AN INVESTIGATION OF THE ACOUSTIC CHARACTERISTICS OF THE PARANASAL CAVITIES

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ABSTRACT

Acoustic characteristics of the paranasal cavities were studied by a direct measurement approach. Our method evaluates the transmission functions of the nasal tracts based on the sound pressure gradient in the tract and the sound pressure at the nostrils. The results from three male subjects show that frequency ranges of the zeros caused by the paranasal cavities are from 310 to 1070 Hz for the sphenoidal sinus, 310 to 950 Hz for the maxillary sinus, and 600 to 1580 Hz for the frontal sinus. The zeros are expected to affect the shaping of nasal formants due to their stability in the low frequency region.

INTRODUCTION

Early studies of the nasal cavity have suggested that the acoustic effect of the "subsidiary cavities" within the nose play an important role in shaping appropriate nasal spectra. For directly measuring acoustical contributions of the paranasal cavities, Lindqvist-Gauffin et al. (1976) used a probe tube sound source to excite the nasal cavity while the velum was closed [1]. They found pole-zero pairs caused by the paranasal sinuses in their results by changing locations of the sound source. Takeuchi et al. (1977) estimated the volume of the paranasal sinuses and their ostia from a cadaver specimen, and observed the resonance properties of the nasal cavity when the sinuses were taken into account[2]. However, some conclusions reported in the previous studies are quite different. For this reason, more accurate observations are required for investigating the acoustic properties of the paranasal cavities. In the present study, we used a method to directly measure acoustic characteristics of the nasal and paranasal cavities for three subjects.

METHOD

Theoretical considerations

The vocal tract can be computationally represented by a cascade concatenation of small sections when the discussion is limited in the low frequency region below 4 kHz. The characteristics of the sound propagation in such a tract are easily described by drawing upon elementary electrical theory and some well-known results for one-dimension waves on transmission lines. For i'th section of l_i in length, with sending-end sound pressure P_{i-1} and volume velocity U_{i-1}, the receiving-end sound pressure and velocity P_i and U_i are given by

$$\begin{bmatrix} P_i \\ U_i \end{bmatrix} = \begin{bmatrix} \cosh \gamma_i l_i & -Z_i \sinh \gamma_i l_i \\ Y_i \sinh \gamma_i l_i & \cosh \gamma_i l_i \end{bmatrix} \begin{bmatrix} P_{i-1} \\ U_{i-1} \end{bmatrix} \quad (1)$$

where γ_i is the propagation constant depending on the length and cross-sectional area of the section. Z_i and Y_i denote the characteristic impedance and admittance of the section, respectively[3]. For a portion of the vocal tract from Section i to the radiation end, the relationship is

$$\begin{bmatrix} P_r \\ U_r \end{bmatrix} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} \begin{bmatrix} P_{i-1} \\ U_{i-1} \end{bmatrix} \quad (2)$$

where P_r and U_r are sound pressure and volume velocity at the radiation end. The matrix of 2×2 is the transformation matrix whose elements depend on the geometry of the portion. Solving the ratio of the input volume velocity to the output velocity, the transmission characteristics T(ω) from Section i to the radiation end are given by

$$T(\omega) = U_r / U_{i-1} = t_{21} z_{i-1} + t_{22} \quad (3)$$

where z_{i-1} denotes the input impedance seen from Section i to the radiation end. It is seen that all of the terms on the right side of Eq. (3) are dependent only on the geometry of the portion from Section i to the radiation end. In other words, the transmission characteristics obtained from Eq. (3) are theoretically independent of the portion behind Section i, and U_{i-1} can be looked upon as a continuous current source to the portion.

An experimental study was conducted to assess accuracy of the method [4]. The results showed that this method yielded accuracy of about 4% error, a ratio of difference between measurement and theoretical values to the theoretical value, for the peaks, and 2% for the zeros of acoustic tubes of known geometry. The locations of the branches within acoustic tubes were measured as well as the frequency properties.

Experimental Procedure

In this study, we investigate acoustic characteristics of the paranasal cavities using the method described above. Figure 1 shows a schematic diagram. The external microphone M3, a B&K-4003, was set about 15 cm in front of the mouth of subjects. Two B&K-4128 probe microphones (M1, M2) were attached to each other to form parallel tubes, and were used for measuring sound pressures within the tract via two flexible tubes. The flexible tubes have an identical length of 30 cm and a matched impedance to the microphones. Outer diameter of the tubes was 0.165 cm, and inner diameter was 0.076 cm. Tip distance of the tubes was adjusted to 0.6 cm. A vinyl ball with a 0.6-cm diameter marked by B in Fig. 1 was used to keep the tips out of touch with inside surface of the nasal cavity.

Three subjects from 30 to 44 years-old participated in this experiment. The nasal tract of the subjects was treated with adrenaline (naphazoline HCl, 0.05%) in order to decongest the nasal mucous membrane. The paired flexible tubes were inserted through the nasal floor of one nasal passage into the nasopharynx about 8 cm from the nostrils. The other nasal passage was collapsed at the nostril by a finger to ensure that there was only one radiation orifice during the measurement. Measurements were taken at 0.5-cm intervals in the portion of the cavity 4 to 8 cm behind the nostrils. Both nasal passages were measured in the same experimental conditions.

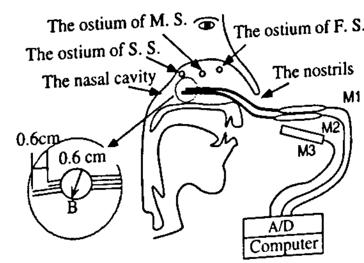

Figure 1. *Diagram of setup for measuring the acoustic characteristics of the paranasal sinuses.*

Speech materials used in this experiment were ten Japanese NV syllables and two nasal consonants. Subjects were asked to utter the speech materials twice, and instructed to prolong the utterance of the nasal consonant in the NV syllables to some extent. Measurements were made in an anechoic room. Sampling rate was 44.1 kHz, and the cut-off frequency was 3 kHz for signal analysis.

Data from a stable segment of nasal consonants were used for analysis. FFT

Table I Locations of the openings of the paranasal cavities from the nostrils. (cm)

Subjects	S. S.	M. S.	F. S.
Sub.1	6.2	5.1 (4.8)*	4.3
Sub.2	6.8	4.3	4.0
Sub.3	6.0	4.5	4.0

**The digit within the parentheses is the opening position on right side.*

with a 4096-point hamming window was applied to the selected segment, and shifted in a 1024-point interval. Frequency properties of the segment were obtained by averaging the results from each frame. The transmission characteristics of each measurement position were the average value of about 20 sound recordings.

Morphology of the nasal cavity

Morphologically, the paranasal cavities consist of four kinds of sinuses: the sphenoidal sinus (S. S.), the maxillary sinus (M. S.), the frontal sinus (F. S.) and the ethomoidal sinus (E. S.). This analysis was focused on the sinuses except for the ethomoidal sinus because the sinus has less effect on the low frequency region below 3 kHz. The locations of the ostium opening for the three sinuses are listed in Table I. Those data were obtained from volumetric MRI images [5], with reference to anatomical data [6]. The opening location of the frontal sinus has lower accuracy than the others because it could not be identified exactly with the MRI data.

RESULTS

According to the theoretical considerations, zeros caused by the paranasal sinuses are expected to appear in transmission characteristics of the frontal portions which include the openings of the sinuses. Using the method, anti-resonances pertaining to each of the sinuses can be estimated, because the openings of the paranasal sinuses are separate along the nasal tract.

The results measured from the left and right nasal passages are shown in Fig. 2 (a) and (b), respectively, for Subject 1. There are several zero patterns

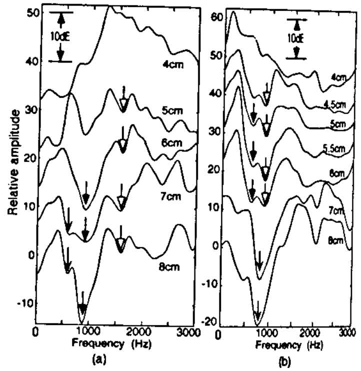

Figure 2. *Transmission characteristics the left (a) and right (b) nasal tracts obtained at a set of measurement positions for Subject 1. (The positions are shown in the right side. V-arrow shows the zeros caused by the sphenoidal sinus; black-arrow for the maxillary sinus, and white-arrow for the frontal sinus.)*

which appear in the transmission characteristics. As shown in Fig. 2 (a), there are three zeros in the frequency region below 2 kHz, which appear at about 590, 890 and 1580 Hz. A zero at 590 Hz, shown in V-arrows, appears in the transmission characteristics obtained in the measurement positions of 7 and 8 cm from the nostrils, and disappears in the measurement positions shorter than 7 cm. This implies that an opening of the sinus was in the frontal portions of 7 and 8 cm, and not included in the other frontal portions. Therefore, the opening is estimated to be between 6 and 7 cm. From Table I, it is known that the opening of the sphenoidal sinus was at 6.2 cm from the nostrils for the subject. According to the morphological data, the opening is uniquely judged to be the ostium of the sphenoidal sinus, and the zero at 590 Hz is determined to be the anti-resonance frequency of the sphenoidal sinus.

Similarly, a zero at about 890 Hz, shown by black-arrows, appears in the transmission characteristics of the frontal portions longer than 5 cm, and becomes much weaker at 5 cm, and disappears in the result measured at 4

Table II Estimated anti-resonance frequencies of the paranasal cavities (Hz).

Subs.	S. S.		M. S.		F. S.	
	left	right	left	right	left	right
Sub.1	595	788	895	612	1579	893
Sub.2	1047	1071	541	453	864	762
Sub.3	314	?	947	316	625	600

cm. With reference to the morphological data, this zero is judged to be caused by the maxillary cavity. There, the zero is more or less seen in the result obtained at 5 cm because the opening of the maxillary sinus, located at 5.1 cm, may affect the result.

A zero at about 1580 Hz, shown by white-arrows, appears in the results of the frontal portions of 5 to 8 cm, and disappears in the results measured at 4 cm. The same consideration gives the idea that an opening of a sinus exists in the region between 4 and 5 cm from the nostrils. The MRI data listed in Table I show that the ostium opening of the frontal sinus is in this region. According to the nasal morphology and the zero patterns, a conclusion can be drawn that the opening is the ostium of the frontal sinus, and the zero is caused by the sinus.

Using the same technique, estimations were made for the right side of the nasal cavity shown in Fig. 2 (b). Anti-resonance frequencies of the paranasal cavities are 788 Hz for the sphenoidal sinus, 612 Hz for the maxillary sinus, and 893 for the frontal sinus.

The anti-resonance frequencies of the paranasal cavities are shown in Table II for three subjects. Anti-resonance frequencies of the maxillary sinus are between 310 and 950 Hz. The ranges of the anti-resonances are from 310 to 1070 Hz for the sphenoidal sinus, and from 600 to 1580 Hz for the frontal sinus. For the three subjects, individual differences of the anti-resonances were generally larger than the differences due to the asymmetry of the paranasal cavities within the subjects.

CONCLUSIONS

Acoustic properties of the paranasal cavities were measured using a direct method. A set of transmission characteristics were obtained using sound pressure gradients at a series of measurement positions and sound pressure at the nostrils. Anti-resonance frequencies of the paranasal cavities were estimated by matching zero patterns of the transmission characteristics to morphological data for three subjects. The results showed that the paranasal sinuses, the sphenoidal sinus, the maxillary sinus and the frontal sinus, contribute zeros to acoustic characteristics of the nasal tract, respectively. It is expected that the zeros caused by the paranasal cavities can affect the shaping of nasal formants because the zeros appear in the low frequency region stably.

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REFERENCES

[1] Lindqvist-Gauffin, J, and Sundberg, J. (1976). "Acoustic properties of the nasal tract," *Phonetica*, 33, 161-168.

[2] Takeuchi, S., Kasuya, H. and Kido, K. (1977). "A study on the effects of nasal and paranasal cavities on the spectra of nasal sounds," *J. Acoust. Soc. Jpn.*, 33, 4 163-172. (in Japanese).

[3] Flanagan, J., L. (1972). *Speech analysis synthesis and perception*, Springer-Verlag, New York (2nd Edition).

[4] Dang, J., Honda, K.(1994). "A new method for measuring vocal tract transmission characteristics," *Tech. Report of ATR* , TR-H-108.

[5] Dang, J., Honda, K., and Suzuki, H. (1994). "Morphological and acoustical analysis of the nasal and the paranasal cavities," *J. Acoust. Soc. Am.* , 96, 4, 2088-2100.

[6] Bunch, M. (1982). *Dynamics of the singing voice*, Springer-Verlag, New York.