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BREATHING BEHAVIOR DURING SINGING

Johan Sundberg

Abstract

Together with Curt von Euler and the late Rolf Leanderson, the author has carried out a series of investigations of the breathing behavior during the last decade. This article presents the picture of phonatory breathing in singing that has emerged from this research.

Subglottal pressure is determined by muscular forces, elasticity forces, and gravitation. The phonatory function of the breathing apparatus is to provide a subglottal pressure. Both in singing and speech this pressure is adjusted according to the intended vocal loudness, but in singing it has to be tailored also to pitch; higher pitches needing higher pressures than lower pitches. As subglottal pressure affects pitch, singers need to develop a quite virtuosic breath control. Some singers activate the diaphragm only during inhalation and for reducing subglottal pressure at high lung volumes, while other singers have been found to co-contract it throughout the breath phrase.

The tracheal pull, i.e., the pulling force exerted by the trachea on the larynx, is a mechanical link between the breathing and phonatory systems. The magnitude of this force depends on the level of the diaphragm in the trunk, i.e., on the lung volume, but it is also probably increased by a co-contracting diaphragm. The pedagogical implications of these findings are discussed.

INTRODUCTION

By experience, voice therapists and singing teachers know very well that an efficient way to improve phonation is to improve the breathing technique. Yet, the breathing technique can only generate an overpressure of air in the lungs. Such an overpressure is needed for bringing the vocal folds into vibration. It is not at all clear why the way, in which the overpressure was achieved, should affect the vocal-fold function. How do the folds know if the overpressure was created by a contraction of the abdominal wall or of the rib cage? And why should that matter?

Lately, several advances have been made in our understanding of the breathing apparatus and its significance to singing. After the pioneering investigations by Proctor, Mead, and associates, summarized in Proctor (1980), important contributions have been made by Hixon and associates (Hixon, 1987) and during the eighties, the author had the privilege of carrying out a series of investigations of singers' breathing together with the neurologist Curt von Euler and the late phoniatrician Rolf Leanderson (Leanderson, Sundberg, & von Euler, 1987; Sundberg, Leanderson, & von Euler (1989).

In this overview, I will first review the anatomy and physiology of the breathing apparatus, and then summarize the picture that has emerged from this research.

ANATOMY

Phonation requires that the air pressure inside the lungs is raised. This air pressure serves as the main physiological control parameter for vocal loudness: the higher the pressure, the louder. The elevation of the lung pressure, henceforth the *subglottal pressure*, is achieved by decreasing the volume of the rib cage, in which the lungs are

hanging. There are three different forces that contribute to this volume: Muscular forces, elasticity forces and gravitation (see the Table below).

FORCES BEHIND SUBGLOTTAL PRESSURE		
	INHALATORY	EXHALATORY
MUSCLES	EXT.INTERCOST. DIAPHRAGM	INT.INTERCOST. ABD. WALL
ELASTICITY	LOW LV: RIB CAGE	HIGH LV: RIB CAGE LUNGS
GRAVITATION	UPRIGHT/SITTING	SUPINE/HANGING

Muscle forces

Some of these forces are produced by muscles. The *intercostal muscles* join the ribs, as shown in Fig. 1. The inspiratory intercostals widen the rib cage by lifting the ribs, and so provide an inspiratory muscle force. The expiratory intercostal muscles decrease the rib cage volume.

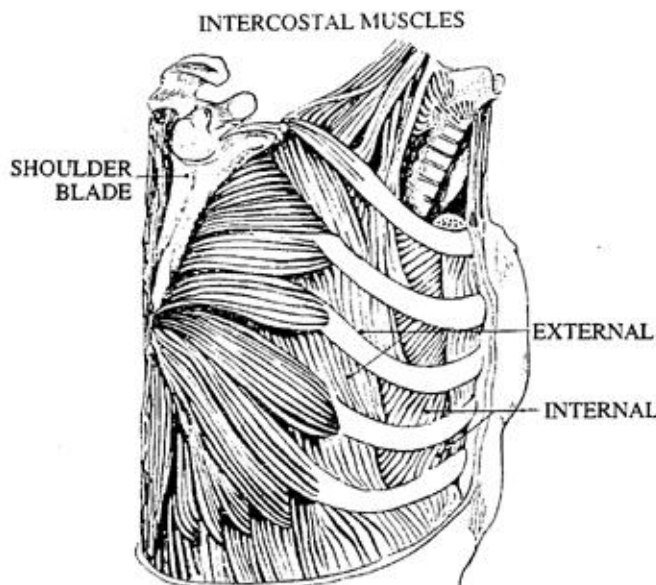


Fig. 1. External and internal intercostal muscles that exhalift and compress the ribs during inspiration and expiration, respectively.

The *diaphragm* is another important breathing muscle. When relaxed, it assumes the shape of a vault pointing into the rib cage. Its edge inserts into the lower contour of the rib cage, as is shown in Fig. 2. When contracting, it is flattened so that the floor in the rib cage is lowered, and its volume is increased. Thus, the diaphragm is an inhalatory muscle.

With the body in an upright position, the diaphragm muscle can be restored to its upward-bulging shape only by means of the *abdominal wall muscles*, shown in Fig. 3. By contracting, these muscles press the abdominal content upward, into the rib cage, so that the diaphragm, the

floor in the rib cage, moves upward and the lung volume is decreased. Therefore, they are muscles for exhalation.

The inspiratory and expiratory intercostals represent a paired muscle group that produces both inspiratory and expiratory forces. The abdominal wall and the diaphragm represent a similar paired muscle group for inhalation and exhalation. It is possible to breath using one or both of these muscles groups. In costal breathing, only the intercostals are used for respiration, and in ventricular breathing only the diaphragm and abdomen are used as respiratory muscles.

The volume of the abdominal content cannot easily be altered appreciably. Therefore, when the diaphragm contracts, it presses the abdominal content downward which, in turn, presses the abdominal wall outward. Actually, expansion of the

abdominal wall during inhalation is a safe sign that the diaphragm was activated. If, on the other hand, the abdominal wall remains flat during inspiration, this means that only the intercostal muscles were used. An expansion of the abdominal wall during phonation is not necessarily a sign of diaphragmatic activation. It may equally well result from the increased lung pressure that is required for phonation. An overpressure in the lungs is transmitted downward through a relaxed diaphragm. Hence, the subglottic pressure will exert a pressure on the abdominal wall. By contracting the abdominal wall muscles, this expansion can be avoided.

ABDOMINAL WALL MUSCLES

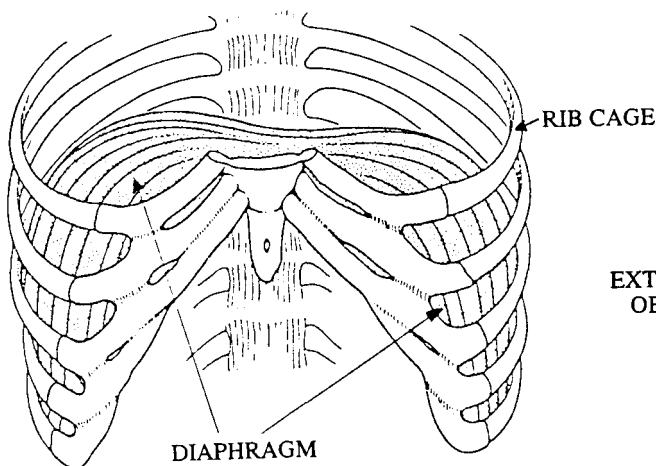


Fig. 2. Diaphragm muscle, the mobile floor of the rib cage. By contracting the floor lowers causing an inspiratory force.

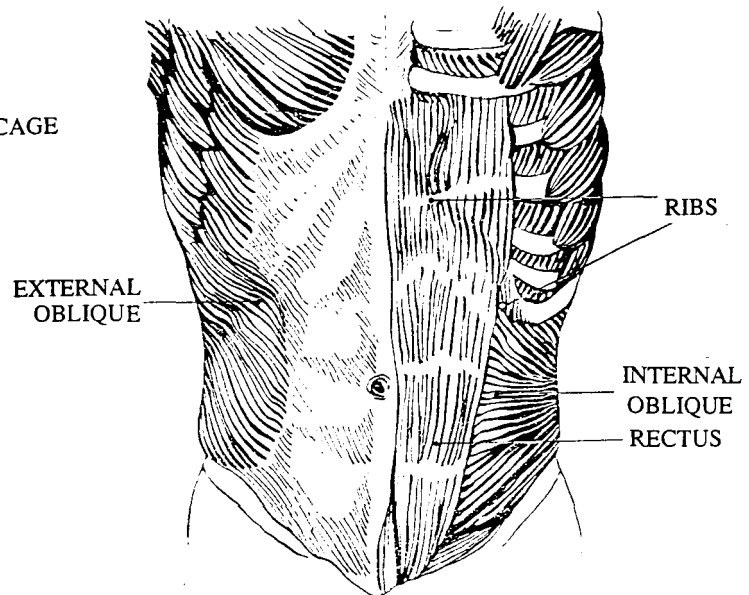


Fig. 3. Abdominal wall muscles that moves the abdominal wall inward so that the abdominal content moves toward the rib cage, thus causing an expiratory force.

Elasticity forces

Apart from these muscular forces, there are also *elasticity* forces. The magnitude of these recoil forces depends on the amount of air contained in the lungs, or the lung volume. The effects and their dependence on lung volume are illustrated schematically in Fig. 4.

The lungs always attempt to shrink, somewhat as rubber balloons, when hanging inside the rib cage. They are prevented from doing so by the fact that they are surrounded by a vacuum. The lungs exert an entirely passive expiratory force that increases with the amount of air inhaled. According to Proctor (1980), this force corresponds to a pressure that may amount to around 20 cm H₂O after a maximum inhalation. After a deep exhalation, it is only a few cm H₂O.

If the rib cage is forced to deviate from its rest volume, e.g., because of a contraction of the intercostal muscles, it strives to return to the rest volume. Therefore, the rib cage produces elastic forces. After a deep costal inhalation, a passive expiratory force is generated that may produce an overpressure of about 10 cm H₂O. Con-

versely, if the rib cage is squeezed by the expiratory intercostal muscles, it strives to expand again to reach the rest volume. After a deep costal exhalation, the resulting passive expiratory force may produce an underpressure of about -20 cm H₂O.

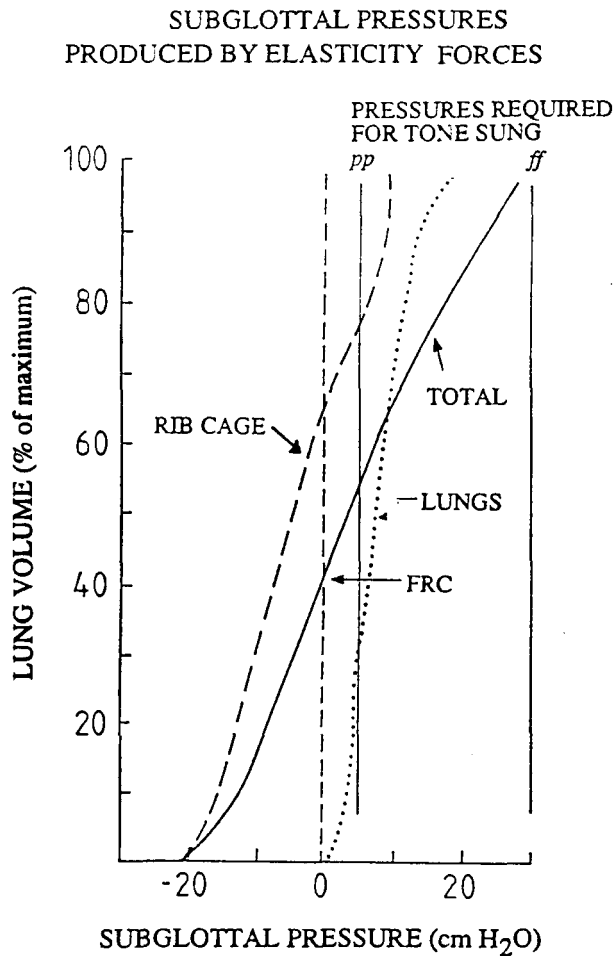


Fig. 4. Subglottal pressures caused by the lung volume dependent elasticity forces of the breathing apparatus. The elasticity of the lungs is always an exhalatory force, while the elasticity of the rib cage is exhalatory at large lung volumes and inhalatory at low lung volumes. The lung volume where inhalatory and exhalatory forces balance each other is called the functional residual capacity, or FRC. To maintain a constant subglottic pressure for a pp or a ff tone, the elasticity forces must be complemented by activation of the breathing muscles that strongly depends on the ever changing lung volume.

REGULATION OF SUBGLOTTAL PRESSURE

Above we have seen that subglottic pressure is dependent on the activity in different respiratory muscles plus the lung volume dependent passive elasticity forces, plus the posture dependent influence of gravitation. As illustrated in Fig. 4, the muscular activity required for maintaining a constant subglottic pressure is dependent on the lung volume because the elasticity forces of the lungs and the rib cage strive to raise or to lower the pressure inside the lungs, depending on whether the lung volume is

Gravitation forces

The air pressure in the lungs is affected also by a third kind of force: gravitation. When we are in an upright position, the abdominal content is pulling the diaphragm downward and hence produces an inhalatory force. If we lie down on our back or if, for some reason, we are hanging upside-down, gravitation strives to move the abdominal content into the rib cage and so produces an exhalatory force.

As there are both exhalatory and inhalatory elasticity forces which depend on lung volume, there is a particular lung volume value for the respiratory mechanism, at which the passive inspiratory and expiratory forces are equal. This lung volume value is called the functional residual capacity (FRC). As soon as the lungs are forced to depart from FRC by expanding or contracting, passive forces try to restore the FRC volume. This effect, by the way, is used when one tries to revive people by artificial breathing: the patient's chest is alternately squeezed and released; when released, elasticity produces an inhalatory force.

greater or smaller than the functional residual capacity, FRC. When the lungs are filled with a large quantity of air, the passive exhalation force is great, and it generates a high pressure. If this pressure is too high for the intended phonation, it can be reduced by a contraction of the muscles of inhalation. The need for this activity then gradually decreases as the lung volume decreases, and it reaches zero at the rest volume, because there, the passive exhalation forces cease. Beyond this point the muscles of exhalation must take over more and more, so that one compensates for the increasing inhalation force of the increasingly compressed rib cage.

Figure 4 also shows two subglottic pressures typically needed for producing a pianissimo (*pp*) note and a fortissimo (*ff*) note. It is evident that the demands for compensatory activity of inspiratory muscles are quite high when a note is to be sung *pp* after a maximum inhalation, and conversely, that a good deal of muscular expiration activity is required if a note is to be sung *ff* with lungs that contain only some small proportion of their full capacity.

When we speak, we generally use rather small lung volumes, typically the middle 50% of what is available (Watson & Hixon, 1985). Under these conditions, the elasticity forces are not very strong. In singing, it is often necessary to use a large portion of the vital capacity, starting with full lungs and ending with the lungs nearly depleted (Watson & Hixon, 1985). Under these conditions, the elasticity forces are considerable. At the same time, subglottal pressure must be varied with great precision. Therefore, the demands placed on the respiratory system in singing are high.

Subglottal pressure and loudness

Ideally, subglottal pressure is measured by inserting a fine needle into the trachea. This is obviously a rather intrusive method and not the only one possible. The lung pressure enters the mouth as soon as the glottis is open and the mouth is shut. This is exactly what happens when we pronounce the consonant [p]. Consequently, it is possible to measure the air pressure in the lungs also in the mouth during the [p]-occlusion (van den Berg, 1959; Rothenberg, 1968; Smitheran & Hixon, 1981). Another possibility that also causes very little discomfort is to measure the esophageal pressure. The subject then swallows a thin catheter or a rubber balloon into the esophagus (van den Berg, 1962; Draper, Ladefoged, & Whitteridge, 1962). The pressure thus captured does not correspond exactly to the subglottal pressure, because the contribution from the lung elasticity does not appear in the esophagus. At high lung volumes in particular, the esophageal pressure is, therefore, considerably lower than the subglottal pressure. This is a problem of minor concern if only changes of subglottal pressure are of interest.

As mentioned, subglottal pressure is the main physiological parameter for variation of vocal loudness. Fig. 5 illustrates this. It shows the sound level and the underlying subglottal pressure in a singer who alternates between *subito forte* and *subito piano* at a constant pitch. Both sound level and subglottal pressure are changed quickly and in synchrony between two rather stationary values such that square-wave-like patterns emerge. The louder portions of the tone are associated with higher pressures.

It is noteworthy that different individuals seem to need different subglottal pressures for achieving the same loudness. Fig. 6 illustrates this, showing the sound level obtained for a subglottal pressure of 10 cm H₂O by different male singers. The figure also shows the relevance of vocal technique: the sound level obtained in pressed

phonation, i.e., with an exaggerated glottal adduction, is much lower than in neutral phonation. Differences in vocal technique may not be the only reason for the inter-individual variation shown in the figure. It is equally possible that the vocal folds are stiffer in some individuals, and that this implies the need for higher subglottal pressures.

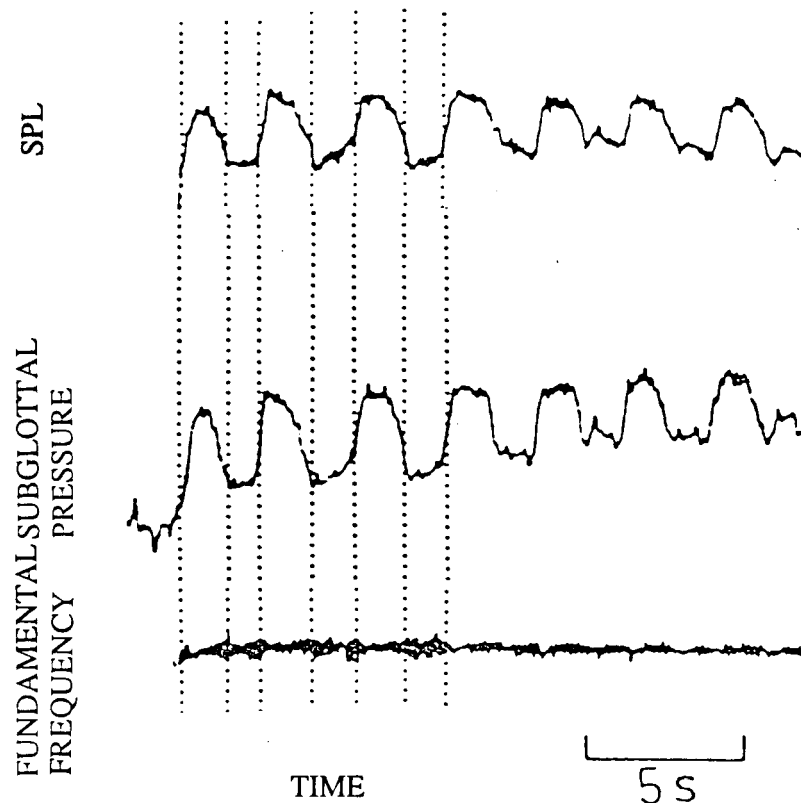


Fig. 5. Variation of subglottal pressure during variation of vocal loudness. The top curve shows sound level, the middle curve esophageal pressure, and the bottom curve fundamental frequency.

Subglottal pressure and pitch

In singing, variation of subglottal pressure is required not only when loudness but also when pitch is changed (Cleveland & Sundberg, 1985). When we increase pitch, we stretch the vocal folds. It seems that stretched vocal folds require a higher driving pressure than laxer vocal folds (Titze, 1989). Thus, higher subglottal pressures are needed for high pitches than for low pitches.

Figure 7 illustrates this. Here, the singer was performing a series of alternating rising and falling octaves. It can be observed that the higher pitch was produced with a much higher pressure than the lower pitch. The wrinkles in the pressure curve are signs of the happy fact that the subject was alive: they reflect his heart beats. The wrinkles in the fundamental frequency curve correspond to the vibrato.

Figure 8 shows the subglottal pressure of a professional baritone singing soft, medium, and loud ascending chromatic scales. It can be seen that pressure consistently rises with pitch. This relationship is typically found in singers. Subglottal pressure is always the main tool for loudness variation but for each pitch, the singer has to adjust the scale, working with high pressures at high pitches and low pressures at low pitches.

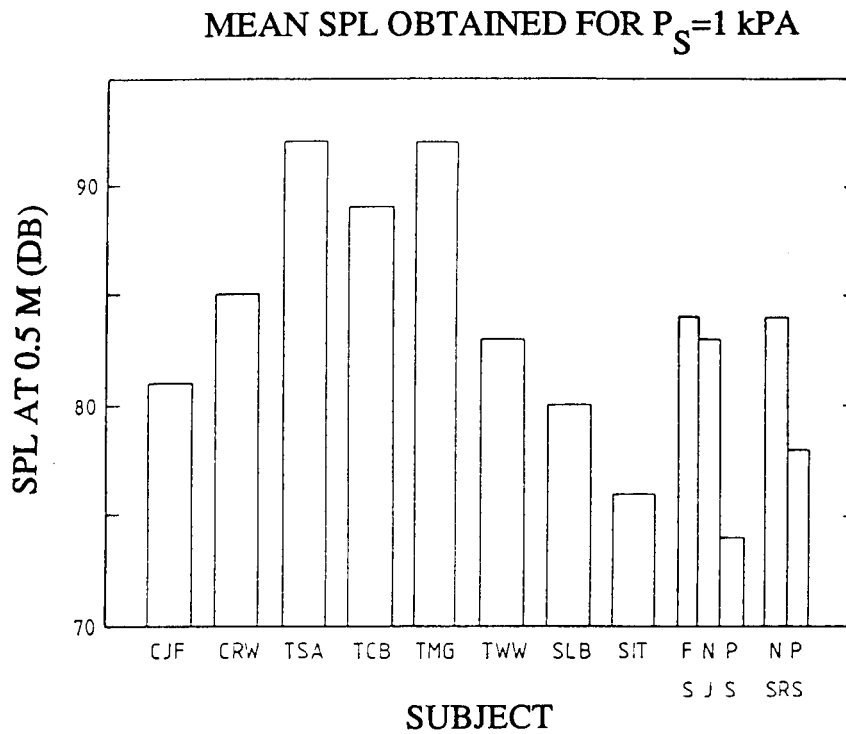


Fig. 6. Comparison of the sound level obtained by different singers for a subglottal pressure of 10 cm H_2O . The two subjects RS and JS used different modes of phonation: pressed and neutral, i.e., with and without exaggerated glottal adduction ; this had clear consequences for the result.

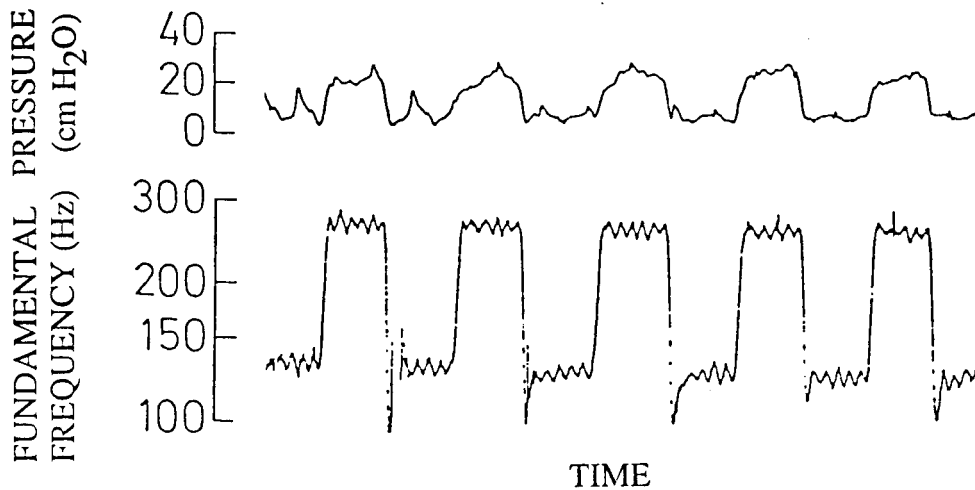


Fig. 7. Variation of subglottal pressure observed when a professional the singer performed a series of alternating rising and falling octaves. The top curve shows esophageal pressure, and the bottom curve fundamental frequency. The wiggles in the top curve reflect pressure variations caused by blood circulation in the aorta while those of the bottom curve depend on the vibrato.

The above has very important consequences for singers. They have to tailor the subglottal pressure for every note, taking into consideration both its loudness and its pitch. Thus, each new pitch has to be welcomed by its own pressure in the respiratory apparatus. Given the fact that pitches tend to change constantly and rather frequently in music, we can imagine that the breathing system keeps its owner busy during singing!

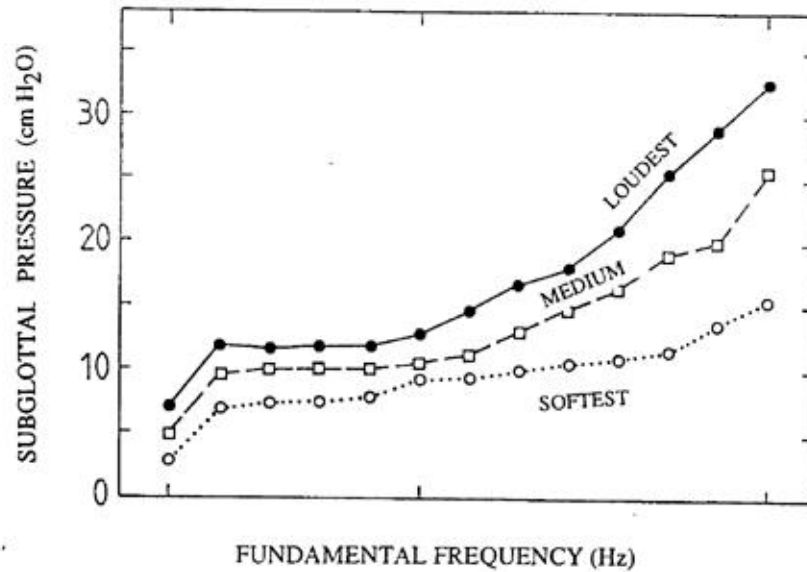


Fig. 8. Pitch and loudness dependence of subglottal pressure measured as oral pressure during [p]-occlusion for the tones in ascending chromatic scales from Eb3 to Eb4 sung at low, middle and high vocal loudness as sung by a professional male singer.

As if this were not enough, there is a musically highly relevant complicating effect of subglottal pressure. It affects the pitch: other things being equal, a raised subglottal pressure raises the pitch. This means that an error in the subglottal pressure is manifested not only as an error in loudness, which, perhaps, may be of limited concern, but also as an error in pitch, which, of course, may be a disaster for a singer.

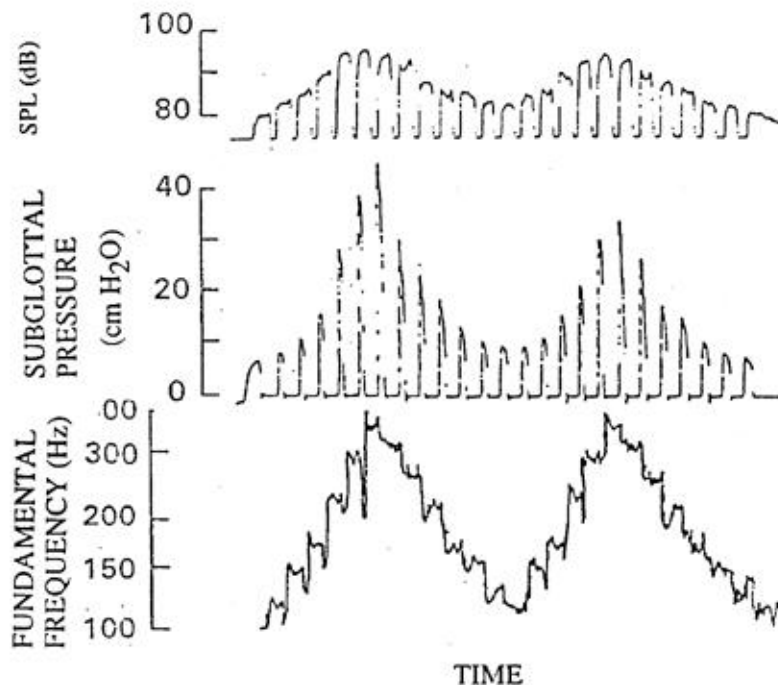


Fig. 9. Pitch and loudness dependent variation of subglottal pressure in singing. The top, middle and bottom curves represent sound level, oral pressure during [p]-occlusion, and fundamental frequency in a professional baritone singer performing an exercise with an ascending triad up to the duodecime on the tonic chord followed by a descending dominant seventh triad.

A singer must, therefore, tune subglottal pressure quite accurately in order to sing all notes in tune. Accordingly, one finds very well-formed subglottal pressure patterns in proficient singers. Fig. 9 illustrates this. It shows the pressures produced by a baritone singing an ascending triad on the tonic chord and a descending triad on the dominant seventh chord. Note that the singer did not give the top pitch the highest pressure. Instead, the peak pressure is given to the first note after the top note. This note is the first that appears over the new chord and, therefore, it represents the musical peak of this phrase. Consequently, the singer gives this note the main stress (Sundberg, 1989).

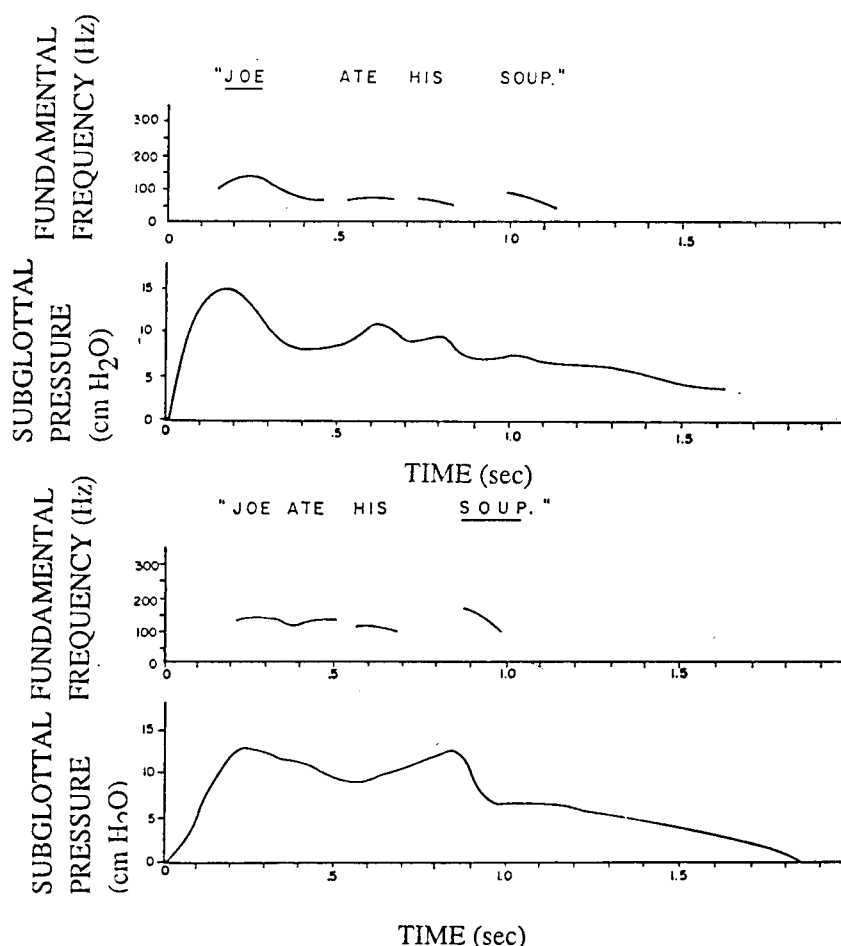


Fig. 10. Subglottal pressure during neutral and emphatic speech. The upper and lower curves represent fundamental frequency and subglottal pressure. The underlined words were emphasized. Emphasis is realized by increases of subglottal pressure. (After Lieberman, 1967.)

The skill required for an accurate reproduction of this exercise is obviously very high, and it is even greater if the tones are sung staccato rather than legato. In staccato, the vocal folds must open the glottis during the silent segments. For this to be possible without wasting air, subglottal pressure must be reduced to zero during the silent intervals. As a consequence, the singer has to switch from the target value, that was required for the pitch, down to zero during the silent interval, and then up to the new target value which is different from the previous one. A failure to reach the target pressures is manifested as a pitch error. This pitch error becomes quite substantial in loud singing, particularly at high pitches. From the point of view of breath and pitch control, this exercise is clearly virtuosic.

It is interesting to compare this type of pressure control with that required for speech. This is illustrated in Fig. 10. It shows subglottal pressure in neutral and emphatic speech. Neutral speech is characterized by the absence of heavy stress; in this type of speech, it is sufficient to signal stress by fundamental frequency and syllable duration. Consequently, there is little need for loudness variation, and the subglottal pressure curve is smooth. In emotive speech, by contrast, also loudness is used for signaling stress. Therefore, sudden increases of subglottal pressure are needed, as illustrated in the graph.

In normal speech, changes in overall vocal loudness are generally associated with shifts in overall fundamental frequency. Thus, when we speak louder, we also raise our voice pitch. Fig. 11 presents typical data published by Gramming and collaborators (Gramming & al., 1988). It shows averages for voice fundamental frequency and sound level observed when different subjects were reading aloud at deliberately varied vocal loudness. The average relation is about 0.4 semitones per dB increase of the equivalent sound level.

From a measured sound level change, it is possible to roughly estimate the underlying increase in subglottal pressure; a doubling of subglottal pressure leads to an increase in sound level of approximately 9 dB (Fant, 1982, Titze, 1989b). The effect of a subglottal pressure increase on pitch can also be estimated quantitatively: on the average, a 1 cm H₂O rise in subglottal pressure results in a fundamental frequency increase of about 4 Hz (Baer, 1979; Titze, 1991). Gramming and co-workers (Gramming & al., 1988) found that, in fact, the postulated pressure increase could explain all of the increase in fundamental frequency. Thus, their subjects did not bother to use the pitch-raising musculature in order to raise their voice pitch in loud reading. Instead, the pitch just increased passively because the subglottal pressure was raised.

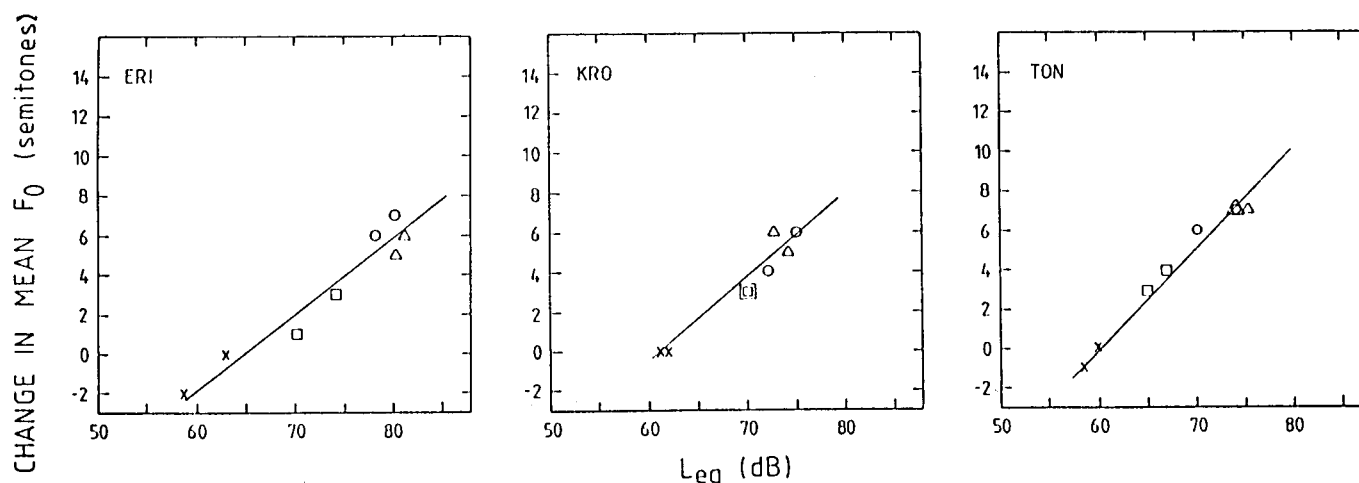


Fig. 11. Averages of voice fundamental frequency and sound level observed when different subjects were reading aloud at deliberately varied vocal loudness. There is a strong correlation indicating that an 1 dB increase of equivalent sound level was associated with an increase of about 0.4 st in average fundamental frequency.

If such a simple relationship between loudness and pitch existed in singing, every crescendo would be accompanied by a pitch rise! In this way, these data reveal a typical difference between singing and speech. While in speech an increase in vocal loudness may gladly be associated with a rise in voice pitch, singers must develop

an *independent* control of vocal loudness and pitch. In addition, singers must produce the required subglottal pressures very accurately to stay in tune. No wonder that the exercise analyzed in Fig. 9 is frequently used in teaching singing. It requires an independent control of pitch and loudness, which is necessary only in singing, and failures are revealed in terms of singing off the pitch.

RESPIRATORY STRATEGIES

In normal speech, the compensatory inspiratory work, required in order to balance the passive expiratory forces of the rib cage and the lungs, is handled primarily by the inspiratory intercostal muscles; most researchers have found that the diaphragm, the other main inspiratory muscle, is passive in speech (Draper, Ladefoged, & Whitteridge, 1959). As the range of lung volumes used in speech is comparatively narrow, the elasticity forces are rather limited. Singers, on the other hand, use a much greater lung volume range and, therefore, have to handle much greater variation of elasticity forces. Hence, they need to change subglottal pressure with great skill. What are the respiratory strategies that singers use in order to meet these severe demands?

One apparent difference among singers can be found in the positioning of the abdominal wall. While some singers sing with their abdominal wall expanded ("belly out"), others sing with the abdominal wall pulled in ("belly in"). The arguments used in favor of these strategies are sometimes quite entertaining. For instance, some voice teachers find support for the "belly in"-method in the fact that this strategy is apparently used by barking dogs. It is surprising that such arguments sometimes are taken seriously in spite of the apparent dissimilarities between the voice sound of a good singer and the voice sound of a barking dog.

Hixon & Hoffman (1978) analyzed the advantages and disadvantages of these two strategies. They point out that a muscle contraction pays off better when the muscle is stretched than when it is already contracted. Therefore, in the "belly in"-method, the expiratory intercostal muscles as well as the diaphragm are stretched and can, thus, be efficiently recruited in order to promptly increase the subglottic pressure. At the same time, the abdominal wall muscles are contracted, a situation that must reduce their efficiency in producing expiratory force.

The "belly-out"-method is generally combined with an elevated and outward positioning of the rib cage. Then, this strategy offers the same advantage as the "belly in"-strategy, since the intercostal muscles are stretched, as are the abdominal wall muscles. The disadvantage lies in the contracted condition of the diaphragm; on the other hand, the diaphragm is pressed upward as lung volume decreases. This will bring it to a more stretched condition at lower lung volumes.

The role of the diaphragm muscle in compensating for the considerable expiratory elasticity force of the rib cage and the lungs at large lung volumes was thoroughly examined in an excellent, pioneering investigation of singing by Bouhuys, Proctor, & Mead (1966). They measured the pressure difference across the diaphragm in non-professional singers. This difference is zero when the diaphragm is flaccid and positive when it is contracting. Their results showed that during singing a long, soft, sustained tone at high lung volume, three of their five subjects used the diaphragm for reducing the expiratory recoil forces.

Together with collaborators, this author studied aspects of the respiratory behavior in four singers who performed phonatory tasks involving rapid changes of sub-

glottic pressure, such as when singing wide pitch jumps (Leanderson & al., 1987). Two different strategies were found.

One strategy was to activate the diaphragm during inhalation only, and leave it entirely flaccid throughout the phrase except when subglottal pressure needed to be quickly reduced at the beginning of a phrase. Thus, the diaphragm contracted suddenly and momentarily for the lower note of a wide pitch jump. Henceforth, we will refer to this strategy, where the diaphragm is used for inhalation and for reducing subglottal pressure only at high lung volumes as the *flaccid diaphragm* technique.

Another strategy was to contract the diaphragm more or less forcefully throughout the phrase. Singers using this strategy were also found to increase their diaphragmatic activity when singing at high subglottic pressures. Thus, the abdominal wall generated an excessive pressure that was reduced to the target value by an increased activation of the diaphragm. Henceforth, this strategy, where the diaphragm is co-contracting with the abdominal wall muscles, will be referred to as the *co-contracting diaphragm* technique.

The advantage of using this last-mentioned strategy may appear questionable. One possibility is the following. An increase of the subglottal pressure is often produced by moving the abdominal content into the rib cage. If this movement is quick, an inertia effect will occur that strives to continue the motion of the abdominal content, beyond its target. This will disturb the subglottal pressure. A concomitant contraction of the diaphragm and the abdominal wall muscles would reduce or eliminate the effect that this inertia might have on subglottic pressure. This strategy, to recruit both the accelerating and the decelerating muscles, seems to be generally applied in tasks requiring rapid and precise movements of different parts of the human body. Both the muscles, that bring the structure into motion and those that can arrest the structure at the target position, contract (Rothenberg, 1968).

TRACHEAL PULL, A LINK BETWEEN RESPIRATION AND PHONATION

There may also be another effect of the diaphragmatic co-contraction strategy and of the "belly out"-strategy. It turns out that the trachea exerts a pulling force on the larynx. This force is often called the *tracheal pull*. It increases if the diaphragm descends, as after a diaphragmatic inhalation. By consequence, it will increase, if an increased contraction of the diaphragm causes the diaphragm to descend.

Rolf Leanderson, Curt von Euler, and I examined this effect in an experiment. The hypothesis was that the tracheal pull affects the anterior gap between the cricoid and thyroid cartilages. This gap is crucial to pitch: the higher the pitch, the smaller this gap. It is narrowed by contraction of the cricothyroid muscles, the major agents for pitch control. Therefore, under conditions of constant pitch, we expected the CT muscle to contract to different degrees depending on the position of the diaphragm.

The first experiment was to have singers phonate at different lung volumes. The cricothyroid contraction was measured in terms of the EMG signal, that was captured by a needle electrode inserted into the muscle. It turned out that the CT contracted more vigorously when the diaphragm was in a low position than when it was in a high position. Thus, the tracheal pull increased the need for CT contraction.*

* Another interesting conclusion of this finding can also be mentioned: the lung volume must be taken into account in EMG investigations of the cricothyroid muscles; a slow pitch glide would provide a poor basis for conclusions regarding the role of these muscles in the control of pitch.

The next experiment was to have the singers perform pitch jumps applying first the flaccid diaphragm technique and then the co-contracting diaphragm technique. A visual feedback was used to assist the subjects in controlling diaphragmatic contraction; the diaphragmatic activity was presented to them in terms of an oscilloscope beam that represented the pressure difference across their diaphragm. When the singers used the co-contracting diaphragm technique, i.e., when they increased the diaphragmatic contraction for the high note, the CT showed a higher degree of activity than when they performed the same task using the flaccid diaphragm technique. This suggested that the co-contracting diaphragm increased the tracheal pull during phonation. In other words, it showed that the breathing strategy affected the voice control mechanism.

In another experiment we analyzed the effect of diaphragmatic co-contraction on the voice source. The voice source is the sound created by the pulsating transglottal airflow. Its characteristics has important consequences to the personal voice timbre. Again, visual feedback was provided to facilitate the subjects' control of diaphragmatic contraction. They were asked to make pitch glides first with a flaccid diaphragm technique, and then with a co-contracting diaphragm technique. The results suggested that the co-contracting diaphragm reduced glottal adduction, i.e., the degree to which the vocal folds are pressing against each other.

This had consequences for the voice timbre. The amplitude of the lowest partial of the voice spectrum was greater when the subjects applied the co-contracting diaphragm technique. In other words, this experiment suggested that the breathing technique affected voice timbre because of a mechanical effect, the tracheal pull, which appeared to reduce glottal adduction.

As tracheal pull increases with lung volume, we could expect that glottal adduction is less forceful at high than at low lung volumes. Conversely, the adductory force needed for phonation can be assumed to be greater at high than at low lung volumes. This assumption was supported by results from an experiment carried out by Shipp, Morrissey, & Haglund (1985). They estimated the adductive force from EMG data in nonsingers and found that it was greater at high lung volumes, at least at high pitches.

The benefit of phonating with reduced glottal adduction is not hard to realize. An exaggerated glottal adduction implies pressed phonation, the type of phonation that speakers generally resort to under conditions of high pitch and loudness: the voice sounds strained. If the vocal folds are firmly adducted, subglottal pressure needs to be high, otherwise the airflow will be arrested by the glottis. A typical example is the voice quality we produce when we phonate while lifting an extremely heavy burden. This is clearly not the type of voice quality that music listeners want to pay for.

Recently, results from another experiment appeared to shed some more light on this matter. A professional mezzo-soprano singer exhibited an interesting breathing pattern during one of her standard vocal warming-up exercises. The exercise is shown in Fig. 12 together with curves representing fundamental frequency, transdiaphragmatic pressure, and esophageal pressure. It can be seen that when performing this exercise, the subject vigorously contracted her diaphragm during the production of the consonant /p/. Corresponding contractions did not seem to happen during the performance of other examples, albeit faint reflections of this pattern could occasionally be observed also in a performance of a coloratura passage.

An interpretation of the goal of this exercise is the following. By contracting the diaphragm during each [p], the tracheal pull was increased before the onset of each scale tone. This would tend to counteract a trend to increase glottal adduction. Thus, this exercise may have the goal to prevent phonation with exaggerated vocal fold adduction. It seemed that this particular exercise was associated with a breathing pattern that used an increased tracheal pull to abduct the vocal folds for each new scale tone (Sundberg & al., 1989). If this interpretation is correct, the result suggests a paramount importance of the conditioning of the vocal folds during warming up exercises.

Two comments should be added. We have seen that the vertical position of the diaphragm affects the CT activity required to maintain a pitch. This means, that when instructing the CT muscles how vigorously to contract, the neural system has to take into account not only the target pitch and the subglottal pressure, but also the diaphragm position which depends on the constantly changing lung volume. This indicates that singing is a truly complex task.

It was mentioned that the tracheal pull changes with the position of the diaphragm, i.e., with lung volume. It was also mentioned that the tracheal pull seems to include an abducting component, so that a forceful tracheal pull produces a clear abducting force. If singing students tend to exaggerate adduction under conditions of loud singing at high pitches, the tracheal pull may be a useful tool for them to vocalize properly. One possibility may be the co-contracting diaphragm technique. Another possibility is to practise high, loud, or otherwise difficult tones only after a deep diaphragmatic inhalation. In any case, it appears that the difficulty of singing loud high tones is greater toward the end of a phrase, when the tracheal pull is faint than at the beginning of a phrase, when the tracheal pull is stronger.

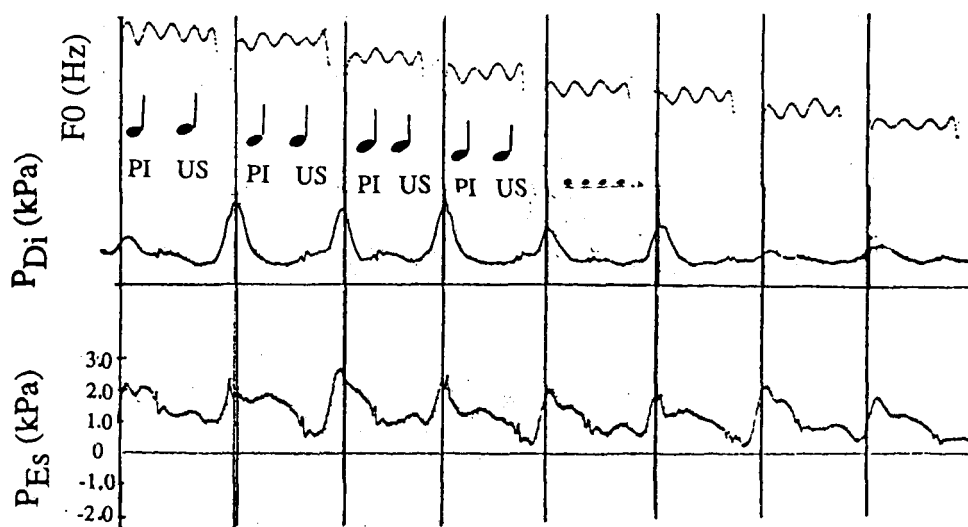


Figure 12. Fundamental frequency, pressure difference across the diaphragm and esophageal pressure in a professional mezzosoprano singer performing one of her warming up exercises, a descending scale repeating the word [pi:us] on each scale tone. The peaks in the transdiaphragmatic pressure reveal vigorous contraction of the diaphragm during the occlusion for the consonant [p]. A still more forceful contraction of expiratory muscles raises subglottal pressure to emphasize the [p]-explosion. The diaphragmatic contractions can be assumed to increase the tracheal pull and so reduce glottal adduction.

CONCLUSIONS

There are great differences in the demands on subglottal pressure control in speech and singing. In speech, subglottal pressure is used mainly for loudness control whereas in singing, subglottal pressure must be tailored with regard to both pitch and loudness. Because a change in subglottal pressure causes an increase in fundamental frequency, singers need to match the target subglottal pressures with accuracy. Moreover, in speech, loudness and pitch are typically interdependent, so that a rise in loudness is associated with a rise in fundamental frequency. While the elasticity forces are moderate in speech because of the narrow range of lung volumes used, they represent an important force affecting subglottal pressure in singing. The tracheal pull represents a clear, mechanical connection between the breathing technique and the phonatory mechanism. It seems that it can be used in vocal pedagogics.

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