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CHARACERIZING THE OUTER EAR TRANSFER FUNCTION IN DEPENDENCE OF INTERINDIVIDUAL DIFFERENCES OF OUTER EAR GEOMETRY

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ABSTRACT

The outer ear transfer function can be used to describe the influence of the outer ear canal and its geometric variance in cross-section as well as its path on the sound field in the ear canal and the sound pressure level resulting at the ear drum.
The variance of outer ear geometry is described by analysis of polysiloxane castings of the outer ear. Algorithms are developed to determine various parameters of the outer ear geometry and to gain access on a huge amount of data (over 100.000 data sets).
Sound transmission in form of the outer ear transfer function is analyzed for various outer ear geometries using a finite element model as well as an experimental setup. In both cases sound (frequency band: 20 Hz to 20 kHz) is send to a model of the outer ear as a plane wave parallel to the plane of the *Pinna*.

Index Terms – Acoustics, sound, outer ear, transfer function, finite element method

1. INTRODUCTION

The outer ear transfer function (OTF) can be seen as a part of the head-related transfer function (HRTF). HRTFs describe sound transmission from a point in space to the eardrum and depict various effects which transform the sound received at the ear drum. These for example may be term differences to the two ears and diffraction as well as reflection effects at anatomical structures of the body [BLAUERT 1997]. Various studies could already show a strong frequency-specific influence of the body, neck and head [SHAW 1974, ZENNER 1994]. Especially the ear canal and its huge geometric variance in cross-section as well as what concerns its path have a strong influence on the complex sound field in the ear canal [HUDDE & SCHMIDT 2009, STINSON & DAIGLE 2008] and the sound pressure level resulting at the ear drum [BLAU et al. 2010].
This study focuses on the variance in outer ear geometry and its interindividual influence on the OTF.

2. MATERIAL AND METHODS

2.1 Outer ear geometry

The variance of outer ear geometry is described by analysis of polysiloxane castings of the outer ear, taken by default during the manufacturing process of hearing aids or hearing protection systems by hearing-aid acousticians [HELBIG et al. 2015a]. (Semi-) automatic algorithms were developed to determine various parameters of the outer ear geometry (see fig. 1) and to gain access to this huge amount of data (typically over 100.000 data sets per acousticians), to make scientific use of it [HELBIG et al. 2015b].

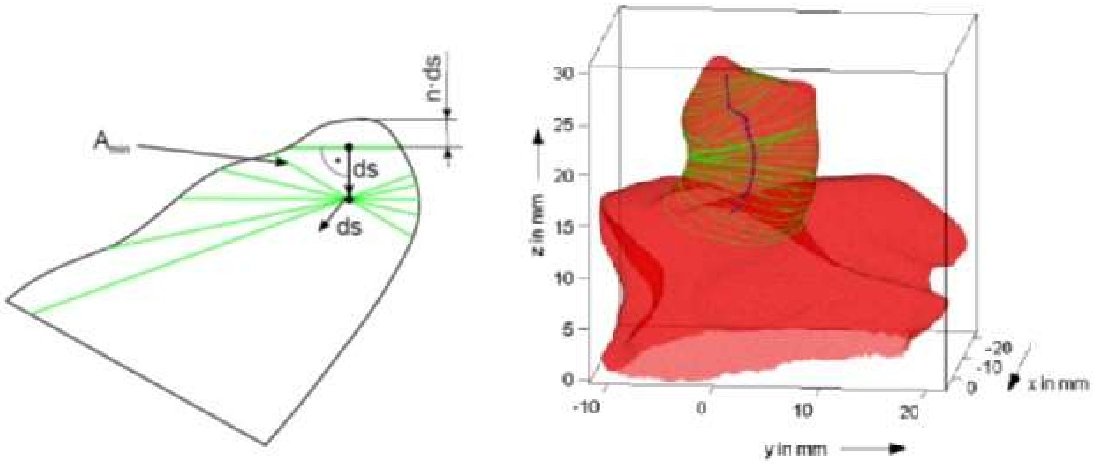

Fig. 1: Analysis of the outer ear canal geometry [HELBIG et al. 2015b]. left – Calculation of following cross sectional areas in the outer ear canal. A new pivot point is found by orthogonal translation *ds* of the known centroid. By three-dimensional rotation of a plane around this pivot point a new cross sectional area with A_{min} is determined, right - automated segmentation of the path (blue) and cross-sections (green) of the ear canal in a digitalized geometry of a polysiloxane casting.

2.2 Outer ear transfer function

Sound transmission is analyzed for various outer ear geometries using a finite element model [BANCES et al. 2014, HELBIG et al. 2016] in COMSOL® Multiphysics (see fig. 2a)) as well as an experimental setup (see fig. 2b)) [HELBIG et al. 2017].

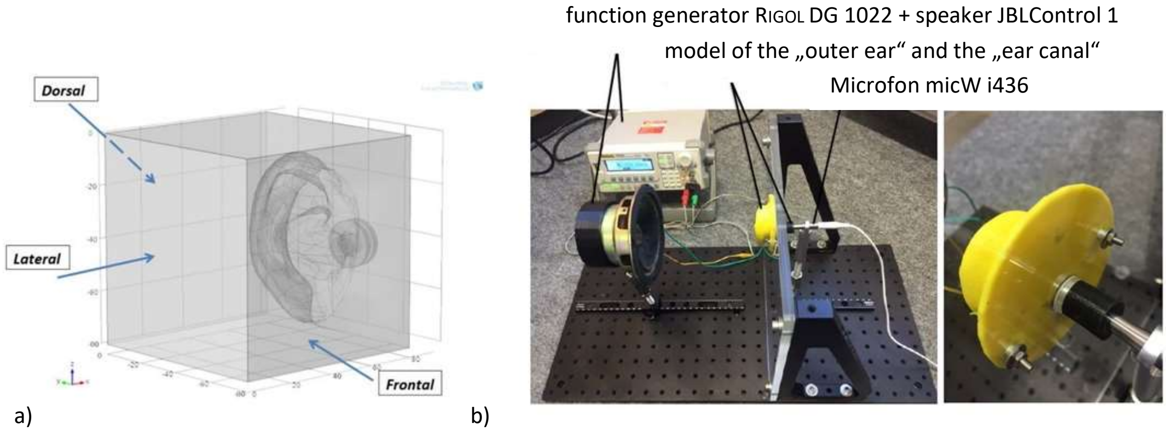

Fig. 2: Analysis of sound transmission in the outer ear. a) Outer ear model for a finite element simulation following BANCES et al. 2014 with an outer ear canal emulator 711 (IEC 60318-5) in the volume for simulation (pinna-box) [HELBIG et al. 2016, p. 330]. b) Experimental setup for analysis of sound transmission and functional tests of hearing protection systems [HELBIG et al. 2017, p. 101]. left – lateral overview, right – detail of the outer ear model (yellow) with the model of the outer ear canal (black) attached to a plexiglas disc. A measuring microphone type micW i436 is inserted into the back of the outer ear canal model to measure sound pressure level in the imaginary plane of the ear drum.

In both cases sound (frequency band: 20 Hz to 20 kHz) is sent to different models of the outer ear (see fig. 3) as a plane wave parallel to the plane of the *Pinna* (= lateral sound source). Outer ear models were designed using the scan of a *Pinna* of an artificial head (type KU-80, Georg Neumann GmbH) and scans of different polysiloxane castings selected for and fitted to the

Pinna [HELBIG et al. 2016]. The models of the outer ear for the experimental setup were fabricated using fused deposition modeling and materials of different stiffness [HELBIG et al. 2017]. Sound pressure level was analyzed in an imaginary plane close to the approximated natural ear drum position.

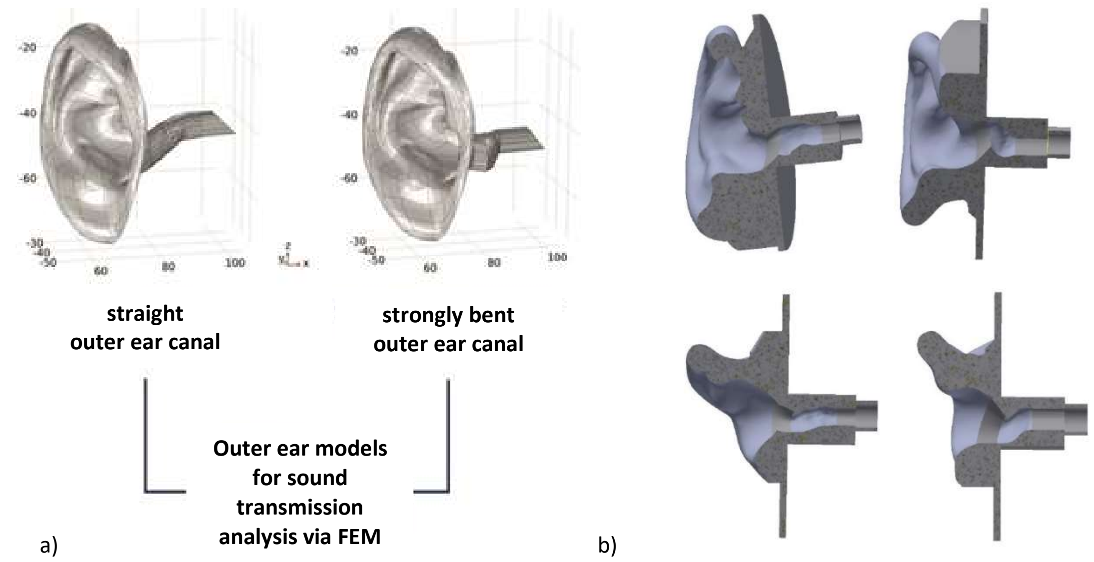

Fig. 3: Outer ear models for the analysis of sound transmission to the ear drum. All models were obtained by the combination of the scan of a *Pinna* of an artificial head (type KU-80, Georg Neumann GmbH) and scans of different polysiloxane castings selected for and fitted to the *Pinna.* a) Surface models for FE-analysis in COMSOL® Multiphysics [HELBIG et al. 2016, p. 329], left - model 1 (straight outer ear canal), right – model 2 (strongly bent outer ear canal), b) Outer ear models in *AUTODESK INVENTOR® PROFESSIONAL 2015.* Original data of the scans is marked light blue. Data added during design process is marked grey, left – model 1 (straight outer ear canal), right – model 2 (strongly bent outer ear canal), top row – sagittal view, bottom row – transversal view.

3. RESULTS

3.1 Outer ear geometry

Outer ear geometry was analyzed for 50 digitalized polysiloxane castings taken by default during the manufacturing process of hearing aids or hearing protection systems by hearing-aid acousticians. With the help of (semi-)automatic algorithms the castings were (cp. [HELBIG et al. 2015a]):

- sorted into right and left ears and
- roughly orientated (main elongation was assumed to be the outer ear canal and was set to the z-axis).

Afterwards a path and cross-sections along the outer ear canal were determined (see fig. 1 – right). Path and cross-sections were used to determine different parameters like:

- length,
- curvature,
- cross sectional area,
- length of the half-axes,
- aspect ratio of the half-axes,

of the outer ear canal (see fig. 4).

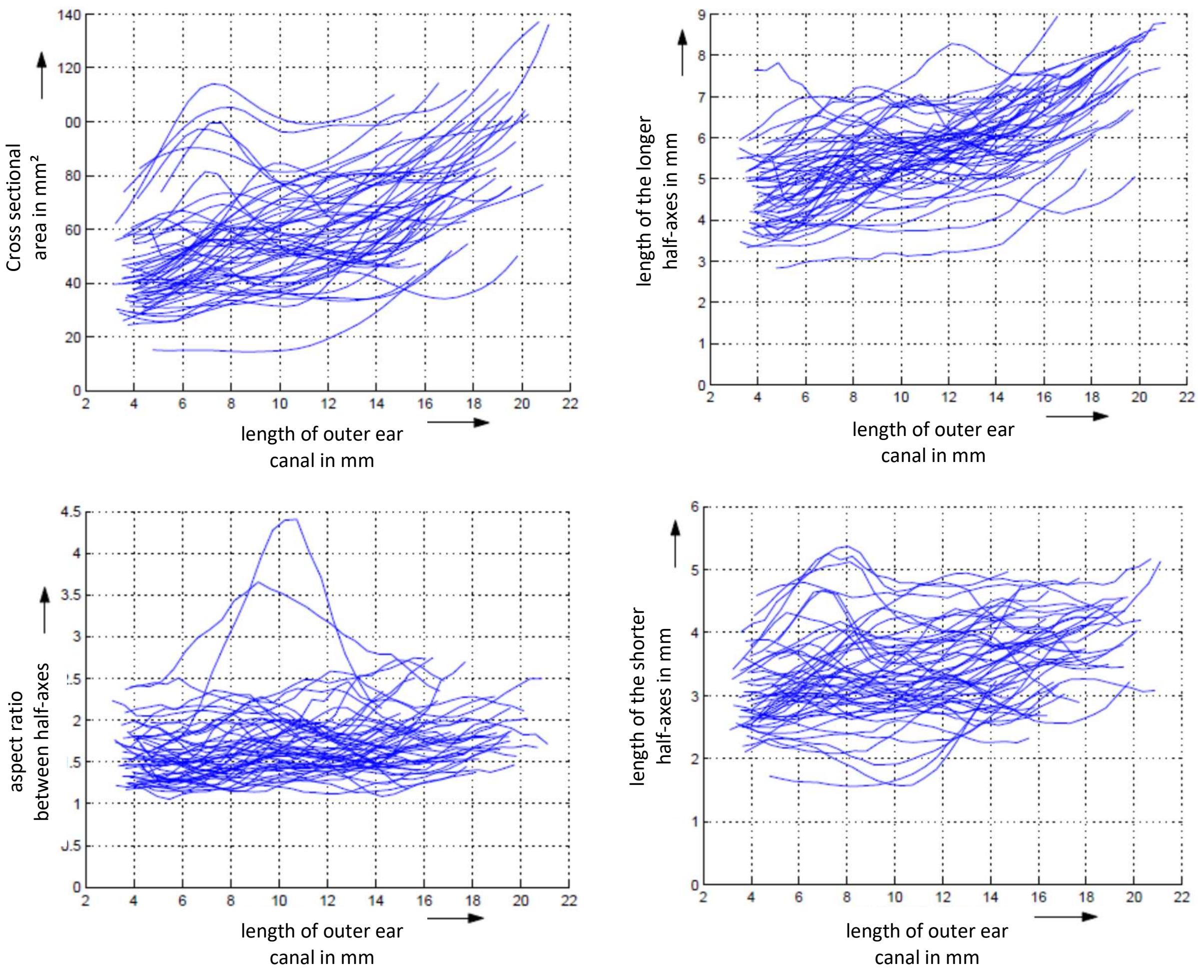

Fig. 4: Analysis of 50 polysiloxane castings of outer ear canals taken by default during the manufacturing process of hearing aids or hearing protection systems by hearing-aid acousticians (cp. [HELBIG et al. 2015b]).
Top left – cross sectional area (in mm²) over the length of the outer ear canal (in mm)
Top right – length of the longer half-axes (in mm) over the length of the outer ear canal (in mm)
Bottom left – aspect ratio of both half-axes over the length of the outer ear canal (in mm)
Bottom right – length of the shorter half-axes (in mm) over the length of the outer ear canal (in mm)

Outer ear geometry shows huge interindividual and intraindividual differences along the path of the outer ear canal in shape and size of the cross-section. Cross sectional area differs between under 20 mm² up to 140 mm². All castings show an increase of the cross sectional area along the path in *peripher* direction. Shape of the cross-section quantified by the aspect ratio between the half-axes differs between nearly round cross-sections (aspect ratio of about 1) to very thin elliptic cross-sections (aspect ratio up to 4.5).

3.2 Outer ear transfer function

Finite element simulation as well as measurements with the experimental setup show that sound pressure level in the plane of the ear drum has a clear dependence on the outer ear geometry for frequencies over 3 kHz (see fig. 5). Sound transmission differs up to 5 dB in level in various frequency bands (9.5 kHz to 10 kHz, 11 kHz to 11.5 kHz) as well as in position of local extremes [HELBIG et al. 2016]. Furthermore, the experimental setup easily allows examining the influence of the stiffness of the outer ear on the sound transmission and to test the function (damping) of existing or new hearing protection systems.

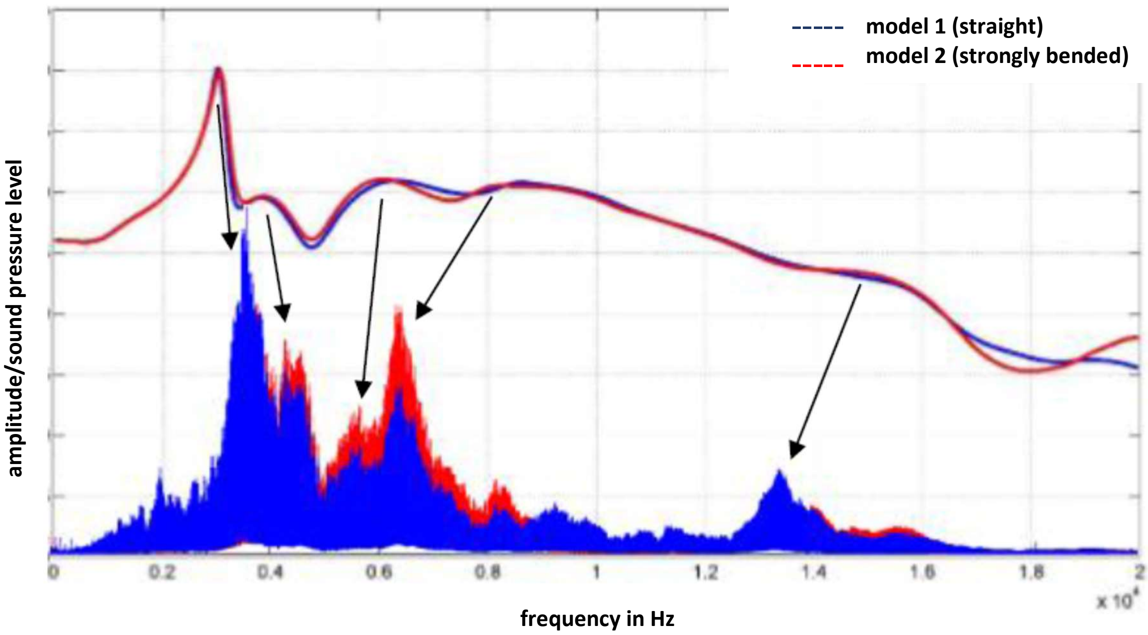

Fig. 5: Qualitative comparison of the results for the emerging sound pressure level in an imaginary plain for the ear drum in dependency of outer ear canal geometry. Results of the finite element simulation are shown as line (cp. [Helbig et al. 2016]). Results obtained with the experimental setup are shown beneath.

4. DISCUSSION

4.1 Outer ear geometry

With the help of the developed (semi-)automatic algorithms a fast way to objectively analyze outer ear castings could be realized. Preliminary results can be compared to other studies like JOHANSON 1975 and STINSON & LAWTON 1989– especially regarding the cross sectional area over the length of the outer ear canal.

Methodical problems arise with the way the data is gained. The polysiloxane castings do not capture the complete length of the outer ear canal. During the casting process a piece of wadding is used to protect the ear drum (cp. [HELBIG et al. 2015a]. This causes an undefined internal end of the outer ear casting and an unknown volume between the end of the casting and the ear drum. Furthermore, a suitable parameter to define the outer end of the outer ear canal has to be found.

A complete discussion of the results of the outer ear geometry can be found in [HELBIG et al. 2015b]

4.2 Outer ear transfer function

Finite element simulation and experimental setup show qualitive similar results regarding the outer ear transfer function. Comparable other studies like BLAU et al. 2010 show similar results but predict even higher differences between different outer ears (up to 20 dB) in the frequency band of 4 kHz to 10 kHz. Main difference between the results of the different methods in this study is an upset of the spectrum of the experimental setup in comparison to the spectrum of the finite element simulation. The reason for that is unknown so far.

Main critic point regarding these promising first results is the low number of samples. So far only two castings were analyzed which prohibits general interpretations. Also, the assumption to always combine the model of a *Pinna* and the models of outer ear canals from different individuals has to be discussed. Examinations with models of the outer ear taken completely of one individual as control group might help to support future results.

5. FUTURE SCOPE

In the future existing methodical problems have to be solved before analyzing a higher number of samples. Especially the source of data has to be re-evaluated. The polysiloxane castings are ideal to access a huge amount of data and to analyze the structures important for hearing protection systems. But they lack the information about the whole *Pinna* and the complete outer ear canal to the ear drum. This data is crucial for the exact analysis of the outer ear transfer function. New methods and systems to scan the outer ear geometry could help to solve this problem and still access a huge number of samples.

Better knowledge about the influence of the outer ear geometry on the outer ear transfer function could lead to new concepts regarding noise prevention and an improvement of audiometric measuring techniques – especially more objective and reproducible measurements with new types of probes or ways to place them in the ear canal. Additionally, these methods could be used to examine the development of hearing during juvenile growth with its changing conditions (length and ratio of the outer ear canal as well as posture of the ear drum relative to the outer ear canal).

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REFERENCES

BANCES E, SCHMIDT T, HELBIG T, WITTE H (2014): *An ear-pinna acoustic analysis coupled with an ear-canal emulator 711*. - In: Shaping the future by engineering: 58th IWK, Ilmenau Scientific Colloquium, Technische Universität Ilmenau, 8 - 12 September 2014; proceedings. - Ilmenau: Univ.-Bibliothek, ilmedia / Ilmenau Scientific Colloquium. Technische Universität Ilmenau ; 58 (Ilmenau): http://nbn-resolving.de/urn:nbn:de:gbv:ilm1-2014iwk-159:6

BLAU M, SANKOWSKY T, ROESKE P, MOJALLAL H, TESCHNER M, THIELE C (2010): *Prediction of the Sound Pressure at the Ear Drum in Occluded Human Cadaver Ears.* Acta Acustica united with Acustica, Vol. 96 (3): 554-566.

BLAUERT J (1997): *Spatial hearing: the psychophysics of human sound localization*. Cambridge, U.S.A.: MIT press.

HELBIG T, GIESE A, KUPPER C, WITTE H, SCHMIDT T (2015a): *Parameter zur automatischen, anatomischen Analyse des äußeren Gehörganges.* - In2: Prävention von arbeitsbedingten Gesundheitsgefahren und Erkrankungen / 21. Erfurter Tage (Erfurt) : 2014.12.04-06. - Quedlinburg : Verlag Bussert & Stadeler, ISBN 978-3-942115-35-3 , p. 345-353

HELBIG T, GIESE A, BANCES E, WITTE H, SCHMIDT T (2015B): *Untersuchungen zur Anatomie des Gehörganges als Basis für klassifizierte Gehörschutzsysteme.* - In: Prävention von arbeitsbedingten Gesundheitsgefahren und Erkrankungen / 21. Erfurter Tage (Erfurt) : 2014.12.04-06. - Quedlinburg : Verlag Bussert & Stadeler, ISBN 978-3-942115-35-3 , (2015), p. 145-165

HELBIG T, ROLAND S, BANCES E, WITTE H, SCHMIDT, T (2016): *Finite-Elemente-Untersuchungen zum Einfluss unterschiedlicher Gehörganggeometrien auf die individuelle Lärmbelastung.* - In: Prävention von arbeitsbedingten Gesundheitsgefahren und Erkrankungen / 22. Erfurter Tage (Erfurt) : 2015.12.03-05. - Quedlinburg : Verlag Bussert & Stadeler, ISBN 978-3-942115-39-1, p. 327-338

HELBIG T, SCHMIDT T, FINKE T T, ROLAND S, BANCES E, WITTE H (2017): *Individuelle Lärmbelastung in Abhängigkeit unterschiedlicher Gehörganggeometrien.* In: In: Prävention von arbeitsbedingten Gesundheitsgefahren und Erkrankungen / 23. Erfurter Tage (Erfurt) : 2016.11.30-2016.12.02. - Quedlinburg : Verlag Bussert & Stadeler, ISBN 978-3-942115-45-2, p. 97-110

HUDDE H, SCHMIDT S (2009): *Sound fields in generally shaped curved ear canals*. The Journal of the Acoustical Society of America. 125(5): 3146-3157

JOHANSEN P A. (1975): *Measurement of the human ear canal*. Acta Acustica united with Acustica vol. 33, 349 - 351

SHAW E A G (1974): *The External Ear*. In: W. D. Keidel, W. D. Neff (eds.): Handbook of Sensory Physiology. Auditory System. Vol. 5 (1). Berlin Heidelberg New York: Springer-Verlag Berlin Heidelberg New York: 455-490.

STINSON M R, LAWTON B W (1989): *Specification of the geometry of the human ear canal for the prediction of sound-pressure level distribution*. J Acoust Soc Am, 85(6):2492-2503

STINSON M R, DAIGLE G A (2008): *The sound field in life-size replicas of human ear canals occluded by a hearing aid*. Institute for Microstructural Sciences.- Proc. Acoustics 08 Paris, July 29. - August 4th 2008 in Paris, France.

ZENNER H-P (1994): *Hören. Physiologie, Biochemie, Zell- und Neurobiologie*. Stuttgart: Georg Thieme Verlag.

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