Cochlear nonlinearity in normal-hearing subjects as inferred psychophysically and from distortion-product otoacoustic emissions

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(Received 28 April 2008; revised 14 July 2008; accepted 14 July 2008)

The aim was to investigate the correlation between compression exponent, compression threshold, and cochlear gain for normal-hearing subjects as inferred from temporal masking curves (TMCs) and distortion-product otoacoustic emission (DPOAEs) input–output (I/O) curves. Care was given to reduce the influence of DPOAE fine structure on the DPOAE I/O curves. A high correlation between compression exponent estimates obtained with the two methods was found at 4 kHz but not at 0.5 and 1 kHz. One reason is that the DPOAE I/O curves show plateaus or notches that result in unexpectedly high compression estimates. Moderately high correlation was found between compression threshold estimates obtained with the two methods, although DPOAE-based values were around 7 dB lower than those based on TMCs. Both methods show that compression exponent and threshold are approximately constant across the frequency range from 0.5 to 4 kHz. Cochlear gain as estimated from TMCs was found to be ~16 dB greater at 4 than at 0.5 kHz. In conclusion, DPOAEs and TMCs may be used interchangeably to infer precise individual nonlinear cochlear characteristics at 4 kHz, but it remains unclear that the same applies to lower frequencies.
 [DOI: 10.1121/1.2968692]

PACS number(s): 43.64.Jb, 43.66.Dc, 43.64.Ri, 43.64.Bt [BLM] Pages: 2149–2163

I. INTRODUCTION

It is almost certain that our ability to perceive sounds over a 120 dB level range is accomplished via a form of compression that takes place in the basilar membrane (BM) (Bacon, 2004). Listeners with sensorineural hearing loss show reduced auditory dynamic ranges and this is typically interpreted as an indication of reduced cochlear compression. It is controversial, however, that this is actually the case (e.g., Heinz and Young, 2004; Plack *et al.*, 2004; Lopez-Poveda *et al.*, 2005) and yet knowing the degree of residual peripheral compression might help in diagnosing the type of hearing loss as well as improving its treatment with hearing aids. The long-term goal of this work is to design a fast and reliable technique to estimate the degree of *individual* residual compression in listeners with sensorineural hearing loss. This paper describes a first effort to determine whether distortion-product (DP) otoacoustic emission (DPOAE) input/output (I/O) functions could be used for that purpose in normal-hearing listeners. The motivation of the present work is thus similar to that of Müller and Janssen (2004).

There exist several psychoacoustical methods to estimate the amount of peripheral compression in humans [reviewed in Bacon (2004)]. Of these, the temporal masking curve (TMC) method of Nelson *et al.* (2001) (see also Lopez-Poveda *et al.*, 2003) is perhaps the most accurate because it minimizes off-frequency listening effects that might occur when the probe level is varied. This method consists of measuring the level of a tonal forward masker required to just mask a *fixed* tonal probe as a function of the time interval between the masker and the probe. A TMC is a graphical representation of the resulting masker levels against the corresponding masker–probe intervals. Because the probe level is fixed, the masker level increases with increasing masker–probe time interval and hence TMCs have positive slopes. Nelson *et al.* (2001) argued that the slope of any given TMC depends simultaneously on the amount of BM compression affecting the masker at a cochlear place whose characteristic frequency (CF) equals approximately the probe frequency and on the rate of decay of the internal (postcochlear) masker effect. By assuming that the decay rate is the same across masker frequencies, BM I/O functions may be estimated by plotting the masker levels of a linear reference TMC (i.e., the TMC for a masker that is processed linearly by the BM) against the levels for any other masker frequency, paired according to masker–probe delays [Nelson *et al.* (2001) provide a full justification of these assumptions; see also Lopez-Poveda and Alves-Pinto (2008)].

The TMC method has been used to infer BM I/O curves in normal-hearing and hearing-impaired listeners in a number of studies (e.g., Lopez-Poveda *et al.*, 2003, 2005; Lopez-Poveda and Alves-Pinto, 2008; Nelson *et al.*, 2001; Nelson and Schroder, 2004; Plack *et al.*, 2004; Rosengard *et al.*, 2005). It is arguably a reliable method but time consuming and requires the active participation of the listener. This would make it inconvenient for clinical purposes, particularly for testing newborns and the elderly.

On the other hand, DPOAE I/O curves share many characteristics with BM I/O functions (Cooper and Rhode, 1997; Dorn *et al.*, 2001; Neely *et al.*, 2003). Specifically, both of

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them are generally linear at low levels but become compressive above a certain compression threshold (Dorn *et al.*, 2001; Kummer *et al.*, 1998) and both of them are similarly labile to outer hair cell damage (Rhode, 2007). Furthermore, measuring DPOAEs does not require the active participation of the listener. This suggests that DPOAE I/O functions could be used as a faster and universal way to infer individual BM I/O functions in clinical conditions (Müller and Janssen, 2004). The aim of the present study is to test this hypothesis by measuring the degree of correlation between BM I/O functions as inferred from TMCs and from DPOAEs in the same subject. Clearly, only if the results of the two methods correlate well will it be possible to add support to the use of DPOAEs to infer *individual* cochlear response characteristics. If they disagree, however, it will be difficult to resolve which of the two methods is more appropriate to reveal the true nonlinear characteristics of the underlying BM responses. Although the long-term goal is to extend the study to hearing-impaired listeners, the focus here is on normal-hearing listeners.

Several earlier studies have addressed this or related questions. Müller and Janssen (2004) investigated the similarity of loudness and DPOAE I/O curves in the same subject sample [Neely *et al.* (2003) had done it previously using different subject samples and slightly different methods]. They found a high resemblance between the characteristics (gain and compression) of the two sets of *average* I/O curves in normal-hearing and hearing-impaired listeners. Müller and Janssen (2004) acknowledged, however, that loudness may be affected by retrocochlear mechanisms (see also Heinz and Young, 2004) and it is also thought that loudness is affected by off-frequency effects (e.g., different spreads of excitation at different levels), which make it difficult to establish a one-to-one relationship between loudness and underlying BM I/O curves (Moore, 2003). This undermines the conclusions of Müller and Janssen (2004). Furthermore, their conclusions applied to *average* I/O curves and frequencies of 2–4 kHz, and thus may not be valid individually or for other frequencies, particularly 0.5 and 1 kHz.

Gorga *et al.* (2007) measured the degree of cochlear compression in a very large sample ($N=103$) of normal-hearing listeners as estimated from DPOAE I/O functions at 0.5 and 4 kHz. As a consequence, the I/O functions they reported likely provide a good description of *average* normal responses. Their results supported the conclusion of earlier psychophysical studies that the degree of compression is similar for apical and basal cochlear sites (Lopez-Poveda *et al.*, 2003; Plack and Drga, 2003). However, their study did not include within-subject psychophysical/physiological comparisons.

Williams and Bacon (2005) inferred cochlear I/O curves from TMCs and DPOAEs in four listeners and for frequencies of 1, 2, and 4 kHz. The results revealed that both methods yield similar *average* compression estimates. Like the above-mentioned studies, this study was not intended to investigate within-subject correlations between the results of both methods. Further, their DPOAE I/O curves could have been influenced by the DP fine structure. Indeed, Gaskill and Brown (1990) showed rapid variations (known as "fine structure") of the magnitude of the $2f_1-f_2$ DPOAE with changing the frequencies of the primaries (f_1 and f_2, with $f_2/f_1=1.21$) only slightly. This fine structure is thought to be the result of constructive and destructive interference between DPs generated at two spatially distant sites (Kummer *et al.*, 1995; Stover *et al.*, 1996; Gaskill and Brown, 1996; Heitmann *et al.*, 1998; Talmadge *et al.*, 1998; 1999; Mauermann *et al.*, 1999; Mauermann and Kollmeier, 1999; Shera and Guinan, 1999). The principal generation site is the BM region of maximum overlap between the excitation caused by the two primaries, that is the BM site with CF=f_2 (e.g., Kummer *et al.*, 1995). This component propagates back toward the oval window but also to the cochlear site with CF=$2f_1-f_2$ where it excites a second generation source. The DP generated at this second source propagates back toward the oval window and is summed with the response of the first source. The fine structure is thought to originate from vector summation of these two components, whose varying phases give rise to constructive or destructive interference and thereby to peaks and valleys in the DP-gram. The f_2 generator site is the dominant source at high stimulus levels [Fig. 3 of Mauermann and Kollmeier (2004)], which explains why the fine structure is more pronounced at low levels.

The fine structure has a large influence on DPOAE I/O curves, especially at low levels. He and Schmiedt (1993) mentioned that the DPOAE magnitude can change by as much as 20 dB for a change in f_2 of 1/32 octave. Mauermann and Kollmeier (2004) reported that the response varied by 10–15 dB when f_2 varied over the interval from 2250 to 2610 Hz. The influence of the fine structure is greater for individual than for average (across subjects) I/O curves, but can also affect average curves when the sample size is small. The sample size was small ($N=4$) in the study of Williams and Bacon (2005). Thus, fine-structure effects may have complicated the interpretation of their results or even led to wrong conclusions.

The present report extends these earlier studies in several respects. First, the focus here is on within-subject as opposed to average psychophysical/physiological correlations. Second, psychophysical BM I/O curves were inferred using what is arguably the most accurate method available to date for this purpose [see Nelson *et al.* (2001) for a full justification; but see also Sec. IV of the present paper]. Third, special care was exercised to reduce the influence of the fine structure on individual DPOAE I/O curves by averaging the magnitude of the $2f_1-f_2$ DPOAE for five f_2 frequencies near the frequency of interest. Fourth, the frequency range considered (0.5–4 kHz) included low and high frequencies. Fifth, the physiological/psychophysical comparisons extended to parameters pertaining to cochlear nonlinearity other than compression magnitude; specifically, compression threshold and the level at which maximum compression occurs.

It will be shown that reasonable correlation exists between the characteristics of individual TMC-based and DPOAE I/O curves at 4 kHz but not at 0.5 and 1 kHz. Reasons for the observed discrepancies at low frequencies will be discussed.

TABLE I. Thresholds (in dB SPL) measured with Etymotic ER2 insert earphones for all subjects and for tone durations of 300 ms (absolute threshold), 110 ms (masker threshold), and 10 ms (probe threshold), respectively. n.a. stands for not available.

Tone duration (ms)	Frequency (kHz) 0.5 300/110/10	1 300/110/10	2 300/110/10	4 300/110/10
S1	13/15/39	6/8/30	12/16/34	13/13/33
S2	14/21/43	10/15/30	20/22/n.a.	21/21/40
S3	13/16/39	7/8/32	5/8/27	4/10/25
S4	17/20/n.a.	10/16/34	16/21/42	21/24/44
S5	23/24/n.a.	13/17/41	7/12/n.a.	0/3/23
S6	9/10/36	10/11/31	9/13/n.a.	4/4/24
S7	6/10/n.a.	10/11/n.a.	16/20/n.a.	12/15/31
S8	11/18/34	5/7/38	25/28/n.a.	11/10/30
S9	12/n.a./n.a.	9/n.a./n.a.	10/n.a./n.a.	10/15/31
S10	5/n.a./n.a.	−2/n.a./n.a.	10/n.a./n.a.	3/1/23

II. METHOD

A. Subjects

Ten normal-hearing subjects participated in the study. Their age ranged from 20 to 39 years. Their absolute thresholds were measured using a two-down, one-up adaptive procedure. Signal duration was 300 ms, including 5 ms cosine-squared onset and offset ramps. All subjects had thresholds within 20 dB HL at the frequencies considered in this study (0.5, 1, 2, and 4 kHz, see Table I).

B. TMC stimuli

TMCs were measured for probe frequencies (f_P) of 0.5, 1, 2, and 4 kHz and for masker frequencies equal (on-frequency) to the f_P. Additional TMCs were measured for a probe frequency of 4 kHz and a masker frequency of 1.6 kHz ($f_M = 0.4 f_p$). The latter were selected as the linear references (Lopez-Poveda and Alves-Pinto, 2008) and used to infer BM I/O curves for all probe frequencies (Lopez-Poveda *et al.*, 2003). The masker–probe time intervals ranged from 5 to 100 ms in 5 ms steps with an additional interval of 2 ms. The duration of the masker was 110 ms, including 5 ms cosine-squared onset and offset ramps. The probe duration was 10 ms, including 5 ms cosine-squared onset/offset ramps and no steady state portion. The level of the probe was fixed at 9 dB sensation level (SL) (i.e., 9 dB above the individual absolute threshold for the probe), except for subject S5 for whom it was 15 dB SL. Stimuli were generated with a Tucker Davies Technologies Psychoacoustics Workstation (System 3) operating at a sampling rate of 48.8 kHz and with analog to digital conversion resolution resolution of 24 bits. If needed, signals were attenuated with a programmable attenuator (PA-5) before being output through the headphone buffer (HB-7). Stimuli were presented to the listeners through Etymotic ER-2 insert earphones. TMC sound pressure levels (SPL) were calibrated by coupling the earphones to a sound level meter through a Zwislocki DB-100 coupler. Calibration was performed at 1 kHz only and the obtained sensitivity was used at all other frequencies because the earphone manufacturer guarantees an approximately flat (±2 dB) frequency response between 200 Hz and 10 kHz.

C. TMC procedure

The procedure was identical to that of Lopez-Poveda and Alves-Pinto (2008). Masker levels at threshold were measured using a two-interval, two-alternative forced-choice paradigm. Two sound intervals were presented to the listener in each trial. One of them contained the masker only and the other contained the masker followed by the probe. The interval containing the probe was selected randomly. The subject was asked to indicate the interval containing the probe. The initial masker level was set sufficiently low that the subject always could hear both the masker and the probe. The masker level was then changed according to a two-up, one-down adaptive procedure to estimate the 71% point on the psychometric function (Levitt, 1971). An initial step size of 6 dB was applied, which was decreased to 2 dB after three reversals. A total of 15 reversals were measured. Threshold was calculated as the mean of the masker levels at the last 12 reversals. A measurement was discarded if the standard deviation (s.d.) of the last 12 reversals exceeded 6 dB. Three threshold estimates were obtained in this way and their mean was taken as the threshold. If the s.d. of these three measurements exceeded 6 dB, a fourth threshold estimate was obtained and included in the mean.

The maximum SPL was set to 104 dB to prevent subject discomfort and/or temporary threshold shifts. A measurement run was stopped and discarded when the subject reached this limit on more than two consecutive trials over the last 12 reversals. Masker levels at threshold were measured for masker–probe time intervals in increasing order. This was done to minimize the possibility that the measurements would be affected by potential temporary thresholds shifts that might have occurred if intervals had been presented in random order and a long interval (high masker level) immediately preceded a short interval. An attempt was made to measure masker levels for all masker–probe time intervals. Missing data indicate that the maximum output level (104 dB SPL) was reached for the time interval in question or that it was impossible within six to ten attempts to obtain three threshold estimates with s.d. ≤6 dB.

The listeners' absolute threshold for the maskers and probes were measured using the same equipment and conditions used to measure the TMCs. At least three measurements were obtained and averaged. Results are shown in Table I. Listeners were trained in the forward-masking task for several hours, at first with a higher probe level of 15 dB SL and later with a probe level of 9 dB SL, until performance became stable. Listeners sat in a double-wall sound attenuating chamber during all measurements.

D. Inferring BM I/O functions from TMCs

BM I/O functions were inferred from TMCs by plotting the levels for the linear reference TMC against the levels for any other masker frequency paired according to masker–probe time interval (Nelson *et al.*, 2001). The off-frequency

TMC for $f_P=4$ kHz was used as the linear reference to infer I/O curves for all other frequencies, as suggested by Lopez-Poveda *et al.* (2003). It was sometimes necessary to extrapolate the linear references to longer masker–probe time intervals to infer BM I/O functions over the wider possible range of levels. In similar situations, some authors have fitted the linear reference TMC with a straight line (e.g., Lopez-Poveda *et al.*, 2003; 2005; Nelson *et al.*, 2001; Plack *et al.*, 2004). There is strong evidence, however, that the decay of forward masking is better described with two time constants (e.g., Lopez-Poveda and Alves-Pinto, 2008; Meddis and O'Mard, 2005; Oxenham and Moore, 1994; Plack and Oxenham, 1998). Based on this, the individual linear-reference TMCs were fitted here (using a least-squares procedure) with a double exponential function of the form:

$$L_m(t) = L_0 - 20 \log_{10}[\alpha e^{(-t/\tau_a)} + (1-\alpha)e^{(-t/\tau_b)}], \quad (1)$$

where $L_m(t)$ is the masker level required to mask the probe at masker–probe time interval t; L_0 is masker level for a masker–probe interval of zero; τ_a and τ_b are time constants; and α determines the level at which the second exponential takes over from the first one. α, τ_a, τ_b, and L_0 were fitting parameters and were allowed to vary freely within certain boundaries: α was restricted to the interval [0, 1]; L_0 was restricted to vary within [50,120] dB; and τ_a and τ_b to the interval [1,200] ms. The lowest correlation between actual and predicted masker levels was $r=0.94$, which shows that the goodness of fit was excellent.

E. DPOAE stimuli

DPOAE I/O curves were obtained by plotting the magnitude (in dB SPL) of the $2f_1-f_2$ DP emission as a function of the level, L_2, of the primary tone f_2. DPOAEs were measured only for f_2 frequencies equal to the probe frequencies for which TMCs had been previously measured (0.5, 1, 2, and/or 4 kHz). The f_2/f_1 ratio was fixed at 1.2. L_2 ranged from 20 to 75 dB SPL in 5 dB steps, except for $f_2=0.5$ kHz for which it ranged from 45 to 75 dB SPL. L_1 and L_2 were related according to $L_1=0.4L_2+39$ dB, the rule proposed by Kummer *et al.* (1998) to obtain maximum-level DPOAEs for $L_2\leqslant 65$ dB SPL. In the current study, this rule was extrapolated to $L_2>65$ dB SPL.

In an attempt to reduce the potential variability of the I/O curves caused by the DP fine structure, DPOAE I/O curves were measured for five f_2 frequencies near the frequency of interest, and the resulting I/O curves were averaged. This procedure is supported by Kalluri and Shera (2001) and Mauermann and Kollmeier (2004), who showed that a "cleaned" DP-gram (i.e., a DP-gram where the fine structure has been accounted for) resembles very closely a moving average of the original DP-gram with fine structure. The five adjacent frequencies were selected to differ by as much as 2% of the frequency of interest based on a suggestion of Mauermann and Kollmeier (2004) that this frequency spacing is appropriate to reveal (or to account for) the influence of the fine structure. That meant measuring DPOAE I/O curves for frequencies of $0.98f_2$, $0.99f_2$, f_2, $1.01f_2$, and $1.02f_2$. For instance, the final DPOAE I/O curve at 4 kHz was the mean of five I/O functions for $f_2=\{3920,3960,4000,4040,4080 \text{ Hz}\}$. To further assess the potential influence of the fine structure around the frequency of interest, DPOAEs were measured for four additional adjacent f_2 frequencies on each side of the five main frequencies. In the case of 4 kHz these were: $f_2=\{3760,3800,3840,3880,\ldots,4120,4160,4200,4240 \text{ Hz}\}$. DPOAEs for these latter frequencies were measured only for $L_2=\{70,60,50,40 \text{ dB}\}$ and the resulting I/O curves were not included in the final mean I/O curve.

The influence of standing waves must be taken into consideration when measuring DPOAE at high frequencies. Siegel (1994) and Whitehead *et al.* (1995) found that restricting DPOAE measurements to $f_2<6$ kHz avoids the majority of the idiosyncratic variations of the sound pressure at the eardrum due to standing waves. For this reason, it was decided to restrict DPOAE measurements to $f_2\leqslant 4$ kHz. Measuring DPOAEs for $f_2<1$ kHz is also problematic due to increased physiological subject noise. The moderate-to-high level part of the DPOAE I/O curve for $f_2=0.5$ kHz could still be measured for most listeners, however, by considering L_2 above 45 dB SPL only.

F. DPOAE stimulus calibration

DPOAE stimuli were calibrated with a Zwislocki DB-100 coupler for each f_1,f_2 frequency. In some studies, calibrated levels are further adjusted with the probe *in situ* to account for the acoustic effects associated with ear-canal resonances. This *in situ* adjustment, however, was not applied here for two reasons. First, Siegel (1994) has shown that it does not always work for frequencies above 2–3 kHz because of the errors in predicting the level at the eardrum from measurements made at the plane of the probe (where the standing waves interact). Second, as this is a comparison study, it was deemed important that the two methods applied the same stimulus level control. Given that the psychophysical equipment did not allow easy *in situ* level adjustment, this option was disabled in the OAE instrument.

G. DPOAE system artifacts

When measuring DPOAE I/O curves at high primary levels it is necessary to control for cubic distortion produced by the measurement instrument. This system artifact was assessed by measuring the magnitude of the $2f_1-f_2$ DP in two different couplers: a DB-100 Zwislocki coupler and a plastic syringe having a volume of approximately 1.5 cc. The test was performed for L_2 from 50 to 80 dB SPL with the same equipment and in the same conditions used to measure DPOAEs. The measurement time was prolonged to maximize the chances of discovering any artifacts. The magnitude of the cubic DP would be $-\infty$ dB SPL for an ideal OAE system. The system artifact limit was set to the higher of the responses for the two couplers that was also 2 s.d. above the mean level of ten adjacent frequency bins in its corresponding spectrum. This procedure was repeated for each of the f_2s considered when measuring DPOAEs.

It is common to accept DPOAE measurements when they are above the system artifact limit. This may be tolerable in a clinical context where it comes to making a "pass/refer" decision. The magnitude of the measured DPOAE is the *vector* sum of DP contributions from any nonlinearity along the signal path, be it from the instrument or from the subject. If the clinical rule was applied, then the true physiological response would be any value within the range $(-\infty, +6]$ dB around the measured DPOAE in the worst possible case (i.e., when the measured DPOAE magnitude just exceeds the artifact limit and the physiological DP has opposite or equal phase to the system's DP, respectively). This uncertainty range, however, seems too broad for the present study where the slope of the I/O curve is of interest. Therefore, a more restrictive rule was applied. A DPOAE measurement was accepted as valid only when it exceeded the artifact limit by 6 dB or more. This guaranteed that the physiological DP contribution was within the range $[-6, +3.5]$ dB in the worst possible case (i.e., when the DPOAE measurement just met the present criterion). Therefore measurements were rejected if they were less than 6 dB above the system artifact limit. This was the case for subject S4 at 4 kHz, for whom most data points were discarded based on this criterion, and also for subject S3 at 1 kHz at high stimulus levels (75 dB SPL).

H. DPOAE procedure

DPOAE measurements were obtained with an IHS Smart system (with SmartOAE software version 4.52) equipped with an Etymotic ER-10D probe. During the measurements, subjects sat comfortably in a double-wall sound attenuating chamber and were asked to remain as steady as possible.

The probe fit was checked before and after each measurement session. The probe remained in the subject's ear throughout the whole measurement session to avoid measurement variance from probe fit. DPOAEs were measured for a preset measurement time. For $f_2 = 4$ kHz, the measurement time ranged from 60 s at $L_2 = 20$ dB SPL to 8 s at high L_2; for $f_2 = 0.5$ kHz, it ranged between 60 and 30 s for L_2 between 45 and 75 dB SPL, respectively. A DPOAE measurement was considered valid when it was 2 s.d. above the measurement noise floor (defined as the mean level over ten adjacent frequency bins in the spectrum). When a response did not meet this criterion, the measurement was repeated and the measurement time was increased if necessary. The probe remained in the same position during these remeasurements. If the required criterion was not met after successive attempts, the measurement point was discarded.

Each recording session consisted of measuring DPOAE I/O curves for one frequency of interest (consisting of five adjacent frequencies) (see Sec. II E) and was allowed to take up to 1 h. Three DPOAE measurements were obtained per condition (i.e., per f_2 and L_2) and averaged, except for subject S2 for whom only one measurement was obtained. Therefore, each point in the final I/O curves was the mean of 15 ($3 \text{ measurements} \times 5$ adjacent frequencies) measurements for each L_2 level. Occasionally, it was not possible to obtain all 15 points, particularly for the lower L_2 levels. In those cases, the direct mean of the available points would have been biased toward the DPOAE values for the frequencies giving the stronger responses. To minimize this potential bias, a mean was calculated only when two (out of the three possible) measurements were available per frequency and when eight of the new ten possible measurements were available. Otherwise, the corresponding point was neglected for further analysis.

III. RESULTS

A. TMCs

Figure 1 shows the TMCs for the ten subjects for probe frequencies of 0.5, 1, 2, and 4 kHz. Note that TMCs were not measured for all frequencies and for all subjects. Subject S5 was unable to perform the TMC task using a probe level of 9 dB SL, thus a probe level of 15 dB SL was used in that case. Even so, it was not possible to measure high masker levels at 4 kHz for subject S5 and the resulting TMC did not allow estimating the true degree of compression (open circles in panel S5 of Fig. 1). Therefore these data were discarded from further analysis.

The shapes of the present TMCs are generally consistent with those of previous studies (e.g., Nelson *et al.*, 2001; Lopez-Poveda *et al.*, 2003; Lopez-Poveda and Alves-Pinto, 2008; Plack *et al.*, 2004; Rosengard *et al.*, 2005). The linear-reference TMCs (open squares) can be described either by a straight line (e.g., S4, S5) or by a shallow and gradually saturating function (e.g., S3, S8). The latter justifies the decision to fit the linear-reference TMCs with a double-exponential function. The continuous, thick lines illustrate these fits. Several on-frequency TMCs show a shallow segment for short masker–probe time intervals (or gaps) followed by a steeper segment for moderate intervals. Others, however, are better described by a segment steeper than the linear reference followed sometimes by a shallower section at high masker levels (e.g., S1, S2, S6, and S8). In any case, all of the on-frequency TMCs have segments that are much steeper than the linear reference TMC. Assuming that the off-frequency masker condition used to generate the linear reference is processed linearly by the BM and that the rate of decay of the internal masker effect is identical across frequencies (Lopez-Poveda *et al.*, 2003; Lopez-Poveda and Alves-Pinto, 2008), the steeper segments may be interpreted to indicate BM compression (Nelson *et al.*, 2001). The validity of these assumptions is discussed in Sec. IV F.

B. DPOAEs

Figure 2 shows a typical example of the amount of data measured to estimate one DPOAE I/O curve (2 kHz in this particular case). Each data point is the average of three measurements. Figure 2 also serves to illustrate the influence of the DP fine structure on the resulting I/O function. The inset indicates L_2 (in dB SPL). Note that DPOAEs were measured for a wider range of stimulus levels (from 20 to 75 dB SPL) for the five central adjacent frequencies only. A narrower range of levels (40, 50, 60, and 70 dB SPL) was considered for frequencies outside this frequency range. This was suffi-

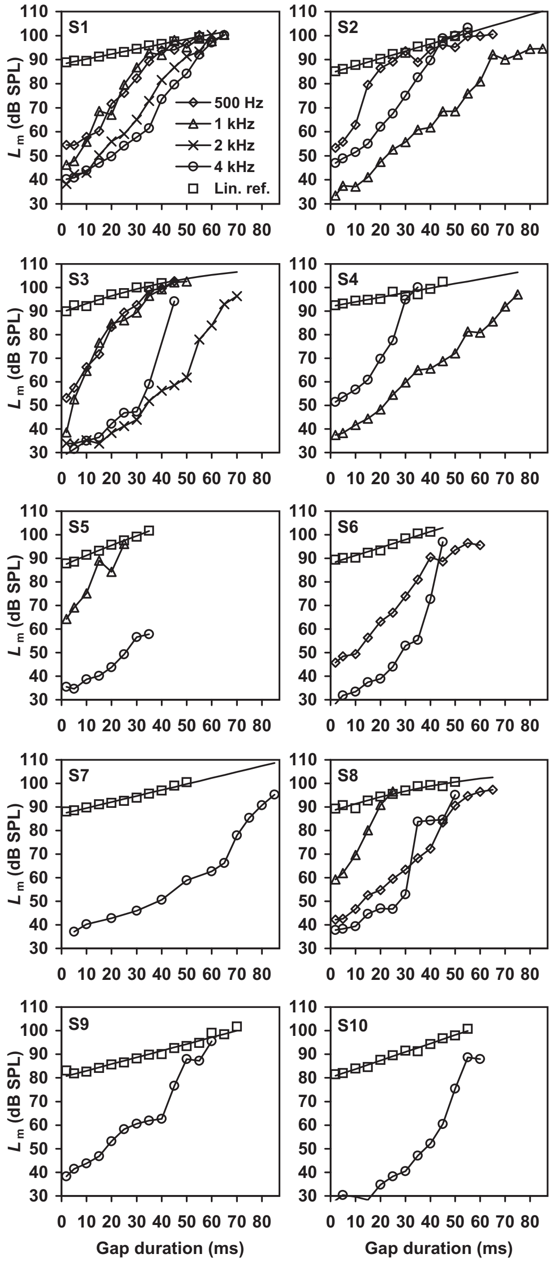

FIG. 1. TMCs for all subjects and probe and masker frequencies. Each panel illustrates the data for one subject. Open squares illustrate the linear reference TMC; i.e., the TMC for a probe frequency of 4 kHz and a masker frequency ($0.4f_P$) of 1.6 kHz. The smoother continuous lines illustrate fits to the linear reference TMC with a double-exponential function. Other symbols illustrate on-frequency TMCs for different probe frequencies (as indicated by the inset in the top-left panel). The probe level was 9 dB SL except for subject S5 for whom it was 15 dB SL.

cient, however, to get an idea of the surrounding DPOAE fine structure and its potential influence on the DPOAE I/O at the frequency of interest.

Obviously the DPOAE I/O curve would change considerably by changing f_2 within a narrow frequency range of 100 Hz, which emphasizes the need to take into account the effect of fine structure when estimating the actual I/O curve. The final I/O curve, representing the BM I/O function at 2 kHz, would be the mean of the five I/O curves for the five central frequencies. Figure 3 illustrates these five I/O curves for subjects S1 and S2 and for all frequencies considered in

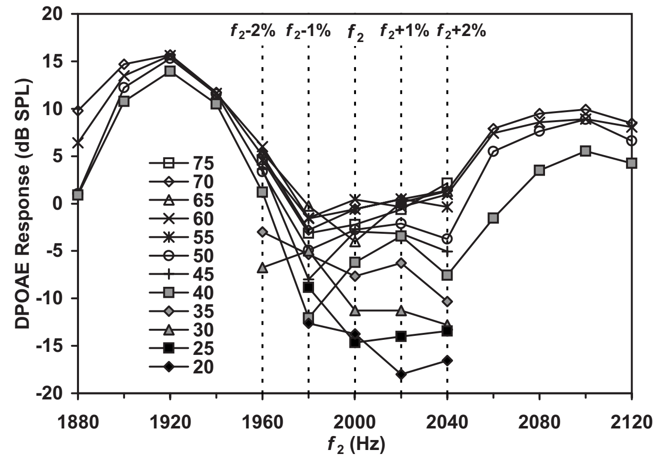

FIG. 2. An example of the influence of the DPOAE fine structure at 2 kHz. An example data set recorded to estimate every I/O curve is also illustrated. The DPOAE magnitude is shown for 12 f_2 frequencies around the frequency of interest (2 kHz) and for different L_2 levels (in dB SPL) as indicated in the inset.

the present study. As can be seen, there is variability across subjects and across frequencies. Nevertheless, variability appears to be greater for the lower stimulus levels. This seems reasonable given that the fine structure is more obvious at low stimulus levels (Mauermann and Kollmeier, 2004).

C. Comparison of BM I/O curves inferred from TMCs and DPOAEs

Figures 4–7 allow within-subject comparisons of DPOAE I/O curves (open squares) with BM I/O curves inferred from TMCs (closed circles) for corresponding cochlear sites with CFs of 0.5, 1, 2, and 4 kHz, respectively. Each panel illustrates the results for one subject. The associated solid lines are third-order polynomials fitted to the data. Error bars denote 1 standard error (s.e.) of the mean. For DPOAE I/O curves, the s.e. was based on up to 15 measurement points for each stimulus level, which explains why error bars are so short. The average error across all subjects and levels was 0.7 dB. The vertical and horizontal error bars of TMC-based I/O curves illustrate the s.e. of the linear reference or the TMC in question, respectively, based on at least three measurements. The average errors across all subjects and time gaps for the linear reference and the on-frequency TMCs were 0.9 and 2.3 dB, respectively.

The open triangles in the top-right panel of Figs. 4–7 and their associated error bars illustrate the mean DPOAE noise floor plus 2 s.d. (based on three measurements for the five adjacent frequencies considered) for one example subject. The noise levels were similar for the other subjects. In general, the noise has the effect of increasing the DPOAE magnitude, particularly at low levels. However, the strict criteria used here should have avoided this influence.

In general, both DPOAE and TMC-based I/O curves are similar in that they are linear at low levels and become gradually compressive with increasing level. There is a tendency in both sets for I/O curves to become linear again at the highest levels tested (e.g., S6 at 0.5 kHz in Fig. 4; or S2 and S5 at 4 kHz in Fig. 7). The degree of similarity between

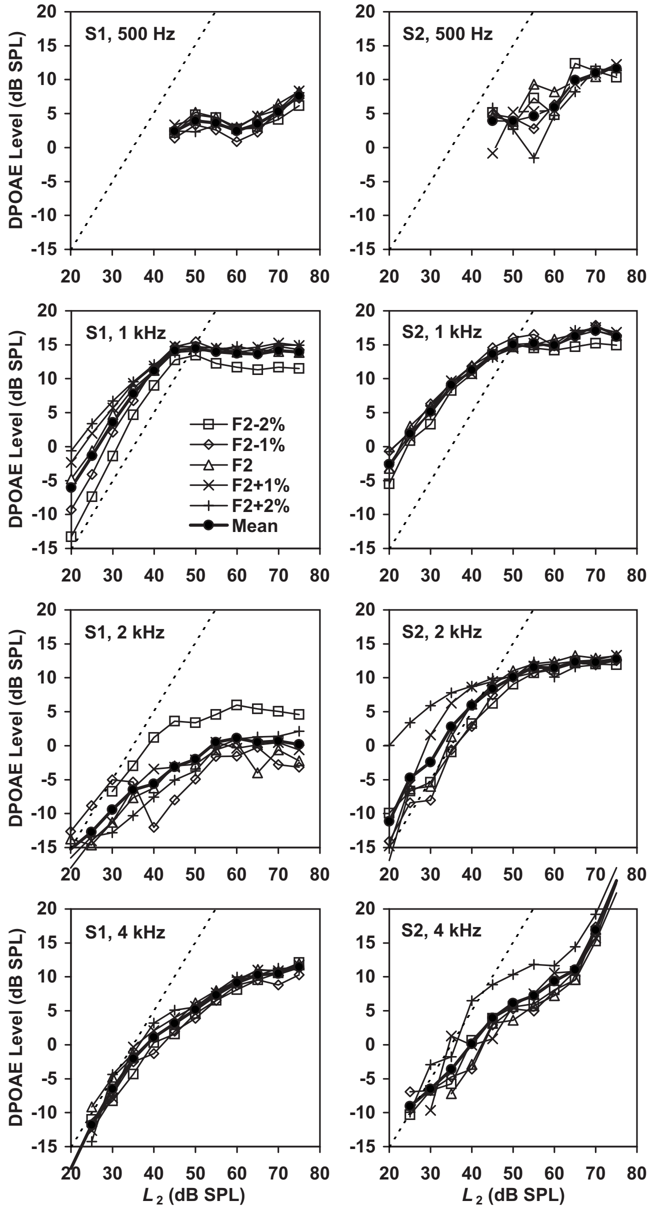

FIG. 3. Example DPOAE I/O curves for subjects S1 (left panels) and S2 (right panels), for frequencies from 0.5 (top) to 4 kHz (bottom) in octave steps. Each final I/O curve (closed circles, thick line) was obtained as the average of five I/O curves for frequencies of $0.98f_2$, $0.99f_2$, f_2, $1.01f_2$, and $1.02f_2$, illustrated with different symbols according to the inset. The dashed line illustrates a linear response for comparison.

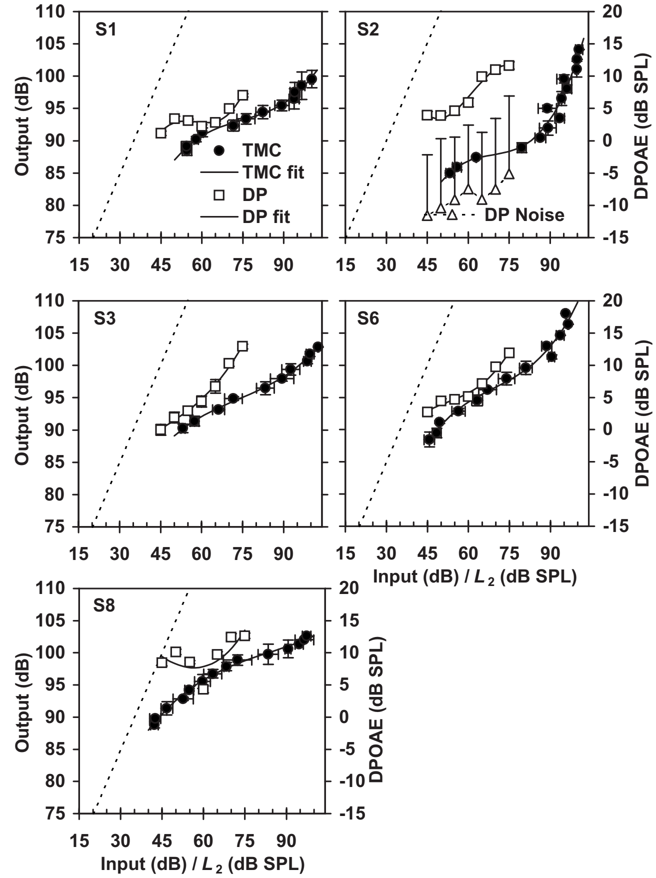

FIG. 4. Experimental DPOAE (open squares) and TMC-based (closed circles) I/O curves at 0.5 kHz ($=fp=f_2$). Continuous lines illustrate third-order polynomial fits to the experimental I/O curves. Error bars denote 1 s.e. of the mean. Horizontal bars (only for TMC-based curves) represent the standard error of the input level (i.e., the standard error for the on-frequency masker level). Each panel illustrates the result for a different subject. The panel for subject S2 also illustrates the mean DP noise floor and its corresponding 2 s.d. Thin dashed lines illustrate a linear response for comparison.

the two sets of I/O curves is greatest at 4 kHz (Fig. 7). At this frequency, both sets of I/O curves indicate equally mild compression for subjects S1, S2, S5, and S7, and equally strong compression for S3 and S8. The strongest disagreement between the two sets of I/O curves at 4 kHz occurs for subject S9 (Fig. 7). S4 deserves a special mention because her DPOAEs could not be measured for levels outside the 40–50 dB SPL level range despite her having normal hearing at 4 kHz (her DPOAE readings for $L_2 < 40$ dB SPL were below the physiological noise level and for $L_2 > 50$ dB SPL they did not meet the instrument artifact criterion, see Sec. II G).

The degree of similarity between the shapes of the two sets of I/O curves is, however, much lower for 0.5 and 1 kHz. It is noteworthy that, for these frequencies, some DPOAE I/O curves show plateaus and notches that do not have a clear correlate with TMC-based I/O curves (e.g., S1, S2, and S8 at 0.5 kHz in Fig. 4; or S3, S4, and S5 at 1 kHz in Fig. 5). Possible explanations for the notches and plateaus are discussed in Sec. IV B.

It was not possible to draw conclusive results regarding the degree of correlation between the two sets of I/O curves at 2 kHz because data at this frequency were collected for two subjects only (Fig. 6). Good correspondence (akin to what was observed at 4 kHz) was found for one of the two subjects (S3). The DPOAE I/O curve for the other subject (S1), however, exhibited a negative gradient at moderate-to-high levels that was not present in the TMC-based I/O curves. This negative gradient was typical of the I/O curves at frequencies of 0.5 and 1 kHz.

D. Comparison of derived cochlear nonlinearity parameters

Third-order polynomials were fitted by least squares to the TMC-based and DPOAE I/O curves (continuous lines in Figs. 4–7) and used to derive the following parameters pertaining to cochlear nonlinearity: minimum compression ex-

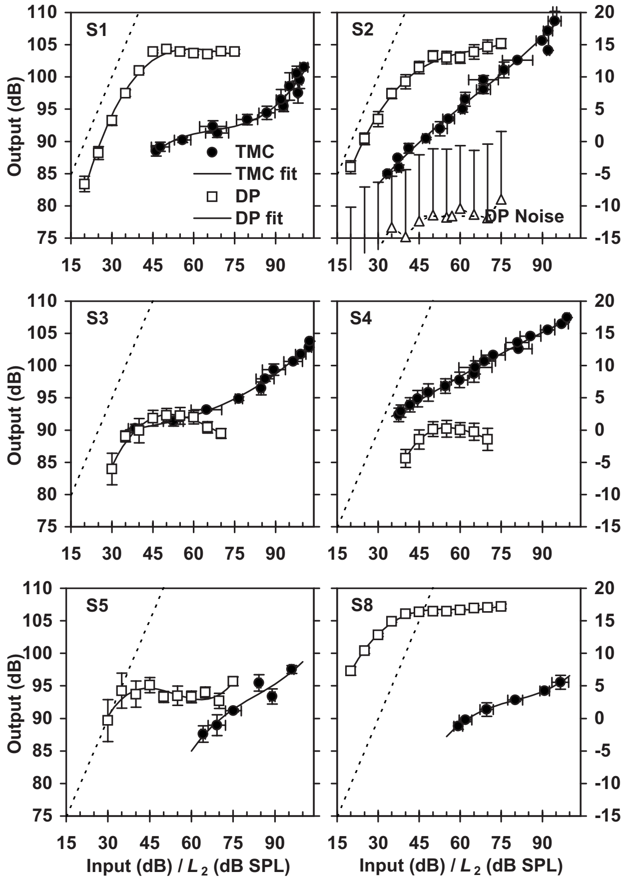

FIG. 5. The same as Fig. 4, but for a frequency of 1 kHz.

ponent, the level at which it occurred, compression threshold, cochlear gain, and the level at which the I/O curves returned to linearity at high levels.

The minimum compression exponent was estimated as the minimum slope of the fitted I/O curves over the measured range of input levels. Figure 8(A) compares the minimum compression exponent as inferred from the I/O curves obtained with the two methods. Closed symbols show the results for 4 kHz separately. Open symbols illustrate the results for the other frequencies (0.5, 1, and 2 kHz), as indicated by the inset. The solid and dashed lines illustrate linear regression fits to the 4 kHz data only or to all data points (including also the 4 kHz points), respectively. Both regression lines were forced to pass through the origin of the graph. Pearson's correlation coefficients were (high) 0.92 for the 4 kHz subsample and (low) 0.19 when all data points (all frequencies) were considered. The mean compression exponents across frequencies were 0.13 and 0.04 for the TMC-based and the DPOAE data sets, respectively. They, however, were 0.10 and 0.11, respectively, considering only the 4 kHz data points. The mean difference was significant when all data points were considered ($p<0.005$ for a paired two-tailed Student's t-test) but not for the 4 kHz subsample ($p=0.81$). This is clearly seen from Fig. 8(A) in that DPOAE-based compression estimates are lower overall than TMC-based ones for 0.5 and 1 kHz.

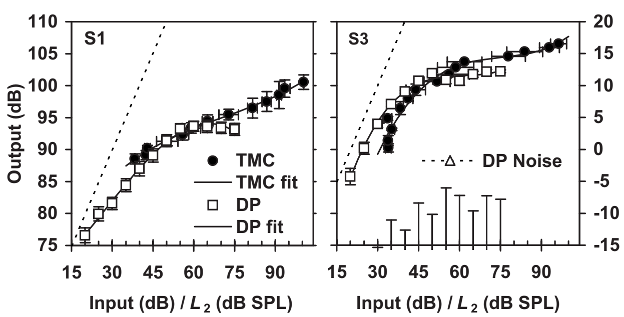

FIG. 6. The same as Fig. 4, but for a frequency of 2 kHz.

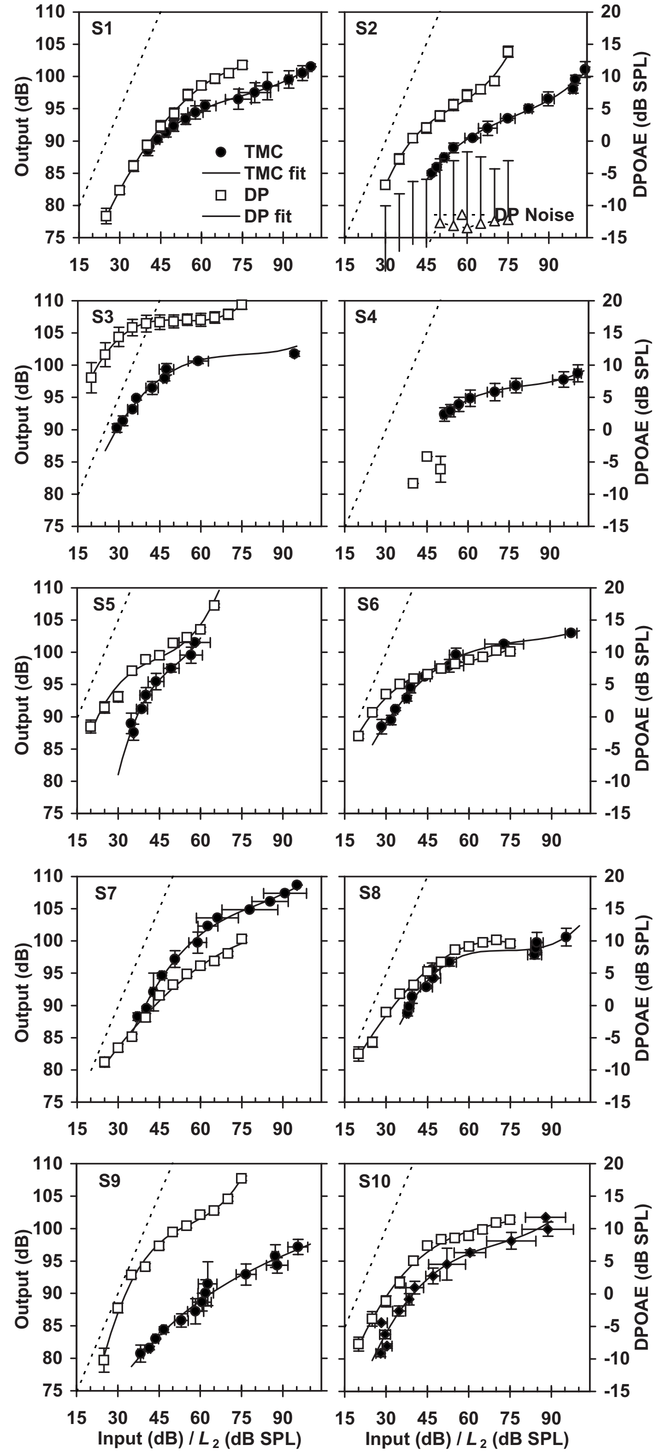

FIG. 7. The same as Fig. 4, but for a frequency of 4 kHz.

The reason for the disagreement between the results at

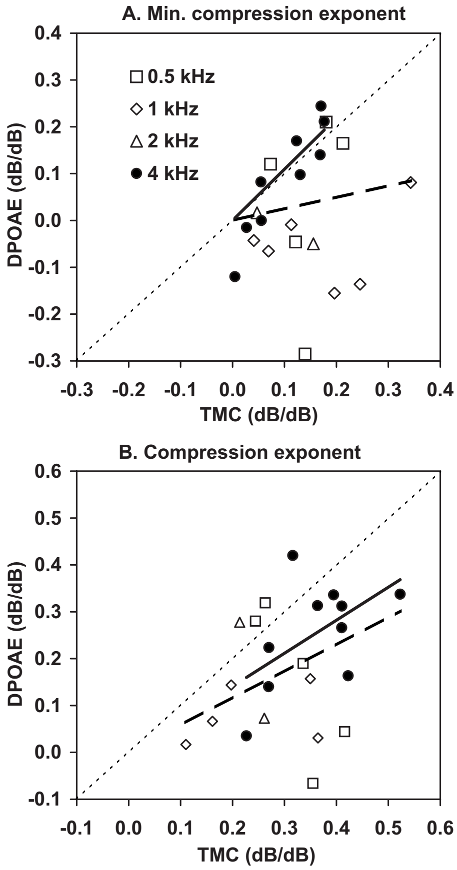

FIG. 8. Correlation between compression-exponent estimates obtained from DPOAE- and TMC-based I/O curves (i.e., each point represents data for one subject). (A) Minimum compression exponent based on third-order polynomial fits to the I/O curves. (B). Compression exponent based on linear-regression fits to the I/O curves over the input-level range 40–65 dB SPL. Closed and open symbols illustrate the 4 kHz data and the data at other frequencies (0.5, 1, and 2 kHz), respectively. Solid lines show linear regression fits to the 4 kHz data points constrained to cross through the origin. Thick dashed lines are linear regression fits considering all data points (including 4 kHz) constrained to cross through the origin. Diagonal thin-dashed lines illustrate perfect correlation.

0.5 and 1 kHz is, almost certainly, that many DPOAE I/O curves for the lower frequencies showed plateaus or notches, which resulted in unexpectedly low compression exponents (slopes <0 dB/dB). Table II summarizes the number of cases across frequencies when the fitted I/O curve exhibited plateaus or negative compression exponents.

These results contrast with those of Williams and Bacon (2005), who reported a high correlation between compression estimates inferred from TMC-based and DPOAE I/O curves also at low frequencies. The compression estimates of Williams and Bacon (2005), however, were calculated differently. They were calculated as the slope of linear segments

TABLE II. Incidence of plateaus and notches in DPOAE I/O curves as a function of f_2.

	Frequency (kHz)			
	0.5	1	2	4
Number of I/O measured curves	5	6	2	10
Number of I/O curves with plateaus or notches	3	5	1	2

fitted to the DPOAE and TMC-based I/O curves over the range of input levels from 40 to 65 dB approximately (they determined the actual level range by visual inspection). This fitting method was also employed here as it could prove less sensitive to notches. Figure 8(B) shows the correlation between compression exponent estimates for the two methods derived by linear regression fits to the I/O curves over the level range 40–65 dB. The 4 kHz data are shown by the closed symbols; open symbols illustrate the results for frequencies of 0.5, 1, and 2 kHz. The solid and dashed lines are linear regression fits to the 4 kHz data and to all data points (including also the 4 kHz data), respectively. Pearson's correlation coefficient considering all data points was 0.32 and Fig. 8(B) illustrates that DPOAE-based compression exponents were generally lower (most points are below the diagonal) than those inferred from TMCs. Group mean compression exponents were 0.31 and 0.18 for TMCs and DPOAEs, respectively. This difference was statistically significant ($p < 0.0005$). A moderately higher correlation was found when analyzing the 4 kHz data separately ($r=0.53$), but the associated mean difference (0.36 and 0.25 for TMCs and DPOAEs, respectively) was still statistically significant ($p < 0.01$).

Another characteristic of cochlear nonlinearity is the level at which maximum compression (or, equivalently, minimum compression exponent) occurs. Correlations were sought between estimates of this parameter for the I/O curves obtained with the two methods. Figure 9(A) reveals that high correlation occurs in a few cases only (points close to or on the diagonal). Most points are below the diagonal, which means that the level at which minimum compression occurred was lower for DPOAE I/O curves than for I/O curves inferred from TMCs. The average input level for minimum compression exponent was 61 and 76 dB for DPOAEs and TMC-based I/O curves, respectively. The difference was statistically significant ($p < 0.001$). Results were similar when the data for each frequency were analyzed separately.

Compression threshold was defined as the input level at which the slope of the fitted polynomial decreased from a value close to one at low levels to 0.4 dB/dB at a higher level. This is an arbitrary definition, but seems reasonable for our purpose. When the slope of the I/O curve at the lowest level for which a data point existed was reasonably close to 0.4 dB/dB, the fitted polynomial was extrapolated up to 5 dB to identify the compression threshold and the value was noted for further analysis. An extrapolated compression estimate was thus included in the analysis only if it was less than 5 dB from an existing data point. Figure 9(B) illustrates the correlation between the compression threshold estimates inferred from DPOAE and TMC-based I/O curves. Three compression estimates were considered outliers [symbols surrounded by an open circle in Fig. 9(B)] and thus excluded from the statistical analysis. The possible reasons for these outliers will be discussed in Sec. IV D. The regression line was constrained to cross through the graph origin. The line indicated a high degree of correlation between the estimates of the two methods and, indeed, Pearson's correlation coefficient was reasonably high ($r=0.8$). The average compression threshold estimates were lower for the DPOAE than for

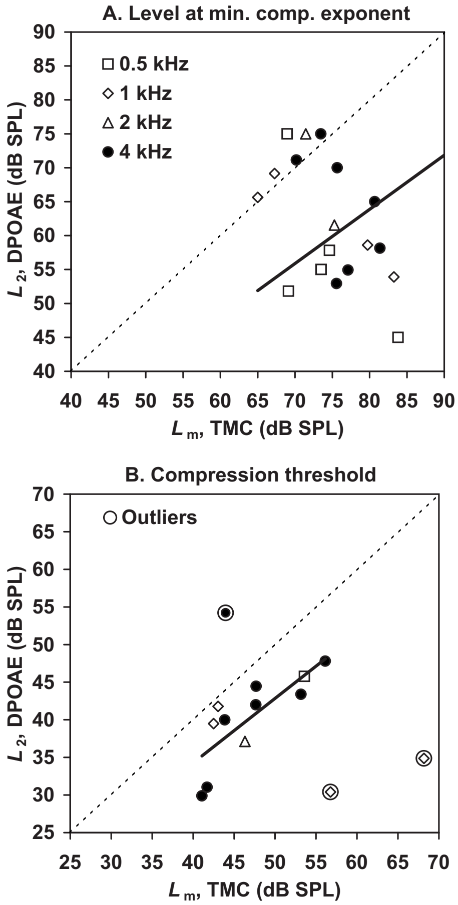

FIG. 9. (A) Correlation between the level at which maximum compression occurs based on the I/O curves inferred from DPOAE and TMCs (i.e., each point represents data for one subject). The solid line shows a linear regression fit to the data constrained to cross through the origin. (B) Correlation between compression-threshold estimates obtained with the two methods. Threshold was defined as the input level at which the I/O curve slope decreased from linearity to 0.4 dB/dB. The solid line shows the linear regression constrained to cross through the origin. Symbols surrounded by open circles illustrate three data points regarded as outliers. Diagonal thin-dashed lines illustrate perfect correlation.

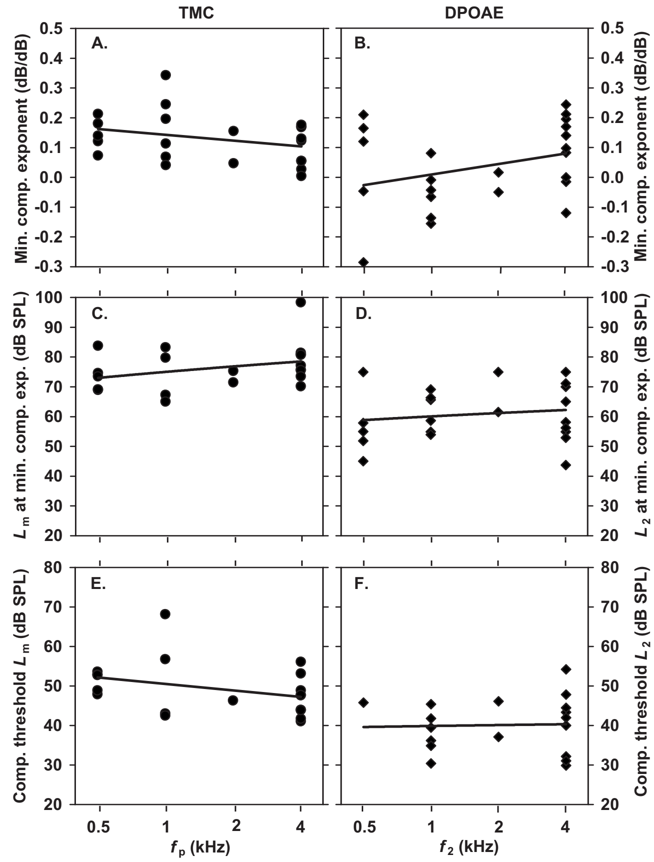

FIG. 10. Frequency dependency of cochlear nonlinearity parameters as estimated from TMCs (left panels) and DPOAEs (right panels). (A), (B) Minimum compression exponent. (C), (D) The level at which maximum compression occurs. (E), (F) Compression threshold.

the TMC-based I/O curves (40 and 47 dB SPL, respectively), which is also clearly seen in Fig. 9(B). This difference was statistically significant ($p < 0.0001$).

E. Cochlear nonlinearity dependency on characteristic frequency

This section addresses whether the parameters considered in the preceding section vary with frequency similarly when they are inferred from TMCs or DPOAEs. Two additional parameters were considered based on TMCs, namely gain and the threshold of return to linearity at high levels. I/O curves may be generally described as having a linear segment (slope of 1 dB/dB) at low levels, followed by a compressive segment (slope <1 dB/dB) at moderate levels, followed by linear segment at high levels (e.g., Lopez-Poveda *et al.*, 2003). Perhaps, the clearest examples of this pattern were the TMCs for S6 at 0.5 kHz and S2 at 4 kHz. Few TMC-based I/O curves showed a linear segment at high levels (e.g., S2 at 0.5 kHz or S1 at 1 kHz). The slope of the I/O curves, however, always increased with increasing level beyond the inflection point of the curve (defined as the level at which maximum compression occurs or, equivalently, the level at which the second derivative of the I/O curve equals zero). This suggests that the I/O curves might approach linearity at very high levels. Since the minimum slopes were always <0.4 dB/dB [Fig. 8(A)], the return-to-linearity threshold was arbitrarily defined here as the level at which the slope of the fitted I/O equated to 0.4 dB/dB for levels above the inflection point. Gain was defined as the difference between the return-to-linearity and the compression thresholds (in decibels).

Figure 10 shows the frequency dependency of the minimum compression exponent (top panels), the level at which it occurs (middle panels), and the compression threshold (lower panels), respectively. Left and right panels show the value of these parameters as inferred from TMCs and DPOAE I/O curves, respectively. Figure 10 illustrates that all these parameters remain approximately constant across frequencies. Indeed, no significant differences were found between the mean values of every parameter across frequencies. The same applied to parameters estimated with both methods.

Figure 11 shows the gain and the return-to-linearity threshold as inferred from TMCs only. Both parameters tend to increase with increasing frequency. Since the compression threshold remained approximately constant across frequencies [Fig. 10(E)], the frequency dependency of the gain is

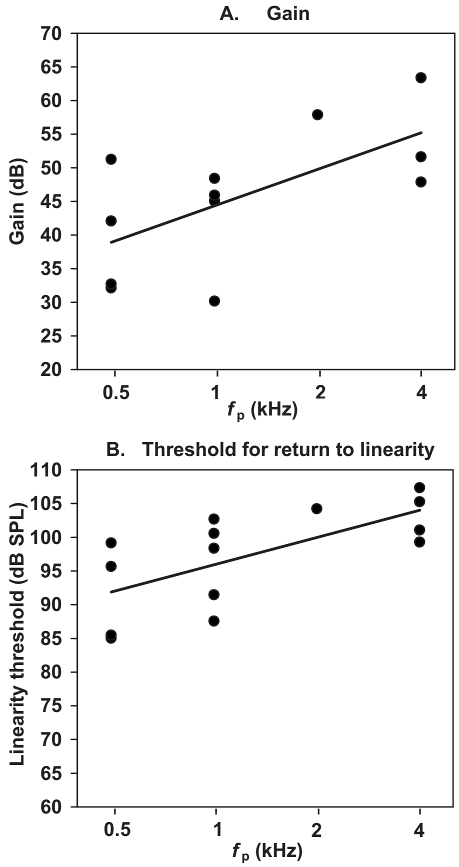

FIG. 11. Frequency dependency of gain (A) and the threshold of return to linearity (B) derived from TMC I/O curves. The latter was defined as the input level at which the I/O curve reached a slope of 0.4 dB/dB from a lower value for increasing input level.

fully attributed to the increase of the return-to-linearity threshold with increasing frequency. In any case, a one-to-one correspondence between these two parameters should not be expected because they are based on data for different subjects. Indeed, it was not possible to estimate the return-to-linearity threshold in several cases (one different subject for each frequency of 0.5, 1, and 2 kHz, and six subjects at 4 kHz). The I/O curves for these subjects may show a return to linearity at input levels higher than those considered in the present study. That the majority of these cases occurred at 4 kHz supports the idea that the return to linearity at higher frequencies occurs at higher input levels than those considered here.

IV. DISCUSSION

The goal of this study was threefold. The first objective was to compare cochlear nonlinearity parameters inferred from TMCs and DPOAEs, and, if coinciding, add support to the notion that they are two equivalent manifestations of cochlear nonlinearity. A second aim was to evaluate the feasibility of using DPOAE I/O curves as a fast tool for estimating individual parameters of cochlear nonlinearity. A third objective was to investigate the frequency dependency of parameters describing cochlear nonlinearity, as inferred from DPOAEs and TMCs.

A. Equivalence between DPOAE and TMC-based I/O curves

The degree of correlation between compression estimates inferred with the two methods was high (0.92) at 4 kHz but much lower at 0.5 and 1 kHz. The assumption has been made that DPOAE I/O curves reflect the characteristics of the BM response to single tones at the f_2 place. Measuring DPOAEs, however, requires presenting the two primaries (f_1 and f_2) *simultaneously*; hence the f_1 primary may have suppressed the BM response to the f_2 primary at the f_2 site. Indeed, Rhode (2007) measured BM excitation and DPOAEs simultaneously in the same preparation and showed that the f_1 primary suppresses the BM response to the f_2 (with a fixed level of 60 dB SPL) for L_1 above 60 dB SPL (see his Fig. 1). As a result, DPOAE I/O curves may not correspond directly to single-tone BM I/O curves, as is commonly assumed.

Unlike DPOAE I/O curves, the I/O curves inferred from TMCs would not be affected by suppression because the masker and the probe tones were not presented simultaneously (in fact, this is one of the reasons that they are so widely used to infer BM I/O curves). Therefore, one might think that mutual suppression between the primary tones may have influenced DPOAE but not TMC-based I/O curves and that the effect would be more pronounced at low CFs because the nonlinear effects extend to a wider bandwidth (Rhode and Cooper, 1996; Lopez-Poveda *et al.*, 2003). This explanation, however, is unlikely to account for the low correlation between compression estimates obtained with the two methods at low frequencies. There is physiological and psychophysical evidence that suppression leads to I/O curves steeper than single-tone I/O curves (Nuttall and Dolan, 1993; Rhode, 2007; Yasin and Plack, 2007). This is true particularly for suppressor/suppressee combinations similar to the primary-tone combinations used here. If suppression had affected the DPOAE I/O curves, they should indicate less compression than TMC-based I/O curves and this has been found *not* to be the case (Fig. 8). Therefore, the most likely explanation for the low correlation at low CFs between the compression estimates obtained with the two methods is the presence of notches and plateaus in the DPOAE I/O curves, which occur more frequently at low CFs (Table II).

The group mean compression-exponent estimates at 4 kHz obtained in the present study (0.10 and 0.11 dB/dB for TMC and DPOAE, respectively) are in agreement with those from Gorga *et al.* (2007), who reported a minimum slope value of ~0.12 dB/dB at 4 kHz based on DPOAEs (estimated from their Fig. 4 at L_2=60 dB SL). As for compression estimated using linear regression over the midlevel range [Fig. 8(B)], the group mean exponent values obtained in the present study (0.36 and 0.25 for TMC and DPOAE, respectively) were moderately higher than those reported by Williams and Bacon (2005) (0.26 and 0.15 for TMC and DPOAE at 4 kHz, respectively). In any case, the present study shows that the estimated degree of compression differs considerably depending on the method used to infer it (e.g., polynomial versus linear regression fits), which emphasizes the need to specify clearly the method used in every study.

The minimum compression exponent found here at 4 kHz (based on polynomial fits) is lower than previously reported values obtained with the same (or different) methods [e.g., 0.14, third-order polynomial, Nelson and Schroder (2004), 0.20, third-order polynomial, Plack and Drga (2003), 0.13, sum of linear and sigmoidal function, and 0.23, straight line, Rosengard *et al.* (2005), 0.20, straight line, Plack *et al.* (2004), 0.25, straight line, Lopez-Poveda *et al.* (2003)]. The difference in TMC-based estimates may relate to differences in the linear reference used by different studies. Here, the linear reference was the TMC for a masker frequency of $0.4f_P$, whereas the above-mentioned studies used the TMC for a masker frequency between $0.5f_P$ and $0.6f_P$. Lopez-Poveda and Alves-Pinto (2008) have suggested that the latter may still undergo as much as 2:1 compression; hence they could lead to an underestimate of the degree of on-frequency compression. The agreement between the present compression estimates obtained from TMCs and DPOAEs at 4 kHz provides circumstantial support to the conclusion of Lopez-Poveda and Alves-Pinto (2008).

B. DPOAE notches and plateaus

Notches and plateaus are common in the present DPOAE I/O curves (Figs. 4–7, especially at the lower f_2 (Table II). This contrasts with the conclusion of Kummer *et al.* (1998), who reported that notches and plateaus were less common when DPOAE I/O curves were measured with their proposed primary-level rule than with other rules. The Kummer *et al.* level rule is based on a group average and thus in some cases it may deviate considerably from the individual optimal (the optimal rule would be the one that evokes the strongest possible DPOAEs at all levels). Therefore, one possible explanation for the present observations is simply that the rule of the Kummer *et al.* (1998) was not optimal for the subjects used in the present study. This explanation is supported by Neely *et al.* (2005), who reported that L_1 should be systematically higher than prescribed by Kummer *et al.* (1998) and that the $L_1 - L_2$ relationship should vary with f_2. Johnson *et al.* (2006) confirmed the latter and further suggested that the f_2/f_1 ratio should vary slightly with f_2. Interestingly, it is for low frequencies and moderate–high stimulus levels where the rule of Kummer *et al.* deviates most from the rules of Neely *et al.* (2005) and Johnson *et al.* (2006). These are also the conditions where plateaus and dips are most common in the present data, which suggests that the rule of Kummer *et al.* is not optimal for the subjects considered in this study at low frequencies. On the other hand, Kummer *et al.* (2000) verified their original paradigm [derived from data of Gaskill and Brown (1990)] with a larger sample and still found it to be independent of frequency.

A second explanation for the plateaus and notches is that some of the DPOAE I/O curves still could have been influenced by the fine structure despite the precautions taken to minimize its effects. Plateaus occur for levels around 45–50 dB SPL (e.g., S1 and S8 at 1 kHz in Fig. 5; S3 at 4 kHz in Fig. 7), where the fine structure certainly can have influence. This is, however, an unlikely explanation for the notches because they always occurred at moderate-to-high levels (60–70 dB SPL) and the fine structure has a higher influence at low levels (Mauermann and Kollmeier, 2004).

A third explanation might be that another DP generation mechanism starts playing a role at high stimulus levels and notches reflect destructive interference between the DPs generated by this "new" high-level source and the normal source (see Mills, 1997). The measurement system is unlikely to be the source in question because a rather strict exclusion criterion was applied in the present study to eliminate system-generated DPs. Liberman *et al.* (2004) showed that genetically modified mice without the necessary prestin protein to drive outer-hair-cell electromotility still generated attenuated DP responses and thus supported the existence of a second possible DP-generation mechanism at high levels. Some of their DPOAE I/O curves showed notches at similar stimulus levels to the notches found in the current study. On the other hand, Avan *et al.* (2003) attributed low and high stimulus level DPOAEs to the same nonlinear mechanism. Also, Lukashkin *et al.* (2002) and Lukashkin and Russell (2002) have shown that a single saturating nonlinearity is sufficient to explain a notch in a DP I/O function.

C. The level at which the minimum compression exponent occurred

Low correlation was found between estimates of this parameter obtained with the two methods (DPOAEs and TMCs). The reason for this is uncertain. Maybe DPOAEs grow faster with increasing stimulus level at high stimulus levels because of the contribution from the second high level DP generation source discussed in the preceding sections.

D. Compression threshold

A moderately high correlation was found between compression-threshold estimates inferred with the two methods [Fig. 9(B)]. DPOAE-based estimates were, however, on average 7 dB lower than TMC-based estimates. A total of 22 I/O curves were measured in the ten subjects, but the compression threshold could be estimated in only 14 of these 22 cases. This could be interpreted as an argument against the apparent equivalence of the two methods with respect to estimating this parameter. Further analysis reveals, however, that there are good reasons why a compression threshold could not be estimated in the remaining eight cases. Four of them corresponded to DPOAE I/O curves at 0.5 kHz (Fig. 4) that extended over a range of input levels above 45 dB SPL that was too narrow to reveal a compression threshold. Another case was S4 at 4 kHz (Fig. 7), who did not have sufficiently strong DPOAE despite her hearing threshold being normal at that frequency. For the three remaining cases, the TMCs did not show a clear compression threshold or did not reach the criterion slope of 0.4 dB/dB (see Sec. III D). These cases were S1 at 2 kHz in Fig. 6; S3 and S4 at 1 kHz in Fig. 5. Three of the 14 cases where both methods demonstrated a compression threshold were considered outliers and excluded from the comparison of compression threshold: S1 at 4 kHz, and S5 and S8 at 1 kHz [depicted as circles in Fig. 9(B)]. The data for S5 and S8 were excluded because these listeners had great difficulties performing the TMC task (they needed six to eight attempts at high masker levels to obtain three measurements each having a standard deviation below

6 dB; Sec. II C). There was no obvious reason to exclude the data point of S1. This data point corresponded to the first condition on which the subject was tested and he might not have been sufficiently trained. In any case, it is noteworthy that DPOAE I/O curves allow estimating a compression threshold much more easily than do TMC-based I/O curves.

The reason why DPOAE-based compression threshold estimates were lower than corresponding TMC-based estimates is uncertain. Maybe the DPOAE response was influenced by mutual suppression of the primaries. This could have linearized the I/O curve (e.g., by decreasing cochlear gain) and thus *increased* the compression threshold suggested by DPOAE I/O curves. This explanation does not fit the data as the actual compression thresholds estimated from DPOAEs were *lower* than those estimated from TMCs. Perhaps the difference in compression threshold estimate for the two methods is caused by the use of suboptimal DPOAE parameters (see Sec. IV B).

The moderately high correlation between the compression-threshold estimates of the two methods also at low frequencies [Figs. 9(B), 10(E), and 10(F)] may seem surprising given the low correlation between the estimates of minimum compression exponent. One possible explanation could be that the DPOAE parameters were adequate for lower L_2, where the compression threshold occurs, but not for higher L_2 levels, at which, coincidentally, plateaus and notches occur.

The average compression threshold estimates at 4 kHz found in the present study were 47 and 40 dB SPL for TMC and DPOAE, respectively. These values are comparable to those (average 37 dB SPL at 3–4 kHz) found psychophysically by Yasin and Plack (2003) based on a three-line segment fitting procedure (Plack *et al.*, 2004). A value of ~35 dB SPL is obtained when applying the present definition of compression threshold to the DPOAE data of Neely *et al.* (2003). A compression threshold was also estimated from the DPOAEs reported by Gorga *et al.* (2007). After discarding their data for lowest stimulus levels because they were most likely contaminated by noise and applying the definition used in the present study (level at which I/O curve slope equals 0.4 dB/dB) to their data in their Fig. 3, the resulting compression thresholds were 30 and 45 dB SPL at 0.5 and 4 kHz, respectively. The present values are reasonably in accordance with their results at 4 kHz but not at 0.5 kHz. Our results indicate that the compression threshold is approximately constant across frequencies [Figs. 10(E) and 10(F)].

E. Gain and the level of return to linearity

It is still controversial that BM I/O functions become linear at very high input levels in healthy cochleae (Robles and Ruggero, 2001). Assuming, however, that this is a truly physiological characteristic, DPOAEs are not considered a reliable predictor of the threshold level of return to linearity at high levels. First, there may be another mechanism involved in generation of DPOAE at the higher stimulus levels, as explained above (Sec. IV B). Second, the best frequency of any BM site shifts with increasing level, hence the BM site where the two primaries cause maximum excitation is likely to shift accordingly with level. This may change the DPOAE response as the region of overlap of the two primaries changes with level. Because of this, the gain and return-to-linearity thresholds were not estimated based on DPOAE I/O curves and not compared with those inferred from TMCs.

The TMC-based I/O curves suggested that the cochlear gain increased with increasing CF because of a parallel increase in the threshold of return to linearity at high levels (Fig. 11). This is in agreement with physiological data (Robles and Ruggero, 2001). Gain estimates based on tip-to-tail level differences of DPOAE suppression tuning curves (Gorga *et al.*, 2008) showed the same tendency for the gain to decrease with decreasing frequency.

F. On the merits of the DPOAEs and TMCs for estimating cochlear I/O curves

The presence of plateaus and notches in the DPOAE I/O curves at 0.5 and 1 kHz results in zero or negative compression-exponent estimates which do not occur in corresponding TMC-based curves. While deep notches in apical BM I/O functions have been reported [e.g., Fig. 7(a) of Rhode and Cooper (1996)], they typically occur for stimulation frequencies higher than the CF (Rhode and Cooper, 1996). Therefore, the notches reported here are unlikely to reflect notches in the underlying BM responses (see also Sec. IV B).

It would be wrong to conclude, however, that it is inappropriate to use DPOAEs to infer cochlear I/O functions at low frequencies. As discussed earlier (Sec. IV B), the present notches are possibly due to using suboptimal primary levels at low frequencies and it might be possible to find DPOAE stimulus parameters that would lead to higher correlations between TMC-based and DPOAE I/O curves.

It would also be wrong to conclude that I/O curves inferred from TMCs are more correct (i.e., reflect more closely the underlying BM responses) than DPOAE I/O functions at low frequencies. The TMC method is an indirect, psychophysical method, thus its results may be influenced by retrocochlear mechanisms unknown to date. Indeed, there exist within-subject differences between I/O functions inferred with different psychophysical methods (e.g., Rosengard *et al.*, 2005). Furthermore, the TMC method rests on several assumptions, the main of which is that the rate of decay of the internal masker effect is identical across frequencies and levels (Nelson *et al.*, 2001; Lopez-Poveda *et al.*, 2003). The validity of these assumptions is still controversial. Stainsby and Moore (2006) have argued that the decay rate is faster for low probe frequencies (or equivalently, low CFs), at least for hearing-impaired listeners. By contrast, Lopez-Poveda and Alves-Pinto (2008) have provided indirect evidence for frequency-independent decay rates, at least for normal-hearing listeners. Additionally, there is evidence that for any given frequency, the decay rate is slower at high levels (Lopez-Poveda and Alves-Pinto, 2008; Wojtczak and Oxenham, 2007). These issues complicate the selection of the linear reference TMC and thus cast doubts on the corresponding I/O curves, particularly at low frequencies (Stainsby and Moore, 2006; Lopez-Poveda and Alves-Pinto, 2008).

In summary, the lack of correlation between the results of the two methods at low frequencies is uninformative at present of their relative accuracy for inferring cochlear I/O curves. Future studies should investigate the reason for the low correlation at low frequencies and whether higher correlations would be obtained using different DPOAE parameters and/or different psychophysical methods or assumptions.

The present study did not evaluate the merit of DPOAE I/O curves as a (*clinical*) tool for assessing residual cochlear compression characteristics in hearing-impaired listeners. The present results, however, suggest that they might be useful to assess residual compression in listeners with presbyacusis, who are mostly affected by high-frequency loss.

V. CONCLUSIONS

(1) The correlation between individual compression exponent estimates inferred from TMCs and DPOAEs is reasonably high at 4 kHz, but low at 0.5 and 1 kHz. Both methods suggest that maximum compression is approximately 10:1 and constant across the characteristic frequency range from 0.5 to 4 kHz.
(2) The low correlation at low frequencies cast doubts on the postulates and interpretation of I/O curves inferred with either (or both) of the two methods. The most likely reason for the lack of correlation at low frequencies (0.5–1 kHz) is the presence of notches and plateaus in the DPOAE I/O curves. This suggests that the DPOAE stimulus paradigm of Kummer *et al.* (1998) may not be optimal (i.e., does not produce maximum DP magnitude) at low frequencies.
(3) A high correlation was found between estimates of compression threshold inferred from DPOAEs and TMC-based I/O curves between 1 and 4 kHz. The DPOAE and the TMC methods indicate that the compression threshold equals 40 and 47 dB SPL, respectively, and is approximately constant across the range of frequencies from 0.5 to 4 kHz for TMCs and from 1 to 4 kHz for DPOAEs.
(4) Cochlear gain and return-to-linearity thresholds were inferred from the TMCs only. Both parameters increased by ~16 dB with increasing characteristic frequency from 0.5 to 4 kHz.
(5) It seems reasonable to use TMCs and DPOAE I/O curves interchangeably to infer cochlear I/O curves at 4 kHz but doubts exist that the same applies to lower frequencies of 0.5 and 1 kHz.

ACKNOWLEDGMENTS

The authors are grateful for the comments and suggestions provided by two anonymous reviewers to improve an earlier version of this paper. This work was supported by IMSERSO 131/06, PROFIT CIT-390000-2005-4, MEC BFU-2006-07536, and The Oticon Foundation.

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