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Three Professional Singers' Vocal Tract Dimensions in Operatic Singing, Kulning, and Edge—A Multiple Case Study Examining Loud Singing

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Summary: Objective. A comprehensive understanding of how vocal tract dimensions vary among different types of loud voice productions has not yet been fully formed. This study aims to expand the existing knowledge on the topic.

Methods. Three trained professional singers together practiced the vocal techniques underlying Opera and Kulning singing styles for one hour and, afterwards, phonated using these techniques on vowel [iː] at pitch C5 (523 Hz), while their vocal tracts were scanned via MRI. One of the participants also produced the samples in the Edge vocal mode using [ɛː]. Several dimensional vocal tract measurements were calculated from the MRIs. Spectral analysis was conducted on the filtered audio recorded during the MRI.

Results. The Operatic technique demonstrated a lower larynx, a larger tongue−palate distance, and larger epilaryngeal and pharyngeal tube diameters compared to Kulning. Edge showed the highest laryngeal position, narrowest pharynx and epilarynx tubes, and the least forward-tilted larynx out of the styles studied. The spectra of Opera and Kulning showed a dominant first harmonic, while in Edge, the second harmonic was the strongest.

Conclusions. The results shed light on the magnitude of vocal tract changes necessary for genre-typical vocal projection. This information can be pedagogically helpful.

Key Words: Loud singing—Laryngeal position—Laryngeal height—Jaw opening—Mouth opening—Tongue position—Epilaryngeal area—Pharynx area.

INTRODUCTION

Western Operatic singing, Kulning, and Edge have each evolved to produce high audibility in their own specific environments. The Operatic singing technique makes the voice carry without electrical sound amplification in large concert halls and through philharmonic orchestral accompaniment. Kulning (also spelled kölning) is a type of sung cattle or herding call traditionally practiced by women in the Swedish provinces of Dalarna, Härjedalen, and Jämtland.[1] The singing style is very loud, high-pitched (up to the sixth octave), and without vibrato to make the sound carry over long distances.[1] According to the Complete Vocal Technique (CVT™) methodology, Edge is a vocal mode ranging from reduced to full metallic sounds and from medium loudness to very loud volumes, and it is used in various music genres.[2] Edge has also been previously categorized as a sub-type of Belting[3] (a term usually referring to non-Classical loud singing at high pitch levels and mostly in the chest register[4]).

To the best of our knowledge, the vocal tract (VT) dimensions of Operatic singing, Kulning, and Edge have not been compared directly through within-subject comparisons in the same study before. The laryngeal positions of two female Classical singers[5] and a Kulning singer[6] were examined in two previous studies using a similar X-ray-based approach. According to these studies, the Classical soprano's larynx was approximately at its rest position, the Classical alto's larynx was below the rest position, and the Kulning singer's larynx was almost 4 cm above the rest position for the highest measured pitch (soprano 950 Hz, alto 600 Hz, Kulning singer 1100 Hz). The laryngeal position of the soprano singer and the Kulning singer also rose as the fundamental frequency (f0) increased, while the alto showed no clear relationship between the laryngeal position and f0.[5,6] In a recent MRI study by Leppävuori et al, Edge demonstrated the highest laryngeal position out of the four CVT™ vocal modes (Neutral, Curbing, Overdrive, and Edge) when examined in two male and two female CVT™-trained singers.[7] Detailed descriptions and sound samples of the CVT™ vocal modes can be found on the Complete Vocal Institute website: https://completevocal.institute/.

In Kulning, a narrow epilarynx tube compared to normal singing in head voice[8] and a narrow pharynx compared to ordinary Swedish folk song[6] were observed in previous single-subject studies. A remarkably narrow epilaryngeal tube in general[2,3] and anterior-posteriorly narrow pharynx

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compared to the other CVT™[7] modes have been reported for Edge. A singer's formant cluster, ie., spectral prominence near 3000 Hz, in turn, is commonly observed in male and female Classical singers when singing at the lower pitch range (approximately below 500 Hz) (see eg Sundberg,[9] Weiss et al,[10] van Lankeren[11]). The main cause for this phenomenon has been suggested to be the clustering of the third (R3), fourth (R4), and fifth (R5) VT resonances due to a VT adjustment where the cross-sectional area of the epilaryngeal outlet is at least six times narrower than the pharyngeal inlet just above the epilarynx tube.[9,12]

Furthermore, Johnson et al observed from radiographs that in Kulning, the tongue position in relation to the lower jaw rose with increasing pitch.[6] Using the same approach, Johansson et al observed that the Classical alto's and soprano's tongue contours at low pitch levels were close to the ones they used for spoken vowels, while at higher pitch levels, the tongue contours in all the three studied vowels ([ɑ], [i], and [u]) showed similar shapes to spoken [ɑ] for soprano and two distinct shapes for alto.[5] Leppävuori et al[7] found that in Edge, the distance between tongue and palate was shorter compared to that in the Neutral mode (note that different vowels were used for Edge and Neutral) and compared to that in Overdrive, when the vowel [ɛ] was considered for both the modes.[7]

It has been proposed that singers in various genres aim to optimize phonation by adjusting the VT resonances to sustain or achieve favorable relations between harmonics and one or more of the resonances as pitch changes.[13−17] This maneuver, often referred to as resonance tuning or resonance strategy, is used especially at high pitch levels and near regions of register breaks.[13−17] The two lowest resonances (R1 and R2) that seem to be essential for the resonance tuning strategies are, according to the literature,[18−20] strongly affected by manipulations to the laryngeal height, tongue position, and jaw and lip opening. Female Operatic singers have been found to raise R1 and tune it in the vicinity of the first source harmonic (H1) as the pitch rises[16,21,22] (eg, at and above 500 Hz). In a similar manner, Johnson et al found a link between R1 and H1 in Kulning.[6] Their results were recently supported by findings of Rosenberg et al, demonstrating a strong H1 in Kulning samples that were the most highly rated by expert listeners. Rosenberg et al also pondered that the tuning of VT resonances could help achieve a spectrum envelope without clear dips among the first five harmonics in Kulning, which was considered to be typical for well-representative samples.[23] In contrast to Opera and Kulning, in female Belting, R1 is usually kept near H2 or other higher harmonics.[13,24−26]

Magnetic resonance imaging (MRI) is increasingly used for the examination of VT during phonation. The objects of interest in some of the previous studies have included the VT shape in relation to the change of register[27−29] and pitch,[22] and the effects of vocal warm-up exercises.[30] These studies and earlier investigations concerning the reliability of MRI in the examination of the VT during phonation[31,32] have demonstrated the usefulness of MRI for this purpose. The two main variants of MRI methodology—dynamic[22,27−29,31] and static[30,32]—have been used in previous studies. Dynamic MRI allows for the two-dimensional (2D) observation of VT movements in real time during phonation, although with a low frame rate (7 fps). Static MRI enables the registration of multiple anatomical slices and, thus, a three-dimensional (3D) observation of the VT shape.

Until now, few studies have examined Kulning and Edge. To the best of our knowledge, this is the first study applying a within-subject comparison to examine the differences between Kulning and Edge and, moreover, to compare these singing styles to the more comprehensively studied Operatic singing. Singing studies that often use small sample sizes can benefit from using a within-subject comparison instead of a between-subject comparison. When the same individuals produce samples representing each of the phonatory conditions to be studied (within-subject comparison), the anatomical differences between the participants do not cause as much noise in the results as in a setup where different individuals produce the samples (between-subject comparison). The noise caused by the anatomical differences can obviously be overcome by acquiring a large sample size; however, acquiring a large sample size is challenging and expensive when busy professional singers are studied and high-cost methods, such as MRIs, are used. The difficulty concerning the within-subject comparison, on the other hand, is that it makes recruiting participants even more challenging, as singers who can perform expertly in multiple singing styles are fewer than experts of one specific style. In the present multiple-case study, an approach that, to the best of our knowledge, has not been used before was attempted to partly manage this issue. An approximately one-hour practice session was arranged for the three participating professional singers to practice the vocal techniques studied and to instruct each other according to their expertise prior to the data acquisition. All the participating singers had expertise in one of the studied high-SPL singing techniques.

The objective of the present study was to 1) better understand how the VT dimensions differ between Operatic, Kulning, and Edge vocal modes, 2) explore the extent to which the VT dimensions, in general, can be manipulated in high-SPL phonation, and 3) test the usability of a training session prior to data acquisition to increase the explanatory power of a study on singing with a small sample size.

MATERIALS AND METHODS

Participants and tasks

Three experienced professional singers volunteered as participants. The participants gave their written informed consent for the collected material to be used for the research. The material was collected and saved, and the results of the analyses were published respecting the Finnish Data Protection Act (Chapter five, section 31). Permission to acquire the MRI data was given by the Regional Ethics Committee of the Northern Ostrobothnia Hospital District (decision 49/2015 § 135). All participants had the possibility of withdrawing from the study at any stage. Each participant had expertise in one of the three studied singing styles. Participant P1 (referred to as the Kulning singer) was a trained, performing singer of the Kulning style who had previously participated as a subject in the 2013 study by Eklund, McAllister, and Pehrson.[33] Participant P2 (referred to as the Operatic singer) was a teacher of Classical singing and a professional lyric soprano who has performed, for example, the role of Gilda in Verdi's *Rigoletto*. Participant P3 (referred to as the CVT™-trained singer) was an authorized Complete Vocal Technique™ teacher, a vocal pedagogue, and a professional singer of contemporary commercial music (CCM). None of the participants reported any voice symptoms prior to the study. The occurrence of any voice pathologies was also excluded by laryngoscopic examinations prior to this study.

The study consisted of a training session lasting approximately for one hour and of two experiments applying MRI. In the first part of the study, the participants together practiced the voice production techniques underlying Operatic singing and Kulning. The original purpose was to include the Edge vocal mode in the training session as well; however, P1 and P2 found Edge to be overly deviant from their normal singing habits and, therefore, it was regarded as more beneficial to allow P1 and P2 to concentrate on learning one unfamiliar vocal technique instead of two. The training focused on learning loud and steady vowel productions at medium-high pitch levels, which resembled the singing task used for the MRI experiments. The purpose of the training was not to have the participants master a new unfamiliar vocal technique in a manner they could apply the technique in the context of a song, since this usually takes several years of practice. The training aimed to achieve the ability to imitate the unfamiliar technique well enough to allow the element of within-subject comparison to be included in the study design. During the training session, the participating experts of the practiced singing technique used different types of pedagogical tools, e.g., model imitation, and instructions related to sound color (e.g., aim for darker timbre) and somatosensory perception to help the non-expert singers to obtain the target sound quality. After the training session, the participants expressed that they were satisfied with each other's ability to produce samples in a practiced manner.

In the second part of the study, the participants attended two experiments that applied MRI (dynamic and static). In both experiments, the singers lay supine on the MRI scanner bed and sang the vowel [iː]) at pitch C5 (523 Hz). They were asked to perform the singing tasks in a loud voice. Only one vowel and pitch were chosen to avoid forcing the participants to spend an unnecessarily long time in the MRI scanner. C5 was the chosen pitch, as it was assessed to suit all three singing techniques. Although it was at the bottom end of the typical Kulning and high Operatic soprano pitch range, the participants expressed comfort in performing the singing task at this pitch. The vowel [iː] was estimated to serve well for comparing the studied singing techniques at the chosen pitch. It was also of interest since it has not been studied as frequently as the open vowel [aː]). However, during the second MRI experiment, where also Edge was studied, the vowel for Edge was changed to [ɛː], since P3 (the CVT™-trained participant) noticed being more comfortable performing the samples of Edge loudly with [ɛː]. According to her and one of the authors, who was an authorized CVT™ teacher, some singers find this to be the case. Since, at this stage, the practicing session was already implemented and some of the MRI material was acquired, it was not reasonable to consider the possibility of using [ɛː] for all the studied techniques.

In the first experiment with MRI (Experiment I), the participants began phonation either in Kulning or Operatic singing and, approximately in the middle of the phonation, switched to the other style. This phonation pattern was repeated five to six times during the dynamic MRI scans. The participant was instructed to maintain a steady and continued phonation for both the styles for approximately 2−3 seconds. During the experiment, one of the researchers, a co-author with a background in vocal pedagogics, was monitoring the success of the target phonation in the MRI room, while the rest of the research group, including the other participants, were evaluating the execution of the task from the MRI control room. After each scan, the participants were asked how well they thought they had managed to execute the task in general. If both the participant and the rest of the research group agreed that the execution was successful, it was further discussed which phonations were the most successful and which the least successful, and this information was noted down. When it was agreed that the execution of the task was insufficient, the MRI scanning was repeated.

In the second experiment with MRI (Experiment II), the participants aimed to produce a sung note lasting approximately 15 seconds, at the same pitch and on the same vowel as in Experiment I, in both the Kulning and Operatic techniques while a static MRI was performed. In Experiment II, the evaluation of the success of the phonation was carried out in the same manner as in Experiment I, ie., based on informal discussion between the participant and the rest of the research group. The participants could carry out several trials so it could be ensured that well-representative samples were acquired. MRI acquisition was initiated a few seconds after the phonation began, and the phonation was continued for a few seconds after completion of the scanning if the participant was able to sustain the phonation for so long. Thus, both the researcher and the participant were able to estimate the phonation without the masking of the noise from the MRI scanner. P3 also performed the task in the Edge vocal mode (on vowel [ɛː]) at the same pitch as in Opera and Kulning. One of the researchers, who was an authorized CVT™ teacher, performed an auditory evaluation of Edge in the MRI room.

MRI acquisition and analysis

MRI data were acquired using a 3T clinical scanner (Siemens Magnetom Skyra, Siemens Healthcare, Erlangen, Germany) and a standard 20-channel head-and-neck coil. Another 18- channel body matrix coil was placed on the chest of each singer to improve image quality in the VT area. The dynamic MRIs were performed using a 2D FLASH sequence (gradient echo, TR 35.8 ms, TE 2.5 ms, FOV 340 mm, matrix 192, in-plane resolution 1.7 mm, slice thickness 6 mm). A single sagittal slice was positioned at the center of the VT, and 200 images were acquired within 31 seconds, yielding a frame rate of 6.5 Hz. The static MRIs were scanned using a 3D VIBE Dixon sequence (TR 4.2 ms, TE 2.6 ms, FOV 450 mm, matrix 320, phase encoding matrix, and FOV reduced to 67.5%, in-plane resolution 1.4 mm, interpolated slice thickness 1.6 mm, 120 slices, acquisition time 10.5 s).

The measurements calculated from the MRIs were similar to those used in previous studies.[22,27–30] Synedra view personal software (a free DICOM and multimedia viewer developed by Synedra information technologies GmbH, Innsbruck, Austria) was used to calculate all the measurements. From the dynamic MRI material, the three most steady phonations where the participants switched from Kulning to Operatic singing, or *vice versa*, were chosen for the analysis. The time values of the audio file—approximately in the middle of the most stable period of the phonation—were noted for both the Kulning and Operatic techniques. The MRIs that most closely corresponded to these time instants were then measured with the distance-measuring tools available in the Synedra software.

The static MRI material was measured using the 3D multiplanar view in the Synedra software. Some of these MRIs contained excessive motion artifacts or otherwise poor quality and were disqualified from the analysis. For each participant, one sample containing the highest image quality was included in the analysis for each singing technique for which the participant provided samples. The final decisions on the analyzed samples in both experiments were made by one of the authors, who was a professional vocologist and a singing teacher. At this point, no evaluation of the vocal performance or the stylistic characteristics of the samples was performed, since this type of evaluation was already carried out during the MRI experiments. Attention was paid to the overall steadiness of the phonation, for instance, the amount of perceivable unintended shifts in pitch and timbre, quality of the MRIs, and in the case of dynamic MRI data, locating the most stable parts of the phonations. The procedure aimed to avoid possible selection bias.

Only one person measured the MRIs. To evaluate the existence of possible measurement bias, a screenshot was captured from the view of the Synedra software each time that all the distance measurements were calculated from a dynamic MR image. At this stage, the view in Synedra showed every distance measurement as a line extending between the two points used as a basis for the measurement and the four marker lines drawn in the MRIs. The screenshot images were afterwards reviewed by a second researcher, who had experience in measuring MRIs. The second researcher confirmed that the measurement principles were applied correctly in all samples. The same procedure could not be implemented for the static MRIs, since the Synedra software removed all the already existing markings from the 3D reconstruction when the 3D view was readjusted.

Four marker lines (*M1, M2, M3*, and *M4*) were formed in all MRIs to serve as reference points for several VT distance measurements (Figure 1). *M1* was determined as the line extending from the lowest point of the odontoid process of the atlas to the spina of the upper jaw, *M2* as the line extending from the lowest point of the odontoid process of the atlas to the caudo-anterior Edge of the sixth vertebra, *M3* as the line along the shortest distance between the lowest Edge of the mandible and *M2* (perpendicular to *M2*), and *M4* as the line along the shortest distance between the anterior commissure of the vocal process and *M2*. All the distance measurements that were calculated from the dynamic and static MRIs are shown in Figure 1 and further described in Table 1.

Two areas were also measured from the static (3D) MRIs using the area measurement tools available in the 3D multiplanar view of Synedra. The pharyngeal area (Aph) was measured as the cross-sectional area of the VT immediately above the epilaryngeal tube, and the epilaryngeal area (Ae) was measured as the cross-sectional area of the uppermost visible part of the epilaryngeal tube (see Figure 2). Both cross-sectional areas were measured perpendicular to the estimated midline of the epilaryngeal tube. The ratio between Aph and Ae was also calculated. Finally, the

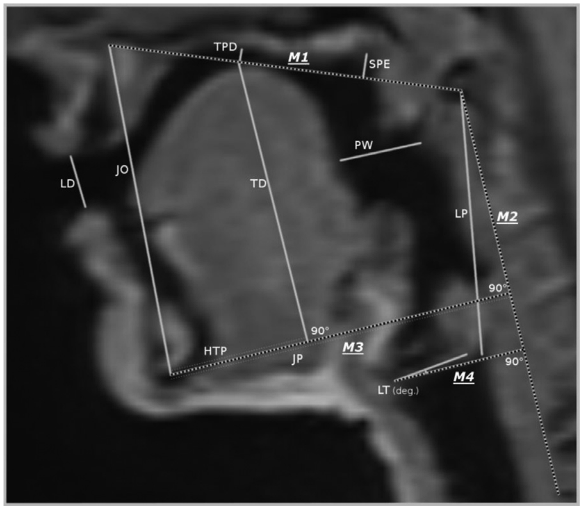


FIGURE 1. The distances measured from the MRIs: Lip distance (LD), jaw opening (JO), jaw protrusion (JP), tongue dorsum (TD), tongue-palate distance (TPD), horizontal tongue position (HTP), soft palate elevation (SPE), pharynx width (PW), laryngeal position (LP), the measure of laryngeal tilt (LT, measured only from static MRIs), and the four marker lines (*M1, M2, M3,* And *M2*) used to calculate some of the measures.

TABLE 1.
Vocal Tract Distance Measurements

Distance Measure	Measured as
LP Lip distance	The shortest distance between the lips
JO Jaw opening	The distance between the spina of the upper jaw and the lowest edge of the mandible
JP Jaw protrusion	The shortest distance between the lowest edge of the mandible and M2
TD Tongue dorsum	The longest distance between marker line M3 and the upper tongue contour
TPD Tongue-palate distance	The shortest distance between the palate and the point where tongue dorsum line ends
HTP Horizontal tongue position	The distance between the lowest edge of the mandible and the tongue dorsum line
SPE Soft palate elevation	The longest distance between the marker line M1 and the soft palate
PW Pharynx width	The shortest distance between the pharyngeal wall and the tongue between the epiglottis and soft palate
LP Laryngeal position	The distance between the lowest point of the odontoid process of the atlas and the posterior end of the inferior surface of the vocal folds

The table presents all the vocal tract distance measurements carried out from the dynamic and static MRIs and describes which anatomical landmarks were used for measuring each distance.

laryngeal tilt (LT) was measured as the angle between the marker line *M4* and the vocal folds (see Figure 1).

In-phase and opposite-phase reconstructions of the VIBE Dixon sequence (static experiment) were used for the 3D reconstruction of the VT in Synedra. LT and LP were measured from the reconstructed opposite-phase projections with a slab thickness of 8.4 mm for the best visibility of the vocal folds. The rest of the measurements were taken from the reconstructed in-phase projections. A slab thickness of 2.8 mm offered the best visibility of the VT boundaries for the area measurements, and a slab thickness of 1.4 mm was best for the other measurements.

Acoustic recordings and spectral analysis

Acoustic recordings were conducted during the MRI scans using a similar technique to Leppävuori et al.[7] One end of a regular 5 m long garden hose (inner diameter 15 mm) was attached to the head coil as close to the singer's mouth as possible (approximately 3 cm from the lips), and the other end was placed in the control room through a wave guide tube through the scan room's wall. Pieces of foam plastic were introduced into both ends of the garden hose to diminish the flutter echo within the hose. A Bruel Kjaer Mediator 2238 level meter/microphone was placed a few centimeters inside the hose end in the control room. Recordings were made via a Focusrite iTrack Solo external soundcard on a laptop using *SoundForge* (version 11) software. A sampling rate of 44.1 kHz and a 16-bit depth were used. The frequency response of the recording system was measured previously by Leppävuori et al[7] using bursting balloons. The response curve showed a peak of approximately 10 dB around 400 Hz−500 Hz frequency range and attenuation of approximately 10 dB / octave.[7]

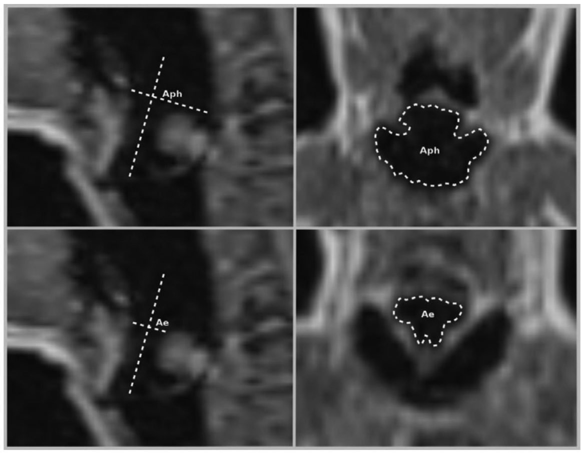


FIGURE 2. The images demonstrate how the pharyngeal and epilaryngeal areas (Aph & Ae) were measured from the static MRIs. Both areas were measured perpendicular to the estimated midline of the epilaryngeal tube. The Ae was measured at the epilaryngeal outlet, where the ring of epilaryngeal folds is still fully visible. The Aph was measured slightly above the epilaryngeal tube at the point where most of the epilaryngeal ring was invisible.

The spectra of the acoustic samples were analyzed using *Praat software* (version 6.1.08, Boersma & Weenink).[34] Hanning windowing was applied to the 0.5−0.7-second sound samples taken from the steadiest parts of the phonations. Spectra were analyzed using the *To Spectrum...* function of Praat with the fast option switched on. Prior to the spectral analysis, the acoustic samples were filtered using a free audio plug-in called ReaFir (Cockos Incorporated)[35] to remove the MRI machine noise from the audio (Figure 3). This plug-in is freely downloadable from the manufacturer's website www.cockos.com as a part of a Windows VST plug-ins package (ReaPlugs). Here, it was Operated inside the *Cubase 10* (version 10.0.6) software (Figure 3.) in the following manner: First, a noise profile (or a filter) was created with the plug-in by analyzing a part of the audio where only the unwanted MRI noise was present. Then the plug-in and the filter were activated on an audio channel containing the audio material to be filtered. The filtered audio signal was

sample: Ins. 2 - reafir_standalone

ReaFir by Cockos Incorporated - www.reaper.fm

Edit mode: Precise

FFT Size: 4096

☑ ReaFir 0.x compatibility mode (low quality)

Mode: Subtract

☐ Automatically build noise profile (enable during noise)

☑ Show analysis, floor: -90.0 dB

Hint: shift draws line, ctrl moves all

Channel Settings : Sample [mono->stereo]

FIGURE 3. View of Cubase 10 software. The upper part of the figure shows the waveform of the audio that was imported to Cubase 10 for filtering. The window in the lower right corner is the Cubase 10 channel setting window, where the plug-in is inserted. The window in the lower left corner is the Reafir plug-in operating window showing the spectrum of the MRI noise signal at the top, spectrum of a sample including both the MRI noise and the singer's voice in the middle, and spectrum of the same sample after filtering at the bottom.

then perceptually evaluated in Cubase 10, and if the filtering was found to have succeeded in removing most of the MRI noise from the signal without having any obvious audible effect on the underlying voice signal, the sample was exported from Cubase 10 as a new filtered wav-file, which was then analyzed in Praat. The noise filter profiles were created separately for each participant's dynamic and static MRI audio samples since the different MRI methods included different types and amounts of noise.

The disadvantage of this type of filtering is that some of the audio material of interest can also be affected by the filter. The extent of this effect was tested by analyzing an audio where one of the participants phonated a few seconds longer than the MRI scanning lasted. Two parts of this phonation were analyzed: the first part right before the scanning finished, and the second part immediately after the scanning finished. Since the temporal distance between these two parts was short, the parts were expected to contain similar spectral content. Figure 4 shows the spectra of the analyzed samples (filtered and unfiltered). Some minor differences in the filtered and unfiltered spectra can be observed. However, the filtering seemed to work sufficiently for the current purpose, especially considering that the same filter settings were used for all the samples that were directly compared. Therefore, possible over-filtering was applied to these samples evenly. The sound samples from which the analysis was performed in Figure 4 can be heard from the supplemental online material. In general, there were several factors in the present study that distorted the acquired audio material, eg, the nonlinear frequency response of the recording system and the presence of the MRI noise. This fact makes drawing conclusions based on minor differences between the spectra of the singing styles unreasonable. The role of the audio material was, therefore, considered mainly supportive.

Error estimation

As a method of measurement error estimation, each sample in the analysis was measured twice. These two rounds of measurements were carried out by the same author to ensure that a similar approach was used both times. All the images were measured consecutively in both measurement sessions. The mean values and standard deviations for the measurement differences were calculated and evaluated. The dependency of the measurement accuracy on the participant was also evaluated.

RESULTS

Measurement accuracy, which also reflects the quality and in-plane resolution of the MRIs, can be estimated by evaluating the measurement differences between the first and the second round of measurements. In general, when all data were considered, the mean difference for the distance measurements was 0.75 mm (SD = 0.49, Min = 0.6, Max = 3.1). The measurement accuracy was slightly higher for P3 (CVT$^{\text{TM}}$-trained singer) (MD = 0.61, SD =0.36, Min = 0, Max = 2.7) than for P1 (Kulning singer) (MD = 0.75, SD = 0.34, Min = 0, Max = 3) and P2 (Operatic singer) (MD = 0.89, SD = 0.69, Min = 0, Max = 3.1). Out of all the distance measurements, LP was the most accurately measured (MD = 0.45, SD = 0.47, Min = 0, Max = 1.6), and HTP the least accurately measured (MD = 1.02, SD = 0.89, Min = 0.1, Max = 3.1). The mean difference for LT was 1.70 deg (SD = 0.92, Min = 0.50, Max = 3.40), for Ae 8.14

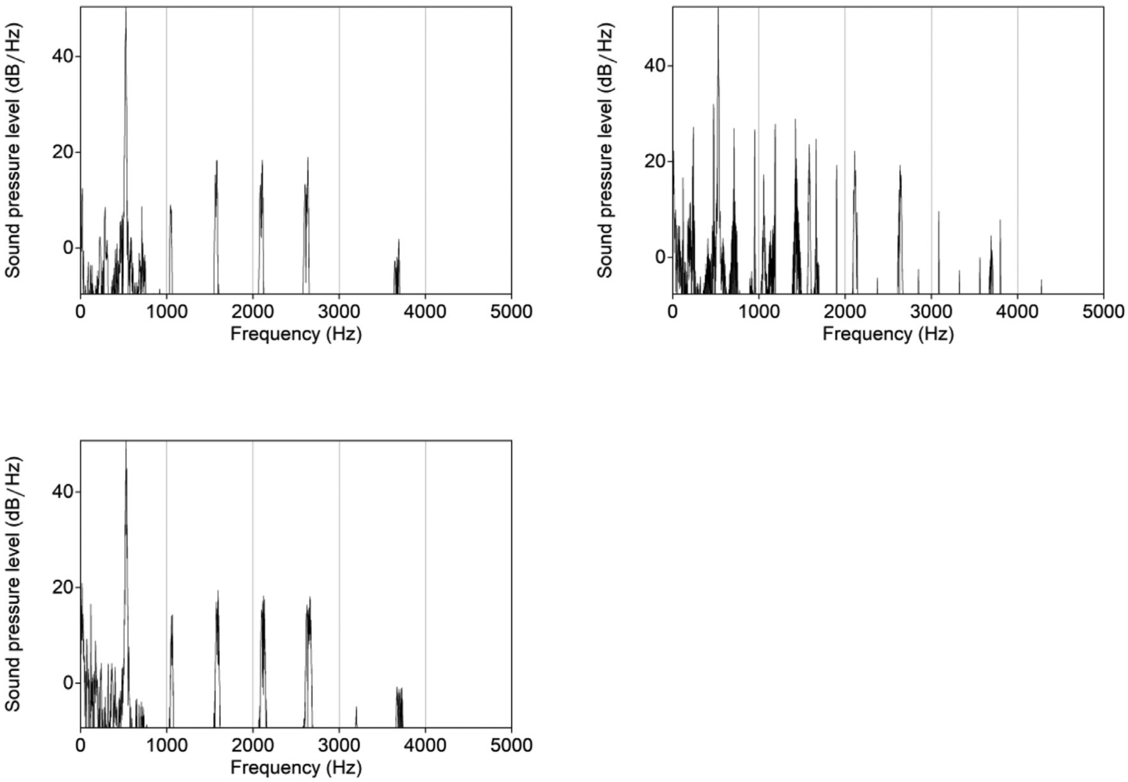


FIGURE 4. Spectra of P2 singing sustained vowel [iː] at pitch C5 (523 Hz), as analyzed with Praat. Top left (filtered) and top right (unfiltered) samples were taken right before the completion of the MRI scanning. The bottom left sample (without filtering) was taken from the same phonation right after the scanning finished.

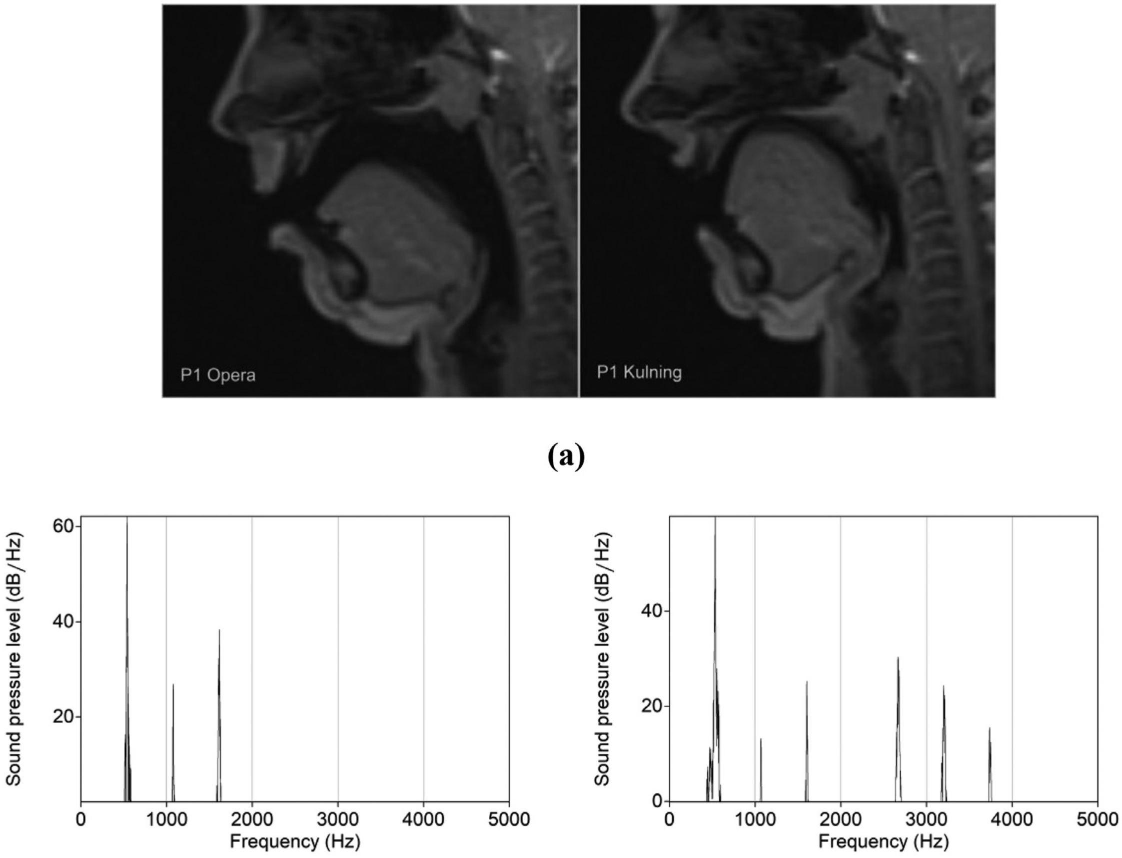
mm^2 (SD=7.52, Min=0, Max=23.00), and for Ap 19,71 mm^2 (SD=15.67, Min=2,00, Max=44,00). In this study, when a vocal tract measure differs between two vocal techniques more than the maximum difference observed between the repeated measurements of that measure, the difference between the vocal techniques is considered meaningful. The maximum differences for all the distance measures are presented in Table 2.

Figures 5−7 present the typical VT shapes in the two-dimensional mid-sagittal plane for P1 and P2, as they are utilizing the Operatic and Kulning techniques, and for P3, while she is utilizing all three vocal techniques. The mean values were calculated for all the distance measurements from dynamic and static MRIs separately for each participant and vocal technique (Table 2). Comparing Opera and Kulning from the mean values reveals that two measures, LP and TPD, varied in the same direction in all the participants, implying a lower larynx, and a wider gap between tongue and palate for Opera (Table 2). Further examining the measurements that were carried out for the individual samples (Figure 8) shows that the larynx was always lower for each participant in Opera regardless of which samples are being compared. This makes an even stronger case for differing laryngeal positions between Opera and Kulning.

TABLE 2.
Results for the VT Distance Measurements

		LD		JO		TD		HTP		TPD		JP		SPE		LP		PW	
		Mean	sd	Mean	sd	Mean	sd	Mean	sd	Mean	sd	Mean	sd	Mean	sd	Mean	sd	Mean	sd
P1	Opera	8.4	2.8	67.8	3.0	53.1	4.0	16.7	2.8	14.1	3.5	72.3	2.9	6.5	2.2	87.4	3.8	16.5	3.5
	Kulning	18.4	5.4	67.6	1.5	61.2	7.3	17.1	4.6	5.9	4.0	70.2	3.9	4.5	1.5	76.6	3.0	15.8	3.1
P2	Opera	9.6	2.2	69.2	1.2	53.6	0.8	20.2	2.1	6.8	1.9	68.3	1.7	3.9	1.8	65.6	3.9	17.3	1.8
	Kulning	13.6	3.3	66.9	2.4	53.7	2.0	19.8	2.1	4.8	1.3	71.0	2.2	2.1	0.9	55.5	3.1	18.4	1.2
P3	Opera	14.1	2.2	82.0	5.4	59.5	3.3	27.1	5.1	13.7	3.4	74.9	1.0	9.9	1.2	89.0	1.8	24.5	3.9
	Kulning	11.0	0.8	74.3	0.7	63.3	1.4	27.6	2.0	4.5	0.9	74.6	0.5	8.9	1.2	59.4	1.4	20.6	1.0
	Edge	36.8		94.2		65.4		34.4		13.9		78.1		10.3		53.8	1	8.25	
Max dif. m1 - m2		2.1		2.3		2.1		3.1		1.5		2.7		1.7		1.6		2.4	

The table presents the mean and the standard deviation in mm for each VT distance measurement calculated separately for each participant and vocal technique. Seven samples, six from static MRI and one from dynamic MRI, were used to calculate the values for the Opera and Kulning techniques. The values presented for Edge are the distances measured from one sample of Edge sang by P3 during static MRI. In the lowest row of the table, the maximum differences between the first and the second round of the measurements are presented.



(a)

(b)

FIGURE 5. (A) Dynamic MRIs showing the Kulning singer's (P1) VT in Opera (left) and Kulning (right). (B). Spectra of Opera (left) and Kulning (right) analyzed from samples sung by P1 during the dynamic MRI scanning. Both samples were collected from the same phonation before and after the transition from Opera to Kulning.

For TPD, the case is weaker when the individual samples are examined (Figure 9). It seems that the gap between tongue and palate was smaller in Kulning throughout when the samples from the same phonation before and after the transition (dynamic MRI) are compared. However, for P2, even in this case, the differences between two pairs of samples (opera 1 vs. kulning 1 and opera 3 vs. kulning 3) did not exceed the maximum difference between the repeated measurements. In addition to LP and TPD, SPE showed some tendency for smaller values in the Operatic technique, suggesting that the palate could be generally more raised in Opera (Table 2). For P3, the mean difference, however, did not exceed the maximum difference between repeated measurements, and when the individual samples from the same phonation are examined, it seems that her soft-palate was in some cases more elevated in Opera and in other cases more so in Kulning (Figure 10). Furthermore, some dependency on the vocal technique was present for JO and TD, as JO tended to be smaller and TD greater in Kulning, but these trends were not as clearly observable in all participants as the ones related to LP and TPD (and SPE).

The results for LT, Aph, Ae, and the Aph/Ae ratio are presented in Table 3. Overall, the data did not suggest a clear trend for LT variation between Opera and Kulning. P3's larynx was more forward tilted in Kulning, while P1 and P2 did not demonstrate a meaningful difference between the techniques. For all participants, both Aph and Ae were greater in Opera; however, for P2, the difference for these measures was less than the maximum difference between the repeated measurements. No consistent trend regarding Aph/Ae was observed. The variation in Aph/Ae seemed to depend mainly on the participants.

All measurements calculated from the static MRIs of P3 are shown in Figure 11. These data show how Edge compared to Opera and Kulning. The highest laryngeal position, narrowest pharynx and epilarynx, and the least forward-tilted larynx were observed in Edge. Edge also showed a larger jaw and lip opening, a somewhat higher tongue dorsum, and a more posterior tongue position than the other singing techniques. The latter-mentioned differences likely reflect the use of a different vowel in Edge ([ɛː] instead of [iː]).

A summary of the observed differences between Opera, Kulning, and Edge is presented in Table 4. It should be noted that none of the participants maintained a completely consistent VT in any of the vocal techniques. The VT dimensions seemed to vary, even when the comparisons were made between the participant's expert samples.

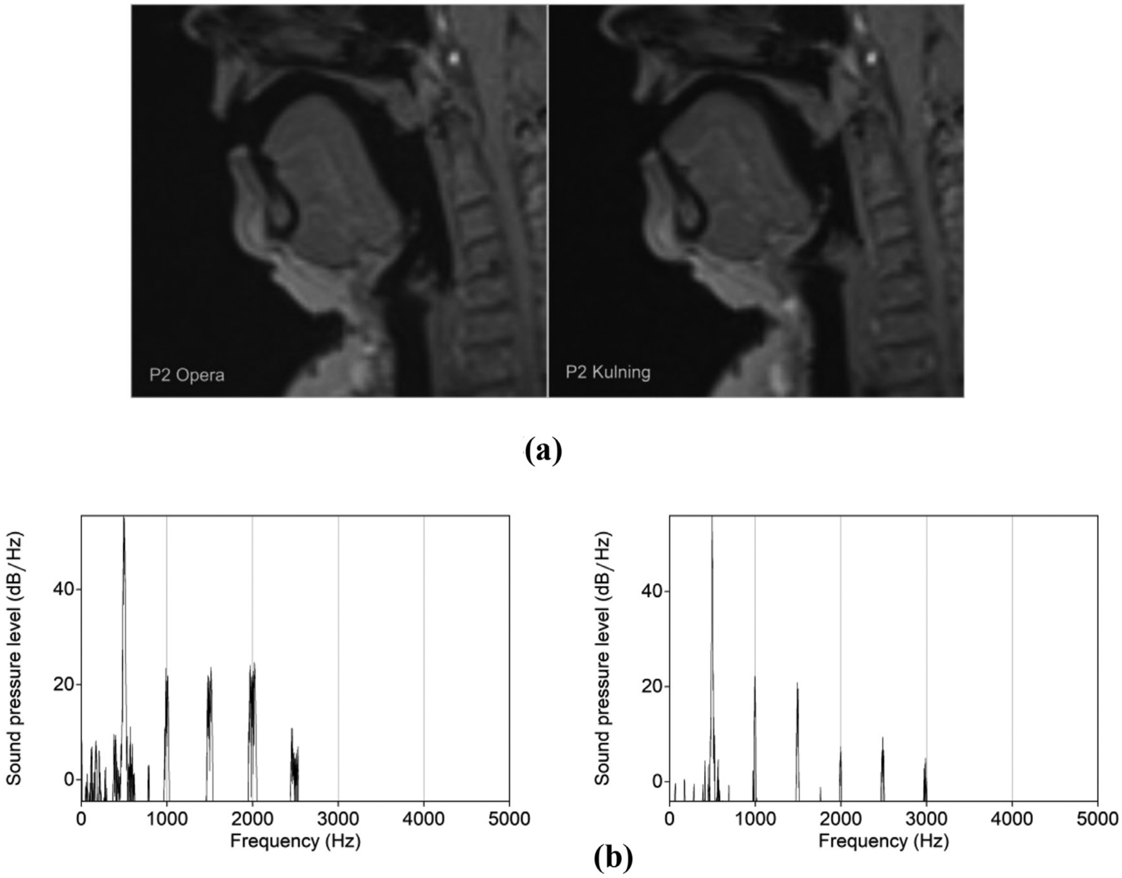


FIGURE 6. (A) Dynamic MRIs showing the Classical singer's (P2) VT in Opera (left) and Kulning (right). (B). Spectra of Opera (left) and Kulning (right) analyzed from samples sung by P2 during the dynamic MRI scanning. Both samples were collected from the same phonation before and after the transition from Opera to Kulning.

The spectra below the MRIs in Figures 5−7 were calculated from the filtered sound samples that were recorded during the MRI scanning. The filtering resulted in some unwanted effects on the spectra, especially for P1. H4 seemed to be missing from all her spectra. This could suggest that her H4 was less intense compared to a harmonic of the MRI sound at the same frequency (ca 2000 Hz) or her singing with lower SPL in general (SPL not measured). The spectra in Figures 5−7 also suggest that the harmonics produced by P1 were located slightly higher frequency wise compared to P2 and P3. Therefore, her H4 could have been at a frequency range that was substantially affected by the filter. As stated earlier, due to the inaccuracies in the spectral analysis, it is not reasonable to draw any conclusions from some minor differences between the spectra. However, overall, it seems that all the participants sang the Opera and Kulning samples with a dominant H1. In Opera, the spectral energy above H1 seemed to concentrate around H3 and H4, whereas it was somewhat higher in Kulning. This was most clearly observable in P3, whose spectra showed a distinct prominence around H3 in Opera and H5 in Kulning. Compared to Opera, Kulning showed more visible harmonics at high frequencies. Edge demonstrated a dominant H2 and notably more energy at the high frequencies compared to Opera and Kulning. Considering that the frequency response of the signal path demonstrated a large slope of 10 dB / octave, the higher frequencies are likely well underrepresented in all the spectra.

DISCUSSION

In the present study, the VT dimensions of three singing styles, where high-SPL is applied regularly, were examined via MRI. The clearest difference between the voice production techniques underlying these styles was observed in LP. With regard to Operatic singing and Kulning, the observation is in line with two earlier studies, one focusing on Kulning[6] and the other on Classical singing.[5] Out of the distance measurements, TPD and SPE also seemed to vary consistently between the Operatic and Kulning techniques. Kulning showed greater JO and TD values than Opera, but the differences were not as clear as those for LP, TPD, and SPE. Since the TPD was more clearly related to the vocal technique than JO and TD, it could be the case that these two measures vary to some extent as a byproduct of adjusting TPD. Increasing JO naturally pulls the tongue further away from the palate and the elevation of the tongue and lowering of the soft-palate could be ways of compensating

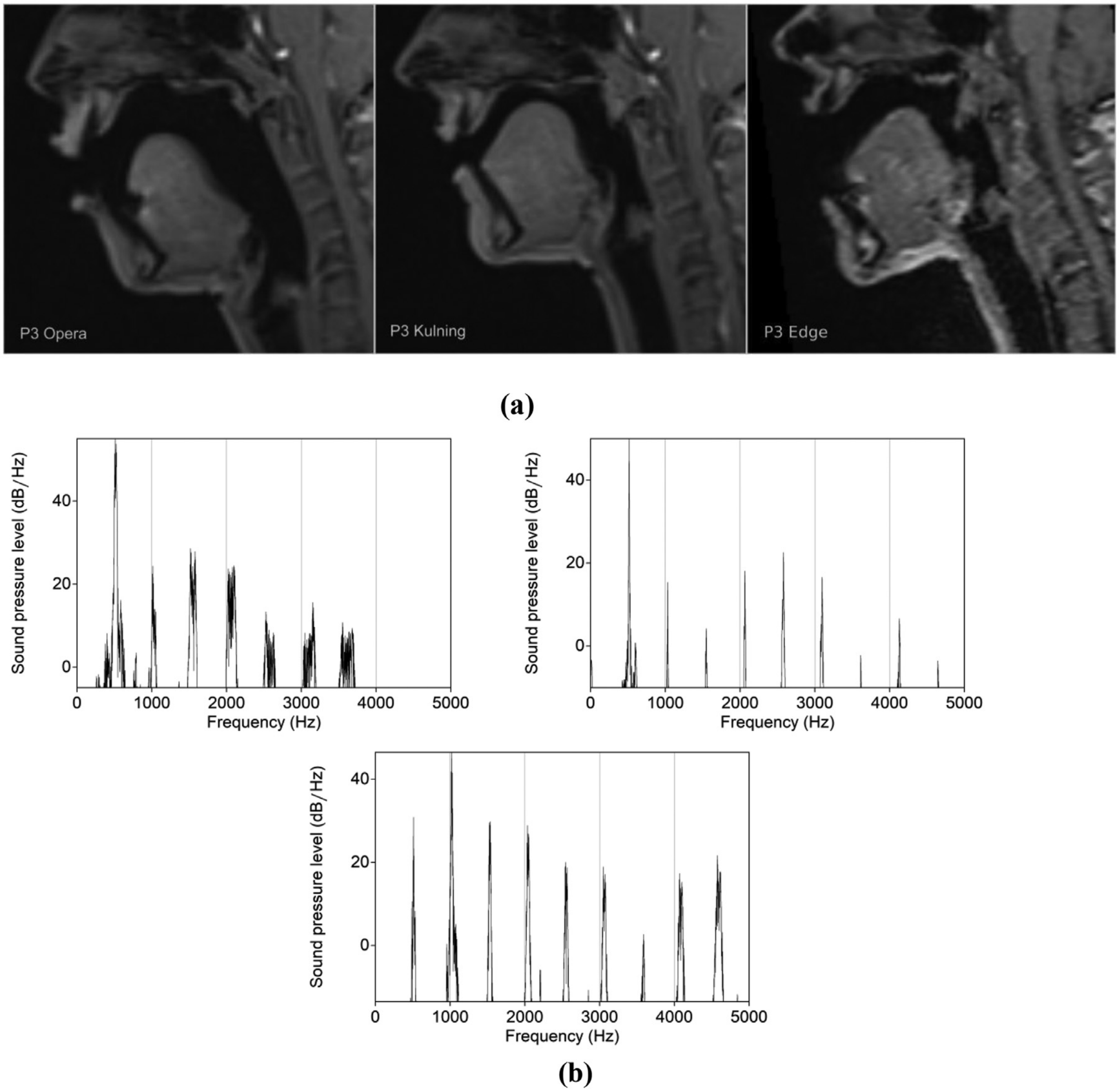


FIGURE 7. (A) Dynamic MRIs (left and center) showing CVT™-trained singer's (P3) VT in Opera (left), Kulning (center), and a static MRI showing her VT in Edge (right). (B). Spectra of Opera (top left) and Kulning (top right) analyzed from samples sung by P3 during dynamic MRI scanning and spectra of Edge (bottom-left) analyzed from the sample sung by P3 during the static MRI scanning. Opera and Kulning samples were collected from the same phonation before and after the transition from Opera to Kulning.

for this effect. Johnson et al[6] observed no difference in JO between Kulning and Swedish folk song style.

Two area measures, Aph and Ae, were studied using static MRI. Both these areas were found to be the greatest in the Operatic technique, although for one of the participants, the observed difference was not greater than the measurement error estimation. Earlier studies point to similar direction; for instance, Johnson et al[6] reported that the pharynx was increasingly constricted with rising pitch in Kulning[6] and Geneid et al[8] observed through nasofiberoscopic and high-speed videoendoscopic examination a narrower epilaryngeal space in Kulning compared to head voice singing.[8] In Complete Vocal Technique™ literature, Edge is characterized as relying on the production of twang.[2] The main physiological characteristic of this bright sound quality has been stated to be the approximation of the epiglottis and arytenoids.[36,37] Indeed, a recent study by McGlashan et al[3] reported a significant anterior− posterior narrowing of the epilaryngeal outlet in Edge. It has also been proposed by several earlier studies that a narrow epilaryngeal tube is a prominent feature of Belting.[26,36,38]

Opera, Kulning, and Edge use voice production techniques that allow daily loud voice use. It is an interesting question how the VT settings of these techniques might help lower the risk of tissue injury in high SPL singing. Larynx lowering has the tendency to pull the vocal folds slightly apart,[39] which in turn could assist "resonant" voice production with minimal adduction[40] and help maintain high SPL with minimal vocal fold contact pressure.[41] Kulning and Edge, in turn, could benefit from high laryngeal position as raising the larynx more or less raises all the VT resonances which increases SPL due to the fact that resonance

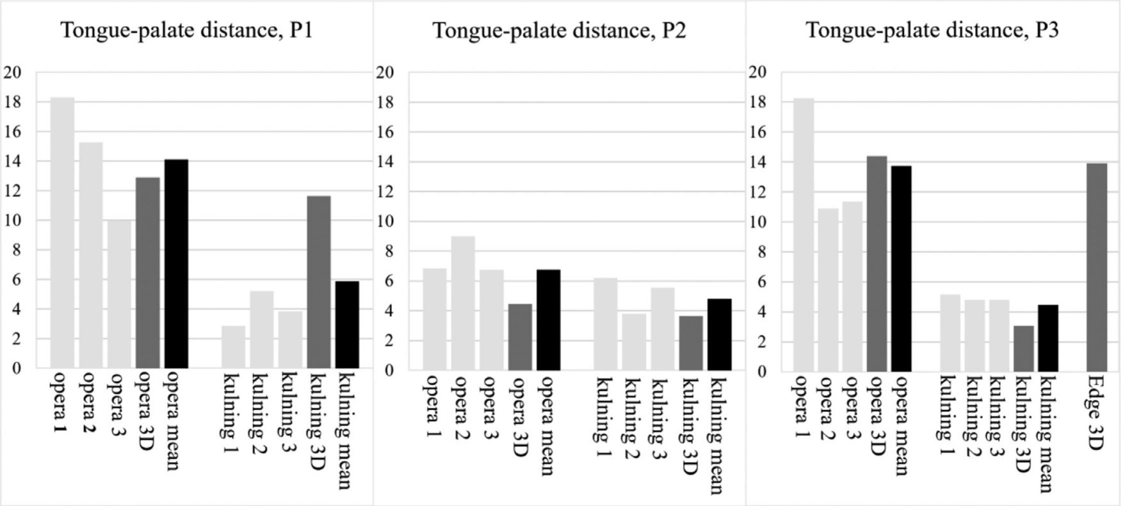


FIGURE 8. Tongue-palate distances individually for each participant and singing style. Bars present the mean of the first and second rounds of measurements in mm. In the Operatic and Kulning singing techniques, the rightmost bar (labeled mean) corresponds to the mean across all dynamic and static MRI measurements within the given singing style.

frequencies generally act as low pass filters.[18] Raising the resonance frequencies also directs energy towards the higher partials (see eg, Fant[18]; Lindblom & Sundberg[20]) and, thus, boosts the amount of spectral energy at the frequency range of 2000 Hz−3000 Hz where the human hearing mechanism is particularly sensitive (see eg, Flecher and Munson 1933[42]). Therefore, additional vocal economy-related benefits could be achieved in Kulning and Edge if these modifications to the voice spectrum can be produced without added stress on the vocal fold tissue.

In Kulning and Edge, the narrow epilaryngeal tube also has a likely significant impact on SPL and loudness. It has been shown that the epilarynx tube diameter is the primary parameter controlling the amount of nonlinear interactions between the voice source and the VT.[43−47] The narrowing of the epilaryngeal tube could increase the voice intensity by increasing the maximum flow declination rate (MFDR) through nonlinear source-filter interactions.[45] In a single-subject study, Sundberg and Thalén[48] found that, when their participant (a voice coach and professional singer) utilized twang instead of singing in neutral voice production, the SPL increased on average 6 dB. They estimated that the main reason for the difference in SPL was the change in the VT dimensions causing the R1 and R2 to rise and the R3 to lower when twang was applied.[48] In the present study, none of the studied singing techniques demonstrated Aph / Ae ratios that would be high enough to produce

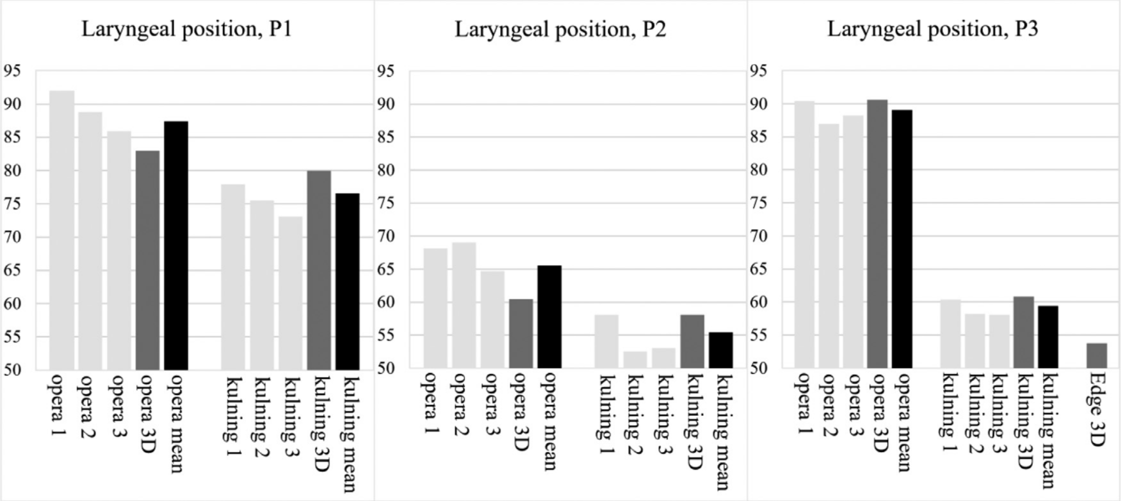


FIGURE 9. Laryngeal position individually for each participant and singing style. A greater value corresponds to a lower laryngeal position. Bars present the mean of the first and second round of measurements in mm. In the Operatic and Kulning techniques, the rightmost bar corresponds to the mean calculated across all dynamic and static MRI measurements within the given singing style. Note that in this figure, the Y-axis is set to start from 50 mm since this value was estimated to reflect the minimum value (highest laryngeal position) more realistically than 0 mm.

TABLE 3.
Results for Laryngeal Tilt (LT), Pharyngeal Area (Aph), Epilaryngeal Area (Ae), and the Aph/Ae Ratio

PARTICIPANT / Style	LT Mean	LT 1−2 (Dif)	AphMean	Aph 1−2 (Dif)	Ae Mean	Ae 1−2 (Dif)	Aph / Ae
P1 / Opera	-5.4	1.2	384.5	7.0	97.2	22.7	4.0
P1 / Kulning	-6.3	0.5	271.3	44.0	54.5	8.7	5.0
P2 / Opera	-1.8	1.5	242.2	31.6	80.2	10.4	3.0
P2 / Kulning	-4.4	1.5	213.3	2.1	76.1	8.3	2.8
P3 / Opera	3.3	2.3	440.9	5.5	96.6	4.7	4.6
P3 / Kulning	8.0	1.5	185.7	27.7	63.1	2.2	2.9
P3 / Edge	-5.3	3.4	154.4	19.2	57.5	0.4	2.7

The table shows the mean and the difference of the two rounds of measurements for LT in degrees, Pha and Ae in mm^2, and the Aph/Ae (P1, Kulning singer; P2, Classical singer; P3, CVT™-trained singer). Note that in LT, a greater value means a more anteriorly tilted larynx.

the singers' formant cluster, according to literature.[9] This is not surprising since the singers' formant cluster is more typically observed in Operatic male voices than in female voices.[10] Classical female singers seem to rely more on strategies where R1 is tuned at the vicinity of H1, or R2 at the vicinity of H2, or both these at the same time.[16]

The spectra of Opera and Kulning were both characterized by strong H1. This feature has been reported for soprano singing in several earlier studies[16,21,22] and for Kulning by Johnson et al[6] and Rosenberg et al.[23] In the present study, the most substantial spectral differences between Opera and Kulning were observed in H3, H4, and H5. In Operatic singing, the energy distribution above H1 seemed to concentrate near H3 and H4, while in Kulning, it was slightly higher near H5. In Kulning, more high harmonics were also visible compared to Opera. According to Lindblom and Sundberg,[20] R2 is especially sensitive to laryngeal height in vowels that have tongue positions similar to [iː]. Lindblom and Sundberg further stated that when the tongue is in a forward position in the oral cavity (tongue body closer to lips), the shortening of the tongue-palate distance tends to rise R2.[20] A partial explanation for the differing distributions of spectral energy in Opera and Kulning in [iː] could, therefore, be higher R2 in Kulning. From this data, it is not possible to determine if the tuning of R2 or R3 occurs in Kulning. Rosenberg et al discussed the possibility of resonances being tuned to several of the lowest harmonics,[23] however, the findings of Johnson et al, who used acoustic models to estimate the frequencies of the four lowest resonances, supported only tuning of R1 to H1.[6] It should be considered that resonance tuning strategies are highly vowel dependent. The results for [iː] were not reported separately by Johnson et al.[6] At this point, the possibility for tuning of R2 and R3 to occur within some pitch ranges in Kulning cannot be dismissed or confirmed.

TABLE 4.
Summary of the Observed Vocal Tract Differences Between Opera, Kulning, and Edge

	Opera	Kulning	Edge
Jaw opening & Lip distance	(+)	(+)	(+++)
Tongue dorsum	(+)	(++)	(+++)
Tongue-palate distance	++	+	
Soft palate elevation	++	+	
Laryngeal position	+++	++	(+)
Pharyngeal & Epilaryngeal areas	(+++)	(++)	(+)
Laryngeal tilt	(+)	(+)	(++)

The table summarizes all the VT measures which demonstrated differences between Opera, Kulning, and Edge. The number of the plus symbols indicates which vocal technique demonstrated the highest values and which the lowest values. Parentheses are used when the difference between the vocal techniques was not demonstrated meaningfully by all three participants. Note that Edge was sung only by P3 and, therefore, samples of Edge were compared only to Opera and Kulning samples of P3.

The different tongue and laryngeal positions could partly explain the differences in the timbres of Opera and Kulning. At the studied pitch, the additional energy at the high parts of the spectrum in Kulning likely leads to a perception of brightness and could perhaps help Kulning carry over long distances in its natural environment. The Operatic soprano, on the other hand, could maintain the relatively dark timbre typical for the genre by using the dominant H1 and the high f0 as the main strategies to carry the voice through orchestral instruments' accompaniment. It is important to note that the current audio recording system did not allow examination of high-frequency spectral content. Therefore, the extent of the high harmonics of Kulning is difficult to estimate. Earlier studies have reported high amounts of spectral energy in Kulning even above 10000 Hz.[33,49]

Edge showed distinct spectral differences from Opera and Kulning. A dominant H2 was observed in Edge instead of dominant H1. This is not controversial, as in female Belting, R1 is generally kept near H2 or other higher harmonics, as reported by earlier studies.[13,24–26] In Edge and other Belting styles, high R1 could be used as a means to achieve high SPL for the reasons stated earlier (see eg, 18, 20). When the pitch rises at the studied pitch levels, increased mouth opening and larynx rising are required for maintaining R1 near H2. The need for larger mouth opening can partly explain the better feasibility of [ɛː] over [iː] in the present study for

P3. The observed differences in the oral cavity dimensions between Edge and the other techniques are mostly explained by the use of a different vowel.

Edge demonstrated the least forward tilted vocal folds out of the vocal techniques studied. This seems consistent with a previous study categorizing Edge as a sub-type of Belting[3] and Belting being often defined as extending the chest register at pitch levels where the head register more naturally Operates (see eg, Miles & Hollien[4]). The Cricothyroid (CT) and Thyroarytenoid (TA) muscles play a central role in the regulation of register and pitch.[50−54] Contraction of the TA increases the tension of the vocal fold body, slackens the vocal fold cover, brings the lower edges of the vocal folds closer to the midline of the glottis, and decreases LT. This is the typical vocal fold adjustment for chest register phonation.[50,52,55] Using a similar MRI-based method of evaluating laryngeal tilt as the present study, Echternach et al observed a less forward-tilted larynx in a professional female musical theater singer singing in the chest register compared to her singing in the head register.[38] In another recent study that used laryngostroboscopic imaging to examine laryngeal gestures of three male CVT™-trained singers, laryngeal tilting was associated with reduced-density condition when compared to fuller condition.[56] CVT™ literature mentions that a note sung with full density is heard as being fuller and with a greater amount of weightiness than reduced density note.[2] The terms full density and chest register could have, therefore, partly crossed meanings since both the phonation types seem to be characterized in the literature with similar physiological and perceptual characteristics.

Some of the shortcomings of the present work should be discussed. The Edge vocal mode was performed by only one of the participants. The initial goal was to have each participant train also Edge, but since P1 and P2, who had a background in Kulning and Classical singing, regarded Edge as overly deviant from their normal singing habits, it was seen as more appropriate to allow P1 and P2 to concentrate on practicing only one unfamiliar vocal technique. Even though it could be argued that Edge brings only a little to the table, maintaining Edge in the study was seen as essential, since it provided a valuable opportunity to compare Edge to Opera and Kulning directly through within-subject comparison. The participant with expertise in Edge seemed to be able to produce quite high-quality samples of Opera and Kulning, so the comparison was estimated to add value to the study.

A one-hour practice session is naturally too short for even an experienced professional singer to learn a new unfamiliar vocal technique comprehensively. However, in the case of the present study, it was not required that the singers master the unfamiliar vocal technique to such an extent that it could be implemented at several pitch levels and vowels in the context of a song. Moreover, the duration of the practicing session was not strictly predetermined but was found to be sufficient for these specific participants to learn imitate one pitch and vowel well enough to allow the element of within-subject comparison to be included in the study design. The required duration of the practice would depend on the participants and on what type of voice production techniques are studied. Although the samples given by the non-expert singers cannot be expected to perfectly represent the studied techniques, these samples were essential for determining that the differences observed between the studied vocal techniques were not mainly due to the anatomical differences between the participants.

The audio material of the present study had two limitations. The frequency response of the audio recording system had a notably large slope of 10 dB / octave and a peak slightly less than 10 dB around 400 Hz − 500 Hz, as shown previously by the measurements of Leppävuori et al.[7] Furthermore, a free VST audio plug-in (ReaFir)[35] was used to filter the MRI noise and, during that process, some of the voice harmonics were affected. Since direct comparisons were made mostly between audio samples recorded and processed in the same manner, and since the conclusions based on the spectra were quite general in nature, it is argued that the methodology used to process and analyze audio was sufficient for the current purpose. The study could have benefited from recruiting separate expert listeners to evaluate the representativeness of the samples. This should be considered in future studies instead of relying only on the participating singers' evaluations that were noted during the MRI session.

The MRI conditions eg, lying in a supine position with an impaired hearing perception, likely affected the singers' ability to perform the singing tasks. The extent of this effect was not tested here. Traser et al[57] previously reported that there were no marked differences in the articulatory adjustments of nine professional tenors between singing in upright and supine positions; however, some statistically significant effects were observed in the laryngeal height and jaw protrusion.[57] At this point, based on the existing literature, the total extent of the effects of MRI scanning on voice production are difficult to estimate. The present results did demonstrate some variation in the VT dimensions, even when the samples were provided by the same singer using her expert vocal technique. These differences could partly reflect the destabilizing effect of the MRI conditions. However, it is also likely that a successful resonance strategy does not require an exact VT setting, since the VT resonances can be modified with a variety of adjustments in VT dimensions; for instance, R2 in vowel [iː] can be adjusted both by modifying the tongue position and the laryngeal position.[20]

Only one pitch (C5, 523 Hz) and vowel [iː] (or [ɛː] in Edge) were chosen for the present study. The scope was limited to avoid making the participants spend overly long time in the MRI scanner and to allow more detailed evaluation of the factors within the scope. Different vowels, pitch ranges, and voice qualities should arguably be examined separately to gain a well-functioning overall understanding of VT behavior in loud phonation. It seems that variations in one of the above-mentioned parameters can cause somewhat unexpected changes to the relationships between VT dimensions and the other parameters. For instance, Echternach et al observed major VT shape variations in ten Classical tenors singing scales across the area of register break with constant sound quality (mixed voice), but witnessed only minor changes when the singers sang the scale with a perceivable change in the voice quality (register shift from modal to falsetto).[58] The present study concentrated specifically on vowel [iː], which according to the authors' experience, has been less studied in the field compared to the more open vowels. The vowel for Edge was changed to [ɛː] during the second experiment applying MRI. A question could be raised as to whether [ɛː] would have been better suited for comparing the studied vocal techniques. Since the practicing session was already implemented and some of the data was acquired when the vowel was changed for Edge, it was not seen as reasonable to consider making a fresh start.

The issue of sample selection should be discussed. One of the authors made a final judgment on what samples to include in the analysis. The author did not make any judgments based on a personal view of the sample's representativeness of the target singing technique. Some of the samples were excluded from the analysis since the participants determined the trials as non-successful during the MRI experiments and some MRI images were disqualified based on insufficient image quality.

The contributions of the present work are several. Only a few examinations on Kulning and Edge techniques have been carried out to date. Here, these singing techniques were compared to each other and to the more comprehensively studied Operatic technique. Trained professional singers likely rely on a high skill acquisition and advanced vocal technique to reduce vocal load when singing loudly. It should be, however, stated that singers, as well as non-singers, do experience voice problems (see eg, Phyland et al[59] and Döllinger et al[60]). Nevertheless, it seems reasonable to assume that studying trained professional singers, who perform high-SPL singing as a daily routine even up to eight shows a week, has the potential to add understanding on how vocal efficiency can be maximized with relatively low cost on the vocal fold tissue. Therefore, studying loud phonation in trained professional singers can be beneficial from the point of view of vocal economy, which is a central theme in the field of voice research.

In addition to clarifying how the VT dimensions differ between the three high-SPL singing voice productions, Operatic singing, Kulning, and Edge, the current findings advocate that high-SPL phonation is achievable in varying, and even quite contrasting, VT settings. It is likely that different types of loud voice productions, at least the ones studied here, rely on different types of reinforcement from the VT. In practice, this is important knowledge, considering the field of voice pedagogics. The singing teachers who teach various music genres should be knowledgeable of the facts and avoid using overly broad generalizations as a basis for their teaching methods. While one type of VT setting could be optimal for a specific type of loud singing, it could produce poor results or possibly even risk the vocal health of a singing student when attempted in another type of loud singing. Furthermore, to the best of our knowledge, the present study tested a novel approach to allow a more robust within-subject comparison of different singing techniques. A training session was arranged prior to the data acquisition for the expert singer participants to practice together the target phonations. We estimate that comparing two singing techniques directly in the same subjects is more informative than comparing different individuals or using only an anatomical reference point. Although it was not quantitatively measured how well the participants learned the unfamiliar singing techniques, they expressed comfort in each other's ability to produce well representative samples during the practicing and MRI data acquisition. The implementation of the practicing session in the present study design was experimental in nature and would have benefited from a more comprehensive documentation of the session, ie., the used instructions and the discussions between the participants and the researchers. This should be considered in future studies.

Our future studies will include modeling to resolve what kind of resonance frequencies correspond to the VT configurations found in this study. Voice simulation may offer interesting information on the linear effects of VT on the radiated power of simulated Kulning, Operatic singing, and Edge. A third question of interest would be the role of subglottic pressure and voice source in these singing styles. Furthermore, the possibilities of studying the laryngeal tilt, the angle of the vocal folds, and the vocal fold length from the MRI should be further evaluated. This could lead to some updates on the understanding of the register phenomenon and pitch control in singing. However, the challenge for studying vocal folds with MRI is to obtain sufficient image quality for the vocal folds to be clearly detected. Another challenge would be that the estimation of the register based on vocal fold angle and length alone is not straightforward, since the activation relationships between the CT and AT muscles in the regulation of pitch and register are complex. As MRI image quality has improved with technological advancement, the possibilities of examining the vocal folds with MRI should be carefully evaluated.

The vocal techniques underlying Operatic singing, Kulning, and Edge vocal mode can produce high loudness levels. This study compared the vocal tract dimensions applied in these techniques on the vowel [iː] ([ɛː] for Edge) at pitch C5 (523 Hz) using dynamic and static MRI. The study also utilized a training session prior to the data acquisition, allowing for within-subject comparisons of the styles. The results implied that the Operatic technique uses lower larynx, larger tongue-palate distance, and larger epilaryngeal and pharyngeal tube diameters compared to Kulning. Edge showed the highest laryngeal position, narrowest pharynx and epilarynx tubes, and the least forward-tilted larynx out of the studied vocal techniques. The results shed light on the magnitude of vocal tract changes required for genre-typical vocal projection.

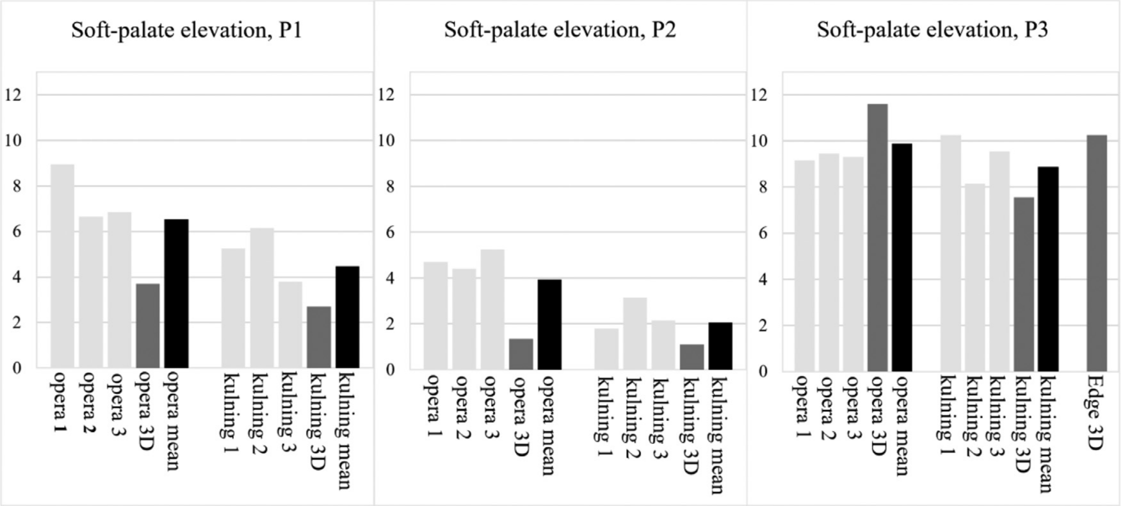


FIGURE 10. Soft-palate elevation individually for each participant and singing style. A greater value corresponds to a greater elevation. Bars present the mean of the first and second rounds of measurements. In the Operatic and Kulning techniques, the rightmost bar corresponds to the mean across all dynamic and static MRI measurements within the given singing technique.

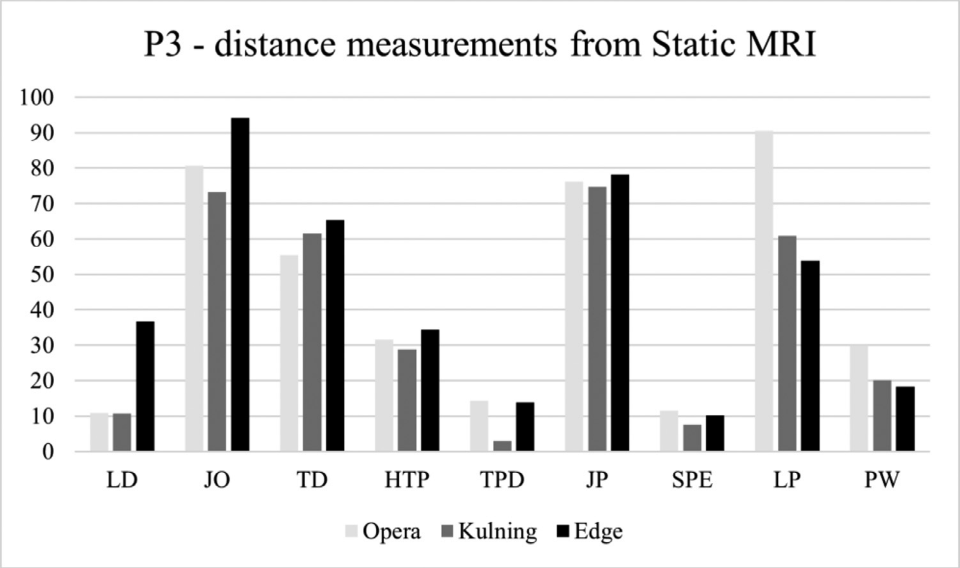


FIGURE 11. Vocal tract distance measurements from the CVT^{TM}-trained singer's 3D static MRIs. Note that for LP, a greater value means a lower laryngeal position.

DECLARATIONS OF INTEREST

None.

ACKNOWLEDGMENTS

We warmly thank the singers who participated in the study.

SUPPLEMENTARY DATA

Supplementary data related to this article can be found online at doi:10.1016/j.jvoice.2022.01.024.

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