The physics of particle formation and deposition during breathing

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In every breath, humans take in particles that may be deposited on the respiratory tract and exhale particles that may contain pathogens. Lidia Morawska and Giorgio Buonanno explain how physics advances are needed to understand these processes.

At rest, humans inhale and exhale approximately 12 times per minute, each breath involving ~0.5 L of air. In breathing, we bring to the lungs millions of particles — ambient concentrations of particles, a key anthropogenic air pollutant, range in cities from 10^3 to 10^5 particles cm^{-3} (REF.[1]). We also exhale particles, some of which are the inhaled particles, presumably unchanged, and others of which come from aerosolization of particles from the surface of the respiratory tract.

Although the health impact of inhalation of particles is well known, the risk created by humans as sources of pathogen-carrying respiratory particles in everyday life was seldom recognized until the COVID-19 pandemic. Fundamental questions are now being asked about the physics of virus-laden particles from human respiration: the location of their formation, their concentrations, the impact of myriad physiological factors, and the entrainment of the virus from the lining of the lung in the process of aerosolization.

All these processes are governed by the physics of airflow, and in a thermodynamic approach, the respiratory system can be considered as an open system in a transient regime, with one incoming mass flow and another, partially generated from the inside, outgoing from the same section.

Inhalation

The human respiratory tract is, to first approximation, a branching tree of tubes with the diameter decreasing (and the airflow velocity increasing) as it branches. The physics of the deposition of inhaled particles depends on the flow velocity and particle size. The particles can be solid, liquid, or a solid core coated with liquid, with incredibly complex chemistry. About 40% of inhaled particles are deposited in different regions of the respiratory tract[2]. Larger particles of a few micrometres diameter entering the respiratory tract likely deposit by impaction or interception in the upper part of the tract, whereas ultrafine particles (<0.1 µm), with very low weight and thus low inertia, mostly deposit by diffusion in the small-diameter tubes of the lower part of the respiratory tract and in the alveoli[2] (FIG. 1, left).

An added complexity is that the respiratory tract is not static: the tubes expand during exhalation and contract during inhalation. Another complexity is that the surface of the respiratory tract is lined with liquid, which increases the likelihood of particles remaining on the surface once deposited, rather than bouncing back. Additionally, the characteristics of the particles change once inhaled, due to differences in the temperature and humidity conditions between the respiratory tract and the inhaled air. Ultrafine particles undergo hygroscopic growth during inhalation[3]. In summary, there are numerous factors influencing particle deposition in the respiratory tract, including:

- the physicochemistry of aerosols: the particle size distribution; their density, shape and surface area; whether they are hygroscopic or hydrophobic;
- the anatomy of the respiratory tract: its diameter and length; the breathing angles of airway segments; and
- the physiology of the respiratory tract: airflow pattern; breathing pattern.

Exhalation

The composition of exhaled air is different to that of inhaled air. We exhale hundreds of aerosolized particles when breathing out, and even more during other respiratory activities, especially speaking[4,5]. These particles are water-based solutions of salts, containing mucus, proteins and anything else that was on the surface of the respiratory tract. Thus, pathogens on the surface of the respiratory tract, such as viruses or bacteria, can be a component of a particle exhaled during breathing (or coughed out during coughing). Such emissions increase the concentration of the pathogen in closed environments and, consequently increase the risk of infection for exposed susceptible persons[6].

During exhalation, multiple processes of particle aerosolization take place (FIG. 1, right). Particle atomization results from an air-stream passing sufficiently quickly over the surface of a liquid. Fluid blockages that form in the respiratory bronchioles during exhalation burst during subsequent inhalation to produce particles. Fluid bathing the larynx is aerosolized during voicing owing

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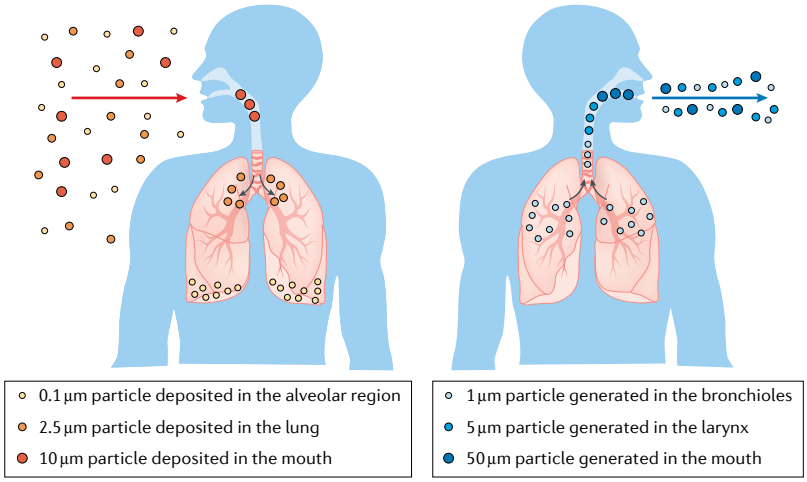

Fig. 1 | **Particle deposition during inhalation and generation during exhalation.** Particles of different sizes are deposited and generated in different parts of the respiratory tract.

to vocal fold vibrations, and saliva in the mouth is aerosolized during interactions between the tongue, teeth, palate and lips during speech articulation. After forming, the particles undergo processes in the respiratory tract before they are exhaled: in particular, deposition, which changes their size distribution. Furthermore, the respiratory tract contains relatively small-scale, curved viscous and viscoelastic films, which wrinkle during exhalation and thereby break up, leading to aerosol production[7].

Experiments and modelling

A fundamental challenge in conducting physics studies on particle deposition or formation is that we cannot send a probe of any kind to measure parameters inside the respiratory tract; we must instead rely on information from indirect studies to piece together what happens. Indeed, we know more about the surface of Mars from direct images, including the dynamics of the impact of airflow and the Martian wind, than we know about the surface of the lung of a living person.

In relation to particle inhalation, we can compare the characteristics (such as size distribution) of what was inhaled with what was exhaled. We have built artificial casts of the human respiratory tract to investigate the deposition of particles with different characteristics, but these do not fully reflect the complexity of the dynamic, liquid-lined system. We can label inhaled particles with technetium 99 m and scan the lung to see where they are deposited (a method used to test the process of drug delivery), but the surface deposition of technetium on poly-dispersed aerosol is unlikely to be uniform. We can measure the characteristics of particles exhaled by volunteers who have inhaled particle-free air, knowing next to nothing about what happened inside: this is something of a black box.

Furthermore, we have quantitative models of particle inhalation, which can be grouped into two categories, referring to the region of interest in the lung – either deposition in the whole lung or deposition in a localized region of the lung. The agreement between theory and experiment indicates that deposition models correctly predict total deposition within a relatively narrow range; however, local deposition models can be validated only to some extent for regional deposition[8]. Moreover, few of the experimental studies have investigated groups such as children[9] or people with lung diseases.

Modelling of particle formation and deposition in the respiratory tract during exhalation is significantly less advanced than modelling of particle inhalation. Some computational fluid dynamics modelling has been developed on deposition[9] but most efforts have been directed towards modelling the dynamics of particles in the air after they have been exhaled. Therefore, the formation process remains in a realm of concepts.

Open questions

The epidemiology of 'bulk' particle inhalation — in terms of mass concentration of all particles with an aerodynamic diameter within two size ranges: fine particles, smaller than 2.5 µm ($PM_{2.5}$) and coarse particles, up to 10 µm (PM_{10}) — is well established, but some fundamental questions remain. Which is more important: the mass of the particles deposited, the number of particles, or their surface area? Particle mass is dominated by a small number of larger particles deposited in the upper parts of the respiratory tract, whereas particle number is dominated by large numbers of ultrafine particles reaching the deeper parts of the respiratory tract; in addition, particle composition typically varies with size. Toxicologists would argue that it is the surface area of the particles in contact with the surface area of the lung that is important. What is the significance of the particle phase (liquid or solid) in affecting health outcomes? A handful of experimental studies have provided contradictory results[10]. Given not only the COVID-19 pandemic but also issues such as air pollution, we therefore need to better understand the physics of breathing to keep ourselves healthy.

1. de Jesus, A. L. et al. Ultrafine particles and $PM_{2.5}$ in the air of cities around the world: Are they representative of each other? *Environ. Int.* **129**, 118–135 (2019).
2. ICRP. Human respiratory tract models for radiological protection. *ICRP Publication* **66**, 1–3 (1994).
3. Asgharian, B. A model of deposition of hygroscopic particles in the human lung. *Aerosol Sci. Tech.* **38**, 938–947 (2004).
4. Asadi, S. et al. Aerosol emission and superemission during human speech increase with voice loudness. *Sci. Rep.* **9**, 2348 (2019).
5. Morawska, L. et al. Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities. *J. Aerosol Sci.* **40**, 256–269 (2009).
6. Buonanno, G., Morawska, L. & Stabile, L. Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: prospective and retrospective applications. *Environ. Int.* **145**, 106112 (2020).
7. Oratis, A. T., Bush, J. W., Stone, H. A. & Bird, J. C. A new wrinkle on liquid sheets: Turning the mechanism of viscous bubble collapse upside down. *Science* **369**, 685–688 (2020).
8. Hofmann, W. Modelling inhaled particle deposition in the human lung — A review. *J.Aerosol Sci.* **42**, 693–724 (2011).
9. Guo, L. et al. Experimentally determined deposition of ambient urban ultrafine particles in the respiratory tract of children. *Enviro. Int.* **145**, 106094 (2020).
10. Tobías, A. et al. Short-term effects of ultrafine particles on daily mortality by primary vehicle exhaust versus secondary origin in three Spanish cities. *Environ. Int.* **111**, 144–151 (2018).

Competing interests
The authors declare no competing interests.