The effect of stimulus-frequency ratio on distortion product otoacoustic emission components

Sumitrajit Dhar[a)]
Hugh Knowles Center, Department of Communication Sciences and Disorders, Northwestern University, Evanston, Illinois 60208

Glenis R. Long
Graduate Center, City University of New York, New York, New York 10016

Carrick L. Talmadge
National Center for Physical Acoustics, University of Mississippi, University, Mississippi 38677

Arnold Tubis
Institute for Nonlinear Science, University of California—San Diego, La Jolla, California 92093

A detailed measurement of distortion product otoacoustic emission (DPOAE) fine structure was used to extract estimates of the two major components believed to contribute to the overall DPOAE level in the ear canal. A fixed-ratio paradigm was used to record DPOAE fine structure from three normal-hearing ears over a range of 400 Hz for 12 different stimulus-frequency ratios between 1.053 and 1.36 and stimulus levels between 45 and 75 dB SPL. Inverse Fourier transforms of the amplitude and phase data were filtered to extract the early component from the generator region of maximum stimulus overlap and the later component reflected from the characteristic frequency region of the DPOAE. After filtering, the data were returned to the frequency domain to evaluate the impact of the stimulus-frequency ratio and stimulus level on the relative levels of the components. Although there were significant differences between data from different ears some consistent patterns could be detected. The component from the overlap region of the stimulus tones exhibits a bandpass shape, with the maximum occurring at a ratio of 1.2. The mean data from the DPOAE characteristic frequency region also exhibits a bandpass shape but is less sharply tuned and exhibits greater variety across ears and stimulus levels. The component from the DPOAE characteristic frequency region is dominant at ratios narrower than approximately 1.1 (the transition varies between ears). The relative levels of the two components are highly variable at ratios greater than 1.3 and highly dependent on the stimulus level. The reflection component is larger at all ratios at the lowest stimulus level tested (45/45 dB SPL). We discuss the factors shaping DPOAE-component behavior and some cursory implications for the choice of stimulus parameters to be used in clinical protocols. © *2005 Acoustical Society of America.* [DOI: 10.1121/1.1903846]

PACS numbers: 43.64.Bt, 43.64.Ha, 43.64.Jb [BLM]   Pages: 3766–3776

I. INTRODUCTION

Kim's (1980) initial prediction of two sources for the distortion product otoacoustic emission (DPOAE) at the frequency $2f_1 - f_2$ (f_1 and f_2 are the frequencies of the stimulus tones and $f_1 < f_2$) has undergone considerable development and formalization over the last decade. The DPOAE at $2f_1 - f_2$, as well as other (apical) DPOAEs where $f_{dp} < f_1 < f_2$, are understood to be a vector sum of (at least) two components, each generated at disparate locations on the basilar membrane due to distinct mechanisms. The nonlinear interaction between the stimulus tones around the tonotopic region of the higher-frequency stimulus tone (f_2) generates the *distortion* or *generation* component. The *reflection* component, on the other hand, is due to linear coherent reflections from a randomly distributed roughness about the tonotopic region of the DPOAE. Detailed analytic descriptions of

the above model, or parts thereof, have been presented by several groups (e.g., Zweig and Shera, 1995; Talmadge *et al.*, 1998; Mauermann *et al.*, 1999) along with several lines of supporting experiments. Although these models apply to all apical DPOAEs, we will use the term DPOAE synonymously with the DPOAE at the frequency $2f_1 - f_2$ in this paper. Evidence in support of such a two-source, two-mechanism model has come from suppression experiments (e.g., Kummer *et al.*, 1995; Heitmann *et al.*, 1998; Talmadge *et al.*, 1999; Kalluri and Shera, 2001), results in the pseudotime domain following Fourier analysis of frequency-domain data (e.g., Kalluri and Shera, 2001; Konrad-Martin *et al.*, 2001, 2002; Knight and Kemp, 2001; Dhar *et al.*, 2002), as well as true time-domain recordings of DPOAEs (Talmadge *et al.*, 1999). An important consequence of the interaction of energy from two sources is the DPOAE fine structure (a pseudoperiodic variation of the DPOAE level and phase as a function of frequency).

In a view parallel to that of the two-source, two-mechanism dichotomy, the two DPOAE components have

---
[a)]Corresponding author: Sumitrajit Dhar. Electronic mail: s-dhar@northwestern.edu

also been referred to as *place* and *wave* fixed. Initially proposed as two sources of DPOAEs originating at the same location on the basilar membrane (Kemp, 1986), the place-/wave-fixed description has embraced the mechanistic and location differences between DPOAE components; with the wave- and place-fixed components equated to the generator and reflection components, respectively (Knight and Kemp, 2000, 2001).

A third view has also recently emerged, driven primarily by experimental comparisons of delay measures of otoacoustic emissions and basilar membrane recordings (Ruggero, 2004; Ren, 2004). Here, otoacoustic emissions (OAEs) are proposed to (i) be generated from a distributed area extending toward the base of the cochlea similar to that associated with cochlear microphonics; and (ii) propagate via acoustic compression waves in the cochlear fluids rather than as traditional traveling waves on the basilar membrane. Arguments for this view come from the presence of OAEs in basilar-membraneless ears of frogs and limited sets of data from gerbils, guinea pigs, and chinchillas (Ruggero, 2004). While these are interesting developments, regularly observed features of OAEs such as phase behavior and fine structure are yet to be explained using this new model. The significance of Ren's (2004) report is also unclear, given his choice of stimulus-frequency ratios for which the propagation of DPOAE energy from the f_2 CF region is known to be predominantly in the apical direction (Schneider *et al.*, 2003). Moreover, evidence in support of this model is yet to be presented from human ears. Our work here, representing experimental results from normal-hearing human ears, is presented using the theoretical framework of the traditional "two-source" model of apical DPOAEs.

Talmadge *et al.* (1998) provide a detailed derivation of a "two-source" model of the DPOAE recorded in the ear canal (P_e) at the angular frequency (ω_{dp}). Two components of the distortion product (DP) are initially generated in the cochlear region of maximum overlap of the waves from the two stimulus tones. One component (P_l) travels basally (backward) toward the cochlear base and into the ear canal where it gives a DPOAE contribution $P_l(\omega_{dp})$. The other generated DP component in the cochlea travels apically (forward) to the DP characteristic frequency (CF) region, where it is partially reflected toward the cochlear base into the ear canal via coherent scattering from assumed cochlear inhomogeneities (Zweig and Shera, 1995; Talmadge *et al.*, 1998). This reflected energy results in an ear-canal signal contribution of $P_r(\omega_{dp})R_a(\omega_{dp})$, where $P_r(\omega_{dp})$ is related to the initial apical moving DP component in the cochlea and R_a is the apical reflectance. In a simplified version of the model it is assumed that all of the reflected energy leaves the cochlea and is not reflected back into the cochlea from the junction of the cochlea and the middle ear. Consequently the DPOAE pressure signal recorded in the ear canal P_e at the frequency ω_{dp} can be represented as

$$P_e(\omega_{dp}) = P_l(\omega_{dp}) + R_a(\omega_{dp})P_r(\omega_{dp}). \qquad (1)$$

Later versions of the model (supported by experiments) include multiple internal reflections between the stapes and the DPOAE CF region (Dhar *et al.*, 2002). However, for the purposes of this paper we assume that the reflectance at the oval widow (R_b in our models) equals zero. We will refer to the representation of P_l in the ear canal as the *generator* component and that of R_aP_r as the *reflection* component.

In this paper we evaluate the relative contributions of the generator and reflection components to the ear-canal DPOAE. Specifically we wish to examine the behavior of these two components as a function of stimulus-frequency ratio. The most comprehensive work in this area has been presented in a series of three articles by Knight and Kemp (1999, 2000, 2001). In the first of the series, they demonstrated similarity between the characteristics of transient evoked OAEs (TEOAEs) and DPOAEs generated for small (*narrow*) stimulus-frequency ratios, alluding to concordance between their generation processes. In the second publication, a detailed analysis of the phase behaviors of multiple orders of DPOAEs was used to demonstrate that the mechanism for DPOAE generation was dominantly place- and wave-fixed for narrow and wide stimulus-frequency ratios, respectively. In the third publication, these authors confirmed these results using the same data transformed into the time domain using inverse Fourier transformation. The essence of the Knight and Kemp findings can be summarized as (i) DPOAE generation is predominantly place fixed at narrow ratios; (ii) the wave- and place-fixed components demonstrate a bandpass shape as a function of stimulus-frequency ratio; (iii) the bandpass shape of the place-fixed component is asymmetrical, the "drop-off" being much steeper at the wide ratios; and (iv) the change in dominance of one mechanism over the other occurs approximately around a stimulus-frequency ratio of 1.1. Note that we refer to the place- and wave-fixed components as the reflection and generator components, respectively.

Schneider *et al.* (2003) investigated the dominance of the components in the guinea pig by examining the DPOAE group delay. In contrast to the work reported by Knight and Kemp, where DPOAE recordings were done with fixed stimulus-frequency ratios, Schneider *et al.* varied the frequency of one stimulus tone while keeping the other fixed in frequency. The transition in dominance from place- to wave-fixed mechanisms occurred at a stimulus-frequency ratio wider than that observed in human ears, consistent with the difference in the sharpness of basilar-membrane tuning between guinea pigs and humans as well as wider fine-structure spacing in rodents (Long *et al.*, 1999; Withnell *et al.*, 2003). Schneider *et al.* (2003) demonstrate the relationship between the two components at stimulus-frequency ratios greater than 1.35 to be ambiguous.

In sharp contrast to the somewhat extensive experimental work presented in this area to date, a theoretical examination of the mechanistic implications of these findings has been limited. Knight and Kemp (1999) base the explanation of their results on the rapid phase variation of the $2f_1-f_2$ wave near the f_2 peak region as f_2/f_1 approaches 1. This variation, the authors point out, will cause a reduction of the magnitude of the backward traveling wave as DPOAE wavelets will fail to combine in phase. While these phase-related arguments may be valid, amplitude effects as a function of changing stimulus-frequency ratio cannot be neglected.

J. Acoust. Soc. Am., Vol. 117, No. 6, June 2005

Dhar *et al.*: Distortion product components and f2/f1 3767

Shera (2003) has included amplitude effects in his treatment of the subject and provided a more complete analytic description of the interplay between the generator and reflection components as a function of the changing stimulus-frequency ratio. These issues, in light of our data, are presented in detail in Sec. IV.

In this paper we extend previous findings by evaluating DPOAE component behavior as a function of stimulus-frequency ratio in normal-hearing human ears. We report novel behavior of DPOAE components at wide stimulus frequency ratios. Our study also differs from previous reports in the use of lower level stimulus tones, which reveals features of DPOAE components not reported previously. We will conclude by providing a theoretical analysis of our results and preliminarily comment on the implications of these findings on the clinical application of DPOAEs.

II. METHODS

A. General methods

The methods used to record and analyze data were similar to those reported by Dhar *et al.* (2002). In brief, high-resolution DPOAE data were recorded from three normal-hearing subjects recruited from the Purdue University community. These three subjects were selected from a total of approximately ten subjects screened. Subject selection was based on a negative family history of hearing loss, normal middle ear function as determined by type-A tympanograms, hearing thresholds better than 10 dB HL at half-octave frequencies measured using tracking audiometry between 250 and 8000 Hz, and a "desirable" OAE profile. OAE screening involved recording of spontaneous OAEs (SOAEs) as well as DPOAEs recorded using stimulus levels of 65 dB SPL and a stimulus-frequency ratio (f_2/f_1) of 1.225; DPOAE results were considered "desirable" when the signal-to-noise ratio between DPOAE-level maxima and the noise floor was approximately 20 dB or greater and distinct fine structure was observed in some frequency ranges. The presence or absence of SOAEs was not used to determine eligibility, but the frequency of the SOAE(s) when present was considered during an examination of the DPOAE fine structure. Subjects were seated comfortably in a recliner inside a double-walled IAC sound chamber for the experimental sessions, that lasted approximately 2 h each.

All experiments were conducted using custom designed software developed in the laboratory running on a NeXT workstation. Signals generated on the computer were passed through a set of TDT PA4 programmable attenuators and a HB6 headphone buffer before being fed to a set of ER2 tube phones. The signals were delivered to the subjects ear canal from the tube phones through a ER10B microphone probe assembly. Signals recorded in the ear canal by the ER10B microphone were passed through the microphone's preamplifier and a battery-operated Stanford Research SR560 low-noise amplifier/filter. The output of the SR560 was digitized using a Singular Solutions AD64x at a sampling rate of 44 100 Hz before being stored on the hard disk of the NeXT computer for offline analysis. The ER10B probe was fitted to the subject's ear using a GSI emittance probe tip matched in size to the ear canal. Stimulus levels were calibrated in a Zwislocki coupler and system distortion, measured in an aluminum 2 cm^3 coupler, was generally below -30 dB SPL in the frequency range of interest for the highest stimulus levels used.

Extensive DPOAE recordings were obtained at various stimulus levels and frequency ratios from three subjects who satisfied the above mentioned inclusion criteria. The following stimulus frequency ratios were used: 1.053, 1.065, 1.08, 1.11, 1.14, 1.18, 1.22, 1.26, 1.30, 1.32, 1.34, and 1.36. Three equal-level stimulus pairs ($L_1=L_2=45$, 65, 75 dB SPL) were used to record data. Additionally, several L_2 (45, 50, 55, and 60 dB SPL) were used in conjunction with an L_1 of 65 dB SPL. The choice of stimulus levels was made to cover a range of input levels. A comprehensive range of stimulus-frequency ratios were chosen consistent with our principal aim—examination of DPOAE-component characteristics as a function of stimulus-frequency ratio. The choice of stimulus levels was less rigorous, and was made simply to provide a range of unequal and equal level inputs. A resolution of 0.025 mm based on the Greenwood map (Greenwood, 1990) was used for frequency spacing. This resulted in approximate frequency resolutions of 4 Hz around 1500 Hz and 8 Hz around 2500 Hz. Each fine structure period was sampled by 16 data points. The fixed-ratio data sets were converted from the frequency domain to the time domain using a custom designed IFFT algorithm and the DPOAE components were isolated using time windowing (Stover *et al.*, 1996; Knight and Kemp, 2001; Kalluri and Shera, 2001; Konrad-Martin *et al.*, 2001). The reader is directed to Dhar *et al.* (2002) for a complete description of the IFFT algorithm and the time-windowing protocol. An example of the transformations used in estimating DPOAE-component magnitudes for subject AE is displayed in Fig. 1.

Frequency domain amplitude and phase data (Fig. 1; panel A) were processed through an IFFT protocol to yield a time-domain representation (Fig. 1; panel B). These data were time windowed to isolate the generator and reflection components. Each component was then converted back to the frequency domain (Fig. 1; panel C). Note that the limits of our time-domain filters were chosen to isolate the principal DPOAE components only. Specifically, the upper limit of the second window was carefully selected, thereby attempting to eliminate any "contamination" of the reflection component by subsequent intracochlear reflections. In practice, subsequent reflections, when present, were analyzed using independent filters; those data, irrelevant to the current issue, are not presented here. The magnitudes of the components, obtained from the reconstructed frequency spectra, were sampled every 24 Hz to yield an average value for each stimulus condition.
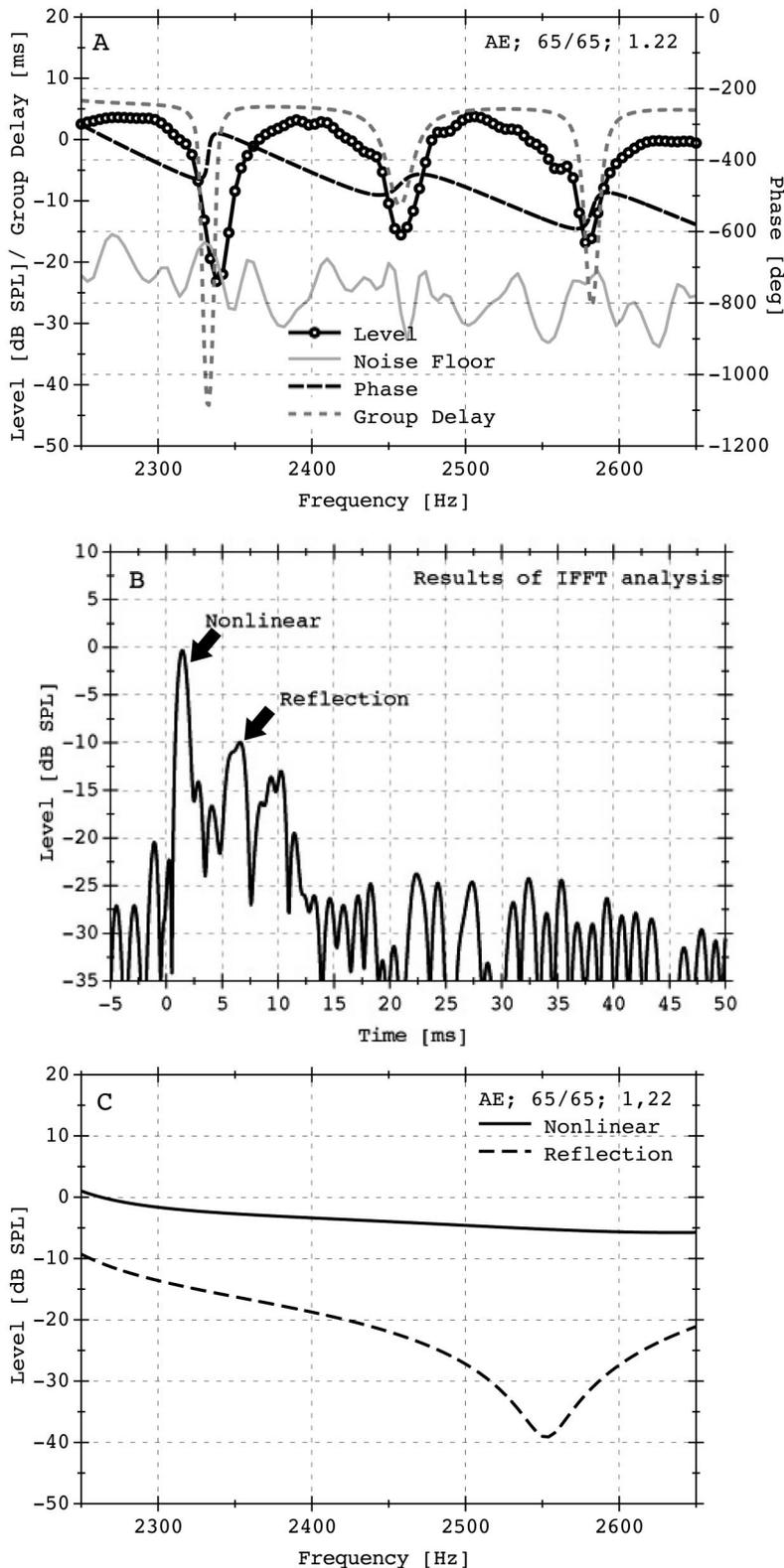
FIG. 1. An example of the process followed to determine magnitudes of DPOAEs components. DPOAE amplitude, phase, group delay, and noise floor are displayed in panel A for subject AE ($L_1 = L_2 = 65$ dB SPL; $f_2/f_1 = 1.22$). These data were processed through an IFFT algorithm to transform them to the time domain. The results of the IFFT analysis for these data are presented in panel B. The components were isolated in time and converted back to the frequency domain (panel C). DPOAE component magnitudes were estimated from these frequency-domain data.

B. Statistical Methods

A repeated measures multifactor analysis of variance (MANOVA) was performed to evaluate the effect of stimulus parameters on component magnitudes. While the magnitudes of the individual components served as dependent variables, stimulus level and frequency ratio were the independent variables. Frequency was used as an observational variable as we recorded data over different frequency ranges for the three subjects to maximize the observation of fine structure, and hence was not included in the model. Separate analyses were performed for the generator and reflection components to avoid interfering with the orthogonality of the models as

J. Acoust. Soc. Am., Vol. 117, No. 6, June 2005

Dhar *et al.*: Distortion product components and f2/f1   3769

independence of the two components could not be easily established. DPOAE-component magnitudes were studied between 2250 and 2650 Hz for subject AE, between 1550 and 1950 Hz for subject CZ, and between 1800 and 2200 Hz for subject KT.

III. RESULTS

A. General results

The main effects of subject ($F = 125.9$, $df = 2$), stimulus level ($F = 483.89$, $df = 6$), stimulus-frequency ratio ($F = 198.27$, $df = 11$) and the interaction of level and ratio ($F = 13.19$, $df = 63$) on the generator component (A_{gen}) were all highly significant ($p < 0.0001$). A similar analysis for the reflection component (A_{ref}) also showed highly significant ($p < 0.0001$) main effects of subject ($F = 597.99$, $df = 2$), stimulus level ($F = 171.68$, $df = 6$), stimulus-frequency ratio ($F = 109.16$, $df = 11$), and the interaction between level and ratio ($F = 9.34$, $df = 63$). Note that data recorded with all stimulus conditions with the exception of $L_1 = L_2 = 45$ dB SPL, $f_2/f_1 > 1.3$ were included in these statistical analyses. Each subject showed differences in the relative amplitudes of the two components across frequency. Interactions between the variable subject and other independent variables were not included in the model as different subjects contributed data from different frequency ranges. Thus, the effects of frequency and subject could not be isolated in this model.

B. Effects of stimulus frequency ratio

The results of a Tukey Studentized Range (HSD) (Inc., 1999) test comparing mean values of A_{gen} and A_{ref} for different stimulus-frequency ratios are presented in Table I. The top and bottom halves of the table present comparisons for A_{gen} and A_{ref}, respectively. While the last two columns of Table I present the computed means for each ratio and rank them in descending order, the initial columns show their Tukey letter groupings. Means sharing the same letter grouping were not significantly different ($\alpha = 0.05$). Thus, the mean values of A_{gen} for stimulus ratios 1.22, 1.18, and 1.26 *did* differ significantly from each other as they have different letter groupings (A, B, and C in this case). However, A_{gen} means for 1.14, 1.32, and 1.11 share the same letter grouping (D) and hence *do not* differ significantly. This is suggestive of a fairly symmetrical bandpass shape. A_{gen} was highest for a ratio of 1.22, while A_{ref} was highest for 1.11. Additionally, the ratios generating the four highest values of A_{ref} *did not* differ significantly from each other, consistent with an asymmetric bandpass shape and/or greater variability between ears and across frequency within a given ear. The lowest values of A_{gen} and A_{ref} were generated at narrow and wide ratios, respectively. The strong statistical overlap between ratios generating high A_{ref} contrasted with the significant differences between 1.22, 1.18, and 1.26 for A_{gen} provides an indication of distinct differences between the magnitude functions for the two components.

Mean values for A_{gen} and A_{ref} for different ratios, collapsed across subjects, frequency, and stimulus levels, are presented in Fig. 2. The solid lines represent A_{gen}, while the dashed lines represent A_{ref}. The error bars represent ± 1

TABLE I. Results of the Tukey Studentized Range (HSD) test for generator (A_{gen}) and reflection (A_{ref}) components for the independent variable ratio. The results are in accordance with the following parameters: $\alpha = 0.05$, $df = 2724$, MSE = 33.234 91 (A_{gen}) and 36.228 47 (A_{ref}), Minimum significant difference = 1.7495 (A_{gen}) and 1.8266 (A_{ref}). Ratios at the extema *(1.053, 1.36)* and midpoint (**1.22**) of the distribution are specially marked; note the different positions of these ratios in the rank hierarchy.

Results for generator component A_{gen}

Tukey grouping	Mean	Ratio
A	−2.8184	**1.22**
B	−4.6063	1.18
C	−7.4451	1.26
D	−10.0574	1.14
E D	−10.3632	1.32
E D	−11.7540	1.11
E	−11.8192	1.30
F	−14.3388	1.34
G F	−16.0069	1.08
G	−16.1129	*1.36*
H	−19.0315	1.065
H	−19.3439	*1.053*

Results for reflection component A_{ref}

Tukey grouping	Mean	Ratio
A	−8.6516	1.11
A	−8.8938	1.18
B A	−9.9972	1.14
B A	−10.1653	**1.22**
C B	−11.3941	1.08
C	−12.0360	1.065
C	−12.2809	*1.053*
D	−14.5252	1.32
D	−15.7227	1.26
E D	−16.2043	1.30
E	−17.8815	1.34
F	−20.8783	*1.36*

standard error. The lighter lines represent means calculated from the entire dataset, while the darker lines represent means calculated from the dataset after excluding data for stimulus levels of $L_1 = L_2 = 45$ dB SPL. Data could not be recorded at all ratios for stimulus levels of 45/45 dB SPL, which resulted in a disparity in cell sizes for different ratios. Consequently, data acquired for stimulus levels of $L_1 = L_2 = 45$ dB SPL were excluded from subsequent plots where data were collapsed across stimulus levels. Data with and without DPOAEs recorded with stimulus levels of $L_1 = L_2 = 45$ dB SPL are presented in Fig. 2 to enable a comparison.

An examination of Fig. 2 reveals that the exclusion of data for stimulus levels of 45 dB SPL causes an upward shift of the traces at the ratios where we were able to record data at 45 dB, without significantly altering the slopes or the peak ratios for either A_{gen} or A_{ref}. The inclusion of DPOAEs recorded with stimulus levels of 45 dB SPL affected the curve for A_{gen} to a greater degree. The A_{gen} ratio function appears narrower and more peaked than that of A_{ref}. A_{ref} is higher than A_{gen} at narrow ratios and the two functions cross between the ratios of 1.11 and 1.14. The A_{gen} ratio function peaks around a ratio of 1.22. The two functions approach each other at ratios of greater than 1.3.

A_{gen} and A_{ref} for individual subjects are displayed in Fig. 3. In keeping with the general trend seen in Fig. 2, A_{ref} is

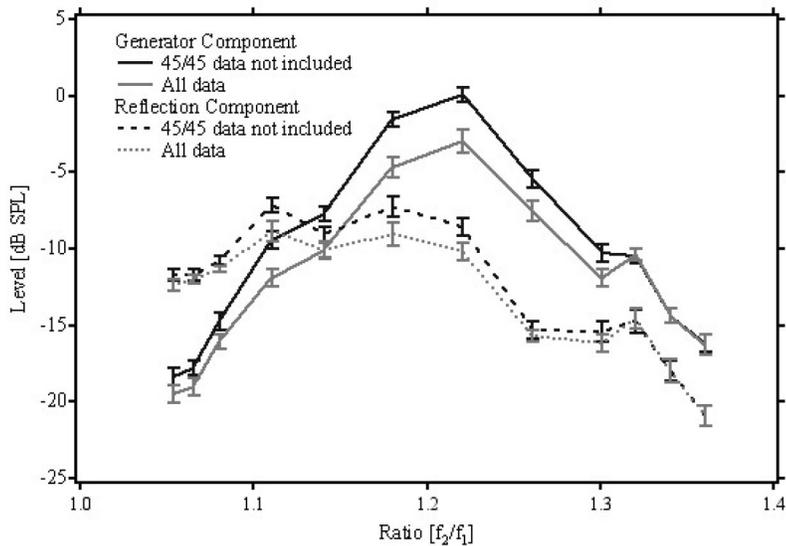Dhar *et al.*: Distortion product components and f2/f1

FIG. 2. Magnitude of DPOAE components as a function of the changing stimulus-frequency ratio. The solid and dashed lines indicate the magnitude of the generator (A_{gen}) and reflection (A_{ref}) components, respectively. The lighter lines represent means calculated on the entire dataset. The darker lines represent means calculated after excluding data points recorded with stimulus levels of $L_1 = L_2 = 45$ dB SPL. The error bars on all traces represent ± 1 standard error.
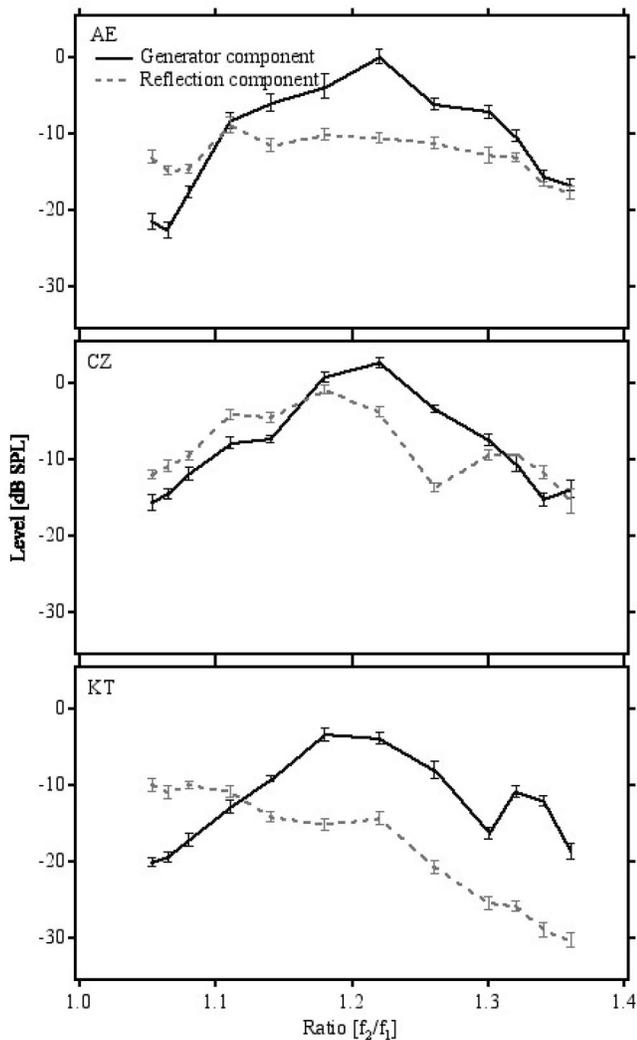

FIG. 3. Component magnitudes for subjects AE, CZ and KT with changing stimulus-frequency ratio. Data panels are marked with the subjects' initials. Solid and dashed lines represent A_{gen} and A_{ref}, respectively. Data used for these plots do not include those obtained with stimulus levels of 45 dB SPL. The error bars signify ± 1 standard error.

higher than A_{gen} at narrow ratios and the A_{gen} exhibits a bandpass characteristic in all subjects. A_{ref} is bandpass for subjects AE and CZ, but low pass for subject KT. Some additional differences between subjects can be observed by comparing the three panels of Fig. 3. In subject CZ, A_{ref} is more peaked compared to the other subjects. This results in a shift in the ratio at which the two traces cross over. While the crossover occurs around 1.11 for subjects AE (top panel) and KT (bottom panel), the crossover ratio is around 1.14 for subject CZ (middle panel). A_{gen} and A_{ref} show relative equivalence at high ratios for subjects AE and CZ, in keeping with the general trend seen in Fig. 2. While A_{ref} is larger than A_{gen} in subject CZ at these ratios (≥ 1.3), A_{gen} remains substantially larger than A_{ref} at high ratios for subject KT. A comparison of the three panels of Fig. 3 also reveals relative equivalence in the pattern and level of A_{gen} between the subjects. However, A_{ref} is very different for the three subjects, with A_{ref} being largest for subject CZ, followed by subject AE and KT.

A_{gen} and A_{ref} for different stimulus levels are presented in Fig. 4. Data for equal stimulus levels are presented in the left column, while the panels in the right column display data for unequal stimulus levels ($L_1 = 65$ and $L_2 = 45, 50, 55, 60,$ and 65 dB SPL). While the general trends observed in the previous two figures are present, some significant variations with the stimulus level are noticable. The differences between A_{gen} and A_{ref} are less pronounced across the entire ratio range for stimulus levels of 65/55 and 65/60. Both A_{gen} and A_{ref} appear less peaked for stimulus levels of 45/45. Finally, A_{ref} remains consistently higher than A_{gen} across the entire ratio range for the lowest stimulus levels used (45 dB SPL). In contrast, little change is observed in A_{ref} at the highest stimulus levels used (75 dB SPL), with A_{gen} remaining higher than A_{ref} at wide ratios.

IV. DISCUSSION

By separating the ear-canal DPOAE signal into its two major components, we have been able not only to investigate the relative levels of the two components, but also to better
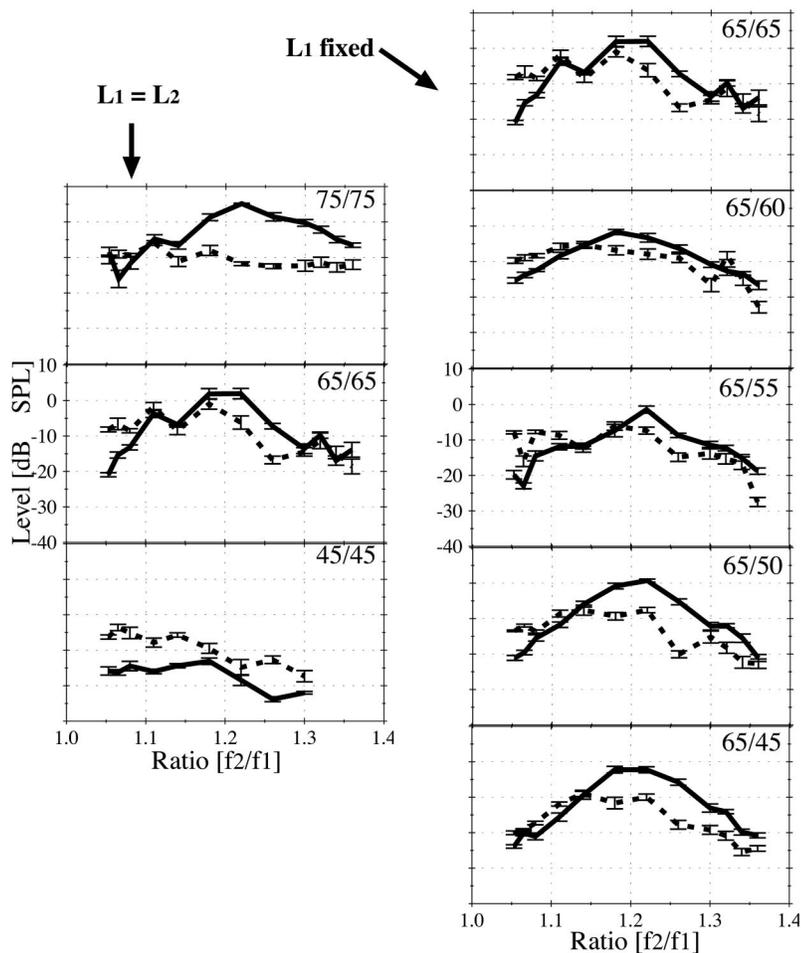
FIG. 4. A_{gen} and A_{ref} for different stimulus-level combinations as a function of the changing stimulus-frequency ratio. Solid and dashed lines represent A_{gen} and A_{ref}, respectively. The error bars signify ± 1 standard error.

understand the properties of each component. While the generator component (A_{gen}) when plotted as a function of the stimulus-frequency ratio showed a distinct bandpass shape with a peak near $f_1/f_2 \approx 1.2$ for all stimulus levels except 45/45 dB SPL, the pattern for the reflection component (A_{ref}) was more variable with the stimulus level and across ears. One of the most striking characteristics of the results is the stability of the generator component and the variability of the reflection component across ears. The influence of stimulus level on absolute and relative component levels is also found to be significant. We begin with a discussion of our data in the context of previous DPOAE publications and then explore the relationship of these data with basilar membrane mechanics. We conclude with some observations about the choice of stimulus parameters for the current clinical applications of DPOAEs.

A. Comparison with previous DPOAE results

The pattern we see in A_{gen} is similar to previous reports of the magnitude of the ear-canal DPOAE signal, when plotted as a function of the stimulus-frequency ratio (Harris *et al.*, 1989; Gaskill and Brown, 1990; O'Mahoney and Kemp, 1995; Stover *et al.*, 1999). Another notable feature in these reports was the presence of a notch in the DPOAE level around a stimulus-frequency ratio of 1.1 in human ears (e.g., Stover *et al.*, 1999). This notch has been interpreted as being due to the cancellation between the two DPOAE com-

ponents when they are roughly equal in magnitude but almost 180° out of phase. In the few studies where amplitudes of the generator and reflection components, A_{gen} and A_{ref}, respectively, were extracted, the former exhibited bandpass behavior as a function of f_2/f_1 and the latter a low-pass or asymmetric bandpass behavior (Knight and Kemp, 1999, 2000, 2001). A_{ref} was $>A_{gen}$ for $f_2/f_1 < 1.1$ in humans (Knight and Kemp, 1999, 2000, 2001) and ≈ 1.2 in guinea pigs (Schneider *et al.*, 2003).

Before making more in-depth comparisons of our data with previous studies, some significant differences in methodology should be pointed out. While our recordings were made using repeated measures with f_2/f_1 fixed for each recording, Schneider *et al.* (2003) used a fixed-f_2 paradigm and estimated the relative dominance of the two components from group delay. Similarly, Konrad-Martin *et al.* (2001) also used a fixed-f_2 paradigm but extracted DPOAE component levels using an IFFT algorithm from the ratio function, resulting in data collapsed across frequency as well as stimulus-frequency ratio. This methodology served the purpose of their work—the examination of DPOAE component levels as a function of the stimulus level; but poses problems in direct comparison with our data. Perhaps most similar to our work in DPOAE-recording methodology are the reports by Knight and Kemp (2000, 2001), who also used IFFT analyses of results from fixed-ratio sweeps. However, signifi-

cant differences in stimulus levels used and the implementation of time-domain filters exist even here. Knight and Kemp use a narrow time window to isolate the (early latency) generator component and associate the reflection component with the accumulated signal that occurs after the early-latency one. In contrast, we use narrow time windows to isolate both the generator and the shortest-latency reflection components. This difference in approach influences the estimate of the reflection component significantly, since the wide time window used by Knight and Kemp allows the inclusion of secondary reflection components due to multiple internal reflections between the stapes and the DP CF region (Dhar *et al.*, 2002). The behavior of A_{gen}, observed here to be similar across subjects, is in close agreement with Knight and Kemp. However, we report much greater variability in the behavior of A_{ref} across subjects and demonstrate interesting effects of stimulus level on DPOAE components that have not been reported before.

Our results indicate a significant influence of stimulus level on the absolute and relative levels of the two components. Although Konrad-Martin *et al.* (2001) and Mauermann and Kollmeier (2004) have examined the effect of stimulus level on DPOAE component behavior in the past, it is difficult to isolate the effect of the stimulus-frequency ratio from that of the stimulus level in these studies. Both these groups use the "scissor" approach where the level difference between the stimulus tones is governed by a linear regression model (Kummer *et al.*, 1998; Janssen *et al.*, 1998), the difference decreasing with an increasing overall level. Additionally, Konrad-Martin *et al.* (2001) also report data recorded with a fixed level difference ($L_1 - L_2 = 10$). Knight and Kemp (2000, 2001) used stimulus levels of 75 dB SPL only. In contrast, we have reported results for both equal- and unequal-level stimulus tones over a wide range (45–75 dB SPL). Our results are consistent with previous reports in that the reflection component is shown to be dominant at low stimulus levels only. Furthermore, we have also shown the dominance of A_{ref} to be consistent across the entire range of stimulus-frequency ratios tested at these levels.

Our results are loosely consistent with the previous measurements cited above for $f_2/f_1 < 1.3$ (Fig. 2). However, they differ from those of Knight and Kemp for $f_2/f_1 > 1.3$ in that A_{gen} and A_{ref} do not "roll off" together [see Fig. 5 of Knight and Kemp (2001)]. The relative behavior of A_{gen} and A_{ref} at these ratios is heavily dependent on the subject in our data (Fig. 3). A_{ref} is significantly lower than A_{gen} for subject KT, and the two component levels are more or less equivalent, with A_{gen} being slightly larger for subject AE. In subject CZ, A_{ref} is larger than A_{gen} at ratios >1.3. Thus, we see great variability in A_{ref} across subjects at these ratios. A_{gen} exhibits a bandpass behavior—with symmetric behavior on both sides of a peak around a ratio of 1.2, while the behavior of A_{ref} in most cases is asymmetric if bandpass or even low pass, with very little rolloff at narrow ratios. It is also noteworthy that our results are in close agreement with that obtained by Knight and Kemp, when data recorded with equivalent stimulus levels (e.g., 75/75 dB SPL) are compared.

The time-intensive experiments necessary to produce

data on DPOAE components has limited the number of participant ears in our as well as previous reports. It is not surprising then that the variety of behavior in A_{ref} has gone unreported in the past. Our purely fortuitous sampling of ears appears to show greater diversity in this area as compared to previous subject pools. It is curious that the rank ordering observed in A_{ref} is consistent with other measures such as hearing thresholds and fine-structure depth. Although all three subjects demonstrated hearing sensitivity within normal limits, CZ had the best thresholds (coarsely measured using 5 dB steps and a clinical protocol), followed by AE and then KT. Fine-structure depth was the greatest in CZ and least in KT.

B. Comparison with psychophysical and physiological results

Insight into the behavior of DPOAE components may also be obtained by examining psychophysical and physiological data. The DP at $2f_1 - f_2$, often referred to as the *cubic distortion tone* (CDT) in the physiological literature, has been examined by recording basilar membrane vibration at the CF place for $2f_1 - f_2$ (see Robles and Ruggero, 2001, for a recent review). Termed the *cubic distortion tone* or the *combination tone* at $2f_1 - f_2$ in the psychophysics literature, this DP has also been studied using cancellation as well as loudness-matching techniques (see Plomp, 1976). Recordings of basilar-membrane motion of the CDT have been reported from guinea pig [basal turn and hook, Cooper and Rhode (1997)] and chinchilla [apical turn, Cooper and Rhode (1997); basal turn Robles *et al.* (1997)] ears. The results depend on the stimulus level as well as the location of the preparation along the length of the cochlea. General observations from these data include a plateau in DP level as a function of increasing stimulus-frequency ratio up to a "corner ratio" and a sharp rolloff as stimulus-frequency ratio is increased beyond this critical ratio. The "corner ratio" is approximately dependent on stimulus level and the location in the cochlea. On occasion, a rolloff in the DP level as the stimulus-frequency ratio approaches 1 is observed. This rolloff is perhaps most-prominent in the hook and base regions as well as for higher stimulus levels (Cooper and Rhode, 1997). The reader is directed to Figures 4g–i of Cooper and Rhode (1997) and 6 and 7 of Robles *et al.* (1997). Note that these figures appear contrary at first glance, with the discrepancy resolved by accounting for the fact that Cooper and Rhode (1997) display the level of the DP relative to that of the lower-frequency stimulus tone. The cutoff ratio was highest and the slope the least steep for the recordings from the apical turn of the chinchilla cochlea.

The results from psychophysical experiments appear to be largely dependent on the method used for an estimation of the combination tone. A monotonic low-pass shape is observed with the use of the cancellation method (Goldstein, 1967), where the stimulus and cancellation tones are presented simultaneously. However, with the use of a nonsimultaneous pulsation technique, the combination tone appears to display an asymmetric bandpass shape (Smoorenburg, 1974; Siegel and Borneman, 1999), much akin to that observed in DPOAE and physiological data.

Prior to the emergence of DPOAE-component data, the discordance between the magnitudes of DPOAEs and basilar membrane motion as a function of the stimulus-frequency ratio was a source of concern. Indeed, Robles *et al.* (1997) contrast the lack of reduction in the level of $2f_1-f_2$ as f_2/f_1 approaches 1 in basilar-membrane measurements with that observed for DPOAEs. However, the more appropriate comparison of the DPOAE level with physiological or psychophysical data is made using A_{ref} rather than the ear-canal DPOAE level. Once the appropriate comparison is made, data from the basilar-membrane, psychophysical, and OAE domains appear to be in approximate qualitative agreement. It should be noted that to expect exact correspondence between data from these three domains is unrealistic due to differences in experimental conditions, and perhaps more importantly, the actual variables being measured. Whether the CDT measured directly on the basilar membrane, or the combination tone measured psychophysically, is equivalent to the reflection component of the DPOAE at $2f_1-f_2$ is an interesting question in itself. Even after the simplifying assumption of a transparent middle ear is made, the equivalence between these quantities would depend on the exact nature of the mechanism by which the incident DPOAE energy is "turned around" at the DPOAE-CF region. For example, Kemp's recent proposal of dichotomous *active* and *passive* reflectance mechanisms (Kemp, 2002) would alter whether the reflection term is "accounted for" in physiological and psychophysical measurements. However, it can be said with some confidence that measurements in all three domains represent some common aspects of peripheral auditory physiology.

C. Component magnitudes and basilar membrane mechanics

We discuss here the behaviors of both A_{gen} and A_{ref} in terms of cochlear models of DPOAEs [see Sec. V of Talmadge *et al.* (1998); and Shera (2003) for much greater model detail]. In the following greatly simplified discussion, we ignore details such as mutual suppression of the stimulus frequency waves when f_2/f_1 is close to 1, and focus on other factors that determine the gross variation of A_{gen} and A_{ref} with stimulus frequency ratio. A comparison with data would suggest that mutual suppression of the stimulus frequency waves mostly influence the behavior of A_{ref} for ratios close to 1.

For the case of a simple cubic nonlinearity, A_{gen} will be approximately proportional to the magnitude of an integral over the $2f_1-f_2$ sources. The integrand of the integral is proportional to the square of the apical-moving f_1 cochlear wave times the complex conjugate of the apical-moving f_2 cochlear wave times the $2f_1-f_2$ apical-moving cochlear wave [see Eqs. (130) through (136) in Talmadge *et al.* (1998)]. The expression for A_{ref} involves the magnitude of the product of R_a (the apical reflectance that results from coherent reflection of a cochlear wave due to cochlear roughness around the DP tonotopic site) times an integration over sources that is essentially the same as the one for A_{gen}, except that the basal-moving DP wave replaces the apical-moving one in the integrand. For large f_2/f_1, both A_{gen} and

A_{ref} decrease with increasing frequency ratio largely due to the decrease of overlap between the activity patterns of the two stimulus waves.

When f_2/f_1 is close to 1, the magnitude of the source integrations for A_{gen} and A_{ref} are mainly determined by contributions from around the f_2 tonotopic site ($\hat{x}_2$). The frequency ratio that will give the largest value of A_{gen} will then be approximately the value that minimizes the variation of the phase of the integrand with distance x along the BM in the region of $x \approx \hat{x}_2$ (the principle of the stationary phase). This phase condition can be simply expressed as (Talmadge *et al.*, 1998):

$$\hat{k} - 2k(\hat{x}_2,f_1) - k(\hat{x}_2,2f_1-f_2) = 0, \tag{2}$$

where $\hat{k}$ is the wave number of a cochlear wave in its peak region (constant in a scale-invariant cochlea) and $k(x,f)$ is the wave number of a cochlear wave of frequency f at location x. The dependences of $k(\hat{x}_2,f_1)$ and $k(\hat{x}_2,2f_1-f_2)$ on f_2/f_1 are estimated in Talmadge *et al.* (1998), where it is also shown that

$$A_{gen} \approx \cdots \exp\{-(\sigma_x^2/2)[\hat{k} - 2k(\hat{x}_2,f_1) - k(\hat{x}_2,2f_1-f_2)]^2\}, \tag{3}$$

where σ_x is a measure of the spatial width of the peak of the cochlear activity pattern. As f_2/f_1 increases from 1, the expression on the left side of Eq. (2) starts out negative and increases through zero. These considerations then imply that A_{gen} as a function of f_2/f_1 has bandpass behavior, in agreement with data presented previously as well as here.

Now consider A_{ref}. Using an approach similar to the one just discussed, it can be shown that

$$A_{ref} \approx \cdots |R_a| \exp\{-(\sigma_x^2/2)[\hat{k} - 2k(\hat{x}_2,f_1)$$
$$+ k(\hat{x}_2,2f_1-f_2)]^2\}. \tag{4}$$

As f_2/f_1 increases from 1, the quantity,

$$\hat{k} - 2k(\hat{x}_2,f_1) + k(\hat{x}_2,2f_1-f_2), \tag{5}$$

in Eq. (4) can be shown to start out positive or negative and increase with increasing ratio. If the value is initially positive, A_{ref} will monotonically decrease with increasing f_2/f_1, resulting in a low-pass shape (similar to that observed for subject KT in Fig. 3). On the other hand, when the value is initially negative, it is still greater than the quantity on the left-hand side of Eq. (2). In this case, A_{ref} will assume an asymmetric bandpass shape with the peak at a ratio less than the peak ratio for A_{gen} (similar to that observed for subject CZ in Fig. 3). Additionally, this relationship leads to the prediction of $A_{ref} > A_{gen}$ as f_2/f_1 increases from 1, given a reasonable magnitude of R_a. A_{ref} is predicted to be equal to A_{gen} (and possibly give rise to a notch behavior in the DPOAE amplitude under the requisite phase-cancellation conditions) for a ratio (typically around 1.1 in our data) smaller than the peak ratio for A_{gen} (typically around 1.2), in agreement with the data of Figs. 2, 3, 4.

From Eqs. (3) and (4), we see that

$$A_{ref}/A_{gen} \approx |R_a| \exp\{(2\sigma_x^2)k(\hat{x}_2,2f_1-f_2)$$
$$\times [\hat{k} - 2k(\hat{x}_2,f_1)]\}. \tag{6}$$

It should be emphasized that R_a, according to the coherent reflection model (Zweig and Shera, 1995; Talmadge *et al.*, 1998; Shera, 2003), depends mainly on the sharpness of tuning of the BM around the DP CF region and the strength of cochlear inhomogeneities around that region. R_a will generally be significant only if both of these factors are present. Thus R_a is expected to fluctuate significantly across healthy ears due to differences in the degree of cochlear roughness across such ears. It is therefore not surprising that the relative levels of A_{gen} and A_{ref} are found to change from ear to ear for $f_2/f_1 > 1.3$ and across frequency within a given ear (see Fig. 1).

In sum $A_{ref} > A_{gen}$ at narrow ratios, overcoming the suppressive effects of the stimulus tones on R_a. This observation is in contrast to the assumption of bidirectional distribution of energy from the generation region (e.g., Allen and Fahey, 1992). Thus, Shera's (2003) assertion that phase appears to "win" in the battle between amplitude and phase in the overlap region can perhaps be confidently extended; not only does phase win, it appears to win by a landslide. The behavior of A_{ref} at wide stimulus-frequency ratios is strongly influenced by R_a. We provide two lines of evidence in support of R_a being the driving force behind the behavior of A_{ref} at wide ratios. First, with an (assumptive) correlation between cochlear health and reflectance, we argue that the rank ordering of A_{ref}, hearing thresholds, and fine-structure depth in our three subjects is not coincidental but due to varying degrees of reflectance in these ears. Second, the influence of R_a on A_{ref} is evident in Fig. 4 where A_{ref} remains larger than A_{gen} for all stimulus-frequency ratios for stimulus levels of 45 dB SPL, due to reduced suppression by the lower-level stimulus tones. The influence of stimulus level on A_{ref} has also been demonstrated elsewhere (Mauermann and Kollmeier, 2004; Konrad-Martin *et al.*, 2001).

We have thus seen that most of the characteristic features of A_{gen} and A_{ref} that we find are at least qualitatively described by cochlear models that incorporate a nonlinear generation process around the f_2 CF region combined with the coherent reflection of the initial apical-moving DP component.

D. Clinical implications

We conclude by making some observations about the relationship between A_{gen} and A_{ref} when stimulus levels (L_1/L_2 in dB SPL) of 65/50 and 65/55 are used. A stimulus-level combination of 65/55 at a stimulus-frequency ratio of 1.2 is often used in clinical applications of DPOAEs. There has been some recent work speculating that DPOAE fine structure is (at least partially) responsible for the failure of DPOAEs in predicting hearing thresholds with accuracy (Shaffer *et al.*, 2003; Shera, 2004; Dhar and Shaffer, 2004). If this speculation was valid and the goal of a clinical protocol was to record DPOAEs with the minimum possible fine structure, stimulus conditions that lead to the biggest difference between A_{ref} and A_{gen} should be chosen. More specifically, the ideal stimulus conditions should bias the ear-canal DPOAE signal toward A_{gen} to the greatest extent possible, if the goal is to monitor cochlear health around the f_2 CF region. Our data appear to suggest that stimulus-frequency ra-

tios around 1.22 satisfy these demands to a great extent, with the exception that a stimulus-frequency ratio of 1.26 leads to similar if not greater bias toward the generator component when stimulus levels of 65/50 are chosen. Considerations such as a good signal-to-noise ratio and the separation between normal and impaired populations also influence the choice of stimulus conditions in a clinical protocol. However, our results indicate that the current choice of stimulus parameters in clinical protocols mostly satisfies the consideration of relative component levels.

Allen, J. B., and Fahey, P. F. (**1992**). "Using acoustic distortion products to measure the cochlear amplifier gain on the basilar membrane," J. Acoust. Soc. Am. **92**, 178–188.

Cooper, N. P., and Rhode, W. S. (**1997**). "Mechanical responses to two-tone distortion products in the apical and basal turns of the mammalian cochlea," J. Neurophysiol. **78**, 261–270.

Dhar, S., and Shaffer, L. A. (**2004**). "Effects of a suppressor tone on distortion product otoacoustic emissions fine structure: Why a universal suppressor level is not a practical solution to obtaining single-generator DP-grams," Ear Hear. **25**, 573–585.

Dhar, S., Talmadge, C., Long, G., and Tubis, A. (**2002**). "Multiple internal reflections in the cochlea and their effect on DPOAE fine structure," J. Acoust. Soc. Am. **112**, 2882–2897.

Gaskill, S. A., and Brown, A. M. (**1990**). "The behavior of the acoustic distortion product, $2f_1 - f_2$, from the human ear and its relation to auditory sensitivity," J. Acoust. Soc. Am. **88**, 821–839.

Goldstein, J. L. (**1967**). "Auditory nonlinearity," J. Acoust. Soc. Am. **41**, 676–689.

Greenwood, D. D. (**1990**). "A cochlear frequency position function for several species—29 years later," J. Acoust. Soc. Am. **87**, 2592–2605.

Harris, F. P., Lonsbury-Martin, B. L., Stagner, B. B., Coats, A. C., and Martin, G. K. (**1989**). "Acoustic distortion products in humans: Systematic changes in amplitude as a function of f_2/f_1 ratio," J. Acoust. Soc. Am. **85**, 220–229.

Heitmann, J., Waldmann, B., Schnitzler, H. U., Plinkert, P. K., and Zenner, H. P. (**1998**). "Suppression of distortion product otoacoustic emissions (DPOAE) near $2f_1 - f_2$ removes DP-gram fine structure—evidence for a secondary generator," J. Acoust. Soc. Am. **103**, 1527–1531.

Janssen, T., Kummer, P., and Arnold, W. (**1998**). "Growth behavior of the $2f_1 - f_2$ distortion product otoacoustic emission in tinnitus," J. Acoust. Soc. Am. **103**, 3418–3429.

Kalluri, R., and Shera, C. A. (**2001**). "Distortion-product source unmixing: A test of the two-mechanism model for dpoae generation," J. Acoust. Soc. Am. **109**, 622–637.

Kemp, D. T. (**1986**). "Otoacoustic emissions, travelling waves and cochlear mechanisms," Hear. Res. **22**, 95–104.

Kemp, D. T. (**2002**). *Exploring Cochlear Status With Otoacoustic Emissions: The Potential For New Clinical Application*, edited by M. Robinette and T. Glattke, Thieme, New York.

Kim, D. O. (**1980**). "Cochlear mechanics: Implications of electrophysiological and acoustical observations," Hear. Res. **2**, 297–317.

Knight, R. D., and Kemp, D. T. (**1999**). "Relationship between DPOAE and TEOAE characteristics," J. Acoust. Soc. Am. **106**, 1420–1435.

J. Acoust. Soc. Am., Vol. 117, No. 6, June 2005

Dhar *et al.*: Distortion product components and f2/f1   3775

Knight, R. D., and Kemp, D. T. (**2000**). "Indications of different distortion product otoacoustic emission mechanisms from a detailed f_1, f_2 area study," J. Acoust. Soc. Am. **107**, 457–473.

Knight, R. D., and Kemp, D. T. (**2001**). "Wave and place fixed DPOAE maps of the human ear," J. Acoust. Soc. Am. **109**, 1513–1525.

Konrad-Martin, D., Neely, S., Keefe, D., Dorn, P., Cyr, E., and Gorga, M. (**2002**). "Sources of DPOAES revealed by suppression experiments, inverse fast Fourier transforms, and SFOAES in impaired ears," J. Acoust. Soc. Am. **111**, 1800–1809.

Konrad-Martin, D., Neely, S. T., Keefe, D. H., Dorn, P. A., and Gorga, M. P. (**2001**). "Sources of distortion product otoacoustic emissions revealed by suppression experiments and inverse fast Fourier transforms in normal ears," J. Acoust. Soc. Am. **109**, 2862–2879.

Kummer, P., Janssen, T., and Arnold, W. (**1995**). "Suppression tuning characteristics of the $2f_1 - f_2$ distortion product otoacoustic emission in humans," J. Acoust. Soc. Am. **98**, 197–210.

Kummer, P., Janssen, T., and Arnold, W. (**1998**). "The level and growth behavior of the $2f_1 - f_2$ distortion product otoacoustic emission and its relationship to auditory sensitivity in normal hearing and cochlear hearing loss," J. Acoust. Soc. Am. **103**, 3431–3444.

Long, G. R., Shaffer, L. A., Dhar, S., and Talmadge, C. L. (**1999**). "Cross species comparison of otoacoustic fine-structure," in *Recent Developments in Auditory Mechanics* (World Scientific, Singapore), pp. 367–373.

Mauermann, M., and Kollmeier, B. (**2004**). "Distortion product otoacoustic emission (DPOAE) input/ouput functions and the influence of the second dpoae source," J. Acoust. Soc. Am. **116**, 2199–2212.

Mauermann, M., Uppenkamp, S., Hengel, P. W. J. van, and Kollmeier, B. (**1999**). "Evidence for the distortion product frequency place as a source of distortion product otoacoustic emission (DPOAE) fine structure in humans. II. Fine structure for different shapes of cochlear hearing loss," J. Acoust. Soc. Am. **106**, 3484–3491.

O'Mahoney, C. F., and Kemp, D. T. (**1995**). "Distortion product otoacoustic emission delay measurement in humans," J. Acoust. Soc. Am. **97**, 3721–3735.

Plomp, R. (**1976**). *Aspects of Tone Sensation*, Academic, London.

Ren, T. (**2004**). "Reverse propagation of sound in the gerbil cochlea," Nat. Neurosci. **7**, 333–334.

Robles, L., and Ruggero, M. A. (**2001**). "Mechanics of the mammalian cochlea," Physiol. Rev. **81**, 1305–1352.

Robles, L., Ruggero, M. A., and Rich, N. C. (**1997**). "Two-tone distortion on the basilar membrane of the chinchilla cochlea," J. Neurophysiol. **77**, 2385–2399.

Ruggero, M. A. (**2004**). "Comparison of group delays of $2f_1 - f_2$ distortion product otoacoustic emissions and cochlear travel times," ARLO **5**, 143–147.

Schneider, S., Prijs, V. F., and Schoonhoven, R. (**2003**). "Amplitude and phase of distortion product otoacoustic emissions in the guinea pig in an (f_1, f_2) area study," J. Acoust. Soc. Am. **113**, 3285–3296.

Shaffer, L., Withnell, R., Dhar, S., Lilly, D., Goodman, S., and Harmon, K. (**2003**). "Sources and mechanisms of dpoae generation: Implications for the prediction of auditory sensitivity," Ear Hear. **25**, 367–379.

Shera, C. (**2004**). "Mechanisms of mammalian otoacoustic emission and their implications for the clinical utility of otoacoustic emissions," Ear Hear. **25**, 86–97.

Shera, C. A. (**2003**). "Wave interference in the generation of reflection and distortion-source emissions," in *Biophysics of the Cochlea: From Molecules to Models* (World Scientific, Singapore), pp. 311–320.

Siegel, J. H., and Borneman, A. L. (**1999**). "Comparable measures of perceptual combination tones and distortion-product otoacoustic emissions," in "Abstracts of the association for research in otolaryngology."

Smoorenburg, G. (**1974**). "On the mechanism of combination tone generation and lateral inhibition in hearing," in *Psychological Models and Physiological Facts in Hearing*, edited by E. Zwicker and E. Terhardt (Springer-Verlag, Berlin), pp. 1–10.

Stover, L. J., Neely, S. T., and Gorga, M. P. (**1996**). "Latency and multiple sources of distortion product emissions," J. Acoust. Soc. Am. **99**, 1016–1024.

Stover, L. J., Neely, S. T., and Gorga, M. P. (**1999**). "Cochlear generation of intermodulation distortion revealed by DPOAE frequency functions in normal and impaired ears," J. Acoust. Soc. Am. **106**, 2669–2678.

Talmadge, C. L., Long, G. R., Tubis, A., and Dhar, S. (**1999**). "Experimental confirmation of the two-source interference model for the fine structure of distortion product otoacoustic emissions," J. Acoust. Soc. Am. **105**, 275–292.

Talmadge, C. L., Tubis, A., Long, G. R., and Piskorski, P. (**1998**). "Modeling otoacoustic emission and hearing theshold fine structures in humans," J. Acoust. Soc. Am. **104**, 1517–1543.

Withnell, R. H., Shaffer, L. A., and Talmadge, C. L. (**2003**). "Generation of DPOAES in the guinea pig," Hear. Res. **178**, 106–117.

Zweig, G., and Shera, C. A. (**1995**). "The origins of periodicity in the spectrum of evoked otoacoustic emissions," J. Acoust. Soc. Am. **98**, 2018–2047.