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

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A B S T R A C T

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 10^9 and reaches a maximum velocity of 0.2 m/s above the head [7]. The

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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 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,

$$q_a(t_a) = \frac{\pi \cdot TV \cdot RF}{60} \sin\left(\frac{\pi \cdot RF}{30} \cdot t_a\right),\ 0 \le t_a \le t_{s,a} \quad (1)$$

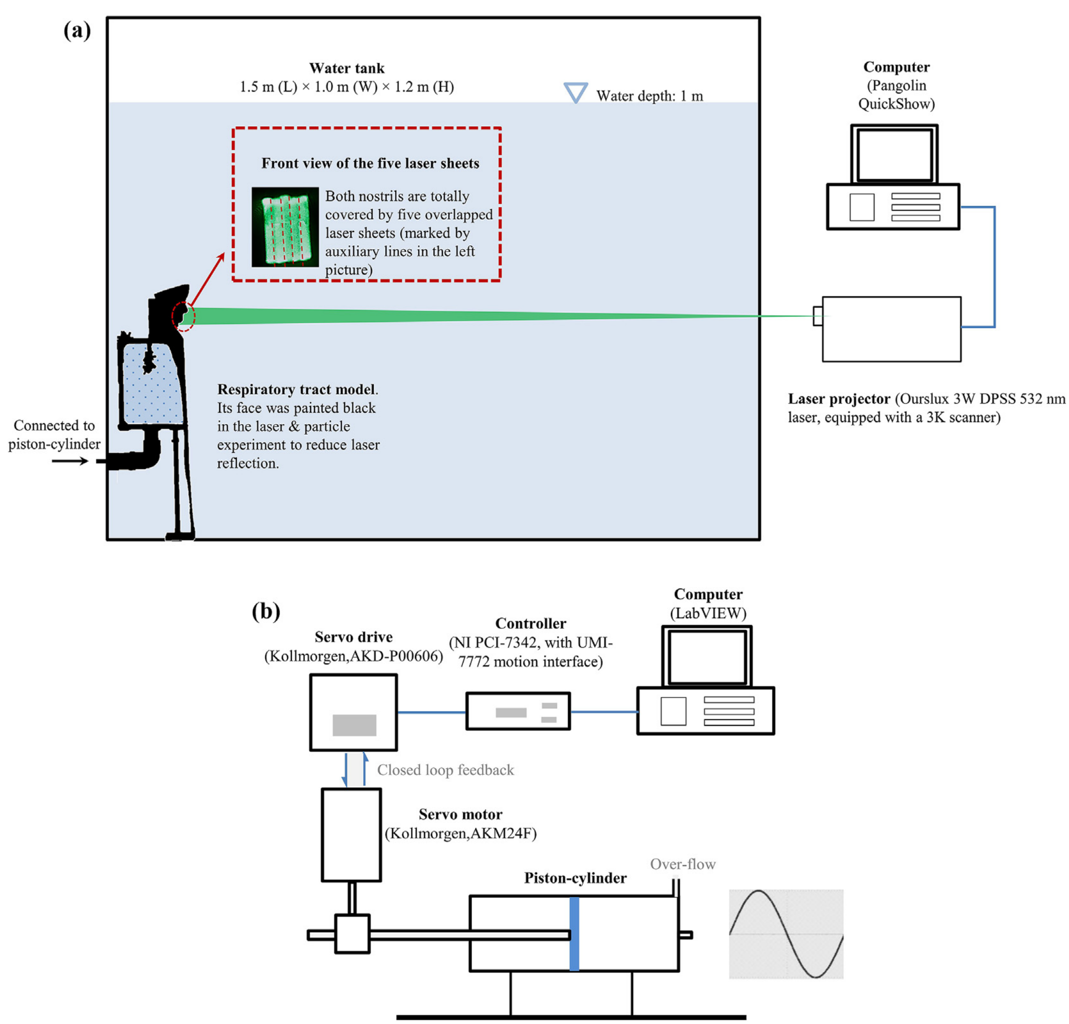

Fig. 1. (a) Layout of water tank experiment for human normal breathing study (quantitative laser-particle experiments – camera not shown). The laser projector can produce five laser sheets which are overlapped to totally cover both nostrils. (b) Schematic of the 'breathing machine'. This consisted of the servo motor unit and the piston-cylinder system.