Sleep apnoea: A model of airway drying during nasal positive air pressure breathing

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Role of the nose

- Olfaction
- Heating and humidifying inhaled air
- Recovering heat and moisture from exhaled air
- Filtration
Obstructive Sleep Apnoea (OSA)

Affects 6% of adult population.
• 3 times as likely to have car accidents.
• Causes excessive sleepiness whilst awake.

Suffer other symptoms such as:
• irritability
• Depression
• sexual dysfunction
• Learning
• memory difficulty

associated with:
• irregular heartbeat
• high blood pressure
• heart attack
• Stroke

Many n-CPAP patients use supplementary humidification to relieve airway drying symptoms.
Produce a computational model for use by engineers and physiologists to investigate nasal conditions during ambient and pressurised breathing.
(in-vivo) Nasal Geometric Properties

Cross-Sectional Area
Cross-Sectional Perimeter
Volume
Surface Area
Hydraulic diameter distribution along patent and congested airways at ambient pressure.

Δ = Hanna (1983),
○ = Craven et al. (2007).
(in-vitro) ASL Water Supply

When ADO>200nM
P1 receptor A2b opens Cl⁻ channel – fluid leaves cell
Na⁺ channel closes – no extracellular fluid entry
CBF increases

When ATP>1nM
P2Y2 receptor open Cl⁻ channel – fluid leaves cell
CBF increases

ASL top up

When ADO<200nM
P1 receptor A2b closes Cl⁻ channel – no fluid exit
Na⁺ channel opens – extracellular fluid enters cell
CBF decreases

When ATP<1nM
P2Y2 receptor closes Cl⁻ channel – no fluid exit
CBF decreases

ASL reduction

Tissue Pressure and Shear Tidal Forces

Wen, J. et al. (2008)
Schematic representation of apparatus set up

- U-tube manometer
- Transport ventilator
- Incubator cabinet
- Air-flow restrictor
- Desiccant
- Tissue bath
- CPAP air delivery unit
- Air vent
Bovine tracheal maximal water flux during ambient and augmented pressure
(in-silico)
Computational Nasal Air-Conditioning Model
MODEL APPROXIMATION

As \( \Delta x \to 0 \)

\[ dx \]

SEGMENT \( k \)

\[ T_{a(k-1)} + \frac{dT_a}{dx} dx \]

\[ C_{a(k-1)} + \frac{dC_a}{dx} dx \]

\[ \cdots \]

\[ \Delta y_{ASL} \]

\[ \Delta y_m \]

\[ T_b \]

\[ T_{ASL} = T_m \]

\[ T_m \]

MUCOSA
Inhalation inter-airway temperature ($T_a$), absolute humidity ($AH$), molar water flux ($N$), heat flux ($Q$) and ASL water equivalent height ($H_{e,ASL}$) distribution from rest to maximal change.

Mask pressure ambient, $AH=9.2\,g\,H_2O/m^3$ dry air ($T=23^\circ C$, $RH=45\%$).

$\Delta = \text{Keck et al. (2000)},$
$\bigcirc = \text{Wiesmiller et al. (2007)},$
$\bigtriangleup = \text{Lindemann et al. (2001)},$
$\bigstar = \text{Hanna (1983)},$
$\Box = \text{Lindemann et al (2002)}.$
Ambient Breathing

**Left Airway - Congested**

- ASL Height (mm)
- Water Flux (mol/mm².s)
- Nett Supply (g/s)

**Right Airway - Patent**

- ASL Height (mm)
- Water Flux (mol/mm².s)
- Nett Supply (g/s)
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in-vivo Nasal Morphology
Simultaneously solve for $T_m(k), C_m(k)$ and $N(k)$:

$$
\frac{k_m}{\Delta V_m} \left( T_s(k) - T_{\text{ASL}}(k) \right) = h_c(k) \left( T_{\text{ASL}}(k) - T_a(k) \right) + m_{\text{ASL}}(x) h_f (3.33)
$$

$$
N(k) = h_a(k) (C_{\text{ASL}}(k) - C_o(k)) (3.37)
$$

$$
C_{\text{ASL}}(k) = \text{linear fit} (3.36)
$$

Solve ODE

$$
V_k \frac{dT_a}{dX} = \frac{4}{D_a(k) \rho_a C_p} \left[ h_l(k) \left( T_{\text{ASL}}(k) - T_s(k) \right) + m_{\text{ASL}}(k) C_p \left( T_{\text{ASL}}(k) - T_a(k) \right) \right] (3.9)
$$

Update $T_a(k)$

$$
T_{a,k} = T_{a,(k-1)} + dT_a
$$

Determine $Le(k), \alpha, \text{ and } D_{AB}$

Calculate $h_m(k)$ from $h_c(k), \rho_a, Le(k) \text{ and } C_{p,a}$

Solve ODE

$$
V_k \frac{dC_a}{dX} = \left( \frac{4}{D_a(k)} \right) h_m(k) (C_{\text{ASL}}(k) - C_o(k)) (3.14)
$$

Update $C_a(k)$

$$
C_{a,k} = C_{a,(k-1)} + dC_a
$$

Given state variables $T_a(k-1), C_a(k-1)$ from the previous segment

Read $D_a(x)$ from morphology data $A(k), P(k)$

Calculate $V_l(k)$ from $D_a(k), m_a$ and $\rho_a$

Calculate $Re_a(k)$ from $V_l(k), D_a(k), \nu$

Calculate $Nu(k)$ from $D_a(k), Re_a(k)$ and $Pr(k)$

Determine $h_c(k)$ from $Nu(k)$ and $k_t$
Schematic representation of ASL water equivalent height of 10 µm representing the hydration difference between normal and severely dehydrated ASL. Diagram adapted from Button et al (2012).
Airflow Stress Stimulation

Pressure (cmH₂O)

Time (sec)

2 mmH₂O

Factor of 100 x