The dynamic effect of the valleculae on singing voice – an exploratory study using 3D printed vocal tracts

Mengli Feng, David M Howard

Department of Electronic Engineering, Royal Holloway, UK

Background and objectives

The valleculae can be seen as a pair of side branches of the human vocal tract like the piriform fossae. While the acoustic properties of the piriform fossae have been explored in detail, there is little evidence of exploration of the acoustic properties of the valleculae. A recent investigation (Vampola et al, 2015), using a finite element model of the vowel /a/, suggests that when valleculae created by two antiresonances and two resonances in the high frequency region (above 4kHz) along with those produced by piriform sinuses. In the current study, we investigate, in multiple vowels, the acoustic influences of the valleculae in the singing voice, using 3-D printed vocal tracts.

Method

MRI data were collected from an operatic tenor singing English vowels /a/, /u/, /i/. The images of each vowel were segmented and edited to create a pair of tracts, where one is the original and one had the valleculae digitally removed. The printed tracts were then placed atop a vocal tract organ loudspeaker and excited by white noise. Recordings were made with the microphone placed in front of the mouths of the tracts, to measure their frequency responses.

Results

Dimensional changes were observed in the valleculae of different vowels, with the long term average spectra illustrating clear differences between the frequency responses of the va-nova (valleculae – no valleculae) pairs, which variess with vowels.

Conclusion

This experiment demonstrates the dynamic nature of the shapes of the valleculae in the human vocal tract and its acoustic consequences. It provides evidence that the valleculae have similar acoustic properties to the piriform fossae but with larger variations, and in some cases can influence acoustically the frequency region below 4kHz. The results suggest that large volume valleculae have the potential to impede to some extent the acoustic effect of the singers formant cluster and small valleculae may do the reverse. Since the volume of the valleculae is observed to be largely dependent on tongue movement and also with changes to the uttered vowel, it can be assumed that the high frequency energy, including that within the singer's formant region, could be vowel dependent. Strategies to control valleculae volumes are likely to be highly relevant to voice pedagogy practice as well as singing performance.

Keywords:

Valleculae, Singer's formant, 3D-printed vocal tract, anti-resonance, vocal tract organ

I. INTRODUCTION

The valleculae are a pair of side branches of the human vocal tract, formed by the gap between tongue root and epiglottis. The valleculae are often considered together anatomically with the piriform fossae, another pair of side branches within the vocal tract. They are both one-end close one-end open tubes (quarter-wave resonators) attached to the main passage of the vocal tract, and both are located symmetrically in pairs on either side of the midsagittal plane of the vocal tract towards its lower end. Based on the structural similarity, we can therefore infer the likely acoustic effects of valleculae from those identified for the piriform fossae, which are identified as one of the main contributors to the production of the singer's formant.

By modelling the piriform fossae as two cylinders using measurements from tomograms, Sundberg1 demonstrated antiresonances between 3 to 4kHz. Later in a vivo experiment,

Dang and Honda (1996) investigated the acoustic characteristics of piriform sinuses by filling them with water in human subjects and by simulation. Spectral troughs were found around 4-5 kHz with increasing frequencies as a consequence of water injection. From a theoretical investigation, Titze and Story (1997) also observed that the 5th formant being lowered in frequency closer to the lower formants, thereby intensifying the singer's formant and leaving a valley (antiresonance) at higher frequencies. Delvaux and Howard (2014) further explored such effect using 3D printed vocal tract, where the piriform fossae create antiresonances around 5kHz when expanding, making the singer's formant more prominent. The frequency of the antiresonance are found to remain essentially consistent (Dang and Honda, 1996) as the geometry of the piriform fossae varies little with vowels in speech and singing.

The valleculae are assumed to have similar effect as the piriform fossae in general, but because of their smaller size, the affected frequencies are expected to be higher. This was observed by Vampola et al (2015) using a finite element model of the vowel /a/. The results suggest that when valleculae are present, two antiresonances and resonances appeared in the high frequency region (above 4kHz) along with those produced by piriform sinuses, possibly affecting the second singer's formant, which is around 7.5 to 9kHz.

In contrast to the piriform fossae, the valleculae can vary considerably in size and shape from vowel to vowel as a function of the movement of the front wall of the vocal tract and the tongue roots. With a small size when at rest, the valleculae can have similar or even larger sizes than those of the piriform fossae in some vowels such as /i/. This means that the resultant antiresonance may influence the acoustic properties of the vocal tract in the context of the production of the singer's formant and even the vowels themselves.

The objectives of this paper are: (a) to establish what the overall spectral output variation is in relation to changes in volume of the valleculae with different vowels, (b) to identify the articulatory factors that underpin it (Articulatory factors refers the movements and positions of the articula- tors that brings the change of valleculae and its acoustic consequences. It is suspected that tongue movement is one of the main factors), and (c) to investigate how this spectral variation shapes the high frequency spectral energy of a singing voice during different vowels. Experiments were conducted using 3-D printed vocal tracts of a professional operatic tenor.

II. METHOD

A. MRI based 3D-printed vocal tracts

Previously, the exploration of vocal tract acoustics was either done with recordings from a live singer or by computational and physical modelling. In the case of side branches like the valleculae and piriform fossae, conducting experiments with a live singer can be tricky as those structures are hidden at the back of the vocal tracts and can shape variations cannot be reliably controlled voluntarily. In early studies, researchers tried filling piriform fossae with cotton or water to find out the their acoustic effect (Flach & Schwickardi, 1966; Dang & Honda, 1997). Although it offers valuable data in vivo, such approaches are no longer adopted due to ethical as well as practical considerations. Numerical modelling, on the other hand, is used more frequently, from coarse estimation method such as 1D mathematical modelling (Radolf, 2016) to more accurate 3D modelling such as Finite Element Method (FEM) (Delvaux & Howard, 2014). However, such modelling tasks can be very time consuming to execute. 3D printing offers an attractive alternative, especially when it has become increasingly fast and accurate when paired with fine resolution MRI imaging techniques. A recent study comparing data from numerical modelling using FEM and MRI based 3D printed tracts shows a 7% difference on average, proving the potential value of the later method (Delvaux & Howard, 2014). The current study therefore adopted this new method for measuring the acoustic effect of the valleculae in different vowels.

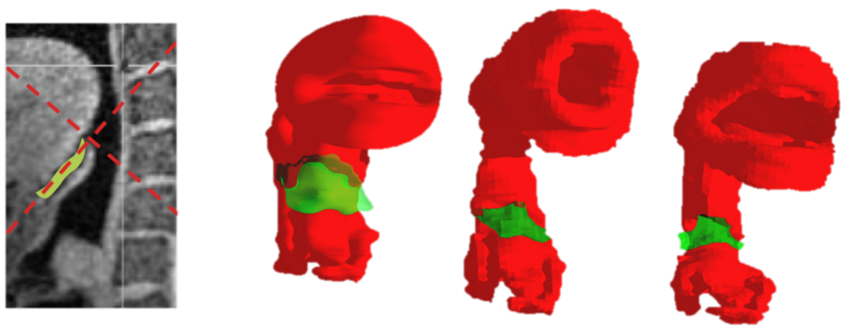


Figure 1. Valleculae cutting. The green areas are the valleculae. a) The red lines shows how the cutting were done perpendicularly to the angle of the valleculae, along the top boundaries of the epi- glottis. b) From left to right are vowel /i/, /u/, and /a/.

B. Modelling and printing

The MRI data of the vocal tracts were collected from a male operatic professional tenor whose native language was German. Vowels /i/, /u/ sung on A3 and /a/ sung on an A4 were chosen for 3D printing. The MRI were done with a 3 Tesla scanner. The images were segmented using ITK-SNAP and pre-processed with meshlab, then went through further modification in blender and were checked out in netflabb before being printed. Measurements of the dimensions of the valleculae were done to the digital models. The 3-D printing was carried out with a Stratasys CONNEX3, using Digital ABS 531 and 515+ (datasheet attached). The interior supporting material was SUP70, which was washed off before the assembly. The tract wall thicknesses were 2mm and the tracts were coupled to a 4mm thick cylindrical base with a 4*10mm rectangular connecting hole to serve as the glottis. Fig.1 shows a 3D printed tract before and after assembling. To investigate the effect of valleculae for each vowel, a pair of tracts, one with valleculae and one without, were printed. The cutting was done perpendicularly to the angle of the valleculae with the cutting area defined by the top boundaries of the epiglottis (see Fig. 2). To evaluate the accuracy of the production process in preparing the experimental tracts, two pair of identical tracts were made (vowel /i/ and /u/), one in the same 3D printing production batch and the other one in a different 3D printing production batch.

C. Measurements on 3D printed vocal tracts

To ensure a more accurate analysis, a series of preassessments were done to check for experimental errors. First, the ambient sound in the recording room (174(w) X 233(L) X 260(h)) and the white noise signal played from the loudspeaker for exciting the tracts were each measured three times. Second, the excitations of the same tract of vowel /i/ and /u/ were measured three times with the tracts being removed and reinstated atop the

Figure 2: 3D printed vocal tracts assembling for the vowel /i/: (a) two halves of the tract before assembling, (b) the assembled tracts without and with valleculae.

loudspeaker in between the measurements. Third, the frequency response of two identical (exactly the same) tracts for vowel /i/ and /u/ excited by white noise signals were measured in order to evaluate the errors of replication. Figure 3 shows the measurement technique. To minimize the influence of room acoustics, the microphone was placed 5mm from the opening of the vocal tracts, with the distance of first reflection being 60cm.

Fast Fourier transform (FFT) analysis of the recordings were done in audacity, with sampling frequency of 48000Hz, FFT size of 512 and frequency resolution of 24000Hz. For each vowel, the frequency responses are the averages of three repeated measurements.

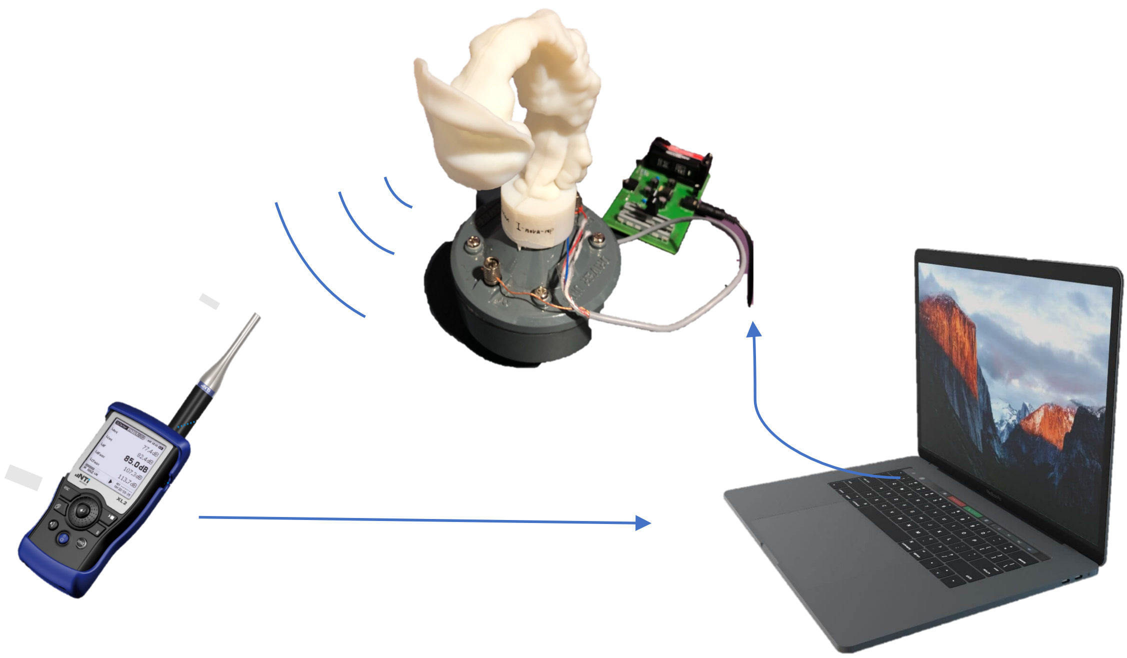


Figure 1. measurement procedure on 3D vocal tracts. A white noise signal (crest factor_PAR*=3.5) was sent from a laptop to a loudspeaker, on which a printed tract sits. The signal emerging from each tract and was recorded for 10 seconds at the mouth end by NTi M2230 microphone with NTi XL2 Sound Level Analyser. The recordings were then sent as wav files to a computer for spectral analysis.

Theoretical estimations of resonance frequencies of the valleculae

To evaluate the measurements and further support the hypothesis, theoretical calculation of resonance frequencies of the valleculae are given. By treating the valleculae as quarter-wave resonant tubes, their resonant frequency can be estimated by the speed of sound c and the effective length le of the valleculae:

$$Rf = c/4 \text{ X } l_e \qquad (1)$$

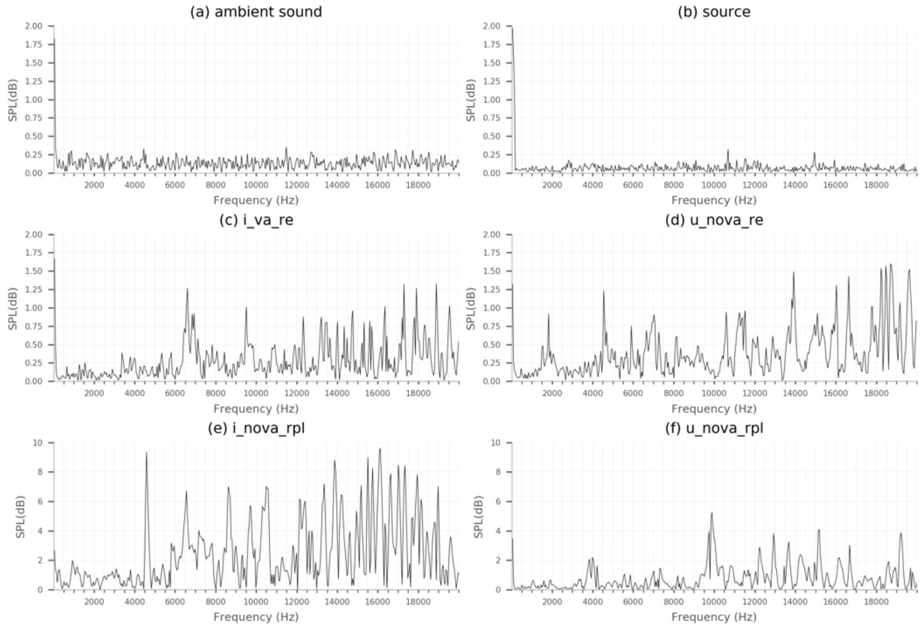
Because the valleculae are not a straight run pipe, the effective length is not equal to physical length. According to Sundberg1, l_c can be estimated from the length l, the end correction coefficient 0.7, and the cutting area A of the valleculae.

$$l_c = 1 + 0.7(A/\pi)^{1/2} \qquad (2)$$

The derivations of the above equations can be found in Sundberg's analysis of piriform fossae (Sundberg, 1974). Further explanation of the underlying physics is beyond the scope of the current paper.

III. RESULTS

A. Error analysis



For evaluating errors, the standard deviation of repeated measurements was calculated, as shown in Fig. 4. The ambient sound and source recordings have a small average variation of 0.133dB, with no difference being larger than 0.5dB across all frequencies. For repeated measurements of the same tract, the average variations are 0.29dB for i_va and 0.36dB for u_nova, with a trend of increasing with increasing frequency. The variation can be larger than 1dB at some frequencies above 4kHz, and can be up to a maximum of 1.6dB at 20.7kHz. For replicates of tracts printed in different patch (e), the variations can become unneglectable, with an average variation of 2.18dB, and many frequencies exceeding 8dB to nearly 10dB. For replicates of tracts printed in the same batch (f), the variation is much smaller, with an average of 0.68dB and the highest value around 5.26dB at about 10kHz.

B. Volumes of valleculae in vowels

The volumes, cutting areas and lengths of the valleculae in three vowels were measured. From Fig.5, we can see that the volumes of valleculae vary the most, from a minimum of 0.65 to a maximum of 6.18 cm3 across three vowels. The /i/ vowel has the largest valleculae (6.18cm3), which is around 4 times larger than the /u/ vowel (1.57cm3) and 8 times larger than the /a/ vowel (0.73cm3). For the inlet area, the /i/ vowel also is the largest (3.78 cm2), followed by that for vowel /a/ (0.65 cm2), which is about one ninth of /i/. /u/ has the smallest inlet area around 0.41 cm2. The lengths of valleculae have the smallest differences, where /i/ ranks first (2.83), followed by /u/(1.99) and /a/(1.08).

(correlation between valleculae volume and tongue position)

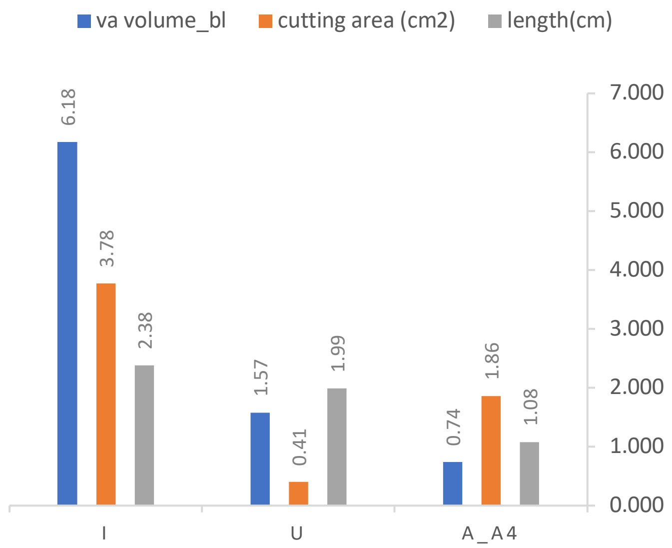


Fig. 5. Volumes and inlet areas of the valleculae in different vowels

C. Frequency responses of 3D printed vocal tracts

The acoustic effect of the valleculae in three vowels is shown in Fig. 6. The black line shows the frequency response of the tracts with their valleculae cut off. The coloured areas shows the changes of the response when the valleculae are present, where green areas are the areas being enhanced and purple areas being suppressed. The white sections are the first and second singer's formant regions defined in the literature (Howard and Murphy, 2008).

The actual singer's formants in the current measurements can be seen as centered around 4000Hz for all three vowels, with that of vowel /a/ being slightly higher at around

Fig. 6. effect of Valleculae in vowel /i/, /u/ and /a/. The solid lines are the average frequency responses of the tracts with their valleculae removed. Green colour shows the areas of increased SPL when the valleculae were present. Purple colour shows the areas of decreased SPL when the valleculae were present.

4250Hz. The second singer's formants are not shown obviously in the spectra. At first singer's formant region, an obvious effect can be seen in vowel /i/, where a resonance appears followed by a strong antiresonance (Titze and Story, 1997) indicated by red arrows in figure 6. The boundary between the resonance and the antiresonance is around 3300Hz. The same effect can be found in /u/ at a higher frequency around 4400Hz. Such effects still exist when the effects of replication are taken into account as illustrated in Figure 7. For the vowel /a/, there is a small depression around 2900Hz, followed with a large one at around 5800Hz. But no clear "peak-dip" pattern like the other vowels can be observed. From the red labels of Figure 8, we can see that the resonances of the valleculae displayed a 3-times relationship, which is consistent with the characteristics of a quarter-wave resonator. For the vowle /i/, the first resonance is at 3980 Hz, with a second resonance at 11,800Hz; for the vowel /u/, they are 4,500 Hz and 13,400 Hz; for the vowel /a/ they are 5,810 Hz and 17,000 Hz.

At frequencies lower than 2500Hz, the changes in spectra when valleculae are present are small compared to higher frequencies, which is clearly illustrated in figure 8.

Figure 7 The effect of valleculae in vowel /i/ and /u/ with error range. The pink area shows the error of tract replication.

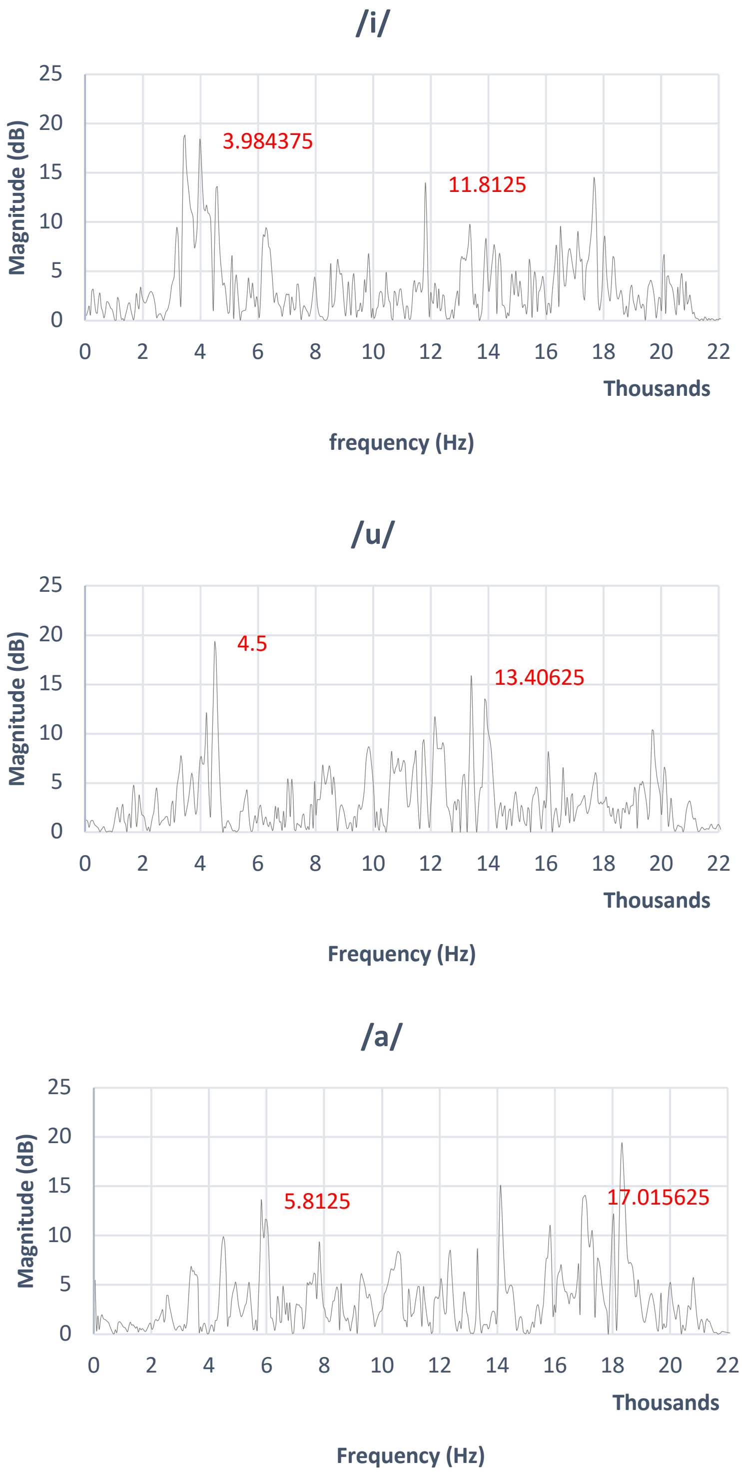


Figure 8: Difference between frequency responses for the three vowels with and without their valleculae. All data are shown as absolute values. The numbers in red show the approximate peak positions of Fs1 and Fs2 (NOTE as comments cannot be added here: The red values have far too many significant figures.

IV. DISCUSSION

Dynamic change of valleculae in vowels and articulatory factors

The geometric change of valleculae across vowels in current study is much bigger compared to the measurements made for piriform fossae by Dang and Honda (1997). The standard deviation (std) of the volume variation in three vowels /a/, /i/ and /u/ is 2.93cm^3 for the valleculae while is only 0.04 for the piriform fossae. Such a large variation also holds

a) /i/ b) /u/ c) /a/

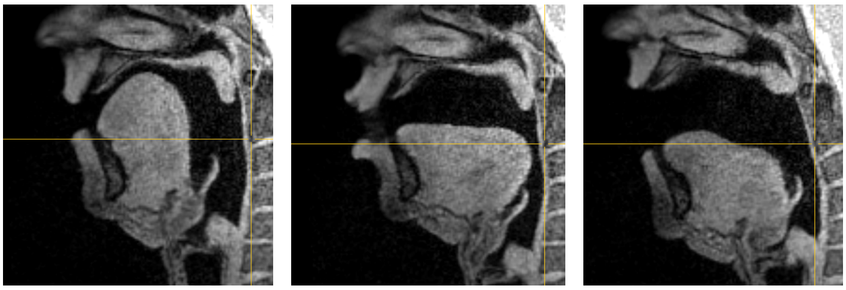


Figure 7 vowel articulation and change of valleculae

for the variations in length, where the std is 0.67cm for the valleculae compared to 0.05cm for the piriform fossae. The large volume differences between the valleculae of different vowels can be explained by their anatomical connection to the surrounding structures. While the piriform sinuses connect to the pharyngeal wall posteriorly and laryngeal cartilages anteriorly, the valleculae are bounded by the tongue root, a much more versatile structure during articulation. Figure 9 shows the cross sections of the vocal tract in the three vowels. It can be seen that the geometry of the valleculae is very sensitive to tongue movement. In a front vowel, such like /i/, the tongue root move forward away from the epiglottis, forming a large uniform in volume valleculae. In a back vowel such as /u/, the tongue root retreated towards the epiglottis fold, forming a narrow valleculae. The epiglottis tip can meet the tongue root to divide the inlets in two. In some cases, the valleculae can be divided into two pockets or branches. In an open vowel such as /a/, the tongue moves downwards and contacts the epiglottis fold at the lower end, forming shallow wedge-shaped valleculae.

Based on the above observations, when including valleculae in models of vocal tracts, It is probably more appropriate to treat them as different geometries for different tongue positions.

A. Dynamic effect of valleculae on the singing voice

How the dynamic change of valleculae can affect the acoustics of the singing voice is of interest. To further evaluate the potential acoustic effect of the valleculae on the singing voice, alongside the observations of measured frequency responses of the 3D printed vocal tracts, theoretical calculations of their resonant frequencies are provided using the geometric measurements.

The estimated resonance frequencies by theoretical calculations and observed resonance frequencies both show that the resonant frequency decreases as the size of the valleculae decreases (see Table 1), which is consistent with previous 2 research on the piriform sinuses. The frequency responses of the 3D printed vocal tracts of /i/ and /u/ confirms the prediction of the valleculae being side branches as clear antiresonances at around 4,000 Hz and 5,000 Hz respectively can be observed, together with adjacent lower frequencies being enhanced. Such "peak-dip" pattern was widely observed for piriform sinuses (ref: Dang, Titze, Vampola). For the vowel /a/, an obvious antiresonance can be observed around 6000Hz, which is in line with the prediction as the valleculae are smaller than thise for both /i/ and /u/. However, no obvious "peak-dip" pattern is observed.

	V	D	Rf
/a/	1.2315	1.75	4359
/i/	1.29325	1.85	4054
/u/	1.227375	1.8125	4160

Table 1 measurements of piriform sinuses (PS) and their resonant frequencies. V: volume (averaged value of right and left PS), D: depth (averaed value of right and left PS), Rf: resonant frequency. Adapted from Dang and Honda, 1997

In the current study, the range of variations of the antiresonances of the valleculae in the three vowels is around 2,000Hz, with an STD of 943Hz, much larger than those measured for the piriform sinuses by Dang and Honda (1997) which is 305Hz with an STD of 155Hz. Detailed measurements can be seen in Tables 1 and 2. For the /i/ vowel, the resonant frequencies of the valleculae and piriform sinuses are both around 4,000Hz, which will create a stronger overall antiresonance around that frequency.

Clear influences of the antiresonances of the valleculae on the singer’s formant (Fs) can be observed (figure. 6). In vowel /i/, the presence of the valleculae largely suppresses the Fs by about 20dB and elevates the frequency peaks on either side flattening the local spectral region. For the vowel /u/ on the other hand, they enhanced the Fs by approximately 5dB and created a dip of 15dB on the higher frequency side of the Fs. For the vowel /i/, a subtle (~1dB) depression along the right side of the Fs peak can be observed. To summarize, whether the effect of valleculae is positive or negative to the overall acoustic projection of the resulting singing voice output seems to be largely correlated with the current vowel, which is likely to be due to the direct influence of the tongue position on the volume of the valleculae.

The findings in here also bring a question about whether the previous observations of antiresonances of

piriform fossae were jointly created by valleculae in some situations.

B. Using 3D printed tract as a tool

There has been a considerable research using 3D printing to for acoustic analysis of vocal tracts. Such an approach retains details of the vocal tract geometry compared to using simplified physical models and it is more time-saving and simple comparing to mathematical modelling. They were able to capture the acoustic features of valleculae as quarter-wave resonator, yielding comparable results to theoretical estimation.

There are two main techniques for measuring transfer functions of 3D printed vocal tracts. The first technique excited the vocal tract at the glottis and measures sound pressure at the mouth end (Arnela et al., 2016; Howard, 2018). The limitation of this method is that the high resistance of the glottal opening and the cavity resonances of the horn of the loudspeaker may affect the behaviour of the loudspeaker (Fleisher et al., 2018). Calibrated impedance heads attached to the glottal end are sometimes used to improve the performance (Wolfe et al., 2016). The second techniques excites the vocal tract at the mouth end and measures sound pressure at the glottis (Delvaux and Howard, 2014; Wolfe et al, 2016), which avoids the complex calibration needed for the first technique. The current study aims at finding acoustic differences between tracts with and with- out valleculae rather than absolute accuracy, therefore it adopted the first technique without using calibrated impedance heads, which can be easily implemented using available equipment in our laboratory. The comparable results of the measurements of 3D printed tracts and theoretical calculation of the resonant frequencies confirms that the technique is sufficient for the task (the slopes of the two regressions are found comparable in a T-test: $p = 0.178 > 0.05$).

However, there are limits of using 3D printed tracts. First, it is difficult and costly to simulate the actual materials and surrounding structures of the vocal tracts by 3D printing. Therefore,3D printed tracts may not be able to recreate accurately the acoustic characteristics of real physical human vocal tracts. In current study, the valleculae may wrongly interpreted as side branches if their boundaries are acoustically transparent. Secondly, the modelling and measurement procedure can bring up potentially significant variations in measurement results, especially in the high frequency region (above about 4 kHz). It is suspected that such variation could be induced due to gluing parts of the printed tracts which is a completely manual process. Future efforts are needed to improve the accuracy when building the models and carrying out the measurements.

C. Pedological indication on vowel choices

Based on the observations in current study, valleculae seem to be of great pedological importance for singing. This is not only because valleculae can make great differences to the overall acoustic output but more importantly because their influence varie greatly with tongue positions. Controlling tongue positions can therefore be important for creating and maintaining the singer’s formant. Specifically, it might be a good idea to avoid excessive tongue root forwarding, which may be interpreted as adding vowel /u/ when producing vowel /i/. In general, the valleculae may be used to created desired depression and enhancement of certain frequencies by adjusting the overall tongue position by using different vowel articulations as guides.

Valleculae as side branches

From the 3D tracts segmented from the professional opera singer's MRI data, the valleculae can be observed as side branches. However, in a conference discussion (Pan-Euro- pean Voice Conference 2019), Johan Sundberg pointed out the geometric observation on MRI data might be subject to errors due to low resolution of the images and the valleculae should be instead modelled as part of the pharynx with the epiglottis as an independent structure in between. This is based on the assumption that the lateral walls of the valleculae are acoustically transparent. The hypothesis stands awaits further investigation of the physiology and geometry of the valleculae and their surroundings. Here, we treat the valleculae as side branches, from the geometric observation of the current 3D printed tract models, as well as the previous MRI data based models (Vampola et al., 2015; Takemoto et al., 2010, 2013). An MRI scan of the valleculae with higher resolution would provide additional insights.

V. CONCLUSION

The current study provides initial data about the dynamic effects of the valleculae during singing using 3D printed vocal tracts. The valleculae are treated as side branches, although more research is needed on the physiology of the valleculae and its surrounding structures to confirm or otherwise whether this is an appropriate description. Compared to the previous measurements of piriform sinuses,2 the results indicate larger variations both in the geometry of the valleculae across vowels as well as in their acoustic con- sequences, most predominantly, with antiresonances. Specifically, it is found that singer's formant can be enhanced or suppressed by the valleculae, depending on the vowels. The findings provide additional suggestions to voice training in the use of vowels to control the singer's formant and higher frequency energy in the voice. The current study provides evidence that 3D printed vocal tracts can be used to investigate the acoustics of the singing voice reliably. They can provide data which reflects geometric detail of the vocal tracts, which can therefore be a useful tool for investigating individual and subtle voice characteristics. Improvements are needed to reduce the errors of repeated measurements and for tract manufacture.

As the current study has shown a diverse variations of geometry of valleculae across vowels, it would be beneficial to collect more data to categorize the geometry of the valleculae and their corresponding articulatory settings.

Acknowledgements

We would like to thank our tenor for agreeing to be scanned, Alex Clarke for technical support for 3D printing and the staff running the MRI scanner in the department of Psychology for their help.

References

1. Sundberg J. Articulatory interpretation of the “singing formant. J Acoust Soc Am. 1974;55:838–844.
2. Dang J, Honda K. Acoustic characteristics of the piriform fossa in models and humans. J Acoust Soc Am. 1997;101:456–465. https://doi. org/10.1121/1.417990.
3. Titze IR, Story BH. Acoustic interactions of the voice source with the lower vocal tract. J Acoust Soc Am. 1997;101:2234–2243. https://doi. org/10.1121/1.418246.
4. Delvaux B, Howard D. A new method to explore the spectral impact of the piriform fossae on the singing voice: benchmarking using MRI- Based 3D-printed vocal tracts. PLoS One. 2014;9. https://doi.org/ 10.1371/journal.pone.0102680.
5. Vampola T, Horácek J, Svec JG. Modeling the influence of piriform sinuses and valleculae on the vocal tract resonances and antiresonan- ces. Acta Acustica United with Acustica. 2015;101:594–602. https://doi. org/10.3813/AAA.918855.
6. Flach VM, Schwickardi H. Die recessus piriformes unter phonia- trischer sicht. Folia Phoniatr. 1966;18:153–167.
7. Radolf V. Sensitivity of acoustic resonance properties to a change in volume of piriform sinuses. Appl Mechan Mater. 2016;821:671–676.
    a. Howard DM, Murphy DT. Voice Science Acoustic and Recording. San Diego, CA: Plural Publishing; 2008.
8. Takemoto H, Mokhtari P, Kitamura T. Acoustic analysis of the vocal tract during vowel production by finite-difference time-domain method. J Acoust Soc Am. 2010;128:3724–3738. https://doi.org/ 10.1121/1.3502470.

9. Arnela M, Blandin R, Dabbaghchian S, et al. Influence of lips on the production of vowels based on finite element simulations and experiments. J Acoust Soc Am. 2016;139:2852–2859. https://doi.org/10.1121/1.4950698.
10. Howard DM. The vocal tract organ: a new musical instrument using 3- D printed vocal tracts. J Voice. 2018;32:660–667. https://doi.org/ 10.1016/j.jvoice.2017.09.014.
11. Fleischer M, Mainka A, Ku€rbis S, et al. How to precisely measure the volume velocity transfer function of physical vocal tract models by external excitation. PLoS One. 2018;13:1–16. https://doi.org/10.1371/
12. journal.pone.0193708.
13. Wolfe J, Tze Wei Chu D, Chen JM, et al. An experimentally measured
13. source−filter model: glottal flow, vocal tract gain and output sound from a physical model. Acoustics Australia. 2016;44:187–191. https:// doi.org/10.1007/s40857-016-0046-7.
14. 14. Takemoto Hironori, Adachi Seiji, Mokhtari Parham, Kitamura Tat- suya. Acoustic interaction between the right and left piriform fossae in generating spectral dips. Journal of the Acoustical Society of America. 2013;134(4).