Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

Instrumentation System Upgrade Supports Mobile Personalized Healthcare Delivery

Roger M. Ellingson, *Member, IEEE*, Wendy J. Helt, Patrick V. Helt, Stephen A. Fausti

Abstract—**Clinicians and patients need mobile tools to detect ototoxic change early and prevent hearing loss. We report on the development of an upgrade of our existing desktop-based clinical-audiological instrumentation into a mobile instrument platform which efficiently supports personalized ototoxicity monitoring on the hospital wards as well as clinic by a trained clinician. Our new wireless-enabled system also serves as the instrumentation platform for the next phase of our work which is remote healthcare delivery with patient-guided at-home ototoxicity monitoring using an evidence-based individualized SRO protocol.**

I. INTRODUCTION

Ototoxity is damage to the hearing or balance functions of the ear by drugs or chemicals. Ototoxic agents are commonly prescribed to aggressively treat various infections and cancers with the desired outcome of extending patients' lives. When ototoxic-induced hearing loss is allowed to progress undetected and without consideration of alternative treatment regimens, the resultant hearing disability can have severe emotional, social, financial and vocational consequences [1]. Thus, early identification and monitoring of ototoxicity are critical to facilitate evidence-based practice by providing practitioners the critical information and opportunity to minimize or prevent the progression of hearing loss into the speech communication range.

Research efforts at our center have resulted in the discovery of a patient-specific, sensitive range for ototoxicity (SRO) [2-4]. The SRO identifies a limited range of frequencies, separated by 1/6th octave intervals, that is unique to each individual based upon his/her hearing configuration, and within which it is possible to monitor for early indications of ototoxicity. The shortened, individualized 1/6th octave SRO protocol is time-efficient, sensitive to ototoxicity early detection, and reliable.

Even though the SRO protocol is efficient, our experience has shown that due to patient illness and time constraints of patients receiving chemotherapy, it is also more efficient to test patients at bedside or on the chemotherapy ward rather than transporting them to the clinic. Therefore, in order to address a significant patient ototoxicity monitoring need, we feel it is important to mobilize ototoxicity monitoring healthcare allowing clinicians to extend the SRO treatment protocol onto the wards. This will save considerable patient transport time and help prevent patient discomfort. Unfortunately, there are very few commercially available clinical audiometers capable of supporting high sound-pressure-level (SPL) 1/6 octave frequency stepping required for the SRO protocol and no known portable instruments with capable performance to meet the need for system mobility.

Introduced in this paper, is Phase I of our work which is to upgrade our clinical instrumentation into a mobile platform suitable for taking ototoxicity monitoring out of the clinic and onto the wards. Based upon the successful mobility upgrade of our system, we envision our new system enabling patient-guided, individualized SRO, at-home monitoring as conceptualized in Fig. 1.

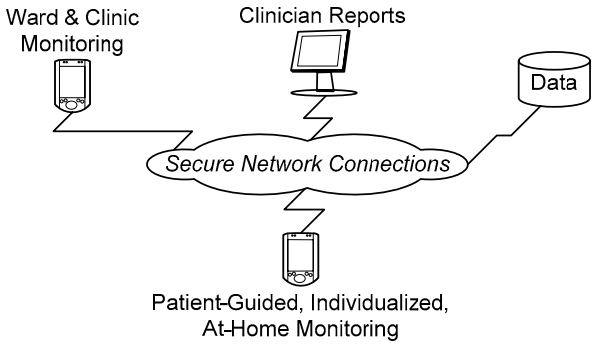

Fig. 1. Conceptual view of complete system with mobile monitoring instruments capable of reporting results back to network storage devices.

Built upon the instrumentation platform of Phase I, the second phase of our work will focus on the development of a patient-guided ototoxicity-monitoring software application to enable at-home, remote delivery of the health-protective SRO protocol. The completion of Phase II will extend health care to previously disserviced patient populations who will otherwise have either no access or very inconvenient access to ototoxicity monitoring healthcare resources.

II. OBJECTIVE

The goal of this project is to upgrade our current ototoxicity monitoring instrumentation into a mobile platform capable of supporting clinician-guided mobile testing in Phase I and supporting patient-guided at-home testing in Phase II. The upgraded system must be capable of

Manuscript received April 3, 2006. This work was supported in part by the Department of Veterans Affairs Grant C3499R.

Roger M. Ellingson and other authors are with the National Center for Rehabilitative Auditory Research, located at the VA Medical Center, 3710 SW US Veterans Hospital Road, Portland, OR, 97207 USA (503-220-8262 x55830; fax: 503-721-1402; e-mail: Roger.Ellingson@med.va.gov).

testing 500Hz to 20kHz in 1/6 octave steps, at signal levels up to 105dBSPL re20uPa to support the SRO protocol. This is difficult to achieve—particularly at the highest frequencies where hearing thresholds approach 100dBSPL, the system must have an acoustically spurious free low frequency range as any audible noise can complicate the identification of hearing thresholds at the testing frequency.

A picture of the current AC-powered system used for clinical ototoxicity monitoring is displayed in Fig. 2. As

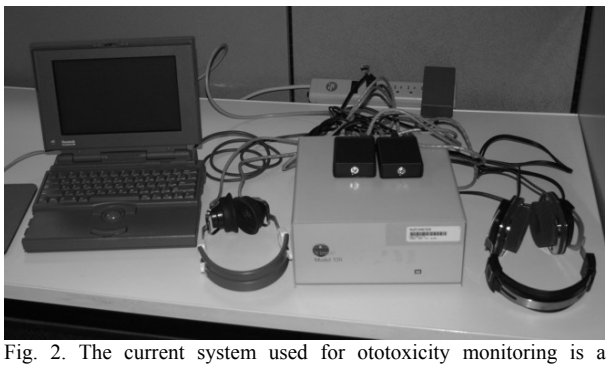

Fig. 2. The current system used for ototoxicity monitoring is a notebook computer with the large audiometric instrument shown in the center surrounded by the two sets of headphones and manual switching required to test over the wide frequency range of human hearing.

shown in Fig. 3, the system is composed of a notebook computer connected to an audiometer instrument capable of generating gated pure-tone signals. To minimize audible artifacts which confuse hearing threshold determination, two separate sets of manually switchable headphones are currently necessary to cover the full range of hearing: one set covers the low frequency range (<8kHz) and the other set is used for high frequency (>8kHz) testing.

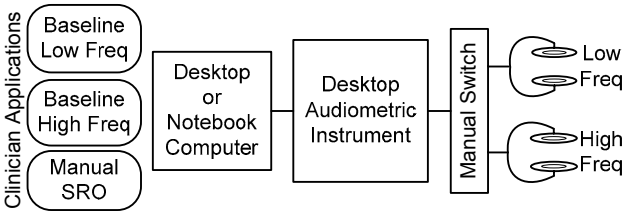

Fig. 3. Current system key components. Three different applications are necessary to establish baseline hearing thresholds and SRO. The applications run on a notebook computer connected to an audiometer instrument. To support the full range of human hearing without audible artifacts, two separate sets of headphones are necessary.

Three software applications are used by the clinician to administer the SRO protocol: 1) Baseline low frequency threshold, 2) Baseline high frequency threshold, and 3) Manual identification and monitoring of SRO range.

With a cart it is possible to tote equipment onto the ward, but the testing is still inefficient due to the complexity and time it takes to switch in and out of multiple application programs and frequency dependent headphone swapping.

The current system has no ambient noise measurement capability which will be necessary to reliably test hearing thresholds in a mobilized "real-world" acoustical environment. The new system also needs some type of acoustic performance-testing ability.

The current system has very limited network connectivity. Full support will be needed for secure internet communications between application nodes in the new system for data transfer and remote monitoring support.

With the foregoing information in mind, the upgrade of the current ototoxicity instrumentation system will be undertaken with the following key objectives:

1) Upgrade the system hardware: a) make system portable enabling ward and at-home testing, b) simplify the system by reducing the number of necessary headphones, switches, and cables, c) provide support for ambient noise measurement to ensure accurate and reliable auditory testing results, d) provide support for acoustic performance verification of system operation in remote locations, and, e) provide connectivity support for mobile based, internet-enabled monitoring results transfer.
2) Upgrade the system software applications: a) reduce the number of clinician applications needed to establish baseline hearing thresholds, b) automate the manual SRO range application, c) provide application support for a new patient-guided, ototoxicity monitoring application enabling remote at-home patient testing, d) provide application support for internet based transfer of testing results from remote locations to central locations for analysis and storage.

III. Methods

The upgrade plan for the current system is shown in Fig. 4. A new portable audiometric instrument will be built with improved signal quality requiring the use of only one pair of headphones for full-frequency-range ototoxicity testing. The instrument will also support two microphones, one for ambient noise measurement and one to verify the acoustic performance of the instrument. These features will directly

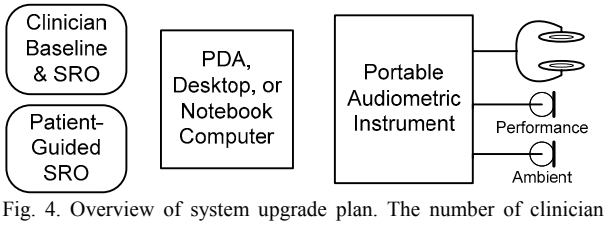

Fig. 4. Overview of system upgrade plan. The number of clinician software applications will be reduced and support will be added for individualized SRO. Support will be provided for a patient-guided SRO application. To support mobile healthcare delivery, the applications will be designed to run on multiple platforms including PDA devices. The audiometric instrument will be reduced in size to make portable. Headphone requirements were simplified. Microphone support will be provided for performance verification and ambient noise measurement.

support the system mobility expansion out of the controlled acoustical clinical environment to the more difficult to control acoustic environment of the hospital ward and patient's home. System performance verification will ensure

proper signal quality and calibration at remote sites, and ambient noise measurement will allow screening of abnormally noisy impacts on hearing threshold determination. Without these innovative features, it would be impossible to determine when hearing thresholds are being impacted by noise generators near a patient's ears which would interfere with results accuracy and monitoring reliability.

A. Hardware Upgrade

The hardware upgrade path is shown in Fig. 5. The new system will be designed to support a wide variety of common computerized graphical user interface (GUI) devices including the Personal Data Assistant (PDA) and the notebook PC. The main application programs will

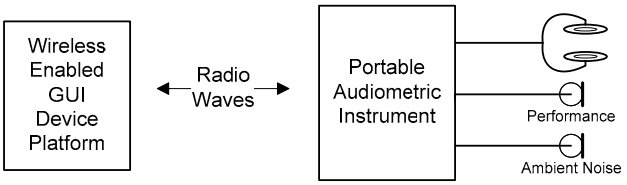

Fig. 5. Hardware upgrade overview. Key upgrade component is the adoption of a wireless interface between the GUI platform and the instrument. The wireless interface reduces system cabling needs and opens up platform support to a wide range of modern devices.

execute on the GUI device which will provide the main user interface to the system. A wireless radio communication infrastructure will be used as a control interface between the GUI device and the audiometric instrument. Wireless interfaces are more common today than yesterday's commonly found RS-232 serial interfaces. Most all modern PDA and PC compatible computing devices offer either built-in wireless or simple upgrades to wireless communications support with even some cellular phones supporting personal area network wireless communication.

A more detailed block diagram of the audiometric instrument hardware upgrade implementation is provided in Fig. 6. The Bluetooth protocol is the selected wireless

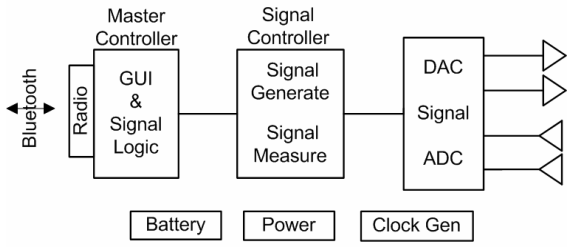

Fig. 6. New hardware audiometric instrument block diagram. Major functional components of the new instrument include a Bluetooth radio enabled master controller, a slaved signal controller with mixed signal data conversion modules for signal analog input and output and battery, power, and clock signal generation support.

instrument control interface. Bluetooth is platform interoperable, supports security, and provides reasonable bandwidth for the responsive needs of the application interface. The master controller processes the GUI interface messages and controls the slaved signal controller which is responsible for proper digital generation of testing signals and signal analysis of incoming digital microphone samples.

The portable instrument also needs battery components and digital and analog power supplies. The clock generator synchronizes the digital audio interface connection between the signal controller and signal converters.

Our hardware design does not distinguish between mobile and clinical testing. All contemplated testing regardless of location is planned to be performed using the same hardware instrument, although the GUI device could change depending on the testing environment.

New firmware is required to be developed to support the upgraded audiometric hardware instrument. An overview of the high-level key tasks the firmware has to support is shown in Fig. 7. The master controller is responsible for keeping the audiometric instrument state synchronized with what the operator sees on the GUI device. The master controller does this by sending parameter messages to the signal controller to change frequency, level, on/off status, etc. The signal controller converts the parameter requests into the digital sample values to be generated in the signal converter module (not shown). Upon request, the signal controller is also performs frequency analysis of microphone signals, returning results back to the testing application.

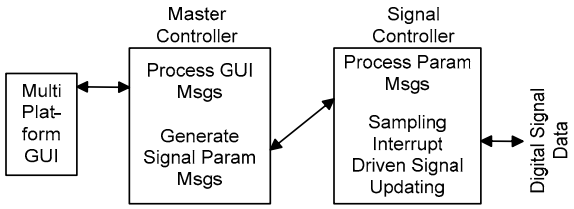

Fig. 7. Audiometric instrument firmware components and function necessary to support upgraded instrument hardware configuration.

B. Ototoxicity Monitoring Software Upgrade

The three currently used clinical software applications for ototoxicity monitoring will be combined into one clinical program that will be useable in clinic, ward, or other remote locations as shown in Table I. The main purpose of this software is to establish baseline hearing thresholds and identify the patient's individualized SRO parameters.

TABLE I
OTOTOXICITY SOFTWARE APPLICATION UPGRADES

Phase	User	Current System	Upgraded Mobile System
I	Clinician	Baseline Low Freq Baseline High Freq SRO Monitor	Baseline & Individualized SRO Monitor
II	Patient	Not available	Patient-Guided Individualized SRO Monitor

In Phase II, a new software application will be written based upon the completion of the clinical software applications. This patient-guided program will take the clinician-established, individualized, SRO parameters and present a simple-to-use interface to the patient for remote at-home testing. The patient software application will be

developed based upon automated threshold gathering algorithms and systems developed by researchers at our center [5,6].

Standard mobile enabled application development tools will be used to develop the mobile patient-guided SRO application which will provide the necessary socket based communication facilities for internet based results transfer, monitoring, and storage necessary for Phase II implementation [7].

IV. RESULTS

The newly mobile system is shown in Fig. 8. In comparison with the old system as shown in Fig. 2 which required a cart to transport the notebook computer, audiometric unit, two sets of headphones, switchboxes and cables onto the ward for testing, the system can be easily transported onto the ward without using a cart and does not require AC power when testing.

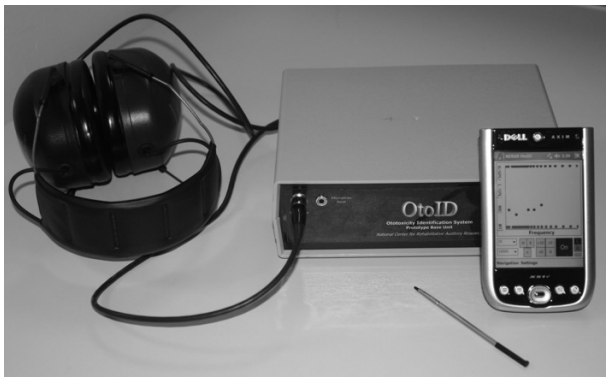

Fig. 8. New mobile ototoxicity monitoring system with audiometric base unit shown in center and headphones shown at left. The PDA device runs the monitoring application software.

The new system has been tested by audiologists experienced in administering the SRO based ototoxicity monitoring protocol. The upgraded clinician software application and the acoustic performance of the upgraded hardware have been found sufficient to support the SRO monitoring protocol. With this system clinicians feel they will be able to test patients receiving treatment on the hospital ward instead of requiring time-consuming transport to the clinic. They also are no longer required to switch in and out of multiple applications and headphones. The combination of these two efficiency improvements enables the testing time to be reduced from one hour down to 30 minutes. Fig. 9 shows the mobile test system being used on the chemotherapy ward to monitor patient hearing.

V. CONCLUSIONS AND FUTURE WORK

We have succeeded in the instrumentation upgrade of the current system to a mobile-enabled instrument platform capable of bringing needed ototoxicity monitoring out of the clinic and onto the hospital wards. The new system is fully portable and efficient reducing testing time 50%. The mobile ward testing extends hearing healthcare onto the wards for patients too ill to endure transport to the clinic or not able to withstand the previously long testing time.

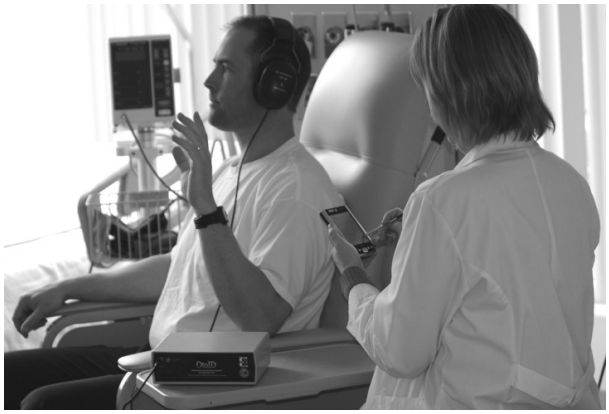

Fig. 9. New mobile system shown in operation on wards with clinician administering SRO-based ototoxicity protocol.

Now that the system platform has been developed and shown to be capable of portable monitoring on the wards by clinicians, we have a mobile enabled platform ready to begin implementing the patient-guided, at-home testing software application. This final step will deliver individualized ototoxicity monitoring healthcare to otherwise hearing healthcare disserviced patients unable to reach clinical facilities on a regular basis during their treatment period.

In today's era of health care service delivery, the current trend is toward patient-centered health care, e-health, telemedicine and telecare, and our new mobile platform is optimally suited to comply with these models.

ACKNOWLEDGMENT

We thank Jane Gordon and Kelly Reavis, NCRAR audiologists, for ongoing design and evaluation support.

REFERENCES

[1] S.A. Fausti, D.J. Wilmington, P. V. Helt, W. J. Helt, D. Konrad-Martin, "Hearing health and care: the need for improved hearing loss prevention and hearing conservation practices." *Journal of Rehabilitation Research and Development*, vol. 42, no. 4, sup. 2, pp. 45-62, 2005.

[2] S. A. Fausti, et al., "An individualized, sensitive frequency range for early detection of ototoxicity." *Ear and Hearing*, vol. 20, pp. 497-505, 1999.

[3] S. A. Fausti, et al., "Early detection of ototoxicity using 1/6th-octave steps." *Journal of the American Academy of Audiology*, vol. 14, no. 8, pp. 444-450, 2003.

[4] N. Vaughan, et al., "An efficient test protocol for identification of a limited, sensitive frequency test range for early detection of ototoxicity." *Journal of Rehabilitation Research and Development*, vol. 39, no. 5, pp. 567-574, 2002.

[5] J. A. Henry, B. Rheinsburg, R. M. Ellingson, "Computer-automated tinnitus assessment using patient control of stimulus parameters." *Journal of Rehabilitation Research and Development, vol.* 41, pp. 871-888, 2004.

[6] J. A. Henry, B. Rheinsburg, K. K. Owens, R. M. Ellingson, "New instrumentation for automated tinnitus psychoacoustic assessment." *Acta Otolaryngology Supplementum,* to be published.

[7] Microsoft Corporation (2006), *Visual Studio.* [Electronic version]. Retrieved April 1, 2006, from http://msdn.microsoft.com/library.