# Supplementary File

**Title:** A Subject-Specific Acoustic Model of the Upper Airway for Snoring Sounds Generation

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## Feature Extraction of Snoring Sounds:

We extracted several temporal and spectral features for all snoring segments (Table S1).

Since sleep stage may change the upper airway control mechanism and the generation of snoring sounds[1], we investigated the patterns of snoring occurrences for the entire sleep and every sleep stage separately. We calculated two features: snoring percentage, which represent the number of snoring segments in each sleep stage divided by the total number of snoring segments in the entire sleep; and snoring time index (STI), representing the total snoring time in each sleep stage divided by time spent in each sleep stage

For calculating spectral features, we first estimated power spectral density (PSD) using welch method with 100 ms hamming window and 50% overlap between adjacent windows. We calculated spectral features for the entire frequency band (100-4000 Hz), and seven sub-bands: 100-150 Hz, 150-450 Hz, 450-600 Hz, 600-1200 Hz, 1200-1800 Hz, 1800-2500 Hz, and 2500-4000 Hz [2],[3]. We choose these sub-bands to determine the dominant and the resonance frequency bands in snoring sounds. Frequencies below 100 Hz were not chosen to remove the effects of heart sounds as frequencies below 100 Hz often contaminated with them[4]. Previous studies have shown that the main frequencies of snoring due to the narrowing at the base of tongue were above 650 Hz; whereas frequencies of palatal snoring were below 450 Hz[5,6]. Fruthermore, previous studies have shown that most of the main peaks of snoring were less than 1000 Hz[7]. Additionally, in some cases it was also reported that the harmonics of the frequencies could be expanded to 2200 and 3500 Hz[8]. Also, the measured first and second formant frequencies (resonance frequencies) of snoring sounds are mostly in the range of 400-800 Hz, 1200 – 1800 Hz respectively[9,10]. Considering all these facts, we choose those seven sub-bands.

From PSD, we calculated three spectral features. The spectral features included the average power of snoring sounds in each frequency band; relative power, which defines as the average power of snoring segments in each sub-band divided by the average power in entire frequency band (100-4000 Hz); and spectral centroid, which determines the frequency with the maximum power in each frequency band.

**Table S1:** Features calculated from the snoring segments

| **Feature Name** | **Equation/ Method** |
|---|---|
| Snoring Percentage, % | Snoring in Sleep stage/ Total number of snoring |
| Snoring Time Index, % | Total Snoring Time/ Total Sleeping Time |
| Average Signal Power, $P_{avg}$ , $dB$* | $P_{avg}\ (f_l \leq f \leq f_u) = \sum_{(f_l \leq f \leq f_u)} p(f)\Delta f$ |
| Relative Signal Power (RSP), %* | $\frac{P(f_l \leq f \leq f_u)}{P(100 \leq f \leq 4000)}$ |
| Spectral Centroid (SC), Hz* | $\frac{\sum_{(f_l \leq f \leq f_u)} f p(f)\Delta f}{P_{avg}\ (f_l \leq f \leq f_u)}$ |
| Pitch, Hz | Robust Algorithm for Pitch Tracking (RAPT) |
| Formant Frequencies, Hz | Linear Predictive Coding (LPC) analysis |

$p(f)$ = estimated amplitude by power spectral density
$f_l$ = Lower band frequency and $f_u$ = Higher band frequency.
* Feature was computed over the entire frequency band: 100 – 4000Hz and seven sub-bands of the power spectrum: 100, 150; 150, 450; 450, 600; 600, 1200; 1200, 1800; 1800, 2500; 2500-4000 Hz.

**Upper Airway Model:**

We developed an electrical equivalent circuit of the upper airway tube considering it as a collapsible tube (Figure 1). We used the impedance type analogy to derive the transfer function of the circuit. The impedance type analogy yields the voltage current relationship of a circuit. The acoustical pressure drop of an element is represented by the voltage drop across the electrical element. For an applied acoustical pressure drop, there is volume of fluid movement happens in response. This fluid flow is represented by the electrical current through the circuit. So, the acoustical impedance can be derived by the acoustical pressure divided by the fluid volume flow. As the sounds wave propagates along a lossy tube, it experiences the viscous and heat conduction losses and dissipates energy. These losses can be represented by the acoustical resistance ($R_a$), inertance ($L_a$), and compliance ($C_a$). The thermal losses at the boundaries and during compressions and expansions are represented by $R_a$. The mass of medium is presented by $L_a$. The expansion and compression ability of the fluid medium is represented by the $C_a$. The heat conduction on the wall is presented by conductance ($G_a$). To consider the effects of wall vibration, the wall resistance ($R_w$), wall inertance ($L_w$) and wall compliance ($C_w$) were included in the model. Table S2 shows the equations of the element used in the model.

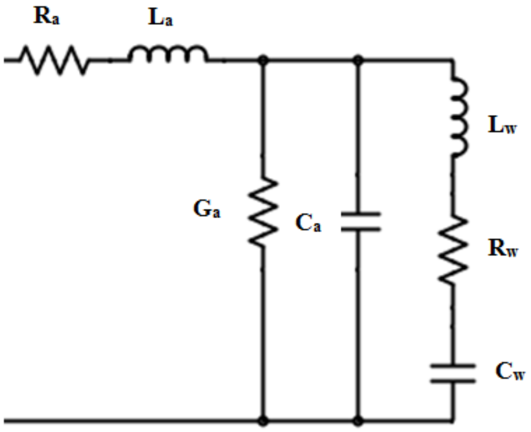

**Figure S1:** Electrical equivalent circuit of the upper airway

**Table S2:** Equation of the elements of the electrical circuit model of the upper airway (equations and values obtained from[11-17])

| Element | Formula |
|---|---|
| Resistance | $Ra = \frac{2l}{\pi r^3}\sqrt{\frac{\omega \eta \rho_0}{2}}$ |
| Inertance | $La = \frac{l\rho_0}{A}$ |

| | |
|---|---|
| Compliance | $Ca = \frac{Al}{c^2\rho_0}$ |
| Conductance | $Ga = 2\pi rl \frac{v-1}{c^2\rho_0}\sqrt{\frac{k\omega}{2\rho_0 c_p}}$ |
| Wall Resistance | $Rw = \frac{\eta_w h}{2\pi l r^3}$ |
| Wall Inertance | $Lw = \frac{\rho_w h}{2\pi rl}$ |
| Wall Compliance | $Cw = \frac{2\pi l r^3}{E_w h}$ |

Density of Median ($\rho_0$): 1.14e-3 (Moist Air, 37 °C) g/cm$^2$; Shear Viscosity($\eta$) : 1.86e-4 (20 Degree, 1 atm) dyne.s/ cm$^2$; Heat Conduction Coefficient ($k$): 0.064e-3 (37 °C) cal/cm-S-°C; Ratio of Specific Heat ($v = c_p/c_v$) :1.4; Specific Heat at Constant Pressure($c_p$): 0.24 (0 °C, 1 atm) Cal/g-°C; Speed of Sounds(c): 3.54e4 (Moist Air, 37 °C) cm/s; Tissue Density($\rho_w$): 1.06 g/ cm$^2$; Tissue Viscosity($\eta_w$): 1.6e3 dyne.s/ cm$^2$; Tissue Elasticity($E_w$): 0.392e6 dyne/ cm$^2$; $\omega$: Radian Frequency; A: Cross Sectional Area; r: Tube Radius; l: Tube Length; h: Wall thickness.

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