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Regional ventilation during phonation in professional male and female singers

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ABSTRACT

The respiratory system is a central part of voice production, but details in breath control during phonation are not yet fully understood. This study therefore aims to investigate regional ventilation of the lungs during phonation. It was analyzed in 11 professional singers using electrical impedance tomography during breathing and phonation with maximum phonation time. Our results show differences in impedance changes between phonation and exhalation in the courses of time and amplitude normalized curves. Furthermore, differences related to gender and professionalism were found in the temporal and spatial profiles of regional ventilation. For female singers (sopranos and mezzo-sopranos) the anterior region participated less at the start of ventilation, and was more stable at the midpoint compared to male singers (tenors). This might be an expression of a smaller relative movement in rib cage and anterior diaphragm, primarily in early phonation.

1. Introduction

The mechanics of the respiratory system have been the focus of pulmonary research for decades, particularly with regard to spontaneous breathing and mechanical ventilation. What is more, the respiratory system is also a central part of voice production since the breathing apparatus regulates subglottic pressure (p_{sub}) arising when the vocal folds are adducted for phonation (Sundberg, 1987). Continuous adjustment of p_{sub} is essential for voice production as it influences other basic parameters of voice production such as sound pressure level, fundamental frequency and vocal tract resonances (Leanderson et al., 1987; McAllister and Sundberg, 1998; Sundberg et al., 1993a). Respiratory patterns in phonation have so far been mainly evaluated in singers, since professional singers develop very consistent breathing strategies (Bouhuys et al., 1966; Leanderson and Sundberg, 1988; Pettersen and Eggebø, 2010; Thomasson and Sundberg, 2001, 1999; Watson and Hixon, 1985; Watson et al., 1990). In previous investigations, methods such as transdiaphragmatic pressure measurements (Bouhuys et al., 1966; Leanderson, 1987; Leanderson et al., 1987; Sundberg et al., 1989), bodyplethysmography (Bouhuys et al., 1966), magnetometry (Collyer et al., 2008) and respiratory inductance plethysmography (Thomasson and Sundberg, 2001; Thomasson, 2003; Watson et al., 1990) have been applied. However, these techniques measure cumulative variables such as airway pressures, flow rates or respiratory excursions. Imaging of the lung has always been challenging: methods using ionizing radiation (computed tomography) are limited in their application for studies in healthy subjects due to ethical concerns, ultrasound suffers from limited penetration depths in the lung and magnetic resonance imaging is disturbed by changes in susceptibility and furthermore is mostly limited to measurements in supine position. There are therefore only very few imaging studies which have assessed the dynamics of the respiratory system during phonation. One was performed by Pettersen et al. using ultrasound, but only small parts of the respiratory system could be visualized (Pettersen and Eggebø, 2010). A very recent dynamic MRI study evaluated the respiratory system during phonation and found that the thorax and different parts (anterior vs. posterior) of the diaphragm acted as separate functional units in singing phonation (Traser et al., 2016). However, the functional relationships between different parts of the breathing apparatus in terms of regional ventilation during underlying phonation are not fully understood.

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Table 1
Age, gender, voice classification and classification according to the Bunch and Chapman taxonomy of subjects.

Subject	Age	Gender	Voice classification	Bunch and Chapman taxonomy
Male 1	36	male	Tenor	7.2
Male 2	24	male	Tenor	4.5
Male 3	32	male	Tenor	7.2
Male 4	24	male	Tenor	7.1
Male 5	46	male	Tenor	2.1
Male 6	41	male	Tenor	5.4
Female 1	34	female	Mezzo-Soprano	4.5
Female 2	32	female	Mezzo-Soprano	3.1b
Female 3	22	female	Soprano	3.15b1
Female 4	30	female	Mezzo-Soprano	5.4
Female 5	27	female	Soprano	4.5

During the 1980s a non-invasive technology (Barber and Brown, 1984) for studying regional ventilation was introduced, which monitored changes in the electrical impedance of the chest, indicating the regional air content inside the lung (Wierzejski et al., 2012), i.e. electrical impedance tomography (EIT). It is non-invasive and radiation-free and allows real-time functional imaging (Wierzejski et al., 2012). As yet, it is mainly used for scientific analyses of the mechanics of the respiratory system (Frerichs et al., 2014; Spaeth et al., 2016; Wirth et al., 2016) but is also considered for clinical monitoring and optimization of ventilation in critical care unit patients or during surgery (Erlandsson et al., 2006; Wrigge et al., 2008).

The aim of our study was to investigate the regional gas distribution during phonation in professional singers. We hypothesized that impedance curves differ (1) between normal breathing and phonation, (2) according to pitch, and (3) between female and male singers.

2. Methods

In this study the regional ventilation of 11 professional western classically trained singers (5 female sopranos/mezzo-sopranos and 6 male tenors) was analyzed during phonation and breathing using EIT.

The Medical Ethics Committee of the University of Freiburg, Germany, approved this study (Nr. 82/14). Subjects gave written informed consent prior to participation. Table 1 shows the subjects' age, gender, voice classification and classification according to the Bunch Chapman taxonomy (Bunch and Chapman, 2000). The Bunch Chapman Classification is based on performance ability and professional status and offers 9 categories ranging from superstar (1) to local community and amateur singers (9). Singers with a Bunch Chapman Classification of ≤4 (international, national and regional/touring singers; n = 6) were pooled and compared to singers with a Bunch Chapman classification of ≥5 (local/community singers, singing teachers and full time voice students; n = 5). In addition two age groups were analyzed (≥30 and ≤31 years).

At the time of the recording none of the participants complained of any vocal symptoms or suffered from a pulmonary disease.

2.1. Tasks

The phonation tasks were chosen according to the voice classification of the singer and represent a low pitch (P_1) and high pitch (P_2 = octave above P_1, P_3 = third above P_2 and P_4 = fifth above P_2) in the tessitura of the respective repertoire of the singer (Table 2). The singers were asked to sing on the vowel [a:] for the maximum phonation time at a comfortable loudness level. This vowel was chosen to avoid possible articulatory effects which might be expected when the fundamental frequency reaches the first vocal tract resonance (Echternach et al., 2010). The duration of phonation was later referred to as phonation time. Prior to the phonation measurements, participants were asked to breathe in and out maximally to allow comparison of regional ventilation between phonation and respiration. For each task, the maximum phonation time was acquired twice: first during sustained phonation, second with interruptions by [p:]-consonants thus performing syllable repetition/papapa/in order to estimate p_{sub}.

Table 2
Task description according to different gender/voice classifications.

Gender Task	Female (Sopranos/Mezzo-Sopranos) Pitch	Male (Tenors) Pitch
P_0	Vital capacity breathing	
P_1	E4 (330 Hz)	E3 (165 Hz)
P_2	E5 (659 Hz)	E4 (330 Hz)
P_3	G#5 (831 Hz)	G#4 (415 Hz)
P_4	H5 (988 Hz)	H4 (494 Hz)

2.2. EIT measurements

EIT measurements were performed using a PulmoVista 500 (Dräger Medical GmbH, Lübeck, Germany). For this purpose, an elastic belt containing sixteen electrodes was fastened around the subjects' thorax between the 4th and 6th intercostal space. The device was set to generate 50 images per second. Ventilation was evaluated for the total cross-sectional area in four regions of interest (ROI_{1-4}) subdividing the cross-sectional thoracic image into equally sized parts from ventral to dorsal (Fig. 1). Mean impedance curves were calculated for the whole image as well as for the four ROIs as the mean value of the impedances of all pixels within the corresponding image or ROI. The gradients of impedance curves of ROI_1 to ROI_4 were analyzed in time steps of 33% (m1/3, m2/3 and m3/3).

2.3. Data normalisation

For inter and intra subject comparison of EIT curves, the time axes were re-scaled from the start of phonation (t_{start}) and to the end of phonation (t_{end}) and the impedance amplitude A was normalized (A_{norm}) to the impedance at t_{start} and t_{end} according to

$$A_{norm}(t) = \frac{A(t) - A(t_{end})}{A(t_{start}) - A(t_{end})} \cdot 100\%$$

In addition, the slope m of all graphs was calculated in steps of 20% of the normalized time (m_1–m_5) as the ratio of changes in the measured distances over time.

$$\mathbf{m}_n = \frac{A_n(t_n) - A_n(t_{n-1})}{t_n - t_{n-1}}$$

2.4. Electroglottography, subglottic pressure and sound pressure level

The synchronous monitoring of glottal resistance during phonation is of fundamental importance, since it is closely associated with p_{sub} and airflow through the glottis (Sundberg, 1987). A simultaneous electroglottographic recording was performed (Laryngograph Ltd. London, UK). It indirectly measures the contact area of the vocal folds during phonation: a weak alternating current is applied via two electrodes placed on the surface of the neck over the thyroid cartilage, and impedance changes caused by the vibration of the vocal folds are recorded at a frame rate of 16 kHz. From this signal the contact quotient, can be calculated as the ratio between the time the vocal folds are in contact with each other, and the vibratory