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Low re-inhalation of the exhaled flow during normal nasal breathing in a pediatric airway replica

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Abstract
To estimate the fraction of the exhaled airflow that is re-inhaled during normal nasal breathing, experiments were carried out in a water tank with an anatomically accurate respiratory tract model of a 4-year-old child. The velocity of respiratory flow was scaled using similarity laws between air and water. Breath simulation was performed via a computer-controlled piston-cylinder system. Food-dye visualization allows a qualitative analysis of the re-inhaled fraction of this exhaled flow. For the quantitative analysis, neutrally buoyant particles were added to the water medium, and illuminated by the laser which illuminates the whole breathing region of the respiratory model, such that the trajectory and quantity of the re-inhaled particles can be recorded and counted. The experimental results in the pediatric airway replica show that a negligible fraction (<0.06%) of the exhaled airflow is re-inhaled during normal nasal breathing in the absence of the rising thermal plume. The artificial plume generated by a heated aluminium brick at the tank bottom increases the re-inhalation ratio by 4 times under the investigated case (albeit still at a very low value of 0.15%). Our results thus reveal that during normal nasal breathing in the present pediatric subject, the vast majority of human exhaled airflow escapes from the inhalation zone and is not re-inhaled.

1. Introduction

Human exhalation flows produced by respiratory activities can carry pathogens that are responsible for the transmission of airborne pathogens [1,2]. With current concerns about new, emerging respiratory viruses (e.g. avian A/H7N9 influenza, Middle East Respiratory Syndrome coronavirus – MERS-CoV), it is useful for infection control purposes to quantify the potential, relative risk posed by such exhaled pathogens. One component of this risk assessment is to estimate the fraction of the exhaled airflow that is re-inhaled during normal (nasal) breathing. This will impact upon risk assessment models that assume human exhaled aerosol as the main source for such exposures, with the fraction of re-inhaled exhaled air potentially not contributing to the final exhaled, airborne pathogen load. This value has been previously reported by Laverge et al. [3] to be about 5% with a tracer gas experiment on the supine thermal manikin (steady condition), and by Zhu et al. [4] to be 17% by CFD simulation on the standing thermal manikin, but no experimental data of dynamic breathing processes has yet been performed, despite of the significant difference in the reported re-inhalation ratios.

Typical respiratory activities were characterized by Gupta et al. [5,6]. The breathing airflow has a maximum velocity of about 1–2 m/s, and can be approximated by a sinusoidal function. Respiratory airflow can be influenced by human thermal plumes. Schlieren optical systems have long been used to visualize the plume and its interaction with human respiratory activities [7–9]. The human thermal plumes were quantified using hot-wire anemometers and Particle Image Velocimetry (PIV) techniques, and by Computational Fluid Dynamics (CFD) approaches [10–14]. The thermal plume of a standing person begins to turn into turbulent flow at the chest level when the Grashof number exceeds $10^5$ and reaches a maximum velocity of 0.2 m/s above the head [7]. The
maximum velocity at the breathing zone is about 0.1 m/s with a boundary thickness of around 0.1 m [10] for a standing occupant in quiescent air. Factors that influence the thermal plume, e.g., supine or sitting postures, clothing insulation, walking of the occupant, have also been investigated [7,15–17].

The tracer-gas technique was often utilized for studying the inhalation zone during nasal breathing, which is distorted from a spherical configuration to a vertically elongated one due to the presence of the thermal plume. The thermal plume plays an important role in particle transport from lower levels to the breathing zone [4,18,19]. In the case of oral breathing in quiescent air, about one third of the inhaled air is entrained from around the mouth, and approximately two thirds is from below [12]. However, these measurements or simulations were mostly obtained under steady exhaling or inhaling conditions. According to Lewis et al. [8], rising air accounts for only about 10% of inhaled air in each tidal nasal inspiration at rest.

This study aims to experimentally investigate, qualitatively and quantitatively, the re-inhalation of exhaled flow during human normal breathing, both with and without the absence of thermal plumes. Unsteady nasal breathing and its interaction with the thermal plume will be also analysed.

2. Methods

An anatomically accurate 3-dimensional upper respiratory tract model including all nasal cavities, the oropharynx, trachea and first three bifurcations of the bronchial tree was designed from CT scan images from a 4-year-old female child (99 cm in height, 16 kg in weight), and re-constructed using 3-D printing technology [20]. Experiments were conducted in a water tank (1.5 m × 1.0 m × 1.2 m), as shown in Fig. 1a; a cylindrical acrylic vessel was used as the chest cavity to contain the lower respiratory tract.

2.1. Breathing simulation

For a 4-year-old female child, a typical respiratory frequency (RF) is 28 breaths per minute (bpm), with a tidal volume (TV) of 0.15 L [26,27]. We also varied RF and TV to study their effects on the re-inhaled ratio of exhaled flow.

The breathing cycle can be approximated with a sinusoidal function,

$$q_a(t_a) = \frac{\pi \cdot TV \cdot RF}{60} \sin \left( \frac{\pi \cdot RF}{30} \cdot t_a \right), \quad 0 \leq t_a \leq t_{s,a}$$

(1)
where the subscript $a$ stands for air, $q_a$ is the volumetric flow rate with time $t_a$, and $t_{sa} = 60/RF$ is the respiratory period.

The equivalent diameter of the nostril is 0.71 cm$^2$, and the peak velocities e.g. maximum velocity in the respiratory process; $L_a$ and $L_w$ are characteristic lengths, namely equivalent diameters of the nose outlets, where $L_a = L_w$ here since a real full size model was used in the present water-tank experiment; the kinematic viscosity, $\nu_a = 1.48 \times 10^{-5}$ m$^2$/s for 25 °C air; $\nu_w = 1.16 \times 10^{-6}$ m$^2$/s for 15 °C water and $\nu_w = 8.73 \times 10^{-7}$ m$^2$/s for 26 °C water. Thus, $\frac{L_a}{\nu_a} = \frac{L_w}{\nu_w} = \frac{1}{12}$ according to Equation (2). The maximum $Re_w$ is 1343 in a typical case. Further, the time scale, namely the respiratory period, can be updated with the known length and velocity scales.

\[ Re_w = \frac{U_w \cdot L_a}{\nu_w} = \frac{U_w \cdot L_w}{\nu_w} = Re_a \]  

(2)

where the subscript $w$ stands for water; $U_a$ and $U_w$ are characteristic velocities e.g. maximum velocity in the respiratory process; $L_a$ and $L_w$ are characteristic lengths, namely equivalent diameters of the nose outlets, where $L_a = L_w$ here since a real full size model was used in the present water-tank experiment; the kinematic viscosity, $\nu_a = 1.48 \times 10^{-5}$ m$^2$/s for 25 °C air; $\nu_w = 1.16 \times 10^{-6}$ m$^2$/s for 15 °C water and $\nu_w = 8.73 \times 10^{-7}$ m$^2$/s for 26 °C water. Thus, $\frac{L_a}{\nu_a} = \frac{L_w}{\nu_w} = \frac{1}{12}$ according to Equation (2). The maximum $Re_w$ is 1343 in a typical case. Further, the time scale, namely the respiratory period, can be updated with the known length and velocity scales.

\[ \tau = \frac{L_w}{\nu_w} (a), \quad \tau_a = \frac{L_a}{\nu_a} (a), \quad \tau_w = \frac{L_w}{\nu_w} \frac{q_w}{\nu_w} = \frac{L_w}{\nu_w} \frac{q_w(t_w)}{\nu_w} (b) \] 

(3)

where, $\tau$ and $\tau_a$ are the normalized time and flow rate, respectively. Combining Equations (2) and (3), we obtain

\[ t_w = \left( \frac{L_w}{\nu_w} \right)^2 \frac{q_w}{\nu_w} \cdot t_a (a), \quad q_w(t_w) = \frac{L_w}{\nu_w} \frac{q_w}{\nu_w} (b) \] 

(4)

The breathing profile was performed with a computer-controlled servo motor in combination with a piston-cylinder system and the working principle of the servo motor system is shown in the schematic in Fig. 1b. We used contour moves (arrays of positions separated in time by a time step, e.g. 10 μs) in the motion control module of LabVIEW. To ensure a very high precision, 8000 sensors monitor each revolution of the motor, with each revolution moving the piston 1 mm (i.e. the piston pitch is 1 mm). To convert the water flow rate into the piston position:

\[ \frac{\pi D^2}{4} l_a(t_w) = \int_0^{t_w} q_w(t_w) dt_w \] 

(5)

where, $D = 5.4$ cm is the internal diameter of the cylinder. Combining Equations (1), (4) and (5), we obtain

\[ l_a(t_w) = \frac{2 \cdot TV}{\pi D^2} \cdot \left( \frac{L_w}{L_a} \right)^3 \left[ 1 - \cos \left( \frac{\pi}{30} \cdot RF \cdot \frac{\nu_w}{\nu_a} \left( \frac{L_a}{L_w} \right)^2 t_w \right) \right], \quad 0 < t_w < t_{sa} \] 

(6)

where the respiratory period in the water tank experiment, $t_{sa}$, can be obtained from Equation (4a) as the characteristic time scale.

2.2. Producing buoyancy and a thermal plume in the water tank

The temperature of human exhaled flow is a function of the ambient temperature, and the former is about 34 °C ($\rho_a = 1.18$ kg/m$^3$) if the ambient air is 25 °C ($\rho_a = 1.18$ kg/m$^3$) [28]. To represent the buoyancy effect caused by this temperature difference, the exhaled stream was left unmodified while 178.5 g salt was added into the 1.5 m$^3$ water (26 °C) of the water tank, to increase its density from 996.81 kg/m$^3$ to 996.90 kg/m$^3$, to ensure the same Archimedes number as that in air.

\[ Ar_0 = g \sqrt{A_0} \frac{\rho_{amb} - \rho_a}{\rho_0} \rho_a U^2 \] 

(7)

where $A_0$ is the outlet area; $\rho_{amb}$ and $\rho_a$ are fluid density in the ambient and at the nostril outlet, respectively. The Archimedes number is a measure of the buoyancy effect by density difference to the inertia effect ($Ar_0 = 6.12 \times 10^{-4}$ in this case.

In addition, two heated aluminum bricks (5 cm × 5 cm × 18 cm) were used to produce an artificial thermal plume. They were painted black to reduce the laser reflection, and placed at the bottom of the respiratory model side by side, together with a 40 cm (width) × 48 cm (height) black plate as the chest (Fig. 2). The velocity field of the thermal plume was measured by the Particle Image Velocimetry (PIV) system. The central cross section of the flow field is illuminated using a continuous Nd:YAG laser, and the image frames of the particles (measurement area: 440 mm × 607 mm, W × H) are recorded by the PCO.1200hs camera at the frequency of 5 Hz. Velocity vectors are then calculated using the Dantec Studio software by the adaptive cross-correlation algorithm (interrogation area: 32 × 32 pixels and 50% overlap) [23]. 1570 vector picture are obtained in each case and averaged for the mean flow field. As shown in Fig. 2, the plume becomes attached to the ‘chest’ over the bricks. As discussed in Section 2.1, $L_a = L_w$ and $U_w / U_a = 1/12.76$. The maximum velocity of the artificial plume is 0.78 cm/s, corresponding to a velocity of 0.14 m/s in the real situation in air. The thickness of the plume around the breathing zone is
about 0.08 m, which is similar to the plume described by Craven and Settles [10]. In addition, a stronger plume with a maximum velocity of 1.48 cm/s was also produced for comparison as described in the Discussion.

2.3. Qualitative/quantitative analysis of breathing flows

Food-dye (Royal blue, AmeriColor) was used to visualise the exhaled airflow, and to allow a qualitative analysis of the re-inhaled fraction of this exhaled flow. The food-dye has a diffusion coefficient around $2 \times 10^{-10}$ m$^2$/s. As the Reynolds number ($Re$) in this experiment and Schmidt number ($Sc$) of food dye in water are both on the order of $10^3$, the food dye was deemed a good tracer of the convective water motion. Special care was taken with the lighting system, e.g. the use of white cloth diffusers. Three cameras were used to obtain video images: two Canon 600D with 18–135 mm Canon EF lens and a Canon 550D with 18–55 mm lens, all in manual mode, at 50 frames per second (fps).

For a more quantitative analysis, neutrally buoyant particles (50 μm polyamide particles by Dantec, $p = 1030$ kg/m$^3$) were added to 10 L water to obtain a suspended particle solution of a specific concentration. A computer-controlled 3 W DPSS 532 nm laser projector (Ourslux Lighting Technology Co, Ltd) produced five laser sheets of 3 mm in thickness, which are overlapped to make sure both nostrils are totally illuminated simultaneously (Fig. 1a), such that the trajectory and quantity of the re-inhaled particles was recorded and counted. The face of the respiratory model was painted black before the laser experiment to reduce any facial reflections to enhance the visualisation. The fraction of exhaled flow that is re-inhaled can be estimated as

$$\alpha = \frac{N}{c \cdot TV} \times 100\% \quad (a), \quad c = \frac{6m}{\pi pd^3V} \quad (b)$$

where $\alpha$ is the fraction of exhaled flow that is re-inhaled, as a percentage (%); $N$ is the number of inhaled particles (pt), which can be directly counted from the videos; $c$ is the particle concentration of exhaled flow (pt/cm$^3$); and $TV$ is the tidal volume (cm$^3$); $m$ is the particle mass used for make the solution with $V = 10$ L water.

Apart from the above quantitative scenario by five laser sheets, a single laser was also used for qualitative visualization of the mid-sagittal plane in the presence of plume.

In each experiment, we first filled the acrylic vessel and the cylinder with dyed water or particle solution, and the water tank to a depth of 1 m, removing any trapped air bubbles as required. Once filled, the water in the tank was left to settle for sufficient time, e.g. 3 h, until it became still. The shutter speed of Canon cameras was set to be 0.01 s, which is longer than the scanning frequency of the laser to ensure sharp images of the particles.

3. Results

3.1. Re-inhalation in the buoyancy-neutral situation

In the food-dye visualization experiment ($RF = 28$ bpm and $TV = 0.15$ L), as we can see from Fig. 3a–c, the exhaled dyed water clearly penetrates and extends in a conical flow to the tank floor, a distance of 27.7 cm by the peak of exhalation, and a total distance of...
41.2 cm at the exhalation-inhalation transition (Fig. 4). The spreading angle of exhaled flow from the sagittal view is 32°, which agrees with experimental results on human beings \( (\theta_s = 23^\circ \pm 14^\circ) \) [6]. A momentum-based estimate gives a total dyed fluid volume of about 6.0 L, indicating an entrained fluid volume of ~40 times the TV of 0.15 L, as it travels. After the inhalation process starts, the exhaled flow continues to travel (Fig. 3c); the bounding floor starts to interfere with the spreading of the flow, but this is unlikely to have much effect on the upper portion (tail-end) of the exhalation flow that may be potentially be re-inhaled in the next breath cycle.

In the first laser-particle experiment \((RF = 28 \text{ bpm and } TV = 0.15 L)\), 0.2068 g polyamide particle was added to 10 L water, to obtain a solution of 307 pt/cm³. Particles in the breathing zone were all illuminated during breathing (Fig. 3d–f). At \( t_w = 0.5t_w \) (Fig. 3b/3e) when the exhalation process ends, the tailing part of the exhaled flow continues to travel and quickly mixes with ambient fluid, such that only a few particles remain in the breathing zone. As a result, only 17 particles were re-inhaled. According to Equation (8), the re-inhaled fraction of exhaled flow is calculated to be 0.037%. To check this, these experiments were repeated another twice, with similar results: 0.026% and 0.022%, respectively. This gives a mean value for the re-inhalation ratio of 0.028% with a standard deviation (SD) of 0.006%.

Additional sensitivity studies were performed (results shown in Fig. 5) to study the effect of varying \( RF \) and \( TV \) on the re-inhalation process. The time ratio of the exhalation-inhalation cycle was also varied, as physiologically, the exhalation process takes longer, as this is mostly a passive maneuver [6].

The results show some variation with different values of \( RF \) and \( TV \). For a given \( RF \), the fractional re-inhaled % reaches the minimum (0.028% and 0.033%, respectively for \( RF = 28 \text{ bpm and } TV = 0.15 \text{ L} \)) at \( TV = 0.15 \text{ L} \), except at the lowest \( RF \) (24 bpm), whereas when varying the cycle time ratio with \( RF \) and \( TV \) fixed, a 1.5:1 ratio for exhalation-inhalation gave the highest fractional re-inhalation, with a value of 0.046% (Fig. 5b). However, overall, the changes in the fractional re-inhaled % do not change much with variations in these parameters, remaining below 0.06%.

### 3.2. Effect of the thermal plume on the re-inhalation ratio

The above experiments are all isothermal. The experiment instead with an artificial thermal plume in saline water is shown in Fig. 6 \((RF = 28 \text{ bpm and } TV = 0.15 \text{ L})\). The effect of the thermal plume was studied at two maximum velocities: 0.78 cm/s (Fig. 2), corresponding to a velocity of 0.14 m/s in air of 25 °C, and a thickness of about 8 cm; and 1.48 cm/s, corresponding to a velocity of 0.27 m/s in the air of 25 °C, and a thickness of about 9 cm.

For the first scenario \((U = 0.78 \text{ cm/s for the plume})\), the starting jet of the exhaled flow is strong enough to overcome the rising thermal plume and travel downwards, but the leading part becomes diverted due to the interaction with the thermal plume at about 0.30 \( t_w \) (Fig. 6a). This jet slows down as it travels, until the
plume near the wall dominates and begins to rise after halting for a while (Fig. 6b/6c). Soon after the expiration stops, the exhaled fluid halts very near the nostril and is readily re-inhaled after the inhalation begins (Fig. 6b/6c). The inhalation region at the peak of inhalation is approximately depicted in Fig. 6c, and fluid far from the nostril will not be affected. The buoyancy force caused by the temperature difference between exhaled flow and the ambient environment does not affect the flow noticeably until at the end of the whole breathing cycle (Fig. 6d). Under this situation, the re-inhalation ratio is 0.15% (SD = 0.06%).

A much stronger plume was produced by increasing the brick heating power from 19.6 W to 60 W, with a maximum velocity of 1.48 cm/s (equivalent to 0.27 m/s in air). The enhanced thermal plume is able to bring exhaled flow back to the inhalation zone efficiently. Even so, the re-inhalation ratio increases to only 0.38%. This is probably because the exhaled flow is much diluted by the ambient flow (about 40 times as mentioned above), and will be diluted again while the thermal plume brings it upwards. According to the experimental results by Laverge et al. [18], the tracer gas released from a point source 8 cm below the nostril is diluted 10 times after it reaches the nostril.

4. Discussion

Both the qualitative dye visualization and quantitative laser-particle experiments on this respiratory model from a 4-year-old girl in this water-tank model show that a negligible fraction (<0.06%) of exhaled flow is re-inhaled during the inhalation

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**Fig. 6.** Qualitative visualization of the breathing cycle in the presence of the rising thermal plume characterized by Fig. 2 (RF = 28 bpm and TV = 0.15 L). The mid-sagittal plane of the respiratory model was illuminated. Red arrows indicate the exhaled airflow direction and the circle indicates where this flow interacts with the rising thermal plume generated by the heated aluminum brick.
process. After including the effect of the rising thermal plume, although this value quadrupled, it is still very small compared with the CFD simulation results of Zhu et al. [3], which is 17%. The 50 μm polyamide particles (p = 1030 kg/m³) is similar in density with water, and it is dynamically equivalent to particles of 1.76 μm in air. Golshahi et al. [21] measured aerosol deposition in a replica of the present pediatric airway, and found that less than 10% of particles with this aerodynamic particle size deposited at the same flow rates considered by us. Regarding interception, it is not possible to use similarity to extrapolate from the measurements of Golshahi et al. [21]. However, since the flow in the present pediatric nasal airways is expected to be laminar [25], a simple estimate for the amount of deposition, assuming neutrally buoyant particles, can be made based on the fractional area of the airway that is within 50 μm of the airway wall. This value is 2% for the present pediatric airway, indicating negligible deposition by interception.

Fig. 7 illustrates the interaction of the thermal plume and exhaled air (also shown in video form, using human volunteers, by Tang et al. [9]). The nasal breathing jet starts with a high momentum, compared with the thermal plume of about 0.1 m/s at the chest and nose level [10], mostly travelling in an undisturbed trajectory. The maximum visible propagation distance and derived exhalation velocity for nasal breathing were 0.6 m and 1.4 m/s, respectively [22], which compares well with our experimental results. However, the momentum decays quickly by convective entrainment, so the exhaled air trapped by the thermal plume may be carried upwards into the breathing region again. The estimated ratio of the trapped air volume in Fig. 7a to the total conical volume is 11%. It is worth noting that the head angle has an important effect, as the exhaled air would impact on the chest and be mostly trapped with the head leaning downwards to 30° (Fig. 7b), while only about 5% of exhaled air is trapped with the head leaning upwards to 30° (Fig. 7c). We are not able to investigate the effect of the head angle, because the connection between the respiratory model and the cylindrical vessel is rigid. Head angle is a topic for future study. It is also expected the effect of a thermal plume in the supine or sitting posture is different from that for a standing posture [7]. Besides, although we tried to use a plate as the human chest in the thermal-plume setting (Fig. 2), the geometry is simplified; simplicity of the body shape might introduce some error, e.g. boundary layer separation at the shoulder and separation of the rising plume under the chin might make the plume itself more complex [12]. It was indicated by Zhu et al. [4] that trapping of exhaled air under the jaw might increase the re-inhalation ratio. In addition, in the presence of background ventilation, it would be more complicated, as ventilated air would weaken or enhance the rising thermal plume as well as interact with breathed airflow directly. For example, the breathing zone will be located in the thermal plume region if the occupant is back-to-the wind in a horizontal airflow, in which situation a relatively higher re-inhalation ratio is expected [29].

It would be interesting to attempt to extend the present results to adults via similarity analysis, but two factors are important. First, it should be noted that others have found that the upper airways of young children (<5 years old) are not geometrically similar to those in adults [24], thereby violating a basic tenet of such analysis. However, the essential flow features of the exhaled air flow are expected to be determined more by the nasal valve and vestibules than the more distal regions of the respiratory tract. While, the breathing parameters such as frequency and flow rate are different between children and adults, the basic aspects of the flows associated with the turbulent exhalation jet and inhalation potential flow structure are likely similar. Hence we believe that the present results of low-re-halation rate may broadly apply to adults.

![Fig. 7](image-url) Exhaled flow trapped by the rising thermal plume at the end of exhalation. In the current experiment, $\theta_m = 32^\circ$, $OB = 0.412$ m; for the thermal plume at the chest and nose level, $L = 0.1$ m, $v = 0.1$ m/s [10]; and $\theta_m = 60^\circ$ [6]. The head angle (α) has an important effect on the trapping of exhaled airflow (α = 0°, −30° and 30°, respectively in a,b and c).
5. Conclusions

We have found that a negligible fraction (<0.06%) of the exhaled airflow is re-inhaled in the following breath cycle, in the absence of the rising human thermal plume and background ventilation. The presence of the rising thermal plume increases this fraction several-fold, however, it still remains a very small fraction of the exhaled airflow that is re-inhaled include the initial inertia of the exhaled air volume (<0.2%). Factors that act to reduce the fraction of exhaled air that is re-inhaled include the initial inertia of the exhaled flow and its dilution by the ambient air. The rising thermal plume seems to have a mixed effect on this phenomenon in that it may also act to dilute this exhaled air to some extent, but also convects some of it back into the inhalation zone, increasing the fraction that could be potentially re-inhaled. More detailed investigations using more realistic full-body thermal breathing investigations using more realistic full-body thermal breathing human-like manikins are required to investigate this phenomenon further in different postures and subject ages, including when sitting and supine, where the effects of the thermal plume will differ.

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