Subglottal resonances in older adults

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Abstract

The subglottal acoustic input impedance partially consists of a series of resonances that are acoustically excited during voiced speech. Measurement of these subglottal resonances (SGRs) has thus far been restricted almost entirely to young adults and children. However, many aspects of the speech production system are known to change as adults age, and there is a possibility that SGR measurements might have clinical value in older adults. This study examined SGRs measured in 10 adults (5 males, 5 females) aged 50-68 years, and probed the dependence of SGR frequencies on vowel quality, posture, pulmonary function, as well as standing height, sitting height, weight, age, and gender. Previously reported data from young adults were also compared with the new data from older adults. Vowel quality affected the frequency of the first subglottal resonance (Sg1) (Sg1 was higher in [a:] than [i:] or [u:]), and age (older adult vs. younger adult) affected the frequencies of the first three subglottal resonance (Sg1, Sg2, Sg3) (SGRs were lower in older adults). Posture did not affect SGR frequencies, and no other significant relationships were found. The interaction of vowel quality with Sg1 is likely due to acoustic coupling between the subglottal and supraglottal (vocal tract) airways during phonation. The interaction between Sg1 and vowel quality was previously reported to be non-significant in younger adults, and the significant interaction in older adults could be due to age-related changes in laryngeal biomechanics and motor control. Based on previous modeling work, the interaction of age with Sg1, Sg2, and Sg3 is most likely due to age-related changes in the geometry and biomechanics of the subglottal airways, but empirical verification of this hypothesis is still needed.

1. Introduction

The subglottal airways comprised of the trachea and the bronchial tree resonate over a wide range of frequencies. Within the speech band (roughly 100 Hz - 8 kHz or more), the three lowest subglottal resonances (Sg1, Sg2, Sg3) are most likely to interact through acoustic coupling with the vocal tract resonances (Stevens, 1998; Chi & Sonderegger, 2007; Lulich, 2006, 2010; Cranen &

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Boves, 1987; Fant et al., 1972; Klatt & Klatt, 1990; Hanson, 1996) and with the vibration of the vocal folds (Lulich & Arsikere, 2015; Zhang et al., 2006; Berry et al., 2014; Titze, 2008; Lulich et al., 2009). A number of studies since the 1960's (i.e. starting with van den Berg, 1960) have measured the frequencies of these SGRs, although almost exclusively in young adults (e.g. Lulich et al., 2012) and in children (Lulich et al., 2011b; Yeung et al., 2018). Young adults are the best-studied population in phonetics research, in no small part due to the ease of recruiting college and graduate students as participants. Children's speech has frequently been studied in order to investigate effects of growth and development. Older adults, on the other hand, are less easily recruited and have already attained their adult height and mature speech motor control, and so they have been participants in speech research much less frequently (Kent & Vorperian, 2018). With regard to SGRs, the only verifiable exceptions known to this author are Ishizaka et al. (1976), who measured SGRs in four laryngectomy patients between the ages of 40 - 72 years, and Hanna et al. (2018), whose 10 participants included four men aged 55-63 years.

Based therefore almost entirely on data from children and young adults, the following understanding of SGRs has emerged. With some caveats discussed below, the SGR frequencies are determined primarily by the effective acoustic length, $l_a = h/k_a$, of the tracheobronchial tree modeled as a simple uniform tube (Lulich et al., 2011a),

$$SgN = \frac{(2N-1)c}{4 \cdot h/k_a} \tag{1}$$

In this equation, $N = 1, 2, 3$ represents the Nth SGR, c is the speed of sound in cm/s, h is the speaker's standing height in cm, and k_a is an empirically determined scale factor relating speaker height to the length of the tracheobronchial tree's equivalent uniform tube (Yeung et al., 2018).

Several additional resonances associated with the cartilage and soft tissues of the tracheobronchial tree walls are also present in the same frequency range as Sg1-Sg3 (Lulich & Arsikere, 2015), although they are usually difficult to identify in spectral analyses. The first soft tissue resonance, SgT, is at a frequency slightly lower than Sg1, and causes the Sg1 frequency to be somewhat raised relative to the quarter-wavelength prediction encapsulated in Equation 1. Furthermore, at higher frequencies the acoustic waves set up by the vibrating vocal folds penetrate less deeply into the tracheobronchial tree, resulting in a shortened value of l_a and a raised resonance frequency. This is observable in children's Sg3, although adults' Sg3 frequencies appear to be low enough that they are not substantially affected by the decreasing penetration depth. Finally, speech content (for example, vowel quality) does not appear to have a substantial impact on SGR frequencies, at least in young adults and children (Lulich et al., 2012; Yeung et al., 2018). For young adults, Sg1 is in the range 660 ± 47Hz for females, and 554 ± 42 Hz for males. Sg2 is in the range 1513 ± 69 Hz for females, and 1327 ± 77 Hz for males. Sg3 is in the range 2426 ± 101 Hz for females, and 2179 ± 126 Hz for males (Lulich et al., 2012).

Stevens (1998, 2002) posited that the subglottal resonances, through their interaction with vocal tract formants, form quantal 'acoustic berms' that separate the formants of front vowels from back vowels, and high vowels from low vowels. Subsequent studies investigated this in several languages (Chi & Sonderegger, 2007; Sonderegger, 2004; Lulich, 2006, 2010; Jung, 2009; Guo et al., 2014; Dogil et al., 2011; Madsack et al., 2008), including Hungarian (Csapó et al., 2009a; Gráczi et al., 2011); explored the development of this quantal hypothesis in children (Jung, 2009; Yeung et al., 2018); and extended it from vowel acoustics to the acoustic properties of stop consonant bursts (Lulich, 2010, 2008; Lulich & Chen, 2009). A single perceptual study of SGR influence on vowel identification was carried out by Lulich et al. (2007), in which a vowel-consonant (VC) formant transition crossed from above to below an antiresonance mimicking Sg2 in the microphone signal. The frequency and time at which the crossing occurred were manipulated, and this affected the rate at which listeners identified the vowel as a back vowel [a] or a central vowel [ʌ], consistent with the quantal hypothesis. Studies of speaker normalization by computers demonstrated that knowledge of Sg1 and Sg2 can improve performance of automatic speech recognition (ASR) systems, especially when talker age (e.g. child vs. adult) and language (e.g. English vs. Mandarin) in the training and test sets are mismatched, and when limited training data is available (Wang et al., 2008a,b, 2009; Arsikere et al., 2012, cf. Morton et al. 2015, who demonstrated that humans can perform talker normalization based on exposure to a single excised vowel).

Whether the SGR quantal hypothesis applies to older adults, and whether knowledge of SGRs is helpful in ASR of older adults' speech, has not been investigated. Previous studies of vocal tract anatomy and acoustic properties have shown that the vocal tract dimensions and volume change with aging, with concomitant changes in vowel formant frequencies, especially the first formant (F1) (cf. Xue & Hao 2003 and Kent & Vorperian 2018 [section 8.2], and references therein). It has also been shown that the trachea dimensions change with aging (Sakai et al., 2010), as do the mechanical properties of the airway walls (Gibellino et al., 1985). Therefore, the relationships between subglottal resonances and vocal tract formants might differ in older adults compared with what is already known primarily from young adults and children.

A further variable that is known to affect speech production but has not been systematically studied across a large research program, and which has never been studied with regard to subglottal resonances, is body posture. The importance of learning about posture's effects on speech may be easily derived from the fact that most speech produced by most humans most of the time is not the kind of speech we typically study in laboratory settings, viz. seated upright in a quiet environment and without performing significant extraneous tasks. A specific example will suffice to make the point: During the height of the COVID-19 pandemic in 2020-2021, attempts were made to use speech data to help make diagnoses and determine severity of disease. Speech data were attractive because they can be obtained non-invasively, at a distance, inexpensively, quickly, and with little effort from patients. However, many such patients at that time were lying supine or reclining in a hospital bed, which are very different postures than the upright seated posture which informs the vast majority of our knowledge of speech, including subglottal resonances. Because the geometry of the subglottal airways is not volitionally modifiable, unlike the vocal tract, it is not clear that the effects of posture (which includes the effects of gravity) on subglottal resonances can be compensated for in any way, and it is therefore desirable to investigate what these postural effects are.

Kent & Vorperian (2018) call for an 'ambitious program of research ... to determine age-related effects in speech' (p. 83), and the present study represents a first step in this direction with regard to subglottal resonances and their interactions with vowel formants in older adults. The main goals are to characterize the frequencies of Sg1, Sg2, and Sg3 in a sample of 10 older adults (5 males, 5 females), and to characterize relationships between the SGRs and 1) the vowel being produced, 2) the posture in which the vowel is produced, 3) measures of pulmonary function such as total lung capacity (TLC), forced vital capacity (FVC), forced expiratory volume in 1 second (FEV1), and functional residual capacity (FRC), and 4) speaker characteristics such as standing height, sitting height, weight, gender, and age.

2. Methods

Ten older adults (5 males, 5 females) aged between 50 and 68 years participated in this study (Table 1). All of the speech recordings and pulmonary function tests for this study were collected in a sound booth in the Speech Production Laboratory at Indiana University. Speech recordings were made with a SHURE KSM32 cardioid condenser microphone mounted on a stand located approximately 4 feet ($\approx 1.2m$) away from the participant's face. Subglottal acoustics recordings were made with a K&K Sound HotSpot accelerometer held against the skin of the neck below the thyroid cartilage. Pulmonary function tests (PFTs) were carried out in a Morgan Scientific whole-body plethysmograph, using Morgan Scientific's ComPAS software. Age (in years) was recorded by self-report, and standing height, sitting height, and weight were recorded using a SECA digital stadiometer in the Speech Production Laboratory. For sitting height measurements, participants were seated on a stool with a measured height of $29in$ ($73.66cm$). Sitting height was incorrectly recorded for one participant (participant 7), and this datum is therefore excluded from further analyses.

For the speech and subglottal acoustics recordings, participants produced sustained vowels [i:], [a:], and [u:] for approximately 5 seconds, in each of three postures: upright seated, supine, and left lateral decubitus (i.e. lying on one's left side). The duration of the sustained vowels was controlled by prompting each participant when to begin, providing feedback in approximately 1-second increments, and prompting when to stop. These prompts and feedback were made using simple hand gestures, and the quality of the recordings was continuously monitored for accuracy. Although vowel identity was previously shown to not influence SGR frequencies in young adults (Lulich et al., 2012), we recorded SGRs in three vowels in each posture, since we posited that either posture or age might affect the acoustic coupling between the vocal tract and subglottal airways. Each vowel/posture combination was recorded once, thus there were 3 vowels x 3 postures = 9 recordings from each participant. Vowel formants (F1, F2, F3) and fundamental frequency (f0) were measured from the microphone recordings, and SGRs (Sg1, Sg2, Sg3) were measured from the accelerometer recordings, as in previous studies (Lulich et al., 2012; Yeung et al., 2018).

The sampling rate for both the microphone and accelerometer signals was 48kHz before down-sampling to 8kHz. The formants and SGRs were measured in two ways. First, using the original recordings with 48kHz sampling rate, long-term averaged spectra (LTAS) were made from a series of 512-point hamming windows zero-padded to 1024 points, with a step size of 64 points, and the peaks in the LTAS were measured. These measurements were compared with a wide-band spectrogram as an additional accuracy check. The fundamental frequency was measured similarly, but with a 2048-point hamming window with no zero-padding, with a step size of 64 points. Second, after down-sampling to 8kHz, newly-calculated LTAS were viewed together with the average linear predictive coding (LPC) spectrum and with the wide-band spectrogram. The LPC spectra were calculated with order $p = 12$. Peaks in the LTAS and the

LPC spectra were generally in close agreement both with each other and with the wide-band spectrograms. Formant frequencies were almost always measured at the peaks of the LPC spectra, except in instances where the LPC spectrum had clearly missed the formant. SGR frequencies were more likely to be missed by the LPC spectrum, especially at low frequencies (Sg1), resulting in a larger proportion of SGR measurements being made from the LTAS. In all cases, both the formant and SGR measurements were compared with wide-band spectrograms as an additional accuracy check. Figure 1 shows an example of how the SGRs were measured from the LTAS and LPC spectra superimposed on a wide-band spectrogram. The two sets of formant and SGR measurements were made several months apart.

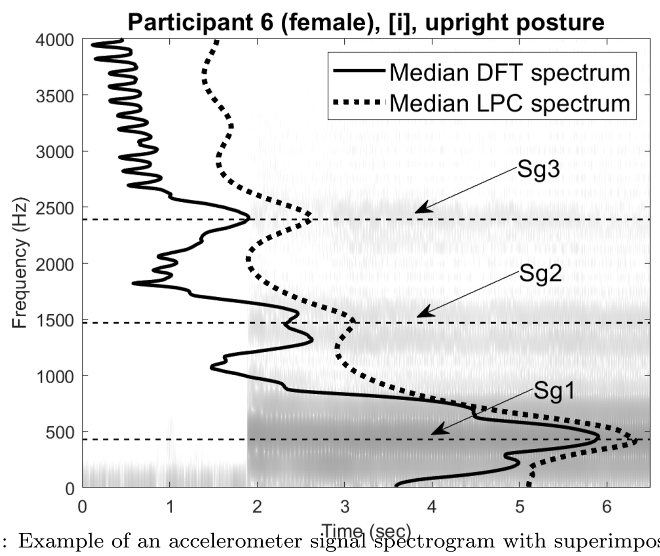

Figure 1: Example of an accelerometer signal spectrogram with superimposed LTAS and LPC spectrum (see text for details). In this example, all three SGRs are measured from the peaks in the averaged LPC spectrum, which aligns well with the peaks in the LTAS. Notice that the double peak in the LTAS around Sg2 is due to the prominence of the two nearest harmonics. In this example, there were approximately 2 seconds of rest, followed by nearly 5 seconds of the sustained vowel [i] produced by a female speaker (Participant 6) in upright posture. The sustained vowel is very stable, showing little acoustic variability throughout its duration.

The two sets of formant and SGR measurements were in excellent agreement, with Pearson correlation coefficients of r = .9545 for F1, r = .9953 for F2, r = .8943 for F3, r = .6134 for Sg1, r = .8951 for Sg2, and r = .9544 for Sg3. The relatively poorer correlation for Sg1 is consistent with previous findings that Sg1 is frequently difficult to measure accurately due to its relatively large bandwidth and its proximity to the loud low-frequency harmonics (Lulich et al., 2012; Yeung et al., 2018). For the remainder of this paper, only those formant and SGR measurements from the second set are used (i.e. from the LTAS + LPC spectra + spectrograms of the down-sampled signals).

For the PFTs, participants completed three successful vital capacity (VC) maneuvers and three successful thoracic gas volume (TGV) tasks. Success was determined automatically by the ComPAS software in accordance with American Thoracic Society (ATS) guidelines, and includes criteria such as the presence of a clear baseline of tidal breathing and absence of a breath-hold between deep inhalation and forced exhalation. The minimum number of attempts was 6 (3 successful VC maneuvers + 3 successful TGV tasks), and most participants completed the PFTs within 8 attempts. One participant was unable to complete 3 successful TGV tasks, and his TGV data are therefore excluded from analysis. From the VC maneuver, the forced vital capacity (FVC) was measured as well as the forced expiratory volume in one second (FEV1). From the TGV task, the total lung capacity (TLC) was measured as well as the functional residual capacity (FRC).

Parametric three-factor analyses of variance (ANOVA) were carried out to test for main and interaction effects of vowel, posture, and gender on fundamental frequency, formant frequencies, and SGR frequencies. Spearman correlation coefficients were calculated for the relationships between the independent variables (age, standing height, sitting height, weight, FVC, FEV1, FRC, TLC) and the dependent variables (f0, F1, F2, F3, Sg1, Sg2, Sg3).

Finally, to evaluate whether there is a difference in SGR frequencies between older and younger adults, we compared data from the present study with data reported in prior studies. Yeung et al. (2018) fit values for c and k_a in Equation 1 using young adult data from Lulich et al. (2012) and child data from Lulich et al. (2011b) and Yeung et al. (2018), and reported best-fit values of $c = 45,400 cm/s$ for Sg1 ($c = 35,900 cm/s$ for Sg2 and Sg3), and $k_a = 8.76$. Root-mean-squared errors in the prediction of Sg1, Sg2, and Sg3 from the resulting model were $49 Hz$, $75 Hz$, and $108 Hz$, respectively, among young adults. The same model was applied to the data in the present study. Two-tailed, two-sample t-tests were used to test whether the model residuals were different in older and younger adults for Sg1, Sg2, and Sg3 ($\alpha = .05/3 \approx .01$ after Bonferroni correction). For younger adults, the mean Sg1, Sg2, and Sg3 values ($N = 50$) reported in Lulich et al. (2012) were used to calculate model residuals; for older adults, the Sg1, Sg2, and Sg3 values across all vowels and postures ($N = 90$) were used to calculate model residuals.

3. Results

The gender, age, standing height, sitting height, weight, and pulmonary function test results for each participant are presented in Table 1. Fundamental frequency (f0) and formant frequencies (F1, F2, F3) for each vowel and posture by participant are presented in Tables 2 and 3, and subglottal resonances for each vowel and posture by participant are presented in Tables 4 and 5.

Three-factor ANOVAs with vowel, posture, and gender as independent factors revealed significant main effects of gender on Sg1 ($p = .0012$), Sg2 ($p \ll .001$), and Sg3 ($p = .0086$), and a significant main effect of vowel on Sg1 ($p = .0057$), but no significant main effects of posture on any of the SGRs. There were also no significant interaction effects on the SGRs. Three-factor ANOVAs with vowel, posture, and gender as independent factors revealed significant main effects of gender on f0 ($p \ll 0.001$), F1 ($p = .0464$), F2 ($p \ll .001$), and F3 ($p \ll .001$), significant main effects of vowel on F1 ($p \ll .001$), F2 ($p \ll .001$), and F3 ($p \ll .001$), and a significant interaction effect of vowel and gender on F2 ($p = .0002$). There were no significant main effects of posture on f0 or the formants, and no additional significant interaction effects.

Table 1: Participant ID, gender, age (yrs), standing height (cm), sitting height (cm), weight (kg), FEV1 (L), FRC (L), FVC (L), and TLC (L).

Participant	Gender	Age	Standing Height	Sitting Height	Weight	FEV1	FRC	FVC	TLC
1	M	68	175.3	79.2	82	3.52	4.48	4.39	8.34
2	M	59	188.9	88.6	146	3.12	4.66	4.43	8.30
3	M	67	175.3	81.6	95	3.37	4.90	4.24	8.33
4	M	54	177.8	81.0	115	3.32	–	4.35	–
5	M	50	168.8	77.3	69	3.31	4.10	4.19	7.47
6	F	68	167.6	73.8	64	1.62	3.30	2.03	5.27
7	F	63	164.6	–	118	2.02	3.28	2.39	6.05
8	F	54	162.6	75.2	75	2.72	2.88	3.22	5.99
9	F	65	153.3	70.8	79	1.64	2.85	2.11	4.67
10	F	59	166.5	79.5	86	2.38	3.51	2.81	5.50

Table 2: Fundamental frequency (Hz) and formant frequencies (Hz) for each vowel by participant (males only) in three postures: seated upright, supine, and left lateral decubitus (lat. dec.).

		[i]				[a]				[u]			
Participant	Posture	f0	F1	F2	F3	f0	F1	F2	F3	f0	F1	F2	F3
1	Upright	141	289	2438	3102	164	836	1195	2750	164	297	1250	2320
1	Supine	141	273	2359	3109	141	703	1125	2641	141	242	1211	2164
1	Lat. Dec.	141	289	2313	3055	164	734	1000	2641	164	281	1180	2156
2	Upright	164	289	2148	2969	164	813	1094	2359	164	281	977	2180
2	Supine	164	328	2398	2602	164	1039	1164	2391	164	438	1023	2117
2	Lat. Dec.	164	305	2203	3508	164	711	1156	2211	164	328	867	2109
3	Upright	141	266	2391	3031	141	633	1078	2492	141	281	1141	1914
3	Supine	164	258	1891	2367	164	594	1078	2523	164	289	1063	2055
3	Lat. Dec.	141	250	1969	2828	141	570	992	2523	141	250	1164	2023
4	Upright	117	219	2305	2766	117	781	1133	2641	117	257	1078	2469
4	Supine	117	227	2367	2914	117	586	1055	2516	117	203	969	2461
4	Lat. Dec.	117	219	2383	2867	117	625	1070	2609	117	211	1141	2539
5	Upright	164	289	2109	2836	164	867	1273	2867	164	297	1188	2867
5	Supine	164	172	2344	2781	164	727	1203	2797	164	164	1195	2820
5	Lat. Dec.	164	148	2578	2945	141	695	1430	2977	141	391	1289	-

Table 3: Fundamental frequency (Hz) and formant frequencies (Hz) for each vowel by participant (females only) in three postures: seated upright, supine, and left lateral decubitus (lat. dec.).

		[i]				[a]				[u]			
Participant	Posture	f0	F1	F2	F3	f0	F1	F2	F3	f0	F1	F2	F3
6	Upright	234	477	2602	3172	211	602	1008	3086	211	445	1383	2594
6	Supine	211	422	2688	3164	211	750	1117	3102	211	398	1453	2797
6	Lat. Dec.	258	234	2477	3180	234	867	1070	3250	234	250	1602	2594
7	Upright	305	289	2680	3266	281	1094	1352	3008	305	383	1133	2867
7	Supine	258	266	2977	3118	258	969	1320	2922	281	258	992	-
7	Lat. Dec.	281	281	2719	3039	258	906	1227	3000	258	273	984	2914
8	Upright	258	234	2531	2773	258	953	1281	2789	258	250	1242	2727
8	Supine	281	258	2563	2977	281	1031	1289	2820	281	258	1086	2633
8	Lat. Dec.	281	250	2602	3000	281	1070	1320	2875	281	250	1094	2648
9	Upright	234	266	2563	3445	234	719	1070	2539	281	250	1102	2711
9	Supine	234	234	2664	3133	234	641	1234	2984	515	461	1141	2672
9	Lat. Dec.	258	242	2781	3273	258	711	1133	2250	281	266	883	2773
10	Upright	234	234	2477	3023	211	852	1219	2508	211	234	992	2867
10	Supine	211	195	2648	3570	211	719	1219	2633	234	211	1008	-
10	Lat. Dec.	234	227	2594	3523	211	586	1305	2352	211	258	1234	2766

Table 4: Subglottal resonance frequencies (Hz) for each vowel by participant (males only) in three postures: seated upright, supine, and left lateral decubitus (lat. dec.).

		[i]			[a]			[u]		
Participant	Posture	Sg1	Sg2	Sg3	Sg1	Sg2	Sg3	Sg1	Sg2	Sg3
1	Upright	516	1320	2398	477	1164	2141	508	1328	2297
1	Supine	477	1203	2313	484	1102	2609	266	1336	2102
1	Lat. Dec.	555	1274	2242	508	1273	2617	508	1219	2086
2	Upright	477	1094	-	406	1086	-	414	1086	-
2	Supine	477	1039	-	297	1102	-	469	1219	2133
2	Lat. Dec.	398	1047	-	289	1117	2063	359	1117	2148
3	Upright	523	1305	-	508	1344	-	500	1320	-
3	Supine	547	1211	2102	609	1234	2070	547	1227	-
3	Lat. Dec.	234	1234	2016	625	1219	2039	422	1227	2148
4	Upright	523	-	-	438	1125	2320	414	1164	2383
4	Supine	242	1164	-	602	1117	-	258	1141	-
4	Lat. Dec.	211	1141	1891	430	1125	1898	219	1148	2180
5	Upright	516	1336	1961	625	1438	1961	523	1344	1961
5	Supine	445	1234	2133	438	1430	-	461	1266	2320
5	Lat. Dec.	398	1289	1969	539	1344	2320	383	1305	-

Table 5: Subglottal resonance frequencies (Hz) for each vowel by participant (females only) in three postures: seated upright, supine, and left lateral decubitus (lat. dec.).

		[i]			[a]			[u]		
Participant	Posture	Sg1	Sg2	Sg3	Sg1	Sg2	Sg3	Sg1	Sg2	Sg3
6	Upright	414	1469	2406	781	1484	2500	398	1383	2516
6	Supine	406	1203	2352	336	1484	2352	406	1406	2344
6	Lat. Dec.	461	1359	2258	625	1227	2297	594	1414	2328
7	Upright	586	1383	-	547	1094	2406	586	1391	2406
7	Supine	531	1313	-	719	1438	-	539	1398	-
7	Lat. Dec.	531	1320	-	734	1453	2422	531	1406	-
8	Upright	469	1563	2445	484	1422	2484	484	1445	2406
8	Supine	469	1531	2477	781	1539	2547	484	1570	2609
8	Lat. Dec.	484	1305	2344	797	1563	2359	594	1594	2609
9	Upright	461	1398	2250	406	1469	2305	438	1398	2172
9	Supine	461	1547	2359	430	1438	2461	469	1563	2438
9	Lat. Dec.	477	1398	2398	422	1492	2242	477	1375	-
10	Upright	484	1258	2047	602	1406	2117	570	1258	2109
10	Supine	391	1289	2039	563	1336	2023	406	1406	2094
10	Lat. Dec.	422	1266	1992	586	1336	2086	633	1281	2000

All demographic and pulmonary function variables except for age were significantly correlated with Sg2. The Spearman correlation coefficients were $r = -.9240$ for standing height ($p < .00015$), $r = -.9167$ for sitting height ($p = .0013$), $r = -.6848$ for weight ($p = .0351$), $r = -.6606$ for FEV1 ($p = .0440$), $r = -.8061$ for FVC ($p = .0082$), $r = -.9333$ for FRC ($p < .00075$), and $r = -.7500$ for TLC ($p = .0255$). No other correlations between demographic or pulmonary function variables and SGRs were significant ($p > .065$). Fundamental frequency (f0) was significantly correlated with standing height ($r = -.8616$, $p = .0014$), FEV1 ($r = -.7853$, $p = .0071$), FVC ($r = -.7117$, $p = .0210$), FRC ($r = -.8984$, $p = .0019$), and TLC ($r = -.7289$, $p = .0316$). The third formant (F3) was significantly correlated with sitting height ($r = -.7333$, $p = .0311$), FEV1 ($r = -.6485$, $p = .0490$), and FVC ($r = -.7939$, $p = .0098$).

The f0, F1, F2, and F3 values (pooled across speakers and postures, but separated by gender; Figure 2, top panels) for the vowels [i], [a], and [u] were similar to previous reports. Whether pooled across speakers and vowels (Figure 2, middle panels) or across speakers and postures (Figure 2, bottom panels), all three SGRs were lower than expected in comparison with young adults. This was further reflected when standing height was accounted for (Figure 3). Two-tailed 2-sample t-tests with Bonferroni correction ($\alpha = .05/3 \approx .01$) showed that model residuals (Figure 4) for Sg1, Sg2, and Sg3 were all significantly lower in older adults than in younger adults ($p \ll .001$).

4. Discussion

In contrast to prior studies of SGRs by Lulich et al. (2012) and Yeung et al. (2018), which reported data from 50 and 43 participants, respectively, the present study is based on a smaller sample of 10 participants. Most of these participants (males and females) were of similar stature, with standing heights ranging primarily between 162cm and 178cm. Participants were recruited from the community by word of mouth, and although some were relatives of other participants, they were related only through marriage and not genetically (e.g. two

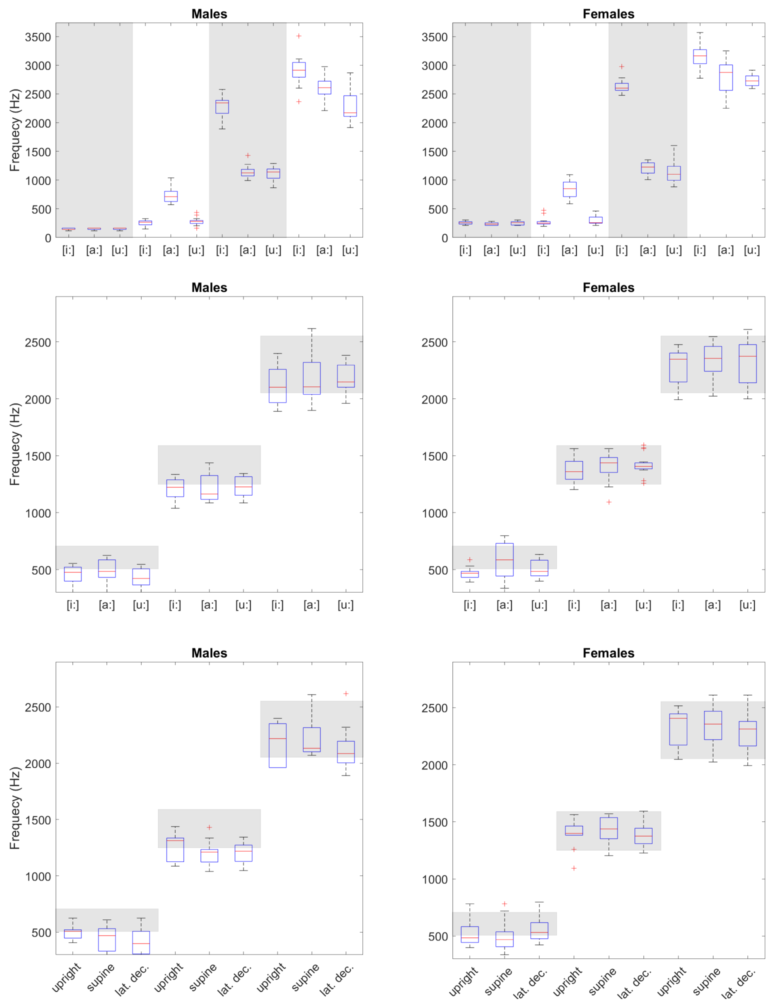

Figure 2: Distributions of fundamental frequency and formant measurements (Top Panels), and distributions of subglottal resonance measurements by vowel (Middle Panels) and by posture (Bottom Panels) for older adults. In the Middle and Bottom Panels, the shaded regions correspond to the expected frequency ranges based on data from Lulich et al. (2012).

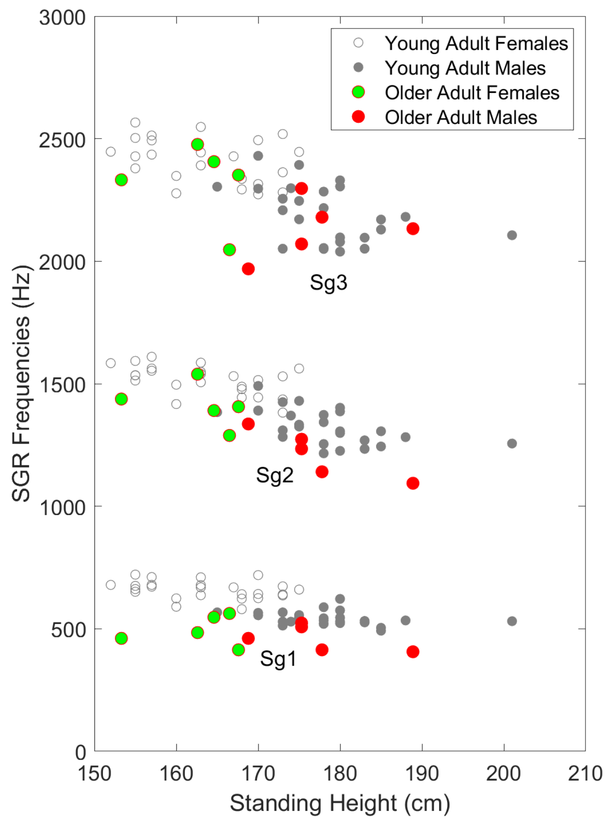

Figure 3: SGR frequencies (Sg1, Sg2, Sg3) as a function of standing height for the 50 young adults in Lulich et al. (2012) and the 10 older adults in the present study. Gray-scale symbols represent data from young adults; colored symbols represent data from older adults. The filled gray and red symbols represent data from male speakers; the open gray symbols and the filled green symbols represent data from female speakers.

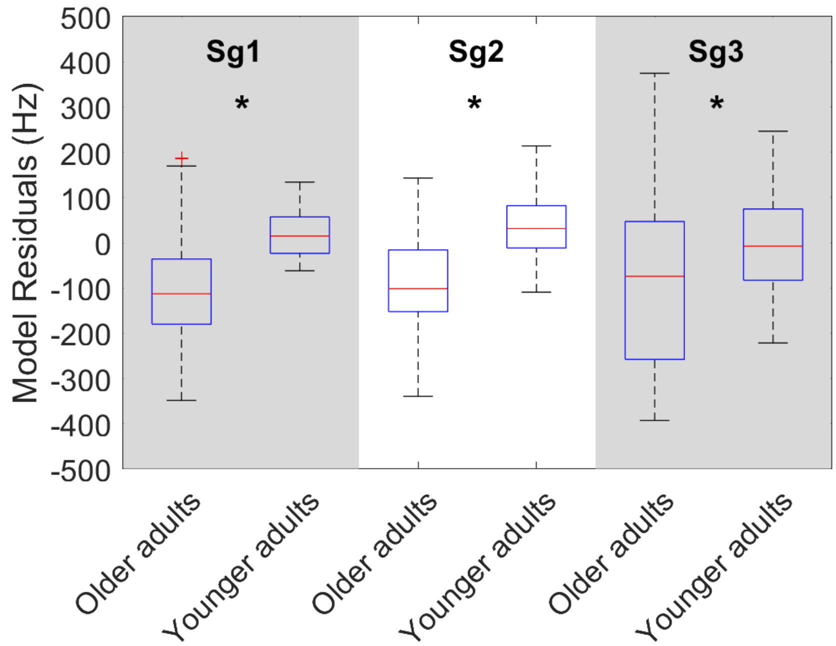

Figure 4: Residuals from applying the best-fit model of Yeung et al. (2018) to both younger adults (Lulich et al., 2012) and older adults (present study). The model used Equation 1 to predict SGR frequencies from standing height, an empirically determined scale factor, $k_a = 8.76$, and a speed of sound, $c = 35,900cm/s$ for Sg2 and Sg3 frequencies and $c = 45,400cm/s$ for Sg1 frequencies. The difference between older and younger adults was significant for all three SGRs.

participants were brother-in-law and sister-in-law). The total range of standing heights among the 10 participants is similar to the total range among participants in the study of young adults by Lulich et al. (2012), with the earlier study including only one male participant with a substantially greater standing height (cf. Figure 3). The small sample size in the present study was therefore sufficient to demonstrate the value of further investigations in this topic. Nevertheless, while the present study was intended as an initial exploration of the possible effects of age and posture on SGRs, future studies should recruit larger and more representative samples of older adults.

Posture was found not to have a significant effect on SGRs, f0, or formant frequencies in this study of healthy older adults in seated upright, supine, and left lateral decubitus postures. Vowel identity affected formant frequencies, as expected, but it also had a significant effect on Sg1. Vowel identity did not affect Sg2, Sg3, or f0. Gender affected all of the SGRs, f0, and formants. Some significant relationships were revealed between SGRs and formant frequencies on the one hand, and speaker characteristics (standing height, sitting height, weight, and age) and pulmonary function test results (TGV, FRC, FVC, FEV1) on the other hand, especially those involving Sg2 and f0. All three SGRs were found to be lower than expected in older adults compared with young adults. An explanation for this cannot be provided by the data presented here, but one possibility is that the decrease in SGR frequencies reflects aging-related changes in the geometry and biomechanics of the subglottal airways.

Subglottal resonances have shown promise in ASR and other speech-based technologies, such as speaker normalization and height estimation. The fact that SGRs are significantly lower in older adults than in younger adults suggests that technologies trained on data from younger adults may suffer performance degradation when applied to older adults, and training data from older adults is therefore desirable for future applications that target this demographic.

5. Conclusion

Subglottal resonances in older adults are not dependent on posture, and only Sg1 was dependent on vowel quality. All of the SGRs were lower in older adults than in younger adults, perhaps due to age-related changes in the geometry and biomechanics of the subglottal airways. With the caveat that the SGRs are lower in older adults than in younger adults, it appears that measurements of SGRs are otherwise comparable in healthy older and younger adults, regardless of posture. Future studies should continue to investigate the effects of healthy aging on subglottal acoustics with larger samples, and extend the sample characteristics to older adults with cardiopulmonary illnesses such as COVID, influenza, pneumonia, asthma, congestive heart failure, emphysema, and others. Not only will such studies contribute to our ability to use speech data in novel clinical settings, but they will also inform our understanding of speech production, phonetics, phonology, and motor control in a broader range of embodied conditions.

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I am grateful to the editors for organizing this special issue in memory of Dr. Tamás Gábor Csapó. I first met Dr. Csapó in 2009 when our mutual friend, Dr. Tamás Mihály Bőhm (1981-2019), arranged for me to teach a graduate course on speech acoustics via Skype at the Budapest Institute of Technology and Economics (many thanks to Dr. Klára Vicsi for facilitating this). Dr. Csapó

was one of the students enrolled in the course (as was Dr. Tekla Etelka Gráczi, one of the editors). Dr. Csapó's final paper in the course investigated subglottal resonances (SGRs) and their relationship with vowel formants in Hungarian. The principal data set for this final paper was a set of speech and subglottal (accelerometer) recordings from Dr. Bőhm, which I have used as pedagogical materials in several of my speech courses over the years. Dr. Csapó's class project led to a series of three papers on SGRs in Hungarian (Csapó et al., 2009a,b; Gráczi et al., 2011). Subsequently, Dr. Csapó spent 6 months as a Fulbright Scholar in my laboratory at Indiana University in 2014, where we worked together to develop 3D/4D ultrasound as a research tool for speech production, culminating in a paper on tongue surface segmentation errors in 2D ultrasound (Csapó & Lulich, 2009). Over the years, and through a handful of visits to Budapest that were never long enough, I was fortunate enough to continue my friendship with Dr. Csapó and his family, and I took a degree of personal pride in his many successes as a scholar and teacher. I was deeply affected to hear of his passing on January 31, 2024. I am grateful to have had the opportunity to join him for lunch on November 17, 2023, when I was in Budapest for the Symposium on Vowel Harmony. My last communication with him was when we wished each other a Merry Christmas on December 25, 2023. It is with sorrow over his passing, mixed with gratitude for his friendship and pride in his accomplishments that I wish to dedicate this paper to his memory.

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