様　式　C－１９、F－１９－１、Z－１９　（共通）

科学研究費助成事業　　研究成果報告書

令和　５ 年　６ 月 １１ 日現在

機関番号：２３２０１
研究種目：基盤研究(C)（一般）
研究期間：2017～2022
課題番号：１７K００２６０

研究課題名（和文）Morpho-acoustic sensitivity analysis of the human outer ear

研究課題名（英文）Morpho-acoustic sensitivity analysis of the human outer ear

研究代表者
ＭＯＫＨＴＡＲＩ　Ｐａｒｈａｍ（MOKHTARI, Parham）

富山県立大学・工学部・教授

研究者番号：００３９５０８９

交付決定額（研究期間全体）：（直接経費）　2,200,000円

研究成果の概要（和文）：ヒトは、耳介での反射によって生成される聴覚的手がかりのおかげで音を3次元的に認識する。このプロジェクトでは、聴覚的手がかりに対する耳介の形状と皮膚の反射係数の影響を研究するために、音響のコンピュータシミュレーションにおける高度な技術を開発した。その結果、音源定位のための聴覚的手がかりを強化するために、いかに耳の表面に物理的に手を加えるべきかが明らかになった。

研究成果の学術的意義や社会的意義
学術的には、このプロジェクトの結果は、ヒトの耳介周囲の詳細な音場を調査するために必要な計算手法に貢献する。社会的には、この研究結果は、空間聴覚の強化に必要な個別の耳介調整を提供し、バーチャルオーディオに関連する技術を進歩させるのに役立つ可能性がある。

研究成果の概要（英文）：Humans perceive sound three-dimensionally thanks to auditory cues generated by reflections in the outer ear. In this project we developed advanced techniques in computer simulation of acoustics, to study the influence of ear shape and skin reflection coefficient on the auditory cues. The results reveal how the surface of the ear should be physically manipulated to enhance auditory cues for sound source localization.

研究分野：人間情報学

キーワード：HRTF notch　FDTD simulation　Sensitivity analysis　Pinna surface reflection

１．研究開始当初の背景

(1) Humans can perceive sound, for example localize sound sources, in three dimensions. All the auditory cues for three-dimensional (3D) sound localization are contained in head-related transfer functions (HRTFs), and HRTF peaks and notches are particularly important for determination of sound-source elevation. However, depending on the individual and elevation angle, HRTF notches are often observed to be shallow, and notch trajectories in the median plane are often discontinuous. Although it is still only a hypothesis, it is conceivable that *deepening* notches and rendering their trajectories more *continuous*, for example by careful adjustment of individual pinna physiology, may help *enhance* these individuals' 3D sound perception. However, the necessary adjustments are not known because, despite some research progress, the relations between HRTF notches and pinna physiology are still not well established.

(2) In this regard, computer simulation of acoustics is a powerful tool for computation of HRTFs and for detailed investigation of acoustic-physiology relations. In particular, we pioneered the use of finite-difference time domain (FDTD) simulation for computation of pinna *sensitivity maps*, which reveal the sensitivity of acoustic parameters (HRTF peaks or notches) to small, local changes in pinna physiology. However, the method is computationally very intensive and a more efficient algorithm is desirable.

２．研究の目的

(1) Accordingly, in this project our first research aim was to develop a more efficient method of computing pinna sensitivity maps for HRTF peaks or notches, using FDTD simulation. Such a method would facilitate further investigation of the relations between individual pinna physiology and auditory cues for sound localization.

(2) Second, we aimed to find, for a given individual's pinna shape, the physical adjustments required to deepen HRTF notches and render their median-plane trajectories more continuous. While perception experiments to assess sound localization improvements are left for future research, here we aimed to develop the necessary computational methods that would enable such research.

３．研究の方法

(1) Central to our research method, was our previously developed FDTD acoustic simulator. Here, we significantly revamped the structure and operation of our computer program. We also added an option to explicitly specify acoustic impedance at the air-skin boundary, so that unrealistic wave propagation inside the head could be safely ignored.

(2) Next, we used the FDTD simulator to compute pinna sensitivity maps using our conventional method (DP: direct perturbation of one voxel at a time) and a potentially much more efficient method (ARP: acoustic radiation pressure computed in only one run). To facilitate the interpretation of results, this was done using a simple pinna shape, i.e., an elliptical concha model.

(3) Lastly, using a human pinna voxelized on a 3D grid (resolution 2 mm), we employed sensitivity analysis with the FDTD simulator to find the necessary adjustments to the local reflection coefficient at the pinna surface, that would be required to deepen HRTF notches in the median plane.

４．研究成果

(1) Regarding our first research aim, we reported results (Mokhtari, 2019) comparing sensitivity maps for the first three resonances of an elliptical concha model. Such maps were calculated using both the conventional DP method and a new ARP method which is 2-3 orders of magnitude more computationally efficient. Results indicated a close match between the two methods which was highly encouraging, but only after setting a coefficient in the ARP equation to a value of about 3, instead of unity as theoretically implied. Thus, we succeeded in developing an efficient computational method, but the reason for the factor 3 is still unknown and warrants further research.

(2) Thanks to streamlining our FDTD simulation program and adding the option of an explicit boundary impedance, we were able to calculate a full set of HRTFs for the left and right pinnae of 19 individuals, and we analyzed this large dataset using principal components analysis (PCA) to extract HRTF eigenmodes. As a result, we were able to publish a journal paper (Mokhtari *et al.*, 2019) with the following three main findings: (i) by comparing with previous psychoacoustic results, we inferred that at least 10, and as many as 24, HRTF eigenmodes would be needed for a virtual-audio system suitable for many listeners; (ii) the frequency characteristics of the top 5 eigenmodes appear to be stable across different groups of individuals and experimental methods, i.e., independent of whether the HRTFs were directly measured or, as in our case, computed by simulation; and (iii) the top 3 eigenmodes encode familiar spatial contrasts, i.e., along the left-right, top-down, and a tilted front-back axis, respectively. It is worth noting that although this study was not initially planned, these results were enabled directly by our efforts in this project; this is a reminder that research projects may lead to unexpected directions, and it is beneficial to be receptive and mindful to advance research even in directions not envisioned at the planning stage.

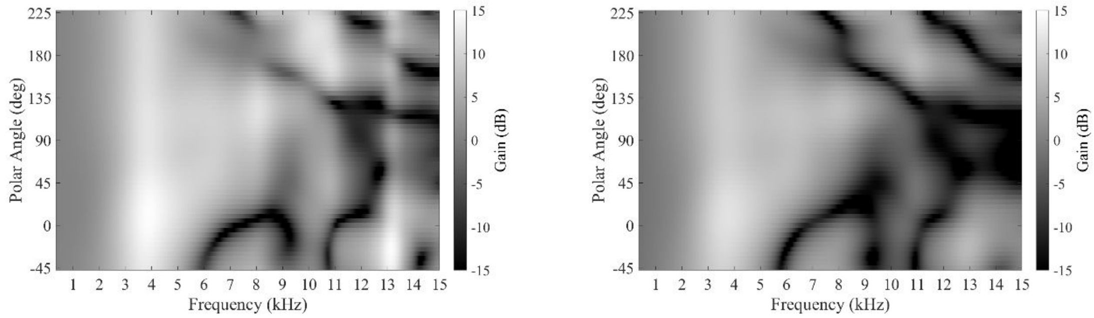

Fig. 1. Median-plane PRTFs simulated with an unmodified human ear shape (left) and with reduced reflection coefficient at certain parts of the pinna surface (right).

(3) Next, regarding our second research aim, we reported results at two domestic conferences (Hirota *et al.*, 2021; Mokhtari *et al.*, 2022a) and as an invited contribution to a structured session on Spatial Hearing at an international conference (Mokhtari *et al.*, 2022b). In summary, starting with an individual's pinna geometry, we used our FDTD simulator to compute pinna-related transfer functions (PRTFs) in the median plane, and conducted sensitivity analyses to find the adjustments to pinna surface reflection coefficients, that are necessary for deepening the notches. As a result, we succeeded in finding a particular pattern of reduced reflection coefficients covering only certain parts of the pinna surface, that deepened notches throughout the median plane (see Fig. 1) and thereby increased the dynamic range of the PRTFs by 7 dB on average. Interestingly, this result was achieved not by modifying the pinna shape – the original pinna geometry was retained – but instead, by reducing only the acoustic reflection coefficient at the concha back wall and a few other local parts of the pinna surface (see Fig. 2).

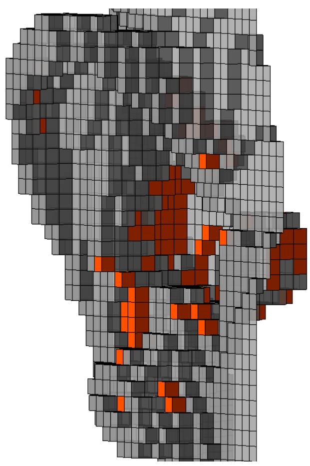

Fig. 2. Parts of the ear surface (colored) reduced in reflection coefficient to achieve the above results.

(4) While our reported results are exciting, further research is needed to: (i) understand the acoustical significance of the identified parts of the pinna; (ii) find practical methods to replicate such results with real, human pinnae; (iii) examine the psychoacoustic effects on sound localization (among other other spatial-hearing phenomena) of the identified surface-reflection adjustments that deepen median-plane notches; and (iv) extend these lines of investigation to a greater number of individuals.

５．主な発表論文等

〔雑誌論文〕　計1件（うち査読付論文　1件／うち国際共著　1件／うちオープンアクセス　1件）

１．著者名 Mokhtari P., Kato H., Takemoto H., Nishimura R., Enomoto S., Adachi S., Kitamura T.	４．巻 9
２．論文標題 Further observations on a principal components analysis of head-related transfer functions	５．発行年 2019年
３．雑誌名 Scientific Reports	６．最初と最後の頁 1-7
掲載論文のDOI（デジタルオブジェクト識別子） 10.1038/s41598-019-43967-0	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

〔学会発表〕　計5件（うち招待講演　1件／うち国際学会　2件）

１．発表者名 廣田 裕太郎, モクタリ パーハム, 森川 大輔
２．発表標題 局所耳介表面反射が耳介伝達関数に及ぼす影響の感度解析による検討
３．学会等名 日本音響学会2021年秋季研究発表会
４．発表年 2021年

１．発表者名 森川 大輔, 加賀 充晃, モクタリ パーハム
２．発表標題 頭部モデルの3D解像度による頭部伝達関数の変化
３．学会等名 日本音響学会2022年春季研究発表会
４．発表年 2022年

１．発表者名 Parham Mokhtari, Yutaro Hirota, Daisuke Morikawa
２．発表標題 Deepening of PRTF notches by selective modification of pinna surface reflection coefficient
３．学会等名 日本音響学会2022年春季研究発表会
４．発表年 2022年

1．発表者名 MOKHTARI Parham
2．発表標題 Evaluation of an Efficient Numerical Computation of Pinna Resonance Sensitivity to Physiological Perturbations: Preliminary Results
3．学会等名 42nd MidWinter Meeting of the Association for Research in Otolaryngology (ARO)（国際学会）
4．発表年 2019年

1．発表者名 Parham Mokhtari, Yutaro Hirota, Daisuke Morikawa
2．発表標題 PRTF notch enhancement by selective modification of pinna surface reflection coefficient
3．学会等名 24th International Congress on Acoustics（招待講演）（国際学会）
4．発表年 2022年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考
研究協力者	加藤　宏明 (KATO Hiroaki)		
研究協力者	竹本　浩典 (TAKEMOTO Hironori)		
研究協力者	西村　竜一 (NISHIMURA Ryouichi)		

６．研究組織（つづき）

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考
研究協力者	榎本　成悟 (ENOMOTO Seigo)		
研究協力者	足立　整治 (ADACHI Seiji)		
研究協力者	北村　達也 (KITAMURA Tatsuya)		
研究協力者	廣田　裕太郎 (HIROTA Yutaro)		
研究協力者	森川　大輔 (MORIKAWA Daisuke)		
研究協力者	加賀　充晃 (KAGA Mitsuaki)		

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関