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AERODYNAMIC ASYMMETRY IN INSPIRATORY VS. EXPIRATORY PHONATION

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Inspiratory phonation (voice production during inhalation) occurs naturally in emotional vocalizations such as laughter, sighs, and crying, and serves as a therapeutic technique for voice disorders. While the basic oscillatory mechanism mirrors expiratory phonation, experimental evidence indicates that inspiratory phonation requires significantly higher phonation threshold pressure. This study presents a theoretical framework explaining this difference based on aerodynamic asymmetries inherent to the laryngeal system. The analysis centers on the transglottal pressure coefficient, which governs the minimum pressure needed to initiate vocal fold oscillation. This coefficient depends critically on pressure losses at the glottal entrance and pressure recovery at the exit, both of which are affected by airflow direction. The key insight lies in the geometric asymmetry of the glottal channel: during expiration, air enters smoothly from the trachea through a convergent profile, minimizing turbulent losses, whereas during inspiration, air encounters an abrupt entrance from the supraglottal region, producing substantially higher pressure losses due to flow separation and turbulence. The results of the analysis show an inspiratory phonation threshold pressure around 1.5 times the expiratory value, which agrees with previous experimental results. This aerodynamic asymmetry suggests that expiratory phonation represents a path of least physical resistance, shaped by self-organizing biomechanical constraints prior to neural control.

Keywords: phonation, vocal folds, laryngeal aerodynamics, voice production, inspiratory phonation

1. Introduction

Phonation is the result of the interaction of the airflow blowing through the glottis with the elastic structure of the larynx, coupled with the acoustical wave generated from such interaction [1]. Since the pioneering work of Van den Berg et al. [2] over six decades ago on casts of the larynx, the physics of such interaction has been investigated in a large number of theoretical and experimental studies under a variety of configurations; e.g. [3, 4, 5].

In general, past phonation studies have focused on the case of expiratory phonation, in which air flows from the lungs to the mouth and nostrils. This is the standard case in speech, singing, and general vocalization, and its main physical principles are well understood. Evidence of such good understanding is the realism obtained through numerical simulations [6], which are capable of capturing main features of voice even in dysphonic cases [7].

Phonation may also occur with an inspiratory flow. In such a case, expansion of the lungs causes a negative pressure and air is therefore inhaled from the mouth and nostrils to the lungs. Inspiratory phonation occurs normally during running speech, singing and crying. It is also used to achieve special voice effects, and it occurs also in the vocalization of other mammals such as monkeys, dogs, and cats, as well as in birds [8].

Although inspiratory phonation seems to follow the same main mechanism as in the expiratory case, namely, a flow-induced oscillation of the vocal folds that generates an acoustical wave, it also presents several differences with that case. For example, experimental measures on human subjects have reported an inversion of the oscillatory pattern of the vocal folds, lower closed quotient of the glottis, higher opening/closing quotient, larger oscillation amplitude, and larger noise components on the acoustic signal [8]. Other differences have been reported in vocal tract morphology [9] and timing control [10]. Despite its occurrence and clinical relevance, relatively few physical studies of inspiratory phonation have been conducted, and its underlying physics still requires further clarification.

This paper focuses on one critical parameter: the phonation threshold pressure (PTP), which represents the minimum pressure gradient across the glottis required to initiate the vocal fold oscillation. This parameter is a measure of the ease of phonation; the lower the threshold, the easier it is to produce vocal fold oscillation [11]. Recent experiments on mechanical replicas of the vocal folds have shown inspiratory values of PTP between 1.2 and 1.8 times the expiratory value, and it has been argued that such a difference may be a consequence of the asymmetric geometry of the glottal channel in the expiratory vs. the inspiratory directions [12]. Here, we investigate further this claim by means of a mathematical model of glottal aerodynamics. Understanding inspiratory vs. expiratory characteristics can shed light on fundamental aspects of voice production and may explain why humans evolutionarily developed expiratory phonation as the default mode for speech.

2. Background

Consider the glottal channel (space between the vocal folds) schematics shown in Fig. 1. Assuming quasi-steady, inviscid and incompressible air flow, Titze [13] characterized the transglottal pressure gradient as

$$\Delta P = P_s - P_e = k_t \frac{\rho |u_g| u_g}{2a_g^2} \tag{1}$$

where P_s is the subglottal pressure (at the trachea), P_e is the supraglottal pressure (at the epiglottis), ρ is the air density, u_g is the volume rate of the glottal airflow, a_g is the glottal area, and k_t is a transglottal pressure coefficient given by

$$k_t = k_c - k_e \tag{2}$$

where $k_c \geq 1$ is a pressure loss coefficient at the entry of the glottal channel (lower edge of the vocal fold) that accounts for effects of nonuniform flow, turbulence in the channel contraction, and formation of a *vena contracta* (contraction of the flow) within the glottal channel; and $k_e \leq 1$ is a pressure recovery coefficient at the exit of the glottal channel (upper edge of the vocal folds) – at the glottal exit, and due to the abrupt expansion of the glottal channel, the air flow detaches from the channel walls and exits in a free jet, losing most of its kinetic energy due to turbulence [5].

During phonation, the vocal folds oscillate in a wave-like motion pattern. A surface wave travels through the tissues in the direction of the airflow, with wave velocity c. Assuming small displacements of the tissues from their rest position, Titze [13] derived a glottal pressure

$$p_g = \frac{2T\Delta P}{k_t c H} \dot{x} \tag{3}$$

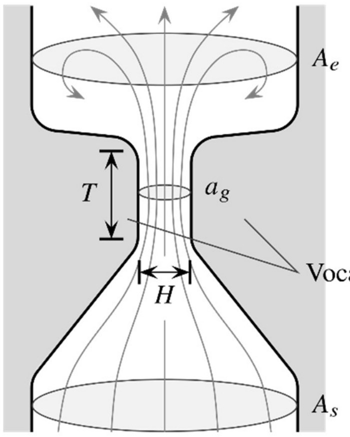

Figure 1: The glottal channel. A_s and A_i are the constant cross-sectional areas at the trachea and epiglottal regions, respectively, a_g is the time-varying glottal area, T is the length of the glottal channel, and H is its height at the rest position (prephonatory position) of the vocal folds. During normal phonation, $a_g \ll A_s \approx A_i$.

where T and H are the length and height of the glottal channel (see Fig. 1), and $\dot{x}$ is the lateral velocity of the tissues (perpendicular to the air flow).

Applying Eq. (3) to a lumped one-mass oscillator model of vocal fold biomechanics, of the form

$$M\ddot{x} + B\dot{x} + Kx = p_g \tag{4}$$

where *M*, *B*, and *K* are the oscillating mass, damping and stiffness coefficients per unit medial surface of the vocal folds, and next applying a standard stability analysis [15], we obtain the oscillation threshold value of the transglottal pressure gradient (PTP)

$$\Delta P_{\mathrm{th}} = \frac{k_t BcH}{2T} \tag{5}$$

As this equation reveals, PTP depends on tissue biomechanical properties (*B*, *c*), glottal channel dimensions (*H*, *T*) and aerodynamic factors (k_t).

The accuracy of Eqs. (1) to (5) to model glottal behaviour has been verified through a number of studies in a variety of experimental setups, [1, 5, 14]. Both entry and exit coefficients k_c and k_e depend on a number of factors as transglottal pressure and glottal height. As standard values, a transglottal pressure of 800 Pa and glottal width $H = 1$ mm correspond to $k_c = 1.22$ and $k_e = 0.06$, which gives a transglottal coefficient of $k_t = 1.16$. Standard values for the other parameters are $Bc = 1000$ Pa and $T = 3$ mm, which results in a PTP of 193 Pa, well within physiological range [4].

3. Theoretical framework

3.1 Asymmetry of the glottal channel

The key to understanding the threshold pressure difference lies in the geometric asymmetry of the glottal channel when viewed from opposite flow directions, as illustrated schematically in Figure 2.

During expiratory phonation (Fig. 2 left), the airstream enters the glottis from the trachea through a gradually converging channel formed by the inferior surface of the vocal folds. This smooth contraction allows the flow to remain largely attached to the channel walls, though some *vena contracta* formation may still occur [2]. At the glottal exit, the flow separates and forms a turbulent jet that dissipates into the supraglottal cavity.

During inspiratory phonation (Fig. 2 right), the airstream must enter from the supraglottal region, encountering an abrupt contraction at the laryngeal inlet. This causes immediate flow separation and a more pronounced *vena contracta* formation than in the expiratory case, substantially reducing the effective flow area at the glottal entrance. The recirculating eddies formed in the separated region produce higher pressure losses.

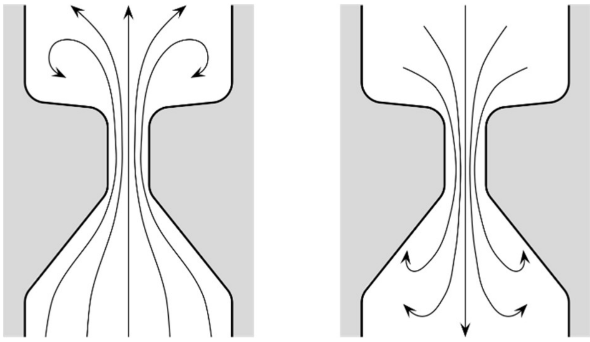

Figure 2: Glottal airflow at expiration (left) and inspiration (right).

The formation of a *vena contracta*—a contracted region of the flow downstream of an abrupt entrance—is a critical factor in the increased pressure losses during inspiration. In classical fluid mechanics, the *vena contracta* coefficient (ratio of contracted area to geometric area) for a sharp-edged orifice is approximately 0.5, meaning that almost 50% of the geometric area is lost to flow separation effects [16]. While the laryngeal geometry is more complex than a simple orifice, the principle remains: abrupt contractions produce significant flow area reductions and associated pressure losses that do not occur with gradual, streamlined entries.

Unfortunately, there are no available measures of pressure loss coefficients at the larynx for an inspiratory flow. However, we can test our argument by using theoretical values of loss coefficients in pipe flows. Following the standard fluid mechanics theory [16], the pressure difference between two points in a pipe with constriction in between is

$$\Delta P = \left(\sum K_L\right)\frac{\rho v^2}{2} \tag{6}$$

where K_L is a loss coefficient, v is the fluid velocity within the constricted region, and the summatory extends to entry and exit of that region. Theoretical values of K_L are given in Table 1.

At expiration, the glottal entry is gradual and the exit is sudden. Therefore, we have a transglottal pressure loss coefficient $k_t = (\sum K_L) = 1.04$. At inspiration, the entry is sudden and the exit gradual, and we have $k_t = (\sum K_L) = 1.5$. The theoretical oscillation threshold pressure ratio at inspiratory vs. expiratory flow is then $1.5/1.04 = 1.44$, which is within the measured ratios in [12].

Table 1: Pressure loss coefficients for contractions and expansion of flow in pipes [16].

K_L	Sudden	Gradual
Contraction	0.5	0.04
Expansion	1	1

In a recent study [17], pressure loss coefficients were computed through numerical simulations of flow in cylindrical pipes. The results are given in Table 2, in terms of head loss.

Table 2: Head losses for contractions and expansion of flow in pipes [17].

h	Sudden	Gradual
Contraction	1.23 m	0.215 m
Expansion	0.746 m	0.22 m

Note that in Table 1, expansion losses are approximated as equal regardless of geometry, since flow separation occurs at any expansion. The numerical simulation results in Table 2 show that gradual expansions recover slightly more pressure, but in both analyses the dominant asymmetry arises from the contraction coefficients.

A gradual contraction followed by a sudden expansion, as in the expiratory case, has a total head loss of 0.961 m. A sudden contraction followed by a gradual expansion, as in the inspiratory case, has a total head loss of 1.45 m. The inspiratory/expiratory ratio is then $1.45/0.961 = 1.51$, close to the previous result.

3.2 Mucosal wave reversal

A distinctive feature of inspiratory phonation is the reversal of the mucosal wave direction on the vocal fold surface. During normal expiratory phonation, the mucosal wave propagates from the inferior to superior margin of the vocal folds, with the lower edge leading the upper edge by approximately 90° to 180° in phase [8]. This bottom-to-top propagation results from the airflow direction: the positive transglottal pressure first pushes the lower margin laterally, and this displacement propagates upward through the tissue.

High-speed videokymography studies by Vanhecke et al. [8] documented that during inspiratory phonation, the wave propagates in the opposite direction—from superior to inferior margin. This reversal is consistent with the reversed pressure gradient: during inspiration, the driving pressure acts from the supraglottal side, initiating displacement at the upper margin first.

The mucosal wave reversal affects the glottal pulse waveform and voice quality. During expiratory phonation, the convergent-to-divergent shape change of the glottal channel is synchronized with the pressure cycle to sustain oscillation. During inspiratory phonation, this shape change sequence reverses, but the basic energy transfer mechanism remains functional, allowing self-sustained oscillation to occur. Whether the wave velocity c changes magnitude with flow direction remains an open question; however, experimental data in [12] show consistent threshold pressure ratios across replicas with varying mechanical properties, suggesting that aerodynamic asymmetry is the dominant factor.

4. Conclusion

This study demonstrates that the geometric asymmetry of the glottal channel produces higher pressure losses during inspiratory than expiratory phonation. The asymmetry arises because air entering the glottis from the trachea (expiration) passes through a smooth convergent profile, while air entering from the supraglottal region (inspiration) encounters an abrupt contraction producing flow separation and increased pressure losses. This mechanism provides a physically grounded explanation for the observed threshold pressure differences and suggests that expiratory phonation represents a path of least aerodynamic resistance—an intrinsic property of laryngeal anatomy that may explain why humans universally speak during exhalation.

We must note, however, that Hasegawa et al. [18] reported decreased threshold pressure during inspiratory phonation in their synthetic vocal fold experiments, opposite to the trend observed in [12] and predicted by the present analysis. This discrepancy may stem from differences in experimental geometry, and shows the need for further studies to properly characterize the oscillation dynamics.

The distinct biomechanics of inspiratory phonation have proven therapeutically valuable for treating various voice disorders. Orlikoff et al. [19] documented that during inspiratory voicing, the pharynx widens and the larynx descends, reducing supraglottal constriction. The ventricular folds move laterally, decreasing their medial compression on the true vocal folds. These effects create a more open laryngeal configuration that can help reset maladaptive muscle tension patterns.

Inspiratory phonation is used clinically to treat psychogenic aphonia, where the reversed airflow direction can bypass psychological blocks on expiratory voicing; ventricular dysphonia, where it promotes separation of the ventricular folds; and muscle tension dysphonia, where it reduces hyperfunction. The present analysis provides a quantitative basis for understanding why inspiratory phonation feels more effortful: patients must generate a higher respiratory pressure to initiate voicing. This higher respiratory demand provides clear kinesthetic feedback and may help establish proper breath support patterns.

Future work should include direct measurements of pressure loss coefficients under inspiratory laryngeal flow, computational fluid dynamics simulations with realistic laryngeal geometry, and investigation of how glottal pulse characteristics change with flow direction.

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