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Detailed analysis of the relationship between tracheal breath sounds and airflow in relation to OSA during wake and sleep

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Abstract—**Tracheal respiratory sound analysis is a simple, inexpensive and non-invasive way to study the pathology of the upper airways. Recently, it has attracted considerable attention for acoustical flow estimation and investigation of obstruction in the upper airways. Obstructive sleep apena (OSA) is characterized by periods of reduction or complete cessation of airflow during sleep. However, the flow-sound relationship is highly variable among OSA and non–OSA individuals; it also changes for the same person at different body postures and during wake and sleep. In this study we recorded respiratory sound and flow from 93 non–OSA individuals as well as 13 OSA patients during sleep and wake. We investigated the statistical correlation between the flow–sound model parameters and anthropometric features in the non–OSA group. The results have shown that gender, height and smoking are the most significant factors that affect the model parameters. We compared the flow–sound relationship in OSA and non–OSA groups in the sitting position while awake. We also examined the variations in the model parameters in OSA patients during sleep and wake in the recumbent position. The results show that the model parameters are different in the two groups even when accounted for height, gender and position. In OSA group, the model parameters change from wake to sleep, even at the same position. The variations in the model parameters can be used to investigate the characteristics of upper airways and examine the factors that can lead to the upper airways obstruction during sleep.**

I. INTRODUCTION

Tracheal sounds analysis is a simple and non–invasive way to study the pathophysiology of the upper airways. It has been used for acoustical flow estimation [1-3] and investigation of the upper airways abnormalities such as airway obstructions [4, 5] in patients with sleep apnea. However, due to the multiple sources contributing in tracheal sound generation, the sound characteristics and flow–sound relationship are highly variable between individuals. It is challenging to use a general flow–sound model for accurate flow estimation in a large population of subjects. Furthermore, the flow–sound relationship may be different among individuals with and without OSA. This study investigates the effects of anthropometric features on the flow–sound relationship in non–OSA individuals. Then we examined if the flow–sound relationship during sleep and wake are different among OSA and non–OSA groups.

Tracheal sounds are generated by the passage of air in the upper airways. Different mechanisms including turbulence of air flow, jet formation and pressure fluctuations in the upper airways are contributing in producing sounds and fluid induced vibrations [6, 7]. Normal tracheal sound has a broad–band spectrum with several peaks; it has been shown that shape and peaks of the spectral curve change with the geometry and pathology of the upper airway [6, 7], while its amplitude and energy change with the amount of breathing flow [1, 6]. Inconsistency of flow–sound relationship between individuals imposes the need for calibration of flow–sound model parameters for every individual, which has been the major drawback of acoustic flow estimation. In a previous study [1], we developed a method which removed the need for calibrating the model at different flow rates, but it did not eliminate it completely. Since tracheal anatomy changes with individuals' anthropometric features [8, 9], these features may correlate with the variations in flow–sound relationship.

Furthermore, one of the main applications of acoustical flow estimation is to detect partial and complete obstruction of the upper airways in OSA patients. OSA is highly prevalent in the general population, approaching about 24% of men and 9% of women aged $30 - 60$ years old [10]. However, the previous studies on flow–sound relationship were all focused on data of awake non–OSA individuals. The flow–sound relationship may change when one sleeps and it may also be different among individuals with and without OSA. Therefore, a crucial step in application of acoustical flow estimation for sleep studies is to have a detailed investigation of flow–sound relationship among OSA individuals during sleep.

In this study we investigated the significance of different anthropometric features on the flow–sound model parameters. Based on the results, we compared flow–sound relationship in non–OSA individuals and a group of matched OSA patients during wake time. Furthermore, the flow–sound relationship in OSA patients during wake and sleep was compared and examined in more detail.

II. METHOD

A. Data

Two data sets were used in this study. The first data set includes data of 93 (52 males) non–OSA awake individuals (35.6 ± 12.9 years old) with no record of respiratory problems. Participants' anthropometric data including ethnicity, age, gender, height, weight, Neck size, chest size, waist size, smoking

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habit and physical activity rate were recorded prior to the experiments. The second data set was recorded from 13 (2 females) individuals suspected of OSA, who were referred to the Miserecordia Hospital Sleep Disorders Clinic for full night sleep studies. Their data were recorded during both wake and sleep. For both data sets, respiratory tracheal sounds were recorded by a Sony microphone placed over the subject's neck and respiratory flow was also measured simultaneously. For OSA individuals, polysomnography study was running simultaneously with our recording and EEG data was used to monitor sleep stages. Details of the recording procedures can be found in [11].

B. Flow–sound relationship

The main sources producing tracheal sounds include turbulence of airflow in trachea and interaction between tracheal wall and airflow. In the previous studies, sound generation mechanisms were investigated in solid pipes and in different models of trachea; it was shown that the produced jet noise and flow follow a power law [12-14]. Another source of tracheal wall's vibration is the fluctuation of turbulent pressure in the tube, which is related to the pressure drop, Δp, along the tube:

$$\Delta p \approx 0.241\ L\ \rho^{0.75}\ \mu^{0.25}\ F^{1.75}\ d^{-4.75}, \tag{1}$$

where L, ρ, μ, F and d are the tube's length, density of fluid, viscosity of fluid, flow and tube's diameter, respectively [6]. Considering these studies, it can be assumed that flow–sound relationship follows a power law as $E_s = kF^{\alpha}$ where, E_s and F represent the tracheal sound's energy and flow, respectively. The model parameters change with respect to the contributions of different components involving in the sound generation.

The power law relationship between flow and sound energy implies that the relationship is linear in the logarithmic scale. The sound's energy (E_s) can be estimated by calculating the signal's variance and we have shown previously that the logarithm of the sound's variance follows the changes in the breathing flow [1]. In previous studies it was shown that the increase in sounds average power is not similar at different flow rates [14]; hence, using the same model at all flow rates will cause over/under estimation of flow at the lower/higher flow rates than the flow rate used for calibrating the model [15]. Therefore, we modified the linear model as:

$$\begin{aligned} \log F &= \bar{E}_s/\bar{E}_{base} \times a \times \log(E_s) + b \qquad (2)\\ &= \bar{E}_s \times \left[a/\bar{E}_{base}\right] \times \log(E_s) + b, \end{aligned}$$

where $[\bar{E}]$ is the average function, E_s is the sound's variance in the overlapping windows (duration of $20ms$ with 50% overlap) of current breath cycle, and E_{base} is the sound's variance in the breath cycle used for calibrating the model. Since, the sound generation mechanisms are different during inspiration and expiration, different parameters should be extracted for each phase. Hence, $a_{ins}, b_{ins}, a_{exp}$ and b_{exp} represent the model parameters during inspiration and expiration phases, respectively where $a_{ins} = a/\bar{E}_{base-ins}$ and $a_{exp} = a/\bar{E}_{base-exp}$ are normalized values of parameter a during inspiration and expiration, respectively. This normalization also cancels the effects of sound variations between individuals.

C. Statistical Analysis of model parameters and anthropometric features

To investigate how the physical characteristics of the trachea affect the tracheal sounds features, we examined the statistical significance of different anthropometric features on the model parameters ($a_{ins}, b_{ins}, a_{exp}$ and b_{exp}). For each feature, data of non–OSA awake individuals (first dataset) were grouped differently. The details of grouping criteria for each feature can be found in [16]. Statistical analysis of variance (ANOVA) was performed to examine whether the average of the model parameters (Eq. 2) were significantly different ($p < 0.05$) in the groups within each anthropometric feature.

Based on the results of ANOVA, the most significant features that affect the model parameters were height, gender and smoking (Table I). We used gender and height parameters to divide the non–smoker individuals into 4 groups of $FH_{G1}, FH_{G2}, MH_{G1}$ and MH_{G2} representing females with height of $\leq 170cm$, females taller than $170cm$, males with height of $\leq 170cm$ and males taller than $170cm$, respectively. For better visualization of the scatter plots of model parameters in different groups, an ellipse was fitted to the data points in each group. Principal component analysis (PCA) was used to find the eigenvectors and eigenvalues of the data points to estimate the direction and length of the ellipse's axes. The average of model parameters in each group was also calculated as the representative point of the group and compared with the average points in the other groups.

Anatomy and physiology of the upper airway such as its dimension, collapsibility, cross–sectional area and thickness are different among non–OSA and OSA individuals [17]. Moreover, the muscle activities deteriorate during sleep which changes the characteristics of upper airway and consequently, affect flow–sound relationship in the upper airways. Therefore, we investigated the variations in the model parameters during wake and sleep in OSA patients and compared the results with data of non–OSA individuals.

III. RESULTS AND DISCUSSION

The results of statistical analysis, shown in Table I, indicate that during both respiratory phases, b–parameters (b_{ins} and b_{exp}) were significantly different for smoking, height and gender features. However, other anthropometric features did not show any significant impact on the model parameters within different groups nor parameter a showed significant variations with height, gender and smoking.

Considering Eqs. 1 and 2, it is clear that the parameter b is associated with the factors multiplying with the flow component such as air density, tracheal length and diameter, while the parameter a depends on the power term (α) of the flow component. The power term (α) and consequently parameter $a = 1/\alpha$ can be considered independent of the physical characteristics of the trachea. This justifies why the parameter a did not change significantly with the variations in anthropometric data of the subjects (Table I). On the other hand, the parameter b is related to the trachea's length and diameter, which are known to be correlated with body height [18]. This explains the significant effects of individuals' height on the parameter b (Table I).

TABLE I

RESULTS OF P-VALUES OBTAINED BY ANOVA FOR INVESTIGATING SIGNIFICANCE OF DIFFERENT ANTHROPOMETRIC FEATURES ON THE SELF–CALIBRATED MODEL PARAMETERS.

Parameter	a_{ins}	b_{ins}	a_{exp}	b_{exp}
Smoking	0.695	$< 0.001^*$	0.072	0.050^*
Height	0.885	0.005^*	0.384	0.004^*
Gender	0.694	$< 0.001^*$	0.151	0.002^*
Age	0.525	0.255	0.096	0.721
BMI	0.450	0.057	0.087	0.425
Ethnicity	0.630	0.060	0.515	0.047
Body-Fat	0.457	0.113	0.139	0.092
Weight	0.369	0.168	0.219	0.795
Neck size	0.853	0.402	0.035	0.152
Chest size	0.503	0.396	0.465	0.742

Smoking has been shown to alter the pathology of airways, deposits semi–micro particles in the airways, induces airway remodeling and airway wall fibrosis [19, 20]. These consequences change the tracheal walls' smoothness, stiffness and thickness, which deviates the tracheal wall from a smooth surface and modifies the flow–sound relationship in trachea. Since smoking remodels the physical and mechanical characteristics of the tracheal wall, it affects parameter b more significantly. Gender is the other factor that significantly affected the parameter b. The authors are not aware of any study which investigates the length of trachea in males and females with similar height. However, in a study on the pathophysiology of the pharyngeal airways, it was shown that the length of pharyngeal airway was significantly longer in men compared with that in women [21]. This may explain the significant differences in the b parameters among male and females.

We used gender and height to divide the non–smoker individuals into 4 groups of FH_{G1}, FH_{G2}, MH_{G1} and MH_{G2} representing short females, tall females, short males and tall males, respectively. Figures 1–a and 1–b show the scatter plot of parameters a and b in these four groups during inspiration and expiration phases, respectively. The average of the individual model parameters (a, b) in each group was calculated as representative parameters of the group. Again it was shown that the average a–parameters did not change significantly in different groups (except for a_{ins} in MH_{G1}), while the variations in the average b–parameters for different groups were affected by the body height. Furthermore, the average b–parameters of the taller females (FH_{G2}) were similar to those of the shorter males (MH_{G1}), which complies with the hypothesis that airway length is smaller in females compared to that in males.

Majority of our OSA individuals (10 out of 13) were tall males which identified as the MH_{G2} group. Figures 1–c and 1–d show the scatter plot of parameters a and b of OSA patients during inspiration and expiration phases, respectively. To be consistent with data of non–OSA individuals, the parameters were extracted from flow–sound data while patients were awake and in the sitting position. The big star markers represent average of model parameters for different respiratory phases. Comparing the results presented in Fig. 1 and Table II, it is clear that average of model parameters are different in non–OSA and OSA individuals, even when matched for gender, height, position and wake conditions. The significant change in parameter a during both respiratory phases are related to variations in the power of flow (Eqs. 1 and 2) which may be more affected by the collapsibility of the upper airways.

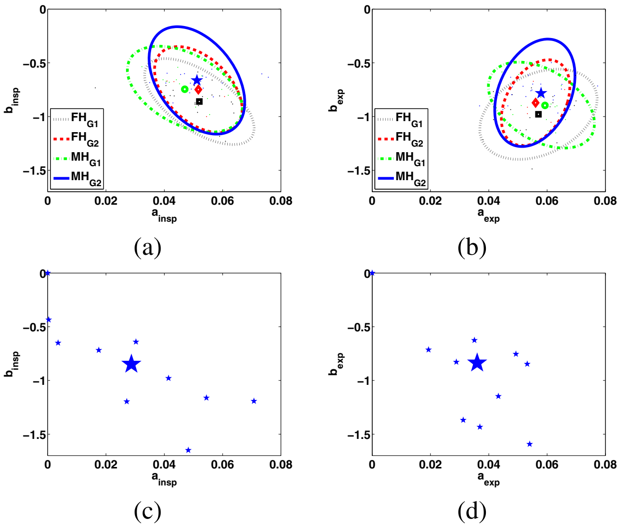


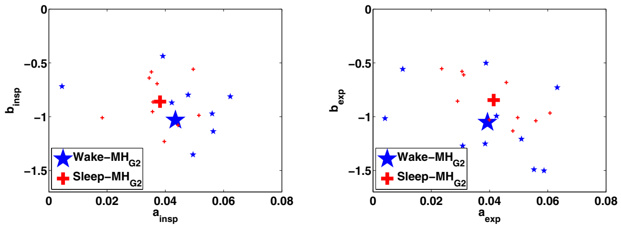
Fig. 1. Scatter of model parameters in non–OSA individuals during a) inspiration and b) expiration phases along with the data of tall OSA males (MH_{G2}) during c) inspiration and d) expiration phases. The data was recorded in wake and sitting position. The big markers show the average of model parameters.

TABLE II

AVERAGE OF THE MODEL PARAMETERS IN NON–OSA AND OSA INDIVIDUALS (MH_{G2}) FOR DIFFERENT BODY POSITIONS DURING WAKE (W) AND SLEEP (S).

Position	Group	*Inspiration*		*Expiration*	
		a	b	a	b
Sitting	NonOSA-W	0.051	−0.664	0.058	−0.783
	OSA-W	0.029	−0.849	0.036	−0.838
	Change(%)	43%	28%	38%	7%
Laying down	OSA-W	0.044	−1.032	0.039	−1.052
	OSA-S	0.038	−0.860	0.041	−0.846
	Change(%)	14%	17%	5%	19%

Scatter plot of the model parameters of OSA patients (MH_{G2}) in the recumbent (laying down) position during wake and sleep are shown in Fig. 2. Average of the model parameters in each group were represented by star and cross markers for wake and sleep data, respectively. The results (Fig. 2 and Table II) indicate that for both respiratory phases the model parameters change from wake to sleep. However, compared to the sitting situation for OSA patients, in the recumbent position the variations in the model parameters from wake to sleep are less. In another word, in the recumbent position, model parameters of the patients are closer to their corresponding values during sleep; this can be later used to investigate the upper airway characteristics in OSA patients. While awake, parameter a increased in the recumbent position compared to the sitting position, which can represent higher



(a) (b)

Fig. 2. Scatter plot of model parameters in tall OSA males (MH_{G2}) in the recumbent position during wake and sleep, a) inspiration, b) expiration. The big star markers show the average of model parameters.

collapsibility of upper airways in the recumbent position; this complies with the previous studies on increased collapsibility of the upper airways in supine position compared to the sitting position [17].

IV. CONCLUSION

In this study, we investigated flow–sound relationship in detail in a large group of individuals with different anthropometric parameters. The results on non–OSA awake individuals showed that gender, height and smoking are the most significant factors in modifying flow–sound model parameters. One of the main applications of acoustical flow estimation is to examine obstruction in the upper airways. Although, acoustical flow estimation was used for sleep apnea diagnosis, in none of the previous studies, neither the flow–sound relationship was investigated during sleep nor in individuals with OSA. In this study, we recorded tracheal sound, flow data and body position from individuals with OSA during both sleep and wake. Then, we compared the flow–sound relationship in OSA and non–OSA individuals during wake time in the sitting position. We also examined the flow–sound relationship in OSA patients in the recumbent position during wake and sleep. The results showed that the coefficients of this relationship are different in non–OSA and OSA individuals. Furthermore, the coefficients change from wake to sleep.

The causes of OSA vary considerably between individuals; however, anatomy of the upper airway and disturbances in its neuromuscular control are some of the major factors that affect upper airway collapsibility. Age, gender and height are major factors contributing to narrowing, increased resistance and collapsibility of the upper airway by altering upper airway length, wall thickness and cross–sectional area. Against this background, the results of our study on the variations of model parameters among non–OSA and OSA individuals during wake and sleep can be used to assess collapsibility and neuromuscular control of the upper airways in OSA patients during wake and sleep. The results will improve the accuracy of acoustical features for characterizing the underlying variations in the anatomy and physiology of patients' upper airways; this will be helpful to improve the phenotypic classification of the patients, and possibly tailor therapy according to the phenotype.

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