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Effect of Stimulus Sweep Direction on Distortion Product Otoacoustic Emission Fine Structure

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ABSTRAK

Tujuan kajian ini adalah untuk mengkaji kesan arah pergerakan stimulus ke atas struktur mikro pancaran otoakustik hasil herotan (DPOAE) 2f1-f2. Ia dihipotesis bahawa struktur mikro DPOAE boleh teranjak sekiranya pergerakan stimulus di ubah dari satu arah ke suatu arah yang berlainan. Di dalam kajian ini, pergerakan frekuensi stimulus secara menaik, menurun dan rawak telah digunakan, di mana frekuensi f2 berbeza di antara 992 Hz dan 2496 Hz dan nilai f2/f1 adalah tetap pada 1.22. Struktur mikro DPOAE telah direkod pada setiap jeda 16 Hz. Saringan, pengukuran pancaran otoakustik spontan (SOAE), dan pengukuran DPOAE telah dijalankan ke atas 19 telinga daripada 19 orang subjek yang berusia di antara 22 dan 30 orang. Hanya data daripada 14 telinga yang mempunyai sekurang-kurangnya satu puncak atau lembah yang signifikan di dalam struktur mikro dimasukkan di dalam analisis utama. Lima daripadanya telah menunjukkan sekurang-kurangnya satu kehadiran SOAE di dalam julat frekuensi 600 Hz hingga 2500 Hz. Data yang diperolehi daripada telinga yang mempunyai dan telinga yang tidak mempunyai SOAE telah dikumpul dan dianalisis secara berasingan. Keputusan analisis menunjukkan tiada kesan perubahan pergerakan stimulus ke atas struktur mikro DPOAE. Secara khususnya, di antara ketiga-tiga arah stimulus yang digunakan, tiada perubahan yang signifikan diperhatikan pada kedudukan frekuensi puncak atau lembah dan pada ketinggian puncak atau kedalaman lembah ($p > 0.05$). Kajian juga menunjukkan bahawa tiada kesan perubahan arah stimulus ke atas tahap DPOAE yang signifikan apabila frekuensi SOAE adalah bersamaan dengan frekuensi DPOAE yang diuji ($p > 0.05$). Kajian ini menyimpulkan bahawa perubahan pada arah stimulus tidak memberi kesan yang signifikan ke atas struktur mikro DPOAE, 2f1-f2, samada pada telinga yang mempunyai SOAE ataupun tidak. Oleh itu, pengukuran struktur mikro DPOAE boleh dijalankan dengan menggunakan mana-mana arah pergerakan stimulus.

Kata kunci: Pancaran otoakustik hasil herotan (DPOAE), struktur mikro, pancaran otoakustik spontan, arah simulus.

ABSTRACT

The purpose of this study was to examine the effect of stimulus sweep direction on the fine structure of the 2f1-f2 distortion product otoacoustic emission (DPOAE). It was hypothesised that the DPOAE fine structure could be shifted if the stimulus sweep changed from one direction to the other. In the present study, ascending, descending and random frequency sweeps were used, with f2 frequency varying between 992 Hz and 2496 Hz and f2/f1 fixed at 1.22. DPOAE fine structure was recorded at 16 Hz intervals. Screening, spontaneous otoacoustic emission (SOAE) and DPOAE measurements were carried out on 19 ears of 19 subjects aged between 22 and 30 years. Data from 14 ears that had at least one significant peak or valley in their DPOAE fine structure were included in the main analysis. Of these, five ears showed at least one occurrence of SOAE over the frequency span 600 Hz to 2500 Hz. Data for ears with and without SOAEs were grouped and analysed separately. The results showed no effect of sweep direction on DPOAE fine structure. No significant differences were observed in peak or valley frequencies, peak height or valley depth between the three stimulus sweep conditions ($p > 0.05$). There was also no significant effect of stimulus sweep direction on DPOAE level at the point at which SOAE frequency equalled DPOAE frequency ($p > 0.05$). In conclusion, the study found no effect of stimulus sweep direction on the fine structure of the 2f1-f2 DPOAE, either in ears with or without SOAEs. Therefore, future measurements of this fine structure may use either sweep direction.

Key words: Distortion product otoacoustic emission, fine structure, spontaneous otoacoustic emission, sweep directions.

INTRODUCTION

Distortion product otoacoustic emissions (DPOAEs) are signals measured in the ear canal when two external pure tones (at frequencies f1 and f2 with f1 < f2) are presented simultaneously. They appear as continuous pure tones at intermodulation frequencies. The most prominent DPOAE occurs at the frequency 2f1-f2. The amplitude of the DPOAE is typically small in human ears and is about 60-70 dB below equilevel primary tones (Probst et al. 1991).

DPOAE fine structure can be observed in a graph of DPOAE amplitudes as a function of fine increments in frequency. The patterns of fine structure across frequency vary between subjects, but are extremely reproducible over time within each subject. Within the fine structure, the DPOAE level can change at rates of up to 250 dB/oct (Gaskill & Brown 1990). He & Schmiedt (1993) reported that most of their subjects showed sharp ripples (peaks and valleys) across frequency with peak-to-valley difference as large as 20 dB SPL. The fine structure of DPOAE resembles audiometric microstructure (Long 1984; Talmadge et al. 1998) at a frequency region below 4000 Hz (He & Schmiedt 1993).

Several studies have suggested that DPOAE fine structure is a result of the interference between two sources of DPOAE generation. The first source is DPOAE energy originating in the region of the maximum overlap of the cochlear excitation produced by the two primary tones. This maximum mostly occurs closest to the tonotopic location of the f2 primary (Kummer et al. 1995). The second source is DPOAE energy originating from the reflection component of the DP wave. The reflected component first travels apically from the overlapping region and then basally towards the ear canal (Kummer et al. 1995; Talmadge et al. 1997, 1998). The first source was proposed to be dominant when low-to-moderate (up to 60 dB SPL) primary levels were used and the second source is dominant at higher primary levels (Talmadge et al. 1999). Further studies have been done by introducing a third tone as a suppressor close to the frequency of the DPOAE (Kemp & Brown 1983; Kummer et al. 1995; Gaskil & Brown 1996; Heitmann et al. 1997; 1998). It was found that the DPOAE fine structure either decreased or entirely disappeared when a suppressor tone was introduced near the frequency of the DPOAE. These findings suggest that the DPOAE fine structure can be obtained from the result of interaction between two sources of DPOAE generation.

DPOAE fine structure (especially for the 2f1-f2 DPOAE) is extremely dependent on several stimulus parameters including the frequency of the primaries (f1, f2), their frequency ratio (f2/f1) and the absolute as well as relative intensity of the primaries (L1, L2) (He & Schmiedt 1997; Kemp 1986). Uppenkamp et al. (1997) noted that the DPOAE fine structure shifted gradually towards lower frequencies as primary levels increased. He & Schmiedt (1993) also noted a similar tendency of shift in ripple even though they found no significantly reduced DPOAE peaks and valleys (between 2 kHz and 4 kHz) at high primary levels.

It has been well demonstrated that Spontaneous Otoacoustic Emissions (SOAEs), Transient Evoked Otoacoustic Emissions (TEOAEs) or Stimulus frequency Otoacoustic Emissions (SFOAEs) may influence DPOAE amplitudes within an individual ear (Kemp 1986; Furst et al. 1988). Generally, a strong enhancement of DPOAE amplitude occurs at or near the frequencies of other emissions (Weir et al. 1988; Moulin et al. 1993). The influence of other OAEs has been shown to decrease with increasing stimulus levels (Kemp 1986; Weir et al. 1988) and f2/f1 ratios (Kemp 1986; Furst et al. 1988).

Long et al. (1988) found that SOAE can be completely pulled in by the external tone, if the external tone frequency approaches the SOAE. Wilson and Sutton (1981) reported that frequency of the SOAE is shifted by some Hz, typically towards the external tone if a continuous tone is presented to an ear with SOAE. Based on these findings, it is suggested that similar effects may occur if stimulus sweep direction is changed. It may be possible to observe shifts in DPOAE fine structure, due to change in the dominant site of DPOAE generation or SOAEs region, if the direction of stimulus sweep is manipulated.

The aim of present study is to measure the effect of ascending, descending and randomising stimulus presentation direction on DPOAE fine structure. It is hypothesised that the DPOAE fine structure will be shifted if the direction of stimulus sweep is changed or randomised. The hypothesis is based on the observations of the mechanism of the DPOAE generation site. Previous studies done in manipulating stimulus parameters found significant shifts in DPOAE fine structure (Talmadge et al. 1999; Harris & Glattke 1992). This appears to be the first study in which effect of manipulation of stimulus sweep direction on DPOAE fine structure is being investigated. It is hoped that this study may help us in further understanding the mechanism of the cochlear amplifier and the characteristics of DPOAEs.

MATERIALS AND METHODS

SUBJECTS

19 volunteers from the University of Southampton were used as subjects in this study. The age ranged between 22 and 30 years (mean = 25.3 years, SD = 2.9 years). Each subject was given an information sheet that fully explained the purpose and nature of the experiment. Informed consent was obtained prior to subject participation. Subjects were selected on the basis that they were otologically normal, this being confirmed by taking an otological history and completing a purpose-designed questionnaire. All subjects were required to pass a battery of screening tests before being included in the experiment. Only one ear with better averaged pure tone thresholds was used from each subject.

SPONTANEOUS OTOACOUSTIC EMISSION (SOAE) MEASUREMENT

SOAE recording was performed twice for each subject prior to the DPOAE measurement. SOAEs were recorded over the frequency range 16 Hz to 16384 Hz in 16 Hz steps and completed within 10 seconds. Apart from the absence of stimulus, the method of recording SOAEs was identical to that for DPOAE recording. An SOAE was considered significantly present if the response obtained was repeatable over a frequency span 600 Hz to 2500 Hz with the level equal to or greater than 3 dB above the noise floor. In this case, the noise floor was defined as an average of noise levels at the 10 points adjacent to SOAE centre frequency.

DISTORTION PRODUCT OTOACOUSTIC EMISSION (DPOAE) MEASUREMENT

DPOAE measurements were carried out at three different stimulus sweep directions; ascending (A), descending (D) and random (R). Two recording were obtained for each stimulus sweep direction in order to assess the repeatability and reliability of the OAE measurements. Each DPOAE measurement was made in 16 Hz intervals across an f2 frequency range between 1000 and 2500 Hz, giving 94 measurements in all. The two primaries, f1 and f2, had a constant frequency ratio of 1.22 with f2 swept from 992 Hz to 2496 Hz. The levels of the primaries, L1 and L2, were also kept constant with L1 at 60 dB SPL and L2 at 50 dB SPL.

PEAK AND VALLEY IDENTIFICATION

For all traces, a peak was classified as present if the level differences between the identified peak and the two valleys on both sides of the peak were greater than or equalled to 2 dB. Similarly, a valley was considered present if the level differences between the identified valley and the two peaks on both sides of the valley were greater than or equalled to 2 dB. In certain analyses, only the biggest peak and valley would be taken into account. The biggest peak was defined as the peak as previously identified that had the largest peak-to-valley difference on either side of the peak. Similarly, the biggest valley was defined as the valley as previously identified that had the largest valley-to-peak difference on either side of the valley.

In addition, for the measurement of peak height and valley depth a specific definition was used. The peak height was defined as the mean of the level difference between peak identified and the deepest valley either side of the peak. Similarly, valley depth was defined as the mean of the level difference between valley identified and the largest peak either side of the valley.

RESULTS

Only 14 from the total of 19 ears tested were included in the following analyses. Five ears were excluded from the current study because of low DPOAE levels or showing neither a peak nor a valley in fine structure. In this study low DPOAE levels were defined as a difference between the mean DPOAE level and the mean noise level for a given trace of less than 3 dB. Five ears from the total of 14 ears showed at least one occurrence of SOAE in the frequency range 600 Hz to 2500 Hz. Data from ears without and with SOAEs were grouped separately for analyses.

Varying degrees of fine structure were evident between subjects. Within subjects, the fine structures were highly reproducible across all conditions. Figure 1 shows an example of non-smoothed 2f1-f2 DPOAE fine structure obtained from ascending stimulus sweeps. The repeatability of the measurement for each condition was determined by using the Pearson’s product moment correlation coefficient. Table I shows that subjects generally had very repeatable traces between run 1 and run 2 for each condition. The correlation coefficient for the sweep combinations were checked for normality with Kolmogorov-Smirnov test. All data were found to be normal or near normal.

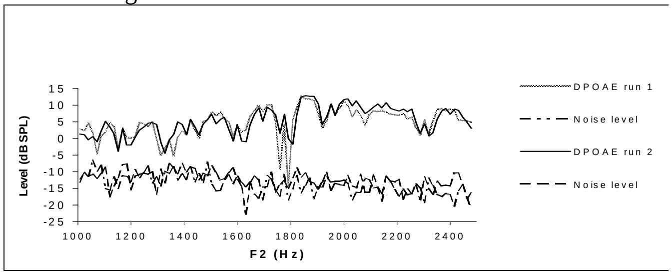


FIGURE 1 Two replicates of non-smoothed DPOAE fine structure obtained from the left ear subject 11 using an ascending sweep

All fine structures were significantly correlated at the $p < 0.01$ level (2-tailed). Within-stimulus sweep direction, the highest correlation coefficient observed was 1.00 (subject 06 for A1-A2) and the lowest was 0.54 (subject 04 for R1-R2). Examination of the signal-to-noise ratios (SNRs) showed that subject 04 had slightly low SNRs for random sweep (SNR: R1- 5.83 dB and R2 – 4.5 dB). In this case, the low signal level might influence the repeatability of the fine structure. The mean and standard deviation for each condition are shown in the last two rows of Table 1. As expected, within similar stimuli sweep gave stronger correlation across the two runs than between two different stimuli sweep correlation.

The correlation coefficients between the two ascending runs (A1-A2) were then compared to those between ascending and descending (A1-D1) and ascending and random (A1-R1) runs. All distributions were normal. A paired sample t-test was performed between the A1-A2 and A1-D1 as well as between A1-A2 and A1-R1 correlation coefficient distributions. No statistically significant differences ($p > 0.05$) were observed for any of these correlation pairings. Therefore, sweep direction did not significantly affect the correlation between replicate measures of DPOAE fine structure.

Seven significant SOAEs were identified from five ears with SOAEs. Five of these SOAEs were within the region of DPOAE frequencies (624-1584 Hz) recorded, while the other two were in the region of the F2 frequency span only. SOAE amplitudes varied between 3 dB SPL and 12 dB SPL (mean = 5.03 dB SPL). DPOAE data from these ears were analysed in a similar fashion to data from ears without SOAEs. The repeatability of the fine structures for each condition was again determined by using the Pearson's product moment correlation coefficient. All data were considered normal or near-normal. The correlation test showed that all fine structures were significantly correlated at the $p < 0.01$ level (2-tailed). Then, a paired sample t-test was performed between the A1-A2 and A1-D1 as well as between A1-A2 and A1-R1 correlation coefficient distributions. No statistically significant differences ($p > 0.05$) were observed for any of these correlation pairings. Therefore, sweep direction did not significantly affect the correlation between replicate measures of DPOAE fine structure in ears with SOAEs. Table 2 shows the Pearson's product correlation coefficients obtained for each ears with SOAEs.

The frequency span tested was divided into two regions, 1000 Hz to 1750 Hz (region 1) and 1751 Hz to 2500 Hz (region 2). In each region, the biggest peak and/or valley was then identified. Then, it was decided to match the peak in an ascending trace with those that existed in the other two traces if the frequency positions were separated by a different in frequency of 4% or less (this is equivalent to half of the typical peak-peak DPOAE interval periodicity). If the peak of interest existed in two traces at frequencies that were within 4% of each other but not present in the third, it was not selected. Peak matching was simply identified visually and the DADiSP was used to get reading off frequency values. Peak matching was carried out in both regions. Exactly the same procedure was applied to extract the biggest valley in all three traces.

The visual matching of peaks and valleys identification extracted at least one 'set' of peak/valley or the maximal four 'sets' of peaks and valleys in each subject's fine structure. Each set represented a group of three peaks or valleys that lay within the specified frequency interval in the three traces. Across the nine ears without SOAEs, eight complete sets of peaks were found in the both regions. In contrast eight complete sets of valley were identified in region 1 and six complete sets were found in region 2. All peak frequency distributions for each stimulus sweep direction in both regions were normal. A repeated measure ANOVA was performed on the peak frequency positions for each region separately. The repeated measure ANOVA showed there was no significant effect of different stimulus sweep direction on the frequencies of the peaks within the fine structure. This was true for both regions (region 1: $F(2) = 0.75$; $p > 0.05$ and region 2: $F(2) = 2.12$; $p > 0.05$).

As with peak frequency data, tests for normality were performed on valley frequency data. All distributions were normal. A repeated measure ANOVA was then performed in both regions separately and the results showed no significant sweep effect on the valley frequency shifts of fine structure in both regions (region 1: $F(2) = 0.00$; $p > 0.05$ and region 2: $F(2) = 0.30$; $p > 0.05$).

Across all five ears, a visual examination of the biggest peak and valley identification extracted four complete sets of peak in both regions. Four complete sets of valley were identified in region 1 and five complete sets were found in region 2. All distributions were found to be normal. A repeated measure ANOVA was performed and the results showed no significant effect of different stimulus sweep direction on either peak or valley frequency positions. This is true in both regions.

The influence of sweep direction on peak height and valley depth was also examined. As for the analysis peak and valley frequency shifts, only the biggest peaks and valleys were considered for this purpose.

The higher frequency region (region 2) showed slightly larger magnitude of peak heights and valley depths than the lower frequency region (region 1) with the exception of the random sweep. The maximum mean value of the largest peak heights was 9.34 dB SPL and the maximum mean value of the deepest valley depths was 8.05 dB SPL. Both mean values were obtained from ascending sweep (region 2). A repeated measure ANOVA was performed to examine any evidence of changes in peak height and valley depth due to change in stimulus sweep direction. The results showed no statistically significant differences either in peak height or valley depth between ascending, descending and random sweeps direction in both regions ($p > 0.05$).

The mean values obtained were higher in the region 2 than in the region 1 for all sweeps. The maximum mean value of the largest peak heights was 11.94 dB SPL and the maximum mean value of the deepest valley depths was 10.23 dB SPL. Both values were obtained from descending sweep (region 2). If compared to the values obtained from the ears without SOAEs, the ears with SOAEs produced higher mean values of the largest peak heights and the deepest valley depths. Similar to the data without SOAEs, a repeated measure ANOVA showed no statistically significant differences either in peak heights or valley depths between the three sweeps direction ($p > 0.05$).

An additional analysis was conducted to examine the effect of stimulus sweep directions at the specific point in the fine structure where the SOAE frequency equalled the 2f1-f2 DPOAE frequency. Only five SOAEs, derived from three subjects, occurred within the DPOAE frequencies region (624-1584 Hz). The other subjects, subject 11 and subject 14 did have at least one SOAE in the tested ear, however the SOAE frequencies were outside the DPOAE frequency region. Figure 2 shows the levels of 2f1-f2 DPOAE for each condition at the point when SOAE frequency was at DPOAE frequency.

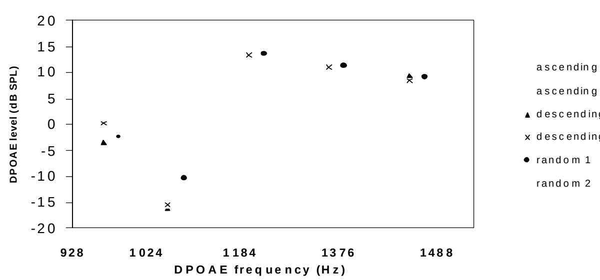


FIGURE 2. The levels of DPOAE at the point on the fine structure when DPOAE frequency equalled SOAE frequency (values obtained from three ears)

A repeated measure ANOVA was performed to examine any significant effect of sweep direction or DPOAE levels at the point when SOAE frequencies were equalled the DPOAE frequencies. The results showed no significant effect of different stimuli presentation orders on the DPOAE levels at those points.

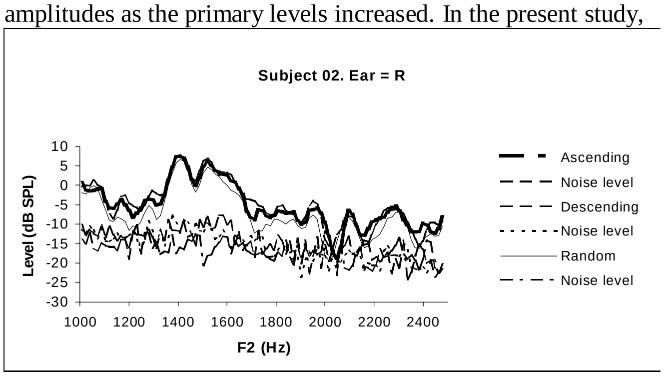
DISCUSSION

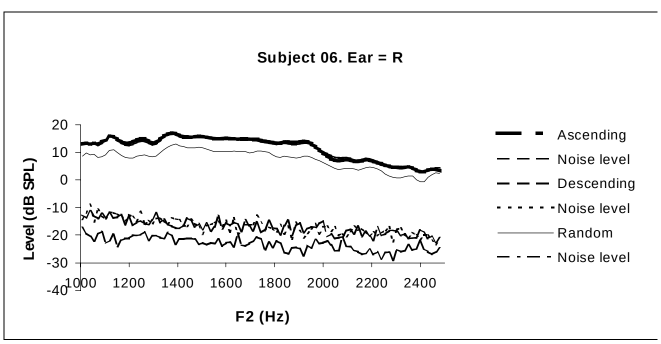
In the present study, DPOAE fine structure was evident to varying degrees in 14 out of 19 (74%) ears when the stimuli were swept in ascending, descending and random directions. In these subjects, the number of peaks that occurred in all three conditions over the frequency span of 1000 Hz – 2500 Hz varied from one to seven (mean = 4) and the number of valleys from zero to seven (mean = 3). Most of the subjects (12 out of 14 subjects) in this study showed marked fine structure at certain frequency regions (Figure 3a), while two subjects had weak fine structure with just one or two low amplitude peaks or valleys. In one of these two cases (subject 06) only one peak could be identified at 1104 (Figure 3b) Hz while the other (subject 12) had only one valley of small amplitude (Figure 3c) in fine structures across all conditions.

In general all but two (subject 02 and 04) subjects showed very stable DPOAE patterns over time. This compares well with the findings of Gaskill & Brown (1990) and Deeks (1998). The traces were very repeatable between the two replicate runs within each condition of sweep direction. The lowest within-condition correlation coefficient (r) was 0.54 in subject 04 for the random sweep condition. In case of subject 02, the within-condition correlation coefficient was relatively low (r = 0.66) for the ascending condition. Subject 02 and 04, also showed poor DPOAE signal-to-noise ratio. In both subjects, the noise level could have influenced the repeatability of the recordings, which may have led to a low correlation coefficient. Overall, for a given sweep condition, DPOAE fine structure recorded in run 1 significantly correlated ($p < 0.05$) with DPOAE recorded in run 2.

It was hypothesised in the present study that change in stimulus sweep direction would create changes in the position of peaks and valleys in the DPOAE fine structure. This was based on the observations of previous studies which found changes or shifts in DPOAE fine structure if stimulus parameters such as primary intensity levels or primaries frequency ratios were manipulated.

In this study, it has been found that changes in stimulus sweep direction did not significantly shift the DPOAE fine structure as hypothesised. The peak and valley frequency positions in the fine structure did not shift significantly in any region tested. The peak heights and the valley depths also did not significantly reduce or increase. Finally, examination at a specific point on the fine structure showed no significant effect of ascending, descending and random presentation orders on the DPOAE levels when the DP frequency equalled the SOAE frequency. Findings in this study do not support the hypothesis.
It is suggested that following explanations be taken into account before a revision of the hypothesis is considered. Firstly, most of the previous studies investigating the effect of stimulus parameters on DPOAE fine structure, manipulated the primary parameters in their experiments. Heitmann et al. (1996) observed narrow dips in some of DPOAE fine structures shifted in frequency and diminished in amplitudes as the primary levels increased. In the present study,





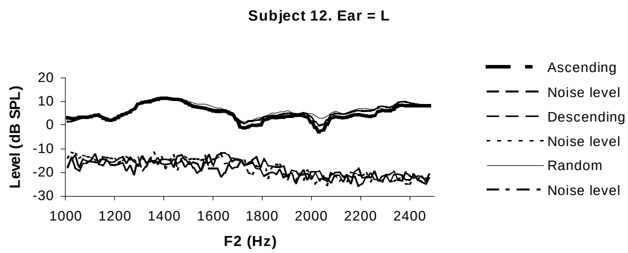


FIGURE 3. (a) Subject 02, showed marked peaks and valleys in the fine structure across frequency. (b) Subject 06, only one peak present in the fine structure. (c) Subject 12, only one valley present in the fine structure

the parameters L1, L2 and f2/f1 were kept at a fixed level, as a result no significant shift in DPOAE fine structure was observed. It is suggested that another study is conducted whereby the present hypothesis is verified by manipulating the primary parameters and adopting a procedure to avoid suppression effect.

Secondly, Deeks (1998) found that at primary levels of 60 dB and 55 dB SPL, the DPOAE fine structure obtained across three recording sections gave less variance than DPOAE measurement at other input levels. In the present study, the primary level L1 = 60 dB SPL was chosen on the basis of the findings of Deeks (1998). However, this level could not demonstrate any significant shift in DPOAE fine structure. Some studies have found that at high stimulus levels, between 60 and 65 dB SPL, DPOAE saturation tends to occur (Probst 1991; Gaskill & Brown 1990). It is possible that the saturation of DPOAE might have affected the rippling pattern in the DPOAE fine structure. Therefore, it is suggested that a different level of presentation (other than 60 dB or 55 dB SPL) be tried to see if it can demonstrate any significant shift. It has to be balanced from the fact that stimulus of lower intensity does not give rise to prominent DPOAE responses (Hall & Mueller 1997).

Thirdly, it was found that in the region of SOAE, the levels of DPOAE did not increase or decrease significantly when the stimulus sweep direction was manipulated. Lonsbury-Martin et al. (1990b) found that the presence of SOAEs within the DPOAE test range failed to correlate with DPOAE level. They also noticed that the input-output functions in ears with many SOAEs tended to be more complex than in ears with no or few SOAEs. Weir et al. (1988) and Moulin et al. (1993) found that the levels of DPOAE was higher if an SOAE occurred within 50 Hz of the DPOAE frequency. It is suggested to replicate these studies for hypothesis to be verified.

Finally, the sample size in the present study was quite small especially for SOAE data (N = 5). Therefore the result may not reflect the general picture of the influence of sweep direction on DPOAE at the point in the fine structure where DPOAE frequency equals SOAE frequency.

CONCLUSION

It is well demonstrated that DPOAE fine structure is highly repeatable and stable over time. In the present study, all fine structures were significantly correlated at the $p < 0.01$ level.

Findings in the present study do not support the hypothesis, because changes in stimulus sweep direction did not significantly shift the pattern of DPOAE fine structure in terms of the frequencies of peaks and valleys. No significant changes in the level of identified peaks and valleys were observed. No significant effect of stimulus sweep direction on the DPOAE at the point in the fine structure where DPOAE frequency equalled SOAE frequency was found in the ears exhibiting SOAEs.

These results suggest that future research or clinical measurements of DPOAE fine structure may use either sweep direction. However, several explanations such as the levels of the primary and the fixation of L1, L2 and f2/f1 values need to be taken into account before any conclusion can be made. It is also suggested that another study should be conducted to verify the present hypothesis by considering the different levels of stimulus presentation, adopting a procedure to avoid other effects such as suppression effect and expanding the number of samples.

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