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Contribution of Paranasal Sinuses to the Acoustic Properties of the Nasal Tract

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Key Words
Paranasal sinuses · Resonance · Sinonasal tract

Abstract

Background: The contribution of the nasal and paranasal cavities to the vocal tract resonator properties is unclear. Here we investigate these resonance phenomena of the sinonasal tract in isolation in a cadaver and compare the results with those gained in a simplified brass tube model. ***Methods:*** The resonance characteristics were measured as the response to sine sweep excitation from an earphone. In the brass model the earphone was placed at the closed end and in the cadaver in the epipharynx. The response was picked up by a microphone placed at the open end of the model and at the nostrils, respectively. A shunting cavity with varied volumes was connected to the model and the effects on the response curve were determined. In the cadaver, different conditions with blocked and unblocked middle meatus and sphenoidal ostium were tested. Additionally, infundibulotomy was performed allowing direct access to and selective occlusion of the maxillary ostium. ***Results:*** In both the brass model and the cadaver, a baseline condition with no cavities included produced response curves with clear resonance peaks separated by valleys. Marked dips occurred when shunting cavities were attached to the model. The frequencies of these dips decreased with increasing shunting volume. In the cadaver, a marked dip was observed after removing the unilateral occlusion of the middle meatus and the sphenoidal ostium. Another marked dip was detected at low frequency after removal of the occlusion of the maxillary ostium following infundibulotomy. ***Conclusion:*** Combining measurements on a simplified nasal model with measurements in a cadaveric sinonasal tract seems a promising method for shedding light on the acoustic properties of the nasal resonator.

Introduction

When coupled to the vocal tract via an open velopharyngeal port, the nasal resonator plays a prominent role in the production of nasal consonants and nasalised vowels. In addition, many voice teachers regard it as an important tool in shaping voice timbre; indeed, classically trained operatic singers have been found to sing with a more or less open velopharyngeal port [1]. Other voice teachers, however, maintain that the port should always be closed in vowel production. Besides, acoustic proper-

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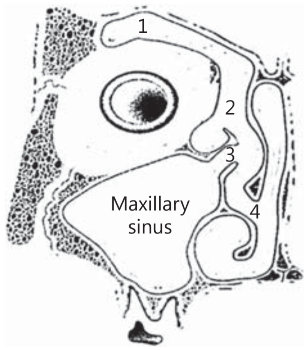

Fig. 1. Schematic illustration of the osteomeatal complex (coronal plane). 1 = Frontal sinus; 2 = frontal recess; 3 = maxillary ostium covered by the uncinate process; 4 = middle meatus flanked by middle and lower concha.

ties of the nasal tract represent a worthwhile issue from a rhinosurgical point of view, as endonasal surgical procedures on nasal and paranasal cavities rank among the most commonly performed surgical interventions in otorhinolaryngology and are carried out without a complete understanding of their potential acoustic impact on speech and voice quality.

The acoustic properties of the nasal tract are complicated by the pairwise arranged paranasal sinuses, which are connected to it via narrow and complex orifices, the so-called ostia. The orifices of the maxillary and frontal sinuses open up to a common duct accessible via the middle meatus, whereas the ostia of the sphenoidal sinuses are directly connected to the posterior parts of the nasal cavity (fig. 1).

The detailed anatomy of this system shows great interindividual variability as well as marked left/right asymmetry. The mucosal lining of the sinonasal tract with its considerable swelling potential provides additional, uncontrollable confounding variables in acoustic measurements, especially when examined in vivo [2]. The morphology of the nasal tract is extremely complex [3]. Due to the anatomical structure of the lateral nasal wall, particularly the voluminous inferior conchae, the nasal cavities are characterised by very great circumference-to-cross-sectional area ratios, thus generating great resistance.

As the contributions of the nasal cavity to voice are produced with the vocal and nasal tracts combined, as in the consonants /m, n/ and in nasalised vowels, most attempts to analyse resonance properties of the nasal tract have incorporated both the nasal and vocal tracts [2–4, 6–8]. The results have demonstrated an extremely complex frequency response, which varies both within and between individuals. Båvegård et al. [3] attempted to account for this complexity by complementing the resonance characteristics by a number of pole-zero circuits.

Koyama [6] investigated the resonance properties of the paranasal sinuses using a plastic model of the human vocal tract coupled to models of the maxillary and sphenoid sinus; he obtained acoustic measures while varying sinus volumes and ostium diameters. He also blocked the ostia in living subjects and observed spectral valleys in the range of 400–1,000 Hz which varied depending on conditions [6]. Using a sophisticated method to locate points of maximum sound absorption along the nasal tract, Dang et al. [8] attempted to measure the resonance frequencies of the sphenoidal, frontal and maxillary sinuses in 3 subjects who phonated a nasal consonant. They also estimated the dimensions of the cavities from MRI data and estimated their resonances by means of the Helmholtz equation. The results showed good agreement between calculated and measured zero frequencies [8]. In their single-subject study, Pruthi et al. [4] constructed a computer model based on MRI data. The model showed that the maxillary and sphenoidal sinuses contribute zeros in the frequency response of the vocal nasal tract, the frequencies of which were heavily affected by variations in the velopharyngeal opening [4]. As the size of the paranasal cavities varies substantially between individuals, the frequencies of spectrum dips in nasalised speech sounds have been used in speaker identification attempts [9].

In summary, MRI-based models as well as analyses of nasal consonants and nasalised vowels have demonstrated the introduction of zeros in the response curve of the investigated sinonasal systems. The observed zero frequencies varied considerably and were attributed to interindividual variability in the complex anatomical morphology. The present investigation aims at further elucidating the resonance properties of the nasal tract by analysing it in isolation, without connection to the vocal tract. First, we demonstrate by measurements on a simplified resonator model the effects on the nasal response curve of adding a cavity of varied size. Then, we test a method of occluding the ostia of the cavities in the stable anatomical condition of a cadaver and measure the frequency response after opening one ostium at a time.

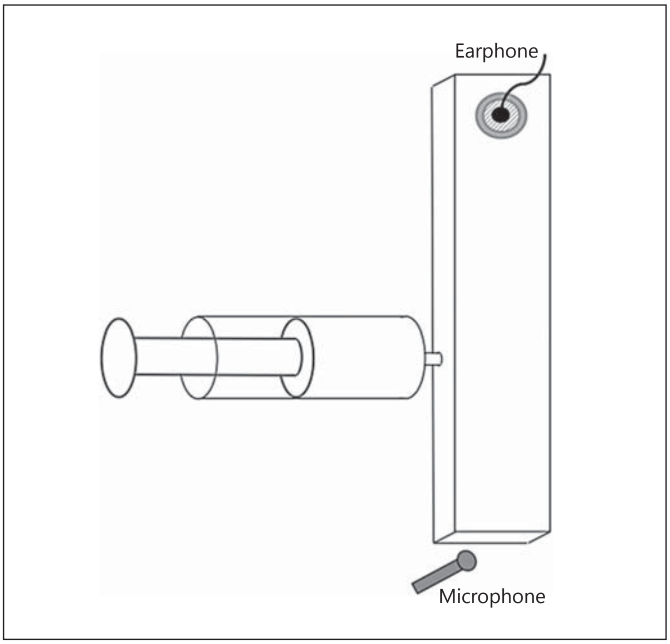

Fig. 2. Schematic illustration of the brass tube model with the shunting tube attached.

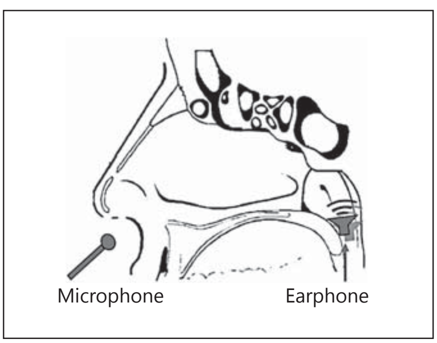

Fig. 3. Schematic illustration of the placement of the earphone and the microphone during the sine sweep measurements in the cadaveric situs (sagittal plane).

Methods

The simplified model consisted of a rectangular closed-open brass tube of 10 cm length. The shunting tube was attached 4 cm from the open end and connected to the main tube with a hole 1.6 mm in diameter and 1 mm in length. The length of this shunting tube, i.e. its volume, could be varied by means of a piston (fig. 2). The model was excited by means of a sine sweep (range 200–4,000 Hz, duration 18 s) produced by an earphone introduced radially 1 cm from the closed end. The microphone was located 5 mm off axis from the open end. The sine sweep was provided and the response curve simultaneously recorded using custom-made Tombstone software (by Svante Granqvist, KTH).

The resonance properties of a true sinonasal tract were examined in an adult male cadaveric situs. The earphone producing the sine sweep was hermetically sealed in the epipharynx by means of Plasticine (fig. 3). For technical reasons, the Tombstone software could not be used; instead the sine sweep was obtained from the Tone® software (by Svante Granqvist, KTH). The response was picked up by a microphone placed 1 cm in front of the columella. Unfortunately, the measurements had to be performed in a room without sound treatment, where the ventilation system produced low-frequency noise. Therefore, the response in the frequency range up to 400 Hz had to be discarded.

As a baseline condition, both middle meatus and sphenoidal ostia were occluded under endoscopic control using maltodextrin food thickener, a jelly-like viscous mass composed of cornstarch powder and water, routinely used in the assessment of swallowing disorders [5]. Under experimental conditions, the occlusion was removed by targeted suction.

Additionally, to provide direct access to the maxillary ostium and enable its selective occlusion, infundibulotomy (removal of the uncinate process) was performed according to the criteria of functional endoscopic sinus surgery. Each condition was measured twice.

Anatomical dissections, rhinosurgical procedures and the broad implementation of CT scan imaging in pre-operative work-up routines for sinonasal surgery in the last two decades have revealed that the drainage passages of the frontal sinuses and of the ethmoidal cells are extremely crooked and narrow [10–12]. Whereas the maxillary ostium represents a relatively constant and detectable anatomical structure shielded from the nasal cavity by uncinate process and middle concha, the fronto-ethmoidal region comprises variably developed cells substantially complicating the accessibility of the frontal recess [11, 12]. Under normal conditions, i.e. without surgical intervention, the acoustic impedance of the fronto-ethmoidal region is supposed to be high. Thus, there are strong reasons to assume that the effects of frontal and ethmoidal sinuses on the acoustic properties of the nasal tract are negligible. Hence, they were excluded from this examination.

Results

Without shunting tubes, the two lowest resonance frequencies of the brass model appeared at 800 and 2,440 Hz (fig. 4a), close to values expected for a 10-cm-long closed-open tube. (Figures 4–7 use a logarithmic frequency scale, since the response in the low-frequency range is the prime interest.)

In the cadaveric situs, under the all-occluded condition (both middle meatus and sphenoidal ostia occluded), a clear resonance peak could be observed at 720 Hz as can be seen in figure 4b. Other heavily damped peaks appeared near 1,400, 2,800 and 3,800 Hz. These resonance frequencies show some similarity with those of an open-closed cylindrical resonator 12 cm in length [$(2n - 1) \times F = 34{,}000/48 = 700$ Hz]. As expected, the reproducibility of the sine sweep response curves was almost perfect in

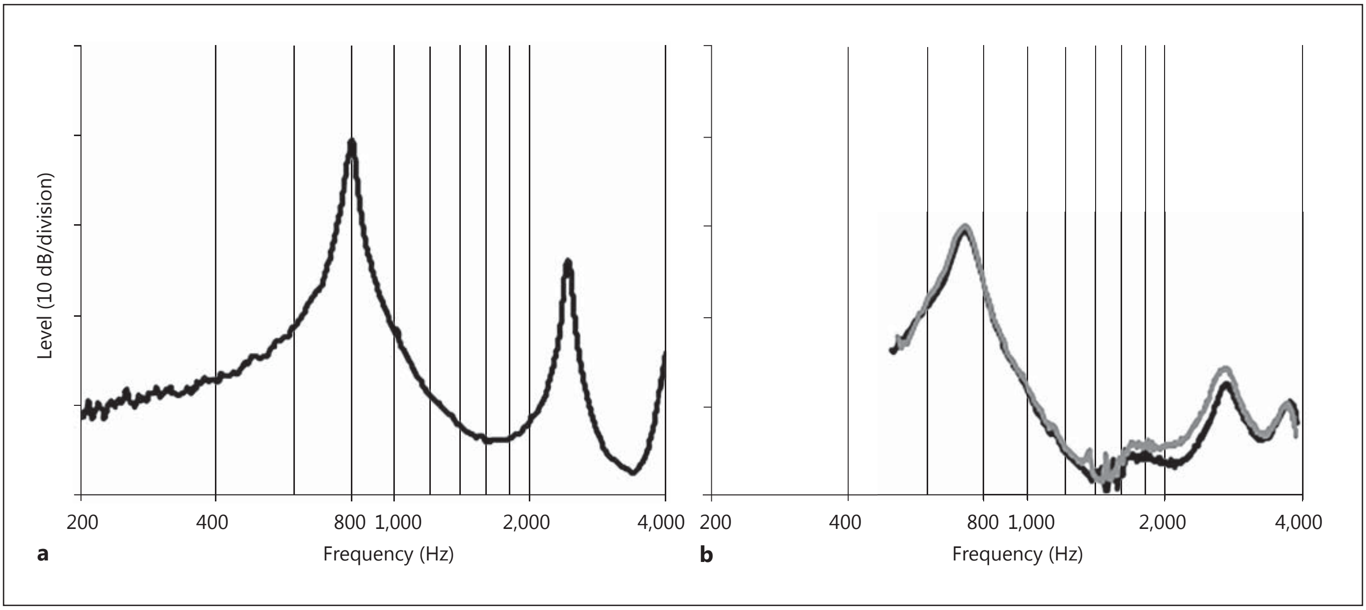

Fig. 4. a Response curves obtained from the brass tube model with no shunting cavities. **b** Response curves obtained from repeated sine sweep excitation of the nasal tract while the middle meatus and sphenoidal ostia were occluded (all-occluded condition). The amplitude of one curve was displaced by 2 dB.

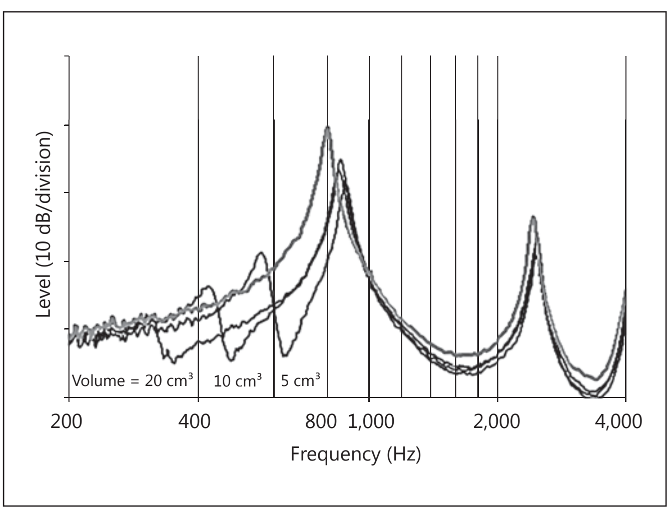

Fig. 5. Response curves obtained when a shunting cavity with the indicated volumes was connected to the brass tube model.

the cadaveric situs. Not surprisingly, the bandwidths in the cadaver were considerably wider than those of the brass tube model, e.g., 43 and 90 Hz for the first formant in the tube model and in the cadaver, respectively.

Figure 5 shows the frequency response curves of the brass model recorded with three different volumes of the shunting tube. Applying the Helmholtz resonator equation, the resonance frequencies were 680, 480 and 340 Hz (volumes of 5, 10 and 20 cm^3). As seen in figure 5, the dips appeared at 640, 467 and 343 Hz for these given volumes, respectively. This indicates that the shunting cavity produced a frequency curve dip appearing near its resonance frequency. Moreover, the lowest resonance peak shifted slightly with the dip frequency (840, 850 and 870 Hz, respectively).

Figure 6 compares the all-occluded condition (grey curve) in the cadaver with the condition after removal of the occlusion from the right middle meatus and the sphenoidal ostium (black curve). In the latter case the resonance at 720 Hz seems to be split into two peaks by a marked zero at 770 Hz. Another peak appeared at 1,330 Hz as well as two blunt peaks at 3,000 and 3,800 Hz.

The orifice of the maxillary sinus hides behind a structure called the processus uncinatus. In functional endoscopic sinus surgery, this structure is routinely removed in cases of suspected maxillary pathology. This surgical procedure allows direct visualisation and inspection of the ostium and the sinus. After removal of the processus uncinatus the two curves shown in figure 7 were obtained, one with the ostium open, the other with the ostium occluded by means of maltodextrin. In the first case, a marked dip appeared at 530 Hz, presumably reflecting the

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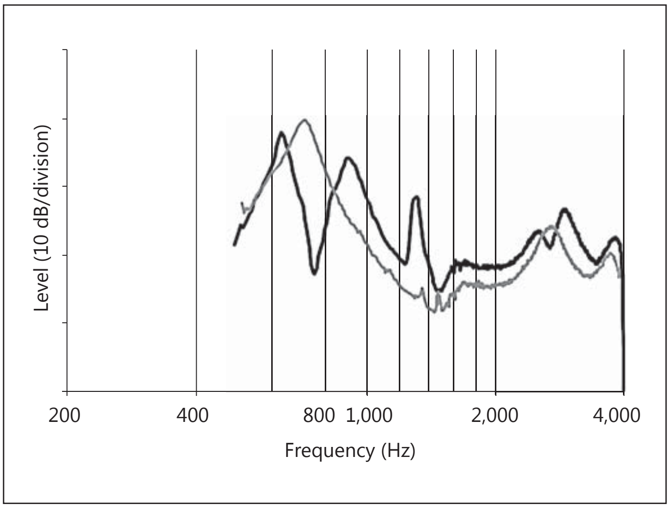

Fig. 6. Response curve obtained from sine sweep excitation of the nasal tract with the occlusion of one middle meatus and one sphenoidal sinus removed (black). The grey curve is the same as in figure 4b.

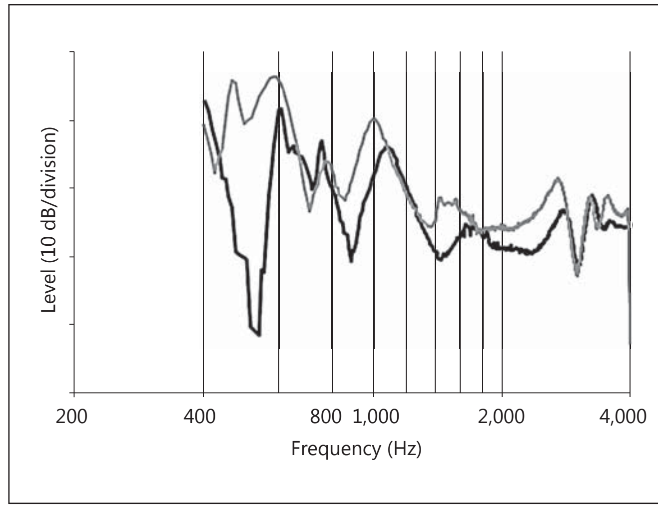

Fig. 7. Response curves obtained from sine sweep excitation of the nasal tract after infundibulotomy, with (black) and without (grey) occlusion of the maxillary ostium.

absorbent effect of the now exposed maxillary sinus. The fact that this dip occurred only after removal of the processus uncinatus suggests that, at least in some cases, the maxillary sinuses may have a minor influence on radiated nasal sounds.

The frequencies of the dips in figures 6 and 7 observed after exposure of the sphenoidal and maxillary ostium appeared at 720 and 530 Hz, respectively. As dip frequencies can be expected to occur at resonance frequencies of the shunting cavities, this suggests that the volume of the sphenoidal cavity is smaller than that of the maxillary sinus.

Discussion

The nasal tract is an extremely complex and also potentially varying resonator as mentioned before [3]. This is due to the intricate sinonasal anatomy as well as the in vivo cyclically changing shape of the mucosa. By using the stable anatomical condition of a cadaver, we obtained quite reproducible response curves to the sine sweeps (fig. 4b). Also, by considering the nasal tract in isolation, we avoided the overwhelming complexity resulting from combining the vocal and nasal tract resonators, coupled by the highly variable velopharyngeal port. Furthermore, by using the removable occlusion method in the cadaver, it was possible to first eliminate the paranasal cavities (even the sphenoidal) from the nasal cavity and then include paranasal cavities and document their contributions to the resonance properties. Of course the minimally invasive occlusion method is applicable also to living subjects, although the sphenoidal cavities will remain inaccessible.

We examined the nasal tract in isolation, without including the vocal tract. Thereby it was important to achieve a complete seal of the velopharyngeal opening, as even a tiny leakage would have influenced the resonance frequencies considerably. The results support the assumption that this condition was met; in the all-occluded condition, the lowest resonance appeared at a similar frequency in the cadaver as in the brass tube model (fig. 4a, b). However, the bandwidths of the resonances observed, particularly those appearing above 2,000 Hz, were much wider in the cadaver than in the brass model and the dips much shallower. This was expected, since the losses in the brass model must be much smaller than in the cadaver with its narrow passages (high circumference-to-cross-sectional area ratio), its mucosa-covered cavity walls and its complex structure and positions of the ostia [13].

Contrary to common assumption, the paranasal cavities function as acoustic absorbents, producing minima in the transfer function, rather than enhancing particular frequency regions in the radiated sound [13]. This could be clearly demonstrated both in the model and in the cadaver.

After removal of the occlusion of the right sphenoidal ostium and the right middle meatus, we observed a marked dip at 720 Hz. It does not seem likely that this dip was caused by the maxillary sinus as our findings suggest that the ostium of this cavity contributed to the sine sweep response only after direct exposure following infundibulotomy. Rather the 720-Hz dip would have emanated from the sphenoidal cavity. Dang et al. [7] and Dang and Honda [8] found examples of a similar resonance frequency for this cavity.

In the cadaver, the maxillary sinus seemed to have a minor influence on the response curve of the nasal tract. On the other hand, Dang and Honda [8] found evident contributions from the maxillary sinuses in 3 living subjects. Under in vivo conditions, an active mucosal lining with its swelling potential would compromise the accessibility. Given the crooked and narrow middle meatus/uncinate process region and the great interindividual variation of nasal tract morphology, it can be assumed that the maxillary sinuses are acoustically inaccessible in some cases and accessible in others.

An effect of the maxillary sinus was observed in terms of a marked zero at 530 Hz, which appeared only after surgical exposure of the ostium by infundibulotomy. Assuming that the paranasal sinuses can be considered as Helmholtz resonators with a neck diameter of 1.6 mm, neck length of 1 mm, and a volume of 10 and 20 cm^3, the lowest resonance frequency should appear at 767 and 543 Hz, respectively. These values are not very far from the zero frequencies observed after exposure of the sphenoidal and maxillary ostium. Moreover it is similar to the antiresonance frequencies of the maxillary sinuses estimated from acoustic measurements by Dang and Honda [8]. Yet, the importance of close agreement with previous findings of resonance frequencies of the paranasal sinuses should not be overestimated, given the substantial intra- and interindividual variability of sinonasal tract morphology.

Conclusion

Acoustic responses of the sinonasal tract can be derived from cadaver experiments, showing good reproducibility. According to brass model experiments, the resonance frequencies of the paranasal sinuses can be expected to produce dips in the frequency response of the nasal tract. Such dips were also observed in the real anatomy of a cadaveric sinonasal tract. Minor acoustic effects are assumed for the maxillary sinus under natural conditions since their orifices are shielded from the nasal cavity. A direct exposure of the maxillary ostium following surgical intervention seems to introduce a marked effect in the response curve. However, the variable morphology of the sinonasal tract impedes the direct attribution of response curve features to specific sinuses.

References

1 Birch P, Gümoes B, Stavad H, Prytz S, Björkner E, Sundberg J: Velum behavior in professional classic operatic singing. J Voice 2002;16:61–71.

2 Lindqvist-Gauffin J, Sundberg J: Acoustic properties of the nasal tract. Phonetica 1976;33:161–168.

3 Båvegård M, Fant G, Gauffin J, Liljencrants J: Vocal tract sweeptone data and model simulations of vowels, laterals and nasals. STL-QPSR 1993;34:43–76.

4 Pruthi T, Espy-Wilson CY, Story BH: Simulation and analysis of nasalized vowels based on magnetic resonance imaging data. J Acoust Soc Am 2007;121:3858–3873.

5 Dewar RJ, Joyce MJ: Time-dependent rheology of starch thickeners and the clinical implications for dysphagia therapy. Dysphagia 2006;21:264–269.

6 Koyama T: Experimental study on the resonance of paranasal sinus. J Otolaryngol Jpn 1966;69:1177–1191.

7 Dang J, Honda K, Suzuki H: Morphological and acoustical analysis of the nasal and the para-nasal cavities. J Acoust Soc Am 1994;96:2088–2100.

8 Dang J, Honda K: Acoustic characteristics of the human paranasal sinuses derived from transmission characteristic measurement and morphological observation. J Acoust Soc Am 1996;100:3374–3383.

9 Zhao C, Dang J, Wei J, Honda K: Individual variation of morphological and acoustic effects of the nasal tract. 2013 IEEE China Summit and Int Conf on Signal and Information Processing, Beijing, July 2013, pp 337–341.

10 Stammberger H, Posawetz W: Functional endoscopic sinus surgery: concept, indications and results of the Messerklinger technique. Eur Arch Otorhinolaryngol 1990;247:63–76.

11 Leunig A, Betz CS, Sommer B, Sommer F: Anatomic variations of the sinuses; multiplanar CT-analysis in 641 patients. Laryngorhinootologie 2008;87:482–489.

12 Han JK, Ghanem T, Lee B, Gross CW: Various causes for frontal sinus obstruction. Am J Otolaryngol 2009;30:80–82.

13 Bjuggren G, Fant G: The nasal cavity structures. STL-QPSR 1964;5:5–7.