# Relationship Between Subglottal Pressure and Sound Pressure Level in Untrained Voices

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**Summary: Objectives.** Subglottal pressure ($P_s$) is strongly correlated with sound pressure level (SPL) and is easy to measure by means of commonly available equipment. The SPL/Ps ratio is strongly dependent on the efficiency of the phonatory apparatus and should be of great relevance to clinical practice. However, published normative data are still missing.
**Method.** The subjects produced sequences of the syllable [pæ], and $P_s$ was measured as the oral pressure during the [p] occlusion. The $P_s$ to SPL relationship was determined at four pitches produced by 16 female and 15 male healthy voices and analyzed by means of regression analysis. Average correlation between $P_s$ and SPL, average SPL produced with a $P_s$ of 10 cm $H_2O$, and average SPL increase produced by a doubling of $P_s$ were calculated for the female and for the male subjects. The significance of sex and pitch conditions was analyzed by means of analysis of variance (ANOVA).
**Results.** Pitch was found to be an insignificant condition. The average correlation between $P_s$ and SPL was 0.83 and did not differ significantly between the female and male subjects. In female and male subjects, $P_s = 10$ cm $H_2O$ produced 78.1 dB and 80.0 dB SPL at 0.3 m, and a doubling of $P_s$ generated 11.1 dB and 9.3 dB increase of SPL. Both these gender differences were statistically significant.
**Conclusions.** The relationship between $P_s$ and SPL can be reliably established from series of repetitions of the syllable [pæ] produced with a continuously changing degree of vocal loudness. Male subjects produce slightly higher SPL for a given pressure than female subjects but gain less for a doubling of $P_s$. As these relationships appear to be affected by phonation type, it seems possible that in the future, the method can be used for documenting degree of phonatory hypofunction and hyperfunction.
**Key Words:** Subglottal pressure–SPL–Female and male voices.

## INTRODUCTION

Subglottal pressure ($P_s$) is known to be a strong predictor of sound pressure level (SPL).[1] Moreover, it can be assumed that the relationship between the two represents an important aspect of phonation efficiency and thus would be clinically relevant; a voice producing a low SPL with a given $P_s$ is likely to need to spend more effort than a voice that obtains a higher SPL for the same $P_s$. Because the logarithm of $P_s$ mostly shows a linear relationship with SPL, the relationship between them can be quantized in terms of an equation representing the trend line. This relationship has been analyzed in several studies.[2,3] It possesses two relevant characteristics, its intercept, for example, the SPL obtained for a given $P_s$ value, and its slope, for example, the SPL increase produced by a doubling of $P_s$.

Several methods have been used for measuring $P_s$. A direct method is by inserting a needle through the trachea. This method has been used in few studies, presumably because of its invasive nature. For the same reason, several alternative methods have been developed. Schutte[3] measured the pressure in an esophageal balloon, which he compensated for lung volume. In the study by Tanaka and Gould,[4] $P_s$ was measured indirectly by means of body plethysmograph. The most common method is to estimate $P_s$ from the intraoral pressure during [p] occlusion.[5–8]

Schutte[3] analyzed airflow, $P_s$, and SPL in 63 healthy voices and 67 patients suffering from various voice pathologies. He found a great interindividual scatter of the SPL obtained for a given $P_s$. This was also noted by Sundberg et al.[6] On the other hand, Tanaka and Gould[4] found a rather small interindividual variation of the relationship between flow, $P_s$, and SPL in an investigation of 10 healthy voices, thus suggesting that the $P_s$ to SPL relationship is clinically useful. For the dysphonic voices, Schutte[3] noted that a given $P_s$ produced lower SPL values than for the healthy voices. Gramming[9] made a similar observation for 10 female and 10 male patients suffering from nonorganic dysphonia. This is a strong support for the previously mentioned assumption that the relationship between $P_s$ and SPL is clinically relevant.

The slope of the trend line is another measure of potential clinical relevance. This parameter can be quantized in terms of the SPL gain generated by a doubling of $P_s$. Schutte[3] found that in healthy voices, a doubling of $P_s$ yielded an average SPL increase of 10 dB for women and 9 dB for men. Similar results have been found in subsequent studies; 9 dB by Tanaka and Gould,[4] 10 dB by Sundberg et al,[6,10] whereas 13 dB was reported by Holmberg et al.[7]

Prior studies have found that the doubling of $P_s$ may be affected by whether the speaker is male or female. Thus, Schutte[3] noted that a doubling in $P_s$ produced a 10-dB increase of SPL in female voices and a 9-dB increase in male voices. After the study by Schutte, this sex difference has not been studied in great detail. Hence, although the difference he observed was small, it cannot be excluded that sex is a relevant factor for normative data on the $P_s$/SPL relationship.

Accepted for publication March 17, 2015.
This work was presented at the Annual Symposium Care of the professional voice, Philadelphia, May 28–June 1, 2014.
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Journal of Voice, Vol. 30, No. 1, pp. 15-20
0892-1997/$36.00

http://dx.doi.org/10.1016/j.jvoice.2015.03.006

Other factors of potential relevance to this relationship are vowel and $F0$. Plant and Younger[11] studied the relationship between $F0$, $P_s$, and SPL in the syllables [pa] and [i] as produced by nine men with healthy voices. Individual variation was considerable, but they noted that around a certain $F0$, changes in $P_s$ had a particularly large impact on SPL in many participants. This is not surprising. SPL mostly equals the SPL of the strongest spectrum partial, the amplitude of which is heavily influenced by its frequency distance to the first formant ($F1$).[12] $F1$ for the vowel [i] lies in the vicinity of 250 Hz, so that for an $F0$ near 110 Hz, the second partial would be quite close to $F1$. Thus, vowel quality and $F0$ should play an important role in the $P_s$/SPL relationship and must be taken into account in an attempt to create normative data. Also, limiting data to one single vowel is preferable.

Summarizing, the $P_s$/SPL relationship has been analyzed in several earlier studies but mostly with few subjects or few $P_s$ values. As this relationship seems relevant to voice function, it seemed worthwhile to analyze it in greater detail. Thus, the aim of the present study was to examine this relationship on a larger sample, with controlled $F0$, sex and vowel quality, and over a wide $P_s$ range.

## METHOD

Sixteen women between 26 and 36 years (Mean, 29 years; standard deviation [SD], 3 years) and 15 men between 25 and 47 years (Mean, 29 years; SD, 6 years) volunteered as subjects. Inclusion criteria were age <50 years and no reported voice problems at the time of the study. Most subjects had none or only a modest experience of singing.

The subjects were asked to repeatedly pronounce sequences of the syllable [pæ] with a gradually increasing or decreasing degree of vocal loudness that ranged from the loudest to the softest possible. They were asked to keep $F0$ constant. They produced four such sequences at four pitches, equally spaced within one octave, 175, 220, 277, and 350 Hz for women and 110, 138, 175, and 220 Hz for men, that is, in the normal ranges for the female and the male speech. The vowel [æ] was chosen because $F1$ is far above the highest $F0$ analyzed.

Oral pressure during the [p] occlusions was measured by a pressure transducer (Glottal Enterprises 162, Syracuse, NY) attached to a thin plastic tube, inner diameter 4 mm, that the subjects held in the corner of their mouths. The pressure signal was sent to a sound card (TEAC RD 200 PCM, US Instrument Services, Southlake, TX) and recorded in the Soundswell program. It was calibrated by recording pressure values measured by means of a manometer; the pressure values were announced on the recording.

The audio signal was recorded with a headset microphone (DPA 4066-C, DPA Microphones A/S, Alleroed, Denmark) at a measured distance of 12 cm from the mouth. The microphone was attached to a preamp (Symetrix SX202, Symetrix Inc., W. Lynnwood, WA) and the signal was sent to sound card (TEAC RD 200 PCM) and recorded in the Soundswell program. Calibration of SPL was made in each recording session by sustaining a vowel sound, the SPL of which was measured by a sound level meter (Ono Sokki LA 210, Yokohama, Japan) at the recording microphone; measured SPL value was announced in recording.

## ANALYSIS

The calibrations of SPL and intraoral pressure were copied into the end of each recorded file, and the recorded intraoral pressure voltage was calibrated using the Swellcal module in the Soundswell program.

A prerequisite of reliable values of the intraoral pressure is that the pressure signal reaches a plateau during the [p] occlusion.[13] Tilting pressure peaks, indicating a changing intraoral pressure during the [p] occlusion, were discarded. The pressure value was taken from a point in time when the pressure signal showed a plateau.

Intraoral pressure and time for each [pæ] syllable were extracted to an excel spreadsheet. SPL data were extracted to a separate file in Soundswell. In each syllable, the mean SPL was measured during first half of the vowel by means of the histogram module of the Soundswell program and was extracted to the spreadsheet together with its time coordinate. In this way, pairs of estimated $P_s$ values and SPL values were obtained.

In some cases, the subject changed the pitch substantially with vocal loudness. Therefore, the pitch of each syllable was controlled. In the case of 34 of the 1513 syllables recorded, $F0$ was >1 semitone off the intended value. These cases were discarded.

## STATISTICAL ANALYSIS

SPL mostly showed a logarithmic relationship to $P_s$. Figure 1 shows a typical example. Thus, the relationship could be approximated with an equation of the type

$$\mathrm{SPL} = \mathrm{k} \times \log(P_s) + \mathrm{I}$$

where k and I are constants.

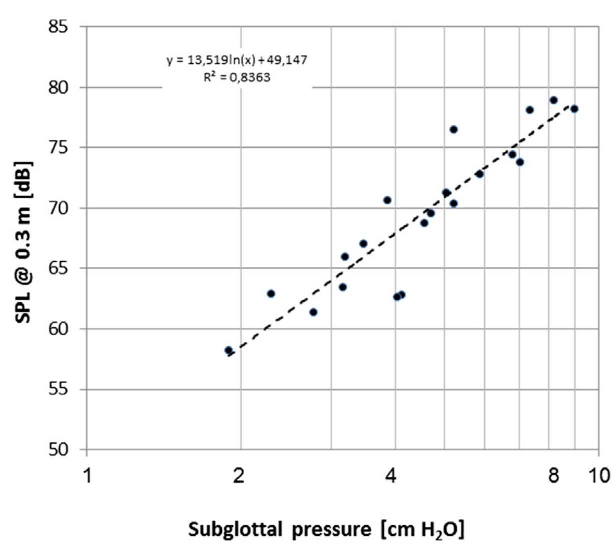


**FIGURE 1.** Typical example of the relationship between subglottal pressure and sound pressure level (SPL). The equation refers to the trend line (*dashed*).

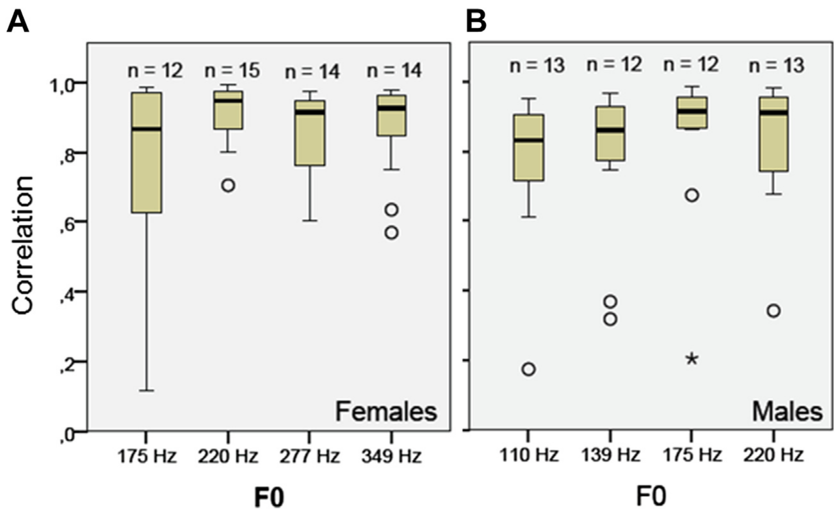


**FIGURE 2.** Estimated correlation between log ($P_s$) and SPL for the female and male subjects (A and B) measured at the indicated $F0$ values; n refers to the number of subjects. Sequences with less than five measurable $P_s$ and SPL values were excluded. *Circles* represent outlier values, *star* represents extreme values.

For each subject and pitch, such a regression analysis was carried out and correlation, slope, and intercept were determined. From these data, two values were derived (1) the increase of SPL for a doubling of $P_s$ ($\Delta SPL_{2Ps}$) and (2) the SPL value predicted by the equation for a $P_s$ of 10 cm $H_2O$ ($SPL_{10\ cm\ H2O}$).

The regression analysis becomes unreliable when based on data obtained from few syllables or from a narrow pressure range. For this reason, sequences with less than five syllables with measurable $P_s$ and SPL were discarded. As a consequence, of the 114 sequences, four were excluded for the female subjects and four for the male subjects. In the remaining material, the median number of syllables produced by a subject at a given $F0$ was nine for the women (first quartile = 7, third quartile = 14) and 14 for the men (first quartile = 9, third quartile = 22).

An analysis of variance (ANOVA) was run in *SPSS* (Quarry Bay, HongKong) to examine whether statistically significant group differences existed between different $F0$ and between the female and the male subjects with regard to correlation, $\Delta SPL_{2Ps}$, and $SPL_{10\ cm\ H2O}$. Also, tested was if the syllable sequences produced with increasing $P_s$ yielded the same results as those produced with decreasing $P_s$.

## RESULTS

The sequences produced with increasing and decreasing loudness generated values of correlation, $\Delta SPL_{2Ps}$, and $SPL_{10\ cm\ H2O}$ that did not differ significantly. Therefore, these data were pooled in the subsequent analyses.

The left and right panels in Figure 2 shows box plots for the correlation at different pitches for the female and male subjects. The correlations are quite high, and significant differences were found neither between $F0$, nor between sexes. The mean correlation across $F0$ and sex was 0.83 (SD, 0.19).

Figure 3 shows the corresponding results for $\Delta SPL_{2Ps}$. Significant differences were found between $F0$ neither for women

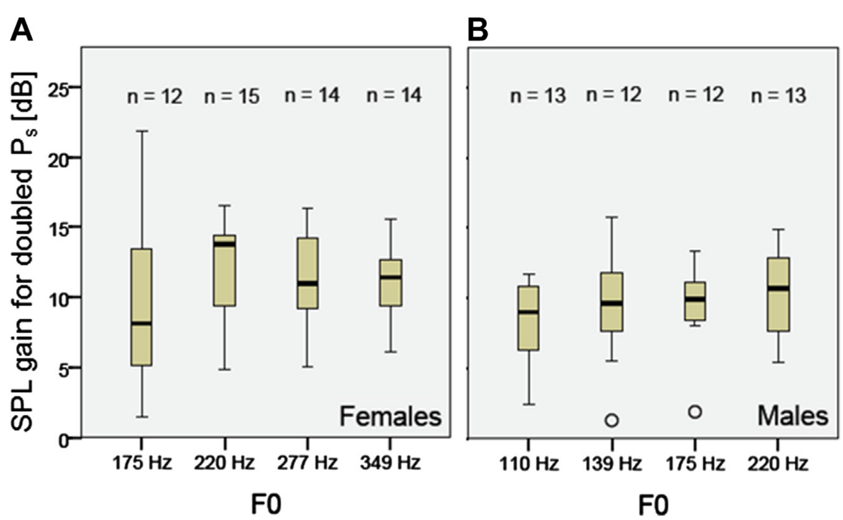


**FIGURE 3.** SPL increase for a doubling of $P_s$ for the female and male subjects (A and B) measured at the indicated $F0$ values; n refers to the number of subjects. Sequences with less than five measurable $P_s$ and SPL values were excluded. *Circles* represent outlier values.

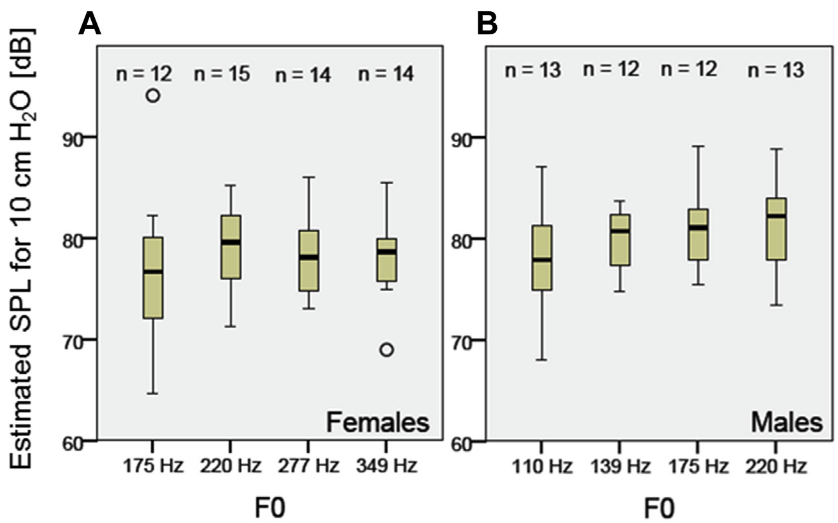


**FIGURE 4.** Estimated SPL at a $P_s$ of 10 cm $H_20$ with microphone distance calculated to 0.3 m for the female and male subjects (A and B) measured at the indicated *F*0 values; n refers to the number of subjects. Sequences with less than five measurable $P_s$ and SPL values were excluded. *Circles* represent outlier values.

nor for men. However, the $\Delta SPL_{2Ps}$, averaged across *F*0, was 11.1 dB (SD, 4.2 dB) for the women which differed significantly ($P < 0.02$) from the values found for the men, 9.3 dB (SD, 3.3 dB).

Figure 4 shows the results for the $SPL_{10\ cm\ H2O}$ for the female and male subjects. No significant differences were found between *F*0, neither for women nor for men. However, the female participants yielded a significantly ($P < 0.04$) higher mean $SPL_{10\ cm\ H2O}$ than the male participants, 78.1 dB (SD, 5.0 dB) and 80.0 dB (SD, 4.3 dB), respectively.

## DISCUSSION

Our results have shown that the $P_s$ estimated from the oral pressure during the occlusion for the consonant [p] is closely related to the SPL. Thus, the relationship can be described in terms of two values, the SPL produced with a pressure of 10 cm $H_2O$ or $SPL_{10\ cm\ H2O}$, and the SPL gain produced by a doubling of $P_s$ or $\Delta SPL_{2Ps}$. The values vary negligibly with pitch and was reasonably similar between subjects, although the $SPL_{10\ cm\ H2O}$ was slightly lower and the $\Delta SPL_{2Ps}$ was slightly greater for the female subjects than for the male subjects.

Our results were based on [pæ] sequences containing at least five reliable pressure peaks. This minimum number of peaks seemed sufficient; limiting the analysis only to sequences that contained at least 10 peaks yielded mean values that deviated no more than 1 dB or less from those obtained from sequences containing at least five peaks. This was true both for the values obtained for $SPL_{10\ cm\ H2O}$ and for the values of $\Delta SPL_{2Ps}$. This suggests that our results based on at least five acceptable pressure peaks were reliable.

The reliability of the trend lines is also affected by the $P_s$ range, which in some cases was quite narrow. This is demonstrated in Table 1, showing the variation of the correlation coefficient *r*, the $SPL_{10\ cm\ H2O}$ and the $\Delta SPL_{2Ps}$ measured for [pæ] sequences produced with narrow and wide pressure ranges (less than 4 cm $H_2O$ and wider than 8 $H_2O$). However, although the values of the SD were much greater for the narrow range, the means remained similar.

The $\Delta SPL_{2Ps}$ averaged across female and male voices was found to be 11.1 dB (SD, 4.2 dB) and 9.3 dB (SD, 3.3 dB), respectively. As can be seen in Table 2, these data are in good agreement with those reported in earlier studies. This applied also to the $SPL_{10\ cm\ H2O}$, as listed in the same table. Interestingly, the subjects in the investigation by Sundberg et al[6] yielded the highest average. In any event, our observations seem to be in good agreement with previously published results.

Some subjects had difficulties to keep the same *F*0 when they varied vocal loudness. However, within sexes, the $\Delta SPL_{2Ps}$ and the $SPL_{10\ cm\ H2O}$ did not vary significantly between the *F*0 values concerned. It would be relevant that an increase of *F*0 is typically accompanied by an increase of SPL. In any event, it seems a minor problem if a subject changes *F*0 as function of vocal loudness. Nevertheless, it might be advisable to avoid extreme *F*0 values that the subjects have difficulties producing.

In the graphs shown in Figures 2 and 3, some outlier values were observed. Such values could have been caused by several factors. In many cases, outliers in $\Delta SPL_{2Ps}$ and in

**TABLE 1.**
**Variation of the Correlation Coefficient *r*, the $\Delta SPL_{2Ps}$ and the $SPL_{10\ cm\ H2O}$ Measured for [pæ] Sequences Produced With $P_s$ Range Less Than 4 cm $H_2O$ and $P_s$ Range Wider Than 8 $H_2O$**

| | $P_s$ Range <4 cm $H_2O$ | | $P_s$ Range >8 cm $H_2O$ | |
|---|---|---|---|---|
| Parameter | Mean | SD | Mean | SD |
| *r* | 0.70 | 0.22 | 0.91 | 0.10 |
| $\Delta SPL_{2Ps}$ (dB) | 9.5 | 5.4 | 10.2 | 2.9 |
| $SPL_{10\ cm\ H2O}$ (dB) | 77.7 | 5.9 | 79.1 | 3.5 |

**TABLE 2.**
**Values of SPL Gain for Doubled Subglottal Pressure ($\Delta SPL_{2Ps}$) and SPL at 0.3 m Microphone Distance Obtained From 10 cm $H_2O$ Subglottal Pressure ($SPL_{10\ cm\ H2O}$) Reported in Previous Investigations**

| | Females | | | | | Males | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Study | n | $\Delta SPL_{2Ps}$ (dB) | SD | $SPL_{10\ cm\ H2O}$ (dB) | SD | n | $\Delta SPL_{2Ps}$ (dB) | SD | $SPL_{10\ cm\ H2O}$ (dB) | SD |
| Schutte (1980) (healthy voices) | 30 | 10 | — | 77.9 | — | 33 | 9 | — | 78.8 | — |
| Tanaka and Gould (1983) | 4 | 9*,† | — | — | — | 6 | 9*,† | — | — | — |
| Perkell et al (1994) | 22 | 13*,† | | | | 25 | 13*,† | | | |
| Sundberg et al (1993) | — | — | — | — | — | 10 | 10 | — | 88.6 | 6 |
| Sundberg et al (1999) | — | — | — | — | — | 10 | 10 | — | — | — |
| Present study | 15 | 11.1 | 4.2 | 78.1 | 5 | 13 | 9.3 | 3.3 | 80.0 | 4.3 |

* Males and females results pooled.
† Calculated from three loudness levels.

$SPL_{10\ cm\ H2O}$ were associated with a low number of data points and/or, in particular, a narrow pressure range. In addition, uncomfortable pitch occasionally tended to produce outlier values of the same parameters, particularly for the female voices at the lowest pitch. The reason would be that subjects changed phonation type toward hyperfunctional or hypofunctional, when facing difficult phonatory tasks; hyperfunctional phonation would produce lower $SPL_{10\ cm\ H2O}$ than a more neutral phonation type.[3] Likewise, $\Delta SPL_{2Ps}$ will decrease if the phonation mode is growing more hyperfunctional with increasing $P_s$. For differentiating between hyperfunctional and neutral phonation, a simple spectrum analysis may help because hyperfunctional voice is characterized by a weakened fundamental and strong overtones in the high frequency range.

Another factor affecting the regression is the fact that the SPL value is mostly determined by one single harmonic.[12,14] Furthermore, the amplitudes of spectrum partials are heavily influenced by their distance to the closest formant. Mostly, it is the partial closest to the first formant that is the strongest in the spectrum and which thus sets the SPL value. Measurements on the MADDE synthesizer (Svante Granqvist, KTH, freeware available at www.Tolvan.com, last inspected January 30, 2015, Tolvan Data, Tyresö, Sweden) showed that the SPL for the $F0$ values concerned in the present study (110, 139, 175, 220, 278, and 350 Hz) may vary by no more than ±2 dB, depending on the distance between the first formant and the spectrum partial closest to it. Replacing SPL by the maximum flow declination rate of the flow glottogram, available after inverse filtering and representing the strength of the vocal tract excitation, would circumvent this problem.

Female subjects showed significantly lower values for $SPL_{10\ cm\ H2O}$ (78.1 dB) than male subjects (80.0 dB). On the other hand, women showed a significantly higher value of $\Delta SPL_{2Ps}$ (11.1 dB) than men (9.3 dB). The reasons for these differences remain an open question, but our observations nicely corroborate the findings reported by Schutte (1980). In any event, these sex differences show that different normative data should be used for female and male voices.

The dependence of SPL on phonation type seems relevant from a clinical point of view. Schutte[3] noted that a given $P_s$ produced lower SPL values in dysphonic than in healthy voices, and Gramming[9] made similar observations for patients suffering from nonorganic dysphonia. This suggests that the method developed in the present investigation possesses a strong potential as a simple and inexpensive tool for clinical applications. For example, it would be worthwhile to use it on different groups of dysphonic voices and for screening purposes.

## CONCLUSIONS

As expected, this study showed that the SPL produced by a voice on a given vowel is strongly related to $P_s$. The relationship between $P_s$ and SPL can be reliably established from series of repetitions of the syllable [pæ] produced with a continuously changing degree of vocal loudness. Our results showed that male subjects produced slightly higher SPL for a given pressure than female subjects but gained somewhat less for a doubling of $P_s$. These differences were statistically significant, thus indicating the need to use different normative data for female and male subjects. As the relationship is affected by phonation type, it seems likely that the method can be clinically useful for documenting degree of phonatory hypofunction and hyperfunction.

### Acknowledgments

This investigation is based on coauthor S.B.'s thesis work at the Department of Neuroscience at the Uppsala University, carried out under the supervision of coauthor J.S. The authors are grateful for lab and office resources provided by the Department of Speech, Music, and Hearing at KTH Royal Institute of Technology.

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