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Sound Radiation of Human Voices in Singing

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Abstract - A topic addressed in this paper is in general how the sound energy of human voices radiates in singing. In particular, we were interested in whether sound radiation from singers is restricted to the mouth. Furthermore, it was investigated whether there are differences among vowels, pitches, and between classical and nonclassical styles of singing. For this study, the sound energy of seven trained singers from four musical genres was measured at 15 parts of the upper body while they sang five vowels (a – e – i – o – u) at different pitches in accordance with their voice classification. In this investigation, a microphone array of 121 microphones was used and the gained information was analyzed using the Minimum Energy Method and Mathematica by which the radiating field and radiation patterns could be visualized. The results showed that the main source of the radiation energy of singing voices is the mouth, as expected, but strong energy can arise from other parts of the body as well. Furthermore, the research findings indicated that the radiation energy of singing voices change according to the frequency analyzed, the vowel, the pitch that is sung, and the person who sings.

Keywords: Human Voice, Singing Voice, Sound Radiation, Microphone Array, Minimum Energy Method

1 INTRODUCTION

In our daily life, we receive various acoustical signals through the air, including the sound of the human voice. The human voice is one of the most important communication mediums to convey feelings or impressions of the speaker or singer [12]. Each voice art, such as “speaking voice” or “singing voice,” and each voice quality, like pressed or husky, occurs from the body; i.e., the same organs (e.g. vocal cords, vocal tract etc.) are used for each production of the voice. However, there are some differences not only between speaking voice and singing voice, but also among voice qualities which arise due to their desired purpose. For example, singers must produce a specific volume, and therefore they use their body as a “musical instrument,” adjusting body parts in a desired way. Especially, classical singers must acquire the ability to surpass the volume level of a loud orchestral accompaniment, for their singing voice to reach the audience. Thus it is essential to acquire expertise for the development of their vocal ability. In contrast, nonclassical singers usually use a microphone while singing, so that the vocal instrument is used for communicative purpose just like in spoken communication, but with music.

However, the fact is that each singer’s voice comes from the body while singing and that the mouth is the main source of its radiation energy. In the process of singing, the mouth is working as a mouth piece, comparable to the mouth piece of a trumpet [1]. But the sound can still be audible, even when it is hummed with closed lips. The energy has to be radiated somehow, otherwise the sound would barely be audible. Another interesting fact is that singers sometimes remark that certain parts of their body tend to vibrate while singing. What about such vibrations? Are these vibrations radiated and what is their strength in the total energy of the singing voice? Or is sound radiation from singers actually restricted to the mouth?

In addition, singers also remark that the strength of such vibrations vary in correlation with the vocal technique, the pitch, and the vowel used. Hence it can be expected that the pattern of sound radiation changes if a singer adopts a different vocal technique or sings a different vowel or tone at a different pitch. But, is that actually so, as most musical instruments have complex patterns of sound radiation, which change with direction, pitches played, and other factors?

Therefore, for a better understanding about the origin of radiation energy of the singing voice, the topic addressed in this study is mainly how strong the radiation energy of the singing voice from the upper body is, in comparison to the mouth radiation, and whether the radiation energy of a singer’s voice varies according to vocal technique, pitch, and vowel.

2 PREVIOUS RESEARCH METHODS

In the past, the topic whether the vocal sound energy is restricted to the mouth only, has been studied repeatedly (e.g. [2]-[7]). These studies found out that the sound vibration depends on the vowels because of the mouth aperture size and on the pitch. Furthermore, stronger vibration was also observed at loud vocal sound. In addition, there are also many researches on voice directivity of singing voices (a review of recent studies can be found [12]). But in this work, we focus just on the vibrations of the singer’s body while singing.

The previous studies on this topic have mostly been executed using an accelerometer, with which the energy of each desired part of the body has been measured. In order to yield an accurate result from each desired part of the body, a measurement using an accelerometer is certainly a suitable research method. But our investigation was executed by means

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of a microphone array with 121 microphones, the so-called Acoustic Camera, because using a microphone array has three advantages which would be ideal for the purpose of this research [8]:

- It is a non-invasive method.
- It enables us to see the radiation field of the radiating source.
- The recorded data can be used to back-propagate the sound field to the surface of the radiating source, so the sound pressure level from the mouth and the vibrating body structures of the singers are directly comparable.

The method which uses a microphone array is commonly used in musical instrumental acoustics nowadays. However, in vocal acoustics, the use of a microphone grid seems to be standard and the research method using an acoustic camera is still relatively new, particularly in the size with 121 microphones.

3 AIM, METHOD AND RESEARCH MATERIALS

3.1 Aim

Mainly, this study attempted to find an answer to the following questions:

- Is it true that the main sound energy of the singing voice only radiates from the mouth? Or are there other body parts involved in the sound radiation of the singing voice?
- If so, are there recognizable differences depending on vocal music genres /singing techniques and vowels?
- How strong is the sum of the radiated energy from all the measured parts of the body in relation to the mouth radiation?

Additionally, another analysis was executed, because the radiation energy originated from the corners of the mouth has presumably a strong influence on the total energy, due to the proximity of these parts to the mouth. Therefore, the question is:

- What about the radiation energy excluding the corners of the mouth?

3.2 Method

The microphone array, which was employed in our investigation, consists of 121 microphones (11 x 11) and the array spacing is a regular grid with a grid constant of 3.9 cm. This construction enables a symmetric visualization of the radiating field later. The microphones record simultaneously with a sampling frequency of 48 kHz, thus covering whole human hearing range up to 20 kHz. This is a very important factor for measurements of musical instruments including singing voice, because musical instruments often radiate high frequency and initial transients are often the most important part of the sound [8].

After the recording, the data obtained by the array were used to back-propagate the sound field to the radiating source surface by means of a near-field method, the so-called Minimum Energy Method [8], for reconstructing a sound pressure field at a radiating surface of musical instruments including the human body for voice research. It samples the source plane by as many equivalent sources as the microphones present in the Acoustic Camera. This method enables a reconstruction of sound pressure fields and a visualization of an overall radiation directivity of a vibrating geometry.

For the analysis, a code written in Mathematica was applied to all the data and the vibrations were analyzed on a total of 15 parts of the upper body (mouth / chin / throat / left and right clavicles / sternum / nose / nasal bone / left and right corners of the mouth / left and right cheeks / forehead / left and right lower eyelids). This setting made it possible to show energy values of the voice radiation from the singer's upper body, including the phase angles and all statical procedures are based on those visualized results. The data are reconstructed and visualized on a photo of the human upper body from the head to the chest.

Furthermore, the strongest radiated area was color-marked: the radiation is adjusted up to -6 dB and the intensity of the radiation energy is visualized by colors (the brighter the color, the stronger the radiated energy). Usually the radiation from the mouth is the strongest, so that the radiated energies of all single frequencies were therefore normalized to 0 dB at the mouth, but there were some figures where the energy value at the mouth is shown in -1 dB. This means that the revealed energy value is not quite 0 dB, so somewhat stronger than 0 dB.

Both, Acoustic Camera and the Minimum Energy Method were developed at the Institute for Systematic Musicology, University of Hamburg, and all information about these recording and analysis techniques can be found in the publications of the developer Rolf Bader (Detailed description about the Acoustic Camera and the Minimum Energy Method as well as exemplary measurements can be found e.g. in [8]-[14]).

3.3 Research Materials

Seven trained singers — three classical, two musical theater, and two popular singers — participated in this study and one popular singer's voice (subject: VS) was recorded twice by means of popular singing technique and by means of Soul singing technique:

1. CH (classical, female, alto)
2. SE1 (classical, female, soprano)
3. JR (classical, male, bass)
4. SS (musical theater, female, mezzo soprano)
5. TF (musical theater, male, tenor)
6. SE2 (Pop, female, mezzo soprano)

7. VS (Pop, female, mezzo soprano)

8. VS (Soul, female, mezzo soprano)

For the study, after a short warming-up vocal exercise, each subject sang five vowels a/e/i/o/u at the following fundamental frequencies;

- 90 Hz (bass), analyzed up to 1.3 kHz (15 partials)
- 120 Hz (males), analyzed up to 2.5 kHz (21 partials)
- 180 Hz (alto/mezzo), analyzed up to 3 kHz (17 partials)
- 250 Hz (all subjects), analyzed up to 4 kHz (16 partials)
- 380 Hz (tenor), analyzed up to 4.5 kHz (12 partials)
- 500 Hz (females), analyzed up to 5 kHz (10 partials)

Each vowel was recorded separately and max. 2 seconds of phonation. In order to get good data, the vowels were repeatedly measured two or three times in the order of a-e-i-o-u, respectively. The measurement was executed in an anechoic chamber. For the recording, the microphone array was attached to the front of a stand and adjusted for the height of the singer, so that their mouth is positioned in front of the center microphone (No. 61). As already mentioned, the Minimum Energy Method is a near-field method, and therefore the center microphone was placed 3 cm in front of the mouth.

We would like to indicate that Takada and Bader have already done research on the radiation energy of singing voices in the same way [15]-[16]. However, the former was just a study on the radiation energy of singing at a fundamental frequency of 250 Hz. For the latter, we examined sound radiation of singing at other fundamental frequencies as well, i.e., like this study. But, only research findings from first analyses were displayed in [16], so that for this paper, further and more particularizing analyses were executed and their results will be shown in the following.

4 RESULTS

The data gained from the measurement was analyzed from various points of view and displayed in different forms, so that the research findings will be shown in two ways. But before starting the discussions, we would like to introduce some abbreviated terms, because of a lack of space in the lists :

- left and right clavicle = LC and RC
- nasal bone = N.Bone
- left and right corner of the mouth = LCoM and RCoM
- left and right cheek = LCh and RCh
- left and right lower eyelids = LLE and RLE

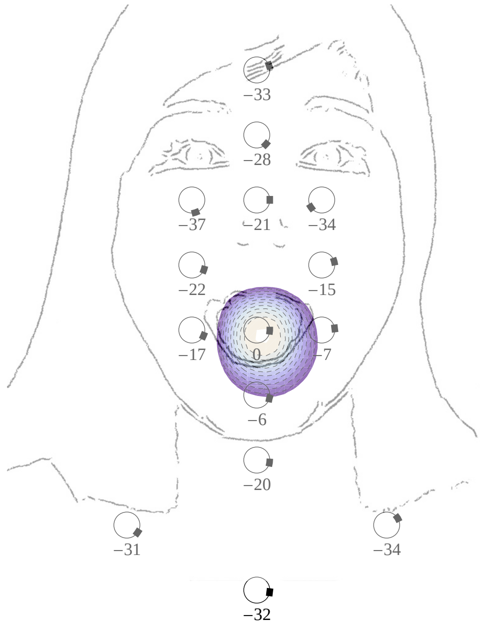

Figure 1: Radiation of a classical soprano (subject: SE1) at a fundamental frequency of 250 Hz for the vowel /a/.

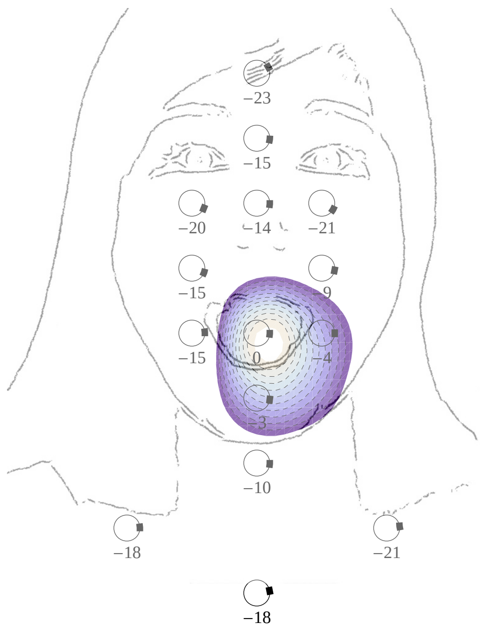

Figure 2: Radiation of a classical soprano (subject: SE1) at a fundamental frequency of 500 Hz for the vowel /a/.

Table 1: Process of the sound energy of a female musical theater singing (subject: SS) at a fundamental frequency of 250 Hz (in dB). The energy values shown in blue increase or decrease more than 10 dB compared to the energy value at the previous or subsequent frequency.

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
/a/														
250 Hz	-18	-37	-52	-59	-43	-35	-35	-22	-29	-27	-34	-51	-31	-48
1000 Hz	-13	-29	-38	-33	-36	-27	-29	-20	-15	-23	-43	-39	-28	-40
2000 Hz	-12	-26	-25	-30	-31	-22	-26	-15	-21	-21	-29	-32	-25	-35
3000 Hz	-9	-20	-19	-23	-23	-18	-19	-8	-15	-13	-21	-21	-26	-26
4000 Hz	-12	-22	-25	-29	-26	-22	-23	-8	-12	-12	-12	-21	-26	-19
/e/														
250 Hz	-20	-38	-51	-51	-41	-33	-34	-27	-16	-28	-24	-47	-30	-47
1000 Hz	-15	-30	-37	-34	-34	-28	-27	-19	-7	-20	-21	-34	-26	-36
2000 Hz	-14	-24	-25	-29	-30	-22	-27	-16	-12	-17	-29	-32	-25	-32
3000 Hz	-14	-22	-20	-24	-23	-19	-21	-12	-14	-14	-26	-21	-25	-29
4000 Hz	-11	-21	-27	-29	-26	-20	-23	-8	-15	-11	-13	-21	-29	-21
/i/														
250 Hz	-32	-39	-52	-55	-44	-39	-37	-26	-17	-40	-29	-49	-34	-54
1000 Hz	-27	-33	-41	-47	-41	-33	-36	-25	-11	-32	-25	-36	-30	-34
2000 Hz	-24	-26	-32	-34	-34	-25	-29	-17	-11	-24	-33	-37	-27	-30
3000 Hz	-15	-22	-22	-24	-24	-20	-21	-13	-11	-16	-29	-23	-25	-29
4000 Hz	-14	-24	-26	-28	-31	-22	-24	-8	-13	-13	-16	-20	-25	-21
/o/														
250 Hz	-26	-52	-54	-57	-48	-42	-42	-24	-22	-42	-44	-56	-39	-52
1000 Hz	-23	-34	-43	-40	-42	-34	-36	-22	-15	-35	-34	-44	-33	-47
2000 Hz	-5	-15	-22	-21	-22	-15	-25	-6	-4	-11	-13	-27	-15	-18
3000 Hz	-12	-22	-21	-25	-25	-21	-20	-11	-8	-19	-26	-24	-25	-27
4000 Hz	-22	-27	-27	-30	-31	-24	-28	-15	-14	-18	-18	-24	-27	-22
/u/														
250 Hz	-23	-53	-53	-63	-47	-38	-41	-22	-24	-37	-43	-54	-38	-48
1000 Hz	-18	-34	-40	-41	-40	-33	-37	-20	-14	-30	-29	-44	-34	-42
2000 Hz	-8	-26	-29	-20	-25	-21	-26	-7	-6	-16	-16	-37	-15	-20
3000 Hz	-13	-20	-23	-25	-26	-20	-21	-14	-8	-18	-27	-23	-21	-25
4000 Hz	-16	-24	-24	-21	-27	-23	-26	-13	-16	-19	-18	-28	-23	-21

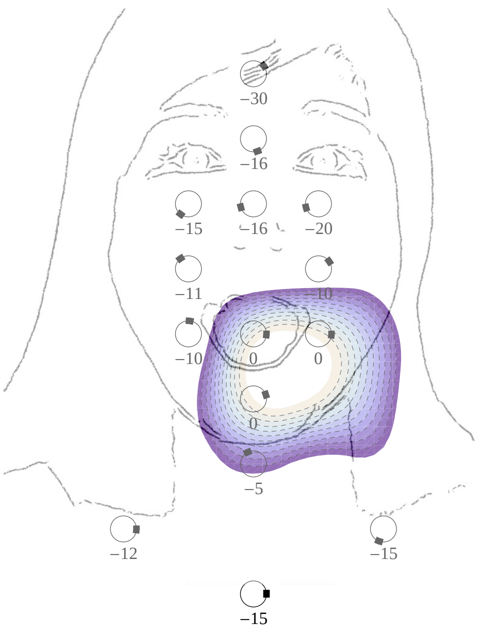

Figure 3: Radiation of the 7th partial singing by a classical soprano (subject: SE1) at a fundamental frequency of 500 Hz for the vowel /a/.

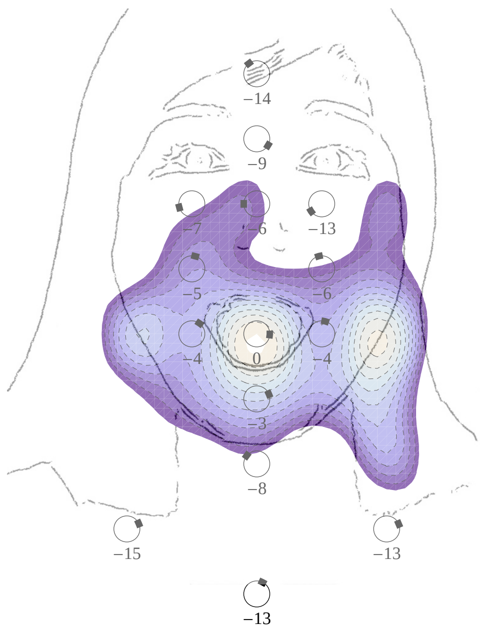

Figure 4: Radiation of the 10th partial singing by a female Pop singer (subject: SE2) at a fundamental frequency of 500 Hz for the vowel /e/.

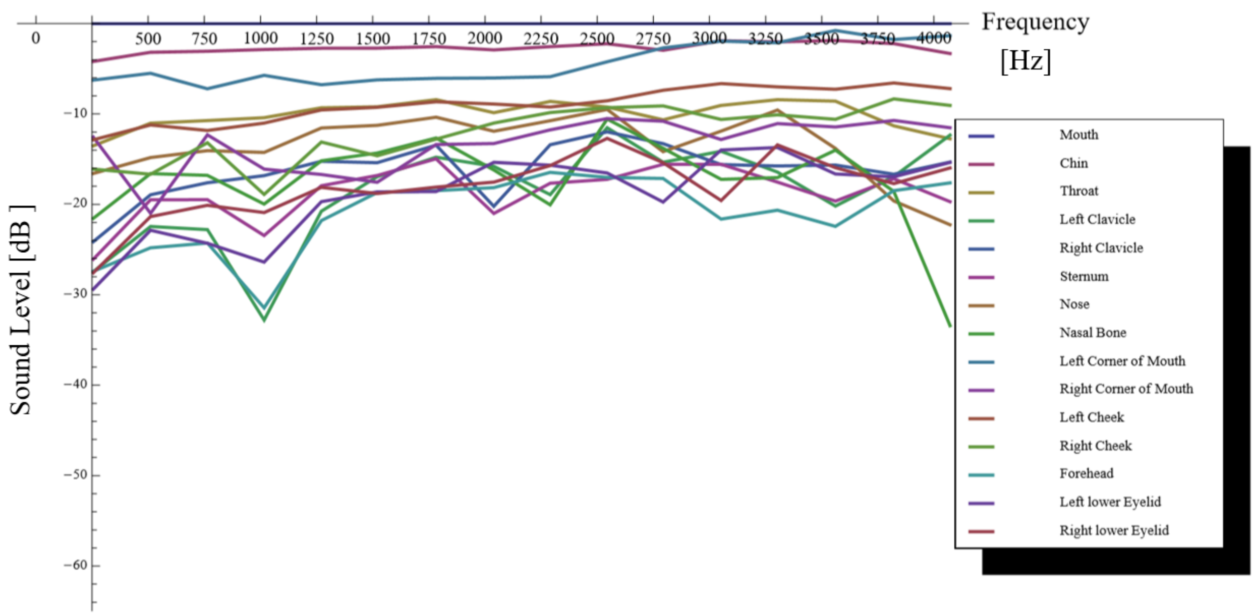

Figure 5: Sound levels of 14 measured parts of the body sung by a classical soprano singer (subject: SE1) relating to the radiation from the mouth (0 dB) at a fundamental frequency of 250 Hz for the vowel /a/ (color-coded sound levels of the parts from top to bottom shown at 250 Hz on the y-axis: chin / left corner of the mouth / right corner of the mouth / left cheek / throat / right cheek / nose / nasal bone / right clavicle / sternum / forehead / left clavicle / right lower eyelid / left lower eyelid).

4.1 Source of the Radiation Energy in Singing

At the fundamentals, it seems for all the subjects that the strongest radiation energy of their singing voice (color-coded area) came uniformly from the mouth, as shown in Figs. 1 and 2. It was already expected that the mouth is generally the strongest radiation source of the singing voice. In addition, the corners of the mouth often vibrated strongest of all the measured parts except the mouth due to their spatial closeness to the mouth, in fact independent of vowel. In general, it was revealed that the closer to the mouth the measured part of the body, the stronger the radiation energy.

Furthermore, when singing at higher pitches, the radiation energy increased in total in comparison to that revealed from singing at lower pitches, so that strong radiation energy came from a large area of the lower part of the face (see Fig. 2). Therefore, by means of visualizing the strongest radiating area up to -6 dB that was marked in color, it is clearly noticeable that the area of strong radiated energy shown at the fundamental became large with increasing pitch that was sung.

The finding that for singing at high pitch, the radiation of the singing voices became stronger at high frequencies, is presumably caused by the high lung volume and high-speed opening and closing of the vocal folds at the pitch, so that strong sound pressure will be produced by these factors. This is just what Sundberg asserted, although the body regions concerned are not confirmed by his recognition: very strong sound pressures in the vocal tract and in the trachea generate the phonatory vibrations in the skull, neck, and chest regions [17].

Because of the higher sound pressure caused by singing at high pitch, it was observed that the radiation energy from some parts of the body can be as strong as that from the mouth at higher partials, as shown in Figs. 3 and 4. Such radiation energy was observed by a shift or an enlargement of the strongest radiated point (radiator), thus from the mouth to other face / body regions, or emergence of multiple energy sources that were often found in the case of the fundamental frequency of 500 Hz, especially. This can be a temporary, but also as a continuing phenomenon.

The radiation patterns observed in our study revealed that the sound radiation changes depending on the frequency, and that the energy from the region of the body outside of the mouth increases strongly up to about 3 kHz, as shown in Figs. 5 and 7, and Table 1. The chin and the corners of the mouth were the parts showing the strongest radiation of energy of the 14 measured parts of the body (except for the mouth radiation), and the radiation from the chin often remained almost unchanged in the whole frequency range analyzed, so that the difference between its maximum and minimum was relatively small. However, it was found that the radiation energy of the parts of the body that are located far away from the mouth, increases dramatically and fluctuates strongly compared to the parts which are in the place near the mouth. This sometimes resulted in a difference of more than 20 dB between the maximum and minimum energies at these parts.

The strong radiation energy from the measured parts of the body at high frequencies is presumably related to the fact

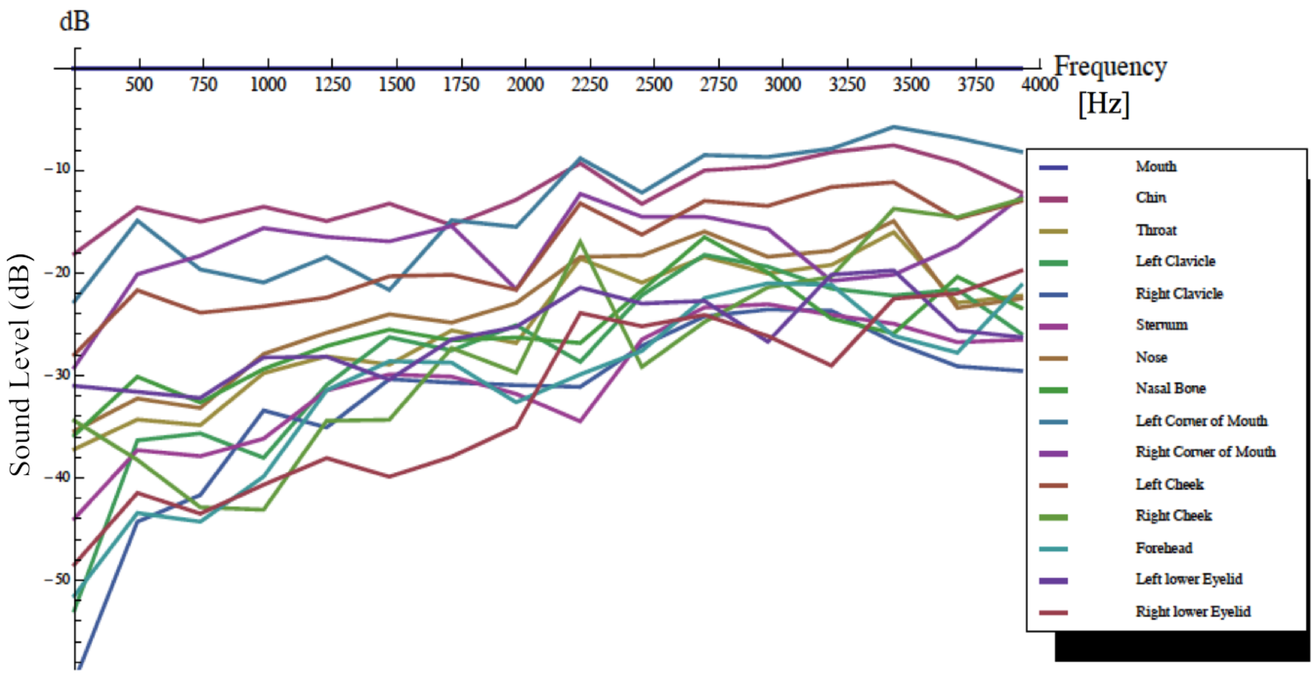

Figure 6: Sound levels of 14 measured parts of the body sung by a female musical theatre singer (subject: SS) relating to the radiation from the mouth (0 dB) at a fundamental frequency of 250 Hz for the vowel /a/ (color-coded sound levels of the parts from top to bottom shown at 250 Hz on the y-axis: chin / left corner of the mouth / left cheek / right corner of the mouth / left lower eyelid / right cheek / nasal bone / nose / throat / sternum / right lower eyelid / forehead / left clavicle / right clavicle).

that the partials at high frequencies radiate forwards, whereas these at low frequencies are emitted almost equally in all directions, as reported by Marshall and Meyer [18].

However, when it comes to the dimension of energy increase, there were large differences among the vowels and individuals. While the progress of the vowels /a/e/i/ was a smooth increase, that of the vowels /o/ and /u/ showed a strong zigzag-like course (see Figs. 5, 6 and 7, and Table 1. The energy from the mouth shown in both figures is displayed at zero on the x-axis (dark blue line).). This fluctuation was visible at all the parts of the body in many cases. Presumably, there were complicated air motions in the vocal tract due to the narrowing of the mouth opening and configuration changes of the vocal tract for these vowels. During the repeated recording and the analysis of both vowels, we heard and found a pronunciation with more air / noise in comparison to a pronunciation of the other recorded vowels, especially in case of nonclassical singers. But, only the results that are usable for this research were analyzed in this study, and therefore, such a zigzag-like course of both vowels is caused rather by complicated air motions in the vocal tract than by noises.

As mentioned above, the dimension of the energy increase was also different in each individual case. Some subjects showed a strong energy value from the beginning, i.e., from the fundamental frequency, so that their energy only slightly increased in comparison to the rest. For example, for classical singers, their energy levels gained from all the parts of the body were relatively close to each other for all the vowels, so that the difference of these energy levels was smaller among the measured parts in comparison to the nonclassical singers (see Figs. 5 and 7. The energy from the mouth is shown at zero on the x-axis (dark blue line).). Therefore, for the classical singers, there was no large increase of the energy from the region of the body outside of the mouth in the frequency range analyzed, in comparison to the energy of the nonclassical singers. This implies that the energy of classical singers radiates rather from their whole upper body while singing.

In regards to the difference in musical genre, the radiation energy of the nonclassical singing techniques for the vowels /o/ and /u/ strongly originates from the mouth area, i.e., from the corners of the mouth and the chin. This is clearly noticeable from the progress of the radiated energy, because there was a large difference in the energy level between these parts of the body and the rest of the parts measured, as shown in Fig. 7 (Top three lines are the results from the corners of the mouth and the chin). Presumably, this is due to different mouth/lip opening: classical singers usually hold the shape of their mouth/jaw opening as constant as possible for all vowels in order to keep certain vocal loudness and beauty of the voice, independently of the changing pronunciation of vowel sound. This difference in musical genre was observed distinctly at low pitch than at high pitch that is sung, likely due to the wider mouth opening at higher pitch.

In our study, we observed fluctuations of radiated energy of the singer's voice in the frequency range analyzed and ascertained that the radiated energy changes depending on the

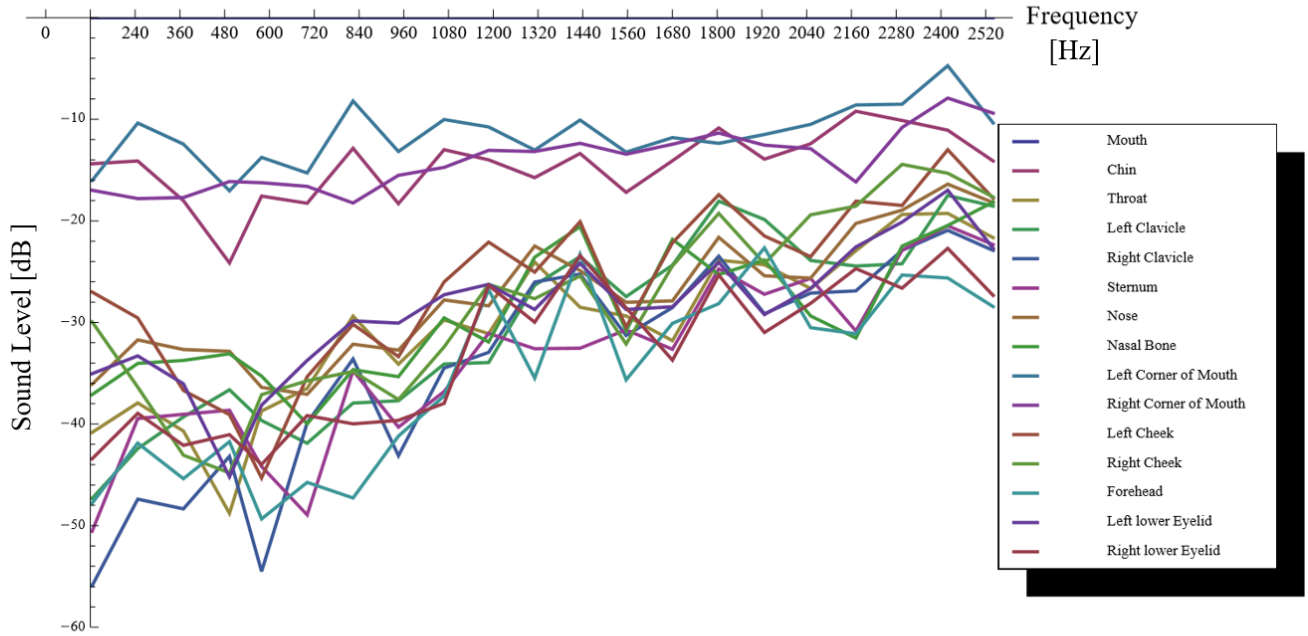

Figure 7: Sound levels of 14 measured parts of the body sung by a male musical theater singer (subject: TF) relating to the radiation from the mouth (0 dB) at a fundamental frequency of 120 Hz for the vowel /u/ (color-coded sound levels of the parts from top to bottom shown at 120 Hz on the y-axis: chin / left corner of the mouth / right corner of the mouth / left cheek / right cheek / left lower eyelid / nose / nasal bone / throat / right lower eyelid / left clavicle / forehead / sternum / right clavicle).

frequency. There it was shown where increasing and decreasing points are located in the frequency range, but because of the steady fluctuations, it was not so easy to realize the location of a minimum and maximum of the radiated energy. Therefore, the locations of these points of each involved subject – where these energies are located in the frequency range analyzed and how many participants showed their minimum and maximum energy there – are listed in Table 2. The numbers of the concerned participants are shown in red (minimum energy) and blue (maximum energy), respectively (there it is possible that there are several color-coded numbers in the tables, when multiple minimum or maximum result are therein. But in the case of spread results where all the subjects showed different results; i.e., there is neither a minimum nor a maximum number, none of the numbers are color-coded.).

This analysis revealed a rough relationship between sung pitches and the change of the frequency range where the minimum of the radiated energy was located, as the results from the vowel /a/ displayed in Table 2: in the cases of the fundamental frequency of 90 Hz (a single case study by a classical bass singer), 120 Hz, 180 Hz and 250 Hz, the minimum energy was located at the fundamental frequency, unlike the measurements at the fundamental frequency of 380 Hz (a single case study by a male musical theatre singer) and 500 Hz where this was not the case. In contrast, the maximum of the radiated energy was mostly located in the frequency range from 3 kHz and this was almost unchanged at each pitch, even though the frequency range analyzed varied according to the pitch that was sung. However, this localization differs slightly from vowel to vowel.

In other respects, the difference of the radiated energy amount among the singers revealed at the fundamental frequency becomes smaller at higher frequencies, even though a low energy value was observed at certain parts of the body at the fundamental frequency. For example, the sound levels of all measured parts of a classical soprano singer showed between ca. -4 and -30 dB (see Fig. 5) at the fundamental frequency of 250 Hz, whereas these of a female musical theatre singer were located between ca. -18 and -60 dB (see Fig. 6). But, at the 10th partial (2500 Hz), the difference of their sound levels is narrowed significantly, so between ca. -3 and -20 dB for the former and ca. -12 and -30 dB for the latter, respectively. Such a phenomenon is caused by a powerful energy increase of the subjects in the higher frequency range who actually revealed low energy values at their fundamental frequency (see also Fig. 7).

Furthermore, from the analysis of the minimum and maximum energy of the measured parts, it was found that there is a convergence of radiated energy values from all these parts in the frequency range between 2 kHz and 4 kHz (see Figs. 8 and 9, and Table 1). For example, in the case of the vowel /a/ sung by a female musical theater singer (SS) at the fundamental frequency of 250 Hz, the maximum and the minimum of the sound level indicated -18 (chin) and -59 dB (right clavicle) at 250 Hz, respectively (see Table 1). The difference of energy values from both parts was 41 dB. However, the difference between the minimum and the maximum of the sound level becomes smaller at higher frequencies (1000, 2000, 3000 and

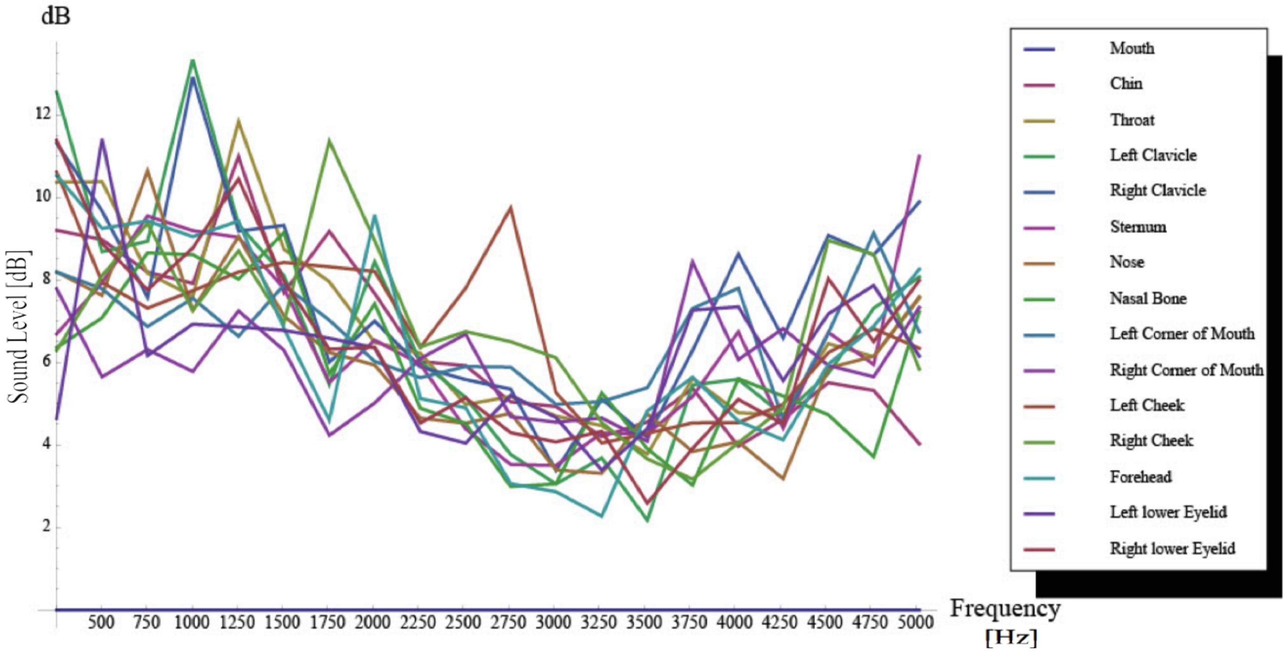

Figure 8: Difference of the radiation energy among the subjects, yielded from each part measured at a fundamental frequency of 250 Hz for the vowel /i/.

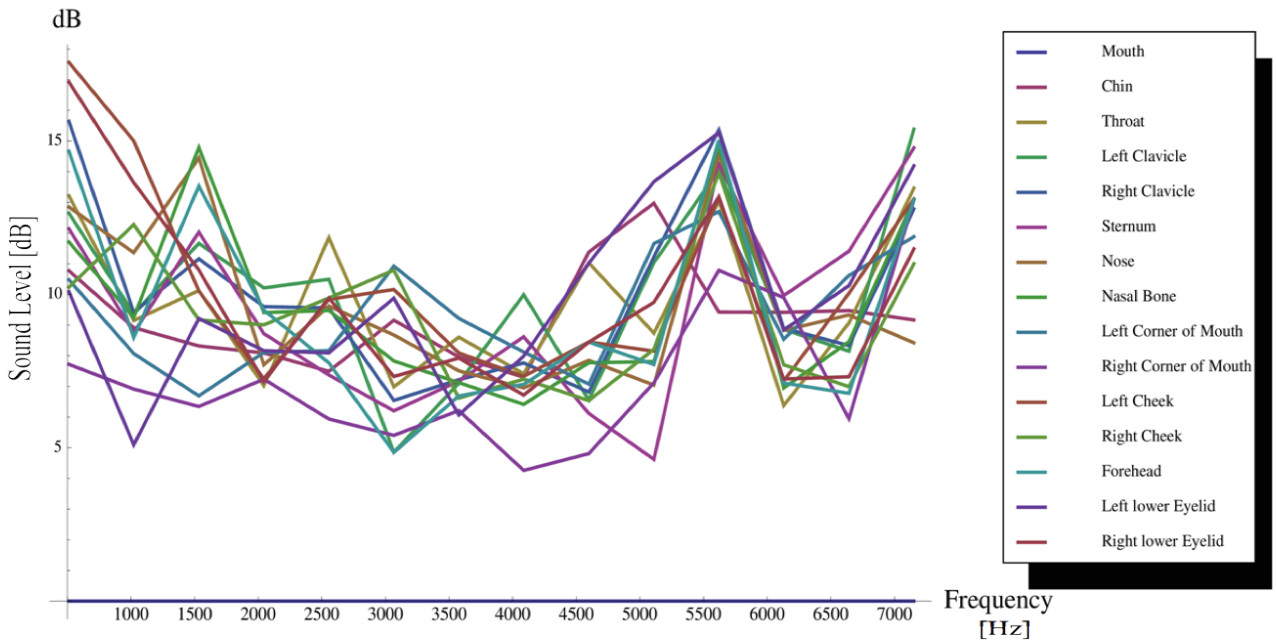

Figure 9: Difference of the radiation energy among the subjects, yielded from each part measured at a fundamental frequency of 500 Hz for the vowel /u/.

Table 2: Localization of the minimum (top) and maximum (bottom) of the radiated sound energy for the vowel /a/ singing at a fundamental frequency of 120, 180, 250, and 500 Hz shown by the number of participating subjects. The number of participating subjects (n) is displayed in the left column beside the sung fundamental frequency.

Localization of the minimum energy

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
Fundamental 120 Hz, n = 2														
120 Hz	1	2	1	2	2	2	2	1	2	1	1	2	1	2
1000 Hz			1							1				
1500 Hz	1						1	1			1		1	
2000 Hz	1							1						
2500 Hz														
Fundamental 180 Hz, n = 4														
180 Hz	3	3	1	3	4	4	4	4	1	3	3	2	3	3
1000 Hz			2	1	1			2			2	1	1	
2000 Hz	1	1	1	1			1			1		1		1
2500 Hz									1				1	
3000 Hz									2					
Fundamental 250 Hz, n = 8														
250 Hz	7	7	4	7	8	7	6	6	3	7	5	7	7	7
1000 Hz			3					2	2	1	4	1		
2000 Hz	2	1	1					3	1	1		1		1
3000 Hz									1					
4000 Hz	1			1		2	2		1			1	1	
Fundamental 500 Hz, n = 6														
500 Hz	1	1		2		3			1	3	2	1	3	2
1000 Hz	1		5		3			3	2	2	2	3	2	1
2000 Hz	2	2	1	2	2	1	1	2	2	2	1	1	1	1
3000 Hz				1					1		1			2
4000 Hz	2	2		1	1	3	5		1					
5000 Hz	1	1					1	1				1		

Localization of the maximum energy

	Chin	Throat	LC	RC	Sternum	Nose	N.Bone	LCoM	RCoM	LCh	RCh	Forehead	LLE	RLE
Fundamental 120 Hz, n = 2														
120 Hz														
1000 Hz														
1500 Hz														
2000 Hz	1	1	1	1	1	1		1	1	1	1	1	1	1
2500 Hz	1	1	1	1	1	1	2	1	1	1	2	1	1	2
Fundamental 180 Hz, n = 4														
180 Hz		1							1	1		1		
1000 Hz									1				1	1
2000 Hz	2	2	2	1	1	1	1		1	1	2	1	2	1
2500 Hz		1	3	2		3	3		2		2	1	1	2
3000 Hz	3	3	2	1	3	1	2	4		2	1	1	1	1
Fundamental 250 Hz, n = 8														
250 Hz	1	1								1		1	1	1
1000 Hz								1	1					1
2000 Hz	2	1				2	1	1				1	1	
3000 Hz	4	6	3	6	7	6	6	4	2	4		5	4	1
4000 Hz	2	3	4	3	1	1	1	4	6	6	7	3	2	6
Fundamental 500 Hz, n = 6														
500 Hz			1				1		1	1		1	1	
1000 Hz	1			1					1					
2000 Hz	1	1	2			1	1					2		
3000 Hz	1		2	2	1		1	2		1	1			
4000 Hz	1	1	2					3	3	1	3	2		2
5000 Hz	6	4	1	3	5	5	4	3	1	4	2	2	5	5

4000 Hz), so that its difference was just 18 dB at 3000 Hz (the maximum: -8 dB at the left corner of the mouth, the minimum: -26 dB at both lower eyelids). The convergence of radiated energy values from all these parts in the frequency range can be seen clearly in Figs. 8 and 9. This finding shows that the difference of the radiated energy among the parts is smallest there due to its energy increase compared to the mouth radiation.

4.2 Total Radiation Energy from Measured Parts of the Body in Comparison to the Radiation Energy from the Mouth

When it comes to the sum of the radiated energy from all the measured parts of the body in relation to the mouth radiation, all the subjects showed that the total energy of their singing voice can exceed the energy from the mouth (see the upper diagram in Fig. 10. The result was compared to the mouth radiation, and thus, the line above zero point means that the total radiation energy is stronger than the radiation energy from the mouth.). But the energy level strongly depended on the frequency analyzed, the vowel and the pitch that was sung, just like the research findings shown in Subsection 4.1.

Comparing the radiated energy from the mouth with the total energy from all the parts excluding the energy from the corners of the mouth (i.e., energy from the following parts is included in this total energy: chin / throat / left and right clavicles / sternum / nose / nasal bone / left and right cheeks / forehead / left and right lower eyelids) made it clear that the energy from the corners of the mouth has a strong influence on the total energy of the singing voice (see the lower diagram in Fig. 10). Particularly, this influence seemed to be strong for the vowels /o/ and /u/. There was a large difference

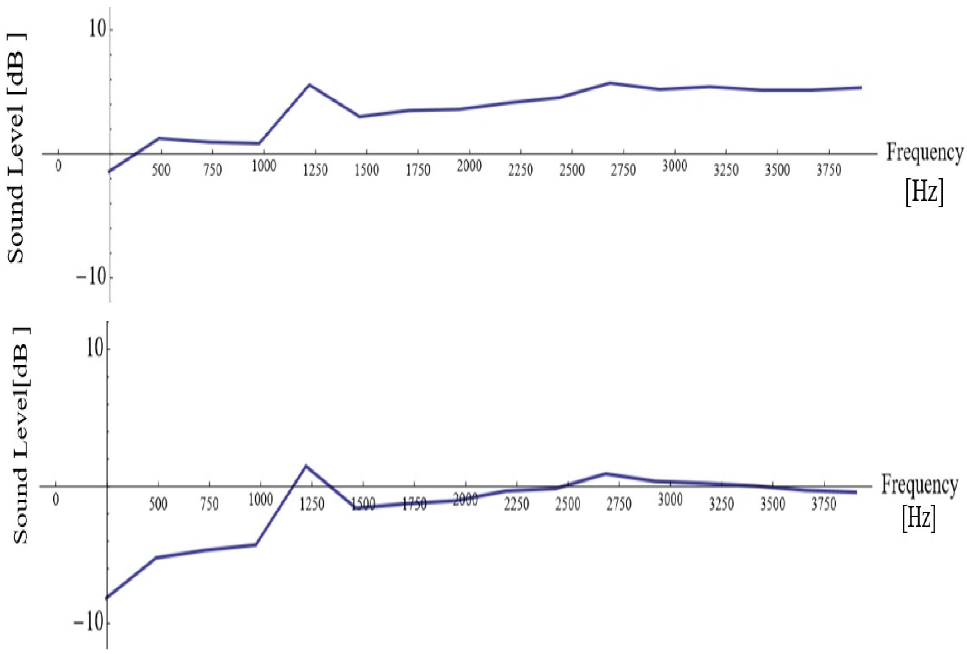

Figure 10: Total radiation energy from 14 measured parts of the body (top) and the total energy excluding the energy from the corners of the mouth (bottom) compared to the mouth radiation sung by a female Pop singer (subject: SE2) at a fundamental frequency of 250 Hz for the vowel /a/.

among subjects and independent of the musical genre. This recognizable difference was distinctive in the progress of the radiated energy analyzed at three partials: at the fundamental and at the partials where the maximum and minimum energy was measured (see Table 3).

But it was also shown that the total energy exclusive of the radiation energy from the corners of the mouth can still exceed the energy from the mouth in general. This emerged either as a temporary occurrence or as a continuing phenomenon at higher frequencies.

5 CONCLUSION

This study deals with the question of the radiated energy of the singing voice from the body in general. In order to find out whether most of the radiation energy comes from the mouth or not, an experiment was undertaken with seven singers from four various musical genres, and their singing voices were measured at 15 parts of the body by an acoustic camera with 121 microphones. The data gained from the measurement was analyzed from various points of view and displayed in different forms, so we hope that some questions have been answered thereby.

Our research findings showed that the mouth is usually the strongest sound source in singing, as expected. However, sufficiently loud sound pressures from other parts of the body, at least from the 14 parts measured, were also observed in this investigation. In most cases, an increase of the energy from these parts was shown up to about 3 kHz for all the vowels, so that the difference of the radiated energy among the parts of the body became smaller at high frequencies, even though the energy level showed a rather changeable process at all the pitches for the vowels /o/ and /u/. This increase depended on the pitch that was sung. A comparative analysis of all the findings gained from different sung pitches revealed that the strongest energy of the singing voice is usually located at around 3 kHz, independent of the singing technique.

Because of this increase, in some cases, a few of the parts of the body revealed even high energy values as much as the mouth radiation at higher partials. In addition, we found that the total energy from the 14 parts even surpasses the radiation energy values from the mouth. This depended strongly on the frequency, but this fact is a remarkable finding for a better understanding about the origin of radiation energy of the singing voice.

Furthermore, it was clarified that the energy from the corners of the mouth has strong influence on the total radiated sound energy level by comparing the energy from the mouth with the total energy from the other parts excluding the energy from the corners of the mouth. This influence was expected, due to their spatial closeness to the mouth.

In other aspects, it was found that the total radiation energy of the singing voice is strongly supported by the enhanced energy from the body regions that are located far from the mouth, because a dramatic increase in energy was found

Table 3: Total radiation energy measured at the fundamental frequency (FF), the minimum (Min) and maximum (Max) energy points from both analyses including (with CoM) and excluding the energy from the corners of the mouth (without CoM) as well as the differences at a fundamental frequency of 250 Hz (shown in dB, the results of JR for the vowel /o/ and VS (Pop) for the vowel /u/ are eliminated due to a lack of recording quality).

		With CoM			Without CoM			Difference		
Subject	**Vowel**	**FF**	**Min**	**Max**	**FF**	**Min**	**Max**	**FF**	**Min**	**Max**
CH (classical, female, alto)	**a**	-2	-8	3	-9	-19	-4	7	11	7
	e	-3	-4	3	-10	-12	-2	7	8	5
	i	-1	-9	1	-9	-17	-4	8	8	5
	o	-14	-18	1	-23	-30	-7	9	12	8
	u	-11	-27	1	-21	-37	-8	10	10	9
SE1 (classical, female, soprano)	**a**	3	3	10	-1	-1	5	4	4	5
	e	4	4	12	-1	-1	8	5	5	4
	i	4	4	11	0	0	7	4	4	4
	o	2	2	10	-3	-3	5	5	5	5
	u	-1	-11	4	-8	-27	-1	7	16	5
JR (classical, male, bass)	**a**	-6	-6	20	-13	-13	17	7	7	3
	e	-11	-15	10	-20	-23	5	9	8	5
	i	-7	-8	4	-15	-15	-1	8	7	5
	o	-	-	-	-	-	-	-	-	-
	u	-10	-12	4	-18	-19	-2	8	7	6
SS (musical theater, female, mezzo soprano)	**a**	-17	-17	2	-26	-26	-4	9	9	6
	e	-12	-14	2	-25	-27	-7	13	13	9
	i	-17	-18	0	-39	-39	-8	22	21	8
	o	-22	-22	17	-38	-38	14	16	16	3
	u	-22	-22	10	-36	-37	4	14	15	6
TF (musical theater, male, tenor)	**a**	0	0	13	-5	-5	8	5	5	5
	e	0	0	9	-7	-7	3	7	7	6
	i	-6	-6	10	-9	-10	3	3	4	7
	o	-6	-10	4	-18	-20	-4	12	10	8
	u	-2	-3	8	-18	-19	-2	16	16	10
SE2 (Pop, female, mezzo soprano)	**a**	-1	-1	5	-8	-8	1	7	7	4
	e	1	-1	9	-6	-6	6	7	5	3
	i	0	0	10	-6	-6	7	6	6	3
	o	0	0	13	-10	-10	11	10	10	2
	u	-7	-9	3	-17	-19	-1	10	10	4
VS (Pop, female, mezzo soprano)	**a**	-1	-1	8	-9	-9	3	8	8	5
	e	-4	-4	4	-13	-13	1	9	9	3
	i	-8	-9	4	-15	-15	0	7	6	4
	o	-5	-5	10	-19	-19	6	14	14	4
	u	-	-	-	-	-	-	-	-	-
VS (Soul, female, mezzo soprano)	**a**	-2	-2	8	-14	-14	1	12	12	7
	e	-6	-6	8	-19	-19	4	13	13	4
	i	-11	-11	1	-21	-22	-4	10	11	5
	o	-3	-3	8	-21	-21	1	18	18	7
	u	-11	-11	6	-38	-38	0	27	27	6

there, and because the energy values from the body regions of the chin, the corners of the mouth, and the cheeks did not change as much. However, for the vowels /o/ and /u/, the radiation energy of nonclassical singers is strongly supported by the corners of the mouth and the chin. For the nonclassical singers, the difference in the radiation energy level between the region of the mouth (i.e. the corners of the mouth and the chin) and the rest of measured parts of the body was much larger than for classical singers. This finding indicated that classical singers use rather their whole body as a musical instrument, and therefore the radiation energy of their singing voice is emitted steadily from there, in fact, independent of the vowel, for example.

In conclusion, the results of this study revealed that the radiation energy of the singing voice is emitted not only from the mouth, but also from other regions of the body. However, the radiation energy of the singing voice depends strongly on the vowels, frequency, pitch and person who sings. This means that the radiation of the singing voice depends rather on the singing technique of each singer than on the musical genre.

We hope that our research findings can give singers and vocal teachers of various musical genres helpful information for their vocal training and teaching.

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