in FIG. **1**. The final stimulus is here the average of the five pure tones.

[0034] FIG. 4 Shows a model of the Cochlear delay based on data from de Boer (1980) and Greenwood (1990).

[0035] FIG. 5 Shows an example with seven pure tones having the frequencies 200, 300, 400, 500, 600, 700 and 800 Hz. The tones with the lowest and highest frequency have half the amplitude than that of the other five pure tones and all pure tones (sinusoidal waveforms) have a time-lag, which compensates for its cochlear delay according to the data in FIG. 4 relative to the delay at 100 Hz.

[0036] FIG. 6 Shows the pure tones in FIG. 5 plotted on top of each other.

[0037] FIG. 7 Shows the final stimulus comprised by the pure tones in FIG. 5. The final stimulus is here the average of the seven pure tones. Due to the introduced time-lag the resulting 'time-pulse' now appears with a left-right asymmetry.

[0038] FIG. 8 Shows an example with six pure tones having the frequencies 250, 350, 450, 550, 650 and 750 Hz. The frequency difference is 100 Hz and each frequency corresponds to a half-integer multiple of this difference. The tones with the lowest and highest frequency have half the amplitude than that of the other four pure tones and all the pure tones (sinusoidal waveforms) have the same starting phase.

[0039] FIG. 9 Shows the pure tones in FIG. 8 plotted on top of each other.

[0040] FIG. 10 Shows the final stimulus comprised by the pure tones in FIG. 8. The final stimulus is here the average of the six pure tones. Since the frequencies are located at half-integer multiples of the frequency difference, f_s, the final stimulus demonstrates polarity-inversion from period to period.

DESCRIPTION OF PREFERRED EMBODIMENTS

[0041] As an example, such a stimulus could be generated by five pure tones with the frequencies corresponding to 800, 900, 1000, 1100 and 1200 Hz. In this example, the tones with the lowest and highest frequency have half the amplitude than that of the other three tones and all tones (sinusoidal waveforms) have the same starting phase. The corresponding five pure tones are shown in FIG. 1. In this example the frequency difference between the pure tones is constant (=100 Hz) and the central spectral component has a frequency (=1000 Hz) that is an integer of the frequency difference (=10*100 Hz). The five pure tones are plotted on top of each other in FIG. 2, and the figure demonstrates that with a repetition frequency that corresponds to the frequency difference (viz. 100 Hz) all five pure tones become in-phase (viz. every 10 ms). This repetition frequency is some times referred to as the 'beat'-frequency. The final stimulus—which is the sum (or the mean) of the five pure tones—is plotted in FIG. 3, and has some similarities to a carrier frequency that is modulated by a complex window function.

[0042] With a classical amplitude modulation approach the periodicity of the final stimulus waveform is defined by the characteristics of the modulation signal. Contrary to this, the periodicity of the final stimulus waveform that is designed via the spectral approach (or the summation approach) would be given—as a first order approximation—by the spacing between the individual frequency components. For example, if the stimulus consists of n spectral components (n=three or more, uneven numbers) with a spacing of f. [Hz], then the frequency area that is covered by the stimulus would correspond to $(n-1)*f_s$ [Hz] placed around the central spectral component, and the temporal periodicity would correspond to $t_s=1/f_s$ [s]. It can further be demonstrated that the temporal envelope of the final stimulus corresponds to a window function with a complexity, which depends on the exact parameter values (the number, frequencies, amplitudes and phases). Such a window function could for instance be described as a special Blackman-Harris window (Harris, 1978).

[0043] With a stimulus designed through the spectral domain approach, each individual spectral components of the ASSR-stimulus could be given a time alignment (or phase adjustment) that compensates for the corresponding cochlear delay. This would result in a stimulus, which would produce larger response amplitudes than those obtained with a corresponding stimulus without such compensation. Preliminary test results have in fact been able to demonstrate this.

[0044] As an example, such a stimulus could be generated by seven pure tones with the frequencies corresponding to 200, 300, 400, 500, 600, 700 and 800 Hz. In this example, the tones with the lowest and highest frequency have half the amplitude than that of the other five tones and each pure tone is given a time-lag which compensates for its cochlear delay. This delay can be estimated from a cochlear model—for instance as the one shown in FIG. 4 that is based on de Boer (1980) and Greenwood (1990). The time-lagged pure tones are shown in FIG. 5, and are plotted on top of each other in FIG. 6. The final stimulus—which is the sum (or the mean) of the five pure tones—is plotted in FIG. 7. Due to the introduced time-lag the resulting 'time-pulse' now appears with a left-right asymmetry.

[0045] By the spectral design approach (or summation approach) some response-artifact problems can be avoided especially for low frequency stimuli. This is obtained by allowing the individual pure tones to be located at frequencies that not are integer values of the constant frequency difference between the different spectral components.

[0046] Following the example in FIG. 1, such a stimulus could for instance be generated by six pure tones with equal amplitude and phase and with the frequencies corresponding to 250, 350, 450, 550, 650 and 750 Hz. The tones with the lowest and highest frequency have half the amplitude than that of the other four tones and all tones (sinusoidal waveforms) have the same starting phase as shown in FIG. 8. As before, the frequency difference between the pure tones is constant (=100 Hz) but now the spectral components have frequencies that do not correspond to integer multiples of the frequency difference. The six pure tones are plotted on top of each other in FIG. 9 and the figure demonstrates—as before—that with a repetition frequency that corresponds to the frequency difference (viz. 100 Hz~10 ms) all six pure tones appear in-phase. The final stimulus is plotted in FIG. 10, and because the pure tones in this example are located half-way between integer values of the frequency difference, the temporal waveform demonstrates polarity-inversion from period to period. This corresponds to the polarity change of brief stimuli that was mentioned previously. If the frequencies of the pure tones were not exactly located half-way between the integer values of the frequency difference, the temporal waveform of the resulting stimulus would have the same envelope but a rolling phase from period to period. In any case, the spectrum of the final stimulus will only have components at the used pure tone frequencies and therefore, will not share any frequency bins with the evoked response.

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1. A method to design and generate frequency-specific electrical or acoustical stimuli for the recording of auditory steady-state responses, ASSR, from human individuals, comprising the step of generating the stimuli a combination of a series of three or more spectral components (i.e. pure tones), each having a specified frequency, amplitude and phase.

2. A method according to claim 1, wherein the frequency difference between the successive pure tones in the series is constant=fs.

3. A method according to claim 1, where the individual pure tone has a frequency that is an integer multiple of the frequency difference, fs.

4. A method according to claim 1, where the individual pure tone has a frequency that corresponds to a half-integer multiple of the frequency difference, fs.

5. A method according to claim 1, where the individual pure tone has a phase (i.e. time-lag), that compensates for the corresponding cochlear delay or any other phase or temporal deviations in the stimulus system, the recording system and/or in the auditory pathway.

6. A method according to any claim 1, where the combination is formed as the sum, the average or the like of the three or more spectral components.

7. A method according to claim 1, where the electrical or acoustical stimuli is generated in software or in hardware.

8. A device for detecting ASSR comprising means for generating stimuli in accordance with claim 1, means for providing the stimuli to a test subject and means for detecting responses to the stimuli from the test subject.

9. A device according to claim 8, comprising a software program for providing the stimuli.

10. A software program for a device according to claim 9, the program comprising program code for providing a combined output to be supplied to a test subject as a stimuli.

11. A software program according to claim 10, comprising code for giving the individual pure tone has a phase (i.e. time-lag), that compensates for the corresponding cochlear delay or any other phase or temporal deviations in the stimulus system, the recording system and/or in the auditory pathway.

12. A software program according to claim 10, where the program is stored on a media, such as a diskette, a CD-ROM, a DVD, a disk drive, a flash memory or a similar memory. duct.

* * * * *