EXAMINATION OF DIAPHRAGM CONTROL AND ITS EFFECTS ON PITCH LEAP DURING OPERA SINGING USING REAL-TIME MRI

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Abstract:

Objectives / Introduction: Opera singers use techniques for controlling vocal tract resonance, such as the singer's formant [1] and formant tuning [2], to produce a *squillo* or ringing voice. In addition, they are able to control the subglottal pressure to change the intensity of phonation. Vocal tract resonance is determined by the shape of the vocal tract while subglottal pressure is determined by changes in lung volume. However, it is difficult to observe the shape of the vocal tract and changes in lung volume directly.

Recently, real-time magnetic resonance imaging (rtMRI) was used to record articulatory movements during speech [3]. This technology can also be applied to lungs, as we demonstrated in a pilot study. In the previous work, rtMRI was used to record the changes in the right lung shape in the sagittal plane of two professional opera singers as they were singing. Then, the changes in the lung shape and diaphragm position were extracted and analyzed from the rtMRI videos [4]. We observed that, although the singers gradually raise the diaphragm to decrease the lung volume while singing, they temporarily lower the dorsal side of the diaphragm to increase the lung volume when there is a drop in pitch [4]. After a temporary lowering, the singers again raised the diaphragm. Through this process, no interruptions in the singing voice were perceived. In the present study, we examined why singers lower their diaphragm during singing by estimating the subglottal pressure.

Methods: The participants were two professional opera singers, a tenor, and a baritone. Fig. 1 shows a singing task consisting of three perfect 5th leaps (①-③) and four octave leaps (④-⑦). The participants performed the singing task in the supine position while undergoing an MRI scan (Siemens MAGNETOM Prisma fit 3T installed at ATR Promotions). While singing, movements of the right lung in the sagittal plane were recorded as a video at a speed of 10 fps for approximately 50 s. The pixel resolution was 1.22 x 1.22 mm and the slice thickness was 10 mm. The singing voice during scanning was recorded using an optical microphone (Optoacoustics, Optimic1140). In addition, because the sound recorded includes the loud scanning noise from the MRI, the singing voice for the same task was recorded in the supine position in a quiet room.

From each video frame, the contour of the right lung was semiautomatically extracted using the machine learning library Dlib [5], as shown in Fig. 2. The area of the right lung was calculated using the contours. Subglottal pressure was estimated from changes in lung area. First, we assumed that the lung volume was proportional to the 3/2 power of the lung area, and the maximum volume was 5,000 cm^3. Based on these assumptions, changes in lung volume could be estimated at 0.1 s intervals. During frame switching from inhalation to phonation, the lung pressure can be considered equal to the atmospheric pressure. At the beginning of the next frame, we assume that the lung volume suddenly changes but remains constant in the frame and that the subglottal pressure changes accordingly by adiabatic compression. In this frame, the mass of airflow per second can be calculated using the following equation:

$$\dot{m} = \frac{Ap}{\sqrt{RT}}\sqrt{\frac{2\gamma}{\gamma-1}\left\{\left(\frac{p_a}{p}\right)^{\frac{2}{\gamma}} - \left(\frac{p_a}{p}\right)^{\frac{\gamma+1}{\gamma}}\right\}} \qquad \text{kg/s},$$

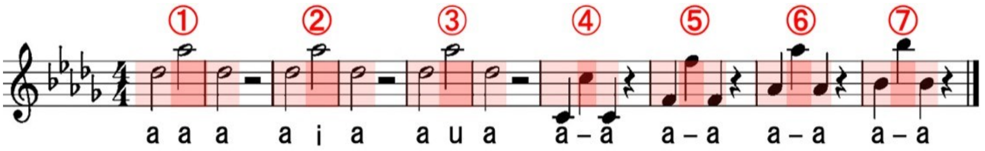

Fig. 1 Singing task

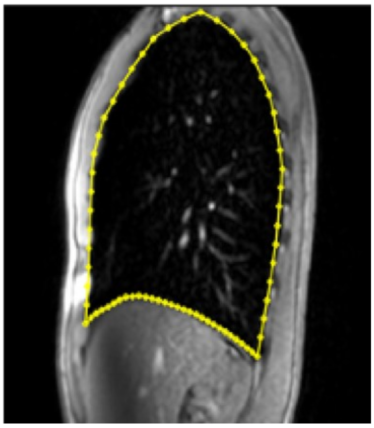

Fig. 2 Lung contour

where A is the time averaged glottal area, 0.05 cm", p is the subglottal pressure which is constant until the end of the frame, R is the gas constant of air, 287.1 J/(kgK), T is the temperature of air, 310 K, γ is the specific heat ratio of air, 1.4, and $p_!$ is atmospheric pressure,100 kPa. At the end of the frame, the subglottal pressure changes by $-\dot{m}\,\Delta t RT/V$, where Δt is the frame interval, 0.1 s, and V is the lung volume in the frame. Assuming that the above process is repeated during phonation, changes in subglottal pressure can be estimated.

Results: Fig. 3 shows the estimated lung volume and subglottal pressure (gauge pressure) of the tenor during the octave leap at ⑥. Although the lung volume tended to decrease overall, it slightly increased from 410th frame to 412th frame, just before the pitch leaped down. The subglottal pressure was high at the high pitch (dark shaded), while it was low at the low pitch (light shaded). This result matches the fact that a high pitch requires high pressure, and a low pitch requires low pressure [6]. If air compressibility is not considered, the increase in lung volume from the 410th frame to 412th frame would cause negative pressure, that is, inhalation. However, in the present study, because air compressibility was considered, the subglottal pressure rapidly decreased, but was still positive for continuing singing. A similar pressure decrease was found for the baritone during the octave leap at ⑥ (Fig. 4). Based on these results, it is confirmed that professional singers can rapidly decrease the subglottal pressure to an extent suitable for a low pitch by intentionally lowering the diaphragm, even during singing. This prediction is supported by the waveform of a singing voice recorded in a quiet room. Fig. 5 shows the waveforms of the two singers. After the pitch leaped down, the amplitude decreased. This matches the estimated subglottal pressure pattern.

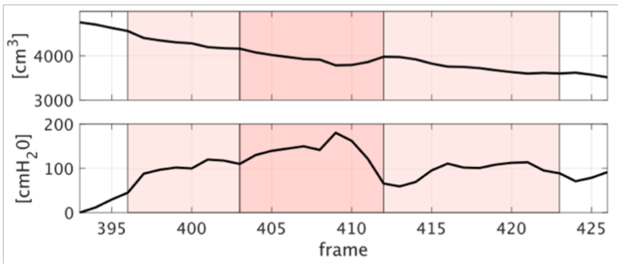

Fig. 3 Estimated lung volume (upper) and subglottal pressure (lower) for tenor

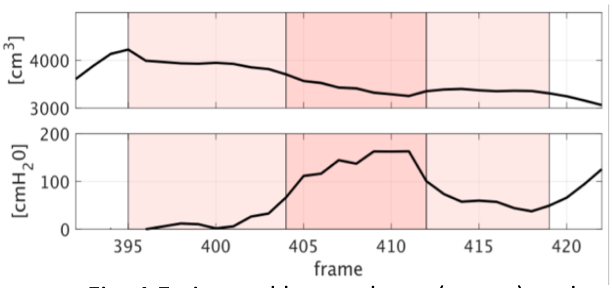

Fig. 4 Estimated lung volume (upper) and subglottal pressure (lower) for baritone

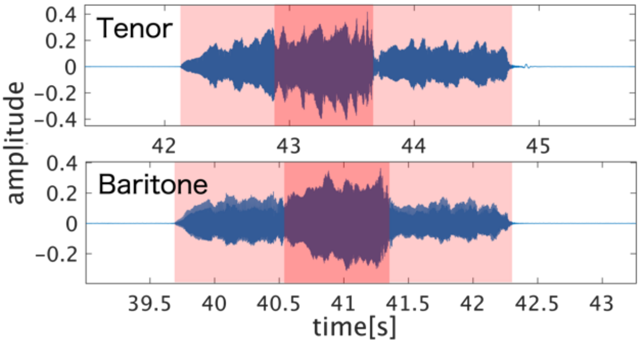

Fig. 5 Sound waveforms

Conclusions: It has long been assumed that singers continue to raise their diaphragm to generate an expiratory flow during singing. However, we demonstrated previously that singers temporarily lowered the diaphragm even while singing [4]. The reason why singers adopted this technique was examined in this study. From the rtMRI data, changes in subglottal pressure were estimated by considering air compressibility. The results indicated that professional opera singers can rapidly decrease the high subglottal pressure suitable for the high pitch to a low pressure during the leap to the low pitch by lowering the diaphragm to increase the lung volume. According to personal interviews, some singers refer to this technique as "re-supporting." "Breath support" might be what singers feel when raising the diaphragm appropriately for pitch and loudness. Therefore, "re-support" could be what singers feel when raising the diaphragm again after temporarily lowering.

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