Glottal volume velocity waveform characteristics in subjects with and without vocal training, related to gender, sound intensity, fundamental frequency and age

Arend M. Sulter, Hero P. Wit

Department of Otorhinolaryngology, University Hospital Groningen, Groningen, the Netherlands

Accepted for publication by the Journal of the Acoustical Society of America.

INTRODUCTION

Voice evaluation is an important topic for assessing a person's vocal abilities. Evaluation implies a frame of reference. Data bases play an important role in this respect. This study is the result of an extensive research project, the aim of which is to supply information on voice characteristics of a large group of subjects with healthy voices. Related studies have already established normative data for phonetograms (1), laryngostroboscopy (2), and glottal closure (3). In this study, normative data on glottal flow characteristics are established for the evaluation of voice production.

Vocal sound is based on the generation of pressure differences in the larynx. These pressure differences are the result of vibratory actions of the vocal folds on the expiratory air flow from the lungs. The cyclical opening and closing of the vocal folds is influenced by physiological and aerodynamic factors, such as subglottal pressure, vocal fold tension, and elastic and
Bernoulli forces (4-6). Characterization of the glottal volume velocity waveform therefore provides useful information on phonatory function (7-9). Measurements of glottal flow can also provide benchmark data for voice source models.

Examination of glottal function during voice production has been problematical due to the relative inaccessibility of the larynx in the human body for investigational procedures. However, since the introduction of the circumferentially vented pneumotachograph (10), measurements on glottal flow can be easily --as a non-invasive procedure-- performed, reflected in numerous publications.\(^1\) Glottal waveform characteristics have been described in normal adults (11-15) as well as in children (16,17), in aged adults (18), and in patients (19-25). Furthermore, correlations with intensity (11, 26-28), voice type (8,24), and singing technique (29,30) were investigated.

Differences in glottal waveform characteristics between singers and untrained subjects have also been studied. Trained singers are accustomed to exploiting a fuller intensity and pitch range, which requires laryngeal adjustments (31) with specific respiratory (32) and vocal function (33). Sundberg and Gauffin (15) and Sundberg and Rothenberg (34) measured higher peak flows in singers, presumably reflecting differences in glottal adductory forces. However, both these studies were performed with a limited number of subjects.

In the present study glottal waveform characteristics of a large group of subjects with and without vocal training were determined to create a data base with normative values. Normative data on untrained, i.e., "normal" subjects might function as a frame of reference for future investigations. Subjects with vocal training were included to offer information about possible "good" glottal characteristics, assuming that glottal waveform characteristics can range from poor to excellent.

To determine potential influences of variables on waveform characteristics, effects of the factors gender, vocal training, sound intensity level, pitch and age were also analyzed.

\(^1\)Most of the direct measurements of the voice source rely on invasive procedures, thereby compromising the integrity of the body. The oral flow is acquired with a non-invasive procedure, which makes it easy to perform. However, the determination of glottal flow is a rather complex matter, regarding the inverse filtering procedure.
METHODS

Subjects
A total of 224 Dutch untrained and trained subjects of both genders, categorized accordingly into 4 groups, were investigated. The untrained subjects in the first two groups were recruited from groups of students and volunteers without complaints of or a history of vocal pathology. Group 1: untrained females, n=92, age 17-44, mean 20.3, median 19, standard deviation (SD) 7.37 years. Group 2: untrained males, n=47, age 17-35, mean 25.0, median 25, SD 4.68 years. Eighteen of the female, and 16 of the male subjects were smokers.\(^2\)

Groups 3 and 4 consisted of amateur singers with a minimum of two years of vocal training. Vocal training consisted either of singing in a choir that organized rehearsals at least once a week, or receiving individual singing lessons with a similar frequency. All the choirs had a professional conductor and used auditions to admit new members. Although a minimum of 2 years of organized singing was used as a selection criterion for the trained group (cf. Teachey et al. [33]), about 60% of the trained subjects had a considerably longer history of singing in a choir (> 5 years). Group 3: trained females, n=42, age 18-59, mean 35.1, median 34, SD 11.86 years. Group 4: trained males, n=43, age 21-75, mean 47.5 median 49, SD 18.52 years. Five of the female, and 11 of the male trained subjects were smokers. Before the actual investigation took place, all subjects were examined laryngostroboscopically to exclude vocal fold pathology. Because we depended on volunteers it was not practicable to match the gender groups according to age.

Speech material
Each subject was asked to perform a set of phonatory tasks. The tasks comprised a word, a sentence and a CVC sequence, which were produced at three sound intensity levels: soft, comfortable (hereafter referred to as normal), and loud. The intensity levels were chosen by the subject with the investigator’s approval, excluding whispering and shouting. Both the word /stagi\_re/ (trainee) and the sentence /hou eens op te bl\_ren/ (stop bawling) contained the stressed vowel /æ/, which had to be slightly elongated. The vowel /æ/ was

\(^2\)Smokers were included in the research groups to use a normal representation of the Dutch population. The percentage of smokers in the research groups was comparable to the percentage of smokers in the normal population. As in the non-smokers, vocal pathology in the group of smokers was excluded by a close videolaryngostroboscopic examination. The number of male and female smokers did not significantly differ between the untrained and trained groups.
Figure 1. Experimental setup. Oral flow (B) is measured with a Rothenberg mask and the MS-100 unit. The output is stored in a digital memory. The content is read out repetitively and manually filtered with the MSIF-2 unit. After low pass filtering (1.6 kHz), the inverse filtered signal is monitored on the oscilloscope and characteristics of the flow can be observed on the GVVW analyzer. After determining a proper setting of the filters, the glottal volume velocity waveforms are recorded.

Chosen for its high first formant and the separation in the frequency range from the second formant (7), as well as the "neutral" shape of the vocal tract during the production of this vowel. The high first formant diminishes interaction with the fundamental frequency, which facilitates the inverse filtering procedure. The "neutral" shape of the vocal tract minimizes the voice source - vocal tract interaction (10, 14, 35). Both allowing the subject to use their comfortable levels of intensity, and the use of a word and a sentence as phonation tasks, presumably resulted in a relatively natural voice production.

Immediately following the utterance of the word and the sentence the subjects phonated the CVC sequence /bæpbæpbæp/ at a rate of 4 syllables per second in each of the intensity conditions. The CVC utterance was produced at the same intensity level as the preceding word or sentence. A correct performance was checked by monitoring sound pressure levels. Intra oral pressure was taken as a representative measure for subglottal pressure (36-39).

Recorded signals

Glottal flow acquisition. Glottal volume velocity waveforms (GVVW) were acquired using a single layer circumferentially vented pneumotachograph with
matching pressure transducers (Glottal Enterprises), in combination with the Glottal Enterprises MS-100 and the inverse filtering MSIF-2 units, a 14-bit digital memory with a sampling frequency of 40 kHz (Cutec CD-425), and a custom-built analog GVWW-analyzer to show flow-based parameter values (see Figure 1). For specifications of the mask, as well as the theory behind the specific approach of inverse filtering, the reader is referred to Rothenberg (10,37). By activating a hold circuitry with a foot switch, the investigator could store a selected part of the oral flow signal, coming from the MS-100 unit, in the digital memory. The memory content of 400 ms was read out repetitively to the inverse filtering unit MSIF-2.

Sound pressure level. The audio signal was registered with a Sennheiser Back-Elektret-Kondensator-Mikrofone MKE 2, mounted on the mask at a distance of 7 cm from the mouth (see figure 1). The Sound Pressure Level (SPL) was derived from the audio signal with an integration time of 100 ms. A dB(A) filter was used to exclude low frequency background noise from contributing to the SPL. The placement of the mask between mouth and microphone was experimentally determined to result in an attenuation of the SPL with 5 dB.³

Intra oral pressure measurement To measure the intra oral pressure (IOP), a 2 cm removable piece of a Charière 8 silicone suction catheter was connected with an adapting tube to a differential pressure transducer (Glottal Enterprises) with a flat frequency response up to about 30 Hz. The other end of the tube was placed in the oral cavity. The position prevented the tube from being filled with saliva during the experiment, while the plasticity of the tube material allowed unhampered conditions for the accomplishment of the speech tasks.

Inverse filtering

To compensate for the resonances of the vocal tract, the digitally stored oral flow signal of 400 ms was manually inverse filtered by monitoring on the oscilloscope (Hameg Digital Storage Scope HM 208) the result of adjusting the two inverse filters of the MSIF-2 unit.⁴ The goal of adjusting the filters was to

³A small experiment was conducted to obtain information on the attenuation of the mask. The mask with the microphone was placed in the experimental design described in the Methods section. The mask was then removed, while keeping the distance from microphone to artificial voice constant. The difference in SPL between both measurements was 5 dB.

⁴The use of Rothenberg’s method for inverse filtering calls for a critical attitude (67). In the process of inverse filtering, well described criteria were used to adjust the two inverse filters with centre frequencies and bandwidths, resulting
arrive at a maximally flat portion of that part of the GVVW, which represents the closed phase of the glottal cycle (40). In a number of cases in male subjects the most optimal setting of filters resulted in a hump of the waveform at the beginning of the most closed phase (cf. 26,35,41). To remove high frequency energy, the derived glottal flow signal was low pass filtered (Frequency Devices 8 pole Bessel 902 LPF) with a cut-off frequency of 1.6 kHz, according to the resonance characteristics of the mask (42).5

Registration of signals

The glottal flow signal, the sound pressure level and the intra oral pressure signal were registered on VHS tapes with an instrumentation recorder (TEAC XR-510 cassette data recorder) at a speed of 38.1 cm/s, offering an effective frequency range from DC to 10 kHz.

Calibration

Flow and sound pressure level Before each measurement session the equipment was calibrated for flow and sound pressure levels. These calibration signals were recorded along with speech signals for each subject. The flow mask with its differential pressure transducer was calibrated at three air flow rates, namely, 0, 400 and 800 ml/s, by placing the mask with a tight seal against an artificial head that had a laminar flow connection with a central air supply. The exact flow level could be adjusted by means of a Brooks 2-tube sho-rate flow meter.

The sound pressure level was calibrated at 70, 75 and 80 dB by placing the mask on a mould, which incorporated the B&K Artificial Voice Type 4219. The artificial voice was driven by the B&K Beat Frequency Oscillator Type 1022 at a frequency of 150 Hz.

Pressure. The transducer for intra oral pressure measurements was calibrated with a water manometer at the levels 0, 10, 20, 30 and 40 cmH₂O before the first subject was investigated. A drifting of the transducer characteristics was checked from time to time but never showed any significant deviation from the original calibration curve.

in high intra-researcher correlation.

5The acoustic properties of the mask used in this study were investigated with the equipment described in the pertinent section. The obtained resonance characteristics were in agreement with those given by Hertegård and Gauffin (42).
Data acquisition

The subject was asked to push the mask firmly against the face, expire, and to explore any leakage of air other than through the mesh wire screen incorporated in the mask. The same mask was used for all subjects and cleaned between recording sessions. In a number of females the back of the nose was too small to fit properly in the mask. In those cases that part of the mask was filled with a mouldable silicone based impression material (Optosil P plus; Bayer Dental). During the experimental tasks, an incorrect position of the mask, resulting in unintended air-leakage, could be monitored with a zero-level indicator and a connected flashing red light on the analog GVVW-analyzer. In case of a leakage, the DC-component of the GVVW is reduced to zero and hence the remaining AC-component indicates an erroneous measuring condition.

Before the actual registration, the phonation tasks were practised with the guidance of the investigator. Of each task, a first recording to register speech signals started at the beginning of the utterance of the subject and ended after activating the hold-circuitry. After the beginning of the /æ/ vowel the hold switch was activated and a 400 ms midvocalic oral flow signal was stored in the digital memory for inverse filtering and subsequent determination of the glottal flow signal. The stored signal was checked for a steady state appearance by comparing the levels of the amplitudes of the signal on the oscilloscope and by listening to the stored signal over headphones to verify the vowel quality. To remove the formant ripple the filters were adjusted manually, while checking the GVVW on the oscilloscope. The final centre frequencies and relative bandwidths were written down in order to trace questionable filter settings. After the completion of the filtering procedure a second recording was made onto tape of the inverse filtered signal.

The IOP signals produced during the phonation of the CVC sequence were registered, while monitoring the excursions of a VU-meter connected to the IOP-transducer to check for a correct performance of the task and a proper function of the equipment.

All examinations were performed by the same investigator.

Signal processing and data analysis

Digitization. The recorded signals were digitized with a 12 bit successive approximation converter (MetraByte DASH 16). A sampling frequency of 500 Hz was used to convert the calibration and the speech signals. The inverse filtered signals were digitized with a sampling frequency of 10 kHz. All the signals were digitized simultaneously and then demultiplexed. The inverse filtered signal was stored in subfiles of 2048 samples, which corresponds to approximately 0.2 seconds.
Analysis. A parameter extraction program was written in a fourth generation signal analysis language (ASYST, MacMillan Software Company) to analyze sound pressure level, intra oral pressure level and glottal volume velocity waveform parameters. Individual calibration files were used to quantify signals.

GVVW parameters. For each utterance parameter extraction was performed on a representative subfile of 2048 samples. Depending on $F_0$, about 20 to 60 cycles were analyzed with fundamental frequencies ranging from 100 Hz to 300 Hz, respectively.

A peak-picking algorithm was used to identify the fundamental period $T$ (see figure 2) and derive the fundamental frequency. Maxima of the GVVW signal and the second derivative of this signal were used to determine maximum flow (A in figure 3), and moments of opening (B in figure 3) and closure (C in figure 3) of the glottis, respectively, within a single fundamental period. After labelling events A, B and C, closed time ($t_1$), opening time ($t_2$) and closing time ($t_3$) (see figure 2) were calculated. Closed quotient ($t_1/T$), closing quotient ($t_3/T$) and speed quotient ($t_2/t_3$) could be determined.

Figure 2. Glottal volume velocity waveform parameters and markers.

$T$ = fundamental period, $t_1$ = closed phase, $t_2$ = opening phase and $t_3$ = closing phase.
Glottal Waveform Characteristics

Minimum flow was calculated by averaging flow over the most closed period ($t_1$). Subtracting minimum flow from maximum flow yielded ac flow. Average flow was calculated by taking the mean of the glottal flow. Maximum flow declination rate (MFDR) was calculated by determining the minimum of the first derivative of the glottal waveform.

Finally, two parameters related to vocal fold function were calculated. Vocal efficiency was determined by calculating the ratio between sound power and the product of air pressure times average flow (43). A glottal resistance measure was determined by calculating the ratio of air pressure to average flow (38).

Intra oral pressure adjustment. After analyzing the CVC sequence and determining intra oral pressure (IOP) and SPL, IOP was standardized for the SPL produced during the utterance of the preceding word and sentence. Regression analysis of individual SPL-IOP functions showed a linear relation with a high correlation coefficient ($r>0.98$) between SPL and the logarithmically transformed IOP values. Regression coefficients were used to predict the IOP pertaining to the utterances.

---

6 The method of inverse filtering presented in this study supplies waveforms with minimal variation of flow during the closed portion of the glottal cycle, as this minimal variation is the main criterion for accepting the filter settings. With the subsequent low pass filtering a waveform results, which generally presents no problem for the algorithms in detecting representative maxima in the second derivative. Soft phonations with very limited modulation sometimes give problems and lead to rejection of some waveforms for further analysis.

7 Representing the maximum in the change of flow, MFDR was regarded as a flow-based parameter.
Statistical analysis

Analysis of variance (ANOVA) and Multivariate analysis of covariance (MANCOVA) of the statistical package SPSS (SPSS Inc.) was used to investigate differences among groups (44). Minimum flow, ac flow, average flow, MFDR, closed quotient, closing quotient, speed quotient, glottal resistance and vocal efficiency were regarded as dependent variables. Gender, vocal training, and intensity condition were introduced as factors. SPL, fundamental frequency, IOP, and age served as covariants. In case of significant interaction between factors, a separate MANCOVA was performed at each factor level. To determine differences among factor levels of the intensity condition, one-way analysis of variance with post hoc Least Square Difference (LSD) tests was performed. Because of the many tests performed, a conservative probability level $\alpha=0.01$ was used with respect to the Bonferroni inequality.

<table>
<thead>
<tr>
<th></th>
<th>male subject</th>
<th>female subject</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>soft</td>
<td>normal</td>
</tr>
<tr>
<td>minimum flow (ml/s)</td>
<td>198</td>
<td>69</td>
</tr>
<tr>
<td>ac flow (ml/s)</td>
<td>245</td>
<td>497</td>
</tr>
<tr>
<td>average flow (ml/s)</td>
<td>263</td>
<td>153</td>
</tr>
<tr>
<td>MFDR (l/s)</td>
<td>210</td>
<td>564</td>
</tr>
<tr>
<td>closed quotient (%)</td>
<td>42.3</td>
<td>48.2</td>
</tr>
<tr>
<td>closing quotient (%)</td>
<td>23.6</td>
<td>18.2</td>
</tr>
<tr>
<td>speed quotient</td>
<td>1.45</td>
<td>1.86</td>
</tr>
</tbody>
</table>

Table 1. Variance in glottal flow parameters for one male and one female speaker after ten times manually inverse filtering the same oral waveform. Mean and standard deviations (between brackets) are given. Eta values represent the strength of association between the averaged value of the parameter and condition (maximum value = 1, minimum = 0). MFDR = Maximum Flow Declination Rate.
RESULTS

Inverse filtering procedure

The variability of inverse filtering, which might result in arriving at different parameter values for GVVW, was determined with a small experiment. A male and female subject uttered the word /stāgāre/ at the three intensity conditions. At each condition the investigator adjusted the filters from a neutral position to an optimal setting ten times. A registration was made of the filtered waveform and the procedure described above was used to analyze GVVW. Table 1 gives the mean parameter values with standard deviations. In general, very low standard deviations were found for all parameters, which indicates the robustness of the manually adjusted inverse filtering procedure. The eta values show the high level of association between parameter values and intensity condition.

Glottal volume velocity waveform analysis

A small number of filtered waveforms (<3%) could not be analyzed or used for further evaluation. These were mostly soft voice productions resulting in waveforms with very limited modulation, which offered insurmountable problems for the parameter extraction program. In other cases the IOP signal did not conform to the typical pattern of alternating zero - non zero pressure levels, which led to rejection of the matching GVVW for further analysis. A total of 1308 analyzed cases could be used for producing summary and inferential statistics.

Summarized data

All data on glottal waveform parameters and other analyzed variables from both utterances were averaged according to gender, vocal training and intensity condition. Mean values with standard deviations are given in Table 2. This table offers normative data on vocal function and can be used to compare with other published data on

Figure 4. Relation between SPL and fundamental frequency (f) for soft, normal and loud intensity. Mean 〇= untrained women; ●= trained women; □= untrained men; ■= trained men) and standard deviations (±) are given.
GVVW characteristics.

Averaged for intensity condition, the sound pressure levels were comparable among groups. Figure 4 presents the relation between fundamental frequency and SPL. Soft voice was produced at about 75 dB, normal voice at about 90 dB, and loud voice at about 100 dB. The increase in intensity from soft to normal voice was larger than the increase from normal to loud (15 dB versus 10 dB, respectively). A three-way analysis of variance with gender, vocal training and intensity condition as factors showed a statistically significant influence of training on SPL ($F(1,1297) = 8.47$, $p=0.004$; trained subjects produced louder phonations than the untrained ones), as well as significant differences in SPL among condition levels ($F(2,1296) = 1711.55$, $p<0.001$). The effect of gender was not significant ($F(1,1297) = 0.19$, $p=0.661$). Except for the loud intensity condition, the measured fundamental frequencies were within the ranges observed in normal Dutch speech (45). The loudest condition demonstrated frequencies within the area of chest register voice production (1). Three-way
<table>
<thead>
<tr>
<th>Variable</th>
<th>Female</th>
<th>Male</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>untrained</td>
<td>trained</td>
</tr>
<tr>
<td></td>
<td>soft</td>
<td>normal</td>
</tr>
<tr>
<td>Vocal intensity (dB)</td>
<td>75.7</td>
<td>88.0</td>
</tr>
<tr>
<td></td>
<td>(6.51)</td>
<td>(6.29)</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>208.9</td>
<td>253.5</td>
</tr>
<tr>
<td></td>
<td>(24.30)</td>
<td>(36.96)</td>
</tr>
<tr>
<td>Minimum flow (l/s)</td>
<td>0.11</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>(0.06)</td>
<td>(0.05)</td>
</tr>
<tr>
<td>AC flow (l/s)</td>
<td>0.17</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>(0.06)</td>
<td>(0.09)</td>
</tr>
<tr>
<td>Average flow (l/s)</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>(0.06)</td>
<td>(0.07)</td>
</tr>
<tr>
<td>Maximum flow declination rate (l/s²)</td>
<td>249.7</td>
<td>504.0</td>
</tr>
<tr>
<td></td>
<td>(112.4)</td>
<td>(220.1)</td>
</tr>
<tr>
<td>Closed quotient (%)</td>
<td>35.3</td>
<td>44.5</td>
</tr>
<tr>
<td></td>
<td>(9.4)</td>
<td>(11.6)</td>
</tr>
<tr>
<td>Closing quotient (%)</td>
<td>25.8</td>
<td>23.7</td>
</tr>
<tr>
<td></td>
<td>(4.2)</td>
<td>(3.2)</td>
</tr>
<tr>
<td>Speed quotient (%)</td>
<td>1.55</td>
<td>1.36</td>
</tr>
<tr>
<td></td>
<td>(0.38)</td>
<td>(0.48)</td>
</tr>
<tr>
<td>Pressure (cm H₂O)</td>
<td>6.0</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td>(2.2)</td>
<td>(4.1)</td>
</tr>
<tr>
<td>Glottal resistance (cm H₂O/l/s)</td>
<td>45.6</td>
<td>81.8</td>
</tr>
<tr>
<td></td>
<td>(31.0)</td>
<td>(47.6)</td>
</tr>
</tbody>
</table>

*Table 2. Summary statistics of variables and glottal waveform parameters. Mean and standard deviation (between brackets) are given. Measured at 7 cm from the mouth. Vocal efficiency values have been multiplied by 10.
analysis of variance of fundamental frequency showed a statistically significant interaction between the factors gender, vocal training and intensity condition \( (F(2,1296) = 5.72, p=0.003) \). Therefore, a separate two-way analysis was performed for male and female subjects. The fundamental frequency of the male subjects was significantly influenced by intensity condition, with louder conditions showing higher frequencies \( (F(2,524) = 806.55, p<0.001) \). No influence of training was observed \( (F(1,525) = 0.24, p=0.626) \). In the female subjects, a statistically significant interaction between training and intensity condition was observed \( (F(2,769) = 6.21, p=0.002) \). The fundamental frequency of both the trained and untrained female subjects was significantly influenced by intensity condition, louder conditions giving higher frequencies \( (F(2,261) = 237.64, p<0.0001, \text{ and } F(2,550) = 349.16, p<0.0001, \text{ respectively}) \). The trained females phonated with a lower fundamental frequency during the tasks with soft voice than untrained ones \( (F(1,285) = 10.78, p=0.0012) \).

To make the relation between the GVVW characteristics and the sound intensity more comprehensible, as well as to show differences between gender and vocal training, plots were constructed for each GVVW parameter. Mean values are given for the four speaker groups. Female groups and male groups are represented by circles and squares, respectively. Untrained groups have unfilled figures and the figures of trained groups are filled. The whiskers indicate the standard deviations. All presented parameters are plotted against SPL.

Figure 5a shows data for minimum flow, plotted against SPL. All mean values for the groups lay close together for soft and normal voice, with the male groups having the largest
standard deviations for the soft intensity condition. In loud voice, the female groups show a tendency of decreasing minimum flow with increasing intensity, whereas the male groups show an increase in minimum flow from the normal to the loud condition.

Figure 5b shows data for ac flow, plotted against SPL. Ac flow increases with intensity for all groups; the male groups, however, show the largest increments with intensity, and the ac flow in these groups is larger than in the female groups.

Figure 5c shows data for average flow, plotted against SPL. In general, the male groups have higher levels of average flow compared to the female groups, and at the loud intensity condition there is a marked increase in average flow for both the untrained and trained male group. The average flow does not show apparent changes over the intensity conditions in the female groups.

Figure 5d shows data for MFDR, plotted against SPL. In the soft intensity condition, the differences between the male and female groups are small; with increasing intensity, however, there is a distinct difference, with male subjects having the largest
values. In all groups, the increase in mean MFDR values with SPL is apparent. The standard deviations are small at the soft intensity condition but become larger at louder conditions.

Figure 5e shows data for the closed quotient, plotted against SPL. With louder intensities, the closed quotient shows higher mean values; however, there is a difference between male and female groups. The male groups already have the highest values in the normal intensity condition, whereas the mean closed quotient further increases in the female groups from normal to loud. In the loud intensity condition, all groups have comparable closed quotients with values close to 50%.

Figure 5f shows data for the closing quotient, plotted against SPL. Compared to the male groups, the female groups have higher mean closing quotient values, which implies that closing of the vocal folds involves a larger part of the glottal cycle in the female groups. All groups have the lowest mean closing quotient values in the normal intensity condition.

Figure 5g shows data for the speed quotient, plotted against SPL. There is a trend toward a more symmetrical shape of the GVVW with louder intensity conditions for all groups; however, the female groups show this tendency more clearly, especially the trained female group with a value of 0.97 for the loud intensity condition. The large spread in the individual values in the loud intensity condition becomes apparent from the large standard deviation for the
Differences between groups and influence of variables

MANCOVA was used to investigate differences between groups, as well as among intensity conditions (44). Table 3 summarizes the effects of the factors gender, vocal training and intensity condition on GVVW parameters and the derived parameters glottal resistance and vocal efficiency. Apart from the speed quotient and vocal efficiency, the factor gender shows a significant influence on all other parameters. Because of the significant interaction between gender and training, as well as between gender and intensity condition, separate MANCOVAs were performed for male and female groups. In the female groups the factor voice training has a significant influence on MFDR and closing quotient with the trained group showing higher values for both
### Table 3. Multivariate analysis of variance summary table.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Gender x Training x Intensity Condition df(2,1292)</th>
<th>Training x Intensity Condition df(2,1292)</th>
<th>Gender x Training df(1,1292)</th>
<th>Gender x Intensity Condition df(2,1292)</th>
<th>Gender df(1,1292)</th>
<th>Voice Training Female df(1,765)</th>
<th>Voice Training Male df(1,523)</th>
<th>Intensity Condition Female df(2,765)</th>
<th>Intensity Condition Male df(2,523)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Flow</td>
<td>0.28 (0.758)</td>
<td>0.20 (0.820)</td>
<td>3.30 (0.070)</td>
<td>11.26 (0.000°)</td>
<td>19.83 (0.000°)</td>
<td>0.40 (0.530)</td>
<td>0.44 (0.506)</td>
<td>1.66 (0.190)</td>
<td>4.95 (0.007°)</td>
</tr>
<tr>
<td>AC Flow</td>
<td>4.03 (0.018)</td>
<td>1.27 (0.280)</td>
<td>3.25 (0.072)</td>
<td>76.22 (0.000°)</td>
<td>339.24 (0.000°)</td>
<td>0.19 (0.660)</td>
<td>4.04 (0.045)</td>
<td>5.93 (0.003°)</td>
<td>9.58 (0.000°)</td>
</tr>
<tr>
<td>Average Flow</td>
<td>1.39 (0.249)</td>
<td>0.79 (0.452)</td>
<td>0.60 (0.437)</td>
<td>27.48 (0.000°)</td>
<td>86.28 (0.000°)</td>
<td>0.35 (0.557)</td>
<td>1.60 (0.206)</td>
<td>0.903 (0.406)</td>
<td>13.24 (0.000°)</td>
</tr>
<tr>
<td>MFDR</td>
<td>2.32 (0.099)</td>
<td>0.18 (0.833)</td>
<td>7.18 (0.007°)</td>
<td>187.03 (0.000°)</td>
<td>284.16 (0.000°)</td>
<td>13.97 (0.032)</td>
<td>4.62 (0.000°)</td>
<td>14.11 (0.000°)</td>
<td>12.92 (0.000°)</td>
</tr>
<tr>
<td>Closed Quotient</td>
<td>0.35 (0.703)</td>
<td>0.71 (0.492)</td>
<td>1.91 (0.167)</td>
<td>11.80 (0.000°)</td>
<td>8.22 (0.004°)</td>
<td>0.79 (0.374)</td>
<td>2.37 (0.124)</td>
<td>3.73 (0.024°)</td>
<td>5.68 (0.004°)</td>
</tr>
<tr>
<td>Closing Quotient</td>
<td>2.65 (0.071)</td>
<td>0.18 (0.834)</td>
<td>29.63 (0.000°)</td>
<td>0.77 (0.000°)</td>
<td>34.50 (0.000°)</td>
<td>13.76 (0.145)</td>
<td>2.13 (0.002°)</td>
<td>6.53 (0.032)</td>
<td>3.45 (0.032°)</td>
</tr>
<tr>
<td>Speed Quotient</td>
<td>0.57 (0.568)</td>
<td>0.37 (0.693)</td>
<td>33.09 (0.000°)</td>
<td>5.44 (0.000°)</td>
<td>0.37 (0.545)</td>
<td>3.05 (0.081)</td>
<td>8.49 (0.004°)</td>
<td>4.69 (0.631°)</td>
<td>1.75 (0.174°)</td>
</tr>
<tr>
<td>Glottal Resistance</td>
<td>0.80 (0.449)</td>
<td>1.35 (0.259)</td>
<td>1.17 (0.279)</td>
<td>27.92 (0.000°)</td>
<td>32.62 (0.000°)</td>
<td>0.86 (0.534)</td>
<td>0.15 (0.699)</td>
<td>2.64 (0.072)</td>
<td>4.01 (0.019°)</td>
</tr>
<tr>
<td>Vocal Efficiency</td>
<td>1.16 (0.314)</td>
<td>0.45 (0.638)</td>
<td>1.08 (0.299)</td>
<td>13.26 (0.000°)</td>
<td>2.74 (0.098)</td>
<td>0.88 (0.349)</td>
<td>0.48 (0.490)</td>
<td>22.67 (0.000°)</td>
<td>17.07 (0.000°)</td>
</tr>
</tbody>
</table>
### Table 4. Regression analysis within subgroups (intensity condition and vocal training).

Only on the parameter speed quotient, trained subjects showing higher values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>B</th>
<th>t-value</th>
<th>p</th>
<th>B</th>
<th>t-value</th>
<th>p</th>
<th>B</th>
<th>t-value</th>
<th>p</th>
<th>B</th>
<th>t-value</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SPL</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) female subjects</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>minimum flow</td>
<td>-1.52</td>
<td>-3.79</td>
<td>0.000*</td>
<td>0.08</td>
<td>1.34</td>
<td>0.180</td>
<td>0.94</td>
<td>1.83</td>
<td>0.067</td>
<td>0.47</td>
<td>1.99</td>
<td>0.047</td>
</tr>
<tr>
<td>ac flow</td>
<td>4.31</td>
<td>8.02</td>
<td>0.000*</td>
<td>-0.45</td>
<td>-5.46</td>
<td>0.000*</td>
<td>6.49</td>
<td>9.42</td>
<td>0.000*</td>
<td>0.94</td>
<td>2.99</td>
<td>0.003*</td>
</tr>
<tr>
<td>average flow</td>
<td>-1.13</td>
<td>-2.22</td>
<td>0.027</td>
<td>0.65</td>
<td>2.16</td>
<td>0.031</td>
<td>2.35</td>
<td>3.59</td>
<td>0.000*</td>
<td>0.65</td>
<td>2.16</td>
<td>0.031</td>
</tr>
<tr>
<td>MFDR</td>
<td>11.96</td>
<td>9.35</td>
<td>0.000*</td>
<td>-0.13</td>
<td>-0.65</td>
<td>0.515</td>
<td>13.51</td>
<td>8.24</td>
<td>0.000*</td>
<td>1.62</td>
<td>2.16</td>
<td>0.031</td>
</tr>
<tr>
<td>closed quotient</td>
<td>0.59</td>
<td>7.73</td>
<td>0.000*</td>
<td>-0.08</td>
<td>-6.45</td>
<td>0.000*</td>
<td>0.24</td>
<td>2.42</td>
<td>0.016</td>
<td>0.07</td>
<td>1.45</td>
<td>0.147</td>
</tr>
<tr>
<td>closing quotient</td>
<td>-0.30</td>
<td>-12.29</td>
<td>0.000*</td>
<td>0.06</td>
<td>17.38</td>
<td>0.000*</td>
<td>0.06</td>
<td>1.92</td>
<td>0.055</td>
<td>0.02</td>
<td>1.60</td>
<td>0.110</td>
</tr>
<tr>
<td>speed quotient</td>
<td>0.00</td>
<td>1.21</td>
<td>0.227</td>
<td>-0.00</td>
<td>-5.52</td>
<td>0.000*</td>
<td>-0.01</td>
<td>-3.48</td>
<td>0.001*</td>
<td>-0.00</td>
<td>-2.71</td>
<td>0.007*</td>
</tr>
<tr>
<td>glottal resistance</td>
<td>0.17</td>
<td>0.49</td>
<td>0.627</td>
<td>-0.04</td>
<td>-0.78</td>
<td>0.437</td>
<td>4.99</td>
<td>11.18</td>
<td>0.000*</td>
<td>-0.03</td>
<td>-0.15</td>
<td>0.881</td>
</tr>
<tr>
<td>vocal efficiency</td>
<td>7.38</td>
<td>8.43</td>
<td>0.000*</td>
<td>0.42</td>
<td>3.18</td>
<td>0.002*</td>
<td>-0.07</td>
<td>-0.06</td>
<td>0.951</td>
<td>-0.12</td>
<td>-0.24</td>
<td>0.812</td>
</tr>
<tr>
<td><strong>Pressure</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) female subjects</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>minimum flow</td>
<td>-2.23</td>
<td>-3.34</td>
<td>0.001*</td>
<td>0.29</td>
<td>1.95</td>
<td>0.052</td>
<td>-0.36</td>
<td>-0.40</td>
<td>0.067</td>
<td>-0.29</td>
<td>-1.22</td>
<td>0.222</td>
</tr>
<tr>
<td>ac flow</td>
<td>11.86</td>
<td>9.25</td>
<td>0.000*</td>
<td>-0.55</td>
<td>-1.92</td>
<td>0.055</td>
<td>1.00</td>
<td>0.59</td>
<td>0.558</td>
<td>0.12</td>
<td>0.26</td>
<td>0.793</td>
</tr>
<tr>
<td>average flow</td>
<td>-1.75</td>
<td>-1.84</td>
<td>0.067</td>
<td>0.06</td>
<td>0.30</td>
<td>0.764</td>
<td>1.81</td>
<td>1.42</td>
<td>0.156</td>
<td>-0.35</td>
<td>-1.05</td>
<td>0.296</td>
</tr>
<tr>
<td>MFDR</td>
<td>29.07</td>
<td>11.75</td>
<td>0.000*</td>
<td>1.31</td>
<td>2.40</td>
<td>0.017</td>
<td>10.53</td>
<td>3.19</td>
<td>0.002*</td>
<td>-3.16</td>
<td>-3.62</td>
<td>0.000*</td>
</tr>
<tr>
<td>closed quotient</td>
<td>0.85</td>
<td>9.70</td>
<td>0.000*</td>
<td>-0.03</td>
<td>-1.58</td>
<td>0.114</td>
<td>-0.33</td>
<td>-2.81</td>
<td>0.005*</td>
<td>0.03</td>
<td>1.09</td>
<td>0.276</td>
</tr>
<tr>
<td>closing quotient</td>
<td>-0.46</td>
<td>-14.43</td>
<td>0.000*</td>
<td>0.06</td>
<td>9.00</td>
<td>0.000*</td>
<td>0.12</td>
<td>2.82</td>
<td>0.005*</td>
<td>0.01</td>
<td>0.56</td>
<td>0.574</td>
</tr>
<tr>
<td>speed quotient</td>
<td>0.01</td>
<td>3.53</td>
<td>0.000*</td>
<td>-0.01</td>
<td>-6.49</td>
<td>0.000*</td>
<td>0.00</td>
<td>0.32</td>
<td>0.748</td>
<td>-0.00</td>
<td>-1.63</td>
<td>0.104</td>
</tr>
<tr>
<td>glottal resistance</td>
<td>0.82</td>
<td>1.82</td>
<td>0.069</td>
<td>0.01</td>
<td>0.83</td>
<td>0.934</td>
<td>2.93</td>
<td>4.87</td>
<td>0.000*</td>
<td>0.03</td>
<td>0.17</td>
<td>0.867</td>
</tr>
</tbody>
</table>

*p<0.01; a) female subjects; b) male subjects.
than untrained ones. The factor intensity condition has a significant effect on many parameters (see Table 3). In the female groups ac flow, MFDR, closing quotient and vocal efficiency, whereas in the male groups minimum flow, ac flow, average flow, MFDR, closed quotient and vocal efficiency are significantly influenced by intensity condition. Post hoc LSD tests showed significant differences among all conditions (soft, normal and loud) for the mentioned parameters in the female groups. In the male groups, there was a significant difference between soft and normal, as well as between normal and loud intensity condition for minimum flow. For average flow, significant differences were found between both soft and normal, and loud intensity condition. For closed quotient significant differences were found between both normal and loud, and soft intensity condition. Finally, significant differences among all conditions (soft, normal and loud) were found for ac flow, MFDR and vocal efficiency.

Differences in IOP values were analyzed by a three-way ANOVA with gender, vocal training and intensity condition as factors. With louder conditions the IOP increases significantly \( F(2,1296) = 960.38, p<0.001 \), and trained subjects use higher pressures during phonation \( F(1,1297) = 10.26, p=0.001 \). No differences were found between male and female subjects \( F(1,1297) = 2.82, p=0.093 \).

The influence of covariants SPL, fundamental frequency, IOP and age were also investigated separately for male and female subjects in the MANCOVAs with regression analysis within subgroups (see Tables 4a and b).

Except for glottal resistance and average flow in both gender groups, and the speed quotient in the females, SPL has a significant relation with all other parameters. Minimum flow and closing quotient have a negative regression coefficient, whereas ac flow, MFDR, closed quotient, speed quotient and vocal efficiency have a positive regression coefficient.

Fundamental frequency has a significant relation with the closing quotient, speed quotient and vocal efficiency. In the females, a significant influence of fundamental frequency is also found on ac flow and closed quotient. The ac flow, closed quotient and speed quotient have a negative regression coefficient, whereas closing quotient and vocal efficiency have a positive regression coefficient.

Intra oral pressure has a significant influence on MFDR and glottal resistance in both genders, and more specifically on ac flow, average flow, and speed quotient in females, and on closed quotient and closing quotient in males. The speed quotient and closed quotient have a negative regression coefficient, whereas the other parameters mentioned have a positive regression coefficient.

Finally, age has a significant negative regression coefficient with MFDR in
male subjects, and on ac flow and speed quotient in female subjects, with a positive and negative regression coefficient, respectively.

DISCUSSION

Sound Pressure Level

Voice production entails the generation of an audible signal. An important feature of the signal to make it understandable is the sound intensity level. Therefore glottal function is described in close relation with SPL. In this study clear differences in SPL were established among the intensity conditions soft, normal and loud voice. Other studies also have employed different intensity conditions to study the behaviour of the voice source; however, a direct comparison of values found in this study with values reported previously shows a clear distinction, with the present study giving higher values. Averaged SPL values measured in the present study range from about 75 dB for the soft, 90 dB for the normal, and 100 dB for the loud intensity condition, whereas Holmberg et al. (11), Perkell et al. (12) and Stathopoulos and Sapienza (27) give mean SPL values that are about 15 dB lower for the normal and loud intensity condition. An explanation for the loud intensities in the present study can be found in the placement of the microphone. In our experimental setup the mouth to microphone distance is 7 cm, whereas in most other studies a distance of about 15 cm is mentioned (e.g. 11,26,27). This difference in distance was experimentally determined to account for 7 dB. A second explanation for the higher SPL in the present study can be found in the different task contents (46-48). In the present investigation a stressed vowel in a word and sentence was used, while most investigations work with a CVC sequence (e.g., /bæpbæpbæp/). Till et al. (49), however, did not establish differences in measurement results for a sustained vowel and a CVC sequence. Despite the differences in SPL, comparisons of glottal flow characteristics obtained in this investigation were made with results from other studies, while similar qualitative (soft, normal and loud) intensity conditions were used.

Flow-based parameters

As in most other studies the following flow-based parameters were used to describe glottal functioning: minimum flow, ac flow, average flow, and maximum flow declination rate. Peak flow (cf. 11) was not introduced because it can be derived from adding minimum flow and ac flow.

Minimum flow is related to leakage of air through a continuously unclosed part of the glottis. Two different minimum flows are used in literature. Stathopoulos and Sapienza (16,27), Sapienza and Stathopoulos (17,25), Dromey et al. (26), Higgins and Saxman (18,47), and Peterson et al. (24)
determine minimum flow at the moment during the closed phase of the glottal cycle with absolute minimum flow, while Holmberg et al. (11), Hillman et al. (20,21), and Hertegård et al. (30,41) mention the flow --which is not necessarily the absolute minimum-- during the most closed phase. In our study, the minimum flow was taken as the average of the flow during the closed phase. This procedure avoids establishing extreme values for minimum flow, which might be acquired due to incorrect filter settings for removing formants in the oral flow signal. Slightly incorrect filter settings result in ripple in the glottal waveform. Also, apart from an upward movement of the vocal folds (vertical phasing, cf. 2,41) in men at low fundamental frequencies, in normal subjects no dynamic events take place at the glottal level during the most closed phase, giving a flat portion in the glottal flow. The reduction of minimum flow with increasing intensity, as observed in the present study, is probably related to the closing of the posterior part of the glottis (2,3,11). In both the untrained and trained male subjects, however, an increase in mean minimum flow is observed from normal to loud voice. Although speculative, an explanation might be that the decrease in unclosed part of the glottis in men is less evident from normal to loud voice compared to women, and that with increasing subglottal pressure from normal to loud voice, those persons with an unclosed part of the glottis show an increase in minimum flow. Another option is that with increasing subglottal pressure, subjects with a complete closure of the vocal folds during normal voice, start leaking from the normal to loud voice condition. Other explanations are based on processes concerning both inverse filtering (source-vocal tract interaction, cf. Rothenberg (50)), as well as parameter extraction (algorithmically defined labelling of the moment of closure).

Ac flow is determined by the amplitude of the vocal fold vibration in combination with the subglottal pressure (7). Mean ac flow values in this study are higher than values reported so far. Only Hertegård et al. (41) found values for normal voice resembling the values reported in this study. Reasons for this difference might be found in one of the following: the use of a vowel instead of a CVC sequence (18,47), the stress on the vowel (46,48), specific filter settings (51), cultural differences in speech production (52), or the higher --compared to other studies-- SPL values measured in the present study. SPL has a positive relation with ac flow (11,13,15,18,25). The differences in ac flow between the intensity conditions in the present study are proportional to the differences in the articles mentioned. The increase in ac flow with louder intensities correlates with the larger amplitudes of vocal fold vibration, as observed in the same subjects (2).

Mean values for average flow resemble those values found in literature (cf. 53 for a review). Previous studies showed a slightly positive relation between average flow and SPL (43,54). With increasing SPL from normal to loud voice,
the average flow significantly increases in men. This increment follows from increased minimum flow and ac flow. The steady average flow of women across the conditions might be the compensatory result of a reduction of glottal leakage and an increase in vocal fold excursions from soft to loud voice, as seen in videostroboscopic ratings (2,3).

Maximum airflow declination rate represents the closing velocity of the vocal folds and serves as an indicator of the excitation of the vocal tract; it is therefore closely related to SPL (55,56). The clinical relevance of this parameter is its assumed relation with vocal fold collision forces. Relatively high levels of MFDR are associated with vocal fold pathology (17,20-22). Because absolute values of MFDR are important in this respect, the intra-individual stability of the parameter (55,57) is crucial for studies using this parameter as an indicator of susceptibility to vocal fold pathology, as is the knowledge about the frequency dependency of low pass filter settings (12,51). MFDR values established in this study are much higher than values reported hitherto. The same explanations as given for the ac flow can be given for these extreme values. However, a similar tendency of exponentially increasing MFDR values with increasing SPL was found, as in other studies (12,17,25,27).

Time-based parameters

The maxima of the second derivative of the glottal waveform, representing the most significant changes in the glottal flow, were used to define moments of closure and opening. These important events in the glottal cycle have been determined using many other criteria. Holmberg et al. (11) used the intersection of visually determined line tangents along the waveform to establish moments of opening and closing. Other investigators use specific impedance information from the simultaneously recorded electroglottographic signal (24,41). Also specific levels of the ac flow are used to establish moments of opening and closing. Apart from their indication of subjective temporal markers, Dromey et al. (26) use a 50% criterion level of ac flow. Stathopoulos and Sapienza (27), in contrast, use a 20% criterion level, while Higgins and Saxman (18) use a 15% level. The differences in definition of moments of opening and closing create a problem in comparing data. In practice, our definition of closing and opening uses temporal labels that occur close to those of Holmberg et al. (11), Hertegård et al. (41), Peterson et al. (24), as well as the subjectively determined markers of Dromey et al. (26). Therefore comparisons will only be made with data originating from these studies.

Instead of an open quotient, in this investigation a closed quotient is used. However, both values are supplementary since the open and closed quotient together yield 100%. The closed quotient of the glottal flow is believed to represent the time that vocal folds are maximally approximated during a glottal
cycle. Apart from elastic and aerodynamical forces, the approximation is supplied by adductory muscular activity. Therefore this parameter has also been described as adduction quotient. High adduction quotients are associated with vocal strain and might cause vocal fold pathology (24). Only few of the articles referred to above provide data on the closed quotient for other than the normal intensity condition. In this condition, the mean values range from 24% in women and 40% in men (11) to 54% in a combined group (24). Our mean values of 45% for women and 50% for men fall in between these extremes. The tendency to increase closure duration with increasing intensity (11,14,26) is also visible in our data from the soft to normal intensity condition. The untrained male subjects reach an averaged maximum of the closed quotient at the normal voice condition. The increase in the closed quotient with intensity from soft to normal voice can be explained by increased adductory muscular activity and Bernoulli forces. The small differences between closed quotient values from the normal to loud intensity condition might reflect a balance between, on the one hand, an increase of adductory muscular activity, and an increase of subglottal pressure, forcing the vocal folds apart, on the other.

The closing quotient represents the time period in which maximum flow is reduced to minimum flow. The magnitude of this parameter is strongly influenced by low pass filter settings (51). Only Holmberg et al. (11) provide data for comparison. Mean closing quotients in the present study are slightly smaller at each intensity condition. Only the closing quotient for women at loud intensity condition is slightly larger (21.0% vs 19%). In our data, the closing quotient has a minimum for all groups in the normal voice condition. This minimum might indicate a preferable condition for sound production, with a high excitation of the vocal tract as a consequence of a fast closure of the vocal folds, combined with limited ac flow levels.

The speed quotient reflects the symmetry of the glottal waveform shape. A value of 1 stands for symmetry, while values larger and smaller than one correspond to a waveform with a relatively shorter and longer closing phase, respectively. The results of investigations performed hitherto show mean values larger than 1, with inconsistent relations with intensity condition (11,26). Our results show mean values >1, with a decreasing tendency with increasing SPL.

Intra oral pressure

Intra oral pressure was used as a representative measure of subglottal pressure. Since the appearance of studies validating this measurement method, data on subglottal pressure have become available in a number of publications (11,18,27,41,58). Results of the present study show mean values, higher than the values given in the pertinent articles. However, Schutte (43) measuring
subglottal pressures with an esophageal balloon, presented pressure ranges that are more in agreement with the results from the present study. In all studies, a positive relation between pressure and SPL has been established.

Derived parameters

From the parameters and variables discussed above a glottal resistance and vocal efficiency were calculated. Because the intra oral pressures from the present study are high compared to results from previous publications, it was no surprise that our mean values for vocal efficiency and glottal resistance are also extreme.

The vocal efficiency is calculated as the ratio of the produced sound power to the subglottic power (see Schutte (43) page 50 for equations). Schutte (43) established vocal efficiency values ranging from $0.12 \times 10^{-5}$ to $400 \times 10^{-5}$ over an intensity range of 47 dB. At 70 dB (microphone to pneumotachograph outlet distance 15 cm), the efficiency varied from $1 \times 10^{-5}$ to $10 \times 10^{-5}$, and at 90 dB from $10 \times 10^{-5}$ to $110 \times 10^{-5}$. In our data, the women surpass this highest value in the loud voice condition, the untrained subjects with a mean value of $150.3 \times 10^{-5}$ and the trained subjects with a value of $143.4 \times 10^{-5}$. Holmberg et al. (11) presents values for women that are lower than the results from the present study, whereas the mean values for the male subjects are much closer. In all studies, the efficiency index is characterized by large standard deviations, indicating the large range in individual values.

A review of the literature reveals a variability in mean glottal resistance (cf. 11,27, 59,60). The present study again provides higher mean values than those reported before, especially for women. For the male subjects, the mean values of glottal resistance are close to those presented by Stathopoulos and Sapienza (27). The high values are explained by the measured high intra oral pressures. As can be observed in the other studies, the glottal resistance increases with increasing intensity, which is related to with the increment in adductory forces.

Influence of factors

Gender. There are important differences in the anatomy of the larynx between men and women (61). The male vocal folds are longer and thicker, which plays an important role in the specific physiology and acoustics of voice production in men and women (62). The observed differences in ac flow, average flow, closing quotient, and MFDR can be explained by considering the effect of longer vocal folds with larger vibrational amplitudes on voice physiology in men (cf. 5). As compared to women, the higher mean closed quotient values in men might be due to differences in prephonatory glottal width, as well as thicker vocal folds. The minimum flow was also observed to be significantly higher in men. This finding conflicts with the observed better
closure of the vocal folds in men (3). It probably can be explained by the algorithm for labelling the moments of closure and opening of the vocal folds, which might introduce the inclusion of the "piston flow" in the minimum flow (cf. 26,35,41). This "piston flow" is observed during the process of vertical phasing of especially male vocal folds and, thus, leads to higher minimum flows in men.

The findings of the present study show differences in GVVW between men and women, which are highly consistent with those reported in the literature (11,12,18,27,41). The differences in GVVW parameters also imply the presence of specific gender-related voice source spectra (46). Apart from the fundamental frequency, these characteristics of the voice source spectrum might be the basis for a perceptual distinction between gender.

Vocal training. To our knowledge the present study is the first one in which differences in GVVWs are investigated in large groups with and without vocal training. The statistical analysis showed a few differences between subjects with and without vocal training.

In the women with vocal training, larger mean closing quotients and MFDRs were found as compared to the untrained subjects. An increase in both the closing quotient and MFDR seems contradictory, considering a higher closing velocity of the vocal folds in a longer time period. An explanation might be found in the higher ac flow values of trained subjects compared to the untrained ones. From studies investigating the effect of singing style on the voice source, it is well known that singers use less adductory forces, presumably resulting in larger vocal fold amplitudes and higher ac flows (24,29,30,34, 55,63). Larger amplitudes of vocal fold vibration may well lead to higher ac flow and MFDR values and larger closing quotients.

The only significant difference between the trained and untrained male subjects was for the speed quotient, with the trained subjects having larger values and, thus, a more asymmetrical pulse shape. Skewing of the waveform is, among others, determined by the relative difference between the duration of the opening and the duration of the closure of the vocal folds. The duration of the closure is influenced by factors such as Bernoulli forces. The more pronounced skewing of the waveform to the right in trained men might be caused by the slightly higher ac flow levels (p=0.045; see Table 3), glottal geometry (64) or by source filter interaction (inertia of the vocal tract) (50).

Knowledge about glottal function in trained persons was expected to give directions towards the definition of potentially "good" vocal behaviour. However, only a few differences in the parameters were found between trained and untrained subjects.

In the present study, the phonation tasks did not include specific singing tasks, which might have revealed differences between untrained and trained subjects.
Glottal Waveform Characteristics

in the sensorineural motor control of the voice source (33,65), possibly resulting in more pronounced differences in GVVW.

Sound pressure level and intra oral pressure Apart from the influence of intensity conditions (soft, normal, loud) on GVVW characteristics, which has already been discussed in the previous sections, the influence of SPL was also investigated within the subgroups. Twelve subgroups were created according to gender, status of vocal training and intensity condition. The influence of SPL on GVVW parameters is very clear (see Tables 3 and 4). There is a strong positive relationship between subglottal pressure ($P_{sub}$) and SPL. An increment in $P_{sub}$ is explained both by an increase of glottal flow and glottal resistance. The increase in flow leads to higher ac flows and, in specific conditions, to higher average flows, while on the other hand the increase in adductory forces, expressed by the glottal resistance, induces an increase in closed quotient and a decrease in minimum flow. These combined effects produce varying closing quotients, decreasing speed quotients in men and exponentially increasing MFDR values. While an increment in SPL is positively related to the closed quotient, $P_{sub}$ itself, as the force that drives the vocal folds apart, has a negative relation with the closed quotient in men.

CONCLUSIONS

Replication of data is important to provide verification of suggested processes or hypothesized functioning of systems (66). In this study glottal functioning was investigated in relation to the factors vocal training, gender and intensity condition, and the variables SPL, fundamental frequency, IOP, and age.

Compared to previous investigations, this study found higher average absolute values of the flow-based parameters ac flow and MFDR. These differences are related to the higher mean SPL values measured in the present study, as compared to previous studies. Other reasons for the observed differences might be the phonatory task contents, equipment or parameter extraction algorithms. Instead of using a word or a sentence, as in the present study, most of the previous studies employed the CVC sequence /bæpbæp/ to acquire glottal flow characteristics. To avoid bias influence of task content, uniformity in phonation tasks is recommended in order to facilitate the use of exchangeable data bases for frames of reference. Before universally accepting either set of phonation tasks, it should be thoroughly analyzed for its representability of normal vocal fold function. Another concern deals with equipment. Previous investigations revealed an important influence of low pass filter settings on resulting parameter values. Low pass filter settings should be
standardized to facilitate making comparisons between investigations. In this respect, finally, parameter extraction should also be performed according to widely accepted guidelines.

From the results of the present study we conclude that voice function basically does not differ between subjects with vocal training and untrained subjects; however differences do exist regarding opening and closing of the vocal folds in a glottal cycle, as well as the velocity of these dynamic events. A phonation task illustrating appropriate singing abilities of the voice source in trained subjects, however, was missing. Such a task might have revealed voice source adjustments which were not obtained in the present study. Because of no differences in flow-based parameters and closed quotient between the trained and the untrained subjects, no statement can be made about a possible "good" vocal behaviour. By way of epidemiologic definition, abnormal voice production, however, is reflected in deviations from normative values of these parameters. Depending on the direction of the deviations, hyperfunctional or hypofunctional voicing can be observed. More glottal flow measurements should be performed to make a further differentiation within these main categories possible.

A number of differences were established between glottal waveform characteristics of men and women. The observed differences can be explained by gender-related differences in anatomical constitution. Differences between men and women also exist in their strategy for varying SPL and \( F_0 \) by adjusting phonatory mechanisms, as reflected in GVVW characteristics. The differences in GVVW between men and women also provide a possible distinction in voice source spectrum, which makes speech, apart from pitch, characteristic for men and women.

References

Glottal Waveform Characteristics

58. Åkerlund L, Gramm P. Average loudness levels, mean fundamental frequency, and subglottal pressure: Comparison between female singers and nonsingers. Voice 1994;8:263-70.
Glottal Waveform Characteristics

64. Titze I. Parameterization of the glottal area, glottal flow, and vocal fold contact area J Acoust Soc Am 1984;75:570-80.