US008194864B2

(12) **United States Patent**
Goldstein et al.

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(45) **Date of Patent: Jun. 5, 2012**

(54) **EARHEALTH MONITORING SYSTEM AND METHOD I**

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(73) Assignee: **Personics Holdings Inc.**, Boca Raton, FL (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 1174 days.

(21) Appl. No.: **11/928,290**

(22) Filed: **Oct. 30, 2007**

(65) **Prior Publication Data**

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Related U.S. Application Data

(63) Continuation-in-part of application No. 11/757,152, filed on Jun. 1, 2007.

(60) Provisional application No. 60/803,708, filed on Jun. 1, 2006.

(51) **Int. Cl.**
H04R 29/00 (2006.01)
A61F 11/06 (2006.01)
A61B 5/12 (2006.01)

(52) **U.S. Cl.** **381/56**; 381/58; 381/72; 73/585

(58) **Field of Classification Search** 381/56–60, 381/72; 600/25; 73/585, 645, 646
See application file for complete search history.

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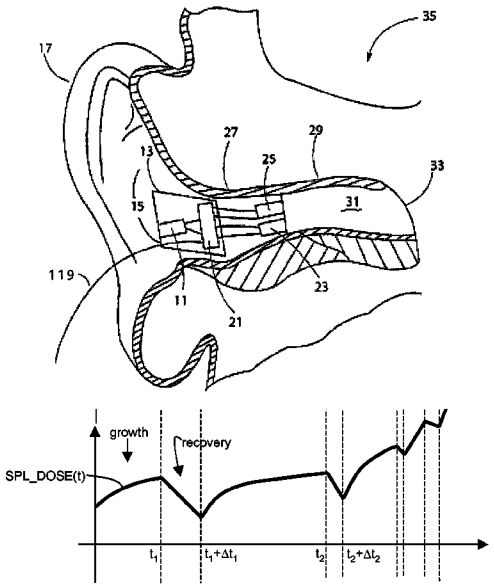
Primary Examiner — Jesse Elbin
(74) *Attorney, Agent, or Firm* — RatnerPrestia

(57) **ABSTRACT**

Methods of operating an audio device are provided. A method includes calculating estimated sound pressure levels (SPLs) for drive signals directed to an ear canal receiver (ECR) during a time increment Δt; calculating an estimated SPL_Dose during the time increment Δt using the estimated sound pressure levels; and calculating a total SPL_Dose at a time t of the audio device using the estimated SPL_Dose.

5 Claims, 22 Drawing Sheets



Samsung v. Zophonos
IPR2026-00085
Exhibit 1010

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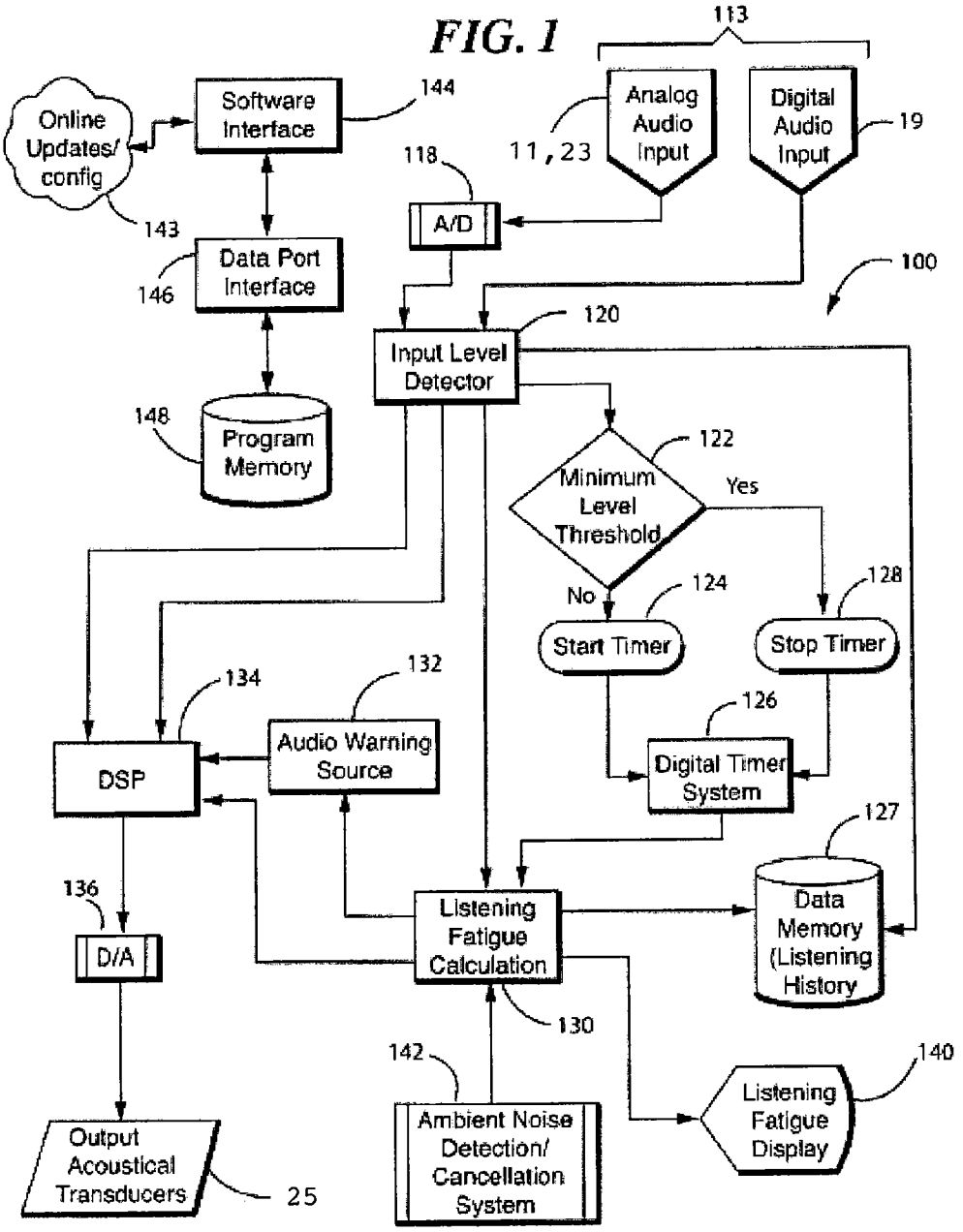


FIG. 1
113
Online Updates/ config
Software Interface
144
Analog Audio Input
11,23
Digital Audio Input
19
118
A/D
143
Data Port Interface
146
100
120
Input Level Detector
148
Program Memory
122
Minimum Level Threshold
Yes
No
124
128
Start Timer
Stop Timer
134
132
126
DSP
Audio Warning Source
Digital Timer System
127
136
Listening Fatigue Calculation
Data Memory (Listening History
D/A
130
142
140
Ambient Noise Detection/ Cancellation System
Listening Fatigue Display
Output Acoustical Transducers
25

FIG. 2

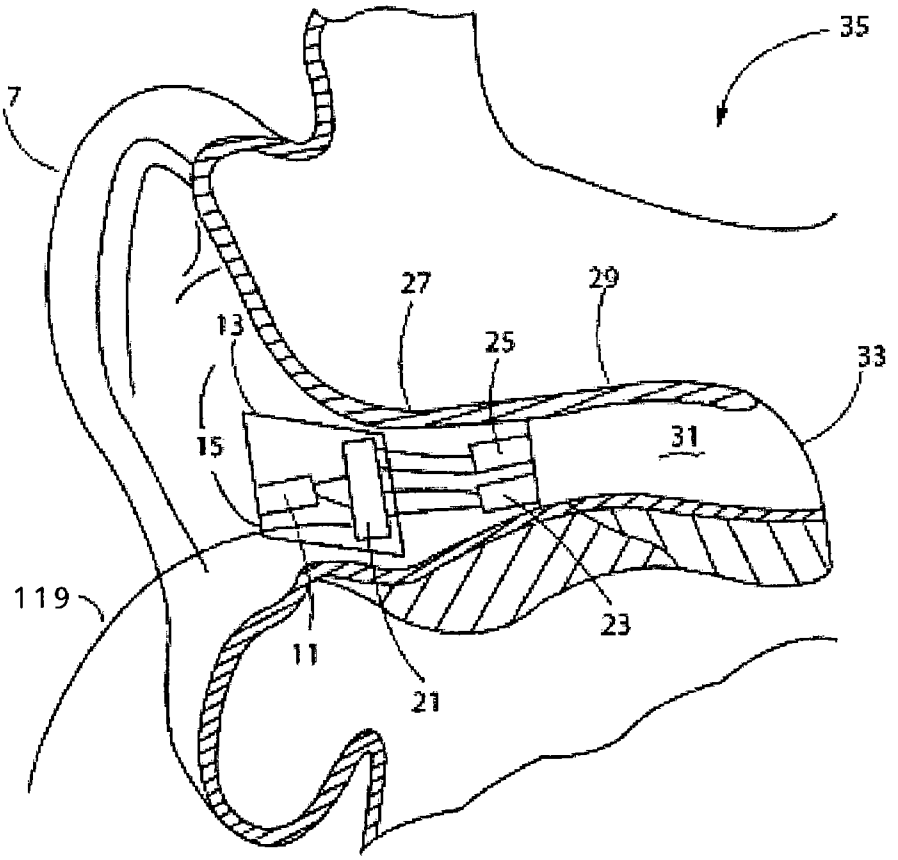


FIG. 3

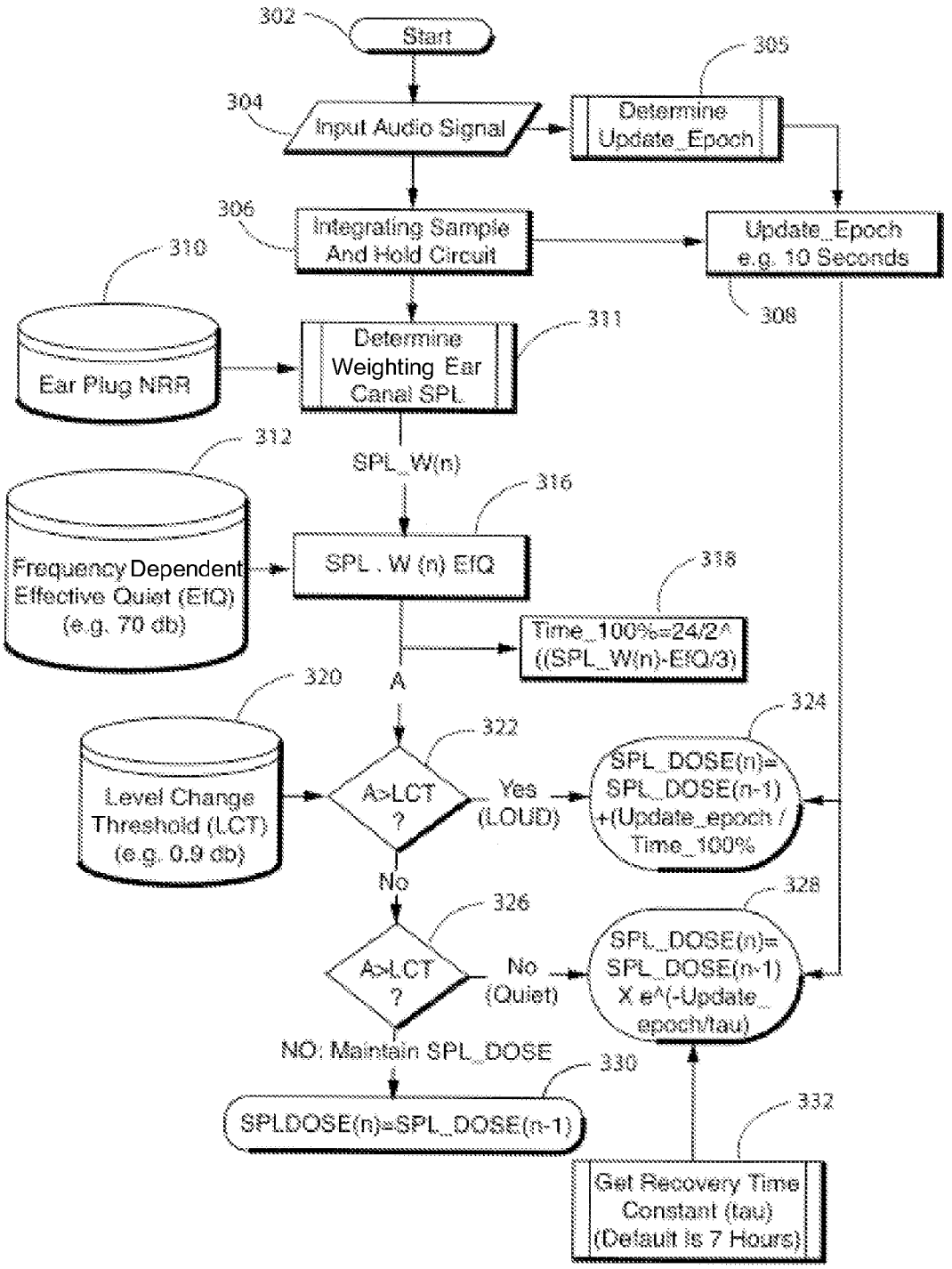

302
Start
304
Input Audio Signal
305
Determine Update_Epoch
306
Integrating Sample And Hold Circuit
Update_Epoch e.g. 10 Seconds
308
310
Ear Plug NRR
Determine Weighting Ear Canal SPL
311
312
SPL_W(n)
316
Frequency Dependent Effective Quiet (EfQ) (e.g. 70 db)
SPL . W (n) EfQ
318
Time_100%=24/2^((SPL_W(n)-EfQ/3)
A
320
322
Level Change Threshold (LCT) (e.g. 0.9 db)
A>LCT ?
Yes (LOUD)
324
SPL_DOSE(n)= SPL_DOSE(n-1) +(Update_epoch / Time_100%
No
326
328
A>LCT ?
No (Quiet)
SPL_DOSE(n)= SPL_DOSE(n-1) X e^(-Update_epoch/tau)
NO: Maintain SPL_DOSE
330
SPLDOSE(n)=SPL_DOSE(n-1)
332
Get Recovery Time Constant (tau) (Default is 7 Hours)

FIG. 4

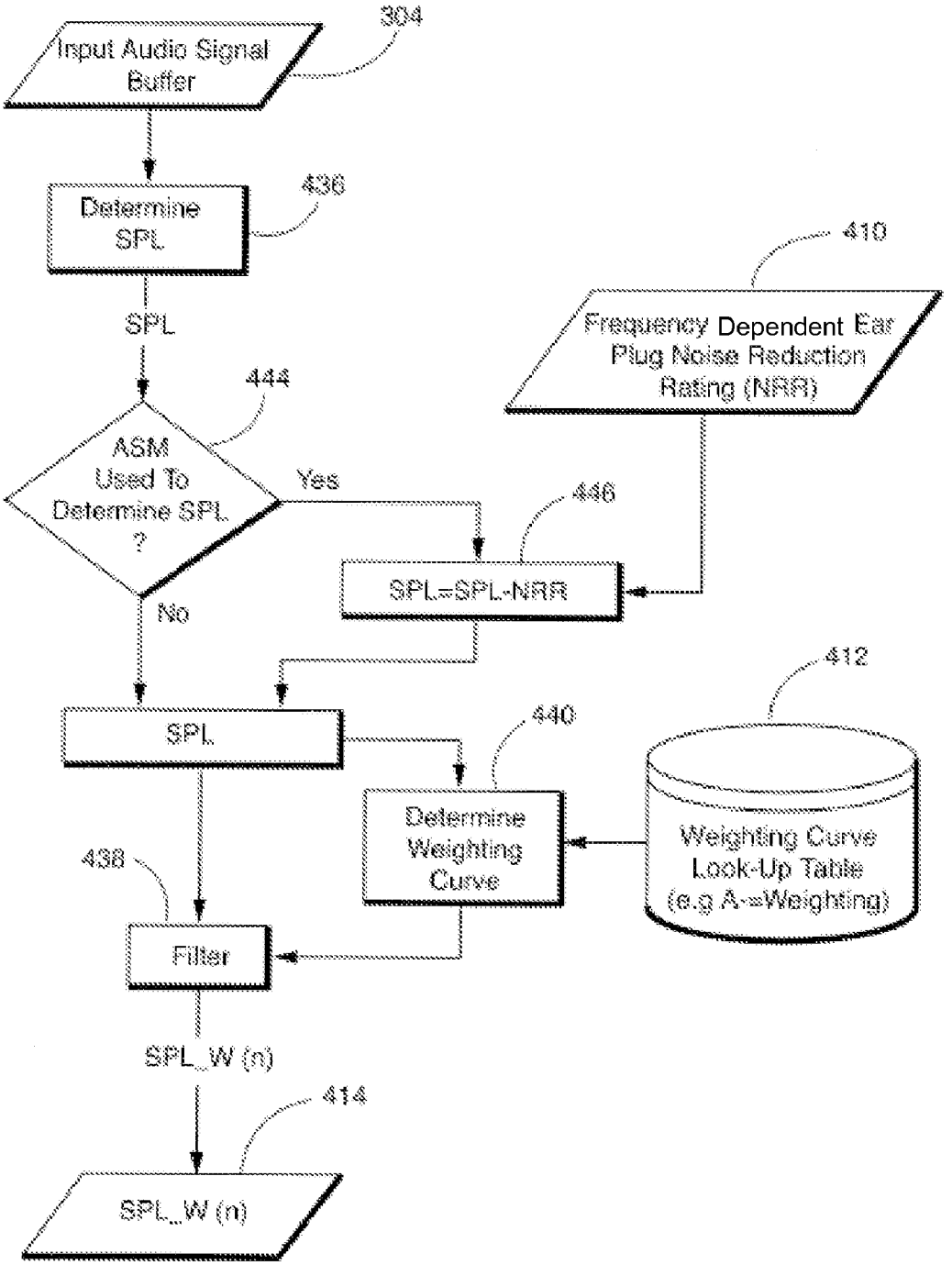

304
Input Audio Signal Buffer
436
Determine SPL
SPL
410
Frequency Dependent Ear Plug Noise Reduction Rating (NRR)
444
ASM Used To Determine SPL ?
Yes
446
SPL=SPL-NRR
No
412
SPL
440
Determine Weighting Curve
Weighting Curve Look-Up Table (e.g A-=Weighting)
438
Filter
SPL_W (n)
414
SPL_W (n)

FIG. 5

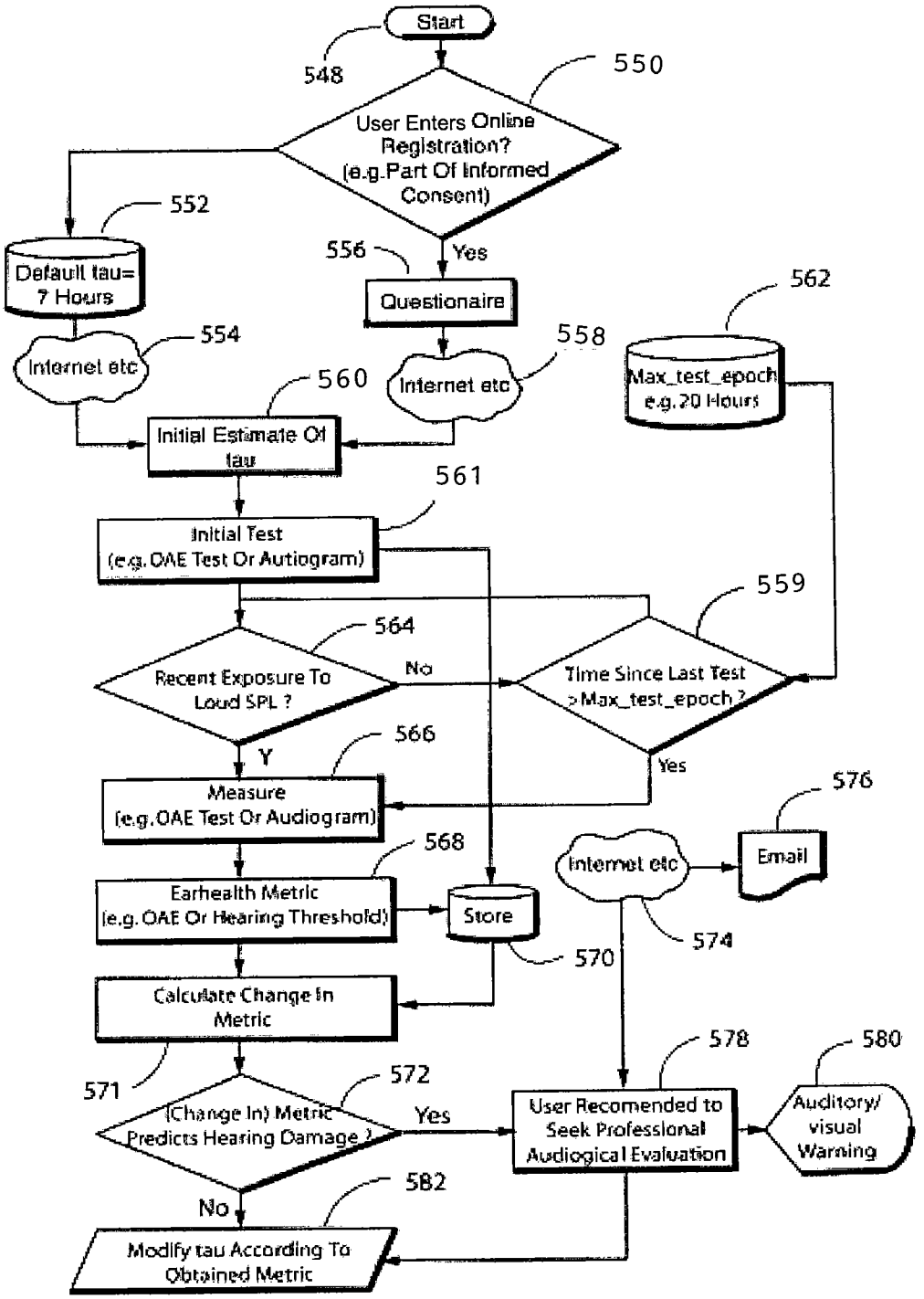

Start
548
550
User Enters Online Registration? (e.g.Part Of Informed Consent)
552
Default tau= 7 Hours
556
Yes
Questionaire
562
554
Internet etc
558
Internet etc
Max_test_epoch e.g.20 Hours
560
Initial Estimate Of tau
561
Initial Test (e.g.OAE Test Or Autiogram)
559
564
Recent Exposure To Loud SPL ?
No
Time Since Last Test >Max_test_epoch ?
Y
566
Yes
Measure (e.g.OAE Test Or Audiogram)
576
568
Internet etc
Email
Earhealth Metric (e.g.OAE Or Hearing Threshold)
Store
574
570
Calculate Change In Metric
578
580
571
572
(Change In) Metric Predicts Hearing Damage ?
Yes
User Recomended to Seek Professional Audiogical Evaluation
Auditory/ visual Warning
582
No
Modify tau According To Obtained Metric

FIG. 6

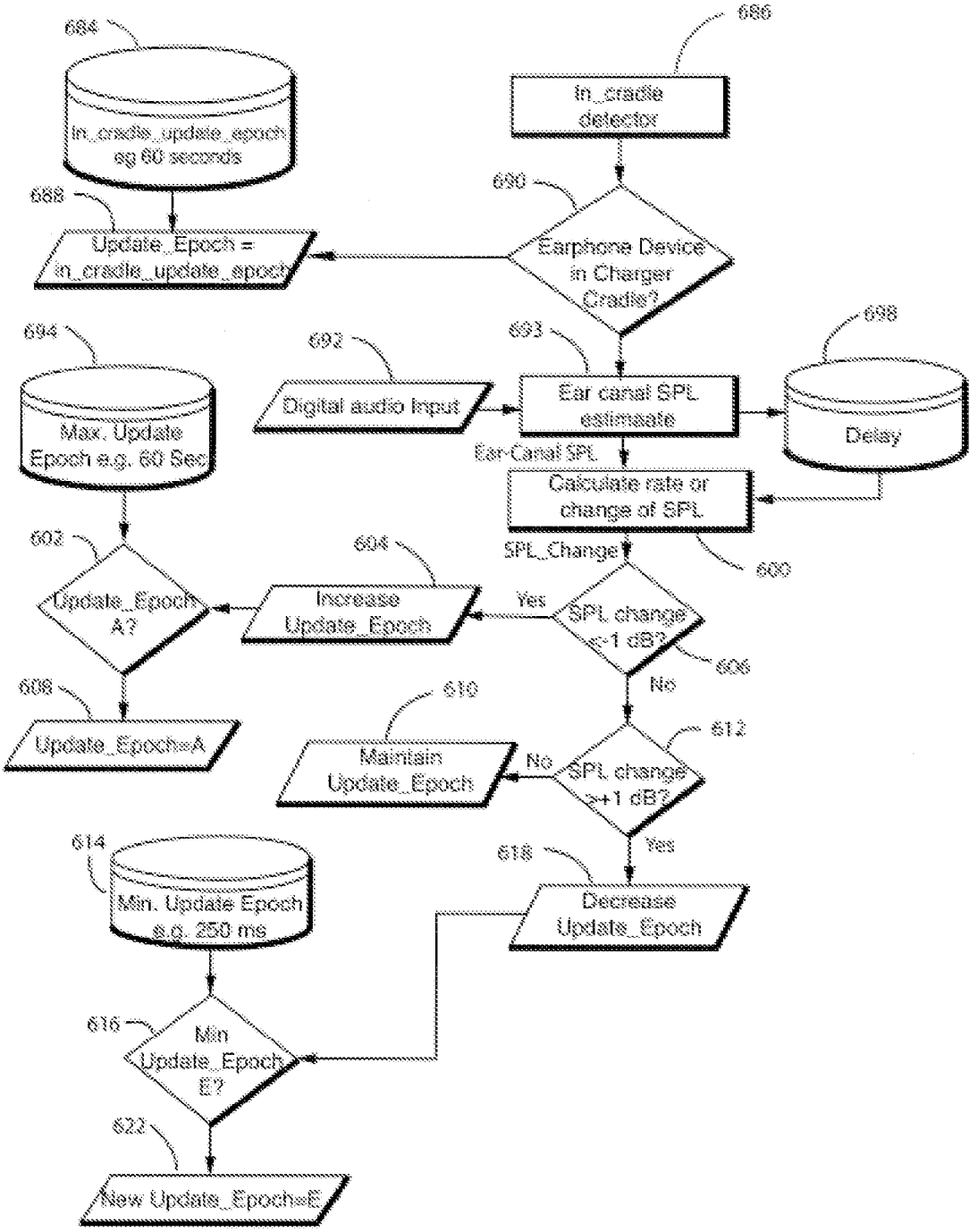
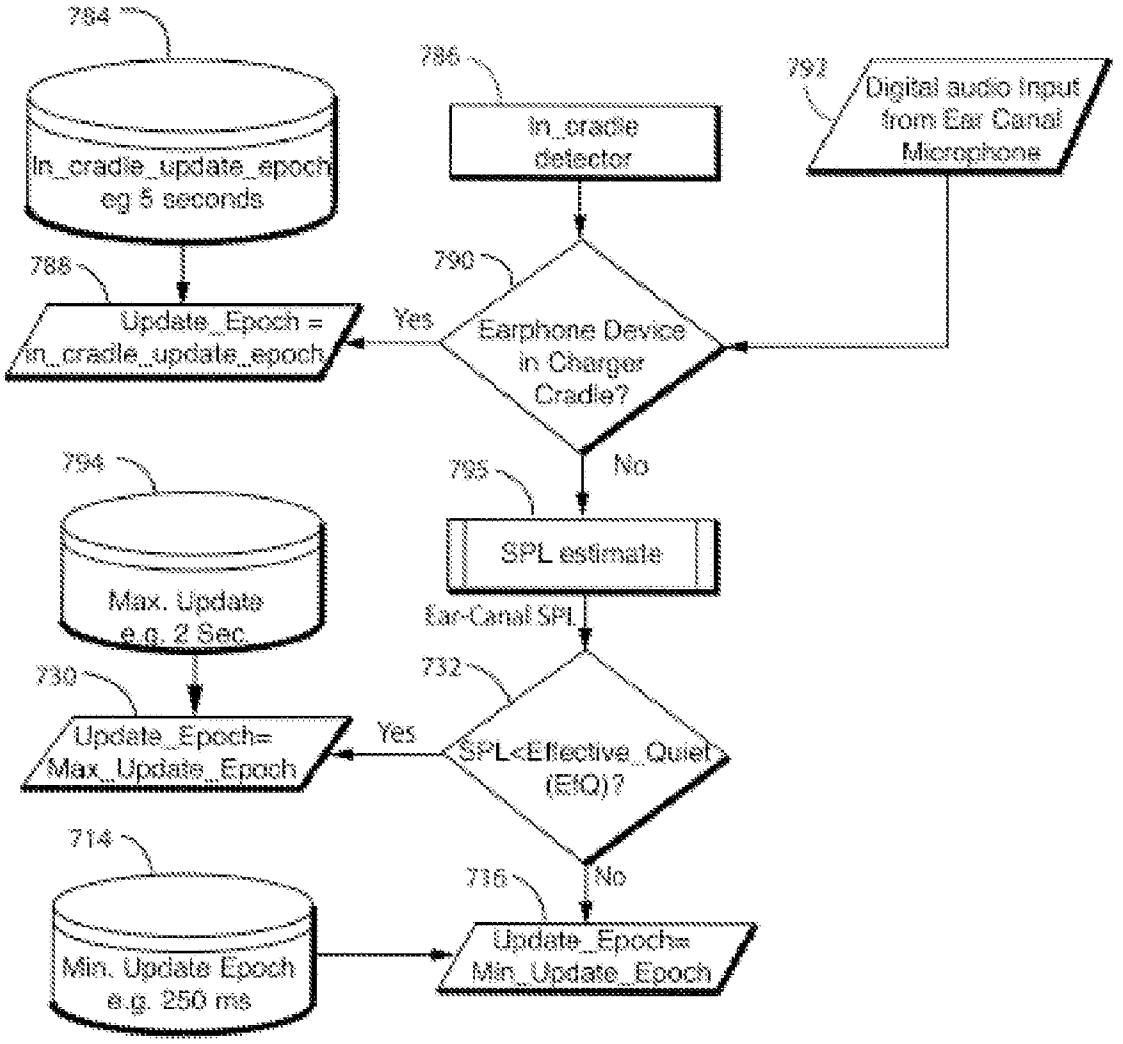

684
In_cradle_update_epoch
eg 60 seconds
686
In_cradle
detector
688
Update_Epoch =
in_cradle_update_epoch
690
Earphone Device
in Charger
Cradle?
694
Max. Update
Epoch e.g. 60 Sec
692
Digital audio Input
693
Ear canal SPL
estimaate
698
Delay
Ear-Canal SPL
Calculate rate or
change of SPL
SPL_Change
600
602
Update_Epoch
A?
604
Increase
Update_Epoch
Yes
SPL change
<-1 dB?
606
No
608
Update_Epoch=A
610
Maintain
Update_Epoch
No
612
SPL change
>+1 dB?
Yes
614
Min. Update Epoch
e.g. 250 ms
618
Decrease
Update_Epoch
616
Min
Update_Epoch
E?
622
New Update_Epoch=E

FIG. 7


784
In_cradle_update_epoch
eg 5 seconds
786
In_cradle
detector
792
Digital audio input
from Ear Canal
Microphone
788
Update_Epoch =
In_cradle_update_epoch
790
Earphone Device
in Charger
Cradle?
Yes
No
794
Max. Update
e.g. 2 Sec.
785
SPL estimate
Ear-Canal SPL
730
Update_Epoch=
Max_Update_Epoch
732
SPL<Effective_Quiet
(EIQ)?
Yes
No
714
Min. Update Epoch
e.g. 250 ms
716
Update_Epoch=
Min_Update_Epoch

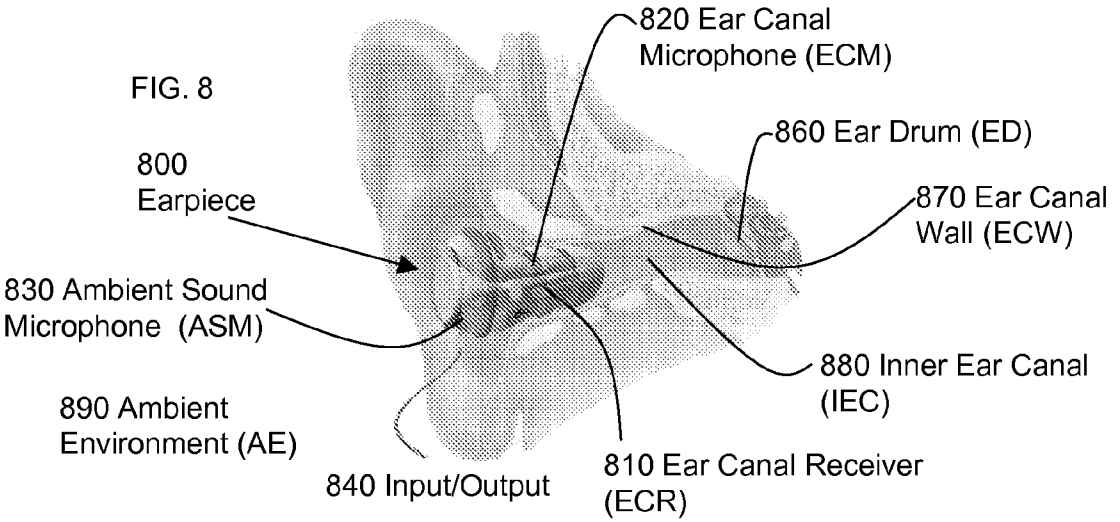


FIG. 8
800
Earpiece
820 Ear Canal
Microphone (ECM)
860 Ear Drum (ED)
870 Ear Canal
Wall (ECW)
830 Ambient Sound
Microphone (ASM)
880 Inner Ear Canal
(IEC)
890 Ambient
Environment (AE)
840 Input/Output
810 Ear Canal Receiver
(ECR)

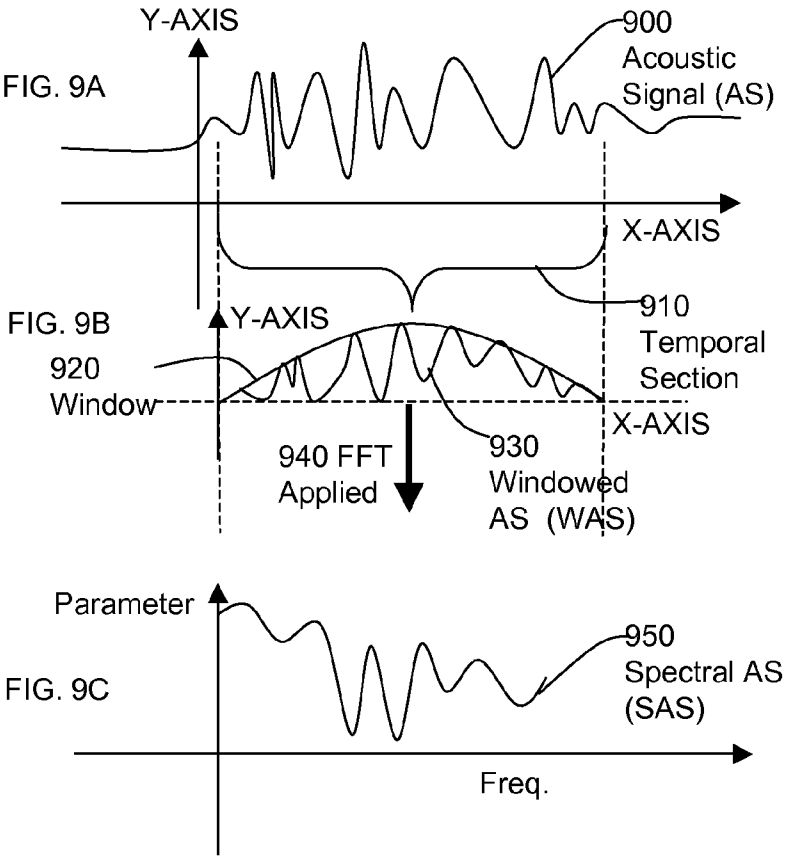

Y-AXIS
FIG. 9A
900
Acoustic
Signal (AS)
X-AXIS
910
Temporal
Section
FIG. 9B
Y-AXIS
920
Window
X-AXIS
940 FFT
Applied
930
Windowed
AS (WAS)
Parameter
FIG. 9C
950
Spectral AS
(SAS)
Freq.

FIG. 10

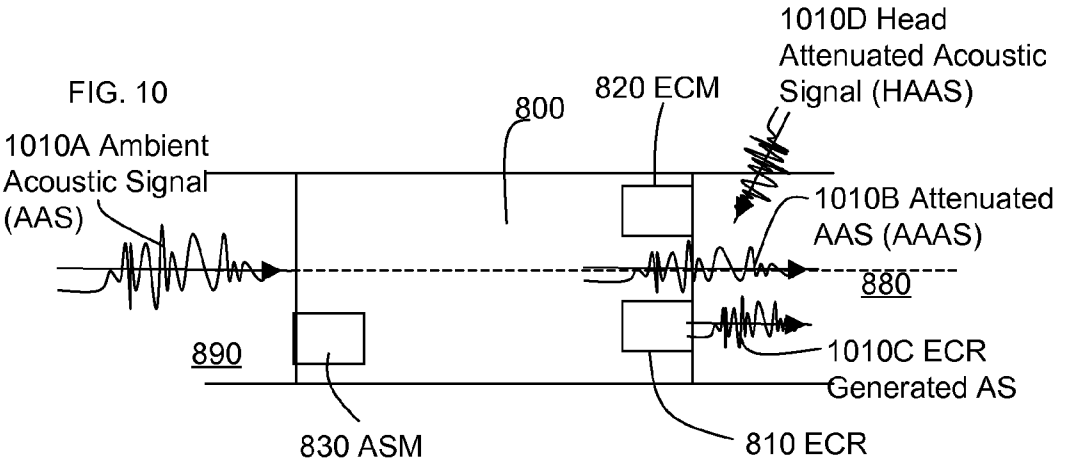

1010D Head
Attenuated Acoustic
Signal (HAAS)
820 ECM
800
1010A Ambient
Acoustic Signal
(AAS)
1010B Attenuated
AAS (AAAS)
880
890
1010C ECR
Generated AS
830 ASM
810 ECR

FIG. 11

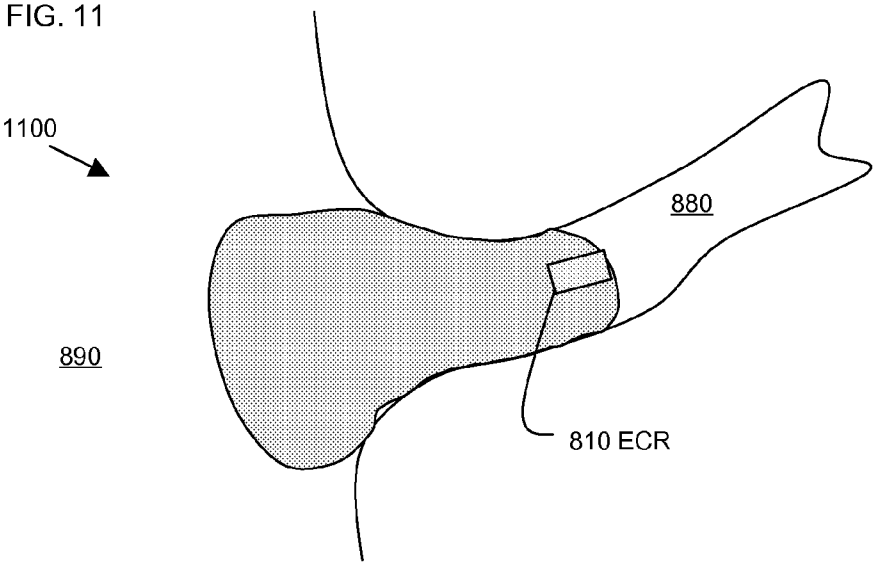

1100
880
890
810 ECR

FIG. 12

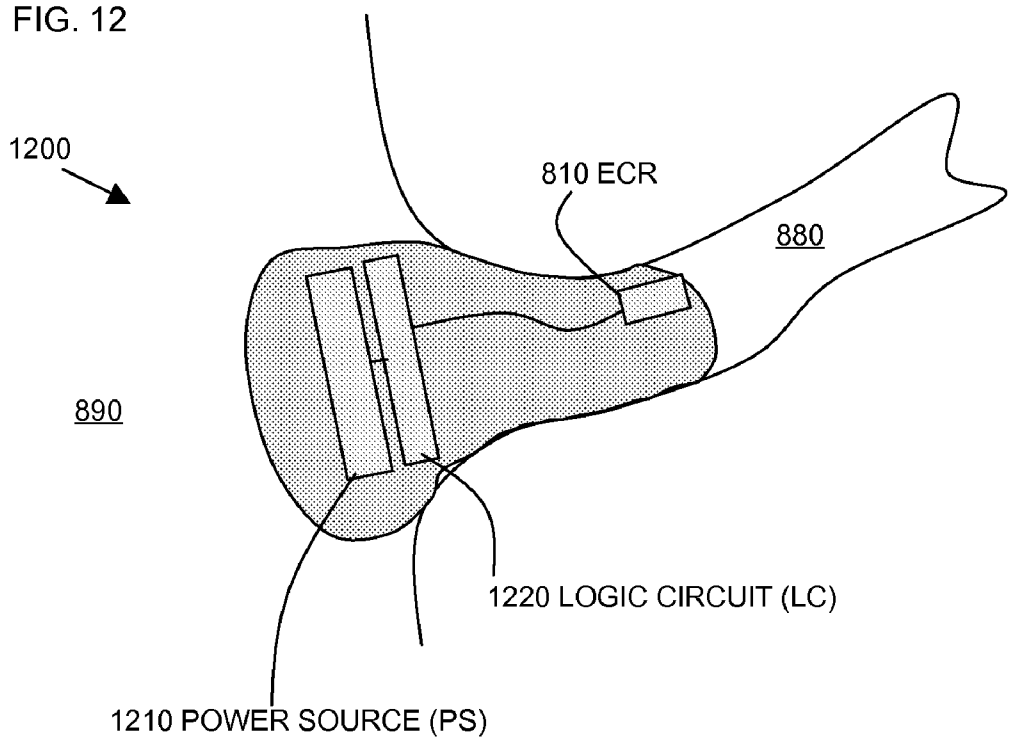

1200
810 ECR
880
890
1220 LOGIC CIRCUIT (LC)
1210 POWER SOURCE (PS)

FIG. 13

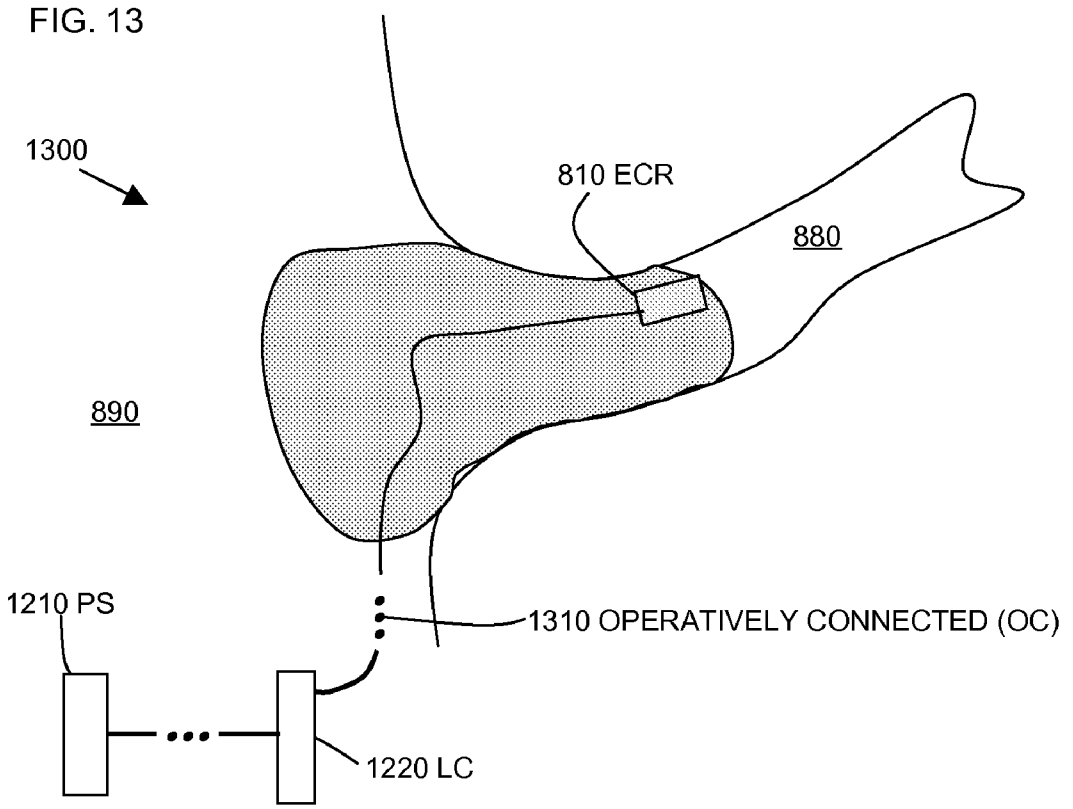

1300
810 ECR
880
890
1210 PS
1310 OPERATIVELY CONNECTED (OC)
1220 LC

FIG. 14A

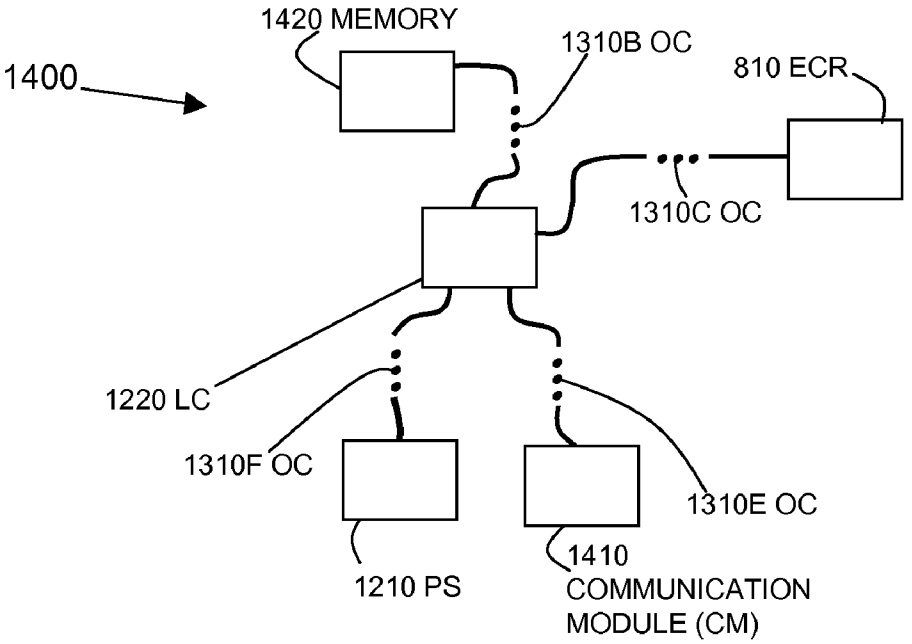


FIG. 14B

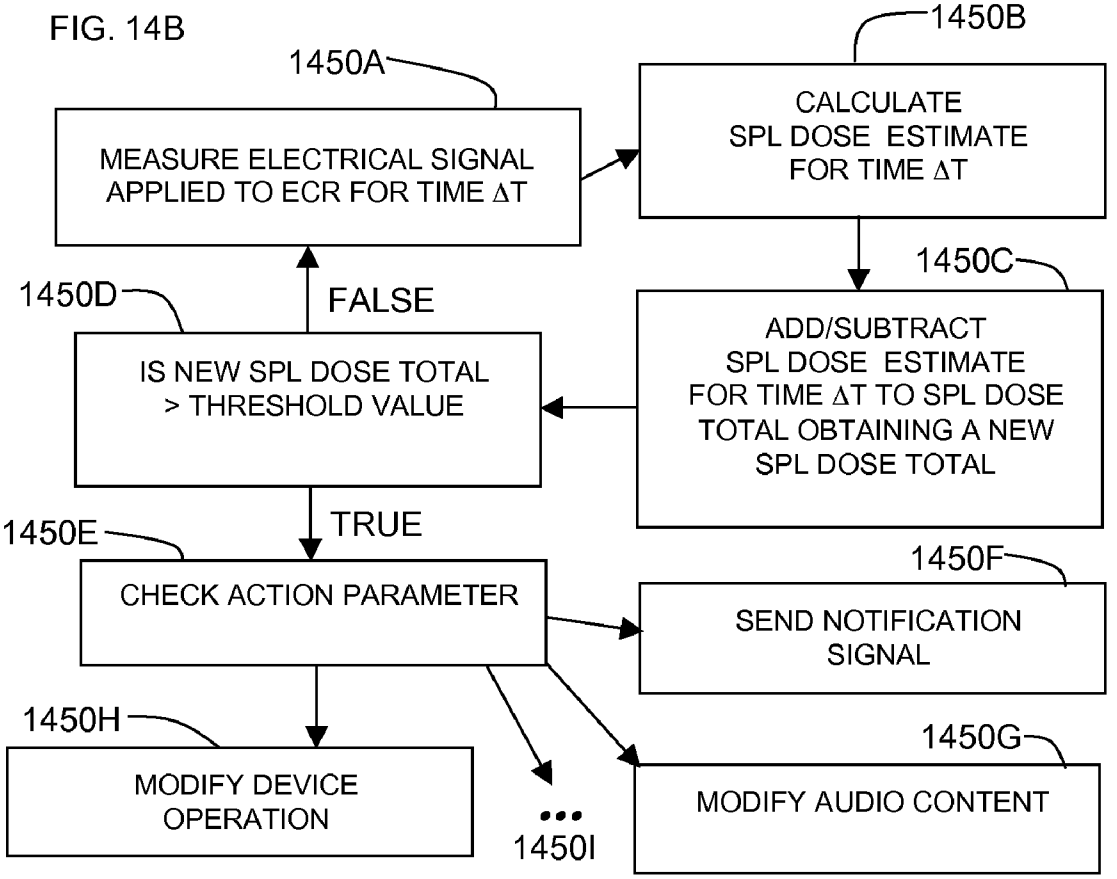


FIG. 14C

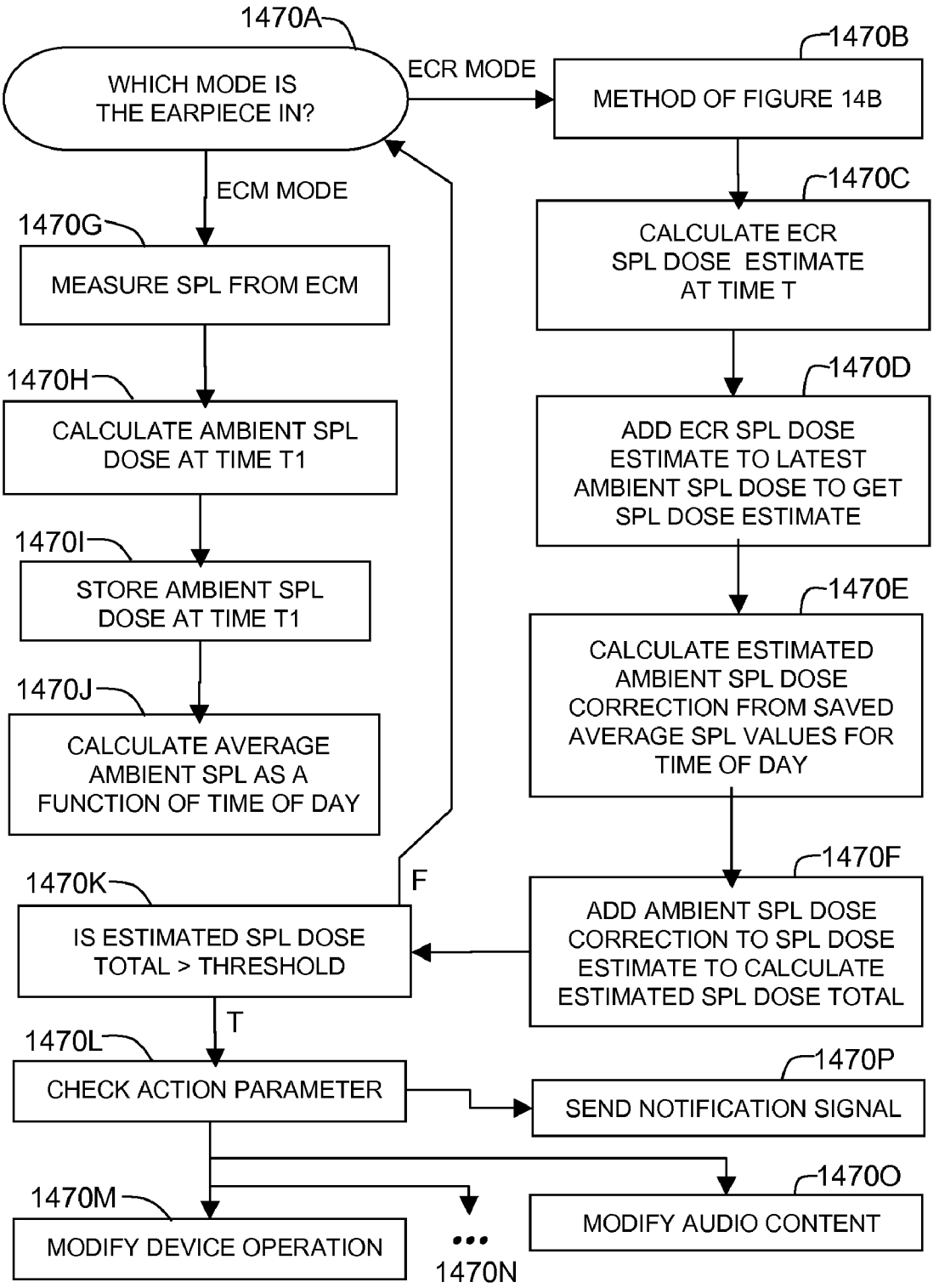
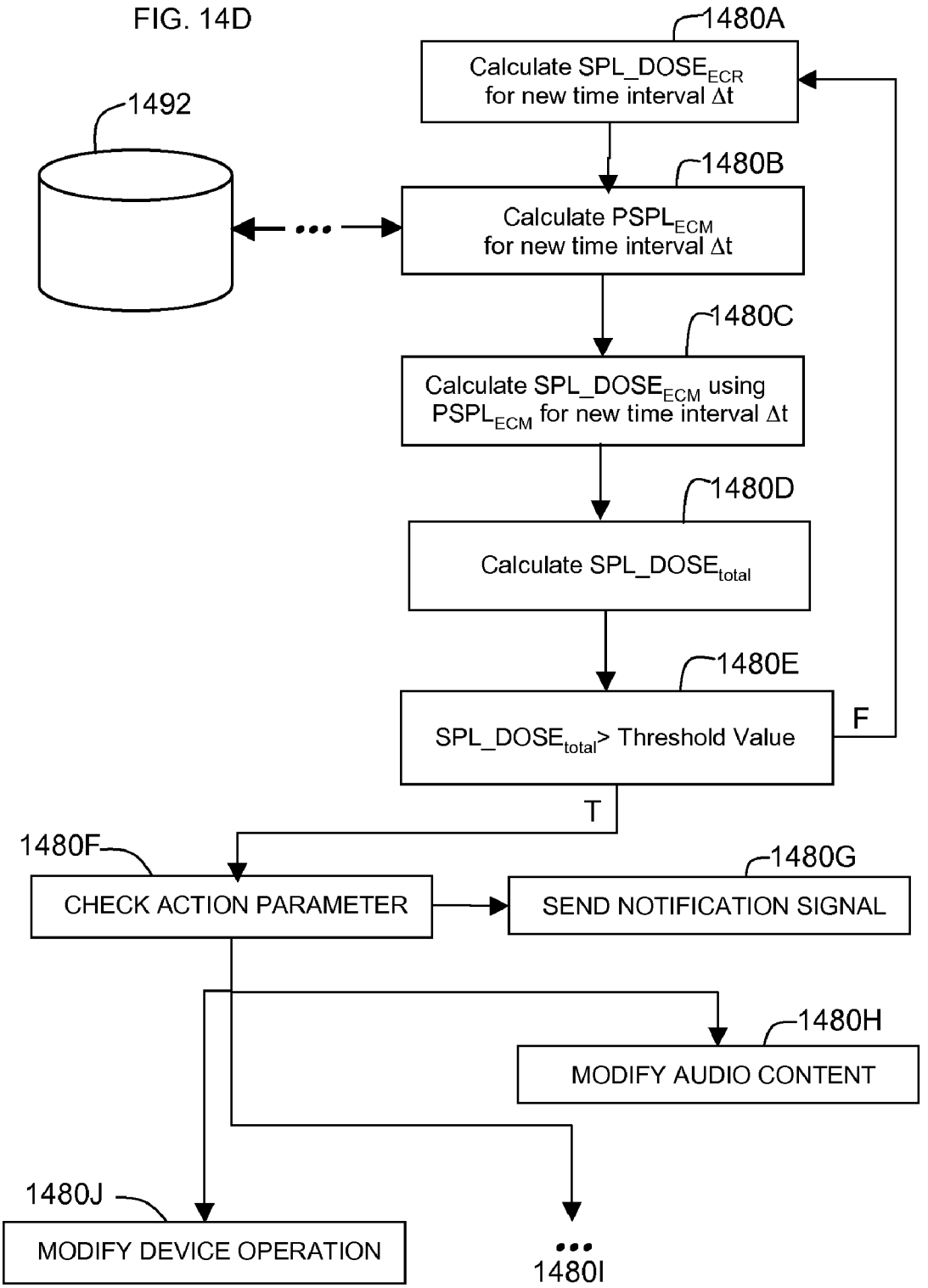

1470A
WHICH MODE IS THE EARPIECE IN?
ECR MODE
1470B
METHOD OF FIGURE 14B
ECM MODE
1470C
CALCULATE ECR SPL DOSE ESTIMATE AT TIME T
1470G
MEASURE SPL FROM ECM
1470D
ADD ECR SPL DOSE ESTIMATE TO LATEST AMBIENT SPL DOSE TO GET SPL DOSE ESTIMATE
1470H
CALCULATE AMBIENT SPL DOSE AT TIME T1
1470I
STORE AMBIENT SPL DOSE AT TIME T1
1470E
CALCULATE ESTIMATED AMBIENT SPL DOSE CORRECTION FROM SAVED AVERAGE SPL VALUES FOR TIME OF DAY
1470J
CALCULATE AVERAGE AMBIENT SPL AS A FUNCTION OF TIME OF DAY
1470F
ADD AMBIENT SPL DOSE CORRECTION TO SPL DOSE ESTIMATE TO CALCULATE ESTIMATED SPL DOSE TOTAL
1470K
F
IS ESTIMATED SPL DOSE TOTAL > THRESHOLD
T
1470L
CHECK ACTION PARAMETER
1470P
SEND NOTIFICATION SIGNAL
1470O
MODIFY AUDIO CONTENT
1470M
MODIFY DEVICE OPERATION
...
1470N

FIG. 14D


1480A
Calculate SPL_DOSE$_{ECR}$ for new time interval Δt
1492
1480B
Calculate PSPL$_{ECM}$ for new time interval Δt
1480C
Calculate SPL_DOSE$_{ECM}$ using PSPL$_{ECM}$ for new time interval Δt
1480D
Calculate SPL_DOSE$_{total}$
1480E
SPL_DOSE$_{total}$> Threshold Value
F
T
1480F
CHECK ACTION PARAMETER
1480G
SEND NOTIFICATION SIGNAL
1480H
MODIFY AUDIO CONTENT
1480J
MODIFY DEVICE OPERATION
1480I

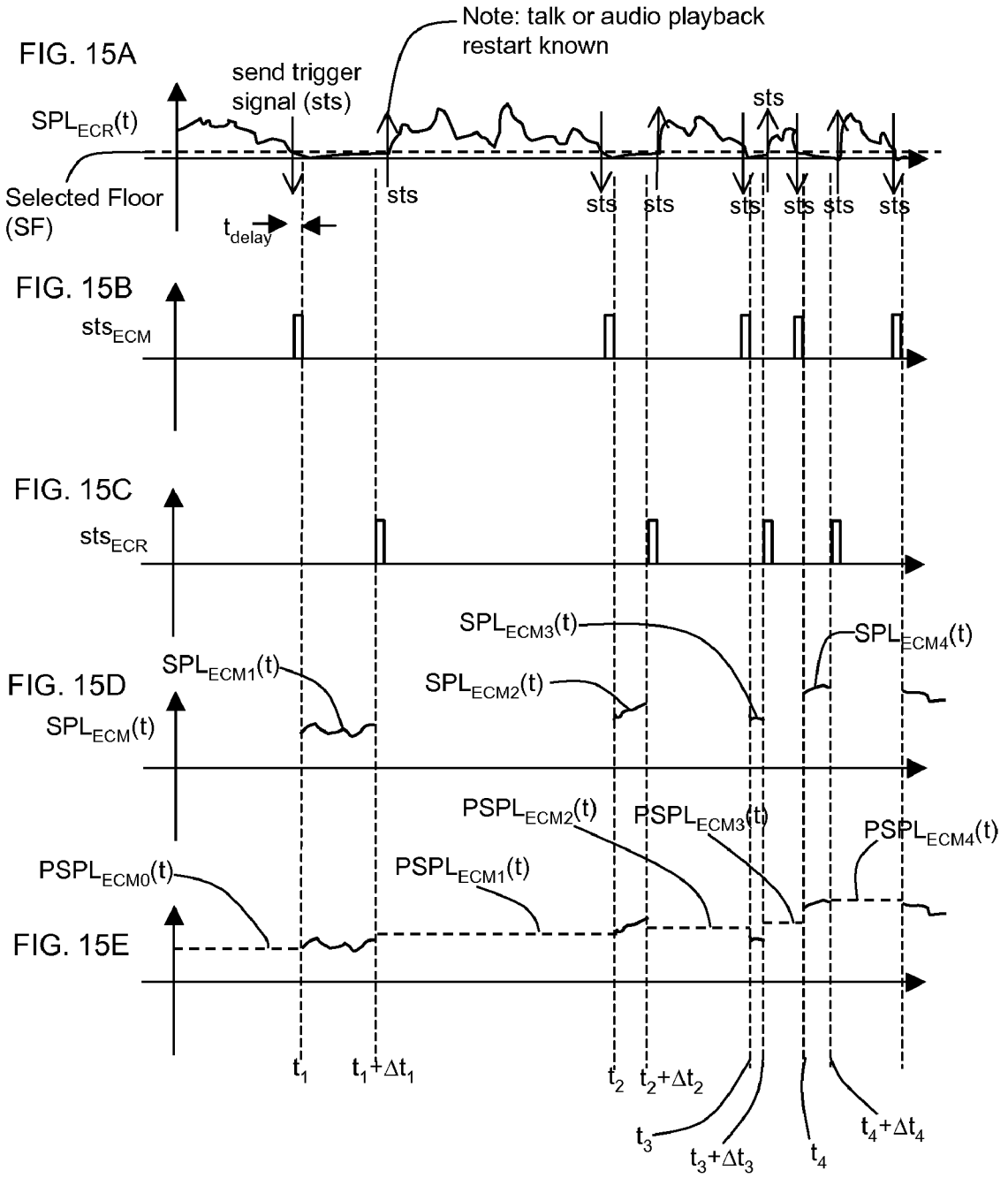
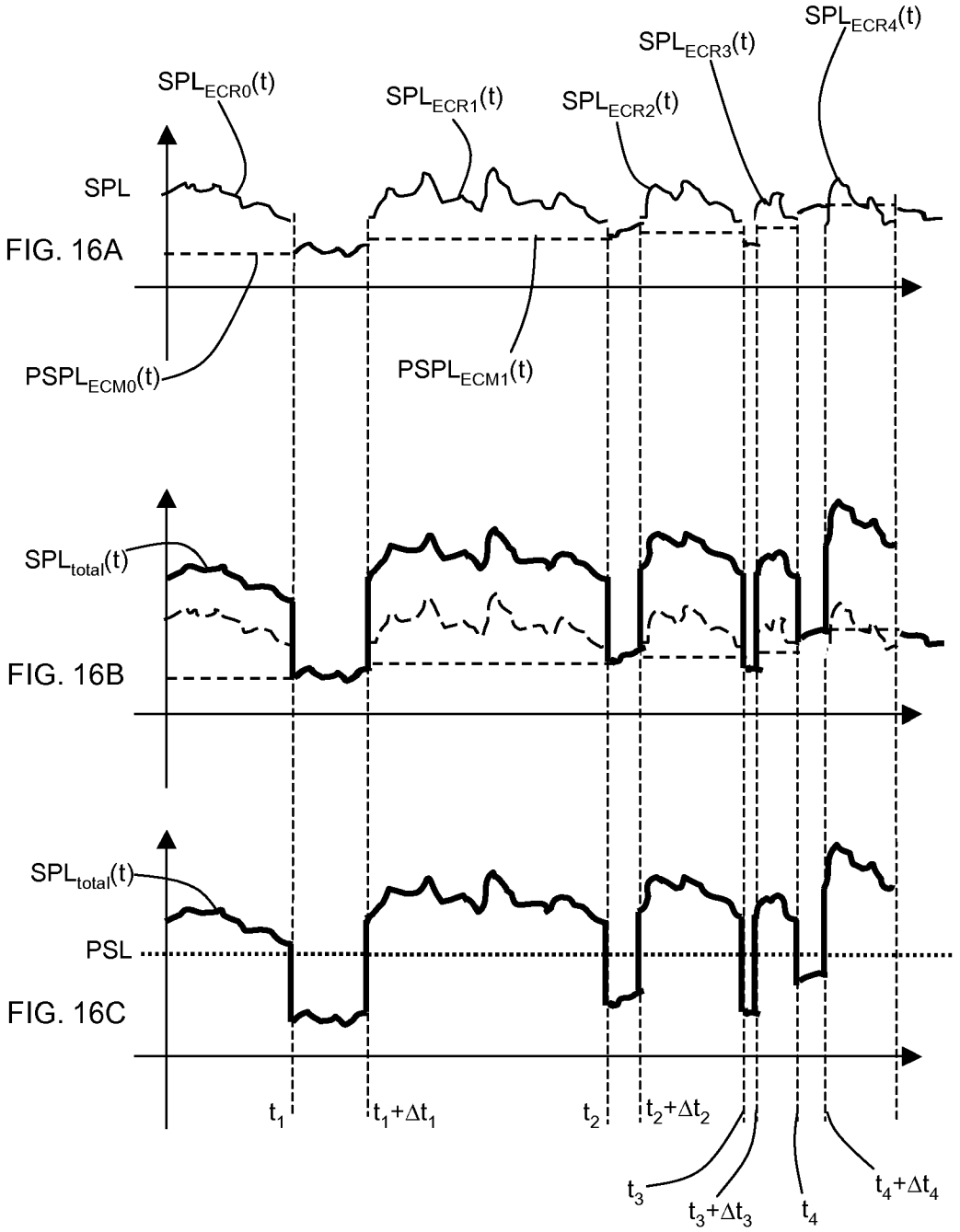


FIG. 15A
Note: talk or audio playback restart known
send trigger signal (sts)
$SPL_{ECR}(t)$
Selected Floor (SF)
t_{delay}
sts
FIG. 15B
sts_{ECM}
FIG. 15C
sts_{ECR}
FIG. 15D
$SPL_{ECM}(t)$
$SPL_{ECM1}(t)$
$SPL_{ECM2}(t)$
$SPL_{ECM3}(t)$
$SPL_{ECM4}(t)$
FIG. 15E
$PSPL_{ECM0}(t)$
$PSPL_{ECM1}(t)$
$PSPL_{ECM2}(t)$
$PSPL_{ECM3}(t)$
$PSPL_{ECM4}(t)$
t_1
$t_1+\Delta t_1$
t_2
$t_2+\Delta t_2$
t_3
$t_3+\Delta t_3$
t_4
$t_4+\Delta t_4$


SPL
FIG. 16A
$SPL_{ECR0}(t)$
$SPL_{ECR1}(t)$
$SPL_{ECR2}(t)$
$SPL_{ECR3}(t)$
$SPL_{ECR4}(t)$
$PSPL_{ECM0}(t)$
$PSPL_{ECM1}(t)$
$SPL_{total}(t)$
FIG. 16B
$SPL_{total}(t)$
PSL
FIG. 16C
t_1
$t_1+\Delta t_1$
t_2
$t_2+\Delta t_2$
t_3
$t_3+\Delta t_3$
t_4
$t_4+\Delta t_4$

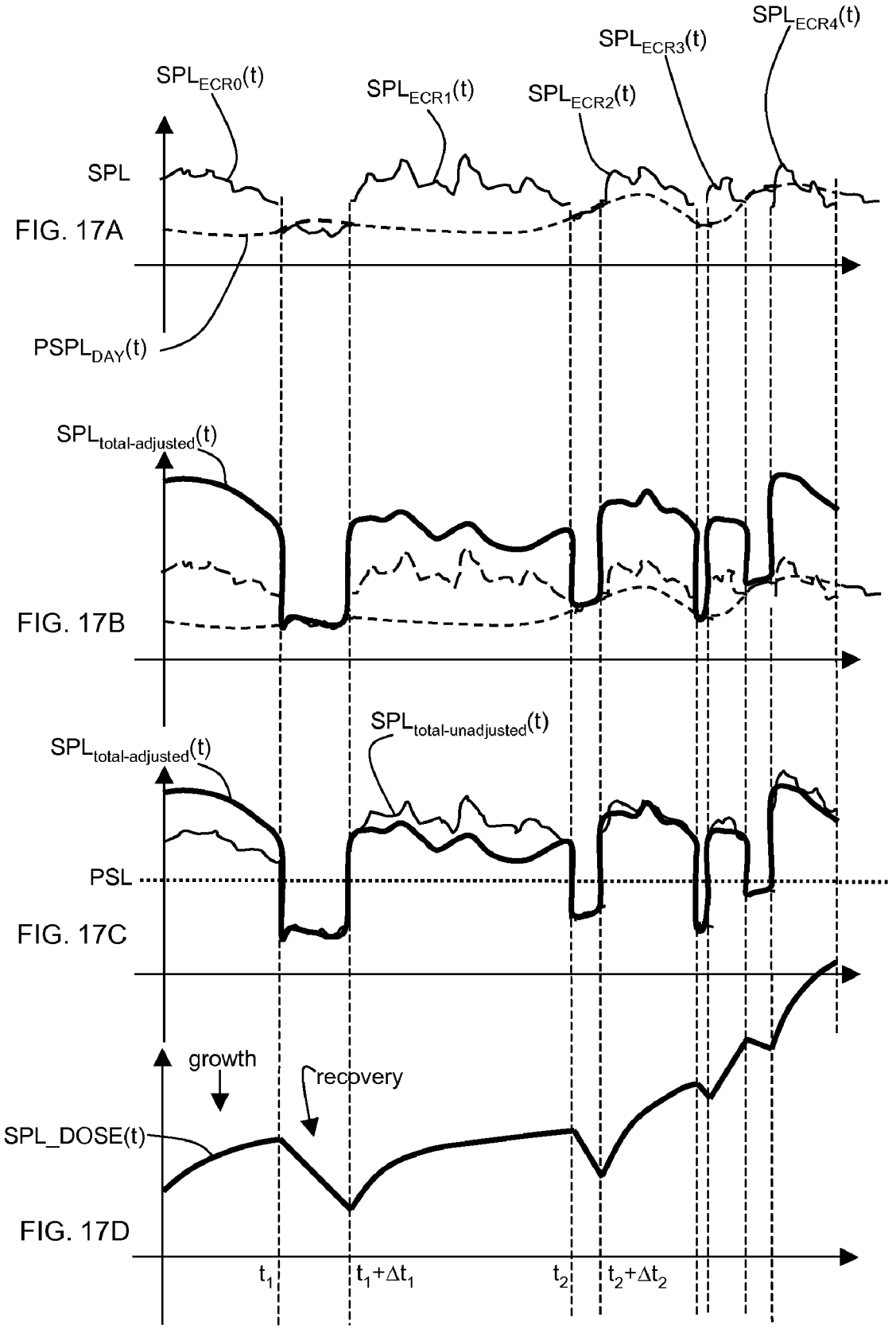

SPL_ECR0(t)
SPL_ECR1(t)
SPL_ECR2(t)
SPL_ECR3(t)
SPL_ECR4(t)
SPL
FIG. 17A
PSPL_DAY(t)
SPL_total-adjusted(t)
FIG. 17B
SPL_total-unadjusted(t)
SPL_total-adjusted(t)
PSL
FIG. 17C
growth
recovery
SPL_DOSE(t)
FIG. 17D
t1
t1+Δt1
t2
t2+Δt2

FIG. 18A

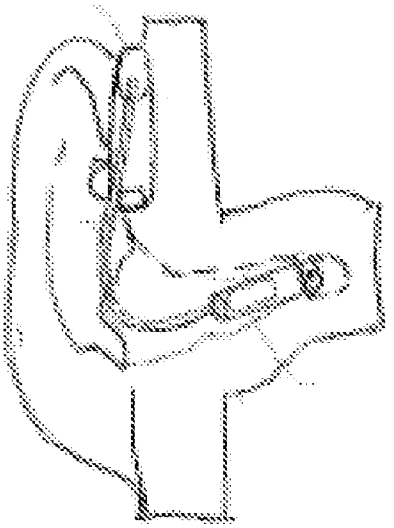


FIG. 18B

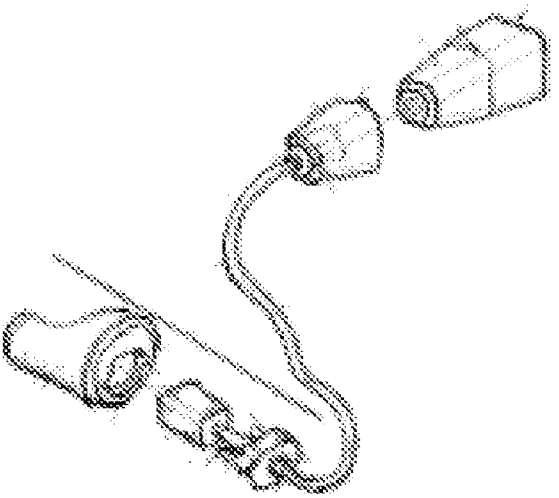


FIG. 18C

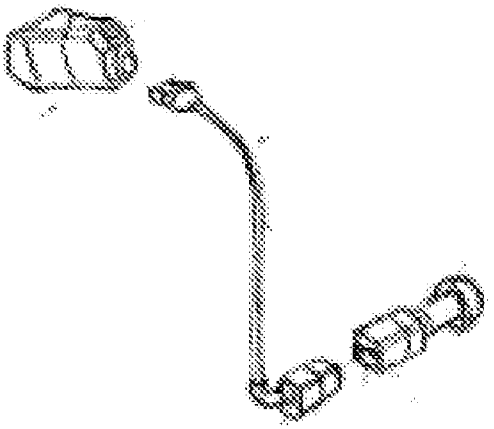


FIG. 18D

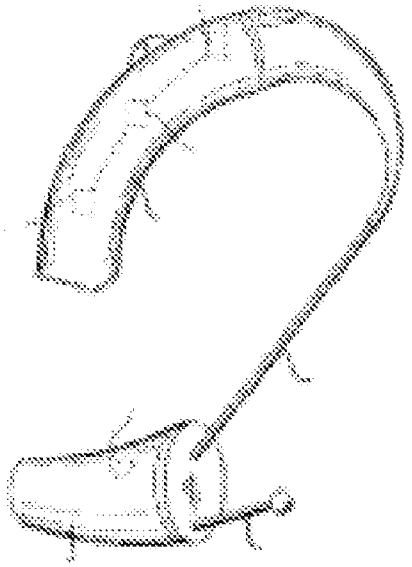


FIG. 18E

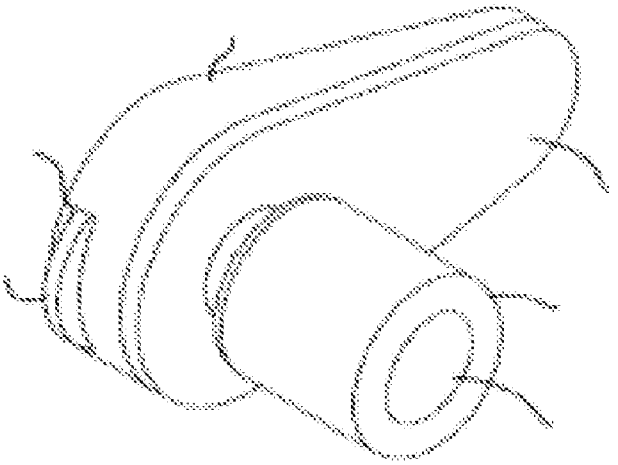


FIG. 18F

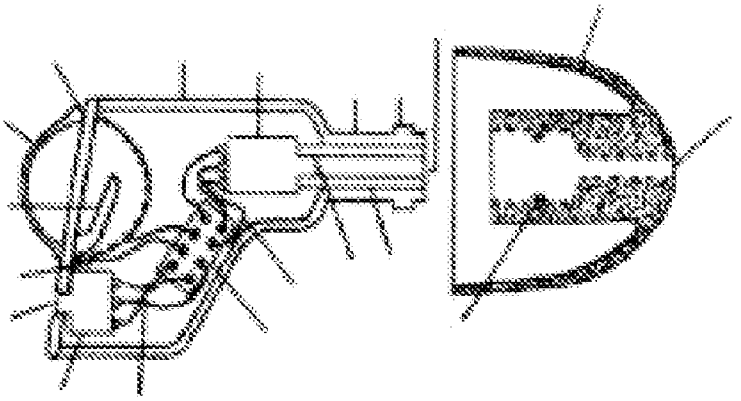


FIG. 18G

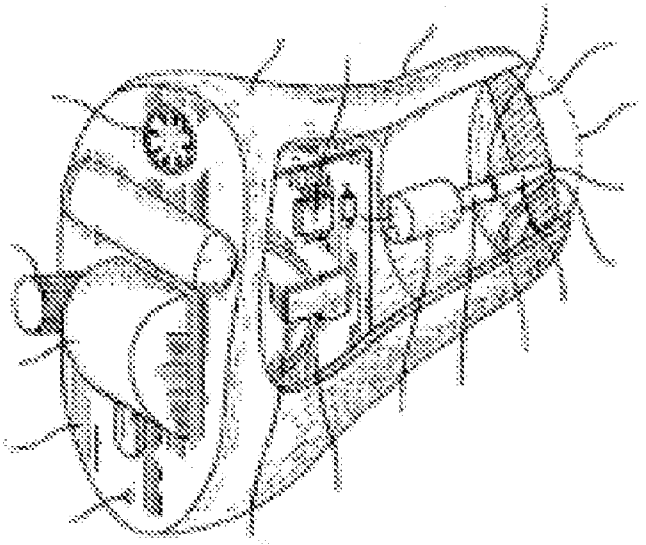


FIG. 18H

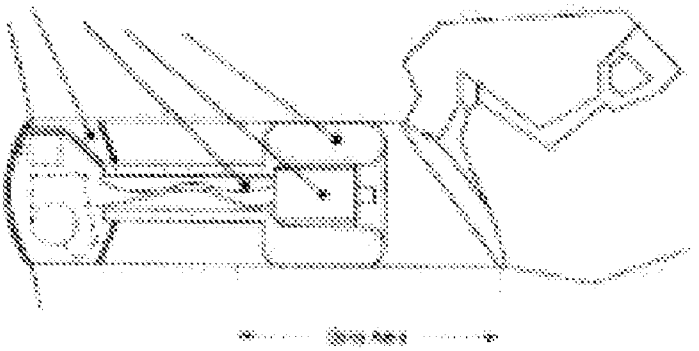


FIG. 18I

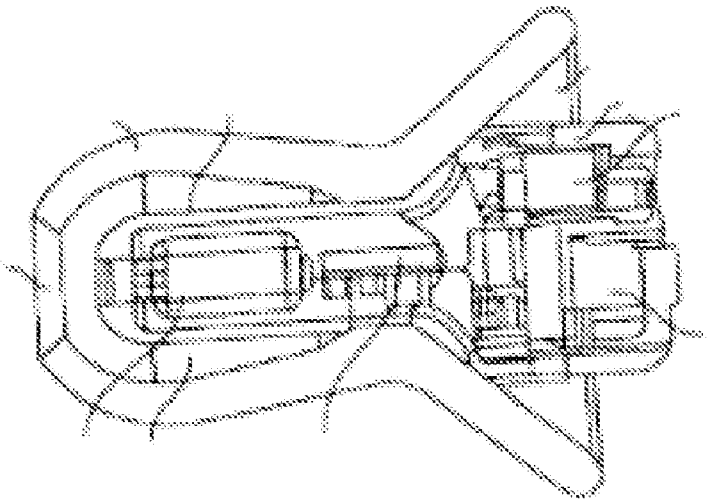


FIG. 18J

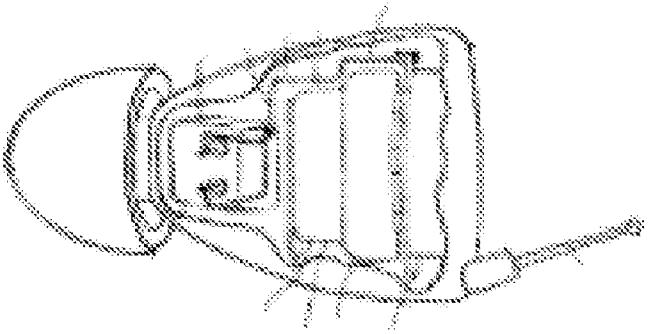


FIG. 18K

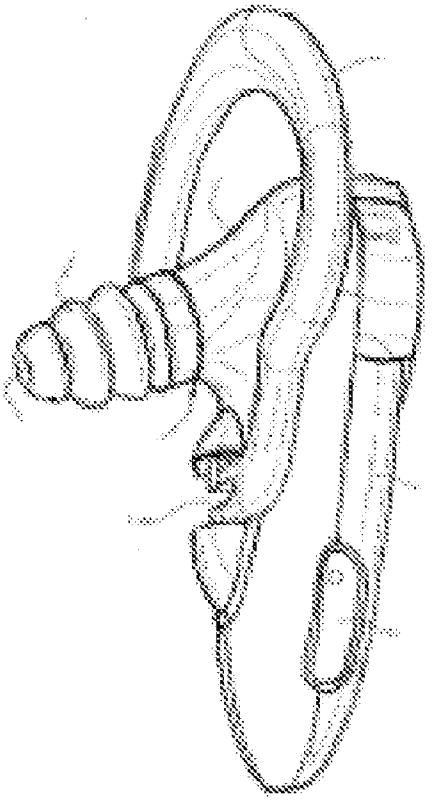


FIG. 18L

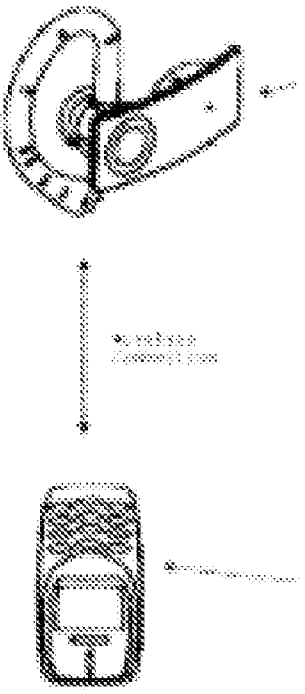


FIG. 18M

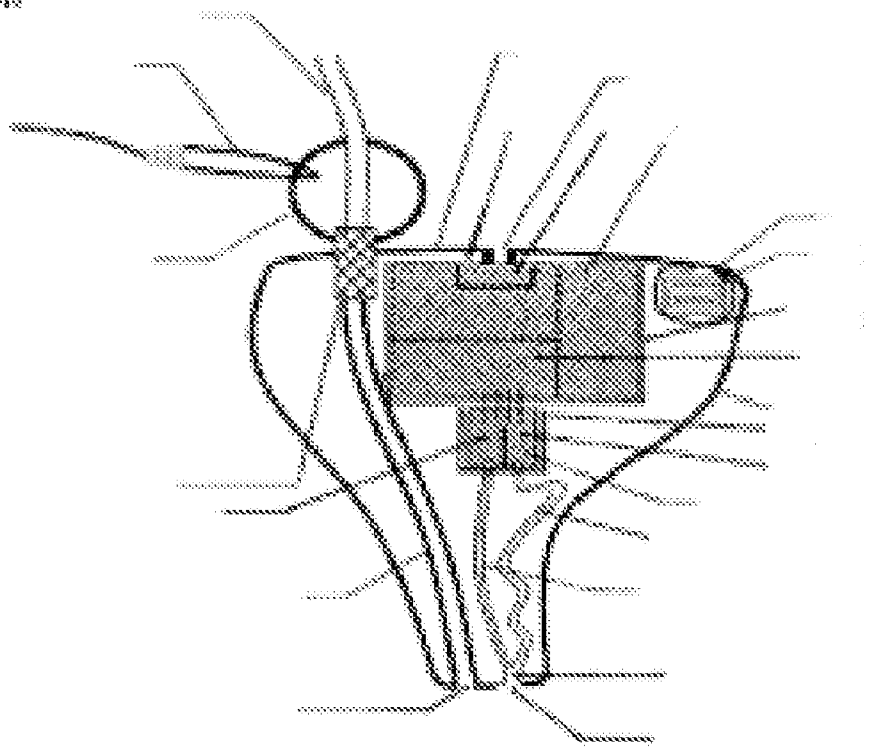


FIG. 18N

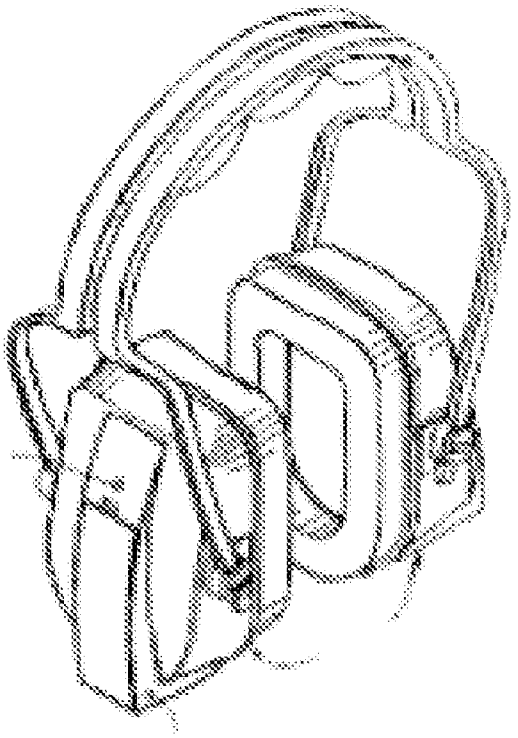


FIG. 19

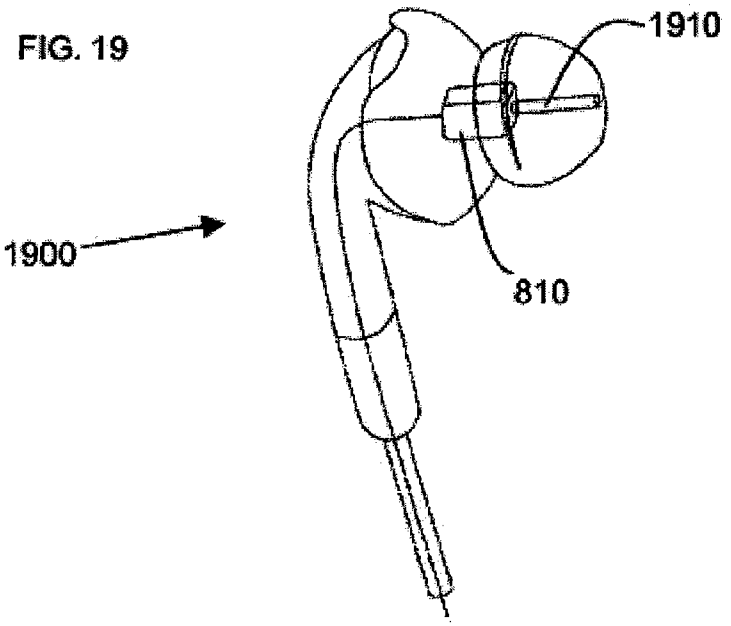
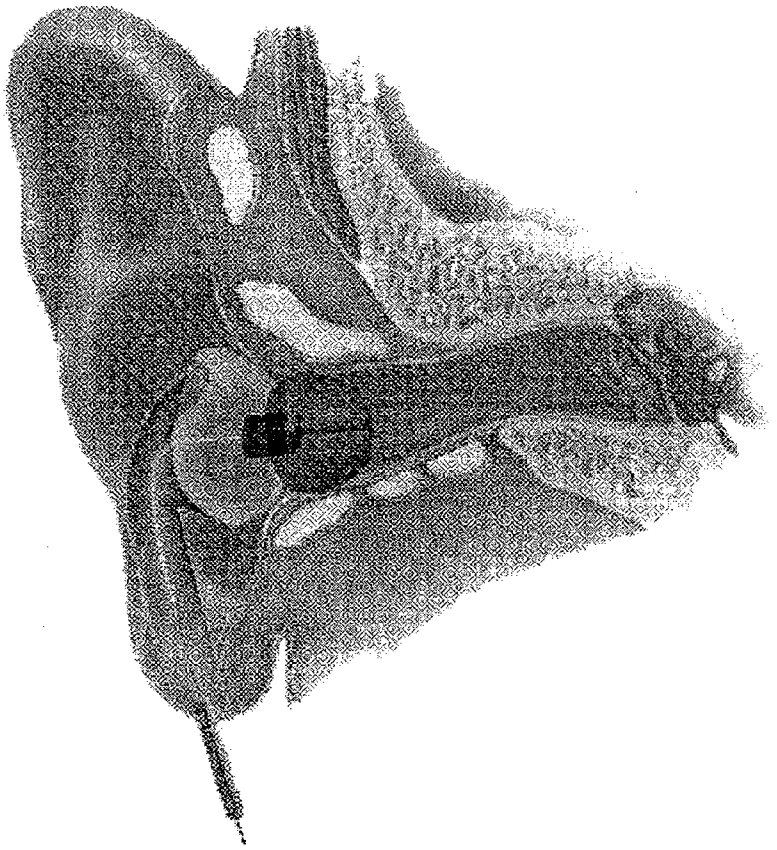


FIG. 20



EARHEALTH MONITORING SYSTEM AND METHOD I

This application is a Continuation-in-Part of U.S. patent application Ser. No. 11/757,152 filed on 1 Jun. 2007, the disclosure of which is incorporated herein by reference in its entirety, which in turn claims priority from U.S. Provisional Application No. 60/803,708 filed 1 Jun. 2006.

FIELD OF THE INVENTION

The present invention relates to a device that monitors acoustic energy directed to an ear, and more particularly, though not exclusively, to an earpiece that monitors acoustic sound pressure level dose received by a user's ear.

BACKGROUND OF THE INVENTION

With the advent of an industrial society, people are exposed to noise pollution at greater and greater levels; both from background, such as street traffic, airplanes, construction sites and intentional exposure to high sound levels such as cell phones, MP3 players, and rock concerts. Studies show that ear damage, leading to permanent hearing impairment is not only increasing in the general population, but increasing at a significantly faster rate in younger populations.

The potential for hearing damage is a function of both the level and the duration of exposure to the sound stimulus. Safe listening durations at various loudness levels are known, and can be calculated by averaging audio output levels over time to yield a time-weighted average. Standard damage-risk guidelines published by OSHA, NIOSH or other agencies are known. This calculation can be even further improved by accounting for aspects of the playback scenario, specifically the characteristics of the sound source and their proximity to the listener's ear.

Studies have also indicated that hearing damage is a cumulative phenomenon. Although hearing damage due to industrial or background noise exposure is more thoroughly understood, the risk of exposing one's self to excessive noise, especially with the use of headphones has also been recently studied. Protecting the ear from ambient noise is primarily done with the use of static earplugs that attempt to shield the inner ear from excessively high decibel noise. Background noise canceling earphones such as those produced by Bose and others, attempt to protect the ear from excessive ambient noise by producing a counter noise wave to cancel out the ambient noise at the ear. These prior art devices have been less than satisfactory because they do not completely prevent high decibel noise from reaching the ear, and do not account for the duration of exposure to harmful sounds at the ear.

It is also known from the prior art to provide active noise reduction at the ear to protect the ear from exposure to loud noises as disclosed in U.S. patent Application No. US2005/0254665. The art actively attenuating noise reaching the inner ear utilizing a control; a connection with an earpiece and attenuating the noise to the ear. However, there is no monitoring of the noise over time to account for the cumulative effect. Furthermore, there is no accounting for any restorative effects within the ear for sound level exposures which are sufficiently low to allow recovery, rather than destruction.

Dosimeters, such as that described in U.S. published Application No. US2005/0254667 are known. The device periodically measures prior sound level in the ambient environment. However, the device does not take into account the cumulative effect of the noise over multiple incidences of exposure (e.g., one day to the next) or the effect of any restorative

period. Furthermore, no remedial action is automatically taken as a result of the readings.

It is also known from the prior art that headphones for consumer electronics have been provided with a predetermined maximum output level in an attempt to prevent ear damage. This approach is ineffective as it does not take into account listening duration and the calculation of risk for auditory injury. Other headphones are maximum-limited to produce levels that can still result in significant overexposure given enough time, or limit the user to levels, which may not be sufficient to achieve an adequate short term listening level. In the latter case, consumer acceptance for the protective gear could be severely limited and a product would fail to survive in a competitive market and therefore be of no use.

Another alternative known in the art is to reduce the headphone output levels by increasing earphone impedance via an accessory placed between the media player and the earphones. The limitation of this approach is that it gives no consideration to the duration of exposure, and again either the user's chosen listening level cannot be achieved because the maximum level is too limited, or the level is sufficient to allow the user access to high enough sound levels, but risk overexposure due to potential duration of use.

It is known from U.S. Publication No. 2007/0129828 to provide automated control of audio volume parameters in order to protect hearing. A method of operating a media player includes the step of playing back audio media and refining a maximum volume parameter for the playing of the media by the media player. The refining is based at least in part on the playback of audio media during a time period existing prior to the execution of refining the maximum volume allowed. The refinement is intended to minimize harm to the user's hearing.

Applicants cannot confirm that such an approach has been commercialized. However, even if commercialized, it suffers from the shortcomings that the refinement is based on a theoretical noise volume delivered to the ear as a function of the output signal of the device and parameters of the earpiece connected to the device and is based upon a credit system based on volume. There is no measurement of the actual noise delivered to the ear. Furthermore, the calculation does not take into account the ambient noise of the device user nor the noise reduction rate of the earpiece relative to the ambient noise. In other words, the actual volume level to which the ear is exposed is not taken into account. Accordingly, a severe miscalculation of the actual ear exposure, and resulting ear harm, may exist as a result of use of this related art method. Additionally the credit system is not described in detail sufficient for one of ordinary skill to construct the device. For example U.S. Publication No. 2007/0129828 refers to Cal-OSHA profiles, and states in the same paragraph that Cal-OSHA appear to be rudimentary and does not deal with exposure "in a sophisticated way with varying exposure over time" and does not "... account for recovery." However, U.S. Publication No. 2007/0129828 states in one example "... the maximum allowed volume is determined based upon determined credits with reference to a profile such as profiles provided by ... (Cal-OSHA) .... " However, U.S. Publication No. 2007/0129828, stated that Cal-OSHA doesn't take into effect recovery, and additionally fails to refer to any detailed recovery calculation. Additionally, the credit system is based upon volume, rather than a predicted sound pressure level (PSPL) emitted by a speaker, and thus is an inaccurate predictor of sound pressure level (SPL) experienced by a user's ears due to emissions from the speaker.

Accordingly, a system that overcomes the shortcomings in the related art would be useful.

BRIEF SUMMARY OF THE INVENTION

At least one exemplary embodiment is directed to a method of operating an audio device comprising: calculating estimated sound pressure levels for drive signals directed to an ear canal receiver (ECR) (which can result in an emitted acoustic signal by the ECR) during a time increment Δt; calculating an estimated SPL_Dose during the time increment Δt using the estimated sound pressure levels; and calculating a total SPL_Dose at the time t of the audio device using the estimated SPL_Dose. Additional exemplary embodiments include comparing the estimated sound pressure levels to a permissible sound level (PSL), and if the estimated sound pressure levels are less than PSL within an error margin, then the step of calculating an estimated SPL_Dose uses a recovery function to calculate the updated estimated SPL_Dose during the time increment Δt.

Additional exemplary embodiments can include: calculating estimated sound pressure levels (SPL1) for drive signals directed to an ear canal receiver (ECR) during a time increment Δt, when the ECR is in the ECR mode; measuring sound pressure levels (SPL2) for ambient acoustic signals received by the ECR during the time increment Δt, when the ECR is in the ear canal microphone (ECM) mode; calculating an estimated SPL_Dose during the time increment Δt using at least one of SPL1 and SPL2; calculating a total SPL_Dose of the audio device at the time t using the estimated SPL_Dose; and comparing either sound pressure levels SPL1 or SPL2 to a permissible sound level (PSL), and if the used sound pressure levels, SPL1 or SPL2, is less than PSL within an error margin, then the step of calculating an estimated SPL_Dose uses a recovery function to calculate the updated estimated SPL_Dose during the time increment Δt.

At least one further exemplary embodiment is directed to a method of operating an audio device comprising: calculating estimated sound pressure levels (SPL1) for drive signals directed to an ear canal receiver (ECR) during a time increment Δt, when the ECR is in the ECR mode; predicting a sound pressure level (PSPL1) for ambient acoustic signals that would be received by the ECR during the time increment Δt, if the ECR was in the ECM mode but is in ECR mode; calculating an estimated SPL_Dose during the time increment Δt using SPL1 and PSPL1; and calculating a total SPL_Dose of the audio device at time t using the estimated SPL_Dose.

At least one exemplary embodiment is directed to a method of operating an audio device comprising: calculating estimated sound pressure levels for drive signals directed to an ear canal receiver (ECR) during a time increment Δt; calculating an estimated SPL_Dose during the time increment Δt using the estimated sound pressure levels; comparing the estimated sound pressure levels to a permissible sound level (PSL), and if the estimated sound pressure levels are less than PSL then the step of calculating an estimated SPL_Dose uses a recovery function that is at least one of a linear function and an exponential function to calculate the estimated SPL_Dose during the time increment Δt; and calculating a total SPL_Dose of the audio device at the time "t" using the estimated SPL_Dose, where $t=t_0+\Delta t$, where t_0 is the time at the beginning of the time increment Δt.

At least one exemplary embodiment is directed to a method of operating an audio device comprising: calculating estimated sound pressure levels (SPL1) for drive signals directed to an ear canal receiver (ECR) during a time increment Δt, when the ECR is in the ECR mode; measuring sound pressure levels (SPL2) for ambient acoustic signals received by the ECR during the time increment Δt, when the ECR is in the ECM mode; predicting a sound pressure level (PSPL1) for ambient acoustic signals that would be received by the ECR during the time increment Δt, if the ECR was in the ECM mode but is in the ECR mode; calculating an SPL total during the time increment Δt using SPL1 and PSPL1 when the ECR is in the ECR mode. If the ECR is in the ECM mode during the time increment Δt then SPL total during the time increment Δt is calculated using SPL2; calculating an estimated SPL_Dose during the time increment Δt using SPL1 and PSPL1 when the ECR is in ECR mode and SPL2 when ECR is in ECM mode; comparing the SPL total to a permissible sound level (PSL), and if SPL total is less than PSL then the step of calculating an updated estimated SPL_Dose uses a recovery function that is at least one of a linear function and an exponential function to calculate the estimated SPL_Dose during the time increment Δt; and calculating a total SPL_Dose of the audio device at time t using the estimated SPL_Dose, where $t=t_0+\Delta t$, where t_0 is the time at the beginning of the time increment Δt.

Further areas of applicability of exemplary embodiments of the present invention will become apparent from the detailed description provided hereinafter. It should be understood that the detailed description and specific examples, while indicating exemplary embodiments of the invention, are intended for purposes of illustration only and are not intended to limit the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram of the system for measuring and determining exposure to sound over time at the ear constructed in accordance with a first exemplary embodiment of the invention.

FIG. **2** is a block diagram of the system in accordance with at least one exemplary embodiment of the invention in situ in the ear;

FIG. **3** is a flow chart for calculating listening fatigue in accordance with at least one embodiment of the invention by measuring a quantity (e.g., the sound pressure level) over time as perceived at the ear;

FIG. **4** is a flow chart for determining a weighted ear canal sound pressure level in accordance with another exemplary embodiment of the invention;

FIG. **5** is a flow chart for determining a personalized recovery time constant in accordance with another exemplary embodiment of the invention;

FIG. **6** is a flow chart for determining an update epoch in accordance with at least one exemplary embodiment of the invention;

FIG. **7** is a flow chart for determining an update epoch in accordance with yet another exemplary embodiment of the invention;

FIG. **8** illustrates the general configuration and terminology in accordance with descriptions of exemplary embodiments;

FIGS. **9**A-**9**C illustrates an example of a temporal acoustic signal and its conversion into a spectral acoustic signature;

FIG. **10** illustrates a generalized version of an earpiece and some associated parts in an ear canal;

FIG. **11** illustrates an earpiece according to at least one exemplary embodiment;

FIG. **12** illustrates a self contained version of an earpiece according to at least one exemplary embodiment;

FIG. **13** illustrates an earpiece where parts are not contained in the earpiece directly according to at least one exemplary embodiment;

FIG. **14**A illustrates a general configuration of some elements of an earpiece according to at least one exemplary embodiment;

FIG. **14**B illustrates a flow diagram of a method for SPL Dose calculation according to at least one exemplary embodiment;

FIG. **14**C illustrates a flow diagram of a method of SPL Dose calculation according to at least one exemplary embodiment;

FIG. **14**D illustrates a flow diagram of a method of SPL Dose calculation according to at least one exemplary embodiment;

FIGS. **15**A-**15**E illustrate a method of switching between ECR and ECM modes in accordance with at least one exemplary embodiment;

FIGS. **16**A-**16**C illustrate the formation of SPL total from ECM and ECR values and estimated values (PSPL);

FIGS. **17**A-**17**D illustrate the formulation of an SPL-Dose by a non-limiting example of an optional end of day correction to the previous estimated values (PSPL);

FIGS. **18**A to **18**N illustrate various non-limiting examples of earpieces that can use methods according to at least one exemplary embodiment;

FIG. **19** illustrates a line diagram of an earpiece (e.g., earbud) that can use methods according to at least one exemplary embodiment; and

FIG. **20** illustrates the earpiece of FIG. **19** fitted in an ear.

DETAILED DESCRIPTION OF THE INVENTION

The following description of at least one exemplary embodiment is merely illustrative in nature and is in no way intended to limit the invention, its application, or uses.

Processes, techniques, apparatus, and materials as known by one of ordinary skill in the relevant art may not be discussed in detail but are intended to be part of the enabling description where appropriate, for example the fabrication and use of transducers. Additionally in at least one exemplary embodiment the sampling rate of the transducers can be varied to pick up pulses of sound, for example less than 50 milliseconds.

In all of the examples illustrated and discussed herein, any specific values, for example the sound pressure level change, should be interpreted to be illustrative only and non-limiting. Thus, other examples of the exemplary embodiments could have different values.

Note that similar reference numerals and letters refer to similar items in the following figures, and thus once an item is defined in one figure, it may not be discussed for following figures.

Note that herein when referring to correcting or preventing an error or damage (e.g., hearing damage), a reduction of the damage or error and/or a correction of the damage or error are intended.

At least one exemplary embodiment of the invention is directed to measuring and determining the exposure of sound to the ear over time. Reference is made to FIG. **1** in which a system, generally indicated as **100**, is constructed in accordance with at least one exemplary embodiment of the invention. System **100** includes an audio input device **113** for receiving sound at the ear. As will be discussed below, audio input device **113** can include an analog audio input **11**, **23** and a digital audio input **19**. In at least one exemplary embodiment, audio input device **113** receives audio input from at least one of three sources, namely; ambient noise around the ear, direct input noise such as a MP3 player or other device which can produce a digital audio input at digital audio input **19**, and noise as detected within the ear canal **31** (FIG. **2**). The audio input device **113** outputs an audio signal corresponding to the received sound. Analog output signals from analog audio inputs **11**, **23** are converted to a digital signal by an analog-to-digital (A/D) converter **118** so that digital sound signals are input into an input level detector **120**.

Input level detector **120** determines the sound pressure level of the sound received at audio input device **113**. Input level detector **120** outputs a sound pressure level (SPL) signal, which is input to a minimum-level threshold detector **122**. Minimum level threshold detector **122** determines whether or not the sound pressure level as detected by input level detector **120** exceeds a minimum level threshold. As will be discussed below, the minimum level threshold can be the PSL (e.g., effective quiet level) of the individual, or some predetermined level substantially corresponding to a level which is ear damage neutral over time or a level of interest, such as 80 dB, because of its effect on the ear. Therefore, if the minimum level threshold is detected as being exceeded, a signal indicating a sound pressure level in excess of the minimum level threshold is output to a start timer **124**, which triggers a digital timer system **126** to begin a clock. Conversely, if the input sound pressure level is detected as being below the minimum threshold, a signal indicating the sound pressure level is below the minimum level threshold is output to a start timer **124**, which triggers a digital timer system **126** to begin a clock of a restorative period. If the sound pressure level is at the minimum threshold (within a margin of error), no clock needs to be started because this is neutral to the desired effect. In a preferred embodiment, the clock signal is changed with every significant (more than 1 dB by way of example) change in sound pressure level to get an accurate profile of sound exposure over time.

Once the sound pressure level as detected at input level detector **120** decreases to or is below the minimum threshold level, a stop timer signal is output from stop timer **128** to digital timer system **126** to stop the clock corresponding to exposure to the excessively intense level. Digital timer system **126** outputs a clock value corresponding to the time period at which the minimum level threshold was not met, or in the preferred embodiment, for each period corresponding to a discrete level change.

A data memory or learning history database **127** receives the clock value from digital timer system **126** as well as the actual input level detected at input level detector **120** and determines a listening history or sound pressure level exposure history. The sound pressure level exposure history is a record of the user's exposure to sound pressure levels over time. Because the effect of exposure is cumulative, it is important that the exposure history be maintained. The listening history, as will be discussed below, can include real ear level data, listening duration data, time between listening sessions, absolute time, sound pressure level dose (SPL Dose) data, including any restorative sound level, number of acoustic transients and crest factor and other data.

The sound pressure level exposure history or listening history includes both the listening habits history and the environmental or ambient noise exposure history. The environmental noise exposure history is the exposure of a user to environmental noise over time as a result of the auditory stimuli inherent to the environment where the user is present. This can be highway traffic, construction site, even the restorative effect of the quiet sound pressure levels, e.g., those typically encountered in a library whereas, the listening habits history is associated for the purposes for this disclosure with user-directed auditory stimuli such as music, words, other noises, which a user intentionally encounters for a pur-

pose such as communication, learning, and enjoyment. Therefore, database **127**, as will be discussed below, stores the cumulative SPL exposure.

It should be noted that in at least one exemplary embodiment, minimum level threshold detector **122** also starts the timer **124** when the sound pressure level is below the predetermined level. In this way, the restorative effect of below PSL (e.g., effective quiet noise) is accumulated for determining overall exposure damage potential.

In effect, the only time that digital timer system **126** is not running is when the detected sound pressure level signal is at the minimum level threshold. A listening fatigue calculator **130** receives the input level signal from input level detector **120** and data from the data memory listening history **127**, and determines whether or not listening fatigue or hearing damage is likely to occur as a result of further exposure. Hearing damage is the injury to the hearing mechanism including conductive and sensorineural decrement in hearing threshold levels. It can be either temporary or permanent so long as it is a result of the noise exposure is above PSL (e.g., Effective Quiet). In other words, listening fatigue calculator **130** will output a signal when a threshold sound exposure, determined as a function of exposure time and sound pressure level, as will be discussed in greater detail below, is achieved. At that point, a listening fatigue signal is output.

It should be noted that in an alternative embodiment, system **100** can make use of an ambient noise detection/cancellation system **142** as known in the art. These systems produce signals, which cancel sound pressure levels at certain frequencies and/or certain levels to reduce the effect of undesired noise, whether environmental noise or user directed noise. It will have some effect in elongating the permissible exposure time by negating the sound pressure level detected by input level detector **120**.

In at least one exemplary embodiment, the signal from the listening fatigue calculator is utilized to prevent damage and encourages some action by the user when exposure levels are near damaging levels. Therefore, in one non-limiting example, a listening fatigue display **140** is provided for receiving the signal from the listening fatigue calculator and displaying to the user a prompt to discontinue exposure to the sound level from the damaging sound source or audio source.

In another non-limiting example, the signal from the listening fatigue calculator is output to an audio warning source **132**, which outputs an output audio warning to the user notifying the user that exposure to the sound source has reached critical levels.

In at least one exemplary, but non-limiting, embodiment, as will be discussed below, system **100** includes an output acoustical transducer **25** to provide an audio signal to the ear. Output acoustical transducer **25** operates under the control of a digital signal processor (DSP) **134**. Digital signal processor **134** receives a digital audio signal from input level detector **120**, which acts as a pass through for the digitized signals from audio input device **113**. Digital signal processor **134** passes the sound signals through to a digital to analog (D/A) converter **136** to drive acoustical transducers **25** to recreate the sound received at audio input device **113** inside the ear canal **31** in at least one exemplary embodiment of the invention as shown in FIG. **2**. With such an exemplary embodiment, audio warning source **132** provides an output to digital sound processor **134** causing output acoustical transducer **25** to output a warning sound inside the ear of the user.

Additionally, in at least one further exemplary embodiment, listening fatigue calculator **130** outputs a listening fatigue signal to digital processor **134** which causes digital signal processor **134** to attenuate the sound signal prior to output to acoustical transducer **25** to reduce the signal output level by any of the linear gain reduction, dynamic range reduction, a combination of both, or a complete shutdown of transducer **25**. Attenuation would be at least to the level, if not below, the PSL (e.g., effective quiet level) to allow for ear recovery prior to damage.

It should be noted, that because personal hearing threshold and discomfort levels can change from person to person, and because both of the time intervals are a function of many variables, in a non-limiting example, to provide a dynamic ever-changing response, system **100** operates under software control. The configuration of the digital sound processor **134**, listening fatigue calculator **130**, the minimum level threshold detector **122**, and the input level detector **120** are operated under software control.

In an exemplary embodiment of the invention, the control programs are stored in a program memory **148** for operating the firmware/hardware identified above. Furthermore, the program stored within memory **148** can be personalized as a result of testing of the user's ear, or by other modeling methods, in which system **100** includes a software interface **144** for receiving online or remote source updates and configurations. The software interface **144** communicates with a data port interface **146** within system **100**, which allows the input of software updates to program memory **148**. The updates can be transmitted across a distributed communications network, such as the Internet, where the updates take the form of online updates and configurations **143**.

It should be noted that there is multiple functionality distributed across system **100**. In at least one exemplary embodiment, at least audio input device **113** and acoustical transducer **25** are formed as an earpiece, which extends into the outer ear canal so that the processing of signals pertains to sound received at the ear. However, it is well within the scope of at least one exemplary embodiment of the invention to provide substantially all of the functionality in an earpiece so that system **100** is a "smart device."

Also note that when referring to measurements in decibels (dB), one is referring to a logarithmic ratio. For example dB is defined as:

$$SPL = \beta(\text{dB}) = 10\log\frac{I}{I_0} = 10\log\frac{\Delta P^2}{\Delta P_0^2} \tag{1}$$

Where I is the intensity measured, I_0 is a reference intensity, $I_0=10^{-12}$ W/m^2, and P_0 is a reference pressure, $\Delta P_0=20$ micropascals, and where ΔP is the root mean squared pressure amplitude in a measured pressure wave (e.g., using a transducer). Thus, the sound pressure level (SPL) can be measured in dB.

Alternatively one can use the above equation and solve for measured pressures instead. For example:

$$\Delta P(t)=10^{(sPL(t)/\mathbf{20.0})}\Delta p_0 \tag{2}$$

In the discussion of formulas herein we refer to SPL as a non-limiting example and one of ordinary skill in the arts could re-derive the equations in terms of measured pressures, ΔP, both are intended to lie within the scope of at least one exemplary embodiment. Reference is now made to FIG. **2** in which system **100** in which the transducer configuration, that portion of system **100**, which converts sound pressure level variations into electrical voltages or vice versa is shown. In this embodiment, acoustic transducers include microphones as an input and loudspeakers as an acoustical output.

FIG. **2** depicts the electro acoustical assembly **13** (also referred to herein as an in-the-ear acoustic assembly **13** or earpiece **13**), as it would typically be placed in the ear canal **31** of ear **17** of user **35**. The assembly is designed to be inserted into the user's ear canal **31**, and to form an acoustic seal with the walls **29** of the ear canal **31** at a location **27**, between the entrance **15** to the ear canal **31** and the tympanic membrane or eardrum **33**. Such a seal is typically achieved by means of a soft and compliant housing of assembly **13**. A seal is critical to the performance of the system in that it creates a closed cavity in ear canal **31** of approximately 0.5 cc in a non-limiting example between the in-ear assembly **13** and the ear's tympanic membrane **33**.

As a result of this seal, the output transducer (speaker) **25** is able to generate a full range bass response when reproducing sounds for the system user. This seal also serves to significantly reduce the sound pressure level at the user's eardrum **33** resulting from the sound field at the entrance **15** to the ear canal **31**. This seal is also the basis for the sound isolating performance of the electroacoustic assembly **13**. Located adjacent to speaker **25**, is an ear canal microphone (ECM) **23**, which is also acoustically coupled to closed cavity **31**. One of its functions is that of measuring the sound pressure level in cavity **31** as a part of testing the hearing sensitivity of the user as well as confirming the integrity of the acoustic seal and the working condition of itself and speaker **25**. Audio input **11** (also referred to herein as ambient sound microphone (ASM) **11**) is housed in assembly **13** and monitors sound pressure at the entrance **15** to the occluded ear canal. The transducers can receive or transmit audio signals to an ASIC **21** that undertakes at least a portion of the audio signal processing described above and provides a transceiver for audio via the wired or wireless communication path **119**.

In the above description the operation of system **100** is driven by sound pressure level, i.e. sound levels are monitored for time periods or epochs during which the sound pressure level does not equal the minimum level threshold or is constant. However, as will be discussed in connection with the next exemplary embodiments of the invention, system **100** can also operate utilizing fixed or variable sampling epochs determined as a function of one or more of time and changes in sound pressure level, sound pressure dosage level, weighting functions to the sound pressure level, and restorative properties of the ear.

Reference is now made to FIG. **3** in which a flow chart for monitoring the sound pressure level dose at various sample times n is provided. The process is started in a step **302**. An input audio signal is generated in a step **304** at either the ear canal microphone (ECM) **23** or the ambient sound microphone (ASM) **11**. Changes in SPL_Dose resulting from duration of exposure time is a function of the sound pressure level, therefore, the epoch or time period used to measure ear exposure or, more importantly, the time-period for sampling sound pressure level is determined in a step **305**. The update epoch is used in the SPL Dose function determination as well as to effect the integration period for the sound pressure level calculation that, as will be discussed below, is used to calculate the weighted ear canal sound pressure level.

Reference is now made to FIGS. **6** and **7**. In FIG. **6**, a method is defined to change the update epoch as a function of the weighted ear canal sound pressure level, which will be discussed in greater detail below. System **100** is capable of determining when earpiece **13** is in a charger or communication cradle (i.e., not in use in the ear of the user). In a step **684**, a predetermined standard is provided for the update epoch, 60 seconds in this example. In step **688**, the update epoch is set as the in-cradle update epoch. The in-cradle state is detected in step **686**. If it is determined in a step **690** that earpiece **13** (also referred to herein as earphone device **13**) is in a charger or cradle mode, then the update epoch is set as the in-cradle epoch; in the step **688**.

However, if in step **690** it is determined that the earphone device **13** is in use, in other words "not in the cradle", then, by default, an audio signal is input to earpiece **13** in step **692**. In step **693**, an ear canal sound pressure level is estimated as a function of the audio input at step **692**. The current (n) ear canal sound pressure level estimate is stored as a delay level in a step **698**. An audio input is determined at a later time when step **692** is repeated so that a second in-time ear canal sound pressure level estimate is determined.

In a step **600**, the delayed (n−1) or previous sound pressure level is compared with the current (n) ear canal sound pressure level estimate to calculate a rate of change of the sound pressure level. The change level is calculated in units of dB per second. This process of step **692** through **600** is periodically repeated.

In a step **606**, it is determined whether or not the sound pressure level change is less than a predetermined amount (substantially 1 dB by way of non-limiting example) between iterations, i.e., since the last time the ear canal sound pressure level is calculated. If the change is less than the predetermined amount, then in step **604** the update epoch is increased. It is then determined in a step **602** whether or not the epoch update is greater than a predefined amount D set in step **694** as a maximum update epoch such as 60 seconds in a non-limiting example. If in fact, the update epoch has a value greater than the maximum update epoch D then the update epoch is set at the higher value D in step **608**.

If it is determined in step **606** that the sound pressure level change is, in a non-limiting example, greater than −1 dB, but less than +1 dB as determined in step **612**, then the update epoch value is maintained in a step **610**. However, if it is determined that the sound pressure level change is, in a non-limiting example, greater than +1 dB, then the update epoch value is decreased in a step **618** to obtain more frequent sampling. A minimum predetermined update epoch value such as 250 microseconds is set in a step **614**. If the decreased update epoch determined in step **618** is less than, in other words an even smaller minimum time-period than the predetermined minimum update epoch E, then the new update epoch is set as the new minimum update epoch value in steps **616** and **622**. In this way, the sample period is continuously being adjusted as a function of the change in sound pressure level at the ear. As a result, if the noise is of a transient variety as opposed to a constant value, the sampling interval will be changed to detect such transients (e.g., spikes) and can protect the ear.

Reference is now made to FIG. **7** in which a method for changing the update epoch is illustrated as a function of the way that the ear canal sound pressure level estimate is provided. Again, in accordance with at least one exemplary embodiment of the invention, the update epoch is decreased when the ear canal sound pressure level is high or increasing.

The difference between the embodiment of FIG. **7** and the embodiment of FIG. **6** is that the update epoch is not continuously adjusted, but is more static. If the ear canal sound pressure level is less than PSL (e.g., effective quiet, a decibel level which when the ear is exposed to over time does not damage or restore the ear), then the update epoch is fixed at a predefined maximum epoch value and this is the value used by system **100** as will be discussed in connection with FIG. **3** below. In this embodiment, if the ear canal sound pressure level is determined to be greater than a permissible (or permitted) sound level (PSL) (e.g., effective quiet), then the

update epoch is fixed at a shorter minimum value and this is returned as the update epoch to be utilized.

In FIG. **7**, specifically, as with FIG. **6**, an in-cradle update epoch of 5 seconds by way of non-limiting example, is stored in system **100** in a step **784**. In a step **788**, the initial update epoch is set as the in-cradle update epoch. A maximum update epoch time, such as 2 seconds by way of non-limiting example, is stored in a step **794**. In a step **714**, an initial minimum update epoch (250 microseconds in this non-limiting example) is stored.

In a step **786** and step **790** it is determined whether or not system **100** is in a non-use state, i.e., being charged or in a cradle. If so, then the update epoch is set at the in-cradle update epoch. If not, then a digital audio signal is input from ear canal microphone **23** in step **792**. A sound pressure level is estimated in step **795**. It is then determined whether or not the ear canal sound pressure level is less than PSL (e.g., effective quiet) in a step **732**. If the sound pressure level is less than the PSL (e.g., effective quiet) as determined in step **732**, then the update epoch is set at the maximum update epoch in a step **730**. If the sound pressure level is louder than the effective quiet, then in step **716**, the update epoch is set to the minimum update epoch.

Returning to FIG. **3**, in a non-limiting exemplary embodiment, the update epoch is set at 10 seconds in a step **302** utilizing either a constant predetermined sample time, or either of the methodologies discussed above in connection with FIGS. **6** and **7**. In a step **306**, the input audio signal is sampled, held, and integrated over the duration of the epoch as determined in step **308**. As a result, the update epoch affects the integration period utilized to calculate the sound pressure level dose as a function of the sound pressure level and/or as the weighted ear canal sound pressure level.

In a step **310**, an earplug noise reduction rating (NRR) is stored. The noise reduction rating corresponds to the attenuation effect of earpiece **13**, or system **100**, on sound as it is received at audio input **11** and output at the output transducer **25** or as it passes from the outer ear to the inner ear, if any exemplary embodiment has no ambient sound microphone **11**. In a step **311**, a weighted ear canal sound pressure level is determined, partially as a function of the earplug noise reduction rating value.

Reference is now made to FIG. **4** where a method for determining the weighted ear canal sound pressure level in accordance with at least one exemplary embodiment of the invention is illustrated. Like numerals are utilized to indicate like structure for ease of discussion and understanding. Weighting is done to compensate for the manner in which sound is perceived by the ear as a function of frequency and pressure level. As sounds increase in intensity, the ear perceived loudness of lower frequencies increases in a nonlinear fashion. By weighting, if the level of the sound of the field is low, the methodology and system utilized by at least one exemplary embodiment of the invention reduces the low frequency and high frequency sounds to better replicate the sound as perceived by the ear.

Specifically, a weighting curve lookup table, such as A-weighting, acts as a virtual band-pass filter for frequencies at sound pressure levels. In a step **304**, the audio signal is input. In step **410**, frequency-dependent earplug noise reduction ratings are stored. These values are frequency-dependent and in most cases, set as manufacturer-specific characteristics.

As discussed above, in a step **306**, the input audio signal is shaped, buffered and integrated over the duration of each epoch. The sound pressure level of the shaped signal is then determined in a step **436**. It is determined whether or not ambient sound microphone (ASM) **11** was utilized to determine the sound pressure level in a step **444**. If microphone **11** was utilized, then the frequency-dependent earplug noise reduction rating of earpiece **13** must be accounted for to determine the sound level within the ear. Therefore, the noise reduction rating, as stored in step **310**, is utilized with the sound pressure level to determine a true sound pressure level (at step **446**) as follows:

$$SPL_{ACT}=SPL-NRR: \tag{3}$$

where sound pressure SPL_{ACT} is the actual sound pressure level received at the ear medial to the ECR, SPL is the sound pressure level determined in step **436** and NRR is the noise reduction rating value stored in step **410**.

If the ambient sound microphone (ASM) **11** is not used to determine the sound pressure level then the sound pressure level determined in step **436** is the actual sound pressure level. So that:

$$SPL_{ACT}=SPL \tag{4}$$

It is well within the scope of at least one exemplary embodiment of the invention to utilize the actual sound pressure level as determined so far to determine the affect of the sound pressure level received at the ear on the health of the ear. However, in at least one exemplary embodiment, the sound pressure level is weighted to better emulate the sound as received at the ear. Therefore, in a step **412**, a weighting curve lookup table is stored within system **100**. In a step **440**, the weighting curve is determined as a function of the actual sound pressure level as calculated or determined above in steps **436**, **446** utilizing a weighting curve lookup table such as the A-weighting curve. The A-weighting curve is then applied as a filter in step **438** to the actual sound pressure level. A weighted sound pressure level value representative of a sampled time period (SPL_W(n)) is obtained to be utilized in a step **414**.

The weighting curve can be determined in step **440** by applying a frequency domain multiplication of the sound pressure level vector and the weighting curve stored in step **412**. In this exemplary embodiment the weighting curve would be appropriate for direct multiplication with the SPL in the frequency domain (i.e., SPL(f)). In another exemplary embodiment the weighted SPL can be expressed as a weighting of the measured pressure vector as:

$$\text{SPL_W}(n)(t) = 20\log\left(\frac{\Delta P^{W_A}(t)}{\Delta P_0}\right) \tag{5}$$

where ΔP(t) is the measured temporal change in root mean squared pressure, which can be converted into spectral space (e.g., FFT) as ΔP(f) which is the measured spectral change in pressure, which can in turn be multiplied by a weighting function (e.g., A-weighting), $W_A(f)$) and expressed as $\Delta P^{W_A}(f)=\Delta P(f)\cdot W_A(f)$–, and then reconverted (e.g., inverse FFT) into temporal space to obtain $\Delta P^{W_A}(t)$. To obtain a single value various integration or summation over the n-th time interval (e.g., which can change in time) can be performed. For example:

$$\text{SPL_W}(n) = \frac{1}{\Delta t_n}\int_{t_{n-1}}^{t_n} 10\log\left(\frac{(\Delta P^{W_A}(t))^2}{\Delta P_0^2}\right)dt \tag{6}$$

The time during which a user may be exposed to the sound level SPL_W(n),i.e. the time to 100% allowable dosage at SPL level SPL_W(n), is referred to below as Time__100% (n).

The weighting curves can be stored as a lookup table on computer memory, or can be calculated algorithmically. Alternatively, the input audio signal can be filtered with a time or frequency domain filter utilizing the weighting curve stored in step **412** and the sound pressure level as calculated. For low-level sound pressure levels, those less than 50 dB, by way of non-limiting example, a weighting curve, which attenuates low and high frequencies can be applied (similar to an A-weighting curve). For higher sound pressure levels, such as more than 80 dB, by way of non-limiting example, the weighting curve can be substantially flat or a C-weighting curve. The resulting weighted ear canal sound pressure level during any respective sampling epoch is returned as the system output SPL_W(n) in step **414**. Note that herein various conventional weighting schemes are discussed (e.g., A-weighting, C-weighting) however in at least one exemplary embodiment non-conventional weighting schemes can be used. For example, generally the threshold level of hearing sensitivity (threshold of detection) is referenced in dB, where 20 micropascals is typically used as the minimum threshold level of pressure variation that an average person can detect. This reference value tends to be used at all frequencies, although the threshold level varies with frequency. Thus, one weighting scheme is to adjust the reference 0 dB level on a frequency basis, by using a conventional dB of threshold hearing chart, which provides the dB (f) at threshold level. A weighting function can be used where the value is about 1 at the reference value (e.g., equivalent to 20 micropascals) at a reference frequency (e.g., 1000 Hz). The other values (e.g., as a function of frequency) of the weighting function can vary depending upon the reference threshold pressure variation for the particular frequency, for example if at 30 Hz the threshold level in dB is 65 dB, then the weighting value can be 1/65 at 30 Hz, de-emphasizing the loudness and/or intensity at 65 dB when SPL Dose (f) is calculated.

Returning to FIG. **3**, a safe listening time is calculated by comparing the weighted sound pressure level with the PSL (e.g., effective quiet level) in step **316**. Therefore, a value A corresponding to how far from safe listening the sound pressure level is, is determined by the equation:

$$A=SPL_W(n)-PSL \tag{7}$$

where PSL is the permissible sound level, for example PSL=EfQ, where EfQ is equal to the sound level of effective quiet (as stored at step **312**). However PSL can be any level chosen for the particular circumstance, for example lower than EfQ.

By utilizing this simple comparative function, fewer machinations and processes are needed. System **100** takes advantage of the fact that because the PSL (e.g., effective quiet level) can be neutral to the ear, sound pressure levels significantly above the PSL (e.g., effective quiet level) are generally damaging and noise levels below the PSL (e.g., effective quiet) generally allow for restoration/recovery.

In a step **318**, the remaining safe listening time at the beginning of any current sampling epoch can be calculated by Time__100% minus the time duration of exposure up to the current sampling epoch. Note that a negative number can occur, indicating that no safe listening time remains. The estimated time (e.g., in hours) until the individual's sound exposure is such that permanent threshold shift may occur, ignoring any previous sound exposure and assuming that the SPL of the sound field exposed to the individual remains at a constant level L can be calculated as follows:

$$\text{Time_100\%}(n)=T_c/(2\hat{}((SPL_W(n)-PSL)/ER)); \tag{8}$$

Where PSL is the permissible sound level, and Tc is the critical time period. For example, if Tc (Critical Time) is 8 hours and PSL is 90 dBA, then that accepts that ~22-29% of people are at risk for hearing loss. If Tc is 8 hours and PSL is 85 dBA, then that accepts that ~7-15% of people are at risk, likewise for if Tc is 24 hours and PSL is 80 dBA, same 7-15% at risk. Thus Time__100% (n) reflects a reduction of the risk to a chosen level. Note that T_c is the critical time period of exposure that one is looking at (e.g., 8 hours, 24 hours), and ER is the exchange rate, for example can be expressed as:

$$\text{Time_100\%}(n)=8(\text{hours})/(2\hat{}((SPL_W(n)-85\text{ dBA})/3\text{ dB})) \tag{9}$$

These values assume a recovery period of 16 hours at a SPL level during that time of less than 75 dBA (where dBA refers to Decibels of an A-weighted value). Of course the realism of such an assumption is questionable given music, TV, and other listening habits of individuals. Thus, we are concerned with exposure over a 24 hour period. Thus, Time__100% (n) can be expressed for a 24 hour period (e.g., T_c=24 (hours)), where, for example using an equal energy assumption (i.e., ER of 3 dBA), as:

$$\text{Time_100\%}(n)=24/(2\hat{}((SPL_W(n)-PSL)/3)). \tag{10}$$

Another further example is the situation where PSL=EfQ, where the Effective Quiet, EfQ is defined as the highest sound level that does not cause temporary or permanent hearing threshold shift, nor does it impede recovery from temporary hearing threshold shift. For broadband noise, it can be 76-78 dBA, although these numbers can be different or refined over time based upon research and/or measurement history.

As a non-limiting example, the lower bound of SPL_W(n) dictating the Time__100% equation would be SPL_W(n)=PSL, and the upper bound of the SPL_W(n) dictating Time__100% equation would be about SPL_W(n)=115 dB.

Note that in at least one exemplary embodiment, the acoustic signals measured by an ECM or an ECR in ECM mode, can be used to detect a user's voice, for example using the technology discussed in Webster et al., U.S. Pat. No. 5,430,826, incorporated by reference in its entirety. If voice is detected then by the magnitude of the SPL (e.g., 80 dB) one can tell whether the user is speaking as compared to a non-user's voice (e.g., 50 dB) that has been attenuated by the earpiece. When a user's voice is detected then SPL_W(n) can be reduced by an amount (DSPL, e.g., 20 dB) that is due to Stapedius Reflex (e.g., when the user's voice triggers a muscle response in the muscles supporting the bones transmitting sound from the eardrum to cochlea), effectively damping some of the sound. Thus $SPL_W(n)_{new}$=SPL_W(n)−DSPL, where $SPL_W(n)_{new}$ is used in the Time__100% (n) equation as opposed to SPL_W(n).

In this embodiment, rather than make use of the Sound Level (L), the period is a function of the loudness and quietness of the weighted sound pressure level. It should be noted that PSL (e.g., effective quiet) is used in the above example, but any level of interest, such as 80 dB, or no sound level, i.e., SPL_W(n)−0, can be used. The weighted sound pressure level and PSL can be expressed as a frequency-dependent numerical array or a value scalar.

It is next determined whether or not the difference between the current weighted sound pressure level and the PSL (e.g., effective quiet) is above a tolerable threshold for risk of hearing damage or not, i.e., whether the weighted SPL in the

eardrum is considered to increase risk for hearing damage or not. A sound pressure level dose is calculated depending upon whether the sound level is loud or not. The sound pressure level dose (SPL Dose) is the measurement, which indicates an individual's cumulative exposure to sound pressure levels over time. It accounts for exposure to direct inputs such as MP3 players, phones, radios and other acoustic electronic devices, as well as exposure to environmental or background noise, also referred to as ambient noise. The SPL Dose is expressed as a percentage of some maximum time-weighted average for sound pressure level exposure.

Because the sound pressure level dose is cumulative, there is no fixed time-period for ear fatigue or damage. At or below effective quiet, the sound pressure level exposure time would theoretically be infinite, while the time period for achieving the maximum allowable sound pressure level dose becomes smaller and smaller with exposure to increasingly more intense sound. A tolerable level change threshold corresponding to the amount of noise above or below the effective quiet which has no great effect on the ear as compared to effective quiet is determined and stored in memory **127** in a step **320**. In a step **322**, the differential between the weighted sound pressure level and the effective quiet is compared to the level change threshold.

A differential value A, corresponding to the level change, can be calculated as follows:

$$A=SPL_W(n)-PSL \tag{11}$$

If A is greater than the level change threshold, the noise is considered to increase risk for hearing damage and the sound pressure level dose is calculated in a step **324** as follows:

$$SPL\ \text{Dose}(n)=SPL\ \text{Dose}(n-1)+(\text{Update_Epoch}(n)/\text{Time_100\%}) \tag{12}$$

where SPL Dose(n−1) is the SPL Dose calculated during the last epoch; Update_Epoch is the time (in hours) since the last SPL Dose was calculated. As described above, Update_Epoch can be adaptive, e.g., shortened when the sound pressure level is louder; and Time_100% (n), the time period remaining for safe exposure is determined by the equation:

$$\text{Time_100\%}(n)=24\ \text{hours}/(2\hat{}((L-PSL)/3)) \tag{13}$$

where L=sound level (in dB) of the combination of environmental noise and audio playback. It should be noted that sound level (L) can be substituted for SPL_W(n).

It should be noted, as can be seen from the equation, that the time value becomes more important than the sound pressure level as updates are spread apart. However, this is to protect overexposure to harmful sounds because a less accurate sample size must account for the unknown. The wider the periodicity, the less accurate determination of actual exposure. Infrequent updates of the SPL Dose assume a relatively constant sound level, ignoring transients (e.g. spikes) and intervening restorative periods. Accordingly, sound pressure level and epoch periodicity are weighed against each other to protect the ear.

If in step **322** it is determined that the differential is not greater than the level change threshold, including negative values for A (which are restorative values), then in step **326** it is determined whether or not the differential, as determined in step **316**, is less than the level change threshold in a step **322**. If it is determined that the differential is not less than the level change threshold, then the received noise was the effective quiet level, i.e., the level change threshold equals zero and in a step **330**, the current SPL Dose is maintained at the same level. There is no change to the dose level. However, if the differential A is less than the level change threshold then this is a restorative quiet as determined in step **326**. Thus, if the differential A (e.g., A=SPL_W(n)−PSL) is less than zero, within measurement error, then this is considered a restorative quiet, then the n-th SPL dose is determined as (at step **328**)

$$SPL\ \text{Dose}(n)=SPL\ \text{Dose}(n-1)*e\hat{}(-\text{Update_epoch}/\tau) \tag{14}$$

Where: τ (referred to as "tau" in the following diagrams) can vary (e.g., equal to about 7 hours). In some exemplary embodiments, tau is adaptive for different users. In at least one exemplary embodiment, the level change threshold (e.g., measurement error) is set at substantially 0.9-1.0 dB.

Note that other forms of a recovery function can be used and the description herein is not intended to limit the recover function to an exponential relationship. For example, during lower exposure times (e.g., 102 minutes) some SPL values (e.g., 95 dB) can be used, if the subsequent SPL is less than PSL, in a linear manner (for example linearly decreasing until there is a near zero threshold shift at 4000 Hz after one day from the time at which SPL<PSL).

Another non-limiting example of a recovery function can be a combination over certain exposure and decay periods (e.g., 7 day exposure at 90 dB, with an initial threshold shift after the 7 days of about 50 dB at 4000 Hz). For example a slow decaying linear relationship can be applied for the first few hours (e.g., 2 hours) where SPL<PSL, then an exponential decay from after the first few hours to a few days (e.g., 4 days) after which a leveling trend can occur.

Additionally although a fractional increase in SPL Dose is given as a non-limiting example, SPL Dose increase can be linear or exponential depending upon the exposure SPL level and the duration. For example the growth can be linear at a certain SPL values (e.g., 95 dB) during different ranges of exposure time (e.g., for 95 dB, from about 4 minutes to 12 hours), then leveling out (e.g., threshold shift of about 59.5 dB) when the exposure time exceeds a certain length (e.g., for 95 dB about 12 hours).

In at least one exemplary embodiment the SPL values measured by an ECM (e.g., in an ECM mode) can be modified by a modification value (e.g., additive or multiplicative), for example $SPL_{new}=\beta SPL_{old}+\delta$, where the values, β and δ, can be time variant, positive or negative. Alternatively the values can be applied to the measured pressure values in a similar manner. One can convert the SPL measured by an ECM to free field values, which then can be compared to free field standards for damage risk criteria. For example Table 1 lists several frequency dependent responses of an earpiece while inserted, the "A" weighting curve offset, and the modification values β and δ.

TABLE 1

Freq. (Hz)	Earpiece Freq. Resp. (dBSPL/V)	"A" weight offset (dB)	β (dB)	δ (dB)
100	95	−19.1	1.0	0.00
500	103.5	−3.2	1.0	−0.13
1000	104.0	0.0	1.0	−1.83
2000	121.0	1.2	1.0	−7.84
4000	106.0	1.0	1.0	−15.57

Thus, for example an SPL (f) measured at 80 dB, at f=1000 Hz, would be subtracted by −1.83 to obtain a free field value to compare with damage-risk criteria, thus obtaining an SPL_{new} of 78.13 dB. Note what is described is a non-limiting example, various other earpieces can have different values, and the SPL_DOSE equations, described herein, (e.g., SPL_Dose(n), Time_100%) can be based upon SPL_{new}. Note that

further discussions concerning frequency responses and free field estimate (FFE) conversion can be viewed in U.S. Pat. No. 6,826,515, Bernardi et al. Alternatively ear canal dBA SPL (e.g., as measured by an ECM) may be converted to FFE dBA SPL using Table 1 of ISO 11904-1 (2002), incorporated herein by reference.

In step **332**, the recovery time constant tau is determined. It may not be a function of exposure, but rather of recovery. It can be a default number or be determined as will be discussed below. As the SPL Dose is calculated by system **100**, it is also monitored. Once the SPL Dose reaches a certain level, as it is a cumulative calculation, ear fatigue calculator **130** determines whether or not the SPL Dose corresponds to a fatigued ear, and if so, it outputs warnings as discussed in connection with FIG. **1**.

Reference is now made to FIG. **5** which depicts an optional methodology for not only updating the recovery time constant (tau) for individual users, but to provide additional methods for acting upon detected damaging exposure. The process is started at a step **548**. In a step **550**, it is determined whether or not the user wishes to make use of a registration process, for example online, for setting a personalized update epoch through communication with a remote registration system. If the user declines the registration, then the default tau is set at 7 hours in a step **552**. In a step **554**, this default value is transmitted to system **100** via a wired or wireless data communication network.

Alternatively, if the user registers in step **550**, a questionnaire is presented in a step **556** in which the user informs system **100** regarding a user sound exposure history, age, work habits and other personal details that could affect the user's personal recovery function time, i.e., the time constant tau. The individual characteristics can be input to a formula or utilized as part of a look up table to determine the tau for the individual user. The estimate of tau determined in step **556** is transmitted to system **100** via a wireless or wired data communication system in a step **558**. In step **560**, the initial estimate of tau is set from the value determined in step **556** (or step **552**).

An initial hearing test is performed in a step **561**, which acquires data indicative of the user's hearing sensitivity. The test may be an otoacoustic emission (OAE) test or audiogram administered utilizing the ear canal receiver or speaker **25**. However, the test can also be administered over the Internet, telephone or other communication device capable of outputting sounds sent across a distributed network and enabling responsive communication. The data is stored in a computer memory as an initial test value in a step **570** and is used in further processing to detect a change in the user hearing response.

In a step **564**, it is determined whether the user has been recently exposed to intense sound pressure levels. This can be done utilizing the sound pressure level dose as stored or permanently calculated by system **100**. If it is decided in step **564** that the user's ear canal sound pressure level is low, then in a step **559** it is determined whether the time since the last test is greater than a maximum test epoch. At the outset, the maximum test epoch is a set number determined in a step **562**. In this non-limiting example, the maximum test epoch is set at 20 hours.

If it is determined that the time since the last test is greater than the maximum test epoch or, that there has been recent exposure to intense sound pressure level, then another test is administered in a step **566**. The resulting test metrics are stored in steps **568**, **570**. In a step **571**, the newly determined test metrics are compared to the initial test metrics to calculate any change in the metrics. In step **572**, it is determined whether the change is predictive of hearing damage. If not, then in a step **582**, the tau is modified according the obtained metric.

If it is determined that the hearing damage is predicted, then in a step **578** the user is recommended to remove themselves from the noise as discussed above with the operation of listening fatigue calculator **130** and furthermore, the user can be recommended to seek professional audiological evaluation in a step **578**. This could be done by an in situ auditory or visual warning in step **580** by system **100**. On the other hand, if system **100** is used in connection with a communications device such as a telephone or a personal digital assistant, an e-mail can be created in steps **574**, **576**; not only warning the user of potential damage, but notifying a health professional so that a follow up examination can be performed.

It should be noted that a change in the hearing metric (e.g., a hearing sensitivity curve) is measured by system **100**. In response to the user's hearing metric, the recovery time constant tau is updated. For example, tau is lengthened if the change in the user's hearing metric indicates the user has "sensitive ears", i.e., if, following loud sound exposure, the user's hearing sensitivity takes longer than seven hours to return to the individual's normal. This modified tau can be used to calculate the sound pressure level dose, in particular in a restorative phase, to determine better overall effect of sound pressure level exposure.

By providing a monitoring and protective system which, in at least one mode, continuously monitors sound pressure level at the ear until a potentially harmful exposure has occurred, rather than only monitoring for a predetermined time as with noise dose monitors which monitor for work shifts, a more accurate predictor of harm to the ear is provided. By utilizing a method, which determines exposure in part as a function of effective quiet exposure as well as intense noise exposure, an enhanced model of potential risk is achieved. By providing a series of warning mechanisms and preventive measures as a function of the determined potentially harmful dosage levels ear damage is more likely to be prevented. By providing the system in an earpiece which substantially occludes the ear and making use of audio inputs at the lateral and medial portions of the ear canal (particularly with an occluding device between lateral and medial portions of the ear canal), a more accurate reading of noise level is provided and more control through a real time warning system is achievable.

It should be known that values for level change threshold, effective quiet time, and epoch were used above as examples. However, it should be noted that any values which when input and utilized in accordance with the methodologies above prevent permanent damage to the ear are within the scope of the invention and the invention should not be so limited to the specific examples above.

Further Exemplary Embodiments

FIG. **8** illustrates the general configuration and some terminology in accordance with descriptions of exemplary embodiments. An earpiece **800** can be inserted into an ear canal separating the ambient environment (AE) **890** from an inner ear canal (IEC) **880** region, where a portion of the earpiece **800** touches a part of the ear canal wall (ECW) **870**. The earpiece **800** can be designed to vary its distance from the eardrum (ED) **860**. The earpiece **800** can have various elements, and the non-limiting example illustrated in FIG. **8**, can include three sound producing or receiving elements coupled to input/output **840**: an ambient sound microphone (ASM) **830** configured to sample the AE **890**; an ear canal micro-

phone (ECM) **820** configured to sample the IEC **880**; and an ear canal receiver (ECR) **810** configured to acoustically emit into the IEC **880**.

FIGS. **9**A-**9**C illustrates an example of a temporal acoustic signal and its conversion into a spectral acoustic signature. FIG. **9**A illustrates a temporal acoustic signal (AS) **900** on a generic X-Y coordinate system (e.g., Y can be amplitude in dB, and X can be time in sec). A section **910** of the AS **900** can be selected for further processing (e.g., for applying filtering treatments such as a FFT). For the non-limiting example of using a Fast Fourier Transform (FFT) on section **910**, a window **920** can be applied to the section **910** to zero the ends of the data, creating a windowed acoustic signal (WAS) **930**. An FFT can then be applied **940** to the WAS **930** to generate a spectral acoustic signal (SAS) **950**, which is illustrated in FIG. **9**C, where the Y-axis is a parameter (e.g., normalized power) and the X-axis is frequency (e.g., in Hz).

FIG. **10** illustrates a generalized version of an earpiece **800** and some associated parts (e.g., ASM **830**, ECM **820**, and ECR **810**) in an ear canal. When inserted the earpiece **800** generally defines the two regions **890** and **880**. Through the earpiece **800** there is some attenuation. For example an ambient acoustic signal (AAS) **1010**A, will travel through the earpiece **800** and/or via bone conduction (not shown) and be attenuated forming an attenuated ambient acoustic signal (AAAS) **1010**B. The AAAS **1010**B then travels to the ED **860**. The other additional acoustic signal **1010**C (e.g., the ECR generated AS or ECRAS), which can travel to the eardrum **860**, can be generated by the ECR **810**. Thus the total AS imparting energy upon the ED **860** can be due to the AAAS **1010**B (which can include a bone conduction part not in the IEC **880**) and the ECRAS **1010**C. Various exemplary embodiments can calculate SPL Dose due to the total imparting AS upon the ED **860**, using various combinations of elements (e.g., parts) such as the ECR **810** (e.g., Knowles FG3629), the ECM **820** (e.g., Knowles FK3451), and the ASM **830** (e.g., Knowles FG3629). Note that ECM **820** can also measure head attenuated acoustic signals (HAAS) **1010**D, which for example could originate from voice.

FIG. **11** illustrates an earpiece **1100** according to at least one exemplary embodiment including an ECR **810** and an ECM **820** (not shown). ECRAS **1010**C generated by the ECR **810** can be predicted and used to predict an equivalent SPL Dose as discussed later. Note that additional elements (e.g., logic circuit(s) (LC), power source(s) (PS), can additionally be included in the earpiece **1100**). For example FIG. **12** illustrates a self contained version of an earpiece **1200** according to at least one exemplary embodiment, including a power source (PS) **1210** (e.g., zinc-air battery (ZeniPower A675P), Li-ion battery), and a logic circuit (LC, e.g., Gennum Chip GA3280) **1220** in addition to ECR **810**. Earpiece **1200** can also include a wireless module for wireless communications (not shown) or can be wired. Earpiece **1200** can also connect remotely to various parts (e.g., via a wired or wireless connection). For example FIG. **13** illustrates an earpiece **1300** where parts are not contained in the earpiece directly according to at least one exemplary embodiment. As illustrated the LC **1220** and PS **1210** are operatively connected (OC) **1310** (e.g., via a wire or wirelessly) to the earpiece **1300**. For example earpiece **1300** can be an earbud that includes ECR **810**, whose signals travel back and forth via a wire that is operatively connected via a wire to LC **1220**, which in turn can be operatively connected to PS **1210**. Note that ECR **810** can also be a dual purpose ECR/ECM, where when the receiver function (ECR mode) is not used the microphone function (ECM mode) can be used. For example U.S. Pat. No. 3,987,245 discusses a dual purpose transducer that can be used as a microphone and/or a receiver.

FIG. **14**A illustrates a general configuration of some elements either in or connected to an earpiece **1400** (e.g., via a wired or wireless connection) according to at least one exemplary embodiment. Illustrated is a logic circuit LC **1220** that is operatively connected **1310**B to a readable memory **1420**. LC **1220** can store and read data on the readable memory **1420** (e.g., RAM). LC **1220** can also be operatively connected **1310**C to ECR **810**, such that acoustic signals can be received by LC **1220** from ECR **810** and signals sent from LC **1220** to ECR **810**, where ECR **810** is configured to direct acoustic energy toward the eardrum. LC **1220** can also be operatively connected **1310**E (e.g., via wire or wireless) to a communication module **1410** (e.g., Bluetooth communication module). To power the various elements a power source **1210** PS can also be operatively connected **1310**F to LC **1220** and to any other element.

FIG. **14**B illustrates a flow diagram of a method for SPL Dose calculation according to at least one exemplary embodiment. A signal (e.g., intended audio playback content, or received voice from a phone) can be sent to LC **1220** to be sent to the ECR **810**. The signal can be converted (e.g., using earpiece frequency response) to calculate the SPL(t) associated with the signal being sent to ECR **810**. Thus the signal to the ECR **810** can be measured in step **1450**A, an SPL measured for a chosen period of time. An SPL_Dose estimate is calculated as described above, in a step **1450**B. The SPL_Dose estimate is added/subtracted to/from a running SPL Dose total to obtain a new SPL Dose total in a step **1450**C. The new SPL Dose total is compared to a threshold value in a step **1450**D. If the threshold value is exceeded the LC **1220** compares a check action parameter, which can be a user defined variable, to determine one or more actions to take in a step **1450**E. For example if the action parameter is a certain value (e.g., 1) then the action can be to modify device operation in a step **1450**H. For example, to shut down the device after a period of time (e.g., 5 seconds). Alternatively or cumulatively, if the action parameter is another value (e.g., 2), a notification signal can be sent (e.g., acoustic notice, for example a ringing) in a step **1450**F, and/or if the action parameter is still another value (e.g., 3) the audio content can be modified (e.g., SPL output by ECR s reduced), in a step **1450**G. Note other actions can be included, in a step **1450**I, for example the NRR can be increased (e.g., if an inflatable system, the inflatable system can be expanded, or active noise cancellation could be activated).

Note that at least one exemplary embodiment can use an ECR **810** without dual functionality (e.g., where dual functionality is an ECR that can be a receiver and/or a microphone) and at least one further exemplary embodiment can be a dual function ECR/ECM. To measure the SPL for an ECR only mode (ECR mode) the same SPL Dose equations described above can be used for the SPL estimated as discussed with reference to FIG. **14**B. Additionally the SPL_{ECR} can be estimated by an ECR instrument response, e.g., a voltage to FFE dBA transfer function, which could be determined one of two ways: apply voltage to ECR **810** and follow the technique outlined in ISO 11904-2 (2002), using an acoustic manikin and/or apply voltage to ECR **810** and follow the technique outlined in ISO 11904-1 (2002), using probe microphone measurements in a human's ear canal; and/or about a 2 cc coupler could substitute for a human's ear canal.

FIG. **14**C illustrates a flow diagram of a method of SPL Dose calculation according to at least one exemplary embodiment. In addition to an exemplary embodiment where only an ECR **810** is operating, a dual ECR/ECM can be used. Thus

ECR **810** can be switched in such a case between an ECR mode, where audio signal is directed to the ECR **810** (e.g., audio playback (e.g., music, audio book, voice message), or voice conversation (e.g., voice from a phone, TV, computer)) or to an ECM mode, where ECR **810** acts as an ECM and samples environmental SPL. FIG. **14**C illustrates a method in accordance with at least one exemplary embodiment and first comprises: determining which mode ECR **810** is in, ECR mode or ECM mode, in step **1470**A. If ECR **810** is in the ECR mode the method as discussed with reference to FIG. **14**B, in step **1470**B, can be used to obtain an SPL_{ECR} estimate, within the sample time "t" in a step **1470**B, to either obtain SPL_Dose_{ECR} in a step **1470**C, or save the value of SPL_{ECR} to be added later to an SPL value for the environment, within sample time "t", to obtain a total SPL and then calculate a total SPL Dose in a step **1470**D. Because in the ECR mode an ECM measurement is not made, the true environmental SPL value is not obtained, however several methods can be used to obtain a predicted sound pressure level (PSPL) for the environment during the ECR mode. One of these methods, others will be discussed with respect to FIGS. **15**E and **17**A, is to use the last SPL_{ECM} value recorded, throughout the sample time "t" to obtain an SPL_Dose_{ECM} then add SPL_Dose_{ECR} to SPL_Dose_{ECM} to get SPL $Dose_{total}$. Alternatively, one can obtain $SPL_{total}=SPL_{ECR}+SPL_{ECM}$, then calculate SPL $Dose_{total}$ where SPL_{total} can be used in "A" to determine if a recovery function is used for calculation of SPL $Dose_{total}$.

Additionally, ECM mode data can be saved as a function of day of the week and time of day, and used to correct any PSPL estimated that may occur at the same time and day in the future, which would correct any SPL_Dose_{ECM} obtained using PSPL in a step **1470**E, and a new SPL $Dose_{total}$ can be calculated in a step **1470**F. The new SPL Dose total can be compared to a threshold value in a step **1470**K, and if the threshold value is exceeded the LC **1220** compares a check action parameter, which can be a user defined variable, to determine one or more actions to take in a step **1470**L. For example if the action parameter is a certain value (e.g., A) then the action can be to modify device operation in a step **1470**M, for example to shut down the device after a period of time (e.g., 10 seconds). Alternatively or cumulatively, if the action parameter is another value (e.g., B), a notification signal can be sent (e.g., acoustic notice, for example a notification voice recording) in a step **1470**P, and/or if the action parameter is still another value (e.g., C) the audio content can be modified (e.g., SPL output by ECR can be reduced) in a step **1470**O. Note other actions can be included in a step **1470**N, for example the ECR emitted intensity can be reduced.

If ECR **810** is placed into ECM mode, then SPL_{ECM} can be measured in ECM mode in a step **1470**G, and an ambient SPL $Dose_{ECM}$ calculated during the sampling time "t**1**" in a step **1470**H. Note the SPL $Dose_{ECM}$ calculated can be stored for future reference in a step **1470**I and/or SPL_{ECM} can be stored as a function of prediction variables (e.g., time of day, day of the week) in a step **1470**J.

FIG. **14**D illustrates a flow diagram of a method of SPL Dose calculation according to at least one exemplary embodiment. The method includes: calculating the SPL_Dose during the ECR mode for time increment "Δt" in a step **1480**A. PSPL for the same time increment is calculated in a step **1480**B. This can include using SPL data from ECM mode measurements saved in a database **1492**. SPL_Dose for the ECM mode is calculated during the same time increment using PSPL. SPL_Dose total is calculated in a step **1480**C. Note that SPL for the ECR mode and PSPL can be combined forming an SPL total and then SPL_Dose total is calculated in a step **1480**D. SPL_Dose total is compared to a threshold value, for example the threshold value can be equivalent to a % of the remaining allowable SPL_Dose during the day (e.g. SPL_Dose is 90% allowable but with only 5% of the day remaining) in a step **1480**E, and if the threshold value is exceeded the LC **1220** compares a check action parameter, which can be a user defined variable, to determine one or more actions to take in a step **1480**F. For example if the action parameter is a certain value (e.g., MOD) then the action can be to modify device operation in a step **1480**J, for example to shut down any ECR generated audio content. Alternatively or cumulatively, if the action parameter is another value (e.g., NOTF), a notification signal can be sent (e.g., acoustic notice, for example an acoustic earcon) in a step **1480**G, and/or if the action parameter is still another value (e.g., AUDCON) the audio content can be modified (e.g., SPL output by ECR can be reduced) in a step **1480**H. Note other actions can be included in an omnibus step **1480**I, for example the ECR emitted intensity can be reduced.

FIGS. **15**A-**15**E illustrate a method of switching between ECR and ECM modes in accordance with at least one exemplary embodiment. FIG. **15**A illustrates a plot of SPL_{ECR} versus time. At certain times, e.g. t**1**, SPL_{ECR} falls below a selected floor (SF), e.g., threshold hearing SPL level at 1000 Hz, which could last to a time of t**1**+Δt**1**. During this time period a dual ECM/ECR mode capable ECR **810** could then monitor ambient SPL levels in an ECM mode. Thus in at least one exemplary embodiment when the SPL in the ECR mode drops below the SF a trigger signal (e.g., sts_{ECM}) can be sent to LC **1220** to switch to ECM mode for measuring ambient SPL (FIG. **15**B). There can be a delay, t_{delay}, between when the SPL in the ECR mode drops below SF and when the signal sts_{ECM}, is received by LC **1220**. Upon receiving sts_{ECM} the dual ECR/ECM mode capacity ECR **810** can start monitoring SPL_{ECM}, FIG. **15**D.

Thus there will be sections of time throughout the day where SPL_{ECM} is measured (e.g., t**1** to t**1**+Δt**1**, t**2** to t**2**+Δt**2**, t**3** to t**3**+Δt**3**, and t**4** to t**4**+Δt**4**), these values can be saved and used later to fit a function of Predicted SPL (PSPL) for the particular day (e.g., $PSPL_{24}=A+Bt+Ct^2+Dt^3$, using a least squares fit to the measured data for that day to obtain coefficients A, B, C, D). In at least one exemplary embodiment $PSPL_{24}$ can be used at the end of the day to refine (e.g., replace, average with) the PSPL used during that day to update the SPL_Dose equation. Note that $PSPL_{24}$ can be saved in a database (i.e., the coefficients A, B, C, D) as a function of various variables (e.g., day of the week, holiday period, seasons) and refined (e.g., updated with more data) over time. Thus, in at least one exemplary embodiment, $PSPL_{24}$ for that day can be used to refine predicted SPL_{ECM} (PSPL) during ECR mode, while the actual data SPL_{ECM} is used when measured (e.g., FIG. **15**E). Note since drive signals (e.g., audio playback signals, voice communication signals, alarm signals) sent (sometimes referred to herein as acoustic signals sent) to ECR **810** are known, then it will be known when to send a signal sts_{ECR} to LC **1220** to switch back to ECR mode (FIG. **15**C). Thus the total ambient SPL (FIG. **15**E) before update with $PSPL_{24}$, will be a combination of calculated PSPL during ECR mode operations and actual measurements SPL_{ECM}.

There are multiple methods of calculating PSPL, and we will discuss five non-limiting examples in detail.

First Example of Calculating PSPL

The first non-limiting example for calculating PSPL uses averages of the preceding and following SPL_{ECM} values with

respect to the PSPL being predicted. Thus, with reference to FIGS. **15**D and **15**E, $PSPL_{ECM1}(t)$ can be estimated as:

$$PSPL_{ECM1}((t_1+\Delta t_1)<t<t_2)=\frac{\left[\left(\frac{1}{\Delta t_1}\int_{t_1}^{t_1+\Delta t_1}SPL_{ECM1}(t)\,dt\right)+\left(\frac{1}{\Delta t_2}\int_{t_2}^{t_2+\Delta t_2}SPL_{ECM2}(t)\,dt\right)\right]}{2.0} \quad (15)$$

Thus, FIG. **15**E illustrates PSPL estimates as straight lines (although of course other methods and techniques can be used that will not result in straight lines). These estimated PSPL can be later refined by use of $PSPL_{tupdate}$, where $PSPL_{tupdate}$, is an equation refined by the data over the tupdate period (e.g., $PSPL_{24}$, where tupdate is 24 hours in the non-limiting example previously discussed, note tupdate can be any period of time with enough data to solve the coefficients of the particular form of the equation). Note that the integrals can be replaced with summations, for example when manipulating digitized data.

Second Example of Calculating PSPL

A second non-limiting example of calculating PSPL uses weighted averages, where the SPL_{ECM} data can be weighted according to several factors, for example the time increment during which measurements are made. A time incremented weighting can be expressed as:

$$PSPL_{ECM1}((t_1+\Delta t_1)<t<t_2)=\frac{\left[\frac{\Delta t_1}{\Delta t_1+\Delta t_2}\left(\frac{1}{\Delta t_1}\int_{t_1}^{t_1+\Delta t_1}SPL_{ECM1}(t)dt\right)+\frac{\Delta t_2}{\Delta t_1+\Delta t_2}\left(\frac{1}{\Delta t_2}\int_{t_2}^{t_2+\Delta t_2}SPL_{ECM2}(t)dt\right)\right]}{2.0} \quad (16)$$

Third Example of Calculating PSPL

A third non-limiting example is a linear model of the PSPL in time. For example, where in general PSPL is expressed as PSPL(t)=X+Yt. Using average values an example of a linear model can be expressed as:

$$PSPL_{ECM1}(t)=\frac{1}{\Delta t_1}\int_{t_1}^{t_1+\Delta t_1}SPL_{ECM1}(t)dt+\eta_{(t_1+\Delta t_1)\to t_2}(t)t \quad (17)$$

Where in this non-limiting example X is the average of the preceding SPL_{ECM} values, and Y is η=constant, where η can be expressed as:

$$\eta_{(t_1+\Delta t_1)\to t_2}(t)=const.=\frac{1}{t_2-(t_1+\Delta t_1)}\left[\frac{1}{\Delta t_2}\left(\int_{t_2}^{t_2+\Delta t_2}SPL_{ECM2}(t)\,dt\right)-\frac{1}{\Delta t_1}\left(\int_{t_1}^{t_1+\Delta t_1}SPL_{ECM1}(t)\,dt\right)\right] \quad (18)$$

Fourth Example of Calculating PSPL

A fourth non-limiting example is a linear model of the PSPL in time. For example, where in general PSPL is expressed as PSPL(t)=X+Yt. Using preceding and trailing last values of SPL_{ECM}, where an example of a linear model can be expressed as:

$$PSPL_{ECM1}(t)=SPL_{ECM1}(t_1+\Delta t_1)+\eta_{(t_1+\Delta t_1)\to t_2}(t)t \quad (19)$$

Where in this non-limiting example X is the last of the preceding SPL_{ECM} values, and Y is η(t), where η can be expressed as:

$$\eta_{(t_1+\Delta t_1)\to t_2}(t)=\frac{1}{t_2-(t_1+\Delta t_1)}[SPL_{EMC2}(t_2)-SPL_{ECM1}(t_1+\Delta t_1)] \quad (20)$$

Fifth Example of Calculating PSPL

A fifth non-limiting example examines a non-linear model of PSPL in time. For example, where in general PSPL is expressed as $PSPL(t)=\alpha+\beta t+\delta t^2+\ldots$. In one method the actual values in the preceding and trailing sections of SPL_{ECM} can be compared to the model PSPL results upon parameter (e.g., α, β, δ) choices in a least squares approach. Note in this case PSPL is modeled from t_1 to $t_2+\Delta t_2$. For example a model of PSPL can be solved via the expression:

$$PSPL_{ECM1}(t)\Rightarrow\alpha,\beta,\delta\xrightarrow{minimize}\left(\int_{t_1}^{t_1+\Delta t_1}[PSPL_i(t)-SPL_{ECM1}(t)]^2\,dt+\int_{t_2}^{t_2+\Delta t_2}[PSPL_i(t)-SPL_{ECM2}(t)]^2\,dt\right) \quad (21)$$

Note to minimize one can take the derivative of the above equation and look for the inflection points as a function of i. Note in the above equation $PSPL_i$ can be expressed as:

$$PSPL_i(t)=\alpha_i+\beta_i t+\delta_i t^2+\ldots \quad (22)$$

where a value for $PSPL_i$ is obtained for "t" by selecting a guess ("ith" guess) for the parameters, then incrementing ("i+1") the parameters to get a new value for $PSPL_{i+1}$, the procedure of which is known by one of ordinary skill in the relevant arts.

Note that the above five examples of calculating PSPL are non-limiting examples and other methods can be used.

FIGS. **16**A-**16**C illustrate the formation of SPL total from ECM and ECR values and estimated values (PSPL). For example FIG. **16**A illustrates two SPL values in the interval 0 to t_1, $SPL_{ECR0}(t)$ and $PSPL_{ECM0}(t)$. Both of these values can be added to form $SPL_{total}(t)$ in the same interval from 0 to t_1 (FIG. **16**B). As discussed the value of SPL_{total} can be compared with PSL to determine whether one is in a SPL_Dose growth phase (SPL_{total}>PSL) or a recovery stage (SRL_{total}<PSL) (FIG. **16**C). Note that the jumps in SPL_{total} can result when no signal is sent to ECR **810** to emit acoustic energy to the eardrum. When SPL total is above PSL, SPL_Dose increases. Over the period of the day, SPL_Dose will increase or decrease. At least one exemplary embodiment adjusts the SPL_Dose after an update period (e.g., 24 hours). For example the data from actual measurements of $SPL_{ECM}(t)$ (e.g., during t_1 to $t_1+\Delta t_1$, during t_2 to $t_2+\Delta t_2$, during t_3 to $t_3+\Delta t_3$, and during t_4 to $t_4+\Delta t_4$) can be used to obtain a

$PSPL_{update}$, for example using a method similar to the fifth PSPL calculating example discussed above. The values provided by the equation $PSPL_{update}(t)$ can be used in place of $PSPL_{ECM0}(t)$, $PSPL_{ECM1}(t)$, etc. . . . and the new values used to update SPL_Dose total. In at least one further exemplary embodiment, instead of replacing $PSPL_{ECM0}(t)$, $PSPL_{ECM1}(t)$, etc. . . . , the relevant values of $PSPL_{update}(t)$ can be combined (e.g., weighted average). For example FIGS. **17**A-**17**C illustrate replacement of $PSPL_{ECM0}(t)$, $PSPL_{ECM1}(t)$, . . . values with relevant $PSPL_{day}(t)$ values, where the update time is 24 hours or a day. Thus FIG. **17**A illustrates the estimated $SPL_{ECR}(t)$ values along with relevant $PSPL_{day}(t)$ values. Note that the actual measured values of $SPL_{ECM}(t)$ can be used instead of the $PSPL_{day}(t)$ values in the time increment (e.g., from t_1 to $t_1+\Delta t_1$). The final $SPL_{total\text{-}adjusted}(t)$ values can be obtained by combining $SPL_{ECR}(t)$ values along with relevant $PSPL_{day}(t)$ values, FIG. **17**B, where $SPL_{total\text{-}adjusted}(t)$ can have different values than $SPL_{total\text{-}unadjusted}(t)=SPL_{total}(t)$ (FIG. **16**C) as illustrated in FIG. **17**C. As mentioned previously when $SPL_{total}>PSL$, SPL_Dose is in a growth stage, and when $SPL_{total}<PSL$, SPL_Dose is in a recovery stage, as illustrated in FIG. **17**D.

Exemplary embodiments of the present invention can be used in many platforms that direct and/or attenuate acoustic energy in the ear canal. FIGS. **18**A to **18**N illustrate various non-limiting examples of earpieces that can use methods according to at least one exemplary embodiment, when the various earpieces have an ECR **810** that is solely an ECR or have an ECR **810** that has dual ECR/ECM modes.

FIG. **19** illustrates a line diagram of an earpiece **1900** (e.g., having earbud **1910**) that can use methods according to at least one exemplary embodiment and FIG. **20** illustrates the earpiece of FIG. **19** fitted in an ear canal. Earbuds **1910** can be used with many devices such as audio playback devices, PDAs, phones, and other acoustic management devices. The software to implement exemplary embodiments can reside in the earpiece (e.g., hearing aid) or can reside in the acoustic management systems (e.g., iPod™, Blackberry™, and other acoustic management devices as known by one of ordinary skill in the relevant arts).

While the present invention has been described with reference to exemplary embodiments, it is to be understood that the invention is not limited to the disclosed exemplary embodiments. The scope of the following claims is to be accorded the broadest interpretation so as to encompass all modifications, equivalent structures and functions of the relevant exemplary embodiments. For example, although specific numbers may be quoted in the claims, it is intended that a number close to the one stated is also within the intended scope, i.e., any stated number (e.g., 80 dB) should be interpreted to be "about" the value of the stated number (e.g., about 80 dB). Thus, the description of the invention is merely exemplary in nature and, thus, variations that do not depart from the gist of the invention are intended to be within the scope of the exemplary embodiments of the present invention. Such variations are not to be regarded as a departure from the spirit and scope of the present invention.

What is claimed is:

1. A method of operating an audio device configured to be inserted in an ear canal, the method comprising:

measuring sound pressure levels (SPLs) for at least one electrical drive signal directed to an ear canal receiver (ECR) during a time period Δt having a plurality of samples;

determining a SPL dose of the at least one electrical drive signal during the time period Δt using the measured sound pressure levels;

simultaneously estimating an ambient SPL dose within the ear canal during the time period Δt;

calculating a total SPL dose of the audio device using the SPL dose of the at least one electrical drive signal and the estimated ambient SPL dose; and

performing an action by the audio device when the total SPL dose is greater than a predetermined threshold.

2. The method according to claim **1**, further including:

comparing the measured sound pressure levels for the at least one electrical drive signal to a permissible sound level (PSL), and if the measured sound pressure levels are less than the PSL within an error margin, then the step of determining the SPL dose uses a recovery function to generate the SPL dose during the time period Δt.

3. The method according to claim **2**, where the error margin is zero.

4. The method according to claim **1**, further comprising:

reading an action parameter from a readable memory when the total SPL dose is greater than the predetermined threshold.

5. The method according to claim **1**, where the action includes at least one of modifying an operation of the audio device, modifying the at least one electrical drive signal directed to the ECR, and sending an acoustic notification signal to a user.

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