Hearing screening for school children: comparison of low-cost, computer-based and conventional audiometry

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Abstract

Background There is a need to develop affordable but effective audiometric screening equipment, particularly for use in low-income countries. With advances in computer technology, low-cost computer-based audiometer software has been developed. However, the efficacy of computer-based audiometers in hearing screening and diagnostic assessment requires investigation. The purpose of this study was to evaluate the accuracy of a low-cost, computer-based audiometric system in a school-based hearing screening programme.

Methods Eighty children were screened using the computer-based audiometer and with a conventional pure tone screening audiometer. Overall refer rates, as well as frequency and age effects on the accuracy of the computer-based audiometer, were considered.

Results There was a significant relationship between the low-cost, computer-based audiometer and a conventional pure tone screening audiometer when a 40 dBHL refer criterion was used in school hearing screening and when test results at 500 Hz were excluded from analysis. However, background noise effects and software limitations in the computer-based system had major adverse effects on screening performance.

Conclusions The study results and preliminary practical experience with the system suggest that, with further software and hardware improvements, a low-cost, computer-based system may well be feasible for routine school screening in developing countries.

Introduction

The World Health Organization (WHO) has estimated that more than 4% of the world’s population, i.e. 278 million people, has hearing loss. Of this proportion, approximately two-thirds live in developing countries (Smith 2008). The prevalence rate of hearing loss is thought to be high among school-aged children in developing countries. In Swaziland a prevalence rate of 4.1% was noted (Swart et al. 1995). In Kenya, it was reported that 5.6% of school children have mild hearing loss (Hatcher et al. 1995). Studies in South India (Rao et al. 2002) and Nigeria (Olusanya et al. 2000) have recorded even higher prevalence rates, of 11.9% and 13.9%, respectively. Although the published prevalence rates in school children vary considerably among developing countries because of differences in study methodologies, populations, screening criteria and other factors, hearing loss is generally more prevalent than in developed countries (Smith 2001; Berg et al. 2006). In comparison, the reported prevalence rate for hearing loss in school children in Finland was 2.5% (Marttila 1986) and for Denmark 3.6% (Parving 1999).

Hearing loss is a significant health problem and, if undetected, can have a significant negative impact on the speech and
language development, educational attainment and social-emotional development of children. In view of the widespread absence of neonatal hearing screening services in developing countries (Olusanya et al. 2007) hearing screening in school-aged children in developing countries should be an essential part of public health services. Unfortunately, while routine screening at school entry has been widely adopted in developed countries, children in developing countries are rarely screened for hearing loss (Madriz 2001; McPherson & Olusanya 2008). There are limited financial resources or trained personnel to provide routine hearing screening for school-aged children. In addition, audiological services are often urban-based and are usually provided in hospitals and private clinics (Gell et al. 1992). People who live in rural areas are often not able to access these services (Jauhaiainen 2001; Gomes & Lichtig 2005).

In view of the limited resources in developing countries, low-cost but effective hearing screening methods would be of value. The costs of hearing screening may be attributed to the cost of personnel required to carry out the screening, the time required to conduct the screening and the costs of equipment used. Hence to reduce the costs of screening, the method should be rapid, and low-cost equipment that can be easily operated by primary healthcare personnel should be used (Downs 2004). The screening method also must be effective in detecting children with hearing loss. Effectiveness is determined by the sensitivity and specificity of hearing screening (Hind et al. 1999). A screening method is said to be effective only when it achieves both high sensitivity and specificity.

School-based hearing screening methods can be classified into two groups: subjective and objective hearing status measures. Subjective approaches include questionnaires and pure tone audiometry. The feasibility of using questionnaires as a hearing screening method has been evaluated in various studies in developing countries (Newton et al. 2001; Gomes & Lichtig 2005). The costs of using questionnaires are considered to be low and the implementation of a questionnaire approach does not require professionals – primary health assistants can be employed. However, generally the sensitivity and specificity of questionnaire-based hearing screening have been poor (McPherson & Olusanya 2008). Objective methods such as otoacoustic emission recording and immittance audiometry screening are often used in hearing screening programmes (Roesser & Clark 2004). The equipment costs of these physiologic methods have decreased in recent years and this increases their feasibility as screening methods in developing countries. Nevertheless, the sensitivity and specificity of these methods are also relatively low when compared with the standard subjective screening approach, pure tone audiometry (Nozza 2001). In addition, objective methods do not aim at measuring hearing per se, but investigate middle and inner ear status. Conventional pure tone audiometry is an accurate method of hearing screening in developing countries (Berg et al. 2006). WHO has suggested that children in developing countries should be screened using an audiometer at school entry (Rao et al. 2002). If this recommendation is followed, a pure tone air conduction audiometer is an essential component of hearing screening. However, the costs associated with it are considerable and the equipment may be unaffordable in many developing countries (McPherson 2008). Low-cost, hand-held screeners have only limited accuracy (McPherson & Knox 1992; Parving et al. 2008).

In order to develop affordable equipment for hearing screening in developing countries, the present study investigated the effectiveness of a low-cost, computer-based audiometer in hearing screening for school-aged children. There are several reasons supporting the use of a computer-based audiometer in hearing screening. The application of computer technology in health care has been a continuing trend, including its use in developing countries (Wootton 2001). With advances in technology, digital signals can be stored in a computer memory and the intensity and frequency of an output signal can be accurately adjusted. There are several advantages for computerization of hearing screening programmes. The personal computer is common nowadays in many developing countries, so accessibility to hearing screening equipment, especially in rural areas, may be improved. The cost of purchasing a personal computer is now low when compared with that of purchasing a conventional pure tone audiometer. Pure tone audiometers are specialized devices that are manufactured in small quantities, making them uncommon and relatively costly. Laptop computers that cost approximately SUS200 are now being manufactured for low-income nations, further increasing the feasibility of using computer-based audiometry in the developing world (Trucano 2008). A potential additional advantage is that computer-based audiometers can be designed with automatic screening procedures. Therefore, personnel with specialized training may not be required to perform screening. Moreover, the use of computerized methods can make the recording of data and quality assurance monitoring of screening programme activities easier (Hong & Csaszar 2005), as well as facilitate telemedicine applications.

As the application of computers in hearing screening is still in its infancy, few researchers have studied the feasibility of using computers in audiometric testing. In one study, an Internet-based, telemedicine audiometric system was compared with conventional audiometry in determining auditory thresholds in
adults. Telemedicine hearing thresholds varied by less than 2 dBHL from those obtained with conventional audiometry (Givens & Elangovan 2003). Another computerized testing system also reported good threshold reliability with both normal and hearing impaired adults (Henry et al. 2003). In the present research project the feasibility of using a computer-based audiometer in hearing screening rather than in obtaining hearing thresholds was evaluated. Results from a conventional pure tone audiometer were treated as the ‘gold standard’ in this study as the reliability of conventional pure tone audiometry in hearing screening is usually high (Berg et al. 2006; Sideris & Glattke 2006), and this screening method has been used extensively in past decades.

In summary, there is a need to develop more affordable and effective audiometric screening equipment, particularly for use in developing nations. Low-cost, computer-based audiometer software has been developed. However, the efficacy of computer-based audiometers in hearing screening for school children is unknown. The purpose of this study was to evaluate the accuracy of a low-cost, computer-based audiometric system in a school hearing screening programme. In addition, screening personnel were debriefed after the study to identify any perceived problems or inadequacies in the computer-based equipment. Results from this study may help determine whether it is feasible to replace the conventional hearing screening audiometer with more affordable equipment in developing countries.

Method

Participants

Eighty participants, aged 6, 7 and 8 years, were recruited from a normal, urban Hong Kong primary school that had offered to participate in this study. The participant age range was chosen to be comparable to the range of school entry age found in many developing countries (Bommier & Lambert 2000). All participants were Cantonese speaking children with no known language or cognitive impairment. Cantonese speakers were preferred as the instructions were given in Cantonese, and control of this factor reduced the possibility that the participants could fail hearing screening because of an inability to follow instructions. Participants were recruited on a voluntary basis, with consent forms signed by parents and children prior to testing, and all children who volunteered were tested. The research project was approved by the appropriate institutional review board at the University of Hong Kong.

Screening personnel

Two Cantonese speaking testers who were speech and hearing sciences undergraduate students operated the conventional audiometer and the computer-based audiometer. They had received 12 h of instruction in audiological assessment procedures during their undergraduate training programme.

Test equipment

Computer-based audiometer

A circumaural headphone (Ovann OV880V) and a joystick for subject response (Blazepro USB) were directly connected to a personal computer (IBM ThinkPad laptop PC, model T22). The computer audiometer software Home audiometer software–v. 1.83 was installed into the PC. The programme can measure thresholds at 125, 250, 500, 750, 1000, 1500, 2000, 3000, 4000, 6000 and 8000 Hz with a nominal range from –10 to 70 dBHL.

Conventional screening audiometer

A portable pure tone screening audiometer (Madsen Micro-Mate) was used for hearing screening. The audiometer was calibrated, according to ISO 389 series standards, prior to screening. The conventional audiometer was fitted with circumaural ME-70 enclosures over TDH-39 supra-aural earphones, an arrangement designed to reduce audible background noise in the screening environment.

Equipment costs

Costs for the conventional and computer-based equipment are shown in Table 1. Low-cost computer system components were deliberately selected, to reflect components typically available and affordable in developing countries. A dedicated, low-cost

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<th></th>
<th>Computer-based audiometer</th>
<th>Conventional screening audiometer</th>
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<tr>
<td>Software: ‘Home Audimeter’</td>
<td>$27</td>
<td>$1026</td>
</tr>
<tr>
<td>USB hub</td>
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<td>USB joystick</td>
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<tr>
<td>Audio headset</td>
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<td>Laptop computer</td>
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<td>Total</td>
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laptop computer for the computer-based system may be found in the $US200 to 500 price range – the upper price limit is used in Table 1.

Test environment

Hearing screening with both procedures was conducted in a quiet, but not sound-treated room at the primary school over two non-school attendance days. Ambient noise level was measured using a sound level meter (Cesva SC30) on five occasions, randomly during testing. The noise level was similar on both days and the average noise level was 36.8 dBA. Background noise levels in occupied Hong Kong primary school classrooms are known to be high, an average of 60.7 dBA (Choi & McPherson 2005), and hence times when classrooms were unoccupied were chosen.

Test procedures: conventional audiometer

Each subject received two hearing screenings, one by conventional audiometer and one by computer-based audiometer. The two screening tests were conducted separately on the same day to minimize any confounding effects of temporal changes in children’s actual auditory status. The order of screening in respect to the two audiometers was random. The two testers were randomly assigned to an audiometer on each day of testing. They were blind to each other's screening results. The participants were seated at right angles to the tester to avoid any visual cues during screening and were fitted with headphones by the tester.

In developing countries, WHO guidelines suggest provision of hearing aids for children with hearing thresholds greater than 30 dBHL in the better ear (WHO 1999). However, in many developing countries children with mild hearing loss (25 to 40 dBHL) are often not screened because priority is given to detecting children with hearing loss that can be most successfully managed through amplification (Arslan & Genovese 1996) or because ambient noise conditions preclude testing at lower sound levels (Jacob et al. 1997). Even isolated village or rainforest locations in developing countries have background noise levels that may at times exceed 40 dBA (Counter 1986). Thus, in this study, the passing criterion was set at a higher intensity level (40 dBHL) across the test frequencies 500, 1000, 2000 and 4000 Hz in order to replicate screening conditions in many developing countries.

With the conventional audiometer, the participants were screened with 500 Hz, then 1000, 2000 and 4000 Hz, at 40 dBHL starting from the left ear to replicate the procedure used in the computer-based audiometer. The passing criterion was having reliable responses in two out of three trials at each frequency at 40 dBHL, in both ears. Failure to respond at any frequency in either ear was regarded as a screening ‘refer’ case. Children were instructed to briefly press the appropriate response button when they heard a tone, no matter how faint it was. Continuous pure tones were presented for approximately 1 to 1.5 s during screening.

Test procedures: computer-based audiometer

With the computer-based audiometer, hearing thresholds at each frequency (500, 1000, 2000 and 4000 Hz) were automatically determined using an adaptive procedure. Testing commenced in the left ear at 500 Hz, then 1000, 2000 and 4000 Hz. The computer software automatically commenced testing at 500 Hz, although hearing screening conventionally starts with tones at 1000 Hz and 500 Hz is presented last in such a frequency series (Hodgson 1985). The initial intensity level was 40 dBHL. Intensity increased in 3 dBHL steps each time a tone was represented until the subject responded. After each response, the intensity level decreased in 3 dBHL steps. Hearing threshold was determined after several series of responses were made by the subject. Children were instructed in Cantonese to press and hold the appropriate response button while they heard a tone, no matter how soft it was. Continuous pure tones of 1-s duration were presented during screening. Hearing threshold results greater than 40 dBHL at any frequency in either ear were regarded as a screening ‘refer’ case. The computer-based audiometer was biologically calibrated before testing commenced according to the instructions accompanying the software. Calibration is dependent on access to an individual with known and accurate audiometric thresholds. Calibration was initially validated by comparing thresholds obtained from four individuals with their known audiograms.

Follow-up procedures

The parents and the school principal received hearing screening reports of all tested children. Based on the conventional screening audiometer findings, parents of referral case children were given recommendations regarding follow-up assessments.

Data analysis

To evaluate the accuracy of the computer-based audiometer, the overall referral rates (failed at any one frequency at either ear)
between the computer-based audiometer and conventional pure tone audiometer were compared using $\chi^2$-test and sensitivity/specificity analysis. The accuracy of the computer-based audiometer as a function of frequency was analysed using a $\chi^2$-test or Fisher’s exact test. Agreement between individual test results for each ear was also compared, using kappa values of agreement.

**Results**

Eighty school children received hearing screening with both computer-based and conventional audiometers. Table 2 shows the demographic characteristics of the participants. Participants with absent responses at 40 dBHL at any frequency at either ear were regarded as refer. Table 3 compares the referral rates before and after excluding results at 500 Hz for both audiometers. The 500 Hz frequency low tone is that most likely to be undetected in noisy environments (McPherson & Olusanya 2008). Before excluding results at 500 Hz, the referral rates for the computer-based audiometer were 56% and 13%, respectively. Results from a $\chi^2$-test showed a statistically significant difference in the referral rates ($\chi^2 = 33.9, P < 0.05, \text{d.f.} = 1$). After excluding results at 500 Hz, the referral rates of the computer-based audiometer and the conventional audiometer were 15% and 11%, respectively. A $\chi^2$-test showed no statistically significant difference in the referral rates ($\chi^2 = 0.49, P > 0.05, \text{d.f.} = 1$) between the results from the two audiometers, when 500 Hz results were excluded. With the conventional hearing screener results as a gold standard, the computer-based screening system had a sensitivity of 1 (95% CI: 0.63–1), specificity of 0.49 (95% CI: 0.37–0.61), positive predictive value of 0.56 (95% CI: 0.45–0.67) and negative predictive value of 0.43 (95% CI: 0.33–0.55) with the inclusion of 500 Hz results for both audiometers. Excluding 500 Hz results, the computer-based screening system had a sensitivity of 0.78 (95% CI: 0.40–0.96), specificity of 0.92 (95% CI: 0.82–0.97), positive predictive value of 0.16 (95% CI: 0.09–0.27) and negative predictive value of 0.83 (95% CI: 0.73–0.91).

In order to determine whether the computer-based and conventional audiometers screen similarly, referral rates at each frequency of 500, 1000, 2000 and 4000 Hz are compared using multiple $\chi^2$-tests. Table 4 shows that referral rates at the right ear were generally lower than the left ear. Using $\chi^2$-tests, there were no statistically significant differences between the two screening procedures in referral rate at any frequencies except at 500 and 1000 Hz for the left ear.

Referral rates for the computer-based audiometer with 500 Hz data excluded decreased as age increased – with rates of 23% at 6 years, 14% at 7 years and 6% at 8 years of age. However, there was no statistically significant age effect ($\chi^2 = 2.50, P > 0.05, \text{d.f.} = 2$). The individual child ear test agreement was kappa = 0.20 (SD = 0.06) when results at all frequencies were considered and kappa = 0.62 (SD = 0.13) when 500 Hz results were excluded. These values are considered to reflect poor agreement and substantial agreement between test results for individual ears, respectively (Landis & Koch 1977).

**Discussion**

With the conventional screening results as a gold standard, the specificity of the computer-based system was low and sensitivity high, using the overall screening data. When 500 Hz results were excluded specificity improved and sensitivity declined in value. With a 40 dBHL and 1000, 2000 and 4000 Hz pass/refer criterion the low-cost, computer-based screening audiometer performed comparably to the conventional screening instrument in terms of refer rates, with no significant difference when results at 500 Hz were excluded. However, the computer-based screening audiometer refer rates were unacceptably high (56% refer) and agreement with conventional screening audiometry for individual ears unacceptably low (kappa = 0.20) when results from all four screen frequencies were used to inform a pass/refer decision. Several
factors may have contributed to this outcome and these are considered below.

Noise effects in screening

In order to gauge the effect of background noise on hearing screening in this study, the overall referral rates of pure tone audiometry before and after excluding 500 Hz results were compared. The overall referral rate for conventional screening decreased from 13% to 11% when the results at 500 Hz were excluded, comparable to school screening initial refer rates obtained by other researchers (North-Matthiassen & Singh 2007). With exclusion of results at 500 Hz, the referral rate of the computer-based audiometer dropped to a far greater extent (from 56% to 15%), indicating that the computer-based audiometer was much more susceptible to ambient noise. This may have been due to the poorer noise attenuation properties of the non-specialist headphones in the computer-based audiometer. The headphones of the conventional screening audiometer were designed for reliable hearing assessment in non-sound-treated conditions. About 18 dB can be attenuated at 500 Hz using such headphones (Frank et al. 1997). The differences in headphone noise attenuation characteristics may have adversely affected the agreement between the results for the two screening modalities. The headphones of the conventional screening audiometer were designed for reliable hearing assessment in non-sound-treated conditions. About 18 dB can be attenuated at 500 Hz using such headphones (Frank et al. 1997). The differences in headphone noise attenuation characteristics may have adversely affected the agreement between the results for the two screening modalities. The headphones in the computer-based system could, in future trials, be replaced by others with better noise attenuation. However, if circumaural noise-excluding headphones are used this would increase the cost of the computer-based audiometer, as such headphones are more expensive to manufacture. Another approach may be to provide low-cost insert earphones that attach to reusable silicone eartips for use with the computer-based system. Insert earphones have superior noise attenuation characteristics to conventional headphones (Wright & Frank 1992) but often are expensive in developing countries and easily occluded with ear wax or discharge (McPherson & Olusanya 2008). Alternatively, testing at 500 Hz could be abandoned. However, 500 Hz is an important frequency for assessing the auditory impact of middle ear disease (Silman et al. 1994) and middle ear disorders are a common cause of hearing loss in many developing countries (Smith et al. 1996).

Participants may have also had difficulty in identifying the initially presented 500 Hz tone in the non-sound-treated screening environment. This may have resulted in unreliable responses and could be resolved by revising the software to conform to the ANSI S3.21-1987 guidelines that advise initial testing at 1000 Hz. A 1000-Hz tone will often be easier to immediately detect in a school acoustic environment and 1000 Hz has better test–retest reliability (Harris 1945). Screening on days when classrooms are not otherwise occupied can be inconvenient and may present practical problems but it does reduce ambient noise effects and should be considered when planning screening schedules.

Software effects in screening

Results revealed that referral rates between the two audiometers were significantly different at the first two test frequencies (500 and 1000 Hz) in the left ear but not for other frequencies. This cannot be simply explained as an ambient noise effect as noise should affect both ears equally at low frequencies. An alternative explanation, as the test always started with 500 Hz in the left ear, may be that participants were at first unfamiliar with the computer-based audiometer screening method and this adversely affected their initial performance, despite a short ‘trial run’ at this frequency before screening commenced. As the computer-based audiometer was an automatic device, the testers were unable to stop the programme and reinstruct children. An improved version of the computer software would allow a complete trial run before actual screening commences.

Participants who passed the conventional audiometer screening but failed with the computer-based audiometer may have failed the latter because of fatigue effects, as it took a longer duration to complete. Screening procedures may be challenging for school-aged children, especially younger children with a more limited attention span. The computer-based audiometer frequency and the intensity levels are preset by the software and controlled by participant responses. Children were required to press and hold down a button every time they heard a tone. As it is an automatic system, the testers were not able to stop the

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<td>Conventional audiometer</td>
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<td>Computer-based audiometer</td>
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*No significant difference between two referral rates (P > 0.05).
test and reinstruct children during screening. However, the testers were able to condition or reinstruct children during conventional hearing screening if they found that children were unfamiliar or had difficulties with the procedures. Results indicated that the number of referrals with the computer-based audiometer was the greatest for the youngest age group (6 year olds), although this effect was not statistically significant in the present relatively small study group. The facility to pause the programme and provide reinforcement or reinstruction by the tester during a child’s screening assessment would be valuable. A pause function would also allow rest intervals for children at any time during screening.

As the hearing thresholds were obtained using 3-dB increments, the duration of the test was much longer (about 15 min) than conventional hearing screening in which only 40 dBHL pure tones were presented (about 5 min). In addition, the screening required more sustained concentration as tones were presented down to individual threshold levels. During the debriefing session with the screening personnel all these issues were highlighted. Screening personnel also suggested that intervals between tone presentations should be irregular in order to minimize the chance of predicting the tone without actual perception. The computer-based programme does not yet have this facility. The software, at least with its default settings, was not well suited to screening in school children.

Conclusions

Results showed that the low-cost, computer-based and conventional audiometers had comparable refer rates when mid and high frequencies were considered, at the study’s 40 dBHL passing criterion. This suggests that low-cost, computer-based audiometers may be a promising alternative for hearing screening of school children in quiet but non-sound-treated environments. With advances in computer technology and decreasing costs, computer-based audiometers integrated into basic personal computers may be a viable alternative for hearing screening in developing countries. However, the high refer rate found at 500 Hz precludes the use of the low-cost computer system, as it is presently configured, in school screening programmes. Further development is necessary to overcome the present constraints imposed by the use of conventional headphones and by the current software design. Successfully overcoming barriers to affordable hearing screening instrumentation may benefit large numbers of school children with hearing impairment throughout the developing world.

Key messages

- Children in developing countries are rarely screened for hearing, despite high prevalence rates.
- A barrier to the introduction of screening programmes is the cost of specialist hearing assessment equipment.
- With the gradual penetration of low-cost personal computers into developing countries it is worthwhile to consider if they could be applied in hearing health services for children.
- Currently available low-cost software and hardware have major limitations in terms of effectiveness in such screening programmes.
- With further development, more appropriate computer-based technology may have a role to play in hearing screening for children in developing countries.

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References


Smith, A., Hatcher, J., Mackenzie, I. J., Thompson, S., Bal, I., Macharia, I., Mugwe, P., Okoth-Olende, C., Oburra, H. & Wanjoji,


