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A REAL-TIME MRI EVALUATION OF CONSONANT PRODUCTION AFTER ORAL TUMOUR SURGERY

1. INTRODUCTION

Investigations on impaired speech are normally argued for by two reasons. First, it is necessary to find out more about the *how* of the impairment in order to get closer to the *why*. In other words, a better knowledge of the amount of the lost and the maintained functionality of the speech organs can lead to a more thorough understanding of the causality of changes in the anatomical structure and the motor outcome. This is especially true for tumour surgery where the localisation of the operation is known, as opposed to speech impairment due to neurological aetiologies or to tumour treatments that are less easy to localise such as radiation therapy or chemotherapy.

Furthermore, changes in the acoustic and articulatory characteristics of distorted speech are also of interest for researchers who strive to find out more about normal speech production. As an example, the parallel investigation of production and perception of speech segments can contribute to the identification of the acoustic and articulatory features which are crucial for the production of the given segments. It is somewhat surprising, that the acoustics of distorted speech has been of relatively little interest for speech research.

From the early 70's on, several studies have been performed on the maintained motor skills of subjects after an oral tumour surgery. Some of the studies focus on medical aspects, such as resection size and/or site or reconstruction type, thus, their aim is to compare and evaluate different surgical methods regarding their impact on motor functions. Other investigations are directed towards the production of speech sounds. Various methods have been used to collect data on the articulation of segments: X-ray, ultrasound, electropalatography (EPG) and electromagnetic midsagittal articulography (EMMA). (For an overview and references, see Mády 2004).

From the late 90's, there has been an increasing interest in the acoustic aspects of impaired speech. The relevant studies provide a detailed analysis of pre- and postoperative vowels and/or stops (Perrier et al. 1999; Savariaux et al. 2001; Zimmermann et al. 2003; Koppetsch/Dahlmeier 2003).

The studies listed above provide an analysis of various important aspects of the speech production in subjects with oral carcinomas. However, all of them focus either on acoustics *or* on articulation/perception, i. e. no direct link is given between production, signal and perception.

Another shortcoming of some studies is that the formerly known methods for visualizing tongue movements are not suited for testing glossectomee speech for practical or ethical reasons. Therefore, we chose a method that had not been used in speech pathology so far: the real-time Magnetic Resonance Imaging (MRI). In addition to being non-invasive and not especially unpleasant for the subjects, this technique allows the visual signal to be recorded digitally, so that information loss due to AD conversion can be avoided (as opposed to X.-ray or ultrasound). One disadvantage of real-time MRI is that the recordings are accompanied by a loud noise, so that the parallel recorded acoustic signal cannot serve as a basis for the acoustic analysis. Another shortcoming is the relatively poor time resolution, although there is a rapid development in this field at present.

The reason why the study covered subjects with oral carcinomas is twofold: firstly, this relatively seldom (1–4 % of all cancer cases) and not very well investigated disease is associated with a relatively high survival rate (50–75 % after 5 years) but with a steep decrease of life quality regarding mastication and speaking. Thus, maintenance of the best possible orofacial functionality is a crucial aspect for the choice of medical therapy. Second, it is assumed that the knowledge of the resected and possibly impaired anatomical structures allows for some cautious conclusions regarding the normal and impaired muscle function.

These were the most important factors that led to our study, as part of a larger project partly supported by the Deutsche Forschungsgemeinschaft (German Research Council).The main goal of the present paper is to provide a narrow link between the acoustics and articulation of speech sounds which have not been subject to investigations in connection with oral tumour surgery so far: fricatives and laterals. Fricatives, as relatively constant sounds, are well suited for testing even with a poor time resolution of the visual recording method, whereas the alveolar lateral /l/ offers a good comparison with the alveolar fricative, of which the PoA is nearly the same, but the manner of articulation is different.

2. Material and methods

2.1. Subjects

Eight male subjects (age mean: 55.8 years, SD: 12.0 years) suffering from a squamous cell carcinoma of the oral cavity were involved in the study. None of the subjects had had any speech impairment prior to the carcinoma. They all had a tumour of the tongue and/or floor of the mouth classified as T1 (< 2 cm) or T2 (2–4 cm), according to the normalised classification by the UICC (*Union International Contré le Cancer*). In seven subjects, the defect was closed by a partial fixation of the tongue at the floor of the mouth. In several cases, a myocutaneous flap (platysma) from the neck was used for the closure. *Table 1* gives a short overview on the classification and localisation of the tumour and the reconstruction type.

subject	*tumour class.*	*localisation*	*reconstruction*
GL1	T2	tongue anterior, right and medial	primary closure with fixation to floor of mouth
GL2	T2	floor of mouth anterior, left and medial	tongue lateral: myocutaneous flap, front: fixation to floor of mouth
GL3	T1	tongue lateral right	primary closure
GL4	T1	floor of mouth anterior medial	right: myocutaneous flap, left: tongue fixed to floor of mouth.
GL5	T2	floor of mouth left	myocutaneous flap, left caudal tongue part fixed to floor of mouth
GL6	T1	floor of mouth anterior right	primary closure with partial tongue fixation
GL7	T2	floor of mouth anterior right	myocutaneous flap left and right, partly no closure
GL8	T2	tongue lateral right	myocutaneous flap left and right

Table 1: Tumour classification, localisation and reconstruction

2.2. Recordings

The acoustic and articulatory analysis was performed on the sounds /s/, /ʃ/, /l/ and /x/ embedded in real German words (*Rosi*, *Schädel*, *lang*, *Tuch*). All subjects were recorded twice: a few days before the operation and approximately 4 weeks after surgery, before the starting of an optional radiotherapy. The data collection involved the following methods:

1. Articulatory movements of the tongue and lips were recorded by real-time MRI, SENSE technique. The imaging was based on the midsagittal plane with a slice thickness of 10 mm. The technical set-up allowed a time resolution of 8 images/sec. Each target word was repeated over 10 seconds, for the duration of one recording sequence. The target consonant occured 5–11 times per sequence, depending on the speed of speech and on word length.
2. The acoustic material was recorded on a PC or on a DAT recorder. All words were repeated 3 times with a normal speech speed and loudness.
3. The operations were documented on a Surgical Mapping Protocol (Mackenzie Beck et al. 1998), that included a lateral, superior and frontal view of the oral cavity. The size and localisation of the resection and the primary reconstruction were filled in separately, making it easier to understand the postoperative functioning of the oral cavity of each subject.

Beside the above methods, other features of postoperative functionality such as intelligibility, subjective evaluation of the clearness of speech, tongue mobility, etc. were also tested and documented during the data collection. These data do not contribute directly to the subject of this paper, therefore they will not be taken into account here (for details, see Mády 2004).

3. Articulatory and acoustic analysis

3.1. Articulatory characteristics of /s/, /ʃ/, /l/, and /x/

The main features of fricative production are place and manner of articulation and voicing. While voicing was ignored in this study (i. e. no difference was made between /z/ and /s/), the size and localisation of the constriction as well as the tongue shape as an indirect indication of the manner of articulation were crucial points of the analysis.

Before describing the analysis method, some important characteristics of the unimpaired production of the sounds investigated will be pointed out. The manner of articulation of fricatives can be described as the emission of an air jet through a constriction at some part of the oral cavity, in which the tongue or the lips are moved towards another anatomic structure, such as the alveolar ridge, palate, teeth etc. This is characteristic for /x/ where the constriction involves the tongue back and the soft palate. However, the sibilants /s/ and /ʃ/ require a second obstacle, the teeth or incisors (Shadle 1990; Ladefoged/Maddieson 1996).

The production of the alveolar /s/ and postalveolar /ʃ/ can be differentiated by three aspects: (1) the constriction in /s/ is formed somewhat more frontal than in /ʃ/, (2) /s/ is produced with a deep and narrow longitudinal groove in the midsagittal part of the tongue that is less distinct in /ʃ/, and (3) /s/ is produced with a flat tongue shape (concave form) whereas in /ʃ/, the tongue back is domed (convex form) (Ladefoged/Maddieson 1996; Hoole et al. 1989). This coincides with a longer constriction and a slight palatalisation of /ʃ/ compared to /s/.

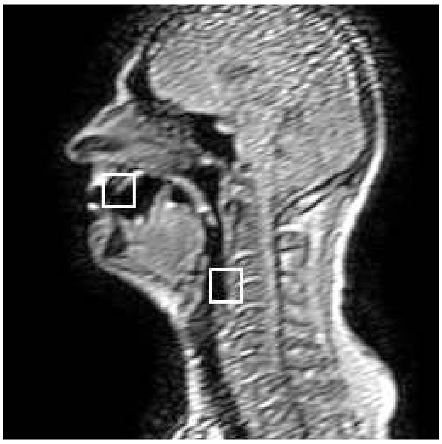
The difference between the tongue shapes of the alveolar lateral and the alveolar fricative can be described as follows: there is a midsagittal closure and lateral opening in /l/ whereas /s/ requires a midsagittal opening and lateral closure. /l/ has a slightly different PoA than /s/: /l/ is always produced by the tongue tip whereas the production of German /s/ mostly involves the tongue blade. Thus, the constriction is supposed to be somewhat more frontal in /l/ than in /s/. The tongue contour of /l/ is even more flat than in /s/, without showing the characteristics of a groove.

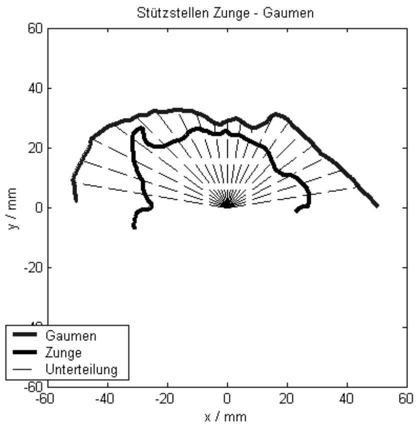
The German fricative /x/ can have a velar or uvular PoA. According to Kohler (1995), velar realisations occur after the high vowels /o/ and /u/, uvular allophones after low /a/ and /ɔ/. Thus, in the target word *Tuch* ('scarf'), the velar realisation of /x/ is more probable than the uvular one.

The fricative differs from the other three consonants not only by the PoA, but also in the constriction size, i. e. the distance between soft palate and dorsum. It has been shown that German /x/ is associated with a relatively large articulatory variability as opposed to alveolar sounds, as the number of back consonant phonemes in German is smaller than that of front consonants and thus, the perceptual categorisation of back consonants is easier even in case of a less careful production. Due to the smaller mobility of the tongue back, the constriction length in /x/ is greater than in apical and laminal sounds.

3.2. Methods of articulatory analysis

The articulatory analysis was based on isolated images that had been segmented from the target words. For an intra- and interindividual comparability, two anatomically defined reference points were chosen (Figure 1a). On these, a semi-polar coordinate system was imposed, in which the tongue and palate contour was shown (Figure 1b). Along each axis of the coordinate system (0–180°), the distance of the tongue and the palate was measured and plotted in a Carthesian coordinate system (Figure 1c). Articulatory characteristics like the place and length of constriction or tongue shape were thus visualised by tongue-palate distance (TPD) trajectories which allow a direct comparison between pre- and postoperative realisations of the sounds by different subjects.


(1a)



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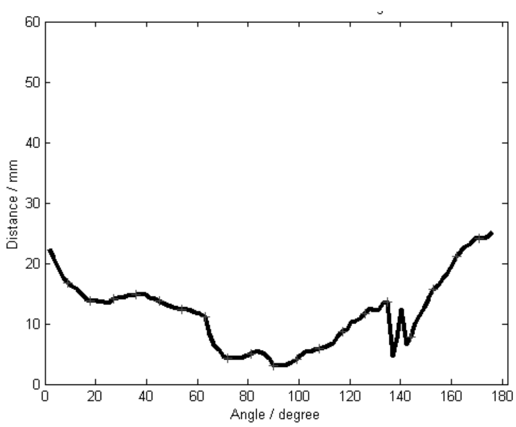


(1c)

Figure 1a–c: (a) Front and back fixed points for the semi-polar coordinate system, (b) tongue and palate contour in the semi-polar coordinate system, (c) tongue-palate distance trajectory.

The characteristics of normal production of the sounds analysed here will be presented in section 4, together with the postoperative results.

3.3. Acoustic characteristics and analysis

As mentioned earlier, there are not much data on the special characteristics of acoustic features in pathological speech. Therefore, a complex analysis of several details had to be undertaken for the consonants dealt with. The following paragraphs will concentrate on parameters that proved to be relevant regarding glossectomee speech production.

According to aerodynamic laws, the backward shift of the PoA coincides with a lowering of the spectral peaks. In other words, a frontal sound is accompanied by a spectral peak of high frequency, whereas a back sound is characterised by low frequencies. This tendency is reflected in the acoustic features of alveolar /s/, postalveolar /ʃ/, and velar /x/: the main and most prominent peak for /s/ is found above 4 kHz, for /ʃ/ at 2.5–3 kHz and for /x/ at 1.5 kHz. The shape of the power spectrum can be quantified in the parameter Centre of Gravity (CoG), the first spectral moment of the overall frequencies shown in the FFT spectrum. (Due to the low sample rate of some of the recordings and the noise and voicing in the low frequencies, the analysis is based on the spectrum between 1 and 5.5 kHz. Therefore, other potentially relevant entities like the second spectral moment that require a spectrum until 11 kHz, are not being discussed here.)

The relatively large difference in CoG between /s/ and /ʃ/ as opposed to the minimal difference in the PoA has led to different hypotheses. The first hypothesis goes back to Perkell/Boyce/Stevens (1979), who claim that the shift from /s/ to /ʃ/ is not accompanied by a continuous shift of the characteristic frequency domain, but rather an abrupt decrease at the point where the lower side of the tongue tip is released from the lower teeth. Thus, the low frequency of /ʃ/ is explained by the presence of a frontal sublingual cavity behind the teeth. This hypothesis was based on own experimental findings of the authors.

Another explanation was provided by Shadle (1990). She found that the acoustic characteristics of /s/ and /ʃ/ are best modelled by the difference whether the air jet is directed towards the upper or the lower teeth. According to this model, /s/ is produced with a secondary obstacle at the upper teeth (incisors), while for /ʃ/ the lower teeth are crucial.

A third hypothesis, more speculative than tested, goes back to an MRI investigation of Narayanan/Alwan/Haker (1995). They suggested that the acoustic difference between /s/ and /ʃ/ resulted from the different route of the air jet above the dorsum: due to the domed tongue shape in /ʃ/, the air flows directly below the hard palate and meets the upper teeth at a higher point than in /s/, where the air flows along the groove and is directed against the upper teeth at a lower point. These hypotheses will be discussed on the basis of our findings in the final section of this paper.

The sonorant /l/ can be best described in terms of a formant structure which is sensitive to changes in the articulatory modus (apical vs. laminal) and of the tongue shape (size of pharyngeal cavity). It is generally assumed that the apical articulation of /l/ results in a shorter tongue-alveolar ridge contact and a smaller pharyngeal distance than in the laminal production. This difference is reflected in F1 (~ 500 Hz) and F2 (~ 1600 Hz): (1) an increase of F1 signalises either a smaller pharyngeal cavity or a greater constriction length, and (2) a higher position of the tongue body leads to an increase of F2.

4. RESULTS

In the following section, each sound will be described in terms of the articulatory and acoustic features presented in 3.1. and 3.2. First, the main parameters of the preoperative realisations will be elaborated. The second step will be to compare these with the postoperative realisations. These were classified according to the severity of the impairment for each consonant, evaluated by the first author. The presentation of the postoperative results will be based on this classification.

4.1. THE SIBILANTS /S/ AND /ʃ/

The factors necessary to distinguish between the production of /s/ and /ʃ/ were described in 3.1.: PoA, constriction length and tongue shape. These will now be demonstrated on the magnetic resonance images and the TPD trajectories.

Preoperative results

Figure 2 shows a preoperative MRI scan of /s/ and /ʃ/ and the midsagittal TPD trajectories that belong to these segments. Regarding the constriction, it can be stated that while the front place of the constriction does not differ for /s/ and /ʃ/, the constriction is longer and thus further back for /ʃ/ than for /s/. This is reflected on the left part of the distance trajectory where the increase for the /ʃ/ trajectory is located between 5 and 10° (0° being the most frontal point of the coordinate system), while the increase for /s/ takes place at around 2°.

The midsagittal flat tongue shape in /s/ is indicated by a steep rising of the /s/ trajectory (*Figure 2c*). Additionally, there is a second minimum at around 30° that seems to go back to a narrowing in the region of the hard palate. In fact, this apparent narrowing concerns only the midsagittal plane of the tongue and is a manifestation of the longitudinal groove in /s/. This feature will prove essential for the postoperative evaluation of /s/ production.

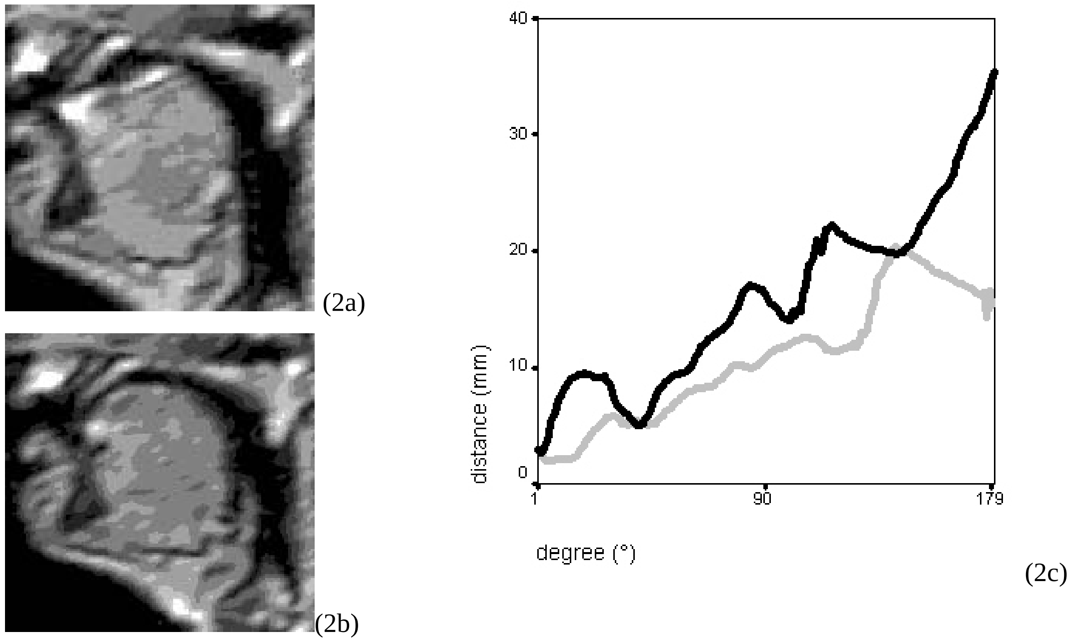


Figure 2a–c: (a) image of preoperative /s/ *and (b)* /ʃ/*, (c) tongue-palate distance trajectories for* /s/ *(black) and* /ʃ/ *(grey).*

As was described in the previous section, /s/ and /ʃ/ can be distinguished by the measure Centre of Gravity. The spectrum of /s/ shows a higher energy level at higher frequencies, expressed by higher CoG (see *Figure 3*).

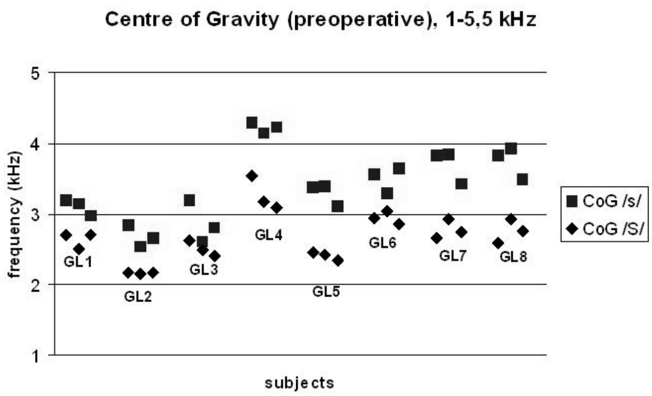


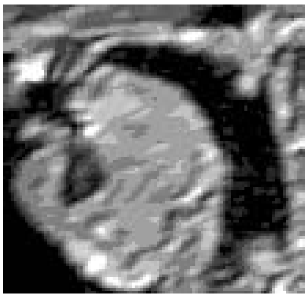
Figure 3: Centre of Gravity measurements for preoperative /s/ and /ʃ/ spectra (1–5.5 kHz).

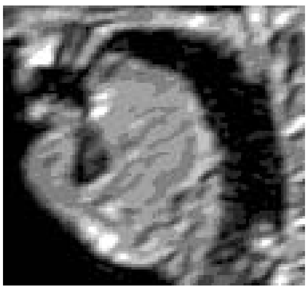
Postoperative results

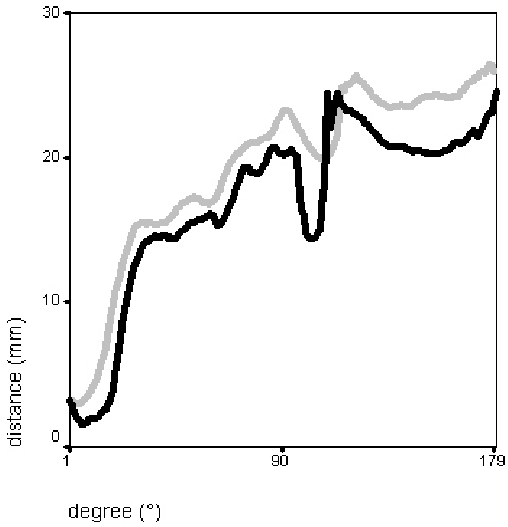
The auditory evaluation of the postoperative sibilants showed that only three subjects (Group 1: GL3, GL4, and GL6) could produce an unimpaired /s/ and /ʃ/. In four other subjects (Group 2: GL1, GL2, GL7, and GL8), /s/ sounded palatalised and /ʃ/ lateralised. The sounds produced by subject GL5 (Group 3) could not be identified as sibilants.

Most postoperative TPD trajectories differ from the preoperative ones, what not necessarily resulted in changed acoustic characteristics. The crucial point was apparently, whether the tongue shape could be maintained for the postoperative /s/ and /ʃ/ production. In terms of our analysis it means, that if the postoperative TPD trajectory for /s/ did not show a steep rise behind the constriction and a secondary minimum within the area of 0–45°, it can be supposed that the longitudinal tongue groove was missing in the midsagittal area. The role of constriction localisation does not seem to be so important: in one subject with an impaired postoperative /s/ production, the only articulatory parameter that was affected postoperatively was the missing secondary minimum of the TPD trajectory, while the constriction localisations were not different from the preoperative ones. It is interesting to note, however, that in the postoperative recordings, some subjects of Group 2 produced /s/ with a longer constriction than /ʃ/.

The postoperative TPD trajectories for /s/ and /ʃ/ in Group 2 are thus neutralised: both trajectories reflect a long constriction as far as the postalveolar area and a domed tongue shape. This is illustrated in *Figure 4a–c*:


(4a)

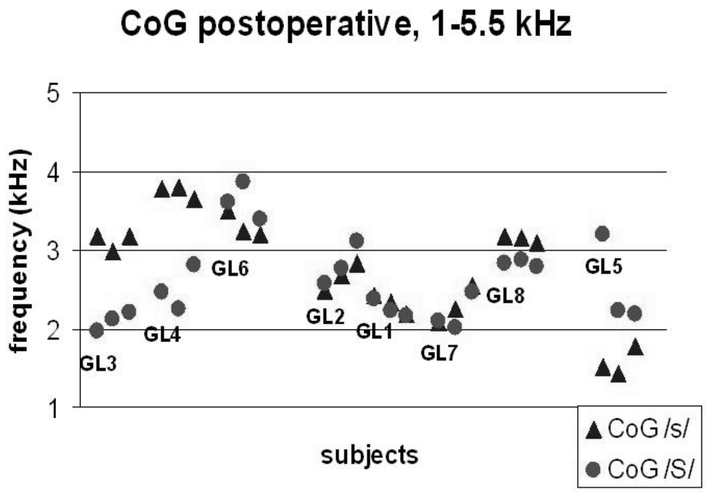

(4b)



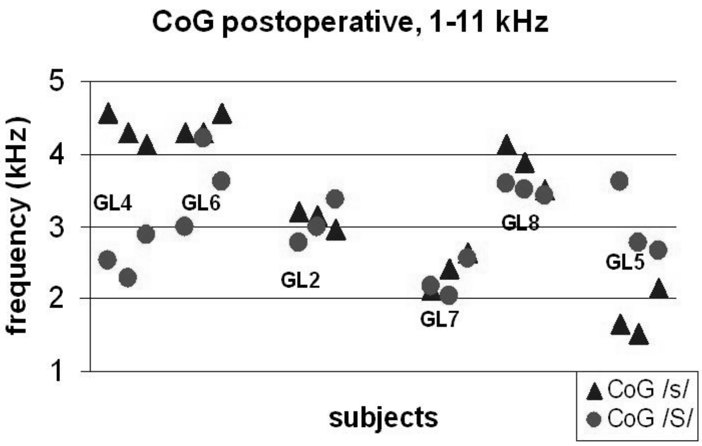
(4c)

Figure 4a–c: Postoperative scan of (a) /s/, (b) /ʃ/, and the tongue-palate distance trajectories (black: /s/, grey: /ʃ/).

The same neutralisation process was observed in terms of postoperative Centre of Gravity measures: whereas the characteristic difference between /s/ and /ʃ/ was maintained in the postoperative Group 1 (in the case of GL6, however, the distinction could only be shown for the spectrum up to 11 kHz), it disappeared in Group 2. The postoperative data for subject GL5 showed no clear tendency. It is interesting that greater postoperative constriction length in /s/ as opposed to /ʃ/ did not lead to higher CoG for subject GL5, although the PoA for /s/ was somewhat further back than for /ʃ/.



(5a)



(5b)

Figure 5a, b: Centre of Gravity measurements for postoperative /s/ *and* /ʃ/ *spectra, (a) 1–5.5 kHz, (b) 1–11 kHz.*

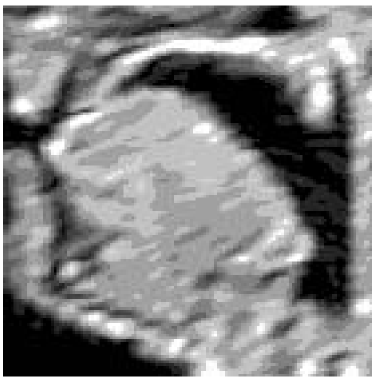
4.2. The lateral /l/

Geumann et al. (1999) postulated a large variability of /l/ production as opposed to the sibilants and especially to /s/. In our data, however, the standard deviation of the tongue-palate distances in /l/ was smaller for all subjects and all measurements in the anterior oral cavity. This might result from the apical character of /l/, whereas in our subjects, /s/ was always laminal.

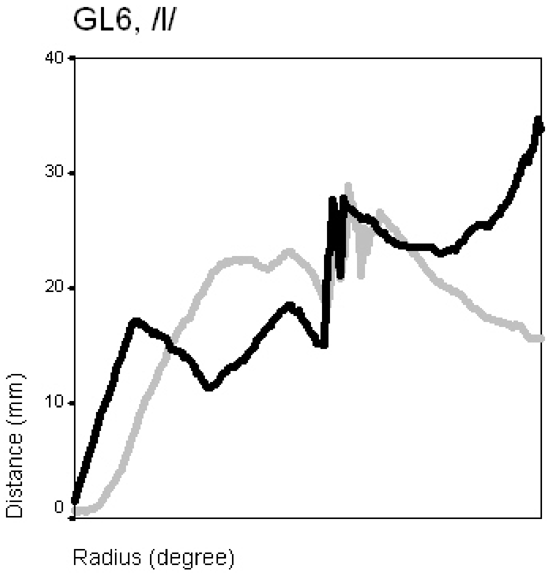
Concerning the TPD trajectories, the flat tongue shape (especially preceding the low vowel /a/, as in the target word *lang*) exhibited a steep rise behind the alveolar contact that was more fronted than in /s/. Although the unimpaired production requires a tongue shape somewhat similar to /s/ from the lateral view, the optional secondary minimum of the TPD trajectory in /l/ is not so well defined and is located further back in the oral cavity than in /s/.

The postoperative production of /l/ seemed to confront the subjects with more difficulties than the sibilants: only one of them (GL3) could achieve an unimpaired auditory impression of a lateral. Four subjects (GL1, GL2, GL4, GL6) had a palatalised articulation, whereas the segment could not be identified as a lateral in the case of three subjects (GL5, GL7, GL8). The laminal and palatalised contact, typical for Group 2, is presented below.

(6a)



(6b)



(6c)

Figure 6a–c: Scan of the lateral /l/, (a) preoperative, (b) postoperative, (c) tongue-palate distance trajectories (black: preoperative, grey: postoperative).

The formants of the preoperative /l/ segments were clearly structured without any overlapping values in the interpersonal formant ranges. This clear-cut structure was not maintained postoperatively: there were some, although not many, overlaps between F2 and F3, and F3 and F4, respectively. In the postoperative recordings, a general increase of F1 and F2 was observed.

As mentioned in 3.3., a higher F2 can be related to a higher position of the tongue body, whereas a rise in F1 can either indicate a longer constriction or a pharyngeal narrowing. What makes an interpretation of formant shift difficult is the fact that the apical /l/ articulation is characterised by a shorter constriction *but* a pharyngeal narrowing (small enough not to lead to the perceptive image of pharyngalisation). This might be a reason for contradictory findings on F1 of the alveolar lateral in different languages, reported in Ladefoged/Maddieson (1996). A further acoustic feature of pharyngeal narrowing is an increased difference between F2 and F3.

The validity of postoperative F1 shift seems to be in agreement with the postoperative MRI images. In all cases a rise of F1 is accompanied either by a longer constriction, or a pharyngeal narrowing, or both. However, F2 requires a somewhat more cautious interpretation: a shift does not necessarily reflect a higher tongue position, it can also be understood as a contribution to the change in the F2-F3 difference. This was the case for one subject where a postoperative higher F2 was not accompanied by a higher tongue body position, but the pharyngeal cavity was larger, what led to a decrease of the F2-F3 difference.

It is not possible to make a distinction between Group 2 and Group 3 (palatalised /l/ production vs. no lateral production) along the articulatory and acoustic parameters analysed here. This could be explained by the fact that the lateral production not only contains an articulation with a midsagittal apical contact and the lowering of the lateral tongue on one, or both sides, but also a characteristic release movement that makes the sound audible as a lateral. The auditory impression of such a release was not found in the segments of Group 3, and the transient movements were slow if present at all. This fact was not reflected in the formant structure the analysis was based on.

4.3. The velar fricative /x/

The preoperative TPD trajectories indicate a low tongue position in the anterior oral cavity and a minimal distance between 55° and 103°. More or less deviating postoperative tongue shapes in the front cavity did not lead to impaired auditory or acoustic characteristics in seven postoperative cases. An audible postoperative change was only observed in GL5.

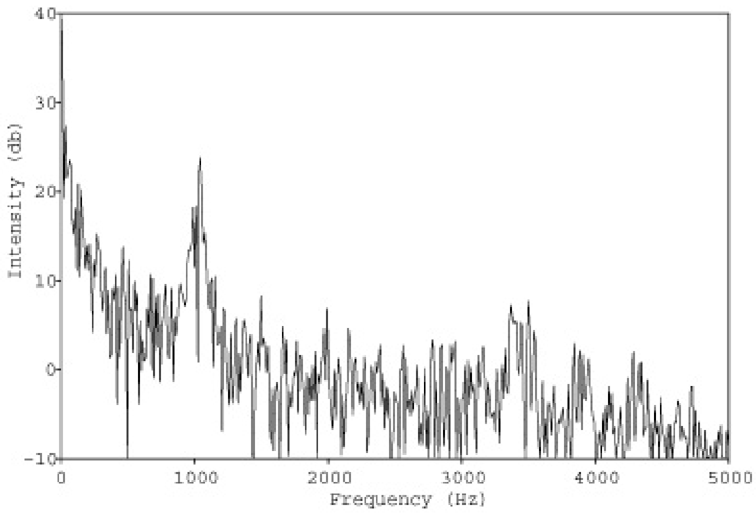
The distribution of the minima indicate that there are two possible places of articulation: one constriction type is located in the area between 55° and 65°, the other between 71° and 103°. The MRI scans conformed that there was a velar-uvular variation in both the pre- and postoperative /x/ production. The mean minimal tongue-palate distances were larger for the velar (4 mm) than for the uvular (2.7 mm) production.

The assumption mentioned in section 3.1., according to which /x/ is realised with a velar PoA following /u:/, could not be verified in this study: 3 of 8 subjects produced /x/ with an uvular PoA before surgery during the MRI recordings. There were even more uvular realisations postoperatively (5 of 8 subjects).

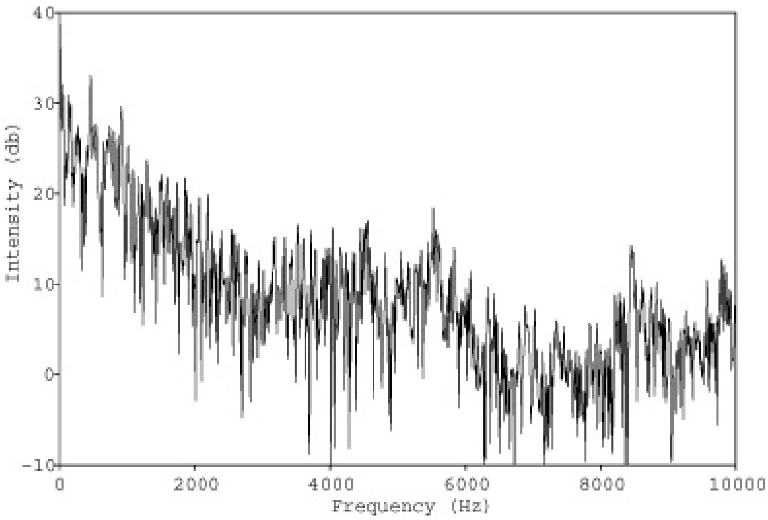
The dominance of the uvular realisations after surgery might be explained with the lower requirement of articulatory effort for uvular production. The velar articulation of /x/ requires a larger tongue elevation, firstly because of the higher position of the soft palate compared to the uvula, secondly because the uvula can be moved towards the dorsum whereas the velum cannot. It is therefore possible that the postoperative PoA shift towards the uvular articulation can be interpreted as a compensatory mechanism. This assumption is supported by the fact that the postoperative constriction length in the uvular /x/ production was strongly reduced, also in the subjects who produced /x/ with an uvular PoA preoperatively.

According to Jassem (1968), the acoustic features of the velar and uvular fricative are very different. The spectrum of [x] is characterised by a prominent peak at 1.5 kHz, a rapid decrease of energy above 2 kHz, and an optional small peak around 4.5 kHz. The spectrum of the uvular [χ] shows high energy from 2 to 8 kHz with the highest peak around 3.5 kHz. The spectrum of the uvular fricative is structured, while the velar spectrum is flat behind the peak at 2 kHz.

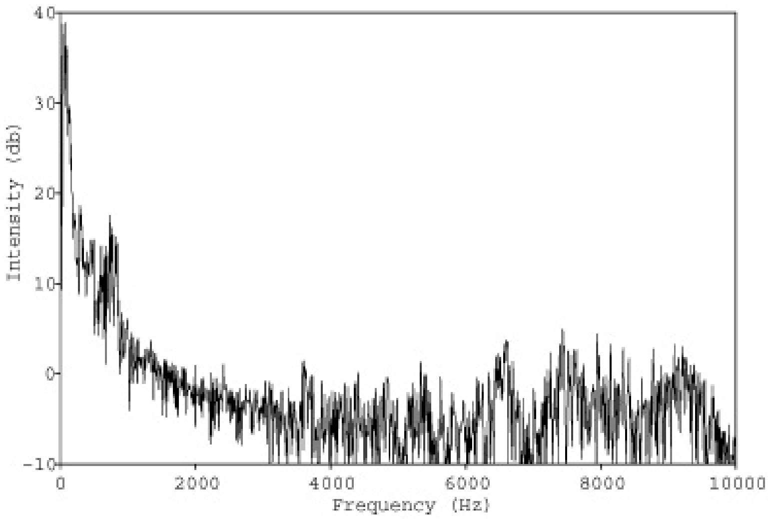
In five preoperative cases, the acoustic characteristics of the segments fitted the description given by Jassem. (N. B. Jassem's data rely on one speaker and on sustained consonants.) In one case (GL8), velar articulation is connected to a spectrum with relatively high intensity and with a peak at 4.5 kHz. In GL4, despite the uvular PoA on the MRI scan, a flat spectrum with a small peak at 3.6 kHz is visible. The supposedly velar segment of GL6 has again a flat spectrum and a peak at 3.5 kHz. In these subjects, either the spectral shape or the localisation of the peak in the higher frequencies (3.5 vs. 4.5 kHz) does not fit the observed PoA in the MRI scan.



(7a)



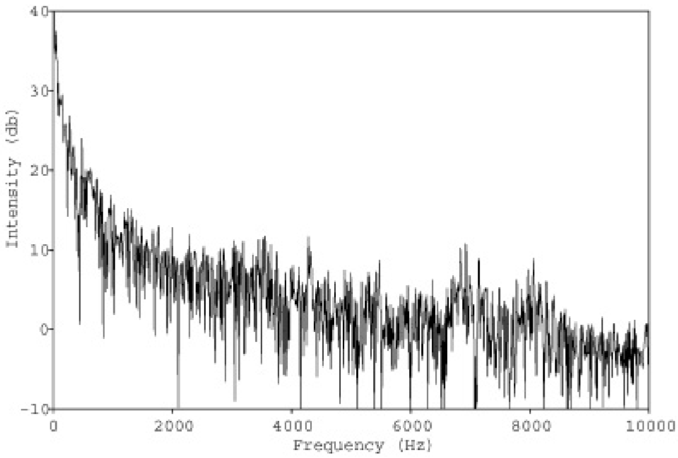
(7b)



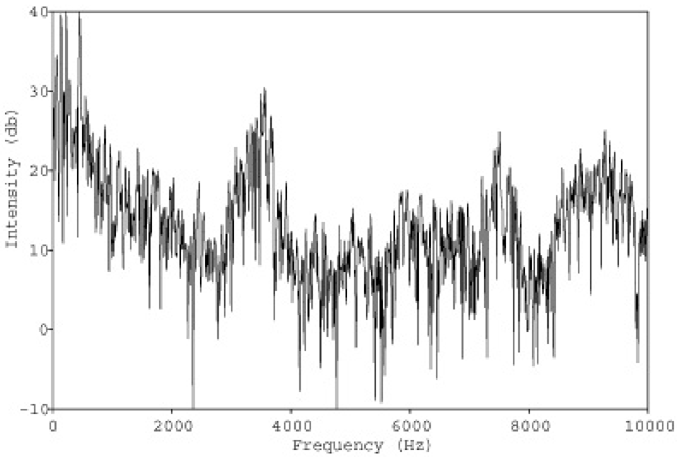
(7c)

Figure 7a–c: Preoperative FFT spectrum of (a) GL6 < 5 kHz, (b) GL8 < 10 kHz, and (c) GL4 < 10 kHz.

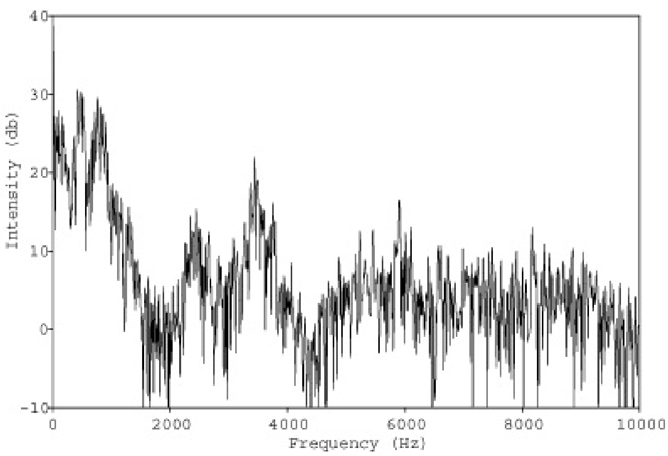
Two of these subjects (GL6 and GL8) can be characterised by a postoperative shift of the PoA, whereas the MRI scans of GL4 show an uvular production pre- and postoperatively. A comparison of the pre- and postoperative spectra, however, does not show the same structure. The pre- and postoperative spectra of GL6 differ by a peak at around 1 kHz that is visible only in the pre- but not in the postoperative spectrum, while both share a flat shape. The postoperative spectra of GL8 and GL4 are rather different from the preoperative ones: they are well structured and have a peak around 3.5 kHz (see *Figure 8*).



(8a)



(8b)



(8c)

Figure 8a–c: Postoperative FFT spectrum of (a) GL6, (b) GL8, and (c) GL4, all < 10 kHz.

Thus, if the evaluation of the PoA during the acoustic recordings is based on the spectral shape, then a velar production must be assumed for GL4 preoperatively and for GL6 pre- and postoperatively. An uvular production is probable in the postoperative data of GL4 and GL8. No suggestion can be given for the preoperative /x/ segment of GL8. On the other hand, if the presence of a peak at 3.5 kHz (uvular) vs. 4.5 kHz (velar) is the main factor for the decision, then only the preoperative realisation of GL8 was velar, all other segments were uvular.

The mismatch of the PoA relying on the articulatory and acoustic findings can be interpreted in two ways. It is possible that some segments were produced with a different PoA during the acoustic and MRI recordings. If the acoustic data were classified by the localisation of the prominent peak, there would be one case like this (GL6, preoperatively). If the spectral shape was taken into account, a PoA different from the MRI scan would be hypothesised in two or three cases (GL4 preoperatively, GL6 postoperatively; the preoperative classification of GL8 is not quite clear). The other interpretation is that the description of the acoustic features given by Jassem (1968) is not sufficient for the distinction of the velar and uvular variants in concatenated speech sounds.

5. Discussion and conclusions

The previous section included a description of the articulatory, acoustic, and auditory characteristics of the consonants /s/, /ʃ/, /l/, and /x/. These will now be discussed in connection with the anatomical structures maintained after the surgery (see 2.1.). After this, some conclusions will be made regarding the unimpaired production of the four consonants.

Three subjects (GL3, GL4, and GL6) were able to distinguish between the sibilants /s/ and /ʃ/ after the surgery. All three had a tumour not larger than 2 cm (T1), thus, the reconstruction involved either no tongue fixation (GL3) or it was restricted to the frontal area of the tongue. A further characteristic not found in the other five subjects was that the upper, but not necessarily the lower, teeth were maintained.

It is somewhat surprising that /s/ was subject to a more severe impairment in Group 2 than /ʃ/. Perkell/Boyce/Stevens (1979) assumed earlier that /ʃ/ required a higher articulatory skill than /s/ because of the sublingual cavity that was necessary for a successful /ʃ/ production. They illustrated this statement by the fact that /ʃ/ is learned at a later stage of first language acquisition than /s/. Our data show, however, that /s/ is more influenced by glossectomy than /ʃ/.

The apical lateral /l/ was produced correctly only by one subject, GL3. He was the only subject without a tongue fixation and with no damage of the Musculus genioglossus. This muscle is responsible for the downward movement of the tongue tip and for pulling the tongue root forwards and downwards. Its activity was proven for /t/, /n/ and /θ/ in EMG experiments by Bole/Lesser (1966), while the genioglossus muscle does not seem to contribute to the production of /s/ and /f/. It is possible that the muscle is also required for the production of the apical lateral. However, the missing ability for apical articulation observed in the other subjects can also result from the restricted mobility of the frontal tongue area.

It seems that the velar/uvular fricative /x/ does not require such a precise movement of the tongue as the anterior sounds discussed here .This might be of a general nature, as the dorsum is larger and less mobile than the coronal part of the tongue. Another possible reason is the affected frontal but not velar part of the tongue in most subjects. A third explanation is based on the phoneme system of German: the velar place of articulation is relatively rare for consonants, while there are several coronal sounds. It is possible that even larger changes in the acoustics of velars are less perceivable than for coronals.

Finally, the hypotheses describing the articulatory and acoustic interaction in /s/ and /ʃ/ (see 3.3.) will be discussed on the basis of our results. Perkell/Boyce/Stevens (1979) underlined the importance of a contact between tongue and lower incisors for /s/ and that of a sublingual cavity for /ʃ/. In our data, however, there is a contradictory example for this hypothesis: GL4 had a tongue fixed to the lower incisors, thus he could not produce a sublingual cavity in the midsagittal area. Still, he was able to produce an unimpaired /s/.

Shadle (1990) suggested that /s/ and /ʃ/ differ in the localisation of the obstacle against which the air jet flows. According to her, the upper teeth serve as the obstacle for /s/, the lower teeth for /ʃ/. However, though the middle lower teeth were maintained in the case of only one subject (GL3), /ʃ/ was produced by two further subjects normally and was identifiable with 4 other subjects.

Thus, the hypothesis of Narayanan/Alwan/Haker (1995) is the only explanation that is supported by our data: all subjects who could differentiate between /s/ and /ʃ/ postoperatively had their upper teeth maintained, and they were all able to produce the groove necessary for /s/. Thus, the possibility for a differentiation in the localisation of the obstacle at the upper teeth was given in all these – and only in these – subjects.

The results presented in this paper are to a certain extent of explorative nature. Both the small number of the examined subjects and the moderate knowledge of the acoustics of pathological speech required a cautious interpretation that allowed only for careful conclusions. A study with a larger number of subjects, with acoustic recordings of higher quality and a better control of articulatory movements (e. g. information from the lateral part of the oral cavity) could shed light on several questions that could not be answered here.

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