RHINOLOGY

ORIGINAL CONTRIBUTION

Ex-vivo and replica measurements of nasal tract resonances

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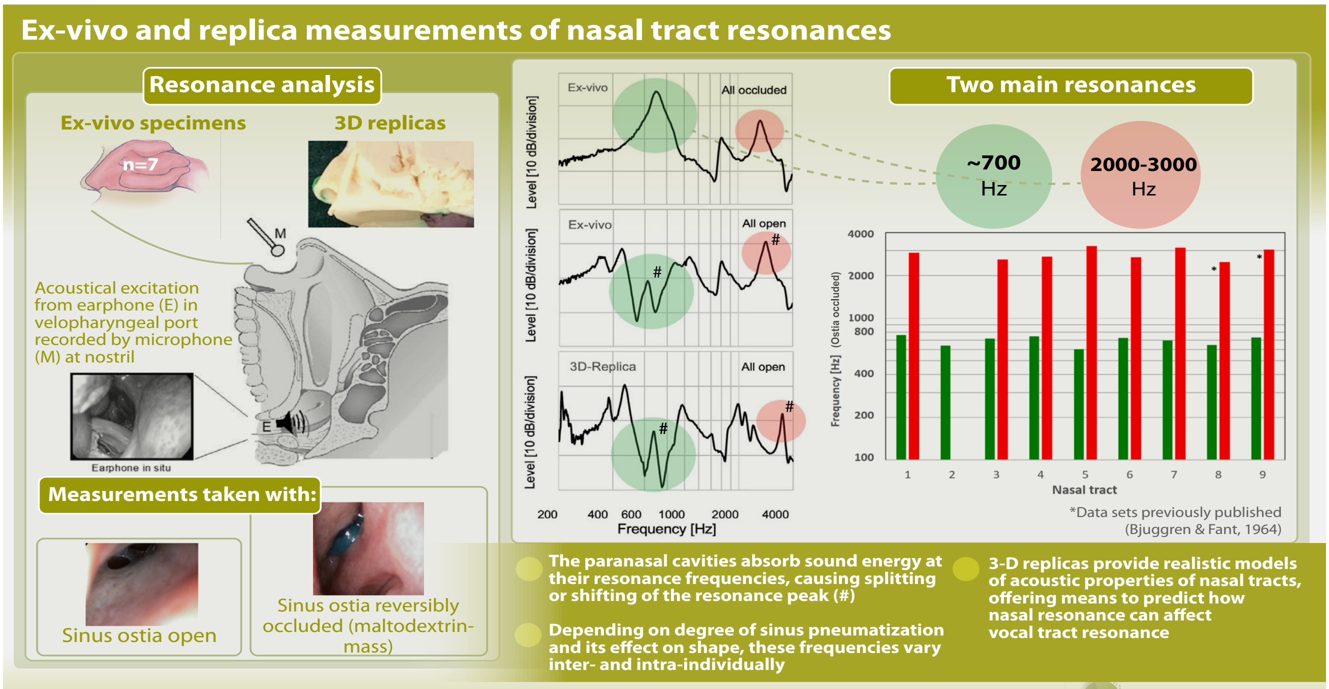
Ex-vivo and replica measurements of nasal tract resonances



- The paranasal cavities absorb sound energy at their resonance frequencies, causing splitting or shifting of the resonance peak (#)
- Depending on degree of sinus pneumatization and its effect on shape, these frequencies vary inter- and intra-individually
- 3-D replicas provide realistic models of acoustic properties of nasal tracts, offering means to predict how nasal resonance can affect vocal tract resonance

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Abstract

Background: The nose is a resonator, the acoustic properties of which are determined by its shape. Due to its complex anatomy and hence intricate acoustical response the identification of universal acoustic characteristics of nasalized vowels and consonants is challenging. The purpose of this investigation was to 1) elucidate acoustic properties of the nasal resonator, 2) document how the paranasal sinuses affect it, and 3) examine if 3D-replicas of anatomical specimens provide reliable data for acoustic analysis.

Methods: In this experimental study the resonance properties of the nasal tract were analyzed in ex-vivo specimens as well as in their 3-D replicas. Their sound transfer characteristics were recorded by sending a sinewave, gliding from low to high frequency from an earphone airtightly sealed into the velopharyngeal port. The response was picked up at a nostril. The acoustical influence of the sinuses was reversibly eliminated by occlusion of the sinus ostia.

Results: Response curves of the nasal tract were found to possess two main resonances, one in the vicinity of 600-750 Hz and one in the 2500 – 3500 Hz range. Comparison of the acoustical responses obtained while including and excluding the influence of the paranasal cavities showed a great inter-individual variation in the response curve morphology. The cavities were found to introduce V-shaped sound level minima in the response curves.

Conclusions: When the influence of the paranasal cavities is eliminated, the nasal cavity presents two main resonances, which are determined mainly by its anatomical length. The resonances of the paranasal cavities introduce minima and maxima in the frequency response of the nasal tract at frequencies with substantial inter-individual variation. Replicas of anatomical specimens provide reliable data for acoustic analysis.

Key words: nasal tract, paranasal sinuses, resonance, response curve, transfer function

Introduction

The resonance characteristics of the nasal tract have been the subject of experimental research for more than half a century. A typical question from patients undergoing rhinosurgical procedures is what the effects on speech and voice might be, questions that have been examined in several publications. Yet, the question what the common acoustic properties of nasal tracts may be, has remained open. Also, among voice clinicians and pedagogues, the relevance of nasal resonance has been a longstanding debate; some argue that a slight degree of nasalization has a beneficial influence on the voice timbre, while others strongly recommend that it should be avoided.

Clinical studies

Several clinical investigations have been undertaken regarding the influence of sinus surgery on voice and speech with varied, non-comparable results, possibly due to diverging methodologies, small sample size or heterogeneous interventions (1-9). In addition, some of these studies include multiple interventions in the main nasal, as well as in the paranasal cavities. This complicates identification of cause-effect relationships between the specific intervention and its outcome, see e. g. Xiao (3).

Tepper et al. reported a pre-post surgery comparison of voice quality, analyzing acoustic parameters in four professional voice users undergoing sinus lifting but observed no changes (10). Hosemann et al. spectrographically analyzed acoustic characteristics of sustained vowels in 21 patients with chronic paranasal sinusitis (6). In this pre- and postoperative analysis, they found formant frequency and spectrum shape alterations and, in six patients, also perceptual changes of the speech. Chen et al. analyzed nasal consonants and nasalized vowels in five patients undergoing sinosurgical intervention (7). They found perceptually decreased nasality in the vowel /i/ and increased in the vowel /ae/, effects that correlated with acoustic measures of "nasal peak amplitude" and the "the lowest resonance peak amplitude of the vocal tract". Following endoscopic sinus surgery in patients with nasal polyposis, Hong et al., found effects on nasalance, i.e. the quotient between nasal and oral acoustic energy, but not on the nasal forman (11). As compared to normative nasalance values, Soneghet et al. noted a significant increase one-month postoperatively in 40 patients undergoing FESS (8).

Other investigations have analyzed the significance of the main nasal cavity as a resonator, mostly focusing on septum and/or concha surgery or decongestion. Studying acoustical effects of septoplasty, Ozbal et al. did not observe any statistically significant change for nasalized vowel /a/ when following a nasal consonant (12). By contrast, Liapi et al. compared pre and post septoplasty analyses in 34 patients with respect to the amount of total acoustical energy and spectrum of the consonant /m/ (13). The patients reported subjective improvement of "vocal resonance".

Changes in acoustic rhinometry and nasometry following application of decongestant were analyzed by Birkent et al. (14). Significant increase in nasalance scores and in acoustic rhinometric parameters were observed, though without significant correlation between the two data sets.

Basic research

In most of the studies mentioned, there was no particular distinction between the acoustical contributions of the nasal and the paranasal cavities. Under in-vivo conditions the acoustical landscape of the sinonasal system is complicated by the ever-present confounding factor represented by the paranasal sinuses. A distinction between these factors is required for the possibility of identifying the specific origins of acoustical characteristics of the nasal resonator. Under in-vivo conditions, apart from anatomy, several further factors contribute to inter- and intraindividual variability, such as mucosal vibration and nasal cyclicity (15); acoustic effects of the mucosa swelling have been experimentally documented (16). Given this potentially confounding factors only a well-controlled experimental ex-vivo setup allows a thorough understanding of the anatomy and function.

The acoustical properties of the nasal tract are determined by its shape. These properties can be specified in terms of its frequency response, henceforth transfer function, which describes how the nasal tract transfers sound of different frequencies from the velopharyngeal opening to the nostrils. This approach was successfully applied in an ex-vivo experiment by Bjuggren and Fant (17).

Previous basic research studies have revealed a great complexity of nasal tract frequency curves. This is not surprising, as it is well known that the nasal tract with its pairwise arranged sinuses shows a great inter- and intraindividual variability (18, 19). These cavities act as sound absorbers, generating V-shaped regions of low sound level (minima) in the frequency curve of the nasal tract (20). Dang and Honda (21) used such minima to determine the resonance frequencies of paranasal cavities.

Given the considerable variability of the endonasal shape, reliable prediction of acoustic effects of elective sinonasal surgery requires well-controllable models. For these reasons it seemed important to check the agreement between ex-vivo specimens and corresponding 3-D replicas.

Despite the great anatomical and physiological variability in dimensions and shape of the nasal tract, nasalization serves as an efficient phonetic feature in many languages. This invites to the hypothesis that nasal tract possesses some yet unclear but still universal acoustic characteristic.

The purpose of the present investigation was to identify acoustic properties of the nasal resonator. To realize this purpose, we analyzed frequency curves of human nasal tracts in ex-vivo settings, following reversible occlusion of the paranasal cavities' ostia. In addition, the frequency curves of the corresponding 3D replicas

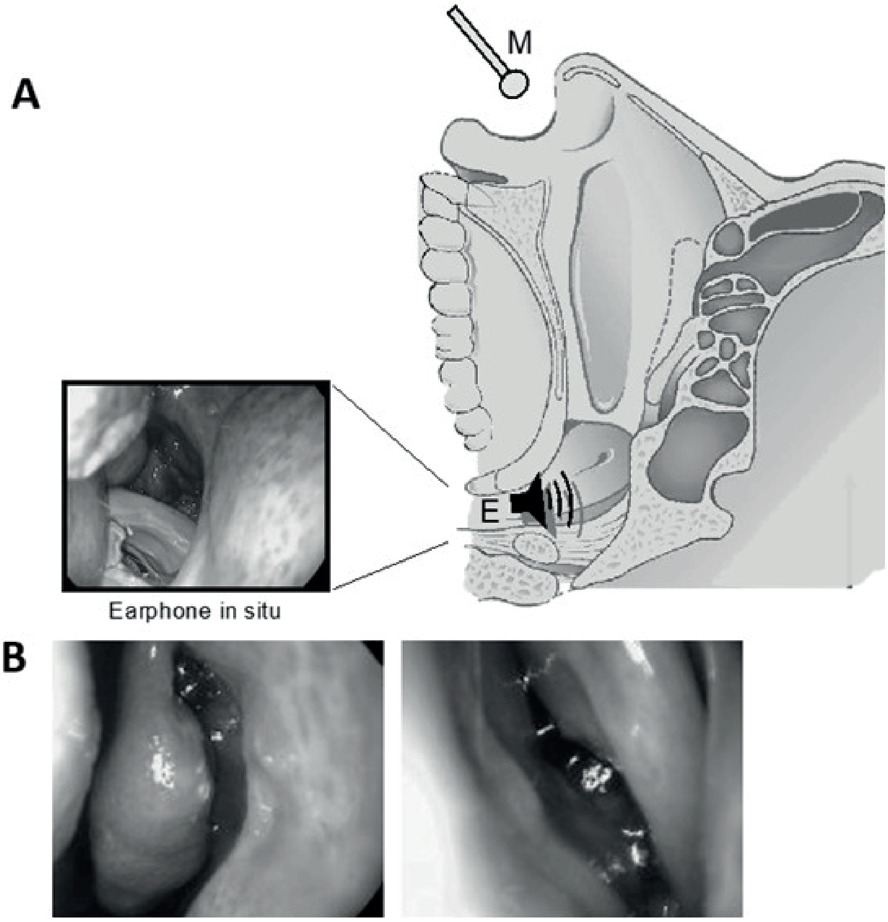

Figure 1. A) Experimental setup for recording the transfer function of the nasal tract (frequency curve showing the amplitude variation resulting from an input sinewave that glides from low to high pitch) in the ex-vivo measurements. Using plasticine, an earphone (E) was airtightly placed in the velopharyngeal port (endoscopic view, left panel) and the microphone (M) at a nostril. B). In situ maltodextrine mass occlusion of the left middle meatus and the left sphenoidal ostium (left and right photos, respectively).

were examined to find out if they provide sufficient detail for acoustic analysis.

The following three hypotheses will be tested:

1. Nasal tracts possess a common main resonance within a limited frequency range.
2. Identification of this resonance can be complicated by paranasal cavity resonances.
3. 3-D models reliably reproduce the acoustic properties of nasal tracts.

Materials and methods

Ex-vivo measurements

Acoustic properties were analyzed in seven embalmed cadavers (two Thiel, five Formaldehyde fixation, all male Caucasian). In all cases, a clinical endoscopic examination of the nasal cavity was performed to rule out major septum deviation, post-surgery condition or endonasal pathology. Additionally, in the last three cases examined (nasal tract 5, 6 and 7), CT imaging was available, where no sinonasal pathology was detected.

Acoustical effects of the maxillary and sphenoidal sinuses were eliminated by applying a reversible occlusion of their ostia. An earphone (Jabra BT 3030, Copenhagen, Denmark) was tightly sealed with plasticine into the velopharyngeal port (Figure 1A). An electret microphone (TCM141, AV-Jefe, Taiwan) was placed close to a nostril.

For the first four ex-vivo measurements, acoustical excitation was obtained from the Tone freeware (available at www.TolvanData.com, last visited April 15, 2024) that provided a sinewave, gliding with constant speed along a logarithmic frequency scale from 200 Hz to 4000 Hz within 18 sec. The sinewave was at least 28 dB above the system noise level. The Sopran freeware (ibidem) recorded the microphone signal into a wav file, from which sound level could be analyzed as a function of frequency. In the three remaining cases, measurements were made using the more recently Tombstone freeware (ibidem). It generates the same excitation signal, and simultaneously records the microphone sound level, band pass-filtered along the frequency scale. It displays the result in graphs showing sound level as a function

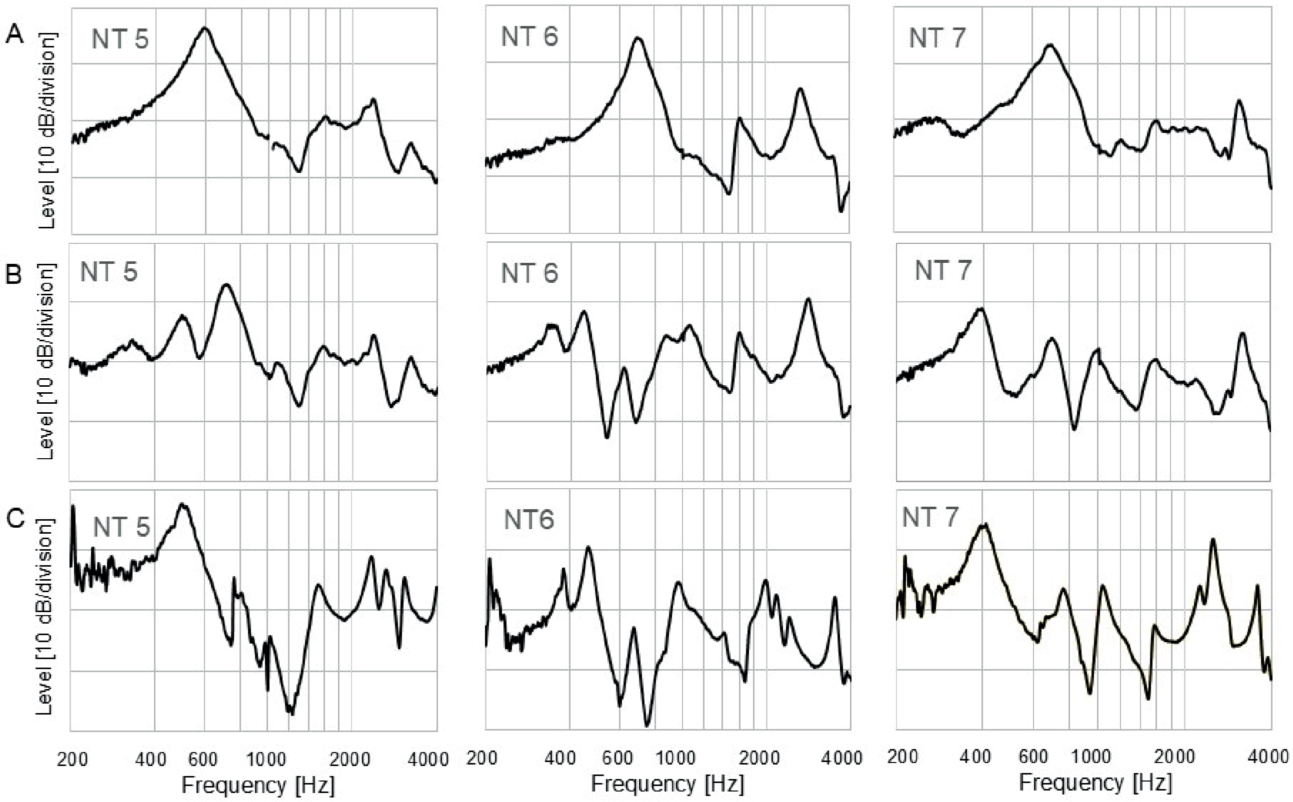

Figure 2. Transfer functions of the indicated nasal tracts (NT), measured ex-vivo under A) the All closed condition, B) under the All open condition. The panels in C) show the corresponding data for their replicas.

of frequency, i.e., the transfer function.

In all recordings the earphone-to-microphone frequency characteristics were measured in free air. Typically, the characteristic was logarithmical, about +10 dB/octave between 200 Hz and 4000 Hz. This characteristic was used for correcting measured level values.

To check the reliability of the data obtained, two ex-vivo recordings were compared before and after dismantling the entire experimental setup. The transfer functions had a standard deviation of 0.4 dB, maximum deviation from the mean 1.5 dB, thus representing reliable transfer functions.

Lack of left-right symmetry of a nasal tract caused some variation between microphone positions close to left/right nostril and columella. The differences were smaller than ±2 dB for frequencies between 300 and 850 Hz. Larger differences appeared at higher frequencies. Identical microphone position was used in all recordings.

Occlusion procedure

To better understand the acoustics of the nasal tract as documented in earlier investigations (20, 22), we compared two cases, with and without acoustical elimination of paranasal cavities. Hence, in *Condition 1/All occluded*, the middle meatus and the sphenoidal ostia were occluded, thus eliminating their acoustical effects. The occlusion was achieved by application of maltodextrine mass (Figure 1B), administered under endoscopic control by means of a syrinx cannula (0°, 4 mm endoscope, Karl Storz, Tuttlingen, Germany). In *Condition 2/All open*, all occlusions were removed by targeted suction.

Replica measurement

The high-resolution CT data were converted to STL files and 3-D replicas were produced via FDM (Fused Deposition Modeling) technology, using thermoplast-filament (Stratasys ABS-P430 Dimension Elite, Stratasys, MN, USA) (7). The surface of this material is porous, which attenuated the tract resonances. To eliminate this disadvantage, the models were treated by dispersing them with 5 mL acetone through both the nostrils and the pharyngeal port.

Results

The acoustic properties of a nasal tract resonator can be visualized in terms of its transfer function, i.e., a frequency curve showing the amplitude variation resulting from an input sinewave that glides from low to high pitch. Figure 2A shows such a transfer function for the three nasal tracts (NT) 5, 6, and 7, measured with the paranasal sinuses acoustically excluded by reversible occlusion of the ostia, i.e., under the *All closed* condi-

Table 1. Main and upper resonance frequencies and bandwidths, in Hz, and Q-values of the seven ex-vivo nasal tracts measured under the *All closed* condition (for technical reasons the higher resonance could not be measured in nasal tract 2). B&F shows data derived from the area functions published in the Bjuggren and Fant study (17).

Nasal tract	Fixation	Main Frequency	Bandwidth	Q value	Upper Frequency
1	Thiel	757	59	12,8	2890
2	Thiel	640	58	11,0	-
3	Formaldehyde	716	52	13,8	2578
4	Formaldehyde	743	103	7,2	2700
5	Formaldehyde	598	93	6,4	3220
6	Formaldehyde	718	116	6,2	2690
7	Formaldehyde	690	120	5,8	3106
	MEAN	695	86	9,0	2864
	SD	57,1	29,0	3,4	255
B&F	Cast 1	647	34	19,0	2470
B&F	Cast 2	726	42,0	17,3	3040

tion. In all three cases, a main resonance peak can be seen in the low frequency range, between 598 and 757 Hz, average 695 Hz (SD 57 Hz). The values are listed in Table 1 together with those of the remaining four anatomical specimens examined.

For further quantitative specification of resonance properties, the attenuation of the resonance/sharpness of the peak can be quantified in terms of the bandwidth (the frequency difference between the rising and the falling part of the frequency curve at 3 dB below its peak) and its ratio to the frequency of its peak, the Q-value. Also, these two characteristics are displayed in the table. As can be seen, the resonance attenuation is similar across the seven specimens examined, bandwidth range 52 Hz to 120 Hz, mean 86 Hz (SD 29 Hz) and Q-value range 5.8 to 13.8, mean 9.0 (SD 3.4). As also shown in the table, the curves displayed a second peak in the frequency range between 2578 Hz and 3220 Hz, mean 2864 Hz, (SD 255).

Figure 2B (middle panels) show the transfer functions of the same three nasal tracts as in the top panels, measured in the *All open* condition, with the paranasal sinuses included in the resonatory system. Here, several dips and peaks can be seen, apparently originating from the paranasal cavities. In nasal tract 5 the main resonance at 598 Hz was divided by a marked dip at 574 Hz. For nasal tracts 6 and 7, two marked dips, the lower ones at 545 Hz and 486 Hz and the higher ones at 689 Hz and 831 Hz, respectively, surrounded the main peaks at 726 Hz and 714 Hz, respectively, apparently reducing their amplitudes. In addition, the paranasal cavities slightly shifted the frequencies of the main resonances by +138 Hz, -93 Hz, and +9 Hz, respectively.

The acoustical properties of the anatomical specimens (Figure 2B, *All open* condition) are compared in the same Figure with those of their replicas derived by 3-D printing (Figure 2C). The sharpness of most dips was greater in the replicas than in the ex-vivo specimens. For nasal tract 5 the dip at 400 Hz failed to appear in the replica, and the dip at 578 Hz was shifted to 744 Hz. For nasal tracts 6 and 7 the frequencies of the main peaks and dips were like those of the anatomical specimens.

Discussion

The universal anatomical characteristic of human noses is a duct, extending from the nasopharynx to the nostrils, complemented by the paranasal cavities. Based on measurements on ex-vivo specimens and their 3-D replicas we here presented an attempt to identify the acoustic effects of this common trait on the nasal tract transfer function.

The paranasal cavities can be considered as Helmholtz resonators acting as side branches of the main nasal duct. They absorb their respective resonance frequencies, thus introducing minima in the transfer function reflecting their volumes and ostia sizes (21, 22). The lack of symmetry in the pairwise arranged sinuses further adds to the complexity, as does the nasal cyclicity of the mucosa (15). Moreover, under in-vivo conditions the limited accessibility of the ostia impairs detection of the main nasal resonance, impeding identification of common nasal tract acoustic properties.

Here we presented ex-vivo experiments where we reversibly occluded the middle meatus and the sphenoidal ostia, thus offering a possibility to compare two conditions, included and acoustically eliminated paranasal cavities (the *All open* and *All closed* conditions) in all seven specimens. Eliminating the cavities revealed a main resonance peak in the frequency range of 598 to 757 Hz, average 695 Hz; and a second peak between 2578 and 3220 Hz, average 2864 Hz, (Table 1). Comparison with the ex-vivo *All open* condition corroborated that the paranasal cavities act as sound absorbing resonators.

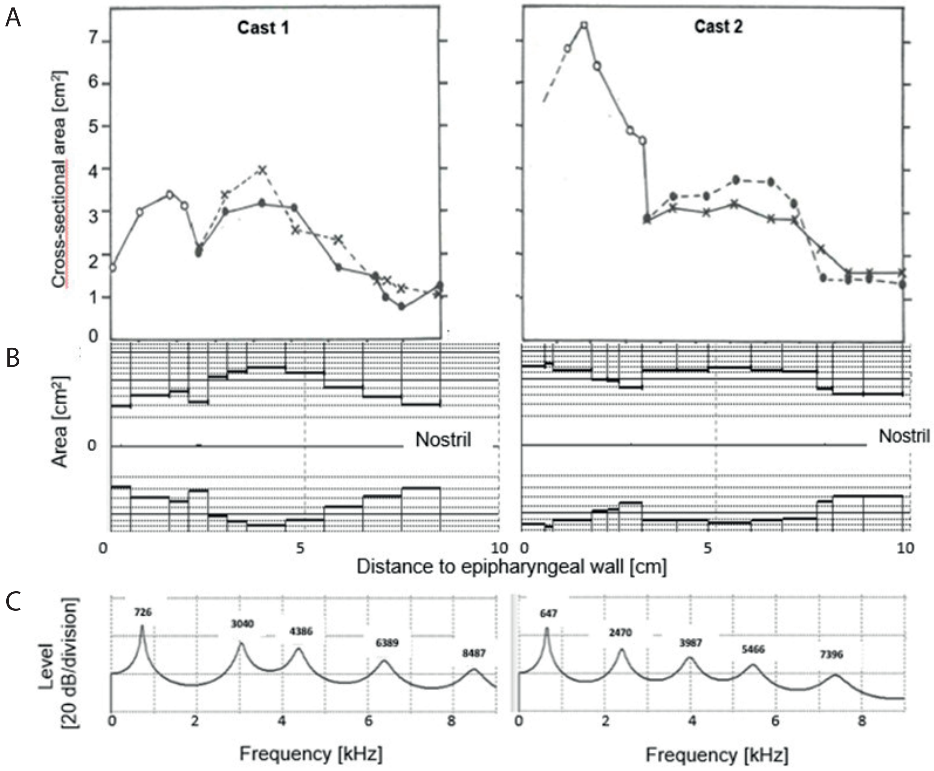

Figure 3. A) Cross-sectional area of two nasal tracts measured under ex vivo condition and plotted as function of the distance to the epipharyngeal wall, modified after Bjuggren and Fant (17). B) Cylinder approximations of these area functions using the same abscissa as in 3A. C) Corresponding transfer functions computed by the custom-made Wormflek software (Johan Liljencrants (29)).

Frontal sinuses

The air-filled paranasal cavities communicate with the main nasal duct and are ventilated by nasal sound (23). In contrast to maxillary and sphenoidal ostia, the frontal sinus drainage pathway is a complex 3-dimensional structure devastatingly complicated by various pneumatized cells (24). Drug deposition experiments have shown that pulsating aerosol introduced into the nostrils successfully reached the maxillary and sphenoidal sinuses, while the frontal sinuses remained unaffected (25, 26). This supports the assumption that the frontal sinuses have a limited acoustic effect on the nasal transfer function.

Embalmment

To approximate as closely as possible the complex anatomy, the present measurements were carried out ex-vivo, requiring measurements on embalmed specimens. Embalmment affects the mechanical properties of the mucosa and could thus affect the acoustical resonance properties in terms of losses caused by wall vibration and friction. Formaldehyde embalmed tissues are supposed to be more rigid, while Thiel fixation might provide more realistic mucosal conditions (27, 28). Interestingly, the two Thiel embalmed specimens did not show resonance properties that clearly differed with respect to resonance frequencies and bandwidths from those treated with Formaldehyde (Table 1). Even though conclusions cannot be based on two cases, it is worth noting, that the difference in embalmment technique did not appreciably affect our measurements.

Porosity

Surface porosity in the replicas caused attenuation of resonances. This effect was substantially reduced by acetone immersion, as evidenced by a greater amplitude variation and a slight increase of the maxima and minima frequencies as compared with the ex-vivo condition.

Ex-vivo specimens versus replica

For the elimination of the paranasal cavities from the resonator system a reversible occlusion method was required. This was provided by endoscopically controlled occlusion of ostia with maltodextrine mass (Figure 1B). However, this maneuver could not be applied in the 3-D replica, because of the rigid cast material. To circumvent this limitation, we divided the replica along the axial plane slightly above the nasal floor, thus allowing direct access to the ostia. Unfortunately, this caused difficulties in achieving a complete airtight seal between the parts, which is critical for obtaining reliable results. Therefore, in the present experiments only undivided replicas, i.e., printed in one piece, were used. This excluded the possibility of measurement of

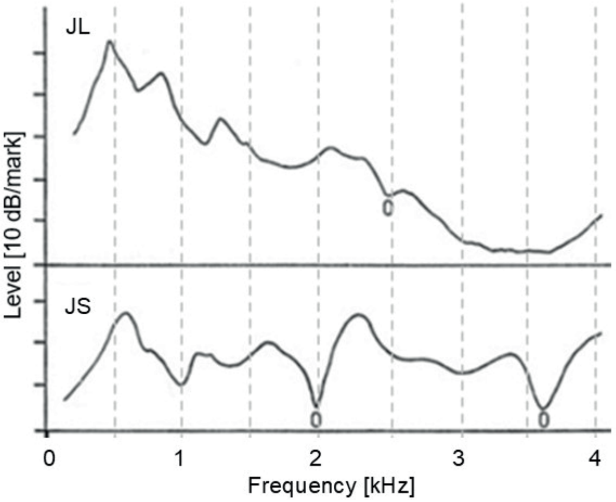

Figure 4. Transfer functions of nasal tracts of two male adults (JL and JS) measured in vivo. The gliding sinewave was introduced via a thin, damped plastic tube with the end near the nasopharyngeal wall. The curve points marked 0 refer to the estimated frequencies of minima reflecting the distance between the open end of the tube and the nasopharyngeal wall. After Lindqvist-Gauffin and Sundberg [16].

replica under the *All closed* condition.

We further found that replicas of the nasal tract, based on 3-D imaging, provided reasonably accurate information of its acoustical properties, as illustrated in Figure 2C. However, in the case of nasal tract 5 the lowest dip near 400 Hz was not represented in the replica, presumably because of a technical issue in the printing process that may have resulted in impaired patency of the ostium. In the replicas, several peaks and dips appeared at slightly higher frequencies than in the ex-vivo condition.

Earlier measurements

Our results can be compared with previously published measurements of the acoustical properties of nasal tracts. In an ex-vivo experiment Bjuggren and Fant [17] sliced the mold of two female nasal tracts and measured the cross-sectional area of each slice. Due to the rigidity of the cast material, the paranasal cavities could not be included. They presented the results in terms of the cross-sectional areas of the slices as a function of their distance to the nostril plane, see Figure 3A. The lengths of the two nasal tracts were similar, 9 cm and 10 cm.

Lindqvist-Gauffin and Sundberg [16] simulated an approximation of these same area functions and measured their transfer functions. They found two main resonances, the lower one near 600 Hz and the higher one near 2000 Hz. Using a custom-made software (Wormflek, Johan Liljencrants [29]), we again calculated the transfer functions of these two Bjuggren-Fant area functions (summating the left and right area values in the nostril region). Figure 3B shows the area functions and Figure 3C the transfer function together with their resonance frequencies; the lowest resonance appeared at 726 Hz and 647 Hz and the second at 3040 Hz and 2470 Hz, respectively. These values are in good agreement with the data we obtained under the *All closed* condition (Table 1).

Lindqvist-Gauffin and Sundberg [16] also measured the transfer function of two male subjects' nasal tracts under in vivo condition. They sent a gliding sinewave tone through a thin, damped plastic tube, the end of which was placed near the closed velopharyngeal port. The microphone was placed at a nostril. The highest resonance peak for these subjects' nasal tracts, obviously measured under an *All open* condition, appeared at 450 Hz and 550 Hz, approximately (Figure 4). These values are like those obtained under the same condition in the present study (Figure 2B).

Our results can be compared with those obtained in an earlier study from a simplified model in terms of a cylindrical tube of 10 cm length, provided with a cylindrical side branch with variable volume [30]. Without the side branch, resonances were found at 800 Hz and 2400 Hz. This corresponds to our *All closed* condition in the present investigation. With 5, and 10 cm^3 side branch volumes, peaks were observed at 420 and 670 Hz followed by dips in the region of 480 - 640 Hz. These results are in good qualitative agreement with the data presented here.

It is also interesting to compare our findings for the *All closed* condition with those of a cylindrical tube open at one end and closed at the other end. For such a resonator the resonance frequencies will appear at

$$F_R = (2n-1)*c/2L; \quad n= 1, 2, 3\ldots$$

where c is the speed of sound, and L is the length of the resonator. Assuming a distance of 10 cm from the nasopharynx posterior wall to the nostril [31, 32] and the speed of sound to 32,000 cm/s, the first and second resonances will appear at 800 Hz and 2400 Hz, quite close to the frequencies found in the ex-vivo measurements under the *All closed* condition. Thus, to the first approximation the nose can be regarded as a cylindrical tube of 10 cm length, provided with four side branches that produce minima in the transfer function. In other words, the universal acoustic characteristic of the nasal resonator in isolation is a main resonance in the 600 to 750 Hz region, physiologically complemented by minima arising from the paranasal sinuses.

Clinical implications

The frequency of the main nasal tract resonance is predominantly determined by its length dimension. Surgical interventions focused on improving or restoring nasal patency and/or on ventilation of paranasal cavities are unlikely to substantially change this frequency. Hence, septum surgery can be expected to mainly affect the resistance balance between the nostrils, with limited impact on voice timbre. Paranasal cavities absorb sound at their resonance frequencies, and surgical intervention on them is likely to exclusively shift their resonance frequency with negligeable effect on voice and speech (33). In the presence of an open velopharyngeal port, the main nasal tract tends to absorb frequency components in the frequency region of its resonance, which is likely to affect voice timbre (34). This is an aspect in need of further investigation.

Conclusion

To our knowledge, this is the first time the resonance characteristics of nasal tracts have been measured under well controlled and realistic conditions. Our analyses support the following conclusions

- In the absence of paranasal cavities, nasal tracts possess a main resonance in the frequency range of 600 - 750 Hz, depending mainly on its length.
- Inclusion of paranasal cavities introduces minima in the transfer function. The sinuses, and, consequently, the frequencies of the minima vary inter- and intra-individually according to the degree of the sinus' pneumatization.
- These sinuses heavily affect the morphology of the transfer function by adding minima, some of which can split, shift or surround the main resonance.
- Replicas based on high resolution 3-D imaging of the human nasal tract provide realistic models for analysis of the acoustic landscape of a nasal resonator, thus offering possibilities to systematically predict how nose resonance will affect the resonance characteristics of vocal tracts.

Conflict of interest

The authors have no conflict to report.

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Authors contributions

MH: conceptualization and realization of the ex-vivo experiments; JS: data acquisition and processing. MH and JS: Drafting, composing and revising manuscript.

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