Original Research

A Browser-Server-Based Tele-audiology System That Supports Multiple Hearing Test Modalities

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Abstract

Introduction: Millions of global citizens suffering from hearing disorders have limited or no access to much needed hearing healthcare. Although tele-audiology presents a solution to alleviate this problem, existing remote hearing diagnosis systems support only pure-tone tests, leaving speech and other test procedures unsolved, due to the lack of software and hardware to enable communication required between audiologists and their remote patients. This article presents a comprehensive remote hearing test system that integrates the two most needed hearing test procedures: a pure-tone audiogram and a speech test. **Materials and Methods:** This enhanced system is composed of a Web application server, an embedded smart Internet-Bluetooth[®] (Bluetooth SIG, Kirkland, WA) gateway (or console device), and a Bluetooth-enabled audiometer. Several graphical user interfaces and a relational database are hosted on the application server. The console device has been designed to support the tests and auxiliary communication between the local site and the remote site. **Results:** The study was conducted at an audiology laboratory. Pure-tone audiogram and speech test results from volunteers tested with this tele-audiology system are comparable with results from the traditional face-to-face approach. **Conclusions:** This browser-server-based comprehensive tele-audiology offers a flexible platform to expand hearing services to traditionally underserved groups.

Key words: auxiliary communication, console device, speech test, tele-audiology, audiology testing

Introduction

It is estimated that by the year 2025 there will be 700 million individuals worldwide with hearing loss. According to the National Institute on Deafness and Other Communication Disorders of the National Institutes of

Health, roughly one-third of Americans over 60 years of age and one-half of those over 85 years of age have hearing loss.^{1,2} These numbers pose a tremendous demand for hearing healthcare services. Tele-audiology, by making diagnostic hearing test services more accessible, presents a potential solution to the pressing needs.

Among several tele-audiology research projects,^{3–17} the authors have developed a browser-server-distributed pure-tone audiometry-only system.^{15–17} The central application server in this system hosts all the required software, with minimum hardware and software resource requirements added to the audiology clinic and patient client sites. These “thin clients” had the advantage of separating technical issues from clinical services and ultimately enhanced end-user convenience. Due to several technical challenges, this pure-tone threshold test-only prototype did not incorporate other test procedures required for in-depth diagnosis (i.e., speech test,¹⁸ otoacoustic emissions,¹⁹ and tympanometry^{20,21}). Specifically, unlike the pure-tone threshold, which can be collected by simply asking a patient to respond to single-tone voices heard from a headset with some simple signals (raising a hand or pressing a button), other hearing test procedures involve more profound operations. In a speech test, for example, not only does the audiologist need to operate the audiometer (AMT) with commands, but also the audio signals generated by the AMT and the patient’s repeating voices both have to be returned to the audiologist, involving much more complicated real-time data exchange.

With these technical challenges addressed, this article presents a new system that can support both speech tests and pure-tone audiograms. Several characteristics in this comprehensive system support the involved interactions required for speech tests:

1. The new system adopts the same browser-server architecture used in its preceding version; therefore it handily inherits all the user convenience features.
2. Newly developed hardware and software support the exchange of both numerical and audio data required during speech tests between the audiologist and patient sites.
3. An auxiliary communication scheme with audio and video capacities boosts coordination among the medical

professional, the patient, and the assistant who assists patients at the remote site.

The rest of the article is organized as follows: Materials and Methods describes the system architecture and its major components, with a focus on how such a system meets the technical needs for multiprocedure hearing tests. Results reports its clinical effectiveness from a comparison study conducted at an audiology laboratory at East Carolina University. Discussion comments on several items observed during this design–implementation–test cycle. The article is then concluded with ideas for future work planned ahead.

Materials and Methods

This study was given East Carolina University Institutional Review Board approval (protocol number 08-0700).

OVERVIEW OF THE TELE-AUDIOLOGY SYSTEM

The system's general network architecture in *Figure 1* appears comparable to many other similar telemedicine applications, where the patients and medical professionals are located at two different geographical locations. As reported previously in our earlier publication,¹⁶ the system features a “thick” application server (Part B in *Fig. 1*) that runs all the software to coordinate test sessions, exempting the users' equipment from any particular software installation and maintenance. As a result, the audiologist terminal is not limited to any particular hardware/software platforms. The server also hosts the databases (Part C). A console device (Part D) is designed and developed in order to connect the hearing test equipment (an AMT here) to the Internet and to exchange information between the server and the adopted Bluetooth® (Bluetooth SIG, Kirkland, WA)-enabled AMT. Built on this console device's touchscreen, the auxiliary communication mechanism (Part F) is designed to provide the critical supports that allow a remote assistant to set up and coordinate test sessions.

The implementation of the application server and its database, the console device, the proce-

Fig. 1. Architecture of the integrated remote hearing test system: part B, application server, graphical user interface; part C, application server, database; part D, console device; part E, hearing test procedures; part F, auxiliary audio communication; part G, options of Internet connection; and part H, browsing devices.

dures involved in a remote speech test, and the auxiliary communication channel (Parts B–F as shown in *Fig. 1*) are detailed next. The Internet connections that remote patients use can be a wired connection, regular 3G cellular infrastructure, or satellite communication, depending on what is available at the time and the location. The description of specific Internet options (Part G) and specific browsing devices (Part H), although graphically depicted in *Figure 1*, are not discussed in this article.

Fig. 2. User interface of the speech test page. dB, decibels; MCL, maximum comfortable level; NR, not recorded; SRT, speech reception threshold; UCL, uncomfortable listening level; WRS, word recognition score.

APPLICATION SERVER: GRAPHICAL USER INTERFACE

An application server hosts several graphical user interfaces (GUIs) that allow users to manage accounts, schedule appointments, conduct hearing tests, and report test results. An ActiveX control is integrated into the hearing test page to enable the real-time audio data transmission, which is essential during speech tests and audiologist-patient/assistant communications. Since some pages are similar to the previous prototype, we elaborate here only the pages unique to the new system:

Hearing test page. Two GUIs—the pure-tone audiogram test GUI and the speech test GUI—can be selected with corresponding tab controls. The screenshot of the speech test page is shown in *Figure 2*. It includes all the necessary components for setting up speech tests and displaying test status. Several Web control components are provided for the audiologist to complete a speech test: a radio checkbox with six test mode options

(e.g., SRT for speech reception threshold, MCL for maximum comfortable level, and WRS for word recognition score); two combo boxes that determine the volume levels of the main channel and masking channel; a speech track list including the track files stored in the AMT; a “Play” and a “Stop” button that starts and stops the playing of a selected track file; and a “Save” button to record the test results. Lastly, two image buttons (a green tick “√” and a red cross “×”) are used to check whether a patient successfully repeats words read by the AMT.

Communication user interface. Three communication means, including text, audio, and video communication, are provided by the tele-audiology system to facilitate interactions required in remote hearing tests. An edit box allows an audiologist to input the text, and a “Send” button sends the text to the console device. Several buttons can be used to start or stop a conversation with the patient or the assistant, as shown in *Figure 3a*. Images of the patient included in this Web page, as shown in *Figure 3b*, further help communication between the remote and local parties.

Formal test report page. After a test (pure-tone audiogram or speech test) is completed, a formal audiometric test report is created and presented to the audiologist (*Fig. 4*). The report page can be found in the “Report” tab; the information displayed includes patient information and test results (pure-tone audiogram results for the two ears, as well as speech test results).

APPLICATION SERVER: SYSTEM DATABASE

A relational database has been developed on the application server to manage physician and assistant accounts and test results. The database contains several tables to store audiologist and assistant information, appointments, test results, and system events. The “Physician Account” and “Assistant Account” tables record audiologist and assistant information such as user name, password, full name, and e-mail address. The “Appointments” table conserves appointment-related items like patient name and scheduled test (date and time). The “Test Results” and “Events” tables store test results and system event logs, respectively. The primary key “Id” in the “Appointments” table is associated with the foreign key “ApptId” in the “Test Results” and the “Event” tables. When the audiologist wants to search for more information related to a specific appointment, he or she only needs to input the primary key “Id”; the audiologist’s name, patient’s name, test date and time, and associated test results can be found and displayed. The structure of the relational database is illustrated in *Figure 5*.

Of the three roles (Audiologist, Assistant, and Patient) that participate in remote hearing tests, “Patient” is not

Fig. 3. Auxiliary communication user interface: (a) text and audio communication and (b) video communication.

ECU Audiometric Test Report																	
Patient Information						Test Information											
Patient Name yaod						Test Date 2013-3-29											
Address						Test Time 10:00											
Right Audiogram						Left Audiogram											
	250	500	1k	2k	3k	4k	6k	8k		250	500	1k	2k	3k	4k	6k	8k
Air		25	30	25	25	25	25	25	Air	NR	35	30	20	20	30	20	25
Bone									Bone								
MCL									MCL								
UCL									UCL								
Speech Table																	
SRT	Intensity	Masking	Comment		WRS	Score	Intensity	Masking	Comment								
Right	30	15	SPONDEES.WAV		Right	60	35	10	NU6-4AS.WAV								
Left	30	15	SPONDEES.WAV		Left	66	35	15	NU6INTRS.WAV								
Binaural	30	15	SPONDEES.WAV		Binaural	55	35	10	NU6-4AS.WAV								

Fig. 4. Audiometric test report page. ECU, East Carolina University; MCL, maximum comfortable level; SRT, speech recognition threshold; UCL, uncomfortable listening level; WRS, word recognition score.

given access to the database in the current tele-audiology system. Instead, a role of “Technician,” in addition to “Audiologist” and “Assistant,” is added. Each of the three roles is given privileges to access the system database. The privileges granted to these roles and their data access

allows an assistant to set up hearing test sessions. It actively manages its Bluetooth communication with the AMT.

Components of the console device. The block diagram of the console device is illustrated in *Figure 7*, composed of five functional modules, including a transmission control protocol (TCP) module, a user datagram protocol (UDP) module, an AMT module, an audio/video module, and a user interface (UI) module.

The TCP module connects the console device to the application server, receives control messages from the server, and sends the patient’s responses to the server. This module sustains a reliable link by periodically sending a heartbeat packet to the server to maintain the connection state.

The UDP module exchanges audio and video data between the server and the console device, while control messages required to build the audio and video channels are transmitted through the TCP socket by the TCP module.

The console device AMT module initiates connections to an AMT via a peripheral interface (here a wireless Bluetooth

Fig. 5. Relational database of the tele-audiology system.

Fig. 6. Role management and data access mechanism.

link) and forwards commands to and responses from the connected AMT.

The audio/video module contains two components: the audio component opens the microphone and speaker and captures and sends the voice data streams to the UDP module, as well as receives and plays voice streams received from the UDP module, following control commands given via TCP messages; the video component captures raw images, compresses them into a JPEG format, and sends them to the server through the UDP module.

The UI module provides functions that display the connection status between the server and the AMT and sets up the network interface and AMT parameters, etc.

Fig. 7. Block diagram of the console device. AMT, audiometer; OS, operating system; TCP, transmission control protocol; UDP, user datagram protocol; UI, user interface.

HEARING TEST PROCEDURES

A hearing test session largely consists of four phases: preparation, test in progress, auxiliary communication, and result assessment. In the preparation phase, the assistant schedules an appointment and notifies the audiologist and the patient. When the scheduled time approaches, the assistant connects the console device to the server while the audiologist and the patient get ready. The sequence of the pure-tone audiogram test is similar to the preceding version.^{15,16} Therefore, only the speech test procedures are discussed here.

Once the speech test mode is entered, the audiologist, based on the patient's clinical needs, selects the proper test option (i.e., SRT, WRS, or MCL), volume level, or a track file and then hits the "Play" button. A command packet reflecting these settings is transmitted to the console device. Upon receiving this packet, the console device parses it and produces the corresponding Bluetooth commands, which are in turn delivered to the AMT while an acknowledgment packet is returned to the server. The AMT then plays the specific track file, records the voice of the patient, and sends the audio data via the Bluetooth audio link (HSP) to the console device, which further forwards the data to the server. When the audio data play on the audiologist's terminal, the successful rate that the patient repeats the words is calculated and stored in the database. The sequence diagram is shown in *Figure 8*.

AUXILIARY AUDIO COMMUNICATION

Given the complexity involved in a speech test, a convenient auxiliary audio communication channel is designed in order to allow smooth coordination between the local and remote sites. The auxiliary audio communication is disabled in the middle of any ongoing speech test. If the audiologist needs to talk with the patient or the assistant, he or she clicks the "Call" button through the GUI, and the server sends a request packet to the console device. The console device then translates the request to appropriate AT commands and forwards them to the AMT or the Bluetooth headset that the assistant wears to set up the Bluetooth audio link. An acknowledgment packet is sent back to the server once the communication is established. The sequence diagram of the audio communication between the audiologist and the patient is shown in *Figure 9*.

Fig. 8. Sequence of the speech test session. ACK, acknowledgment.

Results

In order to examine the functionality of this comprehensive tele-audiology system, experiments have been conducted in an audiology lab in the Department of Communication Sciences and Disorders at East Carolina University. Eighteen volunteers (2 males and 16 females) in the age range of 19–62 years were recruited to participate in the pilot study. The audiologist did not have prior knowledge of the participants' hearing condition. During a study, each subject received a pure-tone threshold test and a speech audiometry test using two different testing approaches. In the pure-tone audiometry, air conduction thresholds and

bone conduction thresholds were collected at octave steps from 250 to 4,000 Hz (250, 1,000, 2,000, 3,000, and 4,000). In the speech audiometry, SRT thresholds and WRS scores in decibels (dB) based on a specific speech volume were collected using a computerized face-to-face approach and the tele-audiology approach. For all tests, the subjects were seated in a sound-treated booth meeting the American National Standards Institute S3.1-1991 standards. The AMT used in the computerized and tele-audiology tests was calibrated to American National Standards Institute S3.1-1996 standards. *Figure 10* illustrates the setup on the patient site, where the subject holds a portable AMT and the console device is mounted on a cart.

From the user experience perspective, minimal disruption is observed during this study. The audiologists who participated in this study had experience with traditional hearing tests. They were able to operate the tele-audiology system with minimal training because the user interfaces were very similar to what they had used previously. Patient subjects did not notice any difference between the remote and face-to-face testing approaches, which is reasonable as the equipment (AMT and headsets) they used in both approaches is essentially the same.

The clinical effectiveness of the prototype system was primarily evaluated from two perspectives: (1) the agreement of the pure-tone threshold findings obtained from the proposed remote tests to those face-to-face tests (using a software program called Symphony²²) and (2) the agreement of the speech thresholds among the two testing approaches.

Fig. 9. Sequence of the voice communication. ACK, acknowledgment; AT, attention command for serial modem communication.

PURE-TONE THRESHOLDS

Tables 1 and *2* present the air conduction and bone conduction, respectively, thresholds from the two testing approaches (again, face-to-face test with Symphony and the remote test). These findings demonstrate that the remote test is within clinically acceptable agreement (<10 dB hearing level) with the non-server-based computerized testing system (labeled as Symphony in *Tables 1* and *2*), where both used the same off-the-shelf AMT (OTOpod²³).

SPEECH THRESHOLDS

Tables 3 and *4* show the means and standard deviations of the SRT thresholds and WRS word recognition rates, respectively, from the remote and face-to-face

Fig. 10. A subject is tested with the developed tele-audiology system.

tests. For the speech test, the tele-audiology produced results comparable to the computerized system with the Symphony software. These results, again, demonstrate that the remote test model is consistent with its face-to-face counterparts, validating the effectiveness of the proposed system.

Discussion and Conclusions

This article presents a browser-server-based tele-audiology system that supports two remote test procedures—the pure-tone audiogram test and the speech test—for patient hearing diagnosis. It elaborated the system architecture, technical implementation, and initial clinical testing results. The system features, with an auxiliary communication channel, uniquely make speech tests convenient. The initial results from the experiments demonstrate that the proposed tele-audiology system generated testing results comparable to those of its traditional face-to-face counterparts.

Table 1. Mean and Standard Deviation of Pure-Tone Thresholds (Air Conduction)

	FREQUENCY (HZ)				
	250	1,000	2,000	3,000	4,000
Symphony (dB)					
Mean	3.57	4.28	5.95	4.52	5.71
SD	5.28	4.82	6.44	7.23	8.25
Remote (dB)					
Mean	4.76	4.28	6.19	5.71	7.14
SD	4.87	5.07	6.50	6.76	9.16

SD, standard deviation.

Table 2. Mean and Standard Deviation of Pure-Tone Thresholds (Bone Conduction)

	FREQUENCY (HZ)				
	250	1,000	2,000	3,000	4,000
Symphony (dB)					
Mean	16.31	11.84	14.74	11.84	4.21
SD	7.42	7.30	7.16	4.47	5.07
Remote (dB)					
Mean	16.05	11.05	15.53	11.58	5.00
SD	8.43	8.43	7.24	7.46	6.45

SD, standard deviation.

Table 3. Speech Recognition Thresholds

	THRESHOLD
Symphony (dB)	
Mean	5.24
SD	5.58
Remote (dB)	
Mean	6.90
SD	7.15

SD, standard deviation.

The proposed system promises to better serve traditionally underserved populations, such as employees working in noisy environments, citizens in rural areas and underdeveloped countries, elderly individuals with no transportation, prisoners, and active and retired military service members.

Table 4. Word Recognition Score

	SCORE
Symphony (%)	
Mean	98.30
SD	2.03
Remote (%)	
Mean	98.90
SD	3.13

SD, standard deviation.

Before its ultimate implementation, multiple milestones need to be achieved next: (a) Due to time constraints, these tests were performed when the audiologist and patient were connected to the system within the same Internet domain; more Internet connection cases will be tested. (b) Non-hospital patient end settings (e.g., on vehicles or in field) will be investigated. (c) Variables with clinical impact (such as consumer and user satisfaction) will be examined.

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Disclosure Statement

No competing financial interests exist.

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