Laser Doppler vibrometry of the middle ear in humans: derivation dependence, variability, and bilateral differences

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Key words: *laser Doppler vibrometry; derivation dependence; variability; bilateral differences.*

Summary. *Objective. Derivation dependence, inter- and intrasubject/intertest variability, bilateral differences of the eardrum vibration characteristics have been investigated using laser Doppler vibrometry (LDV).*

Material and methods. A total of 31 normally hearing adults were examined. In each subject, both ears were consecutively stimulated by the chirp acoustic stimulus that covered 500–3700-Hz frequencies. The laser beam was directed to and the reflection was consecutively picked up from the tympanic membrane surface.

Results. LDV curves derived from different eardrum loci possessed dissimilar characteristics. The derivation area dependence was particularly apparent for the stimulus frequency constituents above 1500 Hz. The intersubject variability of LDV parameters exceeded the intrasubject/intertest one. The intersubject divergences looked selectively distinct for the frequencies over 2000 Hz. Under repeated recordings, LDV parameters remained stable. The intertest differences, if appeared, concerned predominantly the magnitudes of separate frequency bands. LDV waveforms registered by experienced and beginner investigators were alike. Bilaterally derived LDV curves regularly differed from each other. In individual cases, the bilateral divergences approximated the intersubject deviation.

Conclusions. The derivation area on the eardrum should be taken into account when estimating the actual LDV recording. Over repeated recordings in separate individuals, LDV waveforms are stable while the experience of investigator has slight if any influence on the principal LDV characteristics. Due to bilateral differences in the middle ear transfer function, in LDV testing of the ear suspected to the pathology, LDV recording from the opposite healthy ear could hardly be taken as an appropriate reference sample.

Introduction

Ordinary clinical tests for evaluation of the middle ear function can fail the definite diagnosis, especially in cases of a conductive hearing loss but of an intact eardrum and normal tympanic ventilation.

At the beginning of the 1990s, utilizing commercially available laser Doppler vibrometers, the method of an optical estimation of the tympanic membrane displacements has been implemented in the armament of the middle ear diagnostic tools (1–3). The measurement of the eardrum vibration pattern was proved as a noninvasive, safe, and objective approach for investigation of transtympanic conduction properties. Earlier the tympanic membrane motions have been investigated in animals (4–6) as well as in temporal bones of human cadavers (7–11). Later the technology of the laser Doppler vibrometry (LDV) was utilized in clinical studies too (12–15). Recently, the systematic data on the tympanic membrane vibration characteristics were collected in normally hearing individuals (16).

In spite of positive qualities, e.g. of noninvasiveness and reproducibility, the LDV procedure has not been introduced up to now in a wide clinical practice. The high costs of devices and divergences in methodology of measurements appear to be the principal causes of implementation shortages (12, 17). The sound application technique and the coupling of the laser source to the microscope create additional difficulties. Various self-developed equipments have been

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elaborated while just dissimilar setups could be the further reason of discrepancies of separate results (14). At present, no regular technical protocol exists for the clinical LDV assessments. To diminish the potential artifacts, LDV options need thus improvements and standardization, the methodological variety being hardly tolerable with the diagnostic routine (1, 3, 14).

Derivation dependence, waveform variability, and bilateral differences of LDV outcomes were the principal objectives of present investigations. To fulfill the first goal, the LDV curves picked up from distinct eardrum loci have been compared. In the second experiment, the LDV waveforms acquired in different subjects as well as in same individuals over consecutive examination days were matched while the measurements carried out by experienced and beginner examiners were also collated. Intersubject differences and intrasubject/intertest variability of LDV measurements as well as the dependence of the quality of recordings upon investigator's experience were assessed thus. To reach the third aim of experiments, the systematic data were collected on LDV waveforms registered in same individuals from one and another ears. The interest to bilateral LDV peculiarities has been emphasized by the scarcity of respective previous attempts (16).

The purposes of the study were realized utilizing an improved system for sound presentation and LDV construction. The advanced module ensures a strict determination of middle ear transfer function while it is simple for use and is safe hygienically. The results of designed investigations have been expected to promote the utilization of LDV technique for proper diagnosis of middle ear pathologies.

Material and methods

The measurements were carried out in the Hearing Research Laboratory, Clinic of Otorhinolaryngology, Dresden Technical University. A total of 31 volunteers from the clinical staff have been examined: 17 females and 14 males. The age ranged from 20 to 59 years. The mean age was 34.6 years. In each subject, the investigation was performed bilaterally. Sixty-two ears have been tested at all. No history of the ear disorder has been discerned in any case while the current otoscopy did not reveal in any individuals either external ear or tympanic membrane pathology. All subjects exhibited normal hearing thresholds within the checked audiometrical band of 250–8000-Hz frequencies. All subjects held also normal tympanograms and acoustic reflexes as well as displayed ordinary recordings of evoked otoacoustic emissions (EOAEs).

During inspection, the subject laid on own back with the tested ear facing upward. The stimulation was accomplished by the chirp acoustic stimulus delivered through the outer ear canal. The elicited motions of the tympanic membrane were measured by the laser Doppler vibrometer (Polytec CLV 700). The laser beams of a 0.1-mm diameter were focused on and the reflections were consequently derived from eight points of a tympanic membrane (Fig. 1). For the hygienic and convenience logic, the microphone (KE4, Sennheiser) and the specially selected sound generator (KDH6, Sennheiser) were integrated into a single system being placed on the external ring of the ear speculum. The combined unit only slightly exceeded in dimensions the device conventionally utilized in otomicroscopy. For the measurement of sound pressure, the tip of the microphone was positioned at 3-mm distance from the eardrum surface. The probe microphone was calibrated with the reference one. The attained calibration curves were integrated into a signal operation module. The self-elaborated system of the signal processing was employed, being based on the LabVIEW software (National Instruments Incorporation). As it is habitual, a closed sound delivery set-up was preferred to use by applying a glass cover slip to produce an airtight seal and to ensure thus the demanded high sound pressures, in general, at lower stimulus frequencies, in particular.

The delivered acoustic stimulus comprised 36 logarithmically distributed frequencies in the range of 500–3700 Hz. Due to performed adaptation procedures, the sound pressure on the eardrum actually did not change with a frequency. In the vicinity of the tympanic membrane, the stimulus intensities amounted to 80–90 dB SPL. The magnitudes of the frequency response function ($FRF_{u/p}$) of the umbo displacement

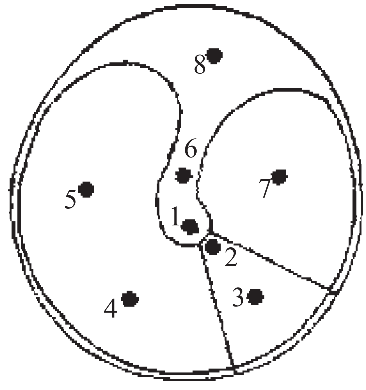

Fig. 1. **Tympanic membrane points (1–8) selected for laser Doppler vibrometry derivation**

versus the sound pressures in the front of the tympanic membrane have been calculated, using the following equation:

$$FRF_{u/p} = \frac{U_{Umbo}\, P_T^*}{P_T\, P_T^*} ,$$

where U_{Umbo} represents the Fourier-transformed umbo displacement, P_T corresponds to the Fourier-transformed sound pressure, and the mark (*) designates a complex conjugated value. The phase angles of the frequency spectral constituents have been simultaneously determined.

To exam the derivation dependence of LDV measures, the laser beam has consecutively been focused on eight selected points of a tympanic membrane, and a site-specific transfer function of the middle ear has been calculated. The intersubject variability of LDV results was compared with the intrasubject one. To be convinced in the reliability of separate test-trials, in some subjects the standard LDV procedure has been repeated two times, each on a separate day while the obtained results were collated. The dependence of a derivation quality on the skillfulness of the investigator has been defined also. To realize the latter purpose, LDV manipulations were executed by experienced and beginner otologists, and the attained data were collated. To match the middle ear transfer characteristics in one and another ear, in each involved individual, similarities and differences of bilaterally derived LDV curves were systematized. The group data were systematically calculated and elaborated. Means and standard deviations as well as 90% tolerance limits were determined, while the significance of bilateral differences of LDV measures were checked statistically by applying the *t* test for the matched pairs.

The Institutional Review Board of the Dresden Technical University judged the planned investigations as safe for tested subjects and to be thus in an agreement with the principles of the Declaration of Helsinki.

Results

Derivation dependence

The LDV curves picked up from different eardrum regions possessed dissimilar characteristics (Fig. 2). The derivation area dependence was selectively distinct with respect to stimulus constituents of frequencies above 1500 Hz. Regarding just to the high frequency band, the vibration features were different even in nearby eardrum loci, e.g. in points 1 and 2 of the tympanic membrane sketch. With respect to lower frequency constituents, below 1500 Hz, the eardrum point-to-point discrepancies of LDV properties seemed less evident. Point 1, the most anterior-inferior region on the bony part of the umbo, appeared to be the most suitable zone for estimation of tympanic membrane motions. At this particular eardrum area, the reproducibility of LDV recordings was the best.

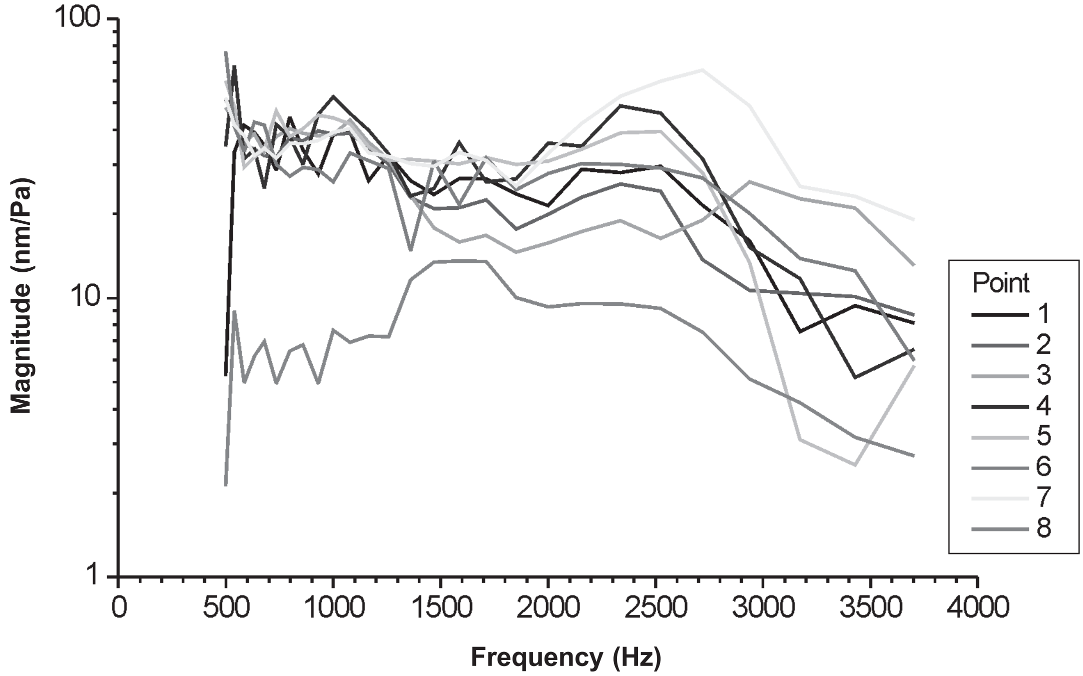

Fig. 2. **Magnitudes of laser Doppler vibrometry waveforms derived from different tympanic membrane loci (points 1–8) in a representative test-subject**

Correspondingly, it most reliably characterized the individual LDV patterns.

Variability

The differences between LDV curves registered in diverse subjects regularly exceeded those between LDV waveforms built up in separate individuals under successive test trials. The intersubject variance of LDV characteristics definitely surpassed thus the intrasubject/intertest variability. The magnitude values of about 90% of individual LDV recordings fell in the range of ±5 dB of the group mean. At lower frequency spectral constituents of acoustic stimuli, below 2000 Hz, the distribution of personal LDV magnitudes appeared narrower (Fig. 3). At higher frequencies, above 2000 Hz, the deviation pattern was broader covering the band of ±10 dB over the means. The phase scores in most subjects were within the

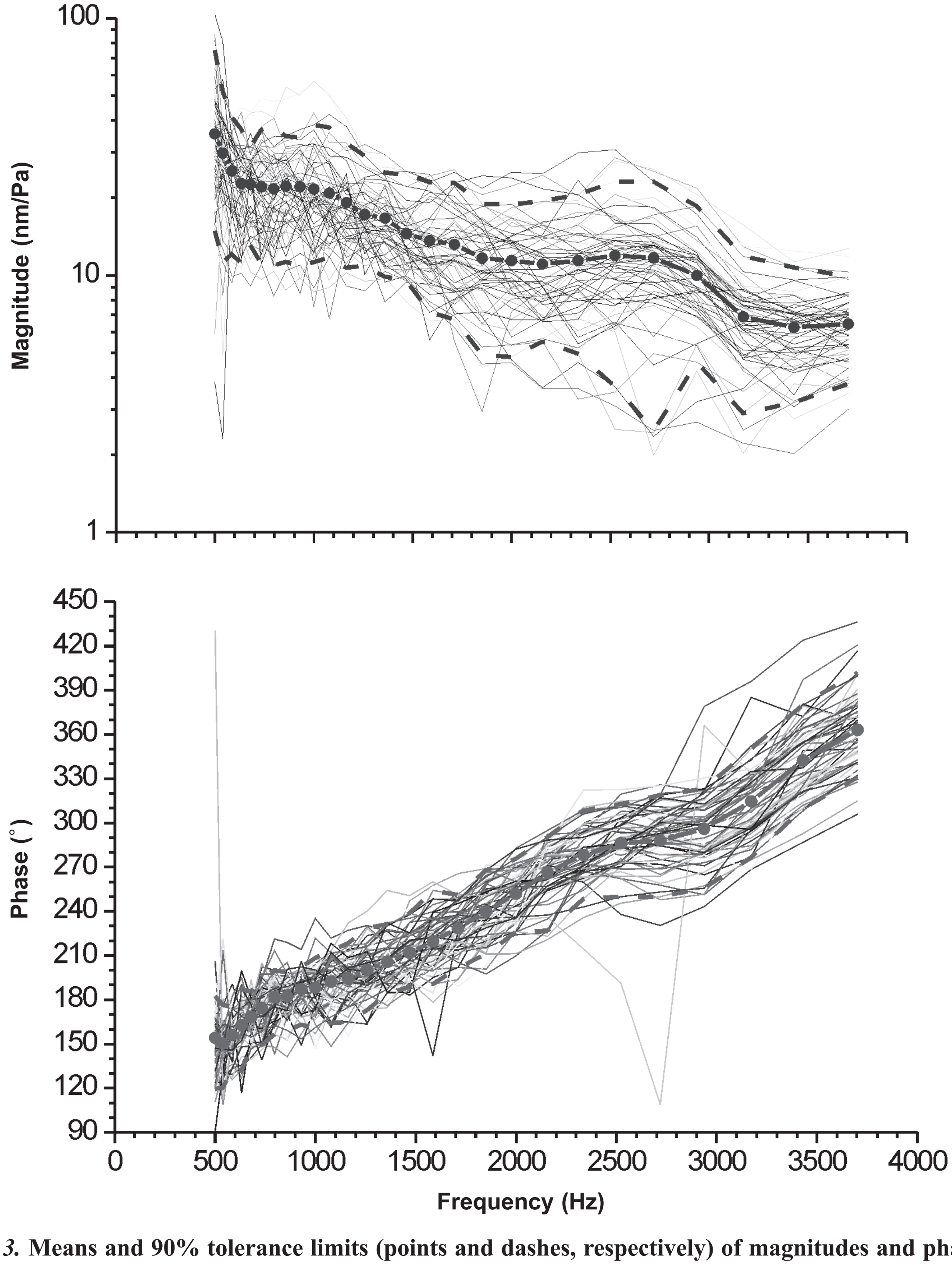

Fig. 3. **Means and 90% tolerance limits (points and dashes, respectively) of magnitudes and phases (in this and in following figures upper and lower panels, respectively) of laser Doppler vibrometry waveforms derived from point 1 of the tympanic membrane in all inspected ears (N=62)**

range of ±30 degrees of the means. The group distribution of phase values, similar to that of magnitude measures, looked tighter at lower than at higher stimulus spectral ingredients (Fig. 3).

General patterns and principal characteristics of the LDV recordings were steady over the time. The test-retest reproducibility of the LDV results in individual subjects was thus high enough. The LDV curves built up in the same test-persons from the same tympanic membrane loci but on different examination days as a rule closely resembled each other (Fig. 4). The intertest variability of both magnitudes and phases, if appeared, concerned preferentially the details of separate frequency bands rather than the general LDV patterns. No systematic differences in LDV characteristics were detected between the cases in which the derivation procedures were performed by the experienced investigator or by the beginner (Fig. 5).

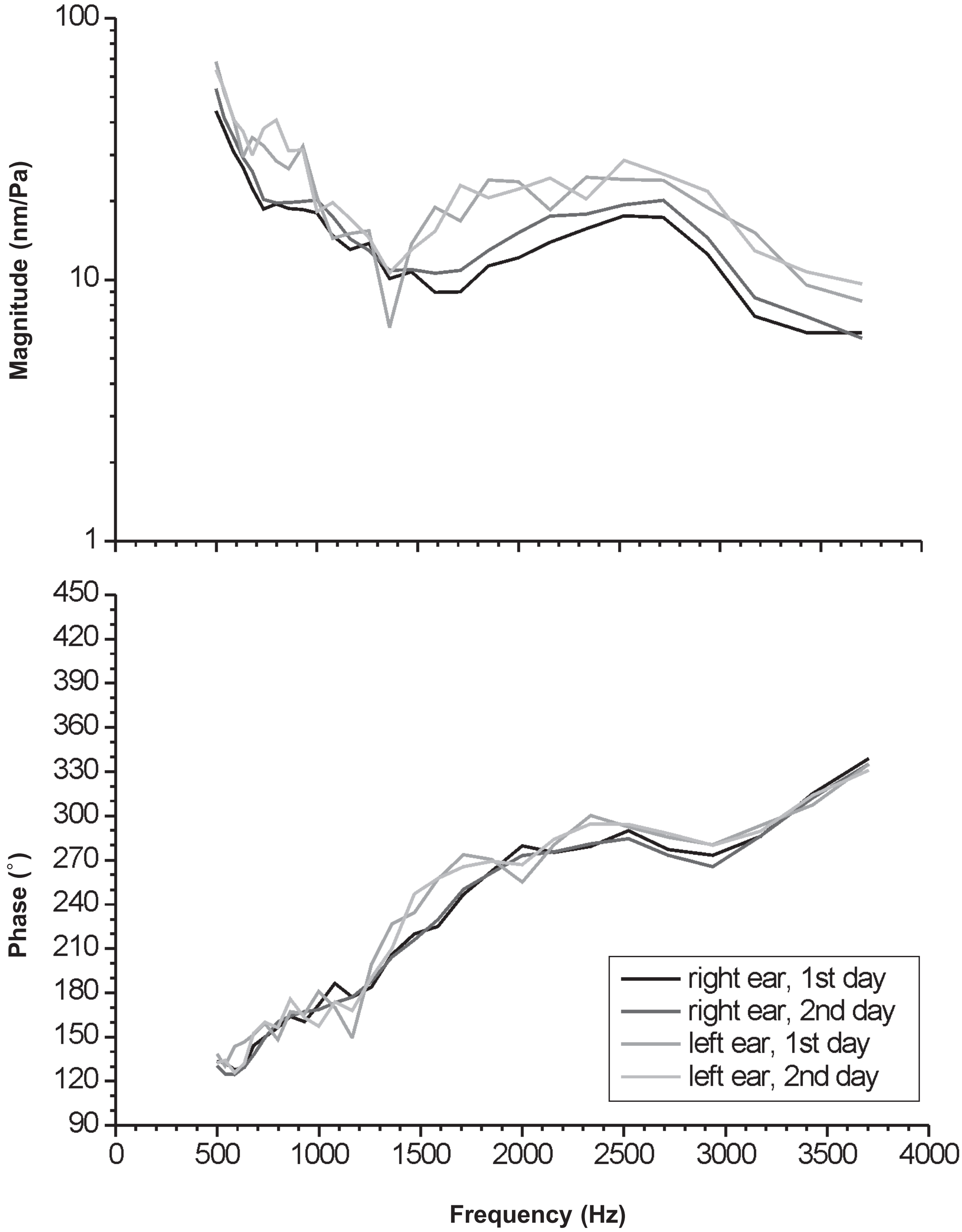

Fig. 4. **Magnitudes and phases of laser Doppler vibrometry waveforms derived from point 1 of the tympanic membrane of the right and left ears in a representative test-subject at two consecutive days (1st day and 2nd day, respectively)**

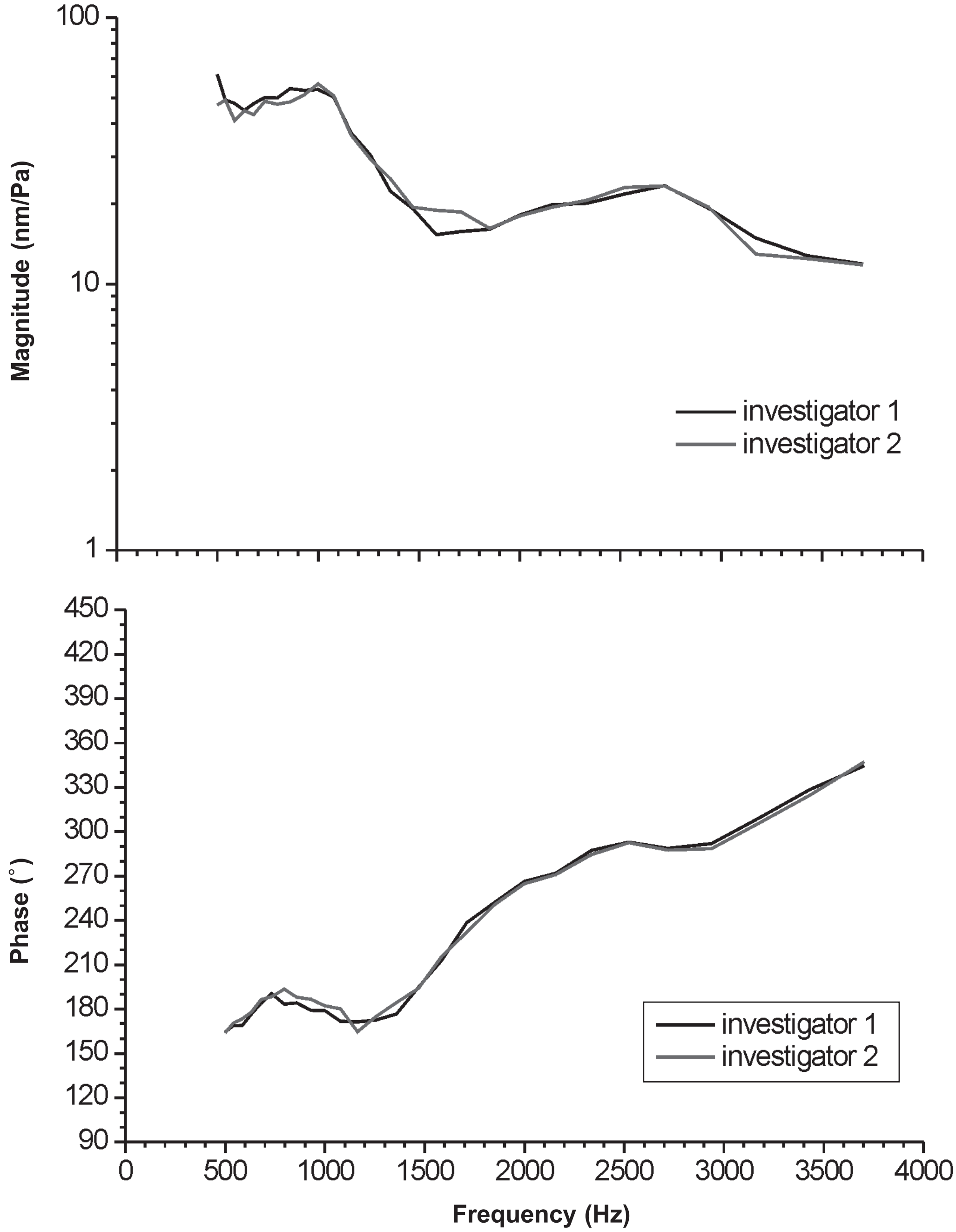

Fig. 5. **Magnitudes and phases of laser Doppler vibrometry waveforms derived from point 1 of the tympanic membrane of the right ear in a representative test-subject by experienced and beginner investigators (1 and 2, respectively)**

Bilateral differences

Both magnitude and phase characteristics of LDV curves constructed in separate individuals from one and another ear appeared statistically dissimilar for measured frequencies ($P<0.05$). A tight resemblance of bilaterally derived LDV curves has never been observed. On the opposite, the LDV designs from two ears in most subjects noticeably differed from each other (Fig. 4). In individual cases, the interaural dissimilarity was eminent and approximated the intersubject one. The differences were manifested in general LDV waveforms as well as in magnitude peaks and troughs and phase angles. The bilateral divergences in LDV amplitude measures were particularly obvious and fell within the range of 5–10 dB in 10 out of 31 tested subjects (32.3%).

Discussion

Derivation dependence

The strict dependence of LDV characteristics on localization of the laser beam on the tympanic membrane has been found in the present experiments. The performed investigations demonstrated that the bony segment of the umbo most reliably reproduces the middle ear vibration features. To achieve the stability of recordings, just this area is recommended therefore to choose for derivation point on a tympanic membrane. The present data fit well with the former holographic studies (18), which displayed the differences in tympanic membrane motion characteristics even under subtle shifts in a drum derivation area. The topographical dependence of the LDV results per se designates the significance of a derivation area in the data reproducibility.

Variability

According to the results of the present study, the LDV characteristics in separate individuals differ significantly. The intersubject variability of LDV properties has been similarly stated earlier (16). It was attributed to the individual peculiarities of the static pressure in the tympanic cavity as well as to those of the background tension of the middle ear muscles. The LDV divergences were also explained by removing the coupler and the subsequent reposition of the laser beam. In our experiments, the LDV design in separate individuals demonstrated a remarkable stability over the time while the experience of the investigator hardly had any distinct influence on the outcome of the measurement. The registered LDV patterns seemed thus to reflect the genuine interindividual differences in the middle ear transfer characteristics rather than the predicted variations in the laser beam focusing.

Bilateral differences

According to the results of performed experiments, in separate subjects, the LDV recordings from both ears differ from each other, in individual persons the degree of bilateral dissimilarities reaching that of intersubject deviations. The umbo transfer function in one and another ear of the same subjects has been matched earlier (16). The comparisons proved likely the bilateral resemblance, although far not all bilaterally constructed LDV curves demonstrated a strict correlation. Considering the high probability of intrinsic bilateral differences in the umbo transfer function, in LDV testing of the ear, suspected to the pathology, the LDV curve of the opposite healthy ear can hardly be taken as an appropriate reference sample.

In previous investigations (19), the dissimilarities were found in both general patterns and magnitudes of EOAEs derived from two ears in the same normally hearing individuals. The bilateral divergences were attributed to the peculiar distribution of the outer hair cells, i.e. of the sources of EOAEs, in the organ of Corti in each ear. Proceeding from the present data, the bilateral EOAE differences can additionally be assigned to the bilateral variances in the middle ear transfer function. The latter can specify the sound transmission from the outer ear canal through the middle ear to the cochlea as well as the backward conduction of an EOAE from the site of its generation in the inner ear to the derivation point in the outer ear canal. The interaural dissimilarity in umbo vibration characteristics implies the existence of an effective mechanical share in discrepancies evident in bilaterally recorded EOAEs. The matching of bilateral differences in the middle ear transfer function and in the EOAEs in the same individuals seems perspective for further clarification of the issue.

Clinical application

The LDV procedure can be regarded as a method of choice for estimation of a tympanic membrane and middle ear ossicular chain function. The requirements for the successful application of LDV technique in clinical practice remain nevertheless dubious. The occurrence of mini vibrometers on a market of medical instruments can solve the problem of their coupling with conventional operation microscopes. The linkage can per se provide a reliable mobility of devices as well as rapidity and facility of measurements. The LDV procedure could be fulfilled within 5–8 minutes. According to our experience, it is generally feasible to achieve a reliable LDV recording from actually every eardrum loci with an adequate signal-to-noise ratio without utilizing additional reflectors that had been regularly employed previously (1, 12).

The hearing benefit of the tympanoplasty in rather many cases remains unsatisfactory (20, 21), while just the LDV technique seems to be the perspective procedure for the proper estimation of the postoperative middle ear transfer function (22).

As an objective tool for the search of the middle ear transfer function, the LDV method discloses new opportunities in inspecting of intrinsic mechanisms of audition. The LDV procedure can successfully be utilized for determination of the middle ear share in preferentially inner ear and/or central neural processes. It appears desirable, for example, to investigate the involvement of middle ear structures in fluctuation of hearing during the daytimes and across the days. The influence of middle ear muscles on umbo transfer function has been evaluated earlier (16). The comparison of LDV curves established before and after application of curare-type muscle relaxants seems particularly attractive for specification of details of participation of intratympanic muscles in middle ear transfer processes.

Conclusions

1. At various eardrum derivation loci, the characteristics of laser Doppler vibrometry are different.

2. The intersubject variability of laser Doppler vibrometry measures exceeds the intrasubject/intertest variability.

3. The experience of investigator has no essential influence on the outcome of laser Doppler vibrometry measurements.

4. The laser Doppler vibrometry waveforms derived in separate subjects from one and another ear are mostly different.

Žmonėms atliekama vidurinės ausies lazerinė Doplerio vibrometrija: priklausomybė nuo matavimo vietos, kintamumas, skirtumai tarp ausų

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Raktažodžiai: lazerinė Doplerio vibrometrija, priklausomybė nuo matavimo vietos, duomenų kintamumas, skirtumai tarp ausų.

Santrauka. *Tyrimo tikslas.* Ištirti lazerinės Doplerio vibrometrijos pagrindinių parametrų skirtumus tarp ausų, priklausomybę nuo matavimo vietos bei duomenų kintamumą.

Tirtųjų kontingentas ir tyrimo metodai. Tyrime dalyvavo 31 normaliai girdintis suaugęs asmuo. Kairioji ir dešinioji ausys buvo stimuliuojamos signalais, kurių dažnis – nuo 500 iki 3700 Hz. Lazerio spindulys buvo nukreiptas į ausies būgnelį, o jo atspindys atitinkamai nuskaitomas.

Rezultatai. Įvairių ausies būgnelio taškų vibrometrijos kreivės turėjo skirtingų savybių. Kreivės ypač skyrėsi, kai stimulo dažnis buvo didesnis nei 1500 Hz. Vibrometrijos parametrų kintamumas tarp subjektų viršijo skirtumus tarp ausų bei atskirų matavimų. Nuokrypiai tarp subjektų buvo ypač akivaizdūs, kai stimulo dažnis viršydavo 2000 Hz. Kartojant tyrimus, vibrometrijos parametrai išliko pastovūs. Tyrimus atliekant tiek patyrusiam tyrėjui, tiek mažai patirties turinčiam tyrėjui, vibrometrijos kreivių bangų formos buvo panašios. Abiejų ausų vibrometrijos kreivės tolygiai skyrėsi viena nuo kitos. Tam tikrais atvejais skirtumai tarp ausų buvo žymūs ir beveik prilygo skirtumui tarp subjektų.

Išvados. 1. Atliekant vibrometrinius tyrimus, reikėtų atsižvelgti į matavimo vietą ausies būgnelyje. 2. Užrašant tyrimo subjektų ausų vibrometrijos rodmenis, kreivių bangų forma išlikdavo pastovi, o tyrėjo patirtis neturėjo didelės įtakos tirtiems rodmenims. 3. Atliekant klinikinius vibrometrijos ausų patologinių pokyčių tyrimus, nerekomenduojama remtis sveikosios ausies kreive dėl galimo didelio skirtumo tarp ausų.

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