

# Development and Evaluation of a Portable Audiometer for High-Frequency Screening of Hearing Loss From Ototoxicity in Homes/Clinics

Peter G. Jacobs\*, *Member, IEEE*, Grayson Silaski, Debra Wilmington, Samuel Gordon, *Member, IEEE*, Wendy Helt, Garnett McMillan, Stephen A. Fausti, and Marilyn Dille

**Abstract**—Cancer treatment often requires patients to be exposed to drugs that can damage hearing. Drugs such as cisplatin can cause permanent damage to hearing if not detected early. Damage typically occurs first in the more basal regions of the cochlea which are specific for high-frequency (HF) hearing and progresses to more apical regions that are relevant to speech understanding. Monitoring of HF hearing loss can be an effective means for early detection of ototoxicity caused by chemotherapy. Once ototoxicity is detected, the oncology medical team could adjust the drug dosage or switch to medications that are less ototoxic. Telehealth technology may improve access to ototoxicity monitoring. Patients could monitor their own hearing using a device that alerts healthcare professionals in the event of a change in hearing. A portable audiometer is currently not available that is 1) capable of automatic or manual (by an audiologist) operation; 2) designed with precision pure-tone functionality up to 20 kHz; and 3) able to remotely transfer health status information to a healthcare professional. This paper describes the design of a technology, the ototoxicity identification (OtoID), that includes a portable audiometer with HF test functionality that meets ANSI/ASA S3.6-2010 standards and is capable of reliably detecting a person's drug-related hearing changes relative to a baseline period (i.e., before ototoxic drugs) using an automated test. The system includes a wireless cellular modem capable of notifying a remote healthcare professional in the event that a significant change in hearing has occurred in the patient. The system was evaluated on test subjects within a sound-proof booth, a noisy hospital ward, and within their homes. Results indicate that the OtoID system can be used by patients to effectively monitor hearing changes remotely within their home or in a hospital ward, ultimately enabling early detection of ototoxicity and potentially avoiding hearing loss.

**Index Terms**—Hearing screening, high-frequency (HF) audiometry, ototoxicity monitoring.

Manuscript received February 18, 2012; revised April 13, 2012; accepted May 29, 2012. Date of publication July 11, 2012; date of current version October 16, 2012. This work was supported in part by the U.S. Department of Veterans Affairs under Grant C6373R. *Asterisk indicates corresponding author.*

\*P. G. Jacobs is with the National Center for Rehabilitative Auditory Research, Portland VA Medical Center, Portland, OR 97239 USA (e-mail: peter.jacobs@va.gov).

D. Wilmington, S. Gordon, W. Helt, G. Mcmillan, S. Fausti, and M. Dille are with the National Center for Rehabilitative Auditory Research, Portland VA Medical Center, Portland, OR 97239 USA (e-mail: debwilm@comcast.net; samuel.gordon@va.gov; Wendy.Helt@va.gov; garnett.mcmillan@va.gov; sa.fausti@frontier.com; marilyn.dille@va.gov).

G. Silaski is with GRAYSON SILASKI, Portland, OR 97221 USA (e-mail: ncc621@gmail.com).

Digital Object Identifier 10.1109/TBME.2012.2204881

## I. INTRODUCTION

CERTAIN cancer-treating drugs are considered to be ototoxic in that they have the potential to irreversibly damage hearing. Each year 1.3 million Americans are diagnosed with cancer with 16% receiving a diagnosis of lung or head and neck cancers [1]. Depending on cancer stage, many patients with lung, head, or neck cancers receive treatment with cisplatin. Cisplatin, the most ototoxic agent, results in hearing shift during treatment in approximately 60% of adults and children [2]–[4]. Our recent work has shown that in Veterans, risk factors for ototoxicity are pre-exposure (to cisplatin) hearing threshold levels and cumulative cisplatin dose [5] such that those Veterans with better hearing are more likely to have hearing shift at lower cumulative doses than those with poorer hearing. This is significant since most Veterans (and some older adults) begin chemotherapy with significant hearing loss. Therefore, any hearing change has immediate impacts on their communication at a time when effective communication with family members and the medical team is important.

Ototoxic damage initially occurs near the HF-coded base of the cochlea before progressing apically to the lower frequency regions that are more relevant for speech understanding [6]. Ototoxic-induced changes in hearing can only be detected by assessing auditory function directly. Fausti and colleagues at the National Center for Rehabilitative Auditory Research (NCRAR) pioneered the use of HF audiometry focused on minimizing significant hearing loss through early detection. This research has identified a one octave range of hearing individualized to each patient's HF limit of hearing, called the sensitive range for ototoxicity (SRO), which is able to detect 94% of early changes in hearing during treatment [7]. The SRO is obtained by initially testing hearing from 0.5 to 20 kHz to find the highest frequency at which a threshold of 100 decibels (dB) of sound pressure level (SPL) is obtained. Thresholds in the next six consecutive lower frequencies, measured in 1/6th octave steps, comprise the SRO. The initial baseline test is done prior to treatment. Then, at each chemotherapeutic treatment interval, these seven frequencies are measured for hearing shift. The SRO technique is both time efficient and has been proven to be sensitive to early effects of cisplatin in the cochlea. Early detection of ototoxicity is important since it has the potential to minimize the significant negative effects of increased hearing loss following treatment by providing an opportunity for oncologists to adjust treatment protocols or to change to less ototoxic chemotherapeutic agents. If dosage

adjustment is not possible, the audiologist can plan for intervention strategies that include assistive listening devices/strategies as well as counseling relating to avoidance of loud noise exposure, which acts synergistically with drug exposure to cause damage.

Despite substantial evidence and clear implications that preventing significant post-treatment hearing loss improves outcomes for patients, early identification and monitoring practices have not been implemented as a standard of care in most medical centers largely due to limitations in audiometric testing equipment. Currently, the patient must go to an audiology clinic for testing. This is generally not feasible since patients are often severely ill or fatigued or live far away from a clinic. Currently, there are no commercially available portable audiometers capable of supporting high SPL output with required signal purity for accurate testing up to 20 kHz in 1/6th octave steps, a requirement for the SRO protocol. Portable audiometry would enable bedside testing of patients during treatment and home testing post-treatment. Furthermore, a portable device that has the capability for self-testing (automated) would reduce healthcare costs by enabling an alternative to requiring all facilities to maintain professional staff and equipment for ototoxicity monitoring.

Clinical testing at treatment intervals which can be two to three weeks apart may not provide earliest detection of hearing shift. Technological advances have allowed telemedicine to improve access, effectiveness, and efficiency of many aspects of healthcare including audiology services. Telemedicine not only enables healthcare delivery outside of centralized settings, but also allows minimally trained healthcare professionals or patients to monitor indicators of health, thus increasing patient access to healthcare. The 2005 technical report of the American Speech-Language-Hearing Association (ASHA) stressed the necessity to develop and to validate telepractice clinical protocols in audiology. There is a need for technology that would permit auditory testing at home by the patient; the technology would enable delivery of the results via a secure Health Insurance Portability and Accountability Act (HIPAA) compliant network to the health care team and would improve healthcare access for patients, particularly those in rural areas.

To address this clinical need, we have developed portable instrumentation called the ototoxicity identification (OtoID) system, to optimize the access, efficiency, and cost effectiveness of ototoxicity early identification practices. The OtoID includes an audiometric monitoring system with the ability to transmit information to healthcare personnel where trained professionals would interpret the results. An early version of this OtoID system was described by Ellingson *et al.* in [8] and [9]. These early versions did not include automated test functionality for self-evaluation of ototoxicity damage and the audiometry was designed using digital signal generation techniques. The current design presented in this paper describes methods to achieve higher quality audio based on an analog oscillator circuit, optical muting capability, discrete attenuators, ambient noise monitoring, and other features necessary for meeting ANSI/ASA S3.6-2010 specifications.

Nakamura [10] described a mobile audiometric testing system using the mobile phone as the platform. However, the purity of the audio is challenging to obtain for phone-based systems given the low-quality audio components on such devices and Nakamura does not show performance results above 10 kHz. Other groups have designed portable audiometers using desktop personal computers [11] or hand-held computers [12]. Performance metrics on these devices may not meet the stringent requirements of ANSI/ASA S3.6-2010 and little detail is provided on the performance of HF audiometry and test/retest performance, which are both critical for early identification of ototoxicity.

In this paper, we discuss the performance of the OtoID system designed for conventional and extended HF (9–20 kHz) audiometric testing for ototoxicity monitoring at home or in the clinic. OtoID is able to alert remote medical personnel through an on-board cell phone module (fully HIPAA compliant) of testing results. Design of the HF audiometric functionality and the telehealth components of the system are discussed. The performance of the OtoID was evaluated using four different groups: 1) the OtoID (automated and manual modes) were compared to a nonportable Grason–Stadler Model 61 (GSI-61) audiometer with an extended HF module (up to 16 kHz) using nine young normal hearing listeners tested in a sound booth; 2) additional 40 subjects were tested in a hospital treatment unit and in the sound booth to determine if thresholds were consistent across both environments; 3) ten of the subjects were trained to use the device independently and they retested themselves on three consecutive days within their home; and finally 4) a single chemotherapy patient was tested using OtoID during treatment to determine if the system could adequately detect threshold shifts. Results indicate that OtoID favorably compares with commercially available audiometers used for clinical testing in both the conventional (250 Hz–8 kHz) and extended HF range (8–16 kHz). Furthermore, test subjects are able to accurately self-evaluate their hearing both in a clinical setting and at home within the frequency ranges and step-sizes needed for ototoxicity monitoring.

The widespread implementation of ototoxicity monitoring best practices will help reduce progression of hearing loss into the speech communication range, ultimately improving outcomes for patients and preserving the quality of their lives following treatment.

## II. SYSTEM DESIGN

The OtoID system is comprised of 1) an ARM-based processor with a touch-screen 800×480 pixel color LCD monitor running Windows CE and the OtoID firmware; 2) a custom audiometer with an extended HF capability printed circuit board (PCB) for generating pure-tone HF audio and measuring ambient noise; 3) Sennheiser HDA 200 modified earphones; and (4) a Verizon Multitech (MTSMC-C1) 900-MHz cellular network modem used for transferring diagnostic results to an audiologist. The audiometer, touch-screen computer, and cellular modem are combined in a custom designed ergonomically styled portable package with a protective carrying case. Such portability is a key requirement for home use. A system diagram of the OtoID is shown in Fig. 1.

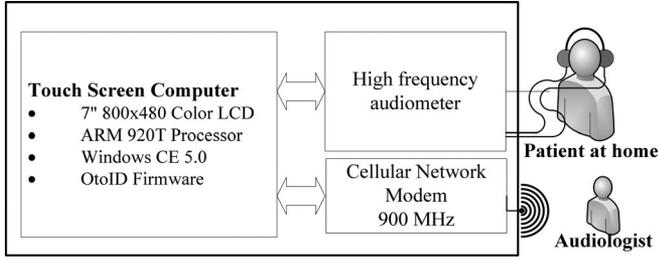


Fig. 1. OtoID includes an ARM-based computer running Windows CE 5.0 with a touch-screen monitor, a custom-built full-frequency audiometer, and a cellular network modem for sending test results to an audiologist.

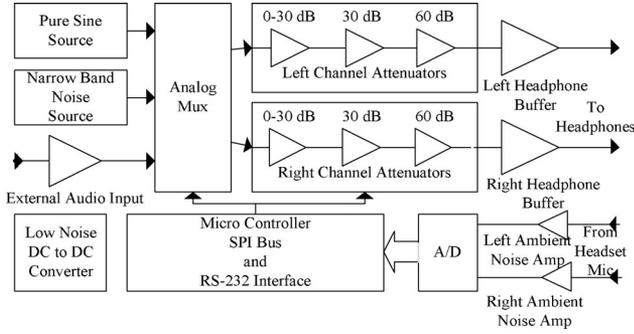


Fig. 2. Block diagram of an audiometer with HF capability.

### A. Design of the OtoID Audiometer Module

The audiometer module shown in Fig. 2 was designed for compliance with ANSI S3.6-2010 Pure-Tone Type 4 and HF requirements for audiometers.

Eliminating unwanted acoustical signals (e.g., hiss, clicks, pops, hums, and beeps) is a challenge in the design of audiometric instrumentation. Patients often have a reduced hearing threshold in the HF range. Any unwanted acoustical signals that might be unintentionally presented along with the stimulus could easily be perceived and incorrectly reported as a positive response. A similar problem is posed when electrical crosstalk between channels allows a stimulus from one channel to be heard in the opposite ear. In addition to producing stimuli of very high quality, the OtoID audiometer employs a number of measures to ensure that the audio channels remain free of any unintended sounds or artifacts, even at high output levels up to 105 dB SPL.

1) *Analog Pure-Tone Generator*: Fig. 3 shows the block diagram of a basic absolute oscillator consisting of two integrators and one inverting amplifier [13]. Each integrator provides  $90^\circ$  of phase shift and the inverting amplifier provides an additional  $180^\circ$  of phase shift that is fed back into the first integrator to reinforce the oscillation. Fig. 3 also shows the simplified schematic for the state variable oscillator used in the OtoID. Op amps  $A_1$  and  $A_2$  are configured as integrators and op amp  $A_3$  is configured as a unity gain inverter. The equation to calculate the frequency of oscillation  $F_{out}$  is derived in [13] and also given in Eq. 1.

$$F_{out} = \frac{1}{2\pi} \sqrt{\frac{R_4}{R_1 R_2 R_3 C_1 C_2}}. \quad (1)$$

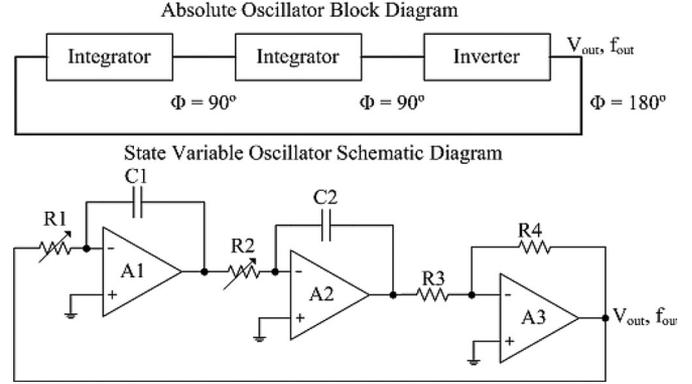


Fig. 3. Circuit diagram of pure-tone oscillator circuitry [14].

Variable resistors  $R_1$  and  $R_2$  are used to vary the frequency. The actual implementation of the variable resistors is accomplished using precision 12-bit multiplying DACs (TIDAC7811). The DACs are programmed by the system microcontroller as needed. With this approach, 4096 different frequencies can be selected by the controller on the audiometer board. The two pure-tone generators in the audiometer are designed around high-quality, analog state variable band-pass filters. Precision automatic gain controls provide unity gain feedback and configure the filter to operate an ultra stable, sine-wave oscillator of exceptional quality. This type of analog oscillator eliminates the spurious artifacts, distortion, and transients commonly encountered when producing sine waves using digital waveform synthesis.

The high performance operational amplifiers (AD8674) used in the sine-wave oscillators ensure low output distortion and low random noise. Passive components insensitive to temperature are used to ensure frequency and level stability.

2) *Optoelectronic Muting Circuits*: OtoID enables switching of the stimulus ON and OFF in a controlled and completely noiseless manner (section 5.4.4 of ANSI/ASA S3.6-2010). The OtoID audiometer design employs optoelectronic components called VACTROLS which are tiny assemblies that contain both an infrared LED light source and a cadmium sulfide (CdS) photoresistive cell. These devices are positioned inside the vactrol so that light from the LED illuminates the surface of the CdS cell. The resistance of a CdS cell will vary according to the amount of light energy illuminating its surface, thereby acting as an ideal continuously variable resistor.

A simplified schematic of one of the attenuator blocks of the audiometer is shown in Fig. 4. Op amp  $A_1$  is configured as an inverting amplifier whose gain is given by  $-R_2/R_1$  where  $R_2 < R_1$ . For example, if  $R_2 = R_1/100$  then the amount of attenuation would be 40 dB. The VACTROL resistive element is connected in parallel to  $R_2$ . The dark resistance of the photoresistor is much greater than the value of  $R_2$ . Increasing the current through the LED will proportionally decrease the resistance of the photoresistor until its resistive value remains much smaller than that of  $R_2$  effectively reducing the gain of the stage to nearly zero. By using a multiplying 12-bit DAC (TI DAC7811) in the place of  $R_1$  a digitally controlled attenuator is created.

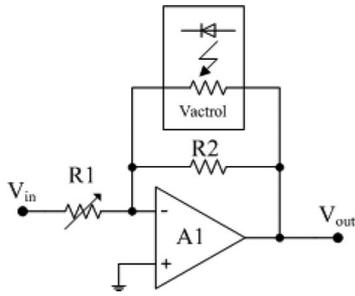


Fig. 4. Circuit diagram of a digital attenuator that uses VACTROL switches to quietly switch attenuator levels.

The VACTROLS are positioned at specific points within the six audio attenuator circuits, and by switching the LED illuminators ON and OFF, audio stimuli can be fully attenuated (muted) and restored (unmuted) at a controlled rate. The microcontroller in the audiometer modulates the VACTROL LED current so that light levels change on the CdS cells, which in turn controls the rise/fall rate of the CdS cell resistance. Using this method, the audiometer can provide calibrated stimulus rise and fall times in compliance with ANSI/ASA S3.6-2010 7.5.3.

3) *Discrete Attenuator Circuits*: The left and right attenuators in the audiometer are of a discrete, distributed design. While there are commercially available, integrated solutions for attenuating audio signals, none have the required distortion and crosstalk performance suitable for use in an HF audiometer.

To address this, each discrete attenuator consists of three stages that are physically separated in order to prevent crosstalk that could negatively affect attenuation linearity over the required 120 dB range of human hearing. The first stage is adjustable over a range of 0–30 dB in 0.1 dB steps. A precision, current-mode digital-to-analog converter (TI DAC7811) is used for fine adjustment in the first stage. The second and third stages are fixed at 30 and 60 dB, respectively, and either or both of these can be switched out. These three stages incorporate precision operational amplifiers (AD8671) to provide excellent signal-to-noise ratio and low distortion.

4) *Headphone Buffers and Output Pads*: The final output stage on the audiometer channels is optimized for driving headphone impedances as low as 10  $\Omega$ . An integrated high-performance, high-current audio buffer (National Semiconductor LME49600) is incorporated into the feedback loop of the third attenuator stage combining the benefits of a low noise, bipolar output stage, and a high-precision, high-speed operational amplifier.

5) *Ambient Room Noise Detection*: OtoID includes a modified set of Sennheiser HDA 200 audiometric headphones. The Sennheiser HDA 200 is a closed-back, stereo headphone providing a wide frequency response suitable for full-frequency audiometry. The circumaural ear cup design of the HDA 200 is based on PELTOR hearing protectors, and provides ambient room noise reduction. The headphones were modified by building an omnidirectional electret microphone (CUI Inc., CMA-6542TF-K) into each ear cup for the purpose of sensing ambient noise. The electret microphones were flush mounted in the ear cup housing to maintain a tight seal of the cup, and to

face into the test room. A cable is run from the microphone to the OtoID audiometer where the signal is amplified, converted to a dc signal with a rectifier circuit, and then digitized using a 10-bit analog-to-digital converter. A firmware algorithm in the audiometer processes the digitized microphone signal using a “leaky integrator” topology where the signal is continually integrated, with a small portion of the result subtracted on a continuous basis, effectively resetting the integrator over time. Finally, the firmware algorithm traps particular events where the integrated signal exceeds a set level, which can be adjusted to suit the particular needs for a given test environment.

6) *Unified Switching Power Supply*: OtoID incorporates a built-in dc-to-dc power converter with a fixed operating frequency, and multiple outputs, each with its own LC filter. This dc-to-dc converter also serves to maintain a degree of electrical isolation between the audiometer board and additional devices powered from the same ac adapter (touch-screen computer and cellular radio modem). The fixed-frequency operation of the power converter combined with the LC filter networks minimizes power supply noise and ripple on the analog power supply rails that can interfere with the signal quality on the audio channels. The switching flyback topology of the converter permits the audiometer to operate from a single external power source from 8 to 14 VDC. A medical-rated, 12 VDC output adapter is currently employed, with the provision for conversion to battery operation in the future.

7) *Multiplexed Digital Links to Analog Circuits*: The microcontroller (Microchip PIC18F42520) in the audiometer controls several analog functions (including attenuators and the pure-tone oscillator itself) using an industry standard synchronous serial communication link called the serial peripheral interface (SPI) bus. Each noise-sensitive analog circuit function group has its own dedicated SPI communication link with the microcontroller. This reduces the potential of the digital signals interfering with the precision analog waveforms being generated. After the controller has changed the settings in a noise-sensitive circuit, the SPI bus is halted thereby eliminating the possibility of digital crosstalk into this circuit. There are a total of four separate SPI links in the audiometer design, each multiplexed to the microcontroller.

## B. Cellular Network Data Communication

Cellular network voice communications and simple messaging services (SMS text messages) are carried over low-frequency (900 MHz) networks while Internet and high speed data access are carried over HF networks. OtoID has a built-in 900 MHz cellular network modem (Multitech, MTSMC-C1) that is used to transmit patient test result information from the patient’s home to the healthcare institution. De-identified patient test data are encapsulated inside of a text message that is sent to a health care provider’s phone. The clinician can interpret the results and make recommendations. This method provides full HIPAA compliance of medical information required by law while providing the broad area coverage required by patient populations. Using a 900-MHz modem enables the OtoID to be used in most rural areas that only have access to low-frequency networks.

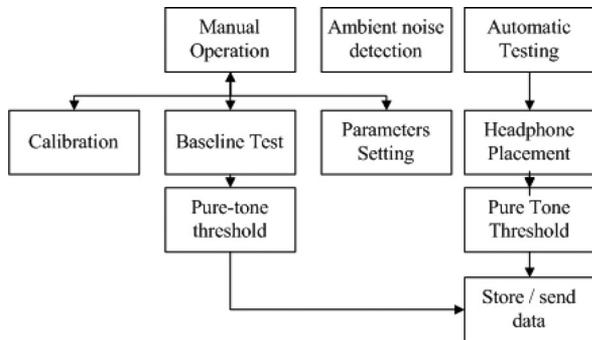


Fig. 5. Software design of OtoID. The software enables either manual or automated testing of conventional and HF hearing thresholds.

TABLE I  
OTOID SPECIFICATIONS

Parameter	Value
Frequency range [Hz]	125 to 20,000
Frequency resolution [Hz]	5
Frequency accuracy [%]	+/- 1
Line level audio output [V RMS]	0.1 to 1.0
Output level [dB SPL]	-15 to 105
Attenuator range [dB]	0.0 to -119.9 dB
Attenuator resolution [dB]	0.1
Attenuator accuracy [%]	+/- 0.4%
Power amplifier output [dB]	40
Power amplifier resolution [dB]	0.1
Transducer output impedance [ohm]	16
Output power maximum [W]	2
Ambient noise frequency [Hz]	125 to 14,000
Harmonic distortion + noise [%]	<0.1
Cellular wireless format	3GSM TS 23.040 Compliant
Data storage format	ASCII text files

### C. Software Design and Training

The software for the OtoID (block diagram shown in Fig. 5) was written in C++ and Nokia's Qt development environment running on top of a Windows CE 5.0 operating system.

A specific touch sequence on the screen is used to put the device into manual operation as compared with automatic testing mode. The audiologist would perform the operation of entering any patient-specific settings, calibrating the device, and performing the baseline (pre-exposure to cisplatin) audiometry. Subsequent testing is automated and completed by the patient at home.

The OtoID system requires very little training by an audiologist because the device includes on-screen instructions. Prior to taking the OtoID home, an audiologist instructed the patient to use the system as follows: 1) sit in a quiet room; 2) take the device out of the case; 3) plug the device into a wall outlet; 4) follow the on-screen instructions; (5) after completing the test, unplug the device and return it to its case. Results are stored and transferred automatically. In addition to these instructions, the patient was asked to run the automated test once in the clinic before taking the device home. Patients reported that OtoID was easy to use and there were no human factors issues reported during the study.

### D. Specifications and Commercial Portable Audiometers

While there are other portable audiometers commercially available, none of them offer all of the features required for

TABLE II  
COMPARISONS WITH COMMERCIAL PORTABLE AUDIOMETERS

	OtoID	Madsen Itera II	AD229e	Otopod	AVANT A2D	EarScan3
ANSI S3.6 2010	Yes	Yes	Yes	Yes	-	Yes
Frequency Range [Hz]	0.125 -20K	0.125 - 16k	0.125 - 8k	0.125 - 8k	0.25 - 8k	0.25- 8k
1/6 Octave frequency steps	Yes	No	No	No	No	No
Intensity range [dB SPL]	10 to 105	-5 to 125	-5 to 125	-5 to 125	0 to 120	-5 to 90
Ambient noise detect	Yes	No	No	No	No	No
Automated capability	Yes	No	Yes	Yes	Yes	Yes
Telehealth capability	Yes	No	No	No	No	No
Requires Peripherals	No	No	No	Yes	Yes	No
Size [inches w x h x d]	10 x 5.5 x 2	17.7 x 11.4 x 3.3	14 x 10 x 4	3.5 dia. x 1.5	6 x 6 x 2	5.8 x 3.6 x 1.3
Weight [oz]	20	160	28.8	5.7	16	9.8

accurate ototoxicity monitoring protocols including extended HF audiometry, 1/6 octave frequency step testing, ambient noise detection, and with telehealth functionality (i.e., can be used by a patient independent of a trained audiologist, with data being transferred automatically to a health care professional). The key data specifications for OtoID are given in Table I. A comparison of commercial portable audiometers with OtoID is given in Table II. The category of "telehealth capability" implies that the audiologist is not needed for the patient to perform the testing at home or in the clinic. The category of "requires peripherals" means that the device requires a separate piece of equipment to perform the test; many devices including the otopod and the AVANT A2D require a laptop PC to be used along with their device. The estimated cost of the OtoID including parts and assembly is \$1500 in small quantities.

## III. RESULTS

In this section, results are presented that demonstrate how the OtoID system meets or exceeds all ANSI/ASA S3.6-2010 calibration standards including frequency accuracy and purity, attenuator accuracy and linearity, rise/fall time accuracy, and low harmonic distortion. Results are also presented from studies in which the OtoID system was used by patients in a sound booth, in a hospital ward, and within their homes. In addition, one patient receiving ototoxic drugs used OtoID to monitor his hearing during treatment.

### A. Attenuator, Frequency, Harmonic Distortion, Linearity

The accuracy of the attenuator is shown in Fig. 6. The accuracy falls well within the ANSI requirement range of 1.2 dB across all levels tested (25 dB SPL up to 105 dB SPL). For

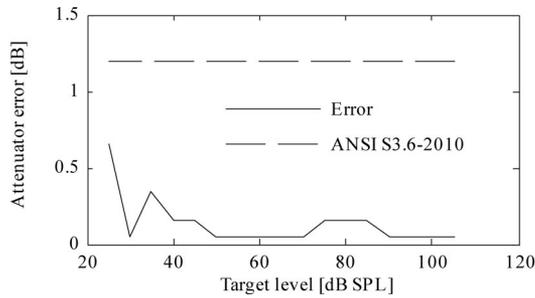


Fig. 6. Accuracy of the attenuator across various level settings. Results shown indicate that OtoID has better attenuator accuracy than ANSI S3.6

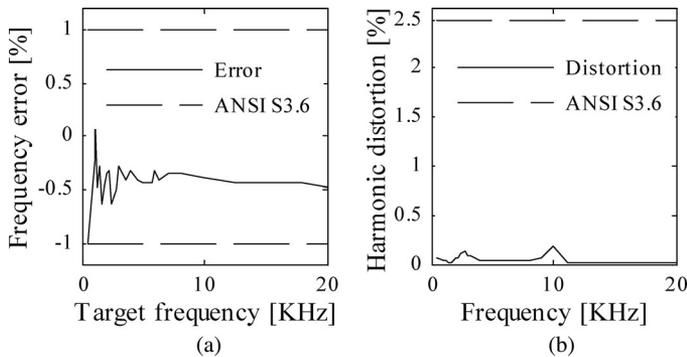


Fig. 7. (a) Accuracy of frequency across 0.5–20 kHz frequency range. (b) Harmonic distortion of OtoID across frequency range.

lower target levels, the signal approaches the noise floor despite calibration in an anechoic chamber, which may cause the measurement accuracy to drop slightly as shown in Fig. 6.

The accuracy of the frequency synthesizer is shown in Fig. 7(a). The ANSI standard permits  $\pm 1\%$  of error in frequency accuracy. The analog pure-tone generator provides excellent accuracy across the entire range of SRO frequencies.

Typical total harmonic distortion plus noise performance for the pure-tone oscillators in the OtoID audiometer is 0.03% measured at the acoustic coupler. This is well below the ANSI/ASA S3.6-2010 6.1.5 limit of 2.5% shown in Fig. 7(b).

### B. Subject Testing Results—Manual Versus Automated

Nine young subjects (age 18–24, five males/four females) were included in this study. All subjects met the following criteria: 1) negative history of ear disease; 2) normal otoscopy; 3) normal tympanography; and 4) hearing better than 25 dB HL.

All subjects were tested with OtoID in a double-walled, sound attenuated booth using both the manual (audiologist tested) and automated (subject tested) modes. Comparisons were made between thresholds obtained using the Grason–Stadler GSI-61 clinical audiometer and the OtoID. The same audiologist performed all of the manual testing and also trained the subject in the use of the OtoID manual mode.

Hearing thresholds in each ear were obtained at 0.5–8 kHz in half-octave steps (0.5, 1, 2, 3, 4, 6, 8 kHz) and 9–16 kHz in 1/6th octave steps (9, 11.2, 12.5, 14, 16 kHz). The thresholds were calculated using a modified Hughson–Westlake technique [14] whereby the level of the tone starts low and increases in 5 dB

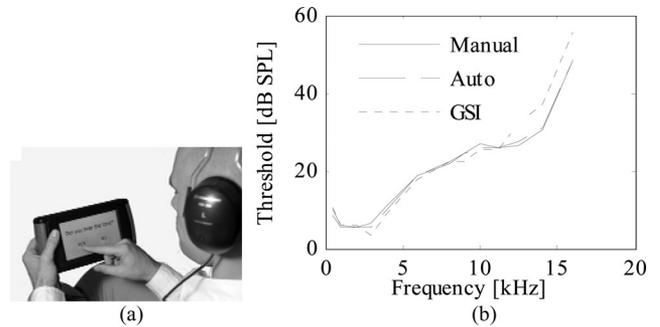


Fig. 8. (a) Test subject evaluating their hearing using the OtoID system. (b) Young normal hearing baseline testing—OtoID and GSI-61.

steps until the patient indicates that a tone is heard. Then the level is decreased in 10 dB steps until the tone is no longer heard. This procedure is repeated until 2/3 of the responses are made at the lowest hearing intensity level measured. The threshold was determined when the subject heard the tone at least 50% of the time at the lowest ascending level. The order of testing with the OtoID manual, OtoID automated, and GSI-61 was counterbalanced, and a 30-min break was given between test conditions. All testing was repeated within one week of the initial test session. Shown in Fig. 8(a) is a subject using the OtoID system in automated mode to monitor their hearing.

Fig. 8(b) indicates that the thresholds were comparable between 1) automated mode; 2) manual mode; and 3) GSI mode. The mean difference between the manual threshold and the automated threshold across frequencies was 0.22 dB with a maximum deviation of 1.2 dB. The mean difference between the automated threshold using the OtoID and the GSI 61 was 1.1 dB with a maximum difference of 7.1 dB at 16 kHz. The bias at the two highest frequencies is repeatable and may be corrected for within the firmware of the OtoID.

### C. Subject Testing Results—Manual Versus Automated

OtoID was evaluated both in a noisy hospital ward and within a home to determine whether it could be used to accurately detect hearing threshold shifts within a real-world hospital and home setting. Forty subjects (half with normal hearing and half with hearing impairment) were tested both within a sound-proof booth and on a noisy clinical ward using the OtoID automated testing mode. An additional ten subjects were tested at home on three consecutive days after a baseline visit. Each subject was given a baseline test at the hospital by a trained audiologist to establish the baseline SRO frequency range and thresholds. Subjects then tested themselves on subsequent test dates either in the hospital or at home. Since none of these subjects were receiving ototoxic drugs, we did not expect any differences between the thresholds measured at the baseline visit and the follow-up test visits. Therefore, the detection of a threshold shift at a follow-up visit was termed a “false-positive.” An ASHA-significant threshold shift is defined as either 1) a 20 dB or greater increase in threshold at any one SRO frequency; (2) a 10 dB or greater increase at any two adjacent SRO frequencies; or (3) loss of response at any three adjacent SRO frequencies

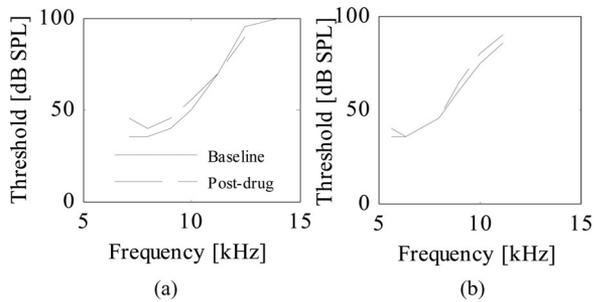


Fig. 9. Results from the ototoxic monitoring study in right ear (a) and left ear (b). Patient receiving cisplatin used OtoID to monitor his hearing thresholds both before (baseline) and after cisplatin (postdrug). The patient's hearing declined slightly as indicated by slightly increased thresholds; the increase was not an ASHA-significant threshold shift.

where responses were initially observed. The performance of the OtoID system under these conditions was measured. The overall false-positive rate was less than 5% for all conditions and there was little difference in false-positive detections comparing the sound-proof booth, hospital ward, or home test environments. The false positive rates in the booth, hospital ward, and at home were 4.2%, 2.6%, and 3.3%, respectively; these results will be further discussed in a forthcoming clinical publication in preparation.

#### D. Case Study of OtoID Evaluation on a Cancer Patient

One subject receiving chemotherapy used OtoID to self-monitor his hearing thresholds. The subject evaluated his hearing during a baseline test session, received one dose of cisplatin ( $60 \text{ mg/m}^2$ ), and then monitored his hearing one week after receiving the drug. While the subject's hearing appeared to worsen slightly in several frequency bands (Fig. 9), an ASHA significant threshold shift was not detected.

## IV. DISCUSSION AND CONCLUSIONS

In this paper, we presented the design and evaluation of a portable audiometer for use within a telemedicine ototoxicity monitoring system (OtoID). The OtoID system is capable of evaluating hearing across a broad range of frequencies (0.5–20 kHz), sound pressure levels, and fine step sizes (1/6 octave) necessary for ototoxicity monitoring. The OtoID system is capable of storing measurements and detecting changes from the baseline indicative of ototoxicity damage. If changes are detected, the system is designed with a cellular modem installed that is capable of notifying health care personnel so that the medical team can consider changes in treatment. The level accuracy, linearity, harmonic distortion, and frequency purity of the OtoID system meet the specifications of ANSI/ASA S3.6-2010. Analysis performed on a group of nine normal-hearing test subjects indicates that the OtoID system calculates thresholds on average within 1.1 dB of the thresholds determined

using a commercial, nonportable audiometer (GSI-61) and that self-testing by a patient is nearly equivalent (0.22 dB difference on average) to testing done by a trained audiologist. The OtoID system was evaluated on two additional groups with and without hearing loss in a variety of test settings (home, booth, hospital treatment unit) and found to be accurate and reliable. One patient receiving ototoxic drugs successfully used OtoID to monitor his hearing during chemotherapy treatment.

Frequent and regular hearing monitoring has the potential to improve outcomes of many cancer patients undergoing treatment with ototoxic drugs. The OtoID system can be used by patients to monitor their hearing at home or in a hospital treatment unit, thereby enabling the early detection of hearing damage and improving the quality of these patients' lives post-treatment. Future developmental work may include adding other testing system platforms to the OtoID to improve the ease and accuracy of ototoxicity monitoring.

## REFERENCES

- [1] NCI/ACS. (2012, Apr. 13). The Cancer Cure Foundation, Cancer Statistics from NCI/ACS. [Online] Available: <http://www.cancure.org/statistics.htm>
- [2] K. R. Knight, D. F. Kraemer, C. Winter, and E. A. Neuwelt, "Early changes in auditory function as a result of platinum chemotherapy: Use of extended high-frequency audiometry and evoked distortion product otoacoustic emissions," *J. Clin. Oncol.*, vol. 25, pp. 1190–1195, 2007.
- [3] K. M. Reavis, D. S. Phillips, S. A. Fausti, J. S. Gordon, W. J. Helt, D. Wilmington, G. W. Bratt, and D. Konrad-Martin, "Factors affecting sensitivity of distortion-product otoacoustic emissions to ototoxic hearing loss," *Ear Hear.*, vol. 29, no. 6, pp. 875–893, Dec. 2008.
- [4] M. Dille, D. Wilmington, G. McMillan, W. Helt, S. Fausti, and D. Konrad-Martin, "Development and validation of a cisplatin dose-ototoxicity model," *J. Amer. Acad. Audio.*, vol. 27, no. 7, in press, 2012.
- [5] M. F. Dille, G. P. McMillan, K. M. Reavis, P. Jacobs, S. A. Fausti, and D. Konrad-Martin, "Ototoxicity risk assessment combining distortion product otoacoustic emissions with a cisplatin dose model," *J. Acoust. Soc. Amer.*, vol. 128, no. 3, pp. 1163–1174, Sep. 2010.
- [6] V. G. Schweitzer, "Cisplatin-induced ototoxicity: The effect of pigmentation and inhibitory agents," *Laryngoscope*, vol. 103, pp. 1–52, 1993.
- [7] S. A. Fausti, J. A. Henry, W. J. Helt, D. S. Phillips, R. H. Frey, D. Noffsinger, V. D. Larson, and C. G. Fowler, "An individualized sensitive frequency range for early detection of ototoxicity," *Ear Hear.*, vol. 20, no. 6, pp. 497–505, Dec. 1999.
- [8] R. M. Ellingson, W. J. Helt, P. V. Kelt, and S. A. Fausti, "Instrumentation system upgrade supports mobile personalized healthcare delivery," in *Conf. Proc. IEEE Eng. Med. Biol. Soc.*, Aug./Sep. 2006, pp. 6233–6236.
- [9] R. M. Ellingson, W. J. Helt, P. V. Kelt, D. J. Wilmington, J. S. Gordon, and S. A. Fausti, "Mobile software apps support personalized-SRO and serial monitoring with results indicating early detection of hearing loss," in *Proc. 2011 IEEE Instrum. Meas. Technol. Conf.*, May 2011, pp. 1–4.
- [10] N. Nakamura, "Development of mobile audiometer for screening using mobile phone," in *Proc. 26th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, San Francisco, Sep. 2004, pp. 3369–3372.
- [11] A. Hemakom, A. Noymai, P. Israsena, S. Boonyanukul, and C. Chinnarat, "Remote hearing screening as part of auditory telerehabilitation; A preliminary report," in *Proc. Int. Conf. Virtual Rehab.*, 2011, pp. 1–5.
- [12] K. Kochanek, L. Sliwa, J. Zajac, and H. Skarzynski, "A universal computer audiometer for objective hearing testing and screening," in *Proc. IEEE Int. Workshop Med. Meas. Appl.*, May 2007, pp. 1–3.
- [13] J. Lepkowski and C. Young, "Designing RC oscillator circuits with low voltage operational amplifiers and comparators for precision sensor application," *Appl. Note, Semicond. Compon. Ind., LLC*, pp. 1–28, Jul. 2001.
- [14] R. Carhart and J. Jerger, "Preferred method for clinical determination of pure-tone thresholds," *J. Sp. Hear. Dis.*, vol. 24, pp. 330–345, 1959.