Automated Classification of Middle- and Inner-Ear Mechanical Pathologies Based on Individual Acoustic Input Impedance and Audiogram

Krystyna Elisabeth Eberhard1,2, Gabrielle R. Merchant3, Hideko Heidi Nakajima1, and Stephen T. Neely3

1Harvard Medical School, Boston, MA, 2Rigshospitalet, Copenhagen, Denmark, 3Boys Town National Research Hospital, Omaha, NE

INTRODUCTION
Transfer functions derived from ear-canal acoustic measurements, collectively known as wideband acoustic immittance (WAI), are increasingly used in the clinical assessment of middle-ear status, especially in differentiating origins of conductive hearing loss (e.g., Allen et al., 2005; Merchant and Neely, 2021). WAI measures are clinically informative because of their sensitivity to lesions in middle-ear and inner-ear mechanics and has potential for wide clinical use, especially for initial assessment.

A recent study by Eberhard et al. (2022) showed improvement, by means of a machine-learning regression analysis, in the separation between superior canal dehiscence (SCD) and stapes fixation (SF) ears when ABG was combined with Absorbance, which is the recommended WAI measure (Feney et al. 2013).

The objectives of this study were to investigate whether an alternate machine-learning approach that combines middle-ear modeling principles with other features WAI measurements (1) reveals insights regarding the mechanisms underlying SCD & SF or (2) provides additional diagnostic benefit compared to ABG+Absorbance.

METHODS
Measurements: This study analyzed WAI measurements from 70 participants who were diagnosed in a previous study (Eberhard et al. 2022) as having one of two specific types of conductive ear pathology, superior canal dehiscence (SCD) or stapes fixation (SF). WAI measurements were made with the Titan Research Platform (Interacoustics). Average ABG was computed by WAI

\[ Y_{ABG} = Y_0 + Y_{1} + Y_{2} \]

\[ Y_{SF} = Y_0 + Y_{1} \]

Absorbance is calculated from ear-canal input impedance \( Z_{IN} \):

\[ T(f) = \frac{Z_{OUT}}{Z_{IN}} \]

\[ A(f) = 1 - |1 - T(f)| \]

Logistic regression, combined with principal component analysis and regularization, was used to categorize SCD and SF ears. Test performance was quantified by (1) area under a receiver-operating-characteristic curve (AUC) and (2) percentage of false predictions in category-confusion matrices. Cross validation was implemented by splitting the data into subsets.

RESULTS
Average absorbance at “tympanic peak pressure” (TPP) obviously differed between SCD and SF ears (see Fig. 2); however, overlap in individual absorbances made classification difficult. Middle-ear impedance (see Fig. 3) showed increased stiffness for SF that was less obvious in ear-canal impedance

\[ Z_{IN} = Y_{ABG} \]

\[ Z_{SF} = Y_{SF} \]

Figure 2. Absorbance averaged across SCD & SF ears.

Figure 3. Ear-canal and middle-ear impedance across SCD & SF ears.

Table 1. Middle-ear model parameters, when averaged across SCD & SF, quantify the trends observed in Figs 2 & 3. Admittances calculated from parameters fit to individual ears can augment absorbance in providing informative features for logistic regressions.

<table>
<thead>
<tr>
<th>Category</th>
<th>M1</th>
<th>R1</th>
<th>K1</th>
<th>M2</th>
<th>R2</th>
<th>K2</th>
<th>M3</th>
<th>R3</th>
<th>K3</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCD</td>
<td>0.52 0.58 0.2058</td>
<td>36 0.19 0.3028</td>
<td>211 0.43 0.9203</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SF</td>
<td>0.57 0.58 0.3761</td>
<td>79 0.74 0.3577</td>
<td>275 1.32 0.9664</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4. Branch admittances averaged across SCD and SF ears. Trends are similar at the two static pressures (TPP & 0Pa).

Figure 5. Scatterplots of individual quality factors (Q3) for the three branch circuits.

Regression analyses indicated that \( ABD+Y_{ABG} \) performed better than \( ABG+Absorbance \) (see Table II) suggesting a benefit of middle-ear modeling to automated classification.

Table II. Diagnostic prediction performance for SCD/SF classification. The regression-parameterized model

<table>
<thead>
<tr>
<th></th>
<th>SCD</th>
<th>SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABD alone</td>
<td>0.05 0.067 0.5</td>
<td></td>
</tr>
<tr>
<td>ABG alone</td>
<td>0.004 0.036 0.234</td>
<td></td>
</tr>
<tr>
<td>ABD + ABG</td>
<td>0.004 0.036 0.2</td>
<td></td>
</tr>
</tbody>
</table>

DISCUSSION
The observation of increased stiffness in branch 1, which we have previously associated with the ossicular chain (Merchant & Neely 2021), is consistent with our understanding of the mechanisms underlying these two pathologies. SF is known to stiffen the ossicular chain. However, the observation of two distinct clusters in the Q3 scatterplot is unexpected and suggests two subgroups of SF (e.g., Karosi et al. 2005).
The regression a further improvement in diagnostic performance, compared to absorbance, could be achieved by the application of ear-canal and middle-ear modeling concepts to an automated classification of middle-ear conductive pathology. Essentially, the modeling approach transforms WAI measurement data into more informative regression-input features.

CONCLUSIONS
- The application of middle-ear modeling principles has the potential to improve automated classification of mechanical pathologies based on individual WAI measurements and audiogram (ABG).
- Estimates of middle-ear admittance contain evidence of two subgroups of stapes fixation.

ACKNOWLEDGMENTS
Research was supported by the National Institutes of Health through award numbers P20GM108023, R01DC008318, L30DC017300, and P20GM108023. Karosi received a PhD fellowship from the William Demant Foundation.

REFERENCES


