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Acoustic properties of the nasal tract

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B. ACOUSTIC PROPERTIES OF THE NASAL TRACT

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Abstract

Sweep-frequency measurements of the transfer function of nasals and nasalized vowels have been found to show a more complex pole-zero pattern than can be predicted with a traditional model of the nasal tract which consists of two parallel tubes coupled to the oral cavities. In this paper we put forward the hypothesis that the more complex transfer function can be explained with reference to the shunting effect of the sinus maxillares and the sinus frontales. The two maxillar sinuses are situated in the bone symmetrically on the right and left side of the nasal tract. The two frontal sinuses are situated above the nasal tract in the bone of the forehead. These cavities are acoustically coupled to the nasal tract via short channels in the bone. Direct sweep-tone data on the transfer function of the nasal tract support this hypothesis.

Introduction

In recent years it has been emphasized that a realistic physiologically oriented model of the speech production mechanisms can be used as a powerful research tool, Lindblom and Sundberg (1970). One important, but not yet fully explored, part of such a model is the acoustic properties of the nasal tract. This has mainly been studied with indirect methods such as spectrum matchings of nasals and nasalized vowels, Fujimura (1960); Fujimura (1962); and Hecker (1962). In an attempt to make a more direct measurement of the size of the nasal cavities, Bjuggren and Fant made a model of the nose of one male and two female cadavers, Bjuggren and Fant (1964). From the area functions thus derived the acoustic properties of the nose could be calculated. Using this simple model of the nasal tract matches of broad-band spectrograms of nasals and nasalized vowels could be obtained. However, direct sweep-frequency measurements of nasal consonants as well as of nasalized vowels, Fujimura and Lindqvist (1964); Fujimura and Lindqvist (1971) show a more complex pole-zero pattern than can be explained with that model, even if asymmetry in the right and left nasal passage is taken into account. The transfer function of these sounds is quite complex and if a regular voice source is used the spectral characteristics cannot be determined with precision. An asymmetry in the nose can be shown to introduce extra pole-zero pairs inbetween the poles of a symmetric nasal tract. If the asymmetry is small, the zero will be quite close to the pole and the effect on the transfer function negligible. If, on the other hand, the asymmetry is large the zero will move upwards in frequency. However, the mean density of the poles cannot exceed that of a tube which is open at both ends and is twice the length of the nasal tract. Anyhow, with a nasal tract length of 9 cm we could hardly get more than two poles below 1 kHz with the velum closed. This is not sufficient to explain the numerous poles and zeros found in most of the sweep-frequency data on nasalized vowels. Similar data on nasals show one or more zeros below the frequency of the lowest zero which are caused by the mouth cavity shunt. These facts are inexplicable with a double-tube model of the nose and indicate the existence of other shunting cavities. In Fig. I-B-1 some examples of sweep-tone measurements of the transfer function of nasals are shown. Note that the lowest two zeros at 300 Hz and 350 Hz do not change when the dimensions of the mouth cavity is reduced from [m] to [n] to [ŋ]. Our hypothesis is that the explanation is to be found in the shunting effect of the sinus maxillares and the sinus frontales.

In order to investigate the validity of this hypothesis direct sweep measurements were made of the nasal tract.

Recording of the transfer function of the nose

The probe sound source consisted of a small earphone (Oticon) coupled to a thin semihard plastic tube. The outer diameter of the tube was 1.8 mm and the inner diameter 1 mm. In order to avoid direct radiation of sound from the earphone this was enclosed in a brass container and acoustically isolated from the walls by means of silicon rubber. By applying suitable acoustic damping the frequency response was essentially flat from 400 Hz to 4 kHz. Fig. I-B-2 shows the frequency response of the probe sound source with an 11 cm plastic tube connected.

The experimental setup for the recording of the response curves is shown in Fig. I-B-3. An FNA-oscillator (Type BN483011) connected to a wave analyzer including tracking filter and recorder (Type BN48301) was used. The filter bandwidth was 10 Hz and the sweeping rate employed was slow enough to follow the change in the microphone signal considering the response time of the filter. The tracking filter reduced the influence of noise and distortion efficiently and allowed a direct recording of the rather weak signal from the sound source. The microphone (B & K 1/2", condenser microphone) was placed about 2 cm below the nostrils.

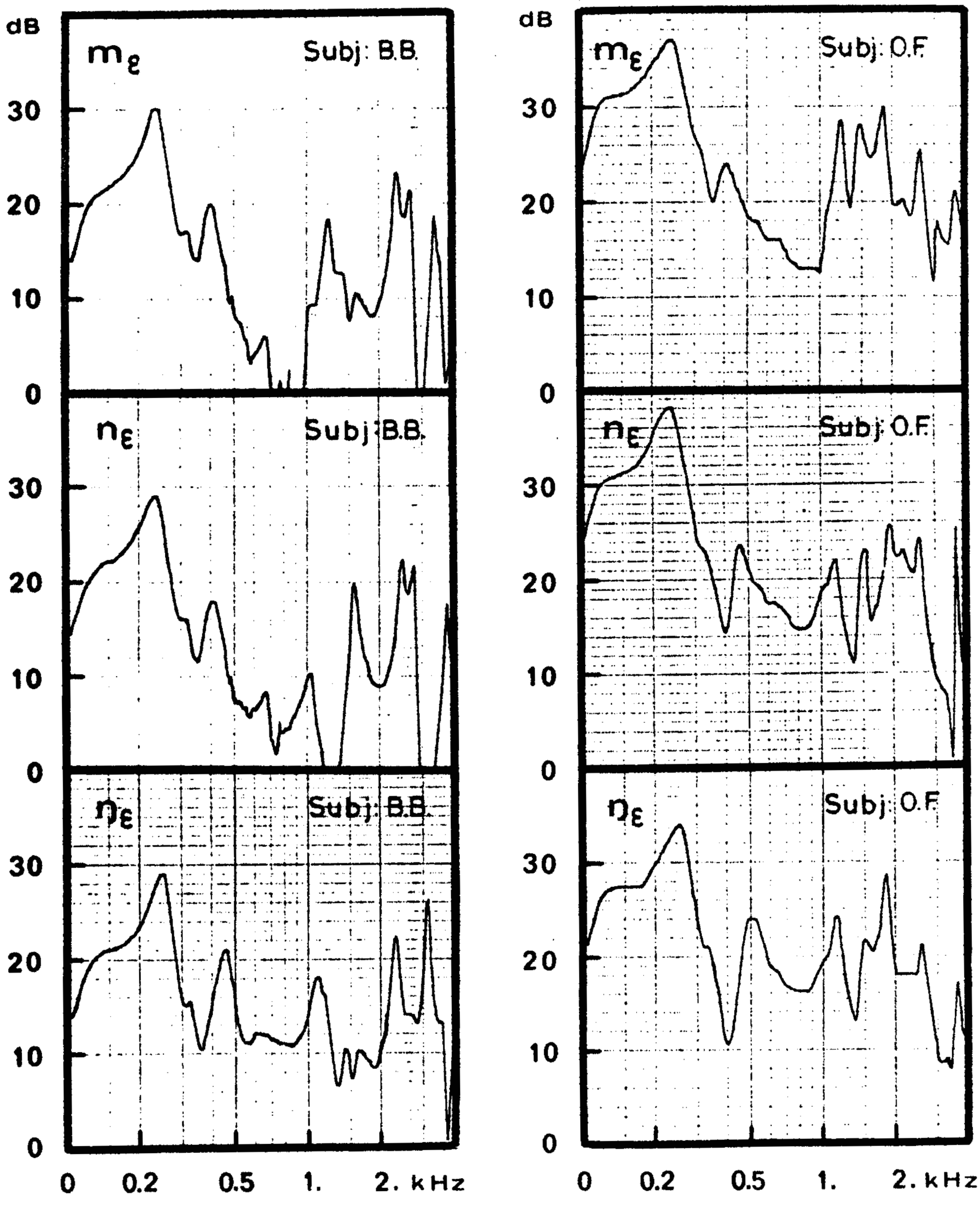

Fig. I-B-1. Sweep-tone measurements of the transfer function for nasals showing a split first formant caused by one or more pole-zero pairs below 500 Hz. (Fujimura and Lindqvist, 1964.)

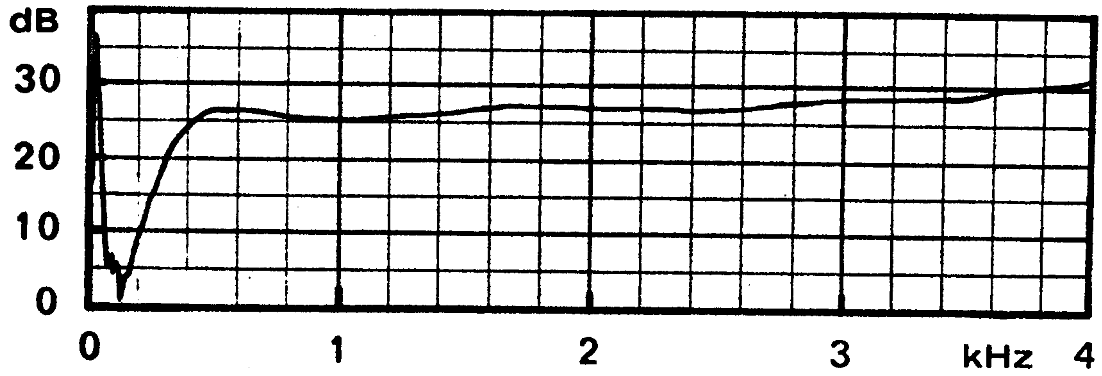

Fig. I-B-2. Response curve for the sound source with an 11 cm probe-tube connected.

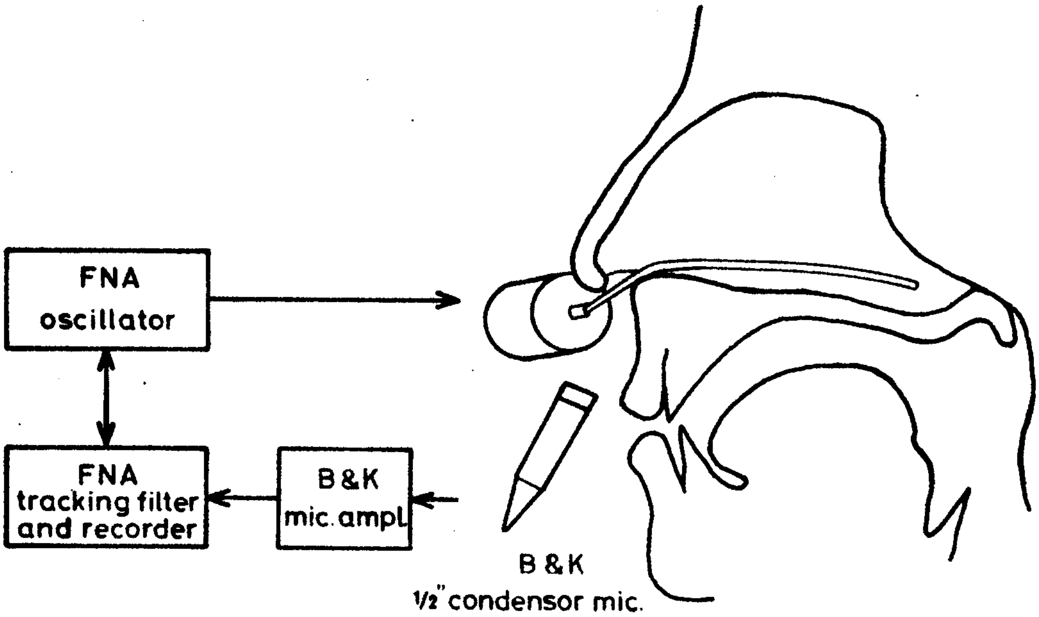

Fig. I-B-3. The experimental setup for recording of the transfer function of the nasal tract.

The closure of the velum was ensured by keeping a slight over-pressure in the vocal tract. Surface anesthetic (Xylocain and Tetracain) was applied before the probe was inserted. In a second experiment with one of the subjects, adrenaline was used to astringe the mucosa in the nostril in which the probe was inserted.

Results

In Fig. I-B-4.a, b, c, d the response curves for the two subjects are shown. In Fig. I-B-4.a, b, and c the tip of the probe sound source was around 2 cm from the closed velum. This fact introduced some extra zeros in the actual frequency range. When the position of the sound source was changed, these zeros (marked 0 in Fig. I-B-4.a and b)moved in frequency while the other poles and zeros in the transfer function were approximately unchanged. In Fig. I-B-4.d the source was approximately 5 cm from the velum.

When the curves in Fig. I-B-4, c and d were obtained adrenaline was used to astringe the mucosa. A marked change in the response curve can be noted.

Model experiment

In order to investigate the effects of the sinuses a model of the nasal tract was made. The area function of this model was approximately the same as that published by Bjuggren and Fant (1964). The length was 10 cm. Fig. I-B-5.a shows the response curve for this two-tube model without any shunting cavities. An asymmetry in this model will introduce only one extra pole-zero pair inbetween each resonance and this will not complicate the transfer function below 1 kHz. In order to explain the measured curves we have to assume the existence of shunting cavities with rather low resonance frequencies.* It is well known that the sinus maxillares and the sinus frontales communicate with the nasal tract, although the acoustic implications of this fact have not been studied. The largest of these cavities are the two maxillary sinuses. The opening of these into the nasal tract is rather small and they can be regarded as Helmholtz resonators shunting the nasal tract approximately at its midpoint. The sinus frontales have a more complicated shape but may also to a first approximation be regarded as

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* By assuming a lossless system the effect of adding a shunting cavity can be studied with a graphical method looking at the sum of the susceptances in the coupling point, see Fujimura (1960); Fujimura (1962).

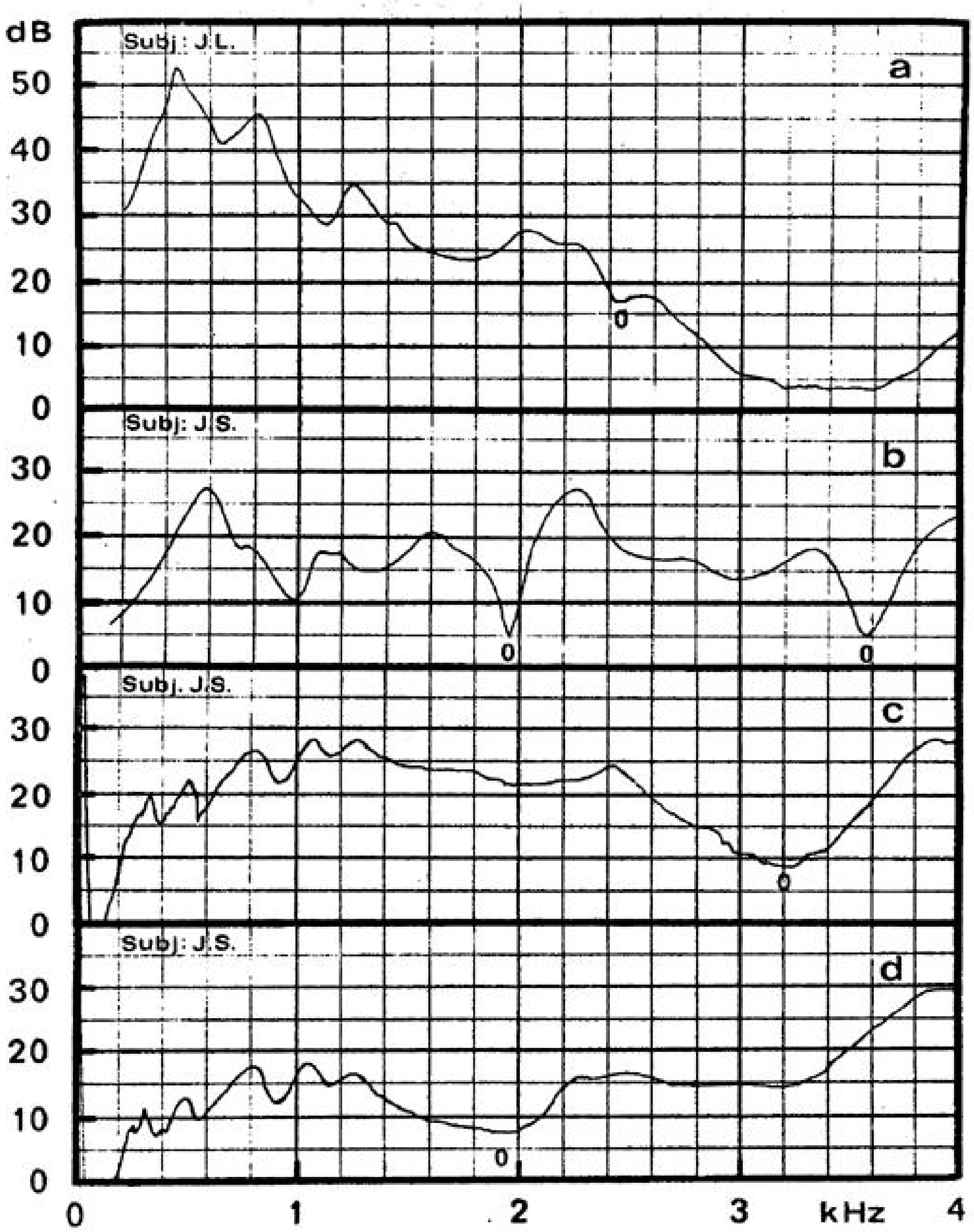

Fig. I-B-4. Response curves of the nasal tract measured on two subjects. In c and d one nostril was treated with adrenaline. The zeros marked 0 appear because the sound source is placed some distance from the closed end of the tube. In c the source is about 2 cm from the velum and in d it is withdrawn another 2 cm.

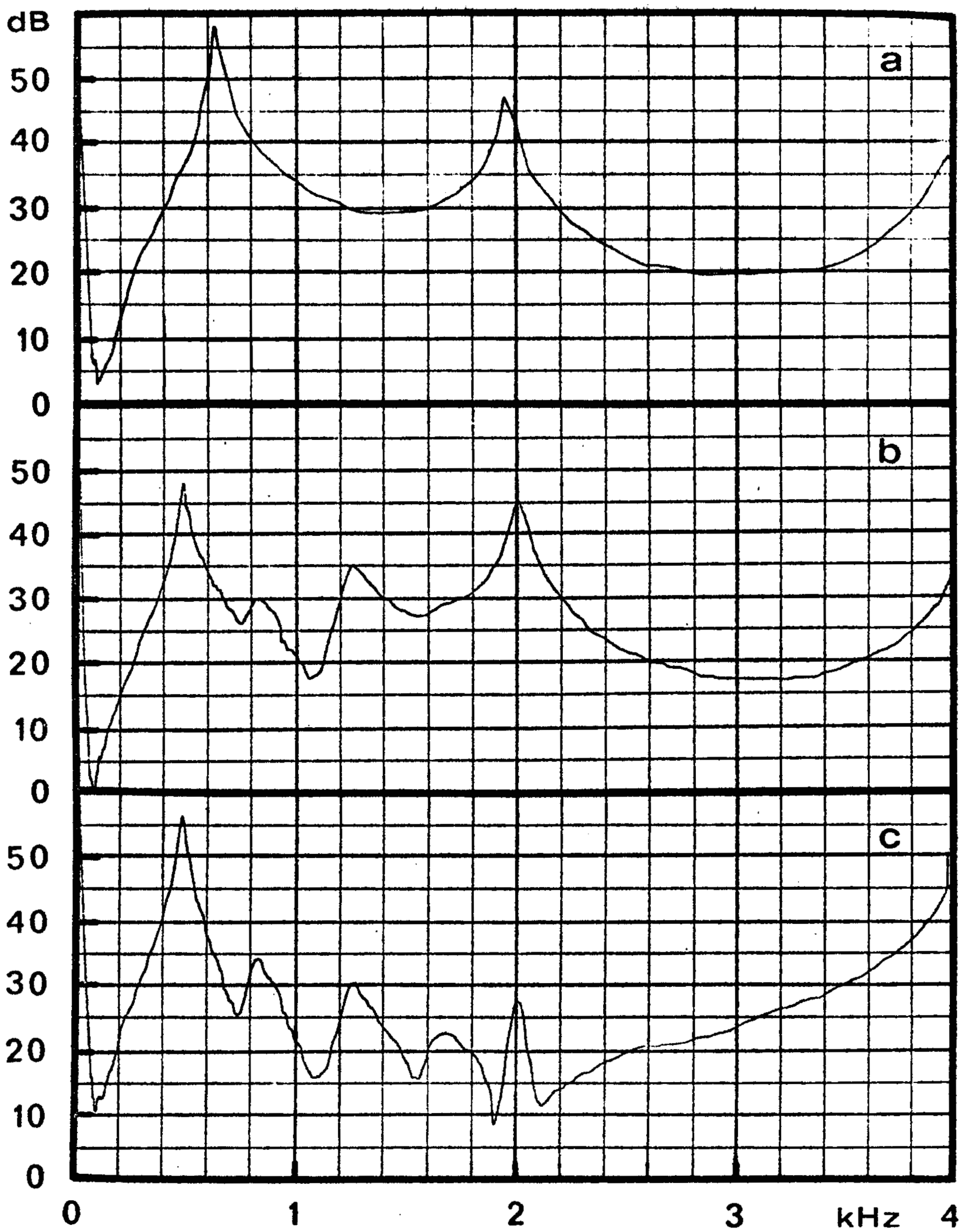

Fig. I-B-5. Response curves for a twin tube model of the nasal tract, a; without shunting cavities, b; with two shunting cavities corresponding to the maxillary and frontal sinuses. In c the source is asymmetrically placed simulating asymmetry in the two nasal passages.

Helmholtz resonators. Owing to lack of data it is hard to estimate the resonance frequencies of these cavities but a reasonable estimate would appear to fall in the range of 200 to 800 Hz for the maxillary sinuses and 500 Hz to 2 kHz for the frontal sinuses. Besides the above-mentioned cavities there are other smaller cavities connected to the nasal tract. The size of both the nasal passages and the sinuses varies widely from one subject to another. It is therefore of minor interest to know the exact resonance frequencies of the sinuses if only the main distribution of resonances and antiresonances in the transfer function of the nasal tract is known.

The acoustic system is also quite complex because zeros are caused not only by shunting cavities but also by asymmetry and mixing of the outputs from the two nostrils. Nevertheless a quite good match of the response curves in Fig. I-B-4.a could be made with only two shunting cavities; see Fig. I-B-5.b. If the sinuses are regarded as Helmholtz resonators they will have only one resonance each in the frequency range studied.

In a complete symmetric nasal tract only one extra pole-zero pair will be generated for each resonance in the pair of shunting cavities. The zero is then at the resonance frequency of the shunt.

If, on the other hand, the sinuses are different in size there will be three extra pole-zero pairs for each pair of sinus. It thus seems as if the transfer functions in Fig. I-B-4.a and b can be approximated with a symmetric model, at least below 1.5 kHz. For the curve in Fig. I-B-4.c and d one nostril was treated with adrenaline. This probably changed the dimensions in this side of the nasal tract so that a considerable asymmetry was generated. Probably an asymmetric model has to be used in order to explain this transfer function.

Concluding remarks

Direct sweep-tone measurements of the transfer function of the nasal tract indicate that the nasal sinuses have to be considered as a relevant part of the acoustic system. In a model of the speech organs the addition of at least two shunting cavities to the nasal may improve the spectrum for nasals and nasalized vowels at lower frequencies.

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