

Numerical modelling of inhalation exposure during close contact in the indoor environment

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論文内容の要旨 Thesis Summary

In a world where people are increasingly spending more time indoors, preventing exposure to harmful chemical compounds, highly contagious airborne pathogens, and enhancing occupant comfort remain a top priority for building users and managers alike. Indoor airborne infection transmission is influenced by effectiveness of ventilation systems and human behavior, which varies between individuals and across cultures. The success of non-pharmaceutical intervention measures in the COVID-19 global pandemic such as backward tracing of susceptible contacts around the index case, enforcing mask wearing, and physical distancing rules underscores the importance of addressing human behaviour, ventilation notwithstanding. However, much of the available human contact data used for epidemic modelling is derived from ethnically homogeneous populations with age-based variations. This limits the models' generalizability, as real-world close-contact patterns show significant heterogeneity/ non-uniformity; consequently, some under-performance in epidemic models can be attributed to these non-uniformities in contact behaviour.

In this study, high-resolution video cameras were used to collect human close-contact behavior data for five consecutive school days in a multinational graduate school student office in Japan. Observed close contact behavior is characterized using stochastic interactions in terms of interpersonal distance, assortativity, posture, duration, and frequency of contact in the multinational population. The results show a remarkable difference compared to findings from a similar study conducted in an ethnically homogenous Asian population with a comparable study setup (graduate student office) and methodology (video monitoring). The interpersonal distance was significantly wider, and the close contact frequency was notably lower, but the close contact duration was significantly longer than in an ethnically homogenous population. Nationality/ethnicity showed stronger homophily. The observed contact network links were dense with high reciprocity. High contact heterogeneity was observed in twenty-five percent of the nodes. These observations highlight the importance of incorporating contact data from both homogeneous and heterogeneous populations to ensure accurate and context-sensitive epidemic modelling.

In this dissertation, some of these observed elements of human behaviour during close contact were incorporated in inhalation exposure analysis using Lagrangian and Eulerian approaches under stagnant indoor airflow conditions (0.05 m/s). In the Lagrangian approach, inhalation exposure to droplets and droplet nuclei exhaled from an infected CSP during a hypothetical close contact event of 17 seconds with a susceptible CSP having a realistic respiratory tract in transient breathing mode is simulated. Seventeen different cases varying in contact posture, face angles and proxemics during high-risk scenarios of loud speaking and coughing were modelled.

Study findings indicate that the face-to-side (cheek) orientation reduced inhalation exposure during speaking but not during coughing. The inhalation and deposition fractions varied inversely with an increase in interpersonal distance (IPD). Inhalation exposure was higher in the standing-standing close contact posture than in the standing-sitting posture at the same IPD due to high velocity magnitude at the nose for the latter. During the speaking scenario, higher fraction of inhaled particles with a wider diameter of $\geq 15 \mu\text{m}$ before evaporation were deposited in the nasal cavity. For the coughing scenario, most inhaled droplets of pre-evaporation sizes $< 10 \mu\text{m}$ passed through the pharyngeal end, with minimal deposition in the nasal cavity. The aspiration efficiency was found to be dependent on the timing of the inhalation period and droplet concentration in the breathing zone.

Through Eulerian approach "rebreathed fractions" of contaminated indoor air in the same 17

hypothetical close contact events were measured. The suitability of CO₂ co-exhaled with droplets and droplet nuclei from infected persons as an airborne infection risk indicator through comparison with droplet inhalation exposure in similar close-contact scenarios is assessed. Findings of this study indicate that the total re-breathed fraction of CO₂ was subject to the close contact posture, IPD, breathing cycle, body thermal plume and ejection flow rate from source. In comparison with droplets' inhalation exposure, exhaled CO₂ overestimates in some cases exposure and underestimated exposure in others. In cases with IPD > 0.7m inhalation time did not coincide but occurred in different breathing cycles than observed in droplets implying that a rebreathed fraction of exhaled air may not always contain co-exhaled virus carrying droplets due to factors such as particle relaxation time, gravitational settling and higher diffusivity of CO₂.

This dissertation consists of seven chapters, each of which is briefly summarized below:

Chapter 1 outlines the background, main objectives of the study and structure of the thesis.

Chapter 2 presents high resolution data on human behaviour during close contact

Chapter 3 expounds on the numerical analysis methodology used in the study to model inhalation exposure during close contact, turbulence modelling, radiation, thermo-physiologically sensible heat generation droplet dispersion and passive scalar transport modelling.

Chapter 4 visually presents the numerical 3D human models used in the study, the integration of a nasal cavity model into the developed CSP and replication of human transient breathing. It also includes the mesh design adopted in the study with detailed configuration.

Chapter 5 presents numerical analysis of inhalation exposure and dermal disposition of droplets and droplet nuclei in two high risk scenarios of loud speaking and coughing during a close contact event between two computer-simulated persons (CSPs). One deemed infected CSP while another is deemed healthy/susceptible CSP.

Chapter 6 presents numerical analysis of inhalation exposure to CO₂ co-exhaled with droplets and droplet nuclei during close contact between two computer-simulated persons (CSPs). The analysis includes exposure during a realistic scenario with both CSPs exhaling CO₂ in an indoor environment with non-uniform distribution of CO₂, and a simplified scenario with only infected CSP exhaling CO₂ into the indoor environment.

Chapter 7 include highlights of the study, associated limitations as well as future research work to enhance wider application of findings and the conclusions made in the study.

Chapter 8 is an additional chapter about a field survey on psychological and physiological perceptions of indoor environmental quality (IEQ) by an ethnically diverse occupancy conducted alongside the study on human close contact behaviour. The survey explores perception, acceptance, and tolerance levels of native and non-native occupants under identical indoor conditions. The goal is to examine whether individuals from different nationalities have acclimatized to the local environment or exhibit significant differences in their subjective evaluation and acceptance of shared IEQ.