Transient Evoked Otoacoustic Emissions in Adults: A Comparison between Two Test Protocols

Joseph Kei*
Ravi Sockalingam*†
Clive Holloway*
Alan Agyik*
Craig Brinin*
Doreen Baine*

Abstract

This study compares the performance of the Quickscreen and Default protocols of the ILO-96 Otodynamics Analyzer in recording transient evoked otoacoustic emissions (TEOAEs) from adults using clinical decision analysis. Data were collected from 25 males (mean age = 29.0 years, SD = 6.8) and 35 females (mean age = 28.1 years, SD = 9.6). The results showed that the mean signal-to-noise ratios obtained from the Quickscreen were significantly greater than those from the Default protocol at 1, 2, and 4 kHz. The comparison of the performance of the two protocols, based on the results using receiver operating characteristics curves, revealed a higher performance of the Quickscreen than the Default protocol at 1 and 4 kHz but not at 2 kHz. In view of the enhanced performance of the Quickscreen over the Default protocol in general, the routine use of the Default protocol for testing adults in audiology clinics should be reconsidered.

Key Words: Adults, audiological assessments, transient evoked otoacoustic emissions

Abbreviations: TEOAE = transient evoked otoacoustic emission

Sumario

Este estudio compara el rendimiento del protocolo Quickscreen y el predeterminado (default) en el Analizador Otodynamics ILO-96, para registrar emisiones otoacústicas evocadas por transientes (TEOAE) en adultos, utilizando análisis de decisión clínica. Se recogió información de 25 hombres (edad media = 29.0 años, DS = 6.8) y 35 mujeres (edad media = 28.1 años, DS = 9.6). Los resultados mostraron que las relaciones señal/ruido medias obtenidas del Quickscreen fueron significativamente mayores que las del protocolo predeterminado, en 1, 2 y 4 kHz. La comparación del rendimiento de los dos protocolos, basado en los resultados generados a partir de curvas características de receptor operante, reveló un rendimiento mayor del protocolo Quickscreen sobre el protocolo predeterminado en 1 y 4 kHz, pero no en 2 kHz. En vista del rendimiento aumentado del protocolo Quickscreen sobre el protocolo predeterminado en general, debería reconsiderarse el uso rutinario del protocolo predeterminado en la evaluación de adultos en las clínicas audiológicas.

Palabras Clave: Adultos, evaluaciones audiológicas, emisiones otoacústicas evocadas por transientes

Abreviaturas: TEOAE = emisiones otoacústicas evocadas por transientes

*Department of Speech Pathology and Audiology, University of Queensland, Brisbane, Australia; †School of Human Communication Disorders, Dalhousie University, Halifax, Canada

Reprint requests: Joseph Kei, Department of Speech Pathology and Audiology, University of Queensland, St Lucia, Queensland 4072, Australia; Phone: +61-7-3365-2824; Fax: +61-7-3365-1877; E-mail: k.kei@mailbox.uq.edu.au

Despite the widespread use of TEOAEs, there are no internationally accepted standards regarding test protocol and pass/fail criteria in TEOAE analysis (Kemp et al, 1990; Norton et al, 2000). The Otodynamics ILO-96 otoacoustic emissions analyzer, commonly used in audiology clinics, allows clinicians to select either the Default or Quickscreen protocol in recording TEOAEs. Both protocols utilize broadband acoustic click stimuli in the nonlinear mode of 0.08 msec duration. However, the Default protocol measures responses over a time window of 2.5 msec to 20.5 msec with a click rate of 50 per second, whereas the Quickscreen setting employs a reduced recording time window of 2.5 msec to 12.5 msec with a click rate of 80 per second.

Presently, the Default protocol has frequently been utilized for testing adults (e.g., Robinette, 1992; Hurley and Musiek, 1994; Musiek et al, 1995; Engdahl, 2002; Engdahl and Tambs, 2002). In the initial stages of the development of TEOAEs, the Default protocol was utilized for all testing, due to its ability to record TEOAEs in the lower frequency range (e.g., < 1 kHz). In 1993, however, White and colleagues reported the successful application of the Quickscreen protocol in testing newborns in the Rhode Island Hearing Assessment Project. Since then, the Quickscreen protocol has gained wide acceptance for the assessment of infants due to its resilience to noise (both ambient and subject-generated noise) (McPherson et al, 1998; Driscoll et al, 1999). Furthermore, the Quickscreen protocol takes less time to complete in neonates than the Default protocol (Vohr et al, 1993). This reduction in test time may render the Quickscreen protocol more feasible and successful in assessing the auditory function of neonates and children with special needs (White et al, 1993; Maxon et al, 1996; Nicholas et al, 1999; Andersson et al, 2000; Driscoll et al, 2002).

The Quickscreen has been found to excel over the Default protocol in eliciting more robust TEOAEs from adults in the presence of an excessive background noise (Rhoades et al, 1998; Smith et al, 2001). Despite the advantage of the Quickscreen over the Default protocol in noisy environments, no systematic investigation of the performance of the two protocols when applied to adults in a clinical setting has been reported. A preliminary study, which investigated the effects of time-windowing on TEOAEs obtained from adults, was conducted by Whitehead and colleagues (1995). In that study, the TEOAE responses were reanalyzed post hoc using different time windows. They showed that, relative to the Default setting, the 2.5–7.5 msec and 2.5–9.0 msec time windows reduced noise levels more than TEOAE amplitudes, thus resulting in increased signal-to-noise ratios (SNR) and greater reproducibility values. They predicted that decreasing the response time window might increase the measurement efficiency of TEOAEs in adults and enhance clinical test performance. However, measures of clinical test performance have not been reported.

The present study compared the efficacy of long (Default) versus shortened (Quickscreen) recording time windows in TEOAE testing of adults in a typical clinical setting (in a sound-treated room with very low ambient noise levels). In particular, the test performance of the two protocols was evaluated using clinical decision analysis (Swets, 1988).

METHOD

Participants

Twenty-five males (mean age = 29.0 years, SD = 6.8, range = 20–44) and 35 females (mean = 28.1 years, SD = 9.6, range = 18–51) volunteered to participate in this study. Participants were recruited from the staff members and students of the University of Queensland, Australia. Written consent was obtained from all participants prior to testing. Adults with a moderate hearing impairment (pure-tone average [at 0.5, 1, and 2 kHz] > 40 and ≤ 55 dB HL) or worse, irrespective of the type of loss, were excluded from the present study because TEOAEs would be absent for hearing losses greater than 40 dB HL (Collet et al, 1991; Robinette, 1992).

Procedure

In addition to the TEOAE test, otoscopy, pure-tone audiometry, and tympanometry were performed for each participant to gather more information about the auditory status of the participant. The TEOAE test was carried out in a sound-treated room with an ambient noise level of 37 dBA (with the ILO-

96 Otodynamic Analyzer and desktop computer turned on), as measured by a Brüel and Kjaer (type 2235) sound level meter. This noise level was considered acceptable for the TEOAE testing of adults (Rhoades et al, 1998). All other tests were conducted in another sound-treated room with an ambient noise level of 24 dBA. Otoscopy was performed first, followed by pure-tone audiometry, tympanometry, and TEOAE testing.

Otoscopy

Otoscopic examination was performed using a handheld otoscope to check for blockage of the ear canal and signs of outer ear abnormality.

Tympanometry

A Madsen Zodiac 901 Middle Ear Analyzer with a probe tone of 226 Hz was used. Ears with a type A tympanogram (middle-ear pressure between +50 daPa and -100 daPa, and static compliance between 0.3 ml and 1.6 ml), as defined by Jerger (1970), were awarded a pass. All other tympanometric types, including type Ad (static compliance > 1.6 ml), were considered a "fail" result.

Pure-Tone Audiometry

An Interacoustics AC30 clinical audiometer with TDH-39 headphones was used to obtain air-conduction pure-tone thresholds. Thresholds at 0.5, 1, 2, and 4 kHz were obtained from both ears of each participant using the Hughson-Westlake procedure. For the purpose of the present study, pure-tone thresholds of 15 dBHL or better were considered normal (Clark, 1981; Hall, 2000). This pass criterion for pure-tone audiometry served as the "gold standard," with which TEOAE results were compared.

TEOAE Testing

All TEOAE data were acquired using the Otodynamics ILO-96 otoacoustic emissions analyzer, installed on a desktop computer. A foam-tip (type R9.5F) was attached to the probe assembly and placed firmly into a participant's ear canal. The probe check-fit procedure was performed prior to the commencement of each test. Broadband clicks of 0.08 msec duration in the nonlinear mode were used for both the Default and Quickscreen protocols. The Default and Quickscreen protocols delivered clicks at a rate of 50/sec and 80/sec, respectively. The stimulus intensity level used for both protocols was tightly controlled and targeted at 80 ± 1 dB pSPL. The equivalence of stimulus intensity levels for both protocols is essential to ensure that any difference in TEOAE results would not be attributed to a difference in stimulus levels. The intensity level was readjusted before commencing data collection if the level fell outside of this range. The noise rejection level was set at the default value of 47.3 dB for all participants for both protocols.

Once the test protocol was selected, recording began, and the tester monitored the stability of the probe and stimulus during the test. The ILO-96 program automatically terminated TEOAE recording after 260 quiet responses were collected. To control for order effects, 30 participants were tested using the Quickscreen protocol first, followed by the Default protocol, while the other 30 participants were tested using the two protocols in the reverse order.

RESULTS

The stimulus intensity level for both the Default and Quickscreen protocols was tightly controlled. As a result of this restriction, five ears were excluded from the study because the difference in stimulus levels in the same ears between the protocols exceeded 2 dB. Hence, the results for the remaining 115 ears were analyzed.

Otoscopic results of the 115 ears were normal. Tympanometry findings were normal, with the exception of three ears showing static compliance values greater than 1.6 ml. Pure-tone audiometry findings revealed 17 ears with thresholds exceeding 15 dB HL (considered a "fail" result in this study) at one or more frequencies. Five failures occurred at 1 kHz, six at 2 kHz, and 10 at 4 kHz. The highest threshold obtained across the frequencies tested was 35 dB HL. The mean thresholds at 1 kHz for males and females were 4.3 dB HL (SD = 3.9) and 6.7 dB (SD = 6.5) respectively. Mean threshold at 2 kHz for males was 2.8 dB HL (SD = 5.6) and for females was 5.8 dB HL (SD = 6.5), and mean threshold at 4 kHz for males was 6.1 dB HL

Table 1 Comparison of TEOAE Variables between the Quickscreen (Qscr) and Default (Def) Protocols (N = 115 Ears)

Variable	Qscr Mean	Qscr SD	Def Mean	Def SD	t-value (df)	p
Stimulus intensity (dB pSPL)	80.3	0.6	80.2	0.5	-1.74 (114)	0.085
Stimulus stability (percent)	96.6	2.2	96.3	2.2	-1.17 (114)	0.243
Percent of quiet responses	98.7	5.8	96.8	8.0	-2.16 (114)	0.033
Response (dB)	6.5	4.8	8.9	4.6	15.06 (114)	<0.0001*
Reproducibility (percent)	89.5	18.4	83.4	20.6	-4.47 (114)	<0.0001*
Test time (sec)	57.7	0.93	50.4	5.59	-14.91 (114)	<0.0001*
Noise (dB SPL)	27.0	3.38	32.08	3.35	14.5 (114)	<0.0001*
AB difference (dB)	-6.16	3.37	-1.1	3.35	14.47 (114)	<0.0001*

* Significant with Bonferroni-adjusted probabilities.

(SD = 7.5) and females 6.9 dB HL (SD = 6.5). An independent samples t-test to compare pure-tone thresholds across gender revealed significant differences at 1 kHz [$t(113) = -2.34$, $p = 0.02$] and 2 kHz [$t(113) = -2.58$, $p = 0.01$], with $p < 0.05$ denoting significance. However, no significant difference across gender was found at 4 kHz.

Table 1 shows mean values for stimulus intensity, stimulus stability, percent of quiet responses, reproducibility (the value of the cross-correlation between the A and B waveforms expressed as a percentage), test time (as appeared on the computer screen), noise (the average sound pressure level detected by the probe microphone), response (the overall level of the correlated portions of the A and B response waveforms), and AB difference (the average difference between the A and B waveforms, the level of energy represented by the cross-hatched area of the response Fast Fourier Transform window) for the Quickscreen and Default protocols of the TEOAE test. A paired samples t-test was applied to the variables across the protocols. The results revealed a significant difference (with Bonferroni adjustment) in the reproducibility, test time, noise, response, and AB difference.

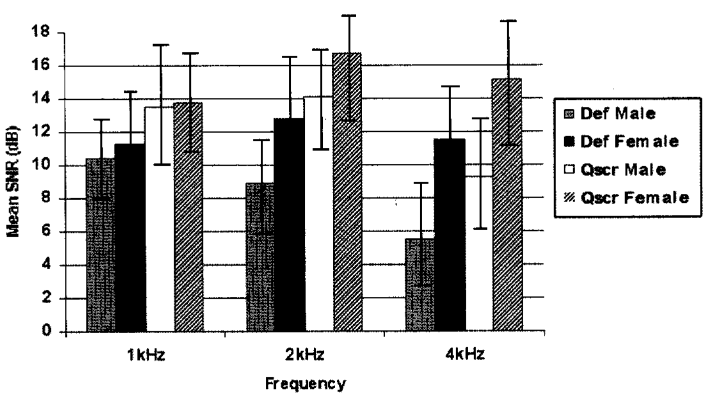

Figure 1 Mean signal-to-noise ratio of TEOAEs across genders (male/female) and protocols (Def/Qscr) as a function of frequency. Vertical bars indicate ±1 SD from the mean (N = 115 ears).

Figure 1 displays the mean TEOAE SNR values for both protocols (Quickscreen and Default) and genders (male and female) at 1, 2, and 4 kHz. As shown, a higher mean SNR is observed for females and for the Quickscreen protocol. In particular, the differences in mean SNRs between the two protocols at 1, 2, and 4 kHz are 3.1, 5.2, and 3.8 dB respectively for males, and 2.5, 3.9, and 3.6 dB respectively for females. An analysis of variance (ANOVA) with SNR at 1 kHz as the dependent variable, and gender (male/female) and protocol (Quickscreen/Default) as independent variables was performed. The results showed a significant effect for protocol [$F(1,107) = 42.1$, $p < 0.001$] with Quickscreen showing greater SNR than the Default protocol. There was no significant gender effect. The gender × protocol interaction was significant [$F(1,107) = 4.7$, $p = 0.03$], indicating that the effect of protocol

(Quickscreen/Default) was different between genders for 1 kHz. The same statistical analysis was repeated for SNR at 2 kHz. The results showed a significant protocol effect [$F(1,110) = 144.6$, $p < 0.001$] and gender effect [$F(1,110) = 7.5$, $p = 0.007$], but the gender × protocol effect was not significant. The same pattern of results was observed for 4 kHz with [$F(1,103) = 158.7$, $p < 0.001$] and [$F(1,113) = 17.9$, $p < 0.001$] for the protocol and gender effects respectively. The gender × protocol interaction was not significant.

Figure 2 displays the percentage of ears with TEOAE SNR less than 3 dB for both protocols and pure-tone threshold greater than 15 dB HL at 1, 2, and 4 kHz. According to Prieves et al (1993), Lichtenstein and Stapells (1996), and Harrison and Norton (1999), the use of 3 dB SNR as the cutoff best separates normal and hearing-impaired ears. As shown in Figure 2, the percentage of ears that did not attain an SNR of 3 dB as determined by the Default protocol is higher than that determined by the Quickscreen protocol at both 2 and 4 kHz. A significant difference in percentages was found at 2 kHz only ($\chi^2 = 7.89$, $df = 1$, $p = 0.005$). At 1 kHz, however, the opposite result was found, with the percentage obtained by the Default protocol being marginally lower than that obtained by the Quickscreen protocol.

To compare the performance of the two protocols, a clinical decision analysis was applied to the data (see Turner [1991] for a description). In this analysis, TEOAE results (Quickscreen and Default protocols) were compared with pure-tone air-conduction threshold results to produce receiver operating characteristics (ROC) curves. The ROC curve is a plot of true positive rate (hit rate [HR]) against false positive rate (false alarm [FA]) for different criteria. SNR criteria at each test frequency were set at ≥ -3, 0, 2, 3, 4, 5, 6, 7, 10, 13, 16, 19, 21, 23, or 25 dB to be classified as a pass. Pure-tone thresholds were required to be no worse than 15 dB HL to be classified as a pass. The ROC curves for 1, 2, and 4 kHz are depicted in Figures 3, 4, and 5 respectively, with the corresponding HR, FA, efficiency index (EF, percentage of

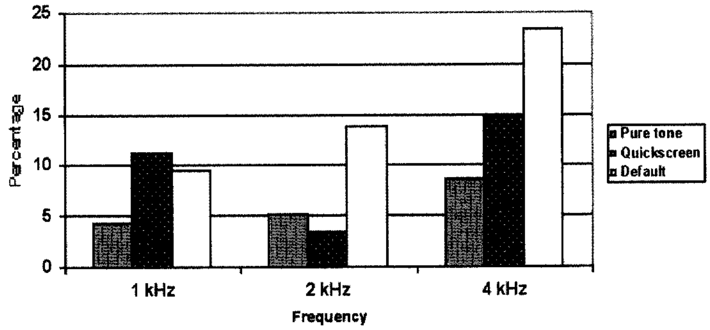

Figure 2 Percentage of ears with signal-to-noise ratio < 3 dB for the two TEOAE protocols (Quickscreen/Default) and pure-tone threshold >15 dB HL as a function of frequency (N = 115 ears).

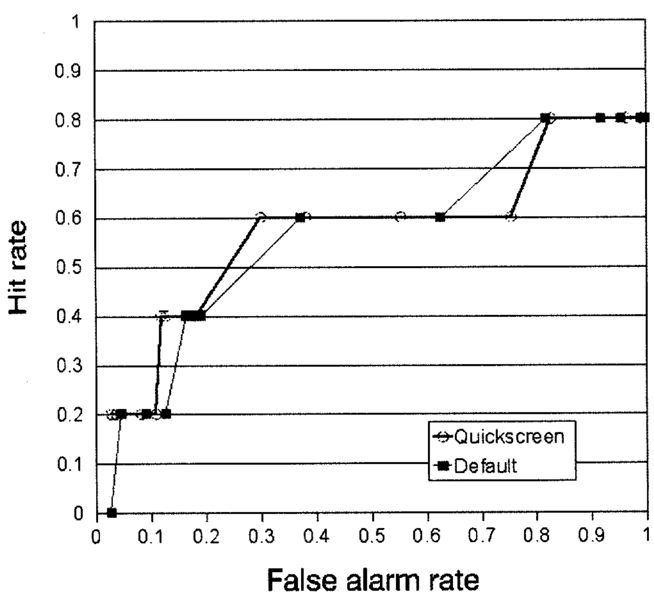

Figure 3 ROC plot for TEOAE signal-to-noise ratio at 1 kHz obtained with an audiometric criterion at 1 kHz for normal of 15 dB HL (N = 115 ears).

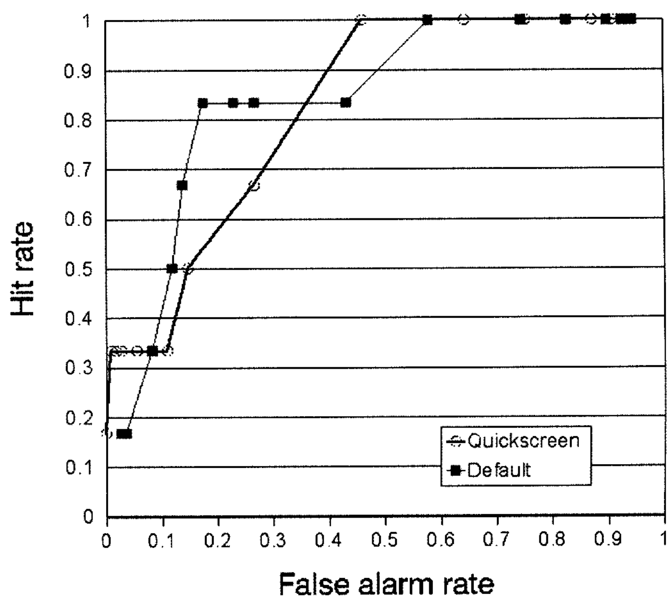

Figure 4 ROC plot for TEOAE signal-to-noise ratio at 2 kHz obtained with an audiometric criterion at 2 kHz for normal of 15 dB HL (N = 115 ears).

correct test results), positive predictive value (Pr[D/+], posterior probability of being correct with a positive test result), and negative predictive value (Pr[N/-], posterior probability of being correct with a negative test result) shown in Appendices A, B, and C.

The results as indicated in Figures 3 show that at 1 kHz, the FA of the Quickscreen is generally lower than that of the Default protocol for the same HR. This finding indicates that the Quickscreen protocol performed better than the Default protocol at 1 kHz. The performance indicators, shown in Appendix 1, suggest optimum test performance at 4 dB SNR for the Quickscreen protocol with HR = 40%, FA = 11.8%, EF = 86.1%, Pr[D/+] = 13.3%, and Pr[N/-] = 97.0%. Optimal results for the Default protocol occur at 5 dB SNR with HR = 40%, FA = 16.4%, EF = 81.7%, Pr[D/+] = 10.0%, and Pr[N/-] = 96.8%. Figure 5 compares the test performance of the two protocols at 4 kHz. The finding, which resembles that at 1 kHz, indicates the superiority of the Quickscreen over the Default protocol in terms of a lower FA for the same HR. Optimum test performance occurs at 3 dB SNR for both protocols, with HR = 55.6%, 55.6%; FA = 11.3%, 20.8%; EF = 86.1%, 77.4%; Pr[D/+] = 29.4%, 18.5%; and Pr[N/-] = 95.9%, 95.5% for the Quickscreen and Default protocols respectively (see Appendix 3).

In contrast to the findings at both 1 and 4 kHz, the Default performed better than the Quickscreen protocol at 2 kHz. At this frequency, the ROC curve (shown in Figure 4) shows the optimal test performance for the Default protocol at HR = 83.3% and FA = 17.4%, corresponding to an SNR value of 5 dB. The optimal test performance for the Quickscreen protocol, as revealed in Appendix 2, corresponds to an SNR value of 10 dB, with HR = 50.0% and FA = 14.7%. Other test performance indicators at the corresponding optimal points, shown in Appendix 2, are EF = 83.5%, 82.64%; Pr[D/+] = 15.8%, 20.8%; and Pr[N/-] = 96.9%, 98.9% for the Quickscreen and Default protocols respectively.

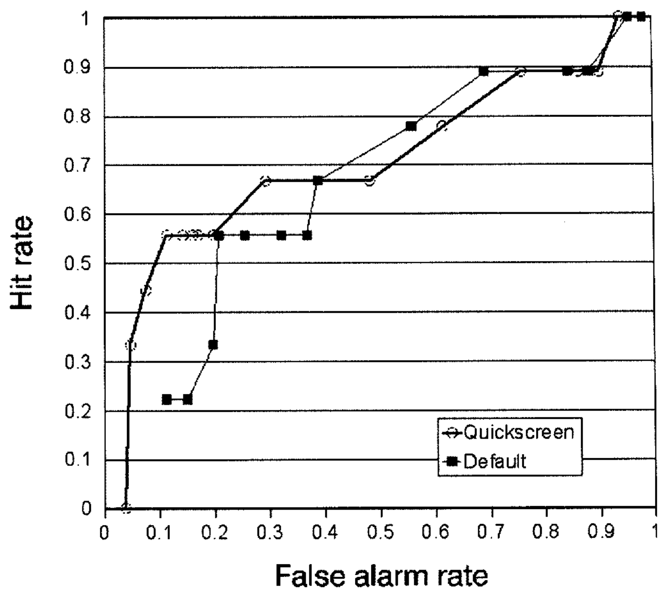

Figure 5 ROC plot for TEOAE signal-to-noise ratio at 4 kHz obtained with an audiometric criterion at 4 kHz for normal of 15 dB HL (N = 115 ears).

DISCUSSION

The main aim of the present study was to compare the efficacy of both the Quickscreen and Default protocols for use with adults in a typical clinical setting. The results indicated that the Quickscreen protocol yielded consistently more robust TEOAEs, in terms of higher mean reproducibility (see Table 1) and SNRs (see Figure 1), when compared to the Default protocol. The difference in mean SNR across the two protocols for the same gender ranged from 2.5 to 5.2 dB. At least three factors may have influenced the TEOAE results. First, there were differences in the analysis time window, with the Default and the Quickscreen protocols sampling the TEOAE responses from 2.5 to 20.5 msec and from 2.5 to 12.5 msec respectively. As reported by Whitehead and colleagues (1995), by reducing the time window, ambient and physiologic noise with broad frequency components will be reduced uniformly (across frequencies) while TEOAEs at the low frequencies will be decreased. The present study supports their results by revealing a decrease of 5 dB in the mean AB difference (noise floor) and a reduction of 2.4 dB in the mean response (TEOAE amplitude), when the Quickscreen was compared to the Default protocol. The lower AB difference value of the Quickscreen protocol, also reported by Rhoades et al (1998) and Smith et al (2001) in the quiet condition, reflects a lower noise contamination in the TEOAEs recorded by the Quickscreen than the Default protocol.

Second, the difference in stimulus intensity levels between the two protocols could have influenced the TEOAE results. However, the stimulus presentation level was tightly controlled in the present study, with no significant difference in stimulus intensity registered between the two protocols (see results from Table 1). Another related factor, which may have the potential to influence the stimulus characteristics, is probe stability (movement of the probe tip during TEOAE recording). This factor, however, was tightly controlled, as the present study did not reveal a significant difference in stimulus stability between the two protocols.

Third, the difference in the stimulus presentation rate between the two protocols could have affected TEOAE results. The increased click rate of the Quickscreen protocol allowed for more signals to be averaged within a given time, resulting in a reduction in noise contamination of the TEOAEs. The exact amount of noise reduction resulting from the increase in click rate of the Quickscreen could not be determined, based on the data from the present study. However, the amount of noise reduced can be estimated mathematically. For instance, the ratio of the number of samples averaged (within a given time) by the Quickscreen to that by the Default protocol is 1.6 (80/50). Hence, the mean noise level should decrease by 2 dB ($10 \times \log 1.6$).

As expected, the lower SNR recorded by the Default protocol resulted in a higher failure rate (using a "< 3dB" fail criterion) when compared to that of the Quickscreen protocol and pure-tone audiometry (using a "threshold >15dB fail criterion) (see Figure 2). A significantly higher percentage of failure for the Default than the Quickscreen protocol was observed at 2 kHz. However, this trend of difference in percentages between the two protocols was not evident at 1 kHz, possibly because of the ambient and physiologic noise at this frequency (Tognola et al, 1995; Kei et al, 2001).

The results from the ROC curve analysis offer further evidence of the enhanced performance of the Quickscreen over the Default protocol in testing adults. Analyses of the results at 1 and 4 kHz revealed significantly greater sensitivity, specificity, and efficiency for the Quickscreen than for the Default protocol (see Figures 3 and 5). However, this finding was not replicated at 2 kHz. Reasons for this apparently inconsistent finding remain to be explored. Perhaps this is a special characteristic of the auditory function of this cohort of participants. Another possibility is the small sample size of the present study with an inherently large variability. In general, the above findings indicate the enhanced performance of the Quickscreen over the Default protocol in testing adults.

The present study revealed a significantly longer test time for the Quickscreen than for the Default protocol, contrary to previous findings obtained from neonates (White et al, 1993). This could be due to the fact that adults produce less physiologic noise than infants. With this low physiologic noise, the percentages of noisy responses rejected by the two protocols were about the same. This claim is supported by the insignificant difference in percent quiet responses between the two protocols (see Table 1). Although the Quickscreen protocol took longer test time to complete in adults in the present study, the difference was small (7.3 seconds) and would likely have little impact on a clinical session.

CONCLUSION

The present study identified significant differences in TEOAEs when using the Quickscreen protocol versus the Default protocol for adult diagnostic testing. Specifically, when the Quickscreen protocol was used, both the TEOAE amplitude and the noise floor were reduced, with the latter showing a greater reduction than the former. Hence, the Quickscreen resulted in larger SNRs at 1, 2, and 4 kHz compared to the Default protocol. The results from the ROC curve analysis offer further evidence of the enhanced performance of the Quickscreen over the Default protocol in testing adults, particularly at 1 and 4 kHz. In view of the enhanced performance of the Quickscreen over the Default protocol in general, the routine use of the Default protocol for testing adults in audiology clinics should be reconsidered.

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Appendix 1 Comparison of Quickscreen and Default TEOAE SNR at 1 kHz with Pure-Tone Screening at 1 kHz

SNR (dB)	HR	FA	EF	Pr[D/+]	Pr[N/-]
Quickscreen					
-3	20	2.7	93.9	25	96.4
0	20	3.6	93.0	20	96.4
2	20	8.2	88.7	10	96.2
3	20	10.9	86.1	7.7	96.1
4	40	11.8	86.1	13.3	97.0
5	40	12.7	85.2	12.5	97.0
6	40	12.7	85.2	12.5	97.0
7	40	18.2	80.0	9.1	96.8
10	60	30.0	69.6	8.3	97.5
13	60	38.2	61.7	6.7	97.1
16	60	55.5	45.2	4.7	96.1
19	60	75.5	26.1	3.5	93.1
21	80	82.7	20.0	4.2	95.0
23	80	96.4	7.0	3.6	80.0
25	80	99.1	4.3	3.5	50.0
Default					
-3	0	2.7	93.0	0	97.3
0	20	4.5	92.2	16.7	96.3
2	20	9.1	87.8	9.1	96.2
3	20	9.1	87.8	9.1	96.2
4	20	12.7	84.3	6.7	96.0
5	40	16.4	81.7	10.0	96.8
6	40	17.3	80.9	9.5	96.8
7	40	19.1	79.1	8.7	96.7
10	60	37.3	62.6	6.8	97.2
13	60	62.7	38.3	4.2	95.3
16	80	81.8	20.9	4.3	95.2
19	80	91.8	11.3	3.8	90.0
21	80	95.5	7.8	3.7	83.3
23	80	99.1	4.3	3.5	50.0
25	80	100	3.5	3.5	0

Note: SNR, HR, FA, EF, Pr[D/+], and Pr[N/-] represent signal-to-noise ratio, hit rate, false-alarm rate, efficiency index, positive predictive value, and negative predictive value, respectively.

Appendix 2 Comparison of Quickscreen and Default TEOAE SNR at 2 kHz with Pure-Tone Screening at 2 kHz

SNR (dB)	HR	FA	EF	Pr[D/+]	Pr[N/-]
Quickscreen					
-3	16.7	0	95.7	100	95.6
0	16.7	0	95.7	100	95.6
2	33.3	0.9	95.7	66.7	96.4
3	33.3	1.8	94.8	50.0	96.4
4	33.3	2.8	93.9	40.0	96.4
5	33.3	5.5	91.3	25.0	96.3
6	33.3	8.3	88.7	18.2	96.2
7	33.3	11.0	86.1	14.3	96.0
10	50.0	14.7	83.5	15.8	96.9
13	66.7	26.6	73.0	12.1	97.6
16	100	45.9	56.5	10.7	100
19	100	64.2	39.1	7.9	100
21	100	75.2	28.7	6.8	100
23	100	87.2	17.4	5.9	100
25	100	90.8	13.5	5.7	100
Default					
-3	16.7	2.8	93.0	25.0	95.5
0	16.7	3.7	92.2	20.0	95.5
2	33.3	8.3	88.7	18.2	96.2
3	50.0	11.9	86.1	18.8	97.0
4	66.7	13.8	85.2	21.1	97.9
5	83.3	17.4	82.6	20.8	98.9
6	83.3	22.9	77.4	16.7	98.9
7	83.3	26.6	73.9	14.7	98.9
10	83.3	43.1	58.3	9.6	98.4
13	100	57.8	45.2	8.7	100
16	100	74.3	29.6	6.9	100
19	100	82.6	21.7	6.3	100
21	100	89.9	14.8	5.8	100
23	100	92.7	12.2	5.6	100
25	100	94.5	10.4	5.5	100

Note: SNR, HR, FA, EF, Pr[D/+], and Pr[N/-] represent signal-to-noise ratio, hit rate, false-alarm rate, efficiency index, positive predictive value, and negative predictive value, respectively.

Appendix 3 Comparison of Quickscreen and Default TEOAE SNR at 4 kHz with Pure-Tone Screening at 4 kHz

SNR (dB)	HR	FA	EF	Pr[D/+]	Pr[N/-]
Quickscreen					
-3	0	3.8	88.7	0	91.9
0	33.3	4.7	90.4	37.5	94.4
2	44.4	7.5	88.7	33.3	95.1
3	55.6	11.3	86.1	29.4	95.9
4	55.6	14.2	83.5	25.0	95.8
5	55.6	16.0	81.7	22.7	95.7
6	55.6	17.0	80.9	21.7	95.7
7	55.6	19.8	78.3	19.2	95.5
10	66.7	29.2	70.4	16.2	96.2
13	66.7	48.1	53.0	10.5	94.8
16	77.8	61.3	41.7	9.7	95.3
19	88.9	75.5	29.6	9.1	96.3
21	88.9	85.8	20.0	8.1	93.8
23	88.9	89.6	16.5	7.8	91.7
25	100	93.4	13.9	8.3	100
Default					
-3	22.2	11.3	83.5	14.3	93.1
0	22.2	15.1	80.0	11.1	92.8
2	33.3	19.8	76.5	12.5	93.4
3	55.6	20.8	77.4	18.5	95.5
4	55.6	25.5	73.0	15.6	95.2
5	55.6	32.1	67.0	12.8	94.7
6	55.6	36.8	62.6	11.4	94.4
7	66.7	38.7	61.7	12.8	95.6
10	77.8	55.7	47.0	10.6	95.9
13	88.9	68.9	35.7	9.9	97.1
16	88.9	84.0	21.7	8.2	94.4
19	88.9	87.7	18.3	7.9	92.9
21	100	95.3	12.2	8.2	100
23	100	98.1	9.6	8.0	100
25	100	98.1	9.6	8.0	100

Note: SNR, HR, FA, EF, Pr[D/+], and Pr[N/-] represent signal-to-noise ratio, hit rate, false-alarm rate, efficiency index, positive predictive value, and negative predictive value, respectively.