Investigation of Parameters That Maximize Low-Frequency DPOAEs

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INTRODUCTION

NONINVASIVE MONITORING OF INTRACRANIAL PRESSURE CHANGES

Recent and current work aims to develop a new paradigm for detecting changes in intracranial pressure (ICP) via distortion product oto-acoustic emissions (DPOAEs) (Buki et al., 1996, 2000; Frank et al. 2000; de Kleine et al. 2000, 2001; Voss et al., 2006). Increases in ICP appear to decrease low-frequency DPOAEs via changes in middle-ear transmission. Detecting and treating increases in ICP is crucial to protecting brains that suffer from a wide range of pathologies that cause brain swelling or bleeding, including head injury, stroke, hydrocephalus, and brain surgery. Existing methods to monitor ICP are invasive and require direct entry of a probe system through the skull (Fig. 1). A noninvasive technique to monitor ICP could revolutionize the care of some patients at risk for increases in ICP.

Figure 1: Surgical placement of an ICP monitoring device. Picture from: http://www.djo.harvard.edu/files/2791_333.jpg

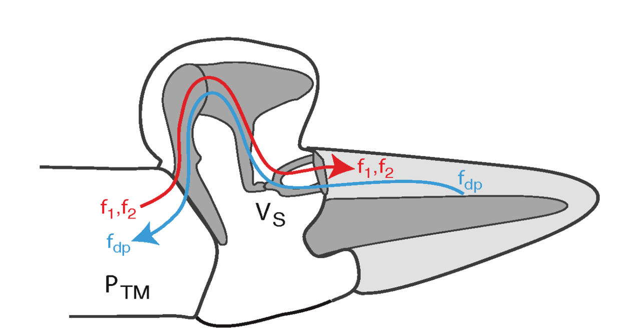


Figure 2: Schematic that represents the generation of DPOAEs. Two pure tones at frequencies f_1 and f_2 are generated by a sound source in the ear canal. Intermodulation distortion is produced by the nonlinear cochlea and the component at the frequency $2f_1$-f_2 is recorded by a microphone in the ear canal as the DPOAE.

WHAT ARE DPOAES?

DPOAEs are low-level signals recorded in the ear canal by a sensitive microphone (Fig. 2). Background or subject-generated noise can make it difficult to separate the DPOAE signal from the noise. Strategies to minimize noise include synchronous averaging (which decreases the noise floor by 1/√N with N being the number of averages) and artifact rejection, in which samples affected by impulsive noise are not included in the average. In general, we exclude data that are within 6 dB of our estimated noise floor.

SIGNAL-TO-NOISE RATIO

Diagnostic use of DPOAEs for monitoring changes in ICP requires a signal-to-noise ratio that is large enough to permit detection of changes in DPOAEs. Older subjects and subjects with either middle-ear or inner-ear disorders often have reduced DPOAEs that approach or are within the noise floor. This work aims to determine parameters that maximize the DPOAE response at low frequencies in order to increase the signal-to-noise ratio.

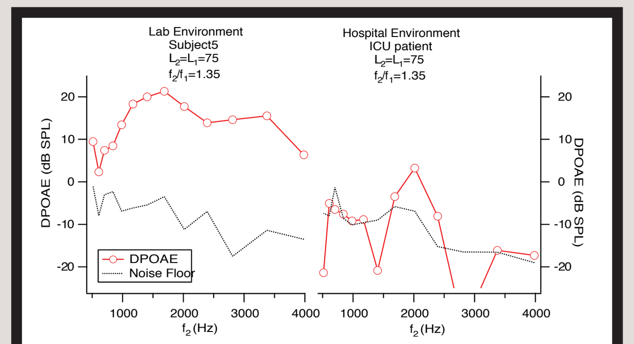


Figure 3: DPOAE measurements from a 20-year old normal hearing female (left) and a 72-year old female ICU hospital patient. Noise floors in both environments are similar, but the DPOAE levels are substantially higher in the younger subject. Diagnostic use of DPOAEs for older patients requires maximizing the signal-to-noise ratio.

GOALS OF THIS WORK

1. Determine DPOAE stimulus parameters (levels L_1 and L_2 and frequency ratio f_2/f_1) that produce maximal magnitude responses for lower frequencies (i.e., f2<1500 Hz).
2. Characterize the intra-subject variability for low-frequency DPOAEs.

RESULTS

1 EFFECTS OF STIMULUS PARAMETERS ON DPOAEs (Figure 4)

☞ The DPOAE response is generally greatest at L_1=L_2=75.

☞ Different patterns exist among f_2/f_1 ratios within each L_1 and L_2 group.

☞ At levels $L_1 = L_2 = 75$, many of the DPOAEs did not depend on the f_2/f_1 ratio. Cases that are statistically larger (p>0.05) are indicated with arrows.

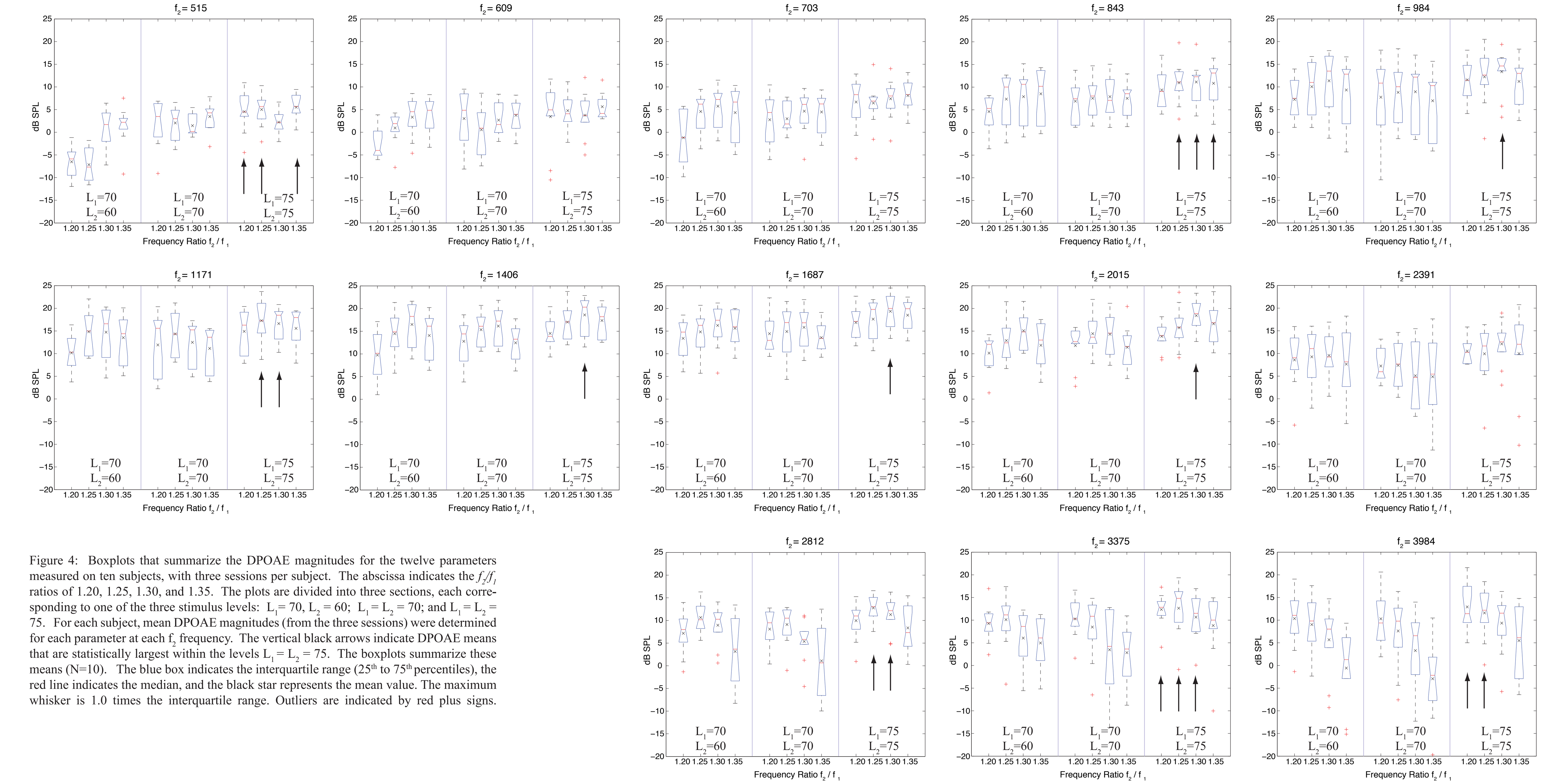


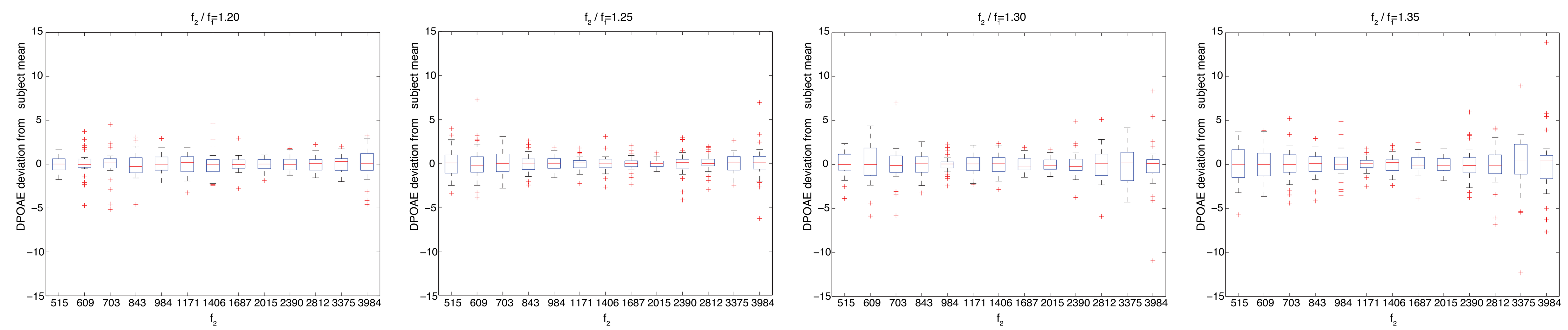
Figure 4: Boxplots that summarize the DPOAE magnitudes for the twelve parameters measured on ten subjects, with three sessions per subject. The abscissa indicates the f_2/f_1 ratios of 1.20, 1.25, 1.30, and 1.35. The plots are divided into three sections, each corresponding to one of the three stimulus levels: L_1= 70, L_2 = 60; $L_1 = L_2$ = 70; and $L_1 = L_2$ = 75. For each subject, mean DPOAE magnitudes (from the three sessions) were determined for each parameter at each f_2 frequency. The vertical black arrows indicate DPOAE means that are statistically largest within the levels $L_1 = L_2$ = 75. The boxplots summarize these means (N=10). The blue box indicates the interquartile range (25th to 75th percentiles), the red line indicates the median, and the black star represents the mean value. The maximum whisker is 1.0 times the interquartile range. Outliers are indicated by red plus signs.

2 INTRA-SUBJECT VARIABILITY at L_1=L_2=75 (Figure 5)

☞ Multiple DPOAE measurements of all subjects repeated during three separate sessions showed variations from their mean on the order of a few dBs (Fig. 5).

☞ Variability is generally highest for frequencies below 843 Hz and above 2390 Hz and for frequency ratios of 1.30 and 1.35.

Figure 5: Boxplots that summarize the intrasubject variability of DPOAE magnitudes across three measurement sessions at $L_1 = L_2$ = 75. For each subject, the mean DPOAE magnitude at each frequency and frequency ratio was subtracted from each corresponding measurement, resulting in the DPOAE magnitude's deviation from the subject mean. The boxplots summarize these deviations (N=30 for 10 subjects and 3 deviations per subject). The blue box indicates the interquartile range (25th to 75th percentiles) and the red line indicates the median. The maximum whisker is 1.0 times the interquartile range. Outliers are indicated by red plus signs.



EXPERIMENTAL METHODS

OVERVIEW: DPOAE magnitudes were measured with 12 stimulus parameter combinations. The 12 parameters were all combinations of the *four* frequency ratios f_2/f_1= 1.20, 1.25, 1.30, 1.35 and the *three* input level combinations of L_1=70, L_2=60; L_1=L_2=70; and L_1=L_2=75. The DPOAE response from each parameter combination is compared to determine the parameter combination that maximizes low-frequency DPOAEs.

SUBJECTS: The experiments were performed on ten healthy female subjects with normal hearing (ages 19 to 21). All experiments were approved by the Smith College Science Center Institutional Review Board. Each subject was given an otoscopic examination to ensure no excessive ear wax was present in the ear canal. Tympanometry and audiometric thresholds were normal (<20 dB hearing level) at all audiometric test frequencies (250, 500, 1000, 2000 and 4000 Hz) in all ears.

MEASUREMENT OF DPOAEs: DPOAE magnitudes were measured with an Etymotic ER-10c probe using HearID v4.0 (Mimosa Acoustics). The DPOAE magnitudes were measured at frequencies $f_{dp}=2f_1-f_2$ for the 12 parameter combinations at the frequencies: f_2 = 515, 609, 703, 843, 984, 1171, 1406, 1687, 2015, 2391, 2812, 3375, 3984 Hz. All measurements were repeated across three sessions on separate days for each subject. Responses were obtained from 2048-point discrete Fourier transforms of the time-domain average of 244 responses (averaging time of 10 s).

NOISE FLOOR: Noise floors were estimated from a narrow frequency band surrounding the response measured at f_{dp}. Data less than 6 dB above this estimated noise floor are eliminated from the analyses

STATISTICAL ANALYSIS: A repeated measurement regression model was employed to compare measurements at a given f_2 with the 12 different stimulus parameters. To account for clustering within subjects that resulted from repeated DPOAE magnitudes measured on the same subject, random effect (or random coefficient) models were used (Laird and Ware 1982, Feldman 1988, Fitzmaurice et al. 2004). Stata version 9.2 was used to fit these models.

DISCUSSION

☞ Diagnostic protocols to monitor ICP changes with DPOAEs might employ different levels and frequency ratios for different f_2 frequencies.

☞ Subjects chosen to participate in this study were young females (ages 19 to 21). This might account for the relatively high DPOAE responses here. Future investigation of DPOAE parameters among male and older subjects is needed.

☞ DPOAE responses are generally lower in older people, which can be a problem for obtaining a usable signal-to-noise ratio.

☞ Findings from this and similar studies will help with the longitudinal study of noninvasive detection of changes in ICP using DPOAEs.

SUMMARY

☞ Sound levels $L_1 = L_2$ = 75 appear to maximize low-frequencies DPOAEs.

☞ Frequency ratios generally do not have a large effect on the DPOAE levels within the group of $L_1 = L_2$ = 75.

☞ Multiple DPOAE measurements repeated over three sessions showed relatively small variations.

☞ Future work includes (1) additional measurements on both older and male subjects, (2) making DPOAE measurement on patients undergoing medically-necessary ICP monitoring using the sound level of $L_1 = L_2$ = 75, and (3) additional work to reduce the noise floor.

REFERENCES

Buki B., Avan P., Lemaire JJ, Dordain M, Chazal J, Ribari O. (1996) Otoacoustic emissions: a new tool for monitoring intracranial pressure changes through stapes displacements. *Hear. Res.*, **94**:125-139.

Buki B., Chomicki A, Dordain M, Lemaire JJ, Wit HP, Chazal J, Avan P. (2000) Middle-ear influence on otoacoustic emissions. II: Contributions of posture and intracranial pressure. *Hear. Res.*, **140**:202-211.

Feldman HA. (1988) Families of lines: random effects in linear regression analysis. *Journal of Applied Physiology*, **64**:1721-1732.

Fitzmaurice GM, Laird NM, Ware JH. (2004) *Applied longitudinal analysis*. John Wiley & Sons, New York.

Frank AM, Alexiou C, Hulin P, Janssen T, Arnold W, and Trappe AE. (2000) Non-invasive measurement of intracranial pressure changes by otoacoustic emissions (OAEs) -- a report of preliminary data. *Zentralbl Neurochir*, **61**:177-180.

de Kleine E, Wit HP, van Dijk P, and Avan P. (2000) The behavior of spontaneous otoacoustic emissions during and after postural changes. *J. Acoust. Soc. Am.*, **107**:3308-3316.

de Kleine E, Wit HP, Avan P, van Dijk P. (2001) The behavior of evoked otoacoustic emissions during and after postural changes. *J. Acoust. Soc. Am.*, **110**:973-980.

Laird NM, Ware JH. (1982) Random-effects models for longitudinal data. *Biometrics*, **38**:963-974.

Voss SE, Horton NJ, Tabucchi THP, Folowosele F, Shera CA. (2006) Posture-induced changes in distortion-product otoacoustic emissions and the potential for noninvasive monitoring of changes in