Vocal Tract in Female Registers—A Dynamic Real-Time MRI Study

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Summary: The area of vocal registers is still unclarified. In a previous investigation, dynamic real-time magnetic resonance imaging (MRI), which is able to produce up to 10 frames per second, was successfully applied for examinations of vocal tract modifications in register transitions in male singers. In the present study, the same MRI technique was used to study vocal tract shapes during four professional young sopranos' lower and upper register transitions. The subjects were asked to sing a scale on the vowel /a/ across their transitions. The transitions were acoustically identified by four raters. In neither of these transitions, clear vocal tract changes could be ascertained. However, substantial changes, that is, widening of the lips, opening of the jaw, elevation of the tongue dorsum, and continuous widening of the pharynx, were observed when the singers reached fundamental frequencies that were close to the frequency of the first formant of the vowel sung. These findings suggest that in these subjects register transition was not primarily the result of modifications of the vocal tract.

Key Words: Magnetic resonance imaging–Voice–Register–Articulation.

INTRODUCTION

The area of vocal registers is in general still unclarified. By contrast to males, in whom marked register transitions can frequently be demonstrated on the level of the vocal folds, for example, by kymography,[1] the registers of female voices cannot always be differentiated as easily. Studies of female registers are still comparatively rare, not only with regard to the voice source, but also concerning the role of the vocal tract.

Up to now, only acoustic analyses have been performed concerning the influence of the vocal tract on register transitions in female subjects.[2] What seems to be needed are analyses of the relationship between vocal tract shape and register transition in female voices.

It is a well-established fact that vowel quality is changed by means of articulatory changes of the vocal tract. Such articulatory changes with respect to the vowels phonated can be analyzed by means of dynamic magnetic resonance imaging (MRI).[3,4] In a pilot study, we were able to demonstrate by dynamic real-time MRI vocal tract modifications in male subjects when they retained modal register at high pitches.[5] These modifications involved the lips, the tongue dorsum, the jaw opening, and the width of the pharynx. When the subjects shifted register from modal register to falsetto, almost no vocal tract modifications were observed, except for the pharynx width.

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It is often assumed that women have a larger number of registers[2,6] than males. In the present investigation according to Nadoleczny[7] and Miller,[2] we assumed that female singers use their modal register in the lower part of their pitch range up to a first critical point (passaggio primo), which typically occurs in the neighborhood of 350 Hz (Figure 1). Here, they shift register to what is frequently referred to as the middle register. This change is comparable with the change between modal and falsetto registers in male voices.[6] The middle register is used up to another critical point (passaggio secondo), which typically occurs in the neighborhood of 700 Hz where another register transition occurs. We will refer to these transitions as the lower and the upper transition, respectively.

The role of the resonatory system in these register changes is unclear. The properties of this system are determined by the shape of the vocal tract. The aim of the present study was to find out if female singers change this shape at the lower and upper register transitions.

MATERIAL AND METHODS

Four professional classical singers volunteered as subjects. According to their singing teachers, all of them were sopranos, three lyrical (subjects 2, 3, 4), and one young dramatic (subject 1). The mean age was 25.3 years (range, 23–27). All of them had at least 4 years of voice training at a music university. None reported any vocal symptoms at the time of the recording and functional as well as organic pathologies were excluded by videostroboscopic examinations in three of the subjects, while in one subject intense gagging reflex prevented such examination.

The subjects were examined radiologically with the 3.0T TIM TRIO (Siemens, Germany) MRI machine, described before.[5,8] Each register transition sequence was performed twice. In the first sequence, the MRI frame rate was 4/s, and in the second, it was 10/s. The MRI was performed with a medio-sagital slab of 11 mm thickness. The resolution was 0.87×0.65 pixel/mm.

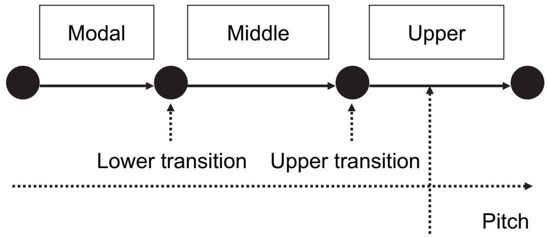

FIGURE 1. In vowel /a/ articulatory changes expected near F0 ≈ 750Hz.

Audio recordings were made by an optic microphone (optic microphone: MR confon, Magdeburg, Germany, *OptiMRI* Noise Reduction Software, Optoacoustics Ltd., Or-Yehuda, Israel). Real-time auditory feedback was provided over headphones (MR confon, Magdeburg, Germany). $F0$ was measured by means of the *PRAAT* software (University of Amsterdam, the Netherlands), and the results were checked on a piano tuned to A4 = 442 Hz.

All subjects were first asked to sing an ascending diatonic major scale on the vowel /a/, starting in the modal register and continuing up into the middle register. In the second condition, they were asked to sing a scale across the upper transition on the same vowel.

The audio recordings of the different scales were presented to a panel of four experts (two otolaryngologists [both classically trained professional singers], 1 voice therapist [semiprofessional singer], and 1 professional musician [a clarinet player with a strong interest in voice]). They were asked to identify the point on the scale recordings, at which the register transitions took place, independently of each other.

In each frame of the MRI recording, a series of measurements was made. As illustrated in Figure 2, these measures

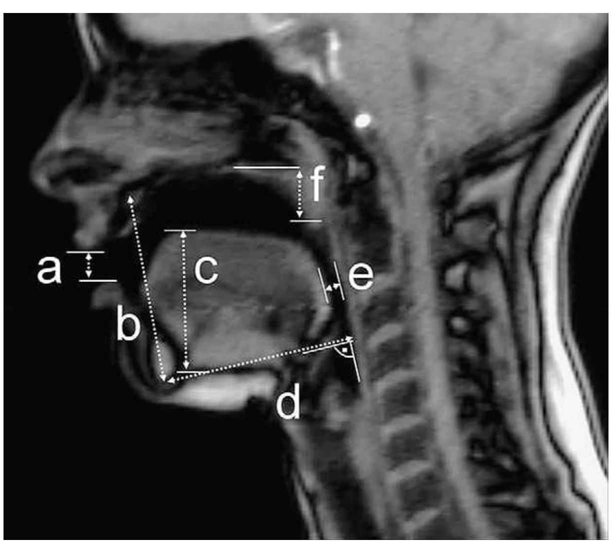

FIGURE 2. Distances measured in the evaluation of the MRI material: (a) lips, (b) jaw opening, (c) tongue dorsum, (d) jaw protrusion, (e) oropharynx width, and (f) uvula elevation.

TABLE 1.
Mean Values and Standard Deviation for Different Measured Distances of Lips, Jaw Opening, Tongue Dorsum, Jaw Protrusion, Pharynx Width, and Uvula Elevation in the Lower Register Transition in All Singers and Both Measured Sequences

				Lips		Jaw Opening		Tongue Dorsum		Jaw Protrusion		Pharynx Width		Uvula	
	Sequence	Shift		Modal	Middle	Modal	Middle	Modal	Middle	Modal	Middle	Modal	Middle	Modal	Middle
Singer 1	1	C#4	Mean (mm)	15.7	14.4	77.2	72.3	58.9	58.4	63.4	63.7	5.3	5.9	23.5	21.8
			SD	1.9	2.2	1.6	1.6	1.3	1.3	0.9	1.7	0.6	0.8	1.2	1.0
	2	C#4	Mean (mm)	16.0	11.5	75.0	67.3	55.7	57.2	66.8	64.6	5.3	5.8	22.5	22.6
			SD	1.4	1.8	4.4	2.4	1.9	1.8	1.7	1.6	1.0	0.9	1.3	1.3
Singer 2	3	D#4	Mean (mm)	24.1	30.4	80.0	88.7	66.3	70.1	55.3	53.0	3.4	3.5	22.1	22.1
			SD	1.3	4.6	0.8	4.2	1.0	1.5	1.2	2.6	0.3	0.5	0.6	0.8
	4	F4	Mean (mm)	19.0	32.0	74.2	85.5	59.0	68.9	59.5	51.2	2.1	2.5	22.0	21.5
			SD	4.4	4.3	5.2	2.6	4.3	2.3	2.9	2.2	0.5	0.4	1.0	1.1
Singer 3	5	A4	Mean (mm)	14.6	14.2	73.6	73.5	55.8	53.3	58.8	59.9	3.0	1.7	20.4	18.5
			SD	2.0	1.3	2.1	1.3	1.4	0.9	1.2	0.7	0.9	0.3	1.4	1.6
	6	A4	Mean (mm)	17.0	17.1	77.9	78.0	55.7	55.4	60.2	62.8	2.6	1.5	18.7	17.0
			SD	1.2	0.7	1.7	2.0	1.9	1.2	1.7	1.3	0.7	0.4	2.6	1.0
Singer 4	7	D#4	Mean (mm)	10.9	13.6	67.1	69.8	50.5	53.4	60.4	60.6	3.6	4.1	20.3	22.5
			SD	0.6	2.1	1.2	2.8	0.9	1.4	1.4	1.4	0.4	0.5	1.4	1.2
	8	D#4	Mean (mm)	12.2	14.9	69.4	69.4	53.0	54.8	60.3	61.3	3.2	3.2	20.5	14.9
			SD	0.9	1.3	0.5	1.4	1.5	1.3	1.1	1.5	0.6	0.5	1.0	1.3

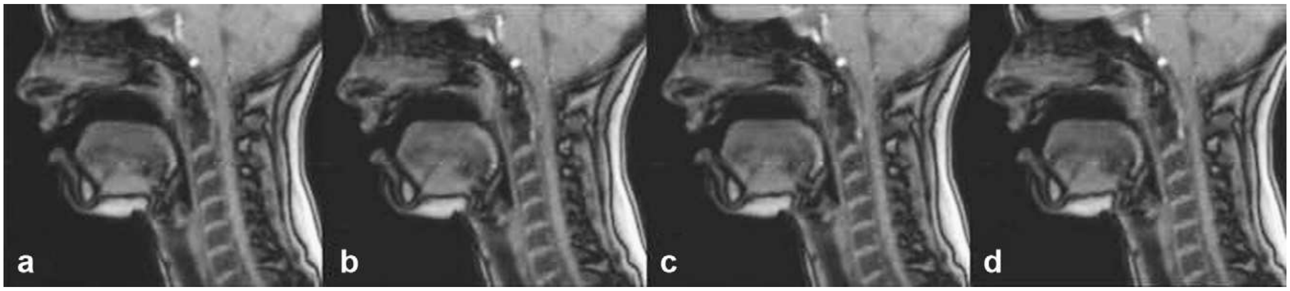

FIGURE 3. MR images taken during the lower transition in singer 4, sequence 1. Pitches: a = B3, b = C#4, c = D#4, d = F#4. The register transition took place between b and c.

were as follows: (1) distance between the lips, (2) jaw opening measured as the distance between the lowermost edge of the jaw bone contour and the anterior end of the hard palate, (3) tongue dorsum measured as the distance between the lowermost edge of the jaw bone contour and the uppermost point of the tongue dorsum, (4) the distance between the lower front edge of the mandible and the contour of the spine at a 90° angle, (5) the pharynx width measured as the distance between the spine contour and the posteriormost part of the tongue contour, and (6) the distance between the hard palate and the lowermost part of the uvula contour.

The relationship between each of these measurements and both pitch and register was analyzed. However, tones sung at $F0 > 750$ Hz were treated separately, because pitch-dependent articulatory modifications could be expected in this range. $F1$ of the vowel /a/ is normally close to 750 Hz, and singers tend to avoid the situation that $F0 > F1$.

For the dependency of lip opening and jaw opening, linear regression was performed. Due to the small number of subjects included (n = 4), comparing statistical analysis for mean values for the distances with respect to the registers was not feasible.

RESULTS

The lower register transition was unanimously identified by the panel (100% agreement) for each of the subjects and sequences. The pitch at which the lower transition was audible identified varied greatly between singers, from C#4 to A4 (Table 1).

Figure 3 shows a selection of typical MRI frames covering the lower transition. Figure 4 presents mean values for the modal and middle registers and Table 1 lists the different parameters measured, averaged for each of the two registers. No clear differences can be observed between these means, although there were individual differences. After the register transition, singer 1 reduced her lip opening, whereas singer 2 increased it. A similar variability was observed with regard to jaw opening.

Also, the upper register transition was unanimously identified by the panel, except for a few sequences. In the different singers, the transition occurred at highly different pitches, ranging from C#5 to G#5. A typical set of MRI frames covering the upper transition is presented in Figure 5. Figure 6 shows mean values for the modal and middle registers, whereas Table 2 lists the different parameters measured, averaged for each of the two registers and frames above 750 Hz.

In the second sequence sung by singer 4, none of the raters was able to identify a register transition, so that no mean value

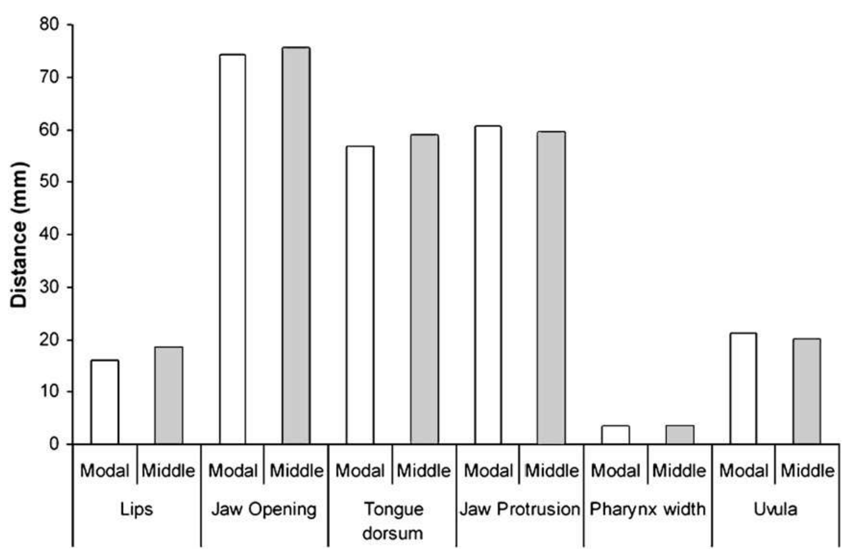

FIGURE 4. Articulatory data, averaged across singers, and observed in the modal and the middle registers (white and light gray columns).

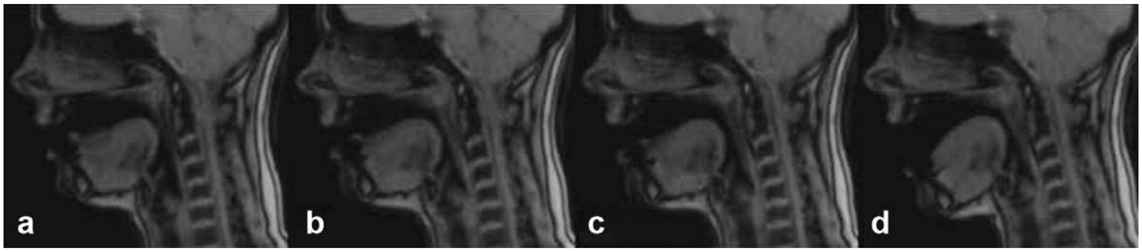

FIGURE 5. MR images taken during the upper transition in singer 1, sequence 1. Pitches: a = C5#, b = D5#, c = F5, d = G5#. The register transition took place between b and c.

of the measurements could be established for the upper register in this case. Hence, in Table 2 all measures for tones above the lower transition and below $F0 = 750$ Hz were classified as "middle register," marking the upper register column with #.

A second difficulty was posed by singer 2, who carried out her register transition above 750 Hz. Even though she retained her middle register above 750 Hz, mean values were calculated only for frequencies up to 750 Hz.

Almost no systematic modification of the vocal tract distances was seen at the transition from middle to upper registers, although individual differences occurred. By contrast, strong vocal tract modifications occurred when the $F0$ reached the vicinity of $F1$. Many cases were observed of a widening of the lip and jaw openings, as well as elevation of the tongue dorsum. A more continuous modification was mostly seen in the elevation of the uvula and in the widening of the pharynx. The lip opening showed a strong correlation with the jaw opening, as expected, see Figures 7A–D.

DISCUSSION

In this descriptive study we have presented, for the first time, dynamic MRI data of female singers' vocal tracts for the lower and upper register transitions. In the previous study mentioned above, dynamic MRI showed no systematic modifications of the vocal tract in male subjects who shifted from modal to falsetto registers.[5] In the present study, we observed very few vocal tract modifications also when our female singers switched from modal to middle or from middle to upper registers. In this regard, these subjects' strategy was similar to what we previously observed in male singer subjects. This suggests that, for the vowel /a/, female and male singers alike do not necessarily change their vocal tract shapes at the modal to middle and modal to falsetto registers, respectively.

Our data were collected from young and internationally not yet well-established singers. It cannot be excluded possible that more experienced singers would exhibit a different behavior.

We chose /a/ as the vowel in our experiment. An important advantage of this vowel was its high $F1$, typically

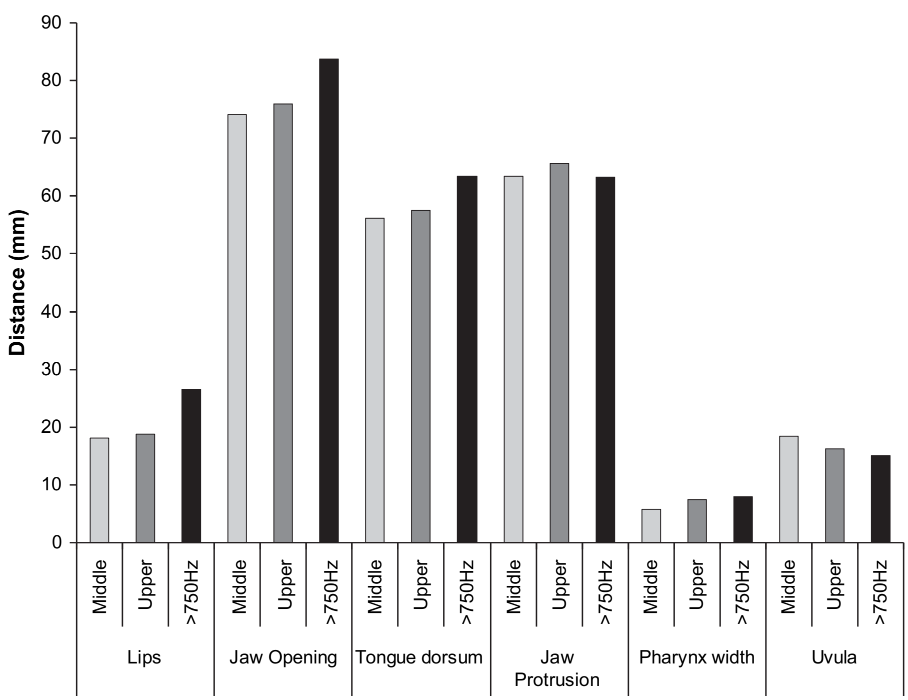

FIGURE 6. Articulatory data, averaged across singers, observed in the middle and upper registers, and at $F0 > 750$ Hz (light gray, dark gray, and black columns) in sequences 1, 2, 5, 6, 7.

TABLE 2.
Mean Values and Standard Deviation for Different Measured Distances of Lips, Jaw Opening, Tongue Dorsum, Jaw Protrusion, Pharynx Width, and Uvula Elevation in the Upper Register Transition in All Singers and Both Measured Sequences

				Lips			Jaw Opening			Tongue Dorsum			Jaw Protrusion			Pharynx Width			Uvula		
	Sequence	Shift		Middle	Upper	>750 Hz	Middle	Upper	>750 Hz	Middle	Upper	>750 Hz	Middle	Upper	>750 Hz	Middle	Upper	>750 Hz	Middle	Upper	>750 Hz
Singer 1	1	F5	Mean (mm)	16.7	20.3	28.9	71.2	76.2	85.2	55.4	56.0	65.5	68.3	70.5	64.8	6.7	10.9	12.3	21.0	18.1	17.3
			SD	1.7	4.1	3.4	1.5	2.5	2.7	1.1	2.2	2.8	2.4	1.5	4.2	1.3	1.1	0.6	2.9	1.4	1.5
	2	C#5	Mean (mm)	17.2	20.3	34.8	70.8	73.0	85.7	56.6	58.6	69.3	68.4	70.7	67.4	9.4	11.5	13.7	19.0	17.8	15.1
			SD	1.3	1.9	3.2	1.6	2.9	3.2	1.7	3.4	1.5	1.3	2.0	2.2	1.1	2.7	1.3	1.8	1.4	0.8
Singer 2	3	F#5	Mean (mm)	16.9	+++	36.7	74.9	+++	92.3	58.4	+++	66.8	68.4	+++	61.0	8.3	+++	8.6	18.2	+++	13.4
			SD	9.1	+++	1.1	8.5	+++	1.1	4.5	+++	1.3	3.1	+++	1.6	2.7	+++	0.9	1.9	+++	0.6
	4	G#5	Mean (mm)	19.6	+++	37.3	74.2	+++	88.2	60.2	+++	66.7	67.1	+++	60.6	7.6	+++	9.2	17.6	+++	14.7
			SD	10.1	+++	1.1	9.8	+++	1.3	5.8	+++	2.1	2.7	+++	1.2	3.5	+++	0.7	1.8	+++	1.4
Singer 3	5	D#5	Mean (mm)	17.3	17.3	21.0	76.8	77.5	79.4	58.3	57.5	55.3	62.3	62.6	65.0	3.2	1.9	2.1	18.5	16.6	15.5
			SD	0.9	0.9	2.7	0.8	0.7	2.1	2.3	0.6	1.9	0.6	1.4	1.7	0.8	0.7	0.9	0.7	1.5	1.1
	6	C#5	Mean (mm)	24.2	16.4	20.6	82.2	77.2	79.9	56.6	55.4	55.9	59.7	61.7	64.5	4.7	2.5	3.0	13.5	11.1	9.3
			SD	2.2	3.3	4.3	1.5	2.7	2.9	1.9	2.1	1.8	2.1	1.7	1.4	1.1	0.9	1.0	3.2	0.9	1.2
Singer 4	7	D#5	Mean (mm)	15.3	20.0	27.9	69.7	75.7	89.1	53.5	59.8	71.5	58.3	62.4	54.3	4.8	10.2	8.7	20.2	18.1	17.7
			SD	0.9	2.2	1.6	0.9	4.5	2.3	1.0	2.4	4.5	2.5	1.9	2.6	1.3	1.2	1.0	2.0	0.9	0.9
	8	§§§	Mean (mm)	18.5	###	29.0	74.7	###	88.9	59.6	###	68.7	62.7	###	55.8	6.3	###	9.9	21.3	###	19.7
			SD	2.4	###	1.5	3.1	###	2.5	3.2	###	2.5	1.9	###	2.3	2.5	###	0.9	1.2	###	1.1

In sequences 3 and 4, the register transition was above 750 Hz. Even though she retained her middle register above 750 Hz, mean values were calculated only for frequencies up to 750 Hz. The column for head register is signed with +++. In sequence 8, no register change was remarked. Measures for tones below $F0 = 750$ Hz were classified as "middle register," marking the head register column with ###.

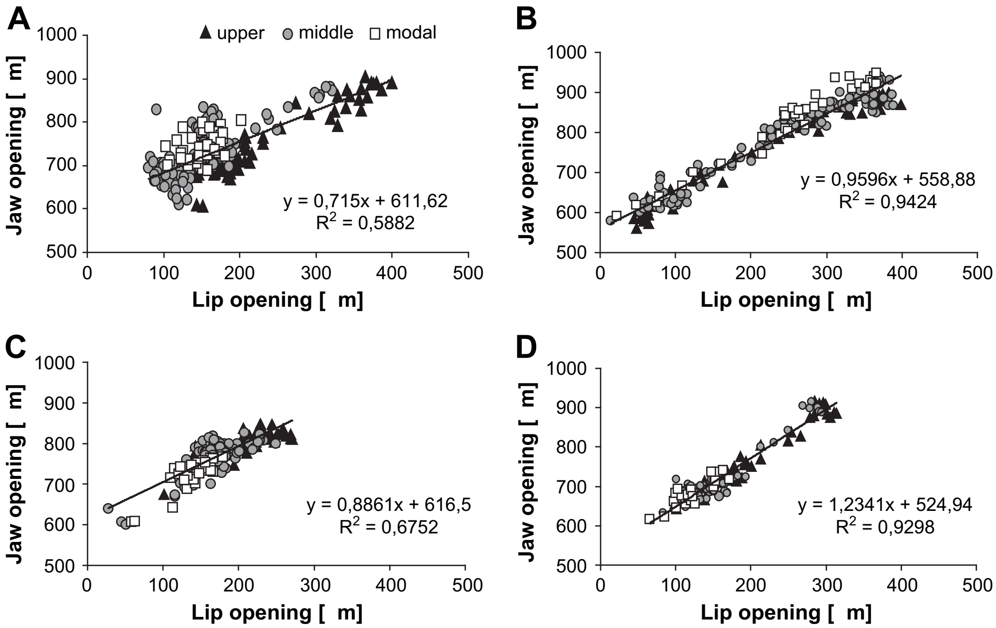

FIGURE 7. (**A–D**) Relationship between lip and jaw openings in subjects 1 (**A**), 2 (**B**), 3 (**C**), and 4 (**D**). The line and the equation refer to the trend line. The data are the values for both the lower and upper transition.

appearing near 750 Hz, which is close to the pitch of F#5. Singers tend to avoid, by articulatory changes, the situation that $F0 > F1$.[9] Hence, articulatory changes motivated by $F0$ being close to $F1$ can be expected in the vicinity of F#5. In some cases, the singers shifted into the upper register at a pitch well below the assumed value of $F1$. In these cases, no articulatory changes were observed that seemed associated with the register transition. This suggests that the upper register transition was not associated with any major articulatory changes.

When the singers reached $F0 > 750$ Hz, they widened their lip and jaw openings, thus increasing $F1$. Simultaneously, three of the four singers continuously widened their pharynges, which should increase $F2$.[10] In addition, the same three singers raised their tongue dorsum, a change possibly associated with the reduction of the pharyngeal constriction. Similar observations were recently made in a baritone when his $F0$ approached the pitch of $F4$ (about 350 Hz) while retaining the modal register.[5] The measure of the tongue is limited by the two-dimensional images. However, because the tongue is a very complex system influencing the vocal tract resonances, 3-D measures are necessary for an exhaustive description. All subjects elevated their uvula for the top pitches. A similar observation was made in a tenor when he kept his modal register also for the top pitches. The acoustic effect of such a uvula elevation on vocal and nasal tract resonances remains unclear. Unfortunately, analysis of formant frequencies by inverse filtering was not feasible, due to the noisy surroundings inside the MRI machine.

Our investigation demonstrates that real-time MRI can be successfully applied for obtaining data on articulatory changes in female singers. However, in the previous investigation of male subjects,[5] we observed that blurred contours prevented measurement of, for example, pharynx length and laryngeal structures. In the present study, we made the same experience. Thus, some structures crucial to phonation and formant frequencies could not be measured by this MRI technique.

CONCLUSIONS

In the present investigation, we observed no systematical changes of the vocal tract shape when young female professional soprano singers shifted their register from modal to middle and from middle to upper registers on the vowel /a/. In this respect, they showed an articulatory behavior similar to that previously observed for a professional baritone and for a professional tenor singer. On the other hand, the sopranos changed their vocal tract shape considerably as the fundamental frequency approached the frequency of the first formant.

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