Asynchronous interpretation of manual and automated audiometry: agreement and reliability

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ABSTRACT:

Introduction: Remote interpretation of automated audiometry offers the potential to enable asynchronous tele-audiology assessment and diagnosis in areas where synchronous tele-audiometry may not be possible or practical. The aim of this study was to compare remote interpretation of manual and automated audiometry.

Materials and methods: Five audiologists each interpreted manual and automated audiograms obtained from 42 patients. The main outcome variable was the audiologist's recommendation for patient management (which included treatment recommendations, referral or discharge) between the manual and automated audiometry test. Cohen's Kappa and Krippendorff's Alpha were used to calculate and quantify the intra and inter-observer agreement, respectively and McNemar's test was used to assess the subject audiologist-rated accuracy of audiograms. Audiograms were randomised and audiologists were blinded as to whether they were interpreting a manual or automated audiogram.

Results: Intra-observer agreement was substantial for management outcomes when comparing interpretations for manual and automated audiograms. Inter-observer agreement was moderate between clinicians for determining management decisions when interpreting both manual and automated audiograms. Audiologists were 2.8 times more likely to question the accuracy of an automated audiogram compared to a manual audiogram.

Discussion: There is a lack of agreement between audiologists when interpreting audiograms, whether recorded with automated or manual audiometry. The main variability in remote audiogram interpretation is likely to be individual clinician variation, rather than automation.

INTRODUCTION

The current, conventional method for assessing hearing in adults involves a clinician manually performing pure-tone audiometry in a suitably sound-treated environment and interpreting the results on-site.[1] However, higher rates of hearing loss and lower rates of intervention uptake in rural and remote populations, coupled with the shortage of audiological services in these areas has been of significant concern in both developed and developing countries.[2,3] Telehealth solutions and the automation of audiometry have been proposed as a potential means to increase access to hearing services in underserved populations[3-5]

A number of automated audiometers have recently been clinically validated, including the AMTAS[6,7] and KUDUwave.[8] The consensus across studies is that automated audiometry is a suitable alternative to manual audiometry,[9] although some studies have identified an absolute mean difference of up to 10dB in automated air conduction thresholds compared to manual hearing thresholds, with further increased variance of approximately 15 dB for bone-conduction thresholds.[10] Automated audiometry has been validated for use without a sound treated environment, and in a clinically heterogeneous population, meaning it has the potential to overcome some of the obstacles associated with testing in rural and remote areas.[10-12]

Synchronous or “live” tele-audiology assessment, where the clinician administers and interprets the hearing assessment simultaneously, may not be possible due to connectivity issues in many rural and remote areas or due to limited clinician time.[13] An alternative may be assessment with automated audiometry and remote interpretation of the results in an asynchronous telehealth model. This offers benefits such as greater coverage for difficult to access and transient populations, such as some Indigenous Australian communities, and allows for opportunistic assessments performed by local health workers which may be more efficient than scheduled appointments in some populations.[14] It may also offer benefits to clinicians, reducing travel and enabling flexible working environments (e.g. working from home). The remote interpretation of test results is common and has been validated in a number of areas of medicine to facilitate telehealth services; including interpretations of retinal images,[15] radiography,[16] echocardiograms[17] and otoscopy.[18,19] However, comparisons between remote interpretations of manual and automated audiometry have not been reported previously.

The aims of the present study were to examine the agreement between remote interpretations of manual and automated audiograms by audiologists and whether the potential variation in hearing thresholds introduced by automated audiometry would affect the clinical decisions made by audiologists.

METHODS

This study compared the intra and inter-observer agreement between remote interpretations of manual and automated audiometry. Results of agreement studies are intended to provide information about the amount of error inherent in any diagnosis, score, or measurement.[20]

Participants for this study were five audiologists recruited from the Ear Science Institute Australia. Audiologists who were more than three years post-qualification and maintained more than one day per week of clinical audiology practice were invited to take part in the study. The audiologists analysed existing data collected from patients in a validation study of automated audiometry which recruited 42 adults (>18 years) presenting with suspected hearing loss at public audiology and otolaryngology clinics at Sir Charles Gairdner Hospital, Perth, Western Australia; see [10,21] for further details of the study population and test procedures. This study was approved by the University of Western Australia's human research ethics committee.

Equipment: Manual audiometry was conducted within a sound-treated room (mean ambient noise level 37 dBA) using Acoustic Analyser AA30 audiometer (Starkey Hearing Technologies; Minnesota), calibrated to ISO389-1:1998 and TDH-39P (Telephonics; North Carolina) supra-aural headphones and Radioear B-71 bone-conductor (Radioear Corp.; Pennsylvania), calibrated to ISO389-3:1994. The bone-conductor was placed on the patient's mastoid for manual testing. Patient history, otoscopy and tympanometry using a GSI 38 Auto Tymp (Grason-Stradler; Minnesota) preceded audiometry testing. Five audiologists were involved in performing the manual audiometry assessments. Automated audiometry was conducted using the KUDUwave (eMoyoDotNet; Pretoria, South Africa) a mobile Type 2B screening, diagnostic and clinical audiometer (IEC 60645-1/2) using the ascending method according to ISO8253-1:2010. The automated assessments were facilitated by authors CGBJ or RHE.

Procedure: Manual audiometry, automated audiometry, tympanometry and participant demographic (age and gender) were extracted and standardised using an audiogram generator so that the manual and automated audiograms could not be distinguished (manual audiometry results were originally recorded by hand, whereas automated results are recorded electronically). The audiograms (and accompanying clinical information) were anonymised, randomised by allocation to a unique, randomly generated 4-digit number and then sorted in ascending order for interpretation (see Appendix 1).

The five audiologists participating in this experiment, blinded to whether manual or automated audiometry was used, independently interpreted the audiograms, together with the other available information (age, gender and tympanometry; a full patient history was not available to participating audiologists). Audiologists were aware that some of the audiograms for interpretation were obtained by automated testing and that these would be compared to manual audiograms. However, they were not aware that they would be interpreting matched pairs of manual and automated audiograms. They were asked to provide a determination of: 1) the level and type of hearing loss; 2) a management plan for the patient given their audiometric results; and 3) their judgement of the reliability of the audiogram. There are no universally agreed standards for determining the type and level of hearing loss, management plan or reliability of the audiogram; these are normally the result of professional training and local clinic protocols.

For the purposes of this study, 1) the options for level of hearing loss were normal hearing, slight hearing loss or significant hearing loss requiring intervention and the options for type of hearing loss were normal hearing, sensorineural, conductive or mixed hearing loss; 2) the management options were no intervention, referral for hearing aids, referral for medical treatment or other, and 3) audiologists were given the option to add comments on the reliability of the audiogram. To measure this outcome a “no” answer was considered to imply that an audiologist had no issues with reliability and a “yes” answer combined with a comment questioning the reliability of the audiogram was considered to indicate that an audiologist questioned the reliability of the audiogram (see Appendix 1).

Data analysis: Firstly, Cohen's Kappa was used to calculate the intra-observer agreement of the audiologist's asynchronous interpretations for determining the type and severity of hearing loss, and the recommendation for patient management. This was to examine whether clinicians agreed with themselves for manual versus automated interpretations.

Secondly, Krippendorff's Alpha and q-statistic[22] was used to calculate the inter-observer agreement of remote interpretations for determining the type and severity of hearing loss, each ear separately, and the recommendation for patient management. Krippendorff's Alpha allows comparison of agreement between multiple coders, in this case audiologists, and was therefore used to compare whether clinicians agreed with each other when interpreting both manual and automated audiograms. The q statistic represents the probability of reaching $\alpha > 0.6$ (substantial agreement).

Thirdly, the main outcome variable, agreement between audiologist's recommendation for patient management between the manual and automated audiometry test, was examined using Cohen's Kappa and p-value for intra-observer agreement and Kripendorff's Alpha and q-statistic for inter-observer agreement. The paired samples t-test was also used to determine the correlation coefficient between manual and automated audiometry for management decisions between audiologists.

Finally, the audiologist-related accuracy of audiograms was examined using McNemar's test; that is, odds ratios for paired nominal data, in this case, dichotomous audiogram reliability scores.

The Landis and Koch (1977)[22] recommendations of agreement classification were applied to Cohen's Kappa and Krippendorff's Alpha analyses, with $a<0$ indicating no agreement, a = 0–0.20 indicating "Slight" agreement, a = 0.21–0.40 indicating "Fair" agreement, *a* = 0.41–0.60 indicating “Moderate” agreement, *a* = 0.61–0.80 indicating “Substantial” agreement and *a* = 0.81–1.00 indicating “Almost perfect” agreement.

RESULTS

Intra-observer pooled agreement for clinician’s interpretations for: (i) the level of hearing loss for manual versus automated audiograms ranged from moderate to almost perfect agreement (*a* = 0.637 [95%CI 0.452 to 0.822]; *p*<0.001); (ii) the type of hearing loss ranged from fair to substantial agreement (*a* = 0.407 [95%CI 0.207, 0.613)]; *p* <0.001; (iii) management outcomes ranged from moderate to almost perfect (*a* = 0.693 [95%CI 0.521 to 0.865]; *p* <0.001), see Tables 1 and 2.

Table 1: Individual clinician (intra-observer) reliability for manual versus automated audiogram interpretations measured with Kappa agreement.

	Level of hearing loss			***Type of hearing loss***		
	α	**[95%CI]**	***p***	***α***	**[95%CI]**	***p***
Clinician 1	0.756	0.577, 0.935	**<.001**	0.433	0.244, 0.622	**<.001**
Clinician 2	0.628	0.4395, 0.816	**<.001**	0.343	0.127, 0.560	**<.001**
Clinician 3	0.629	0.434, 0.824	**<.001**	0.449	0.226, 0.672	**<.001**
Clinician 4	0.543	0.341, 0.745	**<.001**	0.429	0.251, 0.607	**<.001**
Clinician 5	0.631	0.440, 0.821	**<.001**	0.379	0.185, 0.578	**<.001**
Clinician agreement (pooled)	0.637	0.452, 0.822	**-**	0.407	0.201, 0.613	**-**

Table 2: Individual clinician (intra-observer) reliability for manual versus automated audiogram interpretations management measured with Kappa agreement.

	Management outcomes		
	α	**[95%CI]**	***p***
Clinician 1	0.810	0.638, 0.982	**<.001**
Clinician 2	0.771	0.618, 0.924	**<.001**
Clinician 3	0.659	0.481, 0.837	**<.001**
Clinician 4	0.574	0.386, 0.762	**<.001**
Clinician 5	0.651	0.472, 0.829	**<.001**
Clinician agreement (pooled)	0.693	0.521, 0.865	**-**

Inter-observer agreement varied from moderate to substantial in regards to the level of hearing loss, type of hearing loss and management for both automated and manual audiometry (Table 3). However, inter-observer agreement was not significant for interpretation of type of hearing loss bilaterally for either manual or automated audiometry. Inter-observer agreement was significant for both right and left ear interpretations of level of hearing loss using manual audiometry (α = 0.692 [95%CI 0.593, 0.778]; q = 0.029 and α = 0.696 [95%CI 0.569, 0.790]; q = 0.028, respectively). For automated audiometry however, only the right ear level of hearing loss interpretations showed significant inter-observer agreement (α = 0.680 [95%CI 0.604, 0.755]; q = 0.019) (Table 3, Figures 1 and 2).

Figure 1: Inter-observer reliability for automated audiometry with 95%CI.

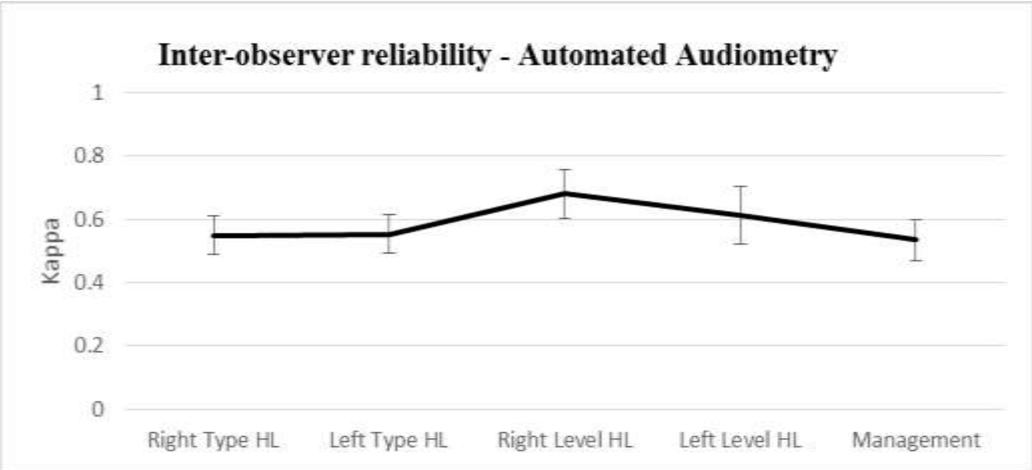

Figure 2: Inter-observer reliability for manual audiometry with 95%CI.

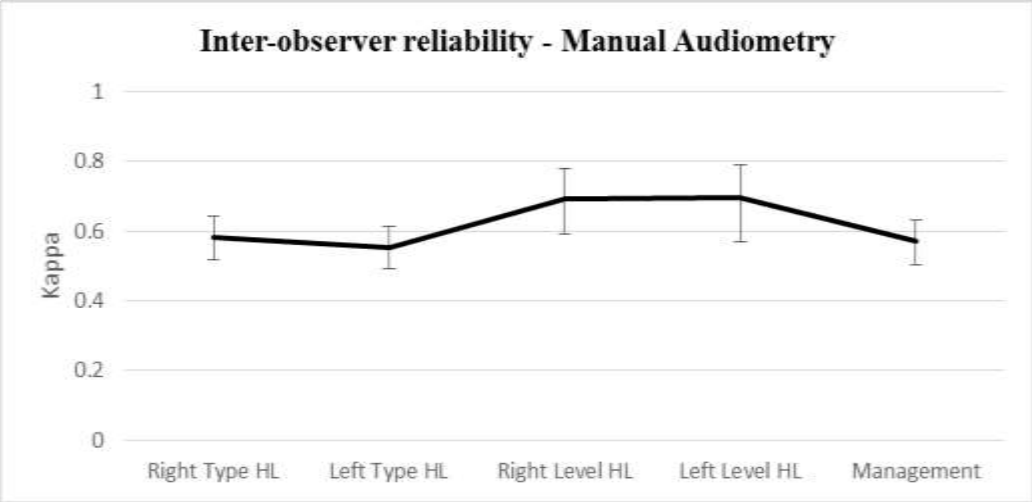

Table 3: Overall clinician (inter-observer) reliability across the five remote interpretation outcomes using Kirpendorff's alpha and probability (*q*) of reaching α >0.6.

Interpretation Outcomes	*Manual audiometry*			*Automated audiometry*		
	α	[95%CI]	*q*	*α*	[95%CI]	*q*
Right Type HL	0.582	0.519, 0.642	0.715	0.550	0.490, 0.610	0.950
Left Type HL	0.551	0.490, 0.615	0.940	0.553	0.494, 0.616	0.936
Right Level HL	0.692	0.593, 0.778	**0.029**	0.680	0.604, 0.755	**0.019**
Left Level HL	0.696	0.569, 0.790	**0.028**	0.615	0.520, 0.704	0.394
Management	0.569	0.505, 0.630	0.833	0.536	0.469, 0.600	0.968

Table 4: Distribution of management decisions for remote interpretations of manual and automated audiometry.

Automated audiometry management	Manual audiometry management, n(%)				
	Discharge	Aud ref	Med ref	Aud + Med	Other
Discharge	45 (93.8)	2 (4.2)	1 (2.1)	0 (0)	0 (0)
Aud ref	2 (9.1)	18 (81.8)	0 (0)	2 (9.1)	0 (0)
Med ref	6 (16.2)	3 (8.1)	21 (56.8)	7 (18.8)	0 (0)
Aud + Med ref	2 (2.0)	7 (6.9)	10 (9.8)	83 (81.4)	0 (0)
Other	1 (100.0)	0 (0)	0 (0)	0 (0)	0 (0)

(Aud = audiology; Med = medical; ref = referral)

There was no significant inter-observer agreement for management outcomes for either manual or automated audiometry (Table 3 and 4, Figure 1 and 2).

The correlation coefficient between manual and automated audiometry for management decisions between audiologists was high and significant (0.823, $p < 0.001$) using a paired samples t-test. Concurrence for discharge/no treatment was highest (93.8%), followed by audiological referral and medical referral (respectively 81.8% and 81.4%), whereas combined medical referral was lower at 56.8% (Table 4).

Audiologists were more likely to question the reliability of automated audiograms than manual audiograms (OR = 2.848; $p<0.001$) (Table 5).

Table 5: Subjective clinician rated reliability of automated versus manual audiograms using McNemar's test.

	Audiometry reliability			
	OR	**[95%CI]**	X^2	***p***
Clinician 1	2.091	0.439, 9.961	0.898	.118
Clinician 2	3.222	0.395, 26.255	1.296	.064
Clinician 3	1.111	0.260, 4.754	0.020	.238
Clinician 4	7.364	0.689, 78.714	3.454	**.006**
Clinician 5	0.951	0.888, 1.019	0.051	.999
Pooled reliability	2.848	1.246, 6.508	6.532	**<.001**

DISCUSSION

The present study shows that agreement for management decisions for participants remains relatively high when automated audiograms are interpreted remotely, with intra-observer agreement ranging from moderate to almost perfect. There was no significant inter-observer agreement for patient management decisions for manual or automated audiometry, indicating that management decisions differed between clinicians regardless of whether manual or automated audiometry was used.

There was significant, moderate to substantial intra-observer agreement for audiologists when determining the level and type of hearing loss using automated compared to manual audiometry. However, for inter-observer agreement, only decisions relating to the level of hearing loss were significant, but this was true for both manual and automated audiometry. Our results show a lack of agreement between audiologists when determining the type of hearing loss and management decisions when interpreting manual audiometry. This highlights that the main source variable in the agreement between decisions made based on remote audiogram interpretation is likely to be individual clinician variation, rather than automation.

Determination of the type and level of hearing loss was deliberately subjective in this experiment with no set quantitative criteria given to the audiologists. Whilst standard criteria exist for classifying the level of hearing loss,[23] the applicability of these arbitrary cut-offs to clinical practice has been questioned.[24-26] Therefore, the audiologists were presented with options of clinical significance (i.e. whether referral for intervention was necessary, and if so, what type). With a lack of definition between sensorineural, conductive and mixed hearing loss the classification of patients into these groups was diverse and agreement was poor between test method and clinicians.

Despite good intra-observer agreement and being blinded as to which audiograms were automated and which were manual, audiologists were 2.8 times more likely to question the reliability of an automated audiogram (Table 5). The specific wording and scoring of the question used in this study may have influenced the reporting rates of reliability. Whilst the question prompted audiologists to consider the reliability of the audiogram (rather than a spontaneous comment) the need for confirmation with a specific comment may have resulted in under-reporting. However, it has also been argued that the use of automated audiometry may actually limit bias; that is, increase reliability in audiometric assessment.[27,28] The tester bias associated with audiometry is well-documented and many audiologists may consciously or sub-consciously alter hearing thresholds to adhere to certain rules or an expected pattern.[29] This perception of poor reliability may be in part influenced by the fact that automated audiometry does not perform these adjustments. When audiometric results are shown that do not fit the expected pattern or conventions, such as when a bone conduction threshold appear worse than air conduction thresholds, this may be interpreted as an unreliable assessment. However, it is also recognised that for some patients, audiometry can be a difficult task to perform and the reliability or accuracy of the audiogram can be compromised with automation.[30] Therefore, the capacity to provide synchronous tele-audiometry assessment for patient's suspected to have poor reliability would be beneficial to complement a predominately asynchronous model.[8]

Audiometry is a key part of any test battery for the assessment of hearing and its impact on daily function and quality of life for patients. The remote interpretation of audiometry potentially offers significant efficiency and financial savings for telehealth programs and potential to improve access to services using automated technology, without the need for a clinician to travel to remote areas. However, the diverse presentation of patients with hearing loss means that audiometric assessment alone is often not sufficient and that the effect of hearing loss on daily function and quality of life should be ascertained before clinical decisions on patient treatment and management are made based on remote audiogram interpretation.

The findings from this study suggest that an asynchronous tele-audiology model, where automated audiometry is performed remotely with results forwarded for management by audiologists or medical personnel is practicable. This could facilitate much wider coverage of ear and hearing services, streamlining metropolitan specialist services and reducing the need for specialists to travel to rural and remote regions to administer services. Future research should investigate the addition of further clinical, contextual and quality of life information that may improve both the inter- and intra-observer reliability of remote interpretations.

Potential limitations of this study include the use of subjective diagnosis criteria and the reliability index used to measure treatment and reliability outcomes. The present study also examines only one automated audiometry device in an adult population Future studies examining different devices in different populations would be beneficial.

CONCLUSION

Remote interpretation of automated audiometry appears to be a reliable approach for diagnosing hearing loss and identifying appropriate interventions. Clinician interpretations vary significantly, both for manual and automated audiograms. It is thought that this variation is not exclusive to remote interpretation of audiometry in a telehealth context, rather it is reflective of the diverse needs of patients with hearing loss and a clinician's personnel experience. The findings from this study highlight that the use of remote interpretations of automated audiometry as a method for assessing hearing ability has equivalent agreement to audiologists interpreting manual audiometry and is therefore feasible in the context of a comprehensive tele-audiological program.

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