MultiFit4: An Improved System for Insert-Type

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ABSTRACT

Earplugs are a widely-used and inexpensive means of preventing noise-induced hearing loss, but low field attenuation performance puts many users at risk. The National Institute for Occupational Safety and Health is addressing this issue with hearing protector training and fit interventions that are best evaluated at worksites with miners and other workers from the target audience. To evaluate these interventions, an improved system has been developed. Called Multifit4, the system is designed to test as many as four subjects simultaneously using the real-ear attenuation at threshold (REAT) method. To allow multi-subject mobile testing, the subjects are seated together in a closed sound-isolated chamber, and the stimuli are presented through circumaural headphones (rather than the loudspeakers typically employed in diffuse-field REAT testing). Subjects signal their responses using a standard hand switch as they perform a Bekesy threshold task with the ears open and then with earplugs inserted (ears occluded) to determine insertion loss. Mutifit4 consists of custom software controlling Tucker Davis Technologies (TDT) Series 3 modules in a Windows® environment. The software directs stimulus presentation and attenuation by the TDT modules. A setup screen is used by the operator to configure the order and type of testing and is flexible enough to accommodate multi-trial randomized experiments. Setup configurations can be saved for fast setup and to develop testing templates. The results of tests and the actual data can be saved in real time automatically to a database. Preliminary testing conducted on mining students has shown that the Multifit4 system is reliable, accurate, and easy to use.

INTRODUCTION

Earplugs are commonly used hearing protection devices that can significantly reduce the risk of noise-induced hearing loss when worn properly. However, their effectiveness is often limited by poor fit, as shown by real-world noise attenuation that is far below optimized laboratory attenuation values such as the labeled Noise Reduction Rating (NRR) (*Berger, Franks, & Lindgren, 1996*). Typical interventions to help earplug users attain higher prevention involve instruction and training (*Park & Casali, 1991*). Less common are interventions that modify the earplug itself, such as the use of a lubricant (*Randolph & Kissell, 2008*). Whatever the intervention, the goal of increased protection can be evaluated by methods that measure improvements in attenuation, typically through a real ear attenuation at threshold (REAT) or microphone in real ear (MIRE) method. However, existing REAT and MIRE systems can only evaluate one subject at a time and some, including REAT testing according to the ANSI S12.6, require the use of a static laboratory. The MultiFit4 system was developed to improve the efficiency of field testing insert-type hearing protectors. Up to four subjects can be tested simultaneously using a largely automated system that provides high accuracy and flexibility and is user friendly. The system was developed to replace and expand on a prior system that Michael & Associates, Inc. developed for the National Institute for Occupational Safety and Health (NIOSH) based on four of the company's FitCheck systems (*Michael, 1998*) and custom software to test four subjects at once (*Michael & Byrne, 2002*). Although the FitCheck-based four-person system was functional, it did place several limitations on the types of experiments that could be conducted and how the stimuli could be presented. For future experiments, a system with greater control over stimuli and experimental procedure was needed, so NIOSH developed the Multifit4 system.

Figure 1

Figure 1 shows the Multifit4 system work area. The black instrument rack contains four independent sound production and attenuation modules, a computer for interacting with and controlling the sound hardware, and a large uninterruptable power supply (UPS). The rack is mounted with a special suspension to minimize

shock transmission. This is necessary because the Multifit4 system is housed within the NIOSH Hearing Loss Prevention Unit, a 32-ft mobile audiometric laboratory, which is towed to worksites to enable researchers to test the target audience of miners and other workers. The Multifit4 system operator sits to the side of the hardware and interacts with the computer through the ubiquitous monitor, mouse and keyboard combination. The entry to the sound isolation testing chamber is shown on the right edge of **Figure 1 (see page 17).** The chamber can seat and sound-isolate up to four subjects and provides each subject with a test switch and a pair of headphones.

Figure 2

The hardware for each channel consists of: one Tucker Davis Technology (TDT) RP2.1 Enhanced Real-Time Processor to produce sound; two TDT PA5 Programmable Attenuation units to attenuate the stereo sounds; a TDT HB7 Headphone Driver to drive the headphones; and a set of Sennheiser HD 280 Pro Headphones (**Figure 2**) to present the sounds to the subjects. A standard desktop computer with the Windows XP operating system runs the software and communicates with the hardware over a TDT FD5 fiber optic zBus Gigabit Ethernet interface. The hardware generates test stimuli

by playing prepared sound files in the Microsoft Audio for Windows (WAV) format. The WAV files contain one-third octave band pulses of noise with specific center frequencies. Although the RP2.1 devices can be internally programmed to produce sounds, WAV files were employed for consistency with the earlier FitCheck system (Michael & Byrne, 2002), greater control over the stimuli, and because it simplified the development process.

Multifit4 was written in Microsoft Visual Basic .NET® using Microsoft Visual Studio 2008®. The software references and communicates with the hardware units as ActiveX® objects. Multifit4 is intended to be used by an experienced operator who controls the system while interacting with the test subjects. When the program is launched, some basic diagnostics are run to determine the presence and status of the TDT hardware. If the hardware is missing, not turned on, or misconfigured, the operator is directed to correct the problem(s). After a successful program launch, the operator is presented with a setup screen to configure the testing, **Figure 3**. Here, the operator sets the number of test subjects, adjusts the initial sound level for each subject, and chooses the test configuration. Default values are provided so that the operator may quickly bypass the setup screen, if desired. Configuration files allow favorite system configurations to be saved and retrieved.
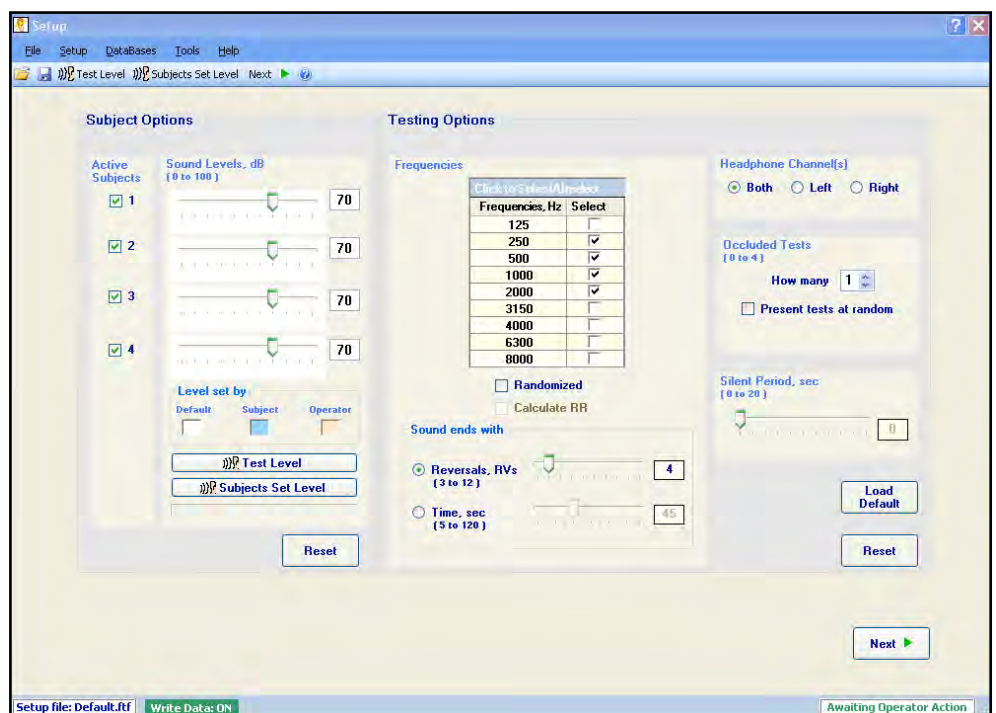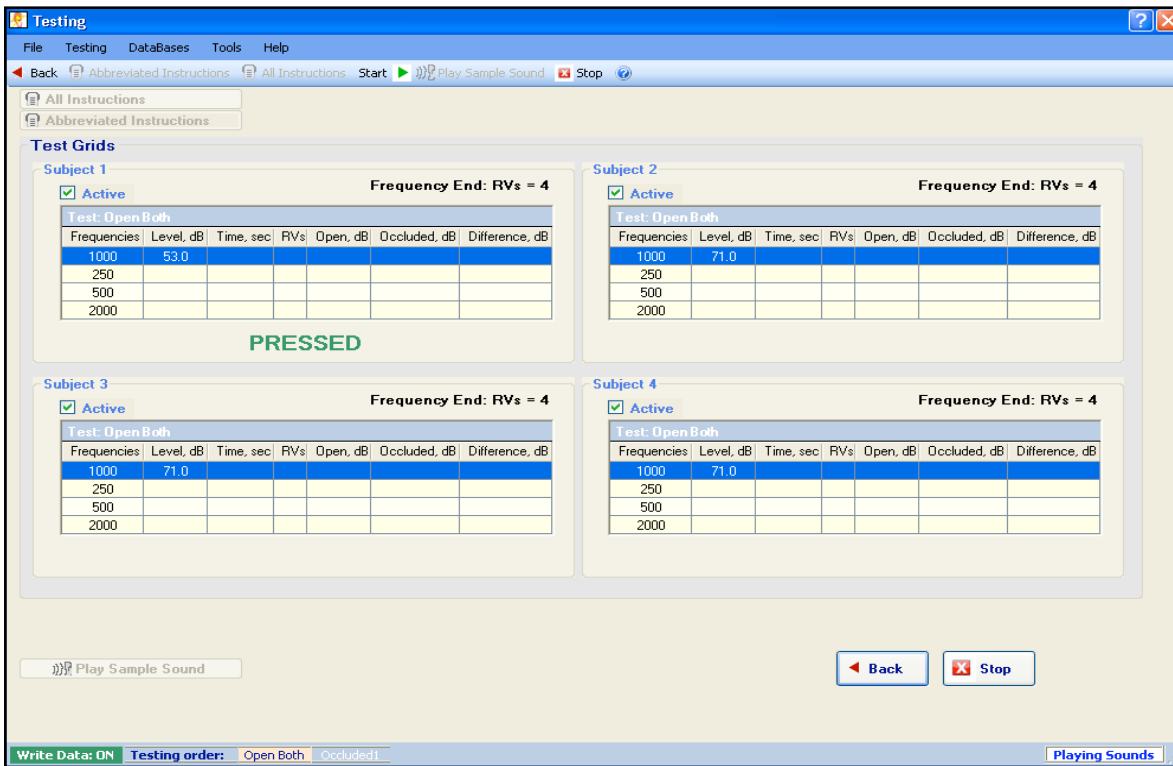

Figure 3

Figure 4

Actual testing is conducted with the operator using the Testing screen, shown in **Figure 4**. Here, the operator and subjects are stepped through hearing tests with the selected conditions. Test grids are presented for each active subject and contain important test parameters. A status bar at the bottom of the form includes information about the testing order, with the current test being highlighted. Also included on this bar are the program status, such as "Awaiting Operator Action" or "Playing Sound" and a button to display and select whether raw data is written to files in real-time. The operator can use the "Play Sample Sound" button to play the 1 kHz sound over the headphones at the starting volume level determined on the Setup screen.

Multifit4 uses headphones to deliver audio stimuli to subjects, whereas traditional diffuse-field REAT testing uses loudspeakers. Headphones offer several advantages over loudspeakers for evaluating insert-type hearing protectors, such as being able to test multiple subjects simultaneously using the same audiometric booth and allowing independent testing of the left and right ears. Past research with the FitCheck and other systems has shown that using headphones for field REAT testing is feasible and reliable (*Michael, 1998*) (*Michael & Byrne 2002*). After evaluating several candidate headphones for repeatability and linearity, Sennheiser HD 280 Pro Headphones were selected for use with the system as they are circumaural, large enough to accommodate earplug wear, and readily available.

DESCRIPTION OF THE SOFTWARE

Figure 5 shows a very simplified flow diagram for a single channel of the software. A primary function of the software is to determine the
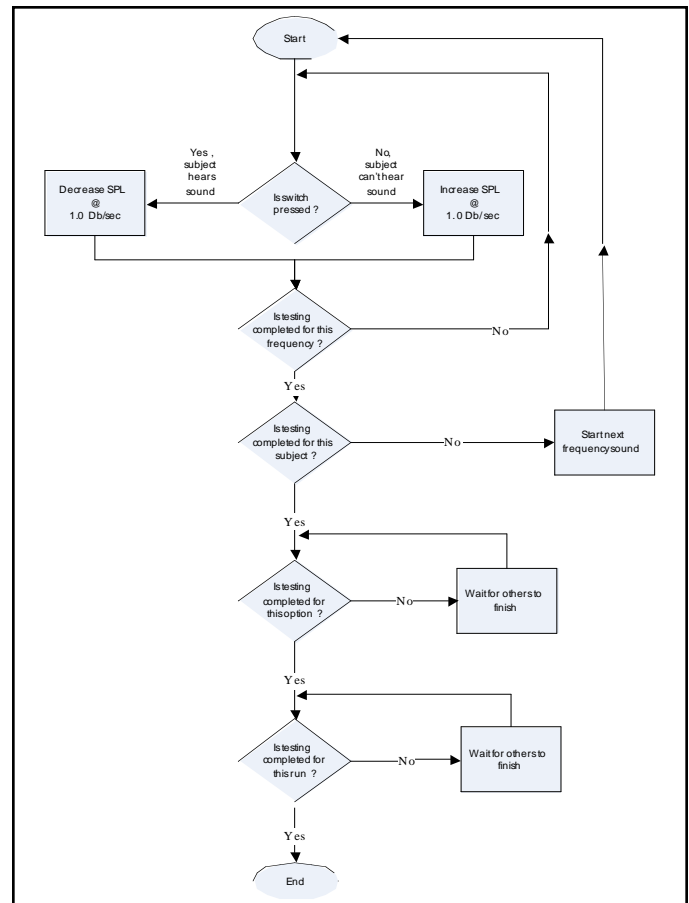
Figure 5

status of the switch held in the subject's hand. When a subject hears a sound, he/she should have their switch pressed and closed. When the software detects that the subject's switch is closed, the sound level is attenuated at the rate of 1.0 dB/sec by sending control signals to the TDT PA5 programmable attenuation units. The subject is instructed to release the switch when he/she can no longer hear the sound. When the software detects that the subject's switch is open, corresponding to a subject not hearing a sound, the sound level is amplified at a rate of 1.0 dB/sec via control signals to the attenuation units. The software reads each active subject's switch position and updates each subject's PA5 attenuation unit every 300 ms. The remainder of the flowchart is described in the "Testing Screen" section.

Setup Screen

On the Setup screen, **Figure 3**, (see page 18) the operator uses the "Active Subjects" checkboxes to select from one to four subjects for testing. The "Active Subjects" checkboxes are located in the "Subject Options" group of the Setup screen.

MultiFit4 employs a descending presentation method that starts at a suprathreshold (perceptible) level. A reason for this is that the actual testing may be preceded by the presentation of about 1 minute of aural instructions and it was desired that the subjects be able to listen to the instructions at a comfortable hearing level. Using the sliders and textboxes adjacent to the "Active Subjects" checkboxes, the operator may increase/decrease or type in the starting sound levels for each subject. The default level is 70 dB. Clicking the "Test Level" button plays a 1 kHz centered one-third-octave noise signal over the headphones at the selected/displayed level. The sound plays for a timed 15 seconds or until the operator toggles the sounds off by re-clicking the button. Additionally, subjects can individually set their own starting sound levels when the operator clicks the "Subjects Set Level" button. This causes instructions to be played over the headphones that direct the subjects on how to adjust and set the sound levels using their hand switch. The background colors of the level sliders are keyed according to how the levels were set, either by default, by the operator, or by the subjects. For example, when subjects are allowed to set their own levels, the background color becomes light blue. Clicking the "Reset" button below the "Subject Options" group resets all values to their default values.

Using the "Testing Options" group, the operator can select from one to nine frequencies to be included in the testing. The frequencies correspond to ANSI S12.6 standards (ANSI/ASA, 2008), ranging from 125 Hz to 8 kHz. The sounds are one-third octave bands of noise with specific center frequencies. The software gives priority to presenting sounds near the 1 kHz center frequency first, consistent with the ANSI S3.21 protocol for air-conduction audiometry (ANSI/ASA, 2009). If the 1 kHz center frequency signal is selected, it will always be presented first. Otherwise, the selected frequency closest to 1 kHz is presented first. The rest of the selected frequencies are then presented in ascending order. However, if the "Randomized" checkbox is checked, the remaining frequencies are instead presented in random order.

If desired, the operator can have the software calculate a Reduction Rating (RR) using a standard formula. The "Calculate RR" checkbox is only enabled if the correct frequencies required to run the analysis are selected.

There are several selectable options for when the presentation of a certain frequency to a subject concludes. If "Time, sec" is chosen using the radio buttons from the "Sound ends with" group, the sound terminates after a timed interval that can be adjusted from 5 to 120 seconds. If "Reversals, RVs" is chosen, the sound ends when the subject has cycled through several reversals (instances of hearing the sound pass through the threshold of audible to inaudible). A reversal is counted when the sound attenuation changes direction because the subject pressed/released the test switch. The software allows selection of 3 to 12 reversals.

The subjects control the sound pressure levels (SPLs) of the sounds by using their hand switches. When the button is pressed (the switch is closed), the sound level is attenuated at the rate of 1 dB/sec. Following the task instructions, subjects release the switch when the sound becomes inaudible. After the button is released (the switch becomes open), the sound level is amplified at the rate of 1 dB/sec. Threshold levels should correspond closely to where subject switch actions reverse.

If desired, the operator can add a short period of complete silence to the end of each individual sound presentation. The silence is accomplished by shutting off the output of the subject's RP2.1 device and setting the PA5 attenuation units to their lowest sound output levels of 0 dB. This silent period can be from 1 to 20 seconds and could be used to detect a subject that is responding arbitrarily or simply guessing, as no switches should be pressed during this absence of sound.

Testing Screen

The Testing Screen is shown in **Figure 4** (see page 19). Before starting the tests, the system plays instructions through the headphones that describe what the subjects can expect and how to perform the threshold task. If the "All Instructions" button is used to start the instructions, the subjects must each listen to the entire 90 second audio recording at least once before they are allowed to continue. Using the "Abbreviated Instructions" button allows each subject to interrupt the instructions by firmly pressing his/her switch. After all subjects complete the instructions, the "Start" button becomes enabled and the testing is ready to begin. Clicking the "Start" button begins the testing. The current sound frequency being played is shown as a highlighted row in each subject's grid, as shown in the figure. Additional information displayed on each row includes the current sound level, the time the sound has been playing, reversals counted, the average open threshold value, the average occluded threshold value, and the calculated earplug attenuation at that frequency. The highlighted row changes colors to indicate the subject pressed or released his/her test switch. The switch status, if pressed, is displayed at the bottom of each grid. The operator is reminded of what conditions were selected to end each sound presentation by the information displayed in the grid's upper right corner.

The software steps every subject through each sound frequency being tested. The sound frequencies are played in the order shown by the rows within the grids. A modified Bekesy method is used where the program selects the sound frequency being played and the subject controls the intensity of the signal by means of the pushbutton switch. Each subject is tested independently from the other subjects, with the software changing the test frequencies as appropriate to complete the subject's testing. To occupy those subjects that complete the testing quickly, the software plays frequency sounds at random until all subjects are done.

After all subjects have completed one condition of the testing, the software alerts the operator and goes into a paused mode that allows researchers to guide the subjects into the next phase of testing. For example, the initial testing may have been conducted open, with no earplugs, and the second phase may be an occluded test calling for the researchers to carefully instruct and guide the subjects on inserting a particular earplug. After all the scheduled phases of testing are completed for each subject, the software instructs the operator that the testing is over and then goes into another paused mode where the Testing screen is kept open. This allows the operator to access the databases or other tools from the menus or to return to the Setup screen by using the "Back" button.

Multifit4 allows subjects that started the testing to be paused, removed, or deactivated. Right-clicking a grid with an active subject causes a menu to appear where the operator can choose to "Pause", "Stop", or "Resume" the currently playing sound. This might allow researchers to interact with a particular subject without disturbing the other subjects. Clicking the "Active" checkbox above an active subject's grid allows the operator to deactivate and remove the subject from the testing, also without interfering with the other subjects. For confirmation, several warning dialog levels will then appear with opportunities to cancel the action.

DATA STORAGE

The software automatically records real-time data to three database tables: "Sessions", "Runs", and "Details". The tables are designed in three separate forms using the Microsoft Access® platform. The operator can access any of the tables while testing is ongoing. Most of this higher-level data is collected and recorded automatically. The operator can also start or stop the writing of low-level data files.

Sessions	Details	Runs
Auto	Date	HearingProtectionOn
SessionsID	Identifier	Date
StationID	Module	RunID
DateOfBirth	Test	SessionID
ExperimentDate	Subject	Ear
SubjectID	Channel(s)	Test
Comments	Volume	Module
	1000Hz	Thresh0250
	250Hz	…
	500Hz	Thresh8000
	2000Hz	
	Comments	

Table 1

Table 1 shows the data fields of the three database tables. The "Sessions" table is mainly for use by the operator to fill in useful demographic information about the test subjects such as "Date of Birth", "Subject ID", and "Comments". The software automatically generates and writes the information for the other data fields. This table can be edited while a test is running. The "Runs" table is generated automatically, and the operator can view but not write to it. As testing progresses, average threshold values are calculated for each frequency and for each subject. This information is written to threshold data fields within the Runs table for each active frequency and subject. Threshold entries are made as text strings where the lead number is the average value and is followed by the individual data readings separated by comma delimiters. The "Runs" table is composed of an individual row for each subject/test combination. Therefore, rows can increase or decrease depending on the number of subjects.
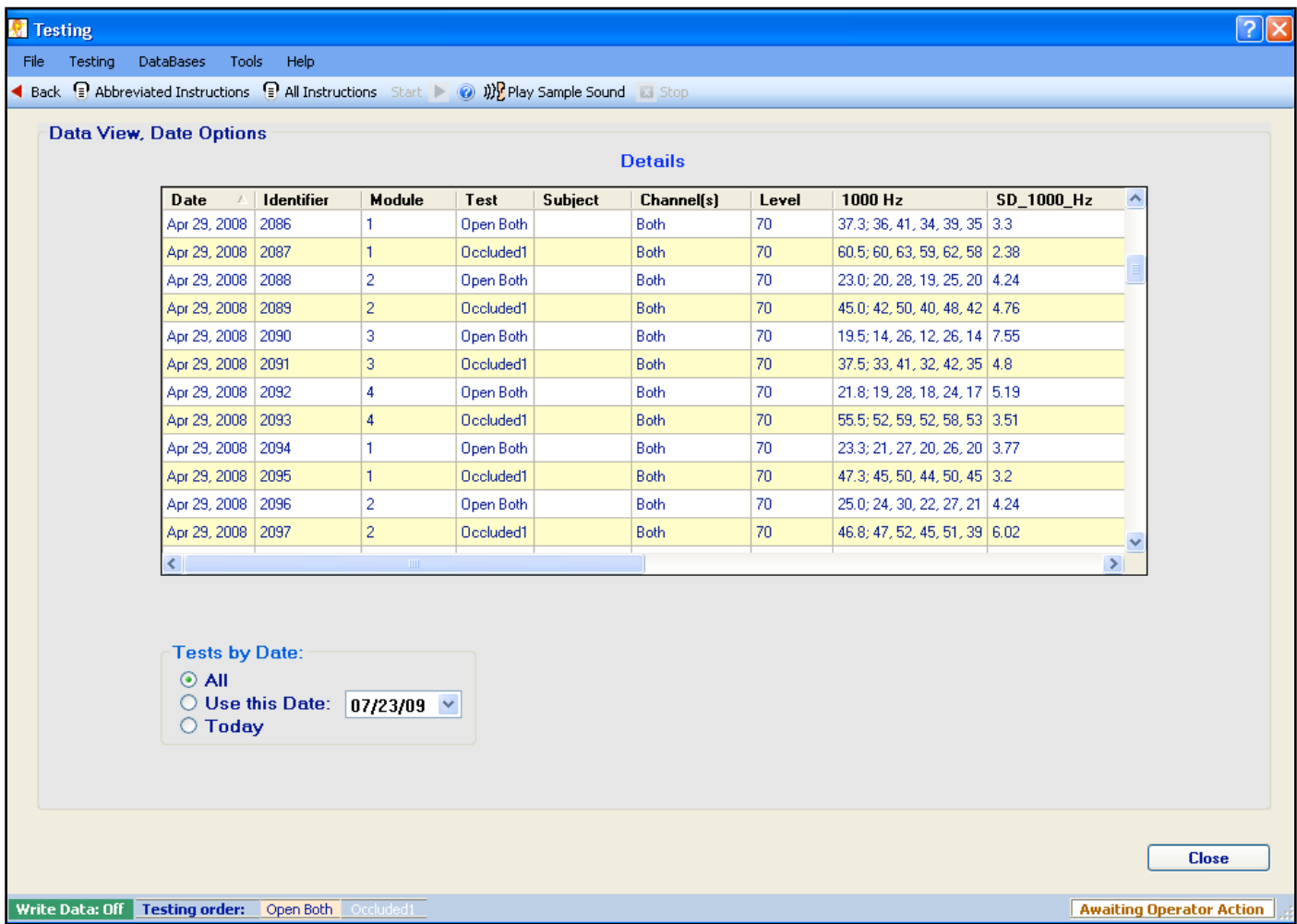
Figure 6

Figure 6 shows the "Details" table as displayed by the Multifit4 program. It records the important values from the testing. Only the "Subject" and "Comments" columns can be edited by the operator and the program automatically writes the other data fields (some of which are not shown).

If the operator elects to record low-level data, a text file is updated every second of elapsed time for each active subject. Each line in the file contains information about the: ear (left, right, or both), current frequency being tested, switch condition (open or closed), present attenuation level, and elapsed time from the start of testing for the current frequency. In the event of problems with the databases, such as corruption, etc., the files contain sufficient information to reconstruct the testing.

TESTING

An independent consultant evaluated the linearity of the Multifit4 system using a Larson Davis IEC 318 coupler (artificial ear for measurement of circumaural headphones) and a System 824 sound level meter with calibration traceable to the National Institute of Standards and Technology (NIST). The evaluation showed the system's linearity to deviate a maximum of 0.3 dB, well within the ANSI S12.6 maximum of 1 dB.

On April 29, 2008, a shake-down test of the Multifit4 system was conducted at the Fayette County Branch of the Pennsylvania State University. The test objective was to determine how the system would perform in a typical research data-gathering session. The test session was planned and run by a researcher with experience in conducting field evaluations of earplugs and who served as the operator of the Multifit4 system. This was a test of the full system, as the mobile trailer housing the system was towed to a site on campus and set up on the morning of the testing.

There were 13 mining students available for testing. Testing was conducted for three groups of four subjects plus an extra subject. It was desired to test four subjects simultaneously, as this is the maximum capacity and as severe a test as possible for the Multifit4 system.

To simulate a typical field data gathering session, the first group of four subjects was tested after detailed instructions were given on how to properly insert foam earplugs. The second group did not receive the instructions. These eight subjects were tested so that an individual sound file was ended when the subject had cycled through five threshold levels involving five reversals. A second set of subjects was tested using a different type of earplug and using a timed interval of 30 seconds to end each sound file presentation. The final single subject was also tested using the timed interval method.

Figure 7 presents some results from the testing as written to the "Details" database table. As shown, data rows are created and written for each subject/test combination. The unique identifier number, "Identifier" column, of each row associates the data with a test subject. The "Level" column contains the starting SPL used. For each frequency tested, a data column and a standard deviation column were created. The data column is identified by the frequency tested and contains the average value and the individual threshold values recorded. The calculated standard deviation for that frequency's data is written to the adjacent column.

Prior to the testing, an otoscopic inspection was conducted on all of the participants to ensure a clear ear canal. One subject had an ear canal that was not clear. Therefore, the second set of testing with this subject was conducted without earplugs (open) and is the reason why the measured values show little attenuation.

The low-level data files were written for all subjects during this testing. Subsequent evaluation of the data contained in these files confirmed that the low level values were consistent with the higher-level values written to the database tables.

A weakness found for the software during the field trial was that the operator did not have full use of the database tables while testing was underway. Originally, the three tables were created inside the same database. With a test ongoing, the software continually writes to all tables and some sharing violation errors occurred when the operator also tried to manually update the tables. This was solved by creating each table within its own database.

Overall, the Multifit4 system performed very satisfactorily in this testing. The database problem and some other small issues were identified and addressed in a subsequent revision of the software.

Date	Identifier	Module	Test	Channel(s)	Level	1000 Hz	SD_1000_Hz	250 Hz	SD_250_Hz
Apr 29, 2008	2086	1	Open Both	Both	70	37.3; 36, 41, 34, 39, 35	3.3	42.8; 40, 45, 40, 45, 41	2.63
Apr 29, 2008	2087	1	Occluded1	Both	70	60.5; 60, 63, 59, 62, 58	2.38	61.5; 59, 65, 58, 64, 59	3.51
Apr 29, 2008	2088	2	Open Both	Both	70	23.0; 20, 28, 19, 25, 20	4.24	32.5; 30, 34, 26, 38, 32	5
Apr 29, 2008	2089	2	Occluded1	Both	70	45.0; 42, 50, 40, 48, 42	4.76	47.8; 44, 51, 44, 51, 45	3.77
Apr 29, 2008	2090	3	Open Both	Both	70	19.5; 14, 26, 12, 26, 14	7.55	33.8; 29, 39, 30, 36, 30	4.5
Apr 29, 2008	2091	3	Occluded1	Both	70	37.5; 33, 41, 32, 42, 35	4.8	36.3; 32, 41, 32, 40, 32	4.92
Apr 29, 2008	2092	4	Open Both	Both	70	21.8; 19, 28, 18, 24, 17	5.19	31.3; 27, 34, 28, 34, 29	3.2
Apr 29, 2008	2093	4	Occluded1	Both	70	55.5; 52, 59, 52, 58, 53	3.51	52.3; 51, 55, 49, 54, 51	2.75
Apr 29, 2008	2094	1	Open Both	Both	70	23.3; 21, 27, 20, 26, 20	3.77	32.8; 30, 36, 30, 35, 30	3.2
Apr 29, 2008	2095	1	Occluded1	Both	70	47.3; 45, 50, 44, 50, 45	3.2	49.8; 45, 53, 47, 52, 47	3.2
Apr 29, 2008	2096	2	Open Both	Both	70	25.0; 24, 30, 22, 27, 21	4.24	32.0; 32, 34, 30, 34, 30	2.31
Apr 29, 2008	2097	2	Occluded1	Both	70	46.8; 47, 52, 45, 51, 39	6.02	44.8; 44, 48, 41, 47, 43	3.3
Apr 29, 2008	2098	3	Open Both	Both	70	24.5; 22, 30, 21, 27, 20	4.8	36.0; 34, 43, 34, 39, 28	6.48
Apr 29, 2008	2099	3	Occluded1	Both	70	43.8; 41, 47, 40, 47, 41	3.77	51.3; 50, 54, 48, 54, 49	3.2
Apr 29, 2008	2100	4	Open Both	Both	70	19.8; 19, 27, 15, 22, 15	5.85	32.5; 29, 37, 29, 36, 28	4.65
Apr 29, 2008	2101	4	Occluded1	Both	70	21.3; 21, 25, 19, 24, 17	3.86	28.3; 29, 35, 25, 33, 20	6.99
Apr 29, 2008	2102	1	Open Both	Both	70	24.3; 22, 26, 21, 28, 21, 27, 21, 26	3.15	39.1; 37, 43, 37, 41, 35, 41, 36, 41	3.08
Apr 29, 2008	2103	1	Occluded1	Both	70	49.4; 47, 51, 46, 52, 47, 51, 48, 51	2.37	51.6; 51, 52, 49, 54, 49, 54, 50, 53	2.23
Apr 29, 2008	2104	2	Open Both	Both	70	20.8; 21, 24, 21, 24, 19, 21, 18, 21, 17, 22	2.44	33.9; 32, 36, 32, 37, 31, 35, 31, 37, 32	2.64
Apr 29, 2008	2105	2	Occluded1	Both	70	42.3; 41, 49, 40, 44, 40, 43, 40, 43, 39	3.28	44.8; 41, 47, 40, 48, 41, 49, 44	3.76
Apr 29, 2008	2106	3	Open Both	Both	70	19.2; 19, 25, 15, 22, 14, 20	4.66	36.6; 35, 40, 33, 39, 33, 37, 34, 40	3.21
Apr 29, 2008	2107	3	Occluded1	Both	70	40.2; 38, 43, 37, 44, 36, 44, 37	3.87	47.5; 45, 50, 44, 51, 44, 50, 46	3.21
Apr 29, 2008	2108	4	Open Both	Both	70	26.4; 24, 33, 23, 29, 21, 26	4.77	32.2; 31, 36, 29, 37, 29, 33, 29	3.71
Apr 29, 2008	2109	4	Occluded1	Both	70	52.8; 46, 60, 46, 55, 50	6.08	54.3; 51, 56, 52, 58, 51, 56, 51, 56	2.87
Apr 29, 2008	2118	1	Open Both	Both	70	20.4; 20, 26, 18, 23, 15, 20	4.28	36.8; 34, 41, 34, 40, 32, 37	3.83
Apr 29, 2008	2119	1	Occluded1	Both	70	41.6; 42, 44, 40, 43, 39, 44, 41, 43, 39, 41	2.01	49.0; 59, 52, 46, 52, 46	3.46

Record: ◄ ◄ 25 ► ►► ►＊ of 122 (Filtered)

Figure 7

SUMMARY

Noise-induced hearing loss is nearly 100% preventable, but once acquired it is permanent and can be life-altering. Individual fit testing of hearing protectors is a recommended "best practice" by the National Hearing Conservation Association's Alliance Program with NIOSH and the Occupational Safety and Health Administration (NIOSH, 2008). The Multifit4 system was designed to be used as a tool by qualified researchers to evaluate hearing protector training and fit interventions at worksites with workers from the target audience. Initial testing showed that the system delivers test stimuli with sufficient accuracy and linearity and functions well in an actual field research setting. Additional studies are planned to compare the Mutifit4 system with laboratory REAT testing conducted in the NIOSH Auditory Research Laboratory that is accredited for ANSI S12.6 testing by the NIST National Voluntary Laboratory Accreditation Program. The Mutifit4 system will then be used in upcoming field evaluations of the NIOSH QuickFit earplug test device (NIOSH, 2008) and other hearing protector training interventions. Subsequent improvements are also expected as the Multifit4 system is used on a more frequent basis and operators' feedback is incorporated into the revised design.

DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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