Screening Infants and Young Children for Hearing Loss: Examination of the CAST Procedure

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Abstract  
A computer-mediated visual reinforcement audiometry (VRA) screening procedure, the Classification of Audiograms by Sequential Testing (CAST), was used with 59 infants and young children who received both CAST screening and conventional audiologic assessment. Approximately one-third of the children had normal hearing, one-third had conductive hearing loss, and the remaining one-third had previously diagnosed sensorineural hearing loss. The sensitivity and specificity of CAST were calculated and the relationship between the predicted CAST pattern and the child's actual audiogram was examined. CAST outcome was also considered along with the results of tympanometry and pneumatic otoscopy to formulate proposed follow-up strategies. CAST appears to be a useful tool for the behavioral screening of infants and young children: one component of a screening program designed to maximize the efficient identification and follow-up of infants and children with hearing loss.

Key Words: Classification of Audiograms by Sequential Testing (CAST), hearing screening, pediatric audiometry, visual reinforcement audiometry (VRA)

Abbreviations: CAST = Classification of Audiograms by Sequential Testing, CNP = could not predict, HR = high-risk category, HVec = high equivalent volume, JCIH = Joint Committee on Infant Hearing, LR = low-risk category, LVec = low equivalent volume, MR = moderate-risk category, NIH = National Institutes of Health, OM = otitis media, PTO = probability of task orientation, VRA = visual reinforcement audiometry

Improving techniques used for the early detection of hearing loss and middle ear disease in infants and young children is important to both the audiologic and otologic communities. Hearing loss, depending on the severity and age of onset, usually has a profound effect upon a child's ability to learn and communicate with others. The rate of hearing loss, as reported annually by the National Health Interview Survey, indicates a prevalence rate of 1.7/1000 for children under 18 years old, or 1.1 million hearing-impaired children (Shewan, 1990).

The importance of hearing loss identification programs has been addressed recently by various professional and governmental agencies. The National Institutes of Health (NIH, 1993) and the Joint Committee on Infant Hearing (JCIH, 1994) have published recommendations concerning the screening of neonates for hearing loss. The JCIH supports the identification of hearing loss in infants prior to 3 months of age and maintains a role for the use of high-risk indicators for hearing loss (i.e., family history of congenital hearing loss, congenital infections, or craniofacial anomalies associated with hearing loss; birth weight less than 1500 gm; bacterial meningitis; ototoxic medications, etc). The NIH recommends the universal screening of all newborns before hospital discharge. Despite the recent increased attention to newborn screening, no recommendations have been forthcoming regarding the development of screening programs for infants and preschool children.

The challenges remain twofold. First, children born with congenital hearing loss still are
not being identified until well into the second year of life. Second, infants and children can acquire communicatively significant hearing loss later in childhood (past the newborn period) or experience progressive types of hearing disorders (NIH, 1993). Consequently, if identification programs were limited only to the neonatal period, not all cases of debilitating hearing impairment of early childhood would be detected.

Our lack of timely and systematic identification programs in the U.S. has resulted in an average age of detection of 2.5 years for sensorineural hearing loss, ranging from 18 months to 5 years of age, depending on the severity of the impairment (NIH, 1993). Clearly, early identification of hearing loss must be an ongoing goal, particularly in the years critical for communication development and prior to entry into the public school system.

The American Speech-Language-Hearing Association (ASHA, 1990) has recommended a four-tier screening protocol for use with cooperative children (beginning at about 3 years of age) and adults. The protocol consists of (1) a history querying otologic complaints, (2) a visual inspection of the ears, (3) tympanometry, and (4) pure-tone audiometry using a 20 dB HL pass-fail screening criteria at 1000, 2000, and 4000 Hz. Individuals with a history of otologic complaints, an abnormal otologic examination, or who fail the audiometric/acoustic immittance portion of the screening on two occasions are referred for a complete audiologic evaluation and medical examination.

Hearing screening protocols specifically designed for use with infants and young children (who do not have the attention span or response capabilities necessary for conventional screening audiometry) are limited. The most appropriate behavioral technique for the audiolologic evaluation of infants and young children is visual reinforcement audiometry (VRA). VRA has been demonstrated to be a valid and reliable method for assessing frequency-specific threshold sensitivity in this age group (e.g., Wilson and Thompson, 1984). A comprehensive VRA threshold assessment, however, may require numerous trials in order to fully delineate the audiogram, and sometimes requires more than a single test session to complete.

Several computer-mediated VRA procedures have been developed in an attempt to obtain complete audiometric data (across the speech-frequency range) more efficiently than is possible using standard test protocols. Bernstein and Gravel (1990) described the three-frequency (500, 2000, and 4000 Hz) Interweaving Staircase Procedure, while Eilers et al developed the four-frequency (500, 1000, 2000, and 4000 Hz) Optimized Hearing Test Algorithm (Eilers et al, 1991a,b). These assessment procedures require, on average, at least 50 test trials and about 15 minutes to complete. Thus, while new VRA algorithms may optimize audiologic assessment, these procedures may still not be sufficiently efficient for hearing screening purposes.

In response to the need for a simple and efficient automated behavioral screening procedure for infants and young children, Özdamar, Eilers, and their colleagues developed the automated Classification of Audiograms by Sequential Testing, or CAST procedure (Özdamar et al, 1990; Eilers et al, 1993). Employing a modification of Bayesian mathematical theory, CAST predicts a child's audiogram based on fewer responses than are necessary for a conventional threshold-search procedure.

Briefly, Bayesian mathematics uses a probability table that considers a static set of symptoms and the frequency with which they are associated with a given condition to predict a diagnosis. The Bayesian model was modified for the CAST procedure to work with the dynamically changing information collected during a hearing test. The accuracy of CAST is derived from a probability database that is dependent on the frequency of occurrence of certain audiometric patterns in infants and young children. Rather than providing only a simple pass-fail decision, CAST selects an audiometric pattern from several contained within its database that most closely matches the child's true audiogram configuration. The CAST database is currently comprised of nine audiometric patterns that, statistically, were found to be common in a clinical population of infants and young children. The CAST patterns are depicted in Figure 1. Each pattern has an initial pattern weight (or probability) assigned to it, predicated on the frequency of occurrence of that pattern within a pediatric clinical sample (see Özdamar et al [1990] and Eilers et al [1983] for a complete description of the CAST).

The CAST algorithm proceeds in the following manner. The frequency-dependent variance for all nine audiometric patterns is calculated using the individual pattern weights. The test frequency presented during each trial is selected to yield the maximum variance among patterns. The test intensity for the trial is chosen based on the weighted mean intensity of patterns at the selected frequency. Either a
response or no response is recorded during the trial interval and the pattern weight for each audiometric frequency is adjusted appropriately. For example, if the child responds to a 2000-Hz signal at 10 dB HL, the probability that hearing is normal would increase, while the probability that the child has mild, moderate, or severe hearing loss would decrease accordingly. After each trial, the new pattern weights are evaluated; if one exceeds the predetermined stopping criteria, then that audiometric pattern is selected as being most consistent with the child's true audiogram configuration. If the stopping criteria are not met, then the optimal test frequency and intensity are recalculated using the new pattern weights and the testing continues. Randomly interspersed control trials (test intervals containing no stimulus) are used to monitor false-positive responding.

Özdamar et al. (1990) tested the CAST using computer simulations (pseudosubjects). In addition to the audiogram pattern, these simulations were designed to include the possible effects of distraction, that is, fussing or inattentiveness that the child might manifest during screening. This behavioral variable was termed the probability of task orientation (PTO). Özdamar et al. (1990) found CAST to be an efficient procedure for audiogram pattern selection, tolerant of infant response errors. Sensitivity of the CAST procedure using data from the pseudosubjects was estimated to be 100 percent, while specificity ranged from 68 percent to 100 percent, depending on the PTO. Widen et al. (1991) and Eilers et al. (1993) examined groups of infants and young children, and compared the results of CAST with conventional VRA audiograms (Table 1). Although CAST efficiently detected mild conductive hearing loss, no children with known sensorineural hearing impairments were included in these samples.

The purpose of the current study was to use CAST to screen the hearing of infants and young children with normal hearing, and conductive and previously diagnosed sensorineural hearing loss to evaluate the procedure's efficiency when hearing impairment was prevalent within the test sample. The sensitivity and specificity of the CAST were calculated and the relationship between the obtained and predicted CAST pattern (based on the actual audiogram) was also examined. Finally, CAST results, along with the findings obtained from tympanometry and pneumo-otoscopic screening, were used to further evaluate the usefulness of CAST as one component of a screening program designed to identify infants and young children at risk for hearing loss and/or middle ear disorder.

### Table 1 Comparison of Studies that Examined the Efficiency of the CAST Procedure

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Age Range (Mo)</th>
<th>Sensitivity (%)</th>
<th>Specificity (%)</th>
<th>Number of Trials to Complete CAST Range (Mean)</th>
<th>Time (Min) to Complete CAST Range (Mean)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eilers et al., 1993</td>
<td>42</td>
<td>6–31</td>
<td>75</td>
<td>84</td>
<td>10–20</td>
<td>3–5</td>
</tr>
<tr>
<td>Widen et al., 1991</td>
<td>43</td>
<td>6–24</td>
<td>85</td>
<td>93</td>
<td>(13)</td>
<td>2–3</td>
</tr>
<tr>
<td>Merer and Gravel (Pass: CAST 1)</td>
<td>59</td>
<td>6–60</td>
<td>100</td>
<td>43</td>
<td>11–37</td>
<td>1.5–10</td>
</tr>
<tr>
<td>Merer and Gravel (Pass: CAST 1 and 2)</td>
<td>59</td>
<td>6–60</td>
<td>95</td>
<td>71</td>
<td>11–37</td>
<td>1.5–10</td>
</tr>
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</table>
METHOD

Seventy-three subjects were selected from infants and children followed at the Children's Evaluation and Rehabilitation Center (CERC) and the Longitudinal Infant Follow-up and Evaluation (LIFE) Program of the Rose F. Kennedy Center, Albert Einstein College of Medicine, Bronx, NY. All children were being evaluated in the audiology/otology clinic for either routine hearing assessment, follow-up of per-sistent otitis media (OM) with effusion, or sens-orineural hearing loss. The average age of the children tested was 38 (range: 8-60) months. Although 8 percent (n = 6) of the children in the sample were known to have additional neuro-developmental disabilities, all had a developmental age greater than 6 months at the time of testing (Moore et al, 1977).

The test arrangement was as follows. A sound-attenuated test booth (Industrial Acoustics Company, Inc., Bronx, NY) was used for both CAST screening and the conventional audiometric evaluation. Two chairs were positioned on opposite sides of a small table, with the control box (for CAST or VRA/play audiometry) located adjacent to the examiner, who was seated in one of the chairs. During testing, the child was close to the parent/caregiver (for the “play” method) or on the parent's/caregiver's lap (when the head turn was the response indicator). Four animated toy reinforcers housed in dark smoked-plexiglass boxes were situated adjacent to a loudspeaker. For the play response, the visual reinforcers/loudspeaker were in front of the child. When the head turn was the behavioral response, the infant was seated relative to the reinforcement unit/loudspeaker such that an approximate 90-degree head movement to one side was required for the child to view the visual reinforcers. The reinforcers were not visible to the child unless they were activated and illuminated.

All subjects were initially tested with CAST (soundfield presentation) by one examiner (DMM), who was trained to administer the hearing screening procedures and to judge correct responses. The test order (CAST always completed first) was instituted in order to simulate a typical screening situation in which a child would be screened without any prior knowledge of his/her true hearing status. After CAST (and without knowledge of the CAST result), an experi-enced clinical audiologist completed a soundfield air-conduction audiogram. Children were usually tested with both procedures during one visit. In two cases where two visits were required to obtain complete data, the sessions occurred within a week of one another, and neither child had conductive hearing loss. Conventional ear-specific audimetric evaluation was sometimes completed but only after both CAST and the soundfield air-conduction audiogram had been obtained. Recall that since some children were known to our clinical program and were already diagnosed with sensorineural hearing loss, previously obtained audiometric results were often available for comparison purposes. All test equipment and the test environment received calibration on a quarterly basis so as to ensure compliance with currently accepted standards. The sound field for both conventional and CAST procedures was calibrated according to procedures suggested by Wilber (1991).

CAST (Intelligent-VRA Version 300; Intelligent Hearing Systems, Inc., Miami, FL) was controlled by a microcomputer located in a room adjacent to the test booth. The CAST algorithm has been described previously. The tester communicated with the computer, initiating trials and signaling responses, through a hand-held control box. Children tested with CAST for whom the head turn was the response indicator received no formal conditioning (Tharpe and Ashmead, 1993). However, those tested with CAST who used a play response (block drop) were taught the motor response prior to CAST screening. The response interval for children of all ages was 4 seconds.

The standard air-conduction audiogram in all children was obtained using traditional manual VRA or play audiometry. When the conventional audiogram was obtained, a correct response was rewarded using a second, separate three-toy reinforcement display. Children used the same behavioral response (head turn or block drop) for both CAST and standard audiometric testing.

After CAST and the conventional audiogram had been completed, children were examined for middle ear status by an otolaryngologist (DMM); first using pneumatic otoscopy and then tympanometry (Grason-Stadler GSI-33; 226-Hz probe frequency). Upon completion of all testing, the following data were available from each child: (1) background information; (2) CAST outcome: pattern 1 through 9 or a could not predict (CNP) result (the algorithm was unable to determine a pattern); (3) number of trials, time to complete CAST testing, and the percent-correct responses to control-trial intervals; (4) (minimally) a soundfield air-conduction audiogram;
(5) the result of pneumo-otoscopic examination of each ear; and (6) a tympanogram for each ear.

Following data collection, a second clinical audiologist (JSG), who was unaware of the CAST results, selected the CAST pattern (1–9) that most closely matched each child's conventional air-conduction audiogram. This predicted CAST pattern was compared to the CAST pattern obtained from actual administration of the CAST procedure. The purpose was to examine how accurately CAST predicted the subject's true audiogram.

**RESULTS**

A complete data set was obtained from 59 of the original 73 children. Approximately equal numbers of children with normal hearing and conductive and sensorineural hearing loss were studied: 21 (36%) were considered to have normal hearing, 19 (32%) had conductive hearing loss, and 19 (32%) had bilateral sensorineural hearing loss ranging from moderate to profound in degree. The data of 14 (19%) children included in our original sample of 73 were not considered in the final analysis (6 were too old: > 60 months of age; 2 were too young: < 6 months of age; 2 had < 50% correct responses to control-trial intervals—both 2 years of age; 2 provided incomplete audiograms—3 and 4 years of age; and 2 had unilateral sensorineural hearing loss—both 5 years of age).

The child's air-conduction audiogram (the "gold standard") was used to calculate the sensitivity and specificity of CAST. Sensitivity is defined as the ability of the screening test to identify hearing loss in confirmed positive cases, while specificity is the ability of the procedure to correctly predict a normal outcome in confirmed normal hearers. The average time needed to complete the CAST procedure was 3.8 minutes (range: 1.1–10.4 minutes), and an average 21 (range: 11–37) trials were required for the screening test.

In accordance with the 1990 ASHA guidelines, we adopted a criterion for audiometrically normal hearing as thresholds 20 dB HL or better at 1000, 2000, and 4000 Hz. We examined the sensitivity and specificity of the CAST, comparing the obtained CAST pattern to this audiometric criterion for normal. Initially, we accepted only pattern 1 as a pass outcome, as suggested by Eilers et al (1993). Using these screening criteria (CAST pattern 1 = pass, CAST patterns 2–9 and CNP = fail), sensitivity and specificity of the CAST were calculated to be 100 percent and 43 percent, respectively. In our next analysis, CAST patterns 1 and 2 were considered passes and patterns 3 to 9 and CNP were considered fails. Sensitivity and specificity of the CAST using these criteria were 95 percent and 71 percent, respectively. A comparison of the results of our analyses, as well as those of some previous studies of the efficiency of the CAST procedure, is presented in Table 1. In Table 2, using the pass-fail criteria just described, a breakdown of the CAST results according to general age groupings is presented. Note that over half (54%; n = 32) of the subjects examined in this investigation were 36 months of age or younger.

Since the detection of middle ear dysfunction is frequently an objective of screening protocols, particularly with infant and preschool populations, the results of tympanometry were also considered. For simplicity, the tympanogram obtained for each ear was broadly typed using the Jerger (1970) classification scheme. Pneumatic otoscopy outcome (a diagnosis of normal, OM with effusion, retracted tympanic membrane, or patent pressure equalizing tube) was then compared to the tympanometry result. The tympanogram type (A [normal], B [flat with either low equivalent volume of the ear canal

<table>
<thead>
<tr>
<th>Age Range (Mo)</th>
<th>Number in Group</th>
<th>Number with Hearing Loss</th>
<th>Average Number of Trials to Complete CAST</th>
<th>Average Time (Min) to Complete CAST</th>
<th>Sensitivity (%)</th>
<th>Specificity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6–18</td>
<td>11</td>
<td>8</td>
<td>18.0</td>
<td>3.2</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>19–30</td>
<td>12</td>
<td>9</td>
<td>24.3</td>
<td>4.3</td>
<td>78</td>
<td>100</td>
</tr>
<tr>
<td>31–36</td>
<td>9</td>
<td>8</td>
<td>19.8</td>
<td>3.9</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>37–48</td>
<td>12</td>
<td>4</td>
<td>20.6</td>
<td>4.5</td>
<td>100</td>
<td>62.5</td>
</tr>
<tr>
<td>49–60</td>
<td>15</td>
<td>9</td>
<td>21.3</td>
<td>3.3</td>
<td>100</td>
<td>50</td>
</tr>
</tbody>
</table>

Data are shown for the number of trials, the number of children with hearing loss within the age group, the time required to complete CAST testing, and the sensitivity and specificity of the procedure. (Pass = CAST patterns 1 or 2.)
(LVec) or high equivalent volume (HVec)], or C [negative pressure <275 daPa]) was in accordance with the otologist's (DMM) pneumo-otoscopic findings in 121 of 141 possible individual ear comparisons (86% agreement, including cases from the original sample of 73 children). Using a test of proportion, the agreement between the measures was found to be significantly ($z = 16.73; p < .001$) better than chance (25% or 1/4). Based on this accord, only the tympanogram results were used for our subsequent classifications.

We next attempted to broadly categorize children's screening results (considering both their CAST pattern and their tympanogram type) and assigned their overall outcome into one of five outcome groups (Table 3). Group I was composed of children displaying pattern 1 or 2 and type A or C tympanograms (or B tympanogram with HVec) in each ear, or a mixed pattern of tympanometric results (type A or C tympanogram in one ear and a poorer tympanogram [type C or type B-LVec, respectively] in the opposite ear). Children in Group I would be considered to be at low risk for significant bilateral hearing loss. Indeed, 93 percent (14/15) of the children having such outcomes had normal hearing according to our previously described audiometric criteria.

Group II consisted of children whose CAST outcomes were patterns 5, 7, 8, 9 or CNP and who had A or C tympanograms or a mixed tympanogram outcome (as above). This group would be considered at risk for hearing loss, specifically, sensorineural. Ninety-five percent (20/21) of the children who had CAST and tympanogram outcomes consistent with this classification had conventional audiograms that indicated some degree of hearing loss.

Group III consisted of children with a CAST pattern of 1, 2, 3, 4, or 6 and flat (type B) tympanograms with LVec bilaterally. Group III was formulated on the assumption that OM with effusion could result in audiograms consistent with the aforementioned CAST patterns. Ninety-one percent (10/11) of children in Group III had audiograms that were consistent with some degree of mild hearing loss and OM bilaterally.

Group IV was considered an equivocal category, composed of children displaying CAST patterns 3, 4, or 6 and type A or C tympanograms, or mixed tympanogram types. Neither the CAST pattern (all suggesting mild hearing impairments ≤40 dB HL) nor the tympanometric outcome was consistent with any particular type (conductive or sensorineural) of hearing loss. Of Group IV, 58 percent (7/12) of the children had abnormal audiograms.

Group V would consist of children with CAST patterns 5, 7, 8, 9 and CNP and tympanogram type B (LVec or HVec) bilaterally. This outcome suggests a child at risk for mixed (conductive component compounding a sensorineural) hearing loss or a child with sensorineural hearing loss and patent ventilating tubes. No children in our study cohort met the criteria for inclusion in this group (although in a larger sample, the finding would be considered reasonable).

In our final analysis, we compared the CAST pattern obtained (CAST obtained) with the CAST pattern predicted (CAST predicted) by the audiologist to best fit the child's true audiogram. Forty-seven comparisons were possible (the CNP outcome was eliminated). CAST obtained and CAST predicted were in complete accord in 36 percent (17/47) of the cases. Using a test of proportion, this result was determined to be significantly ($z = 5.47; p < .001$) better than chance (11% or 1/9). Examination of the 95 percent confidence interval (.27-.45) suggests that the CAST would predict the audiogram correctly.

### Table 3 Outcome Groups (I–V) Delineated according to CAST Pattern

<table>
<thead>
<tr>
<th>Outcome Group (n)</th>
<th>CAST Pattern</th>
<th>Tymanogram Type</th>
<th>Normal Audiograms (%)</th>
<th>Impaired Audiograms (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I (n = 15)</td>
<td>1, 2</td>
<td>A, C, M, B-HVec</td>
<td>93</td>
<td>7</td>
</tr>
<tr>
<td>II (n = 21)</td>
<td>5, 7, 8, 9, CNP</td>
<td>A, C, M, B-HVec</td>
<td>5</td>
<td>95</td>
</tr>
<tr>
<td>III (n = 11)</td>
<td>1, 2, 3, 4, 6</td>
<td>B (bilateral)-LVec</td>
<td>9</td>
<td>91</td>
</tr>
<tr>
<td>IV (n = 12)</td>
<td>3, 4, 6</td>
<td>A, C, M</td>
<td>42</td>
<td>58</td>
</tr>
<tr>
<td>V (n = 0)</td>
<td>5, 7, 8, 9, CNP</td>
<td>B (bilateral)</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

A = normal; B = flat, noncompliant; C = negative peak pressure; M = mixed tympanogram (different type in each ear); HVec = high equivalent volume; LVec = low equivalent volume of the ear canal.

The percentage of infants and children in the current study who displayed normal and abnormal (impaired) conventional audiometric test results in each of the outcome groups is displayed.

CNP = could not predict; NA = not applicable.
less than half of the time. When the CNP outcome was included in the analysis, the results of the comparison improved. We considered the CNP outcome to portend the possibility of a severe to profound hearing loss for two reasons. First, the maximum intensity of test stimuli could have been below a child's hearing threshold, resulting in the CAST algorithm being unable to predict a representative pattern. Second, the child may not have been under adequate operant control for reliable VRA testing. When the CNP CAST outcome was included, the agreement between CAST and the actual audiogram was 46 percent (27/59). A test of proportion indicates that this result is significantly ($z = 9.10; p < .001$) better than chance (10% or 1/10); the resulting 95 percent confidence interval ranged from .32 to .58.

**DISCUSSION**

The goal of this work was to expand our understanding of the efficiency of the CAST algorithm as a hearing screen tool for use with infants and young children. In the studies of Eilers et al (1993) and Widen et al (1991), CAST was compared to conventional VRA audiograms. Based on the samples of children they studied, both research groups found CAST to be a potentially effective screening procedure for use with young children. However, while children with conductive hearing loss were included in these previous studies, the cohorts represented a clinical population in which sensorineural hearing loss was a low prevalence disorder, while conductive hearing loss was characteristically widespread. In our study, we purposely included children (nearly one-third) who had previously identified sensorineural hearing loss. With the addition of children with this type of hearing impairment, our sensitivity was higher than reported by previous authors (Widen et al, 1991; Eilers et al, 1993), but our specificity was somewhat lower (see Table 1). These differences in specificity may be due to variations among studies in assessment methods used to obtain the conventional audiogram, or to somewhat different criteria adopted for judging normal hearing. We found CAST to be as time and trial efficient as has been reported previously (see Table 1).

When CAST performance was examined as a function of age group (see Table 2), the most notable finding was observed in the 19- to 30-month category, where sensitivity was lower than in the other age groups. It was within this...
(patterns 1 and 2 = pass), but we included tympanometry as a secondary means of classifying the screening results. We combined the CAST and tympanogram data and divided the children into one of five outcome groups (see Table 3). In Table 4, we propose a means of further categorizing children for appropriate follow-up.

We would consider children who fall into follow-up category low risk (LR) to have a low probability of either bilateral sensorineural hearing loss or significant middle ear pathology that could result in a bilateral conductive hearing loss. Therefore, we suggest that follow-up category LR children should be re-screened using tympanometry at a later date. If tympanometry were normal bilaterally, follow-up would proceed on an as needed (PRN) basis. If the tympanograms were abnormal on repeat middle ear screening, the CAST would be repeated. Follow-up would be initiated based on the results of the repeat screening.

Follow-up category high risk (HR) children are those who have a CAST pattern that suggests the probability of significant hearing loss, either sensorineural or mixed in type. Children in follow-up category HR should be rescreened on the same day, or within days, with the CAST. If the outcome is the same, the child should be referred for a complete audiologic evaluation. If hearing loss is confirmed, evaluation by an otolaryngologist would follow immediately.

Follow-up category OM consists of children with a high probability of bilateral middle ear pathology and concomitant hearing loss. Category OM children should be referred to either their primary medical care provider or to their otolaryngologist for treatment. Note that a similar outcome on a repeat CAST and tympanometry screening (separated by at least 2 weeks) is suggested before medical/otologic referral is made. Audiologic evaluations to delineate the degree of hearing loss and monitor the treatment course may be appropriate (AHCPR, 1994). At a minimum, comprehensive audiologic assessment should always be completed after medical and/or surgical intervention to confirm that the child has normal hearing sensitivity bilaterally.

The children in follow-up category moderate risk (MR) have either normal middle ear function or negative middle ear pressure and a CAST pattern indicating the possibility of mild hearing loss (sensorineural in type or conductive secondary to permanent middle ear involvement such as adhesions or scar tissue). Another

<table>
<thead>
<tr>
<th>Table 4 Proposed Strategy for Follow-up of Children</th>
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<tbody>
<tr>
<td>Follow-up Category LR</td>
</tr>
<tr>
<td>Outcome Group</td>
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<tr>
<td>Plan</td>
</tr>
</tbody>
</table>

Follow-up categories (LR = low risk, HR = high risk, MR = moderate risk, OM = otitis media) are displayed for each outcome group (I–V) with suggested management plans. PRN = as needed, ENT = ear, nose, and throat (otolaryngologic) examination.
reason for this outcome might be a less-than-optimal response/attentional state during CAST screening. Our recommendations for these children are rescreening within a brief time period with CAST and tympanometry. Referral for a complete audiologic evaluation should follow if children remain in group MR after repeat screening or move to the HR or OM category.

In this study, we also examined the relationship between the predicted CAST pattern and standard audiometry. While significantly better than chance, the CAST-obtained pattern was not always in complete accord with the CAST-predicted pattern (which was based on the child's actual audiogram). The accuracy of the comparison improved somewhat when the CNP outcome was considered an at-risk indicator. If we had examined the CAST results more broadly—for example, determined serious prediction errors versus minor prediction errors—undoubtedly, the results would have been far more positive. However, we chose the more stringent comparison to emphasize a point. In our opinion, if there is any inherent drawback to the CAST, it is that a child might be labeled by an unqualified or inexperienced examiner as having a specific audiogram (hearing loss) based on CAST alone. We consider this to be both a very undesirable and potentially serious circumstance. CAST should not be viewed as an alternative to a complete audiologic assessment—an evaluation that should always be completed by a qualified and experienced audiologist. Rather, as its developers intended, CAST should be used as a screening tool. Indeed, our analyses suggest that the CAST pattern predictions may be most useful when they are considered broadly (or categorically) and in conjunction with tympanometry (or validated pneumatic otoscopy). In this manner, both a hearing screening and a middle ear screening are combined to provide a potentially efficient means of classifying children into groups for appropriate and timely follow-up.

As computer-assisted procedures become more common in audiologic practice, we anticipate that CAST will become a more widely used procedure. CAST may be of greatest benefit to audiologists working in settings where large numbers of infants and young children are initially referred for suspected developmental delays, or in facilities that systematically follow graduates of neonatal nurseries who are at risk for hearing loss. CAST provides a behavioral method for the rapid screening of infants and young children who are 6 months (developmental) of age or older, a population that has traditionally not received the benefit of direct screening initiatives. Moreover, even young children who have no neonatal risk factors are frequently at risk for the development of OM with effusion, a condition that can cause early, mild, and, in some cases, chronic fluctuant bilateral hearing loss throughout childhood (Gravel and Ellis, 1995). The hearing loss associated with OM in the first year of life has been shown to have long-term aural communication/academic consequences for some children (Gravel and Wallace, 1992, 1995).

Because CAST is automated, appropriately trained assistants (under the supervision of an audiologist) can administer CAST screening. Similar to many newborn screening programs, CAST provides a means of increasing the number of young children who can be screened behaviorally through an automated test procedure that may be administered by trained support personnel. This eliminates the need for a professional audiologist to perform screening. Overseeing the quality of all aspects of the identification program, interpreting screening results, administering the subsequent comprehensive audiologic assessment of identified children, and developing and carrying out the follow-up program remain the responsibility of the audiologist.

The pressures on today's health care delivery systems suggest that procedures like the CAST may be our most efficient and effective means of screening large numbers of children behaviorally. With the demands on the time of the audiologist increasing, the identification of hearing disorders in early childhood must remain one of our most important priorities. This implies that we identify children with peripheral, as well as higher order, auditory deficits. Thus, while other methods (notably, otoacoustic emissions and tympanometry) can provide valuable insight into the integrity of the peripheral hearing mechanism, behavioral methods still provide our best insight into the young child's global auditory function.

**CONCLUSIONS**

The addition of children with a variety of degrees and configurations of sensorineural hearing loss in a sample of children tested with the CAST algorithm found the sensitivity of the screening test similar to, if not better than, previously reported. Notably, CAST accurately identified all young children in our sample with
The characteristics (sensitivity and specificity) of any screening instrument are dependent on the gold standard against which the test is examined. Therefore, sensitivity and specificity of the CAST may vary for individual screening programs, depending somewhat on the audiometric criteria adopted for normal versus impaired hearing. A screening test's characteristics (sensitivity, specificity, positive and negative predictive accuracy) will vary with (1) the prevalence of the disorder within the population; (2) the conditions (degree and type of disorder) that the screening program desires to identify; (3) response limitations imposed by the age of the population being screened; and (4) other test circumstances (e.g., the acoustic environment). Considering the aforementioned issues, as well as the number of false-positive outcomes that the system can tolerate, the audiologist implementing and overseeing the screening program must select the screening test characteristics that best meet the goals and resources of the individual initiative. We proposed a follow-up model that might be used by screening programs that adopt CAST as their hearing screening tool. Ultimately, the efficiency of our proposal must be determined through another, independent study, ideally based on a larger, more normally distributed cohort of infants and young children.

CAST appears to be an efficient tool for the behavioral screening of hearing in infants and young children at risk for conductive, sensorineural, or mixed hearing loss. We emphasize that CAST not be used for assessment, but rather as a screening tool. The procedure seems very useful in programs designed to maximize the efficient audiologic and otologic follow-up of infants and young children identified as at risk for debilitating hearing loss in early childhood.

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