16. Inhalative health risks of dust particles and fibres

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When we breathe, we directly expose our lung tissue with a surface area of about the size of a tennis court (85 m²) to the air. This vital exchange of carbon dioxide for oxygen gas is usually accompanied by the inhalation of dust particles. Evolution has provided our lungs with clearance mechanisms that can cope with a wide range of particles that are omnipresent in natural environments. While larger particles tend to be deposited in the upper airways and can be removed from the lungs by coughing or swallowing, smaller particles can reach the deep lung tissue where gas exchange takes place in small alveolar compartments. Particles small enough to enter the narrow opening of such an alveolus are called "respirable". They may be dissolved in the alveolar lining fluid or ingested by alveolar macrophage cells ("phagocytosis"). If these cells manage to encapsulate a dust particle in a "phagosome" (a compartment formed by engulfing the cell membrane), into which cell's "lysosomes" release an oxidative cocktail, the particle can now be dissolved under harsher conditions. Each macrophage has a limited capacity to take up particles. When exhausted, the macrophage leaves the alveolus and sacrifices itself by being shed into the lung lining fluid.

The higher the rate of particles entering the alveolar tissue that are not soluble in the fluid lining the alveoli, the busier the macrophages are to clear the alveoli. Busy macrophages signal the immune system to provide additional macrophages, leading to an inflammatory response. Exposure to continuous high rates of dust particles and high accumulated doses of biodurable particles cause chronic inflammation and can lead to, e.g., fibrosis or chronic obstructive pulmonary disease.

Inhalation of fibres has somewhat surprising consequences. Fibres tend to orient themselves along the flow lines of the inhaled air. In the direction of flight, they therefore look like small particles with a hidden tail. Although they are large dust particles, they can evade the filtering effect of the narrow opening and enter an alveolus.

As most natural fibres are made from (low crystalline) cellulose, fibres thin enough to enter an alveolus tend to be soluble. However, with the industrial use of asbestos, especially workers became exposed to high concentrations of durable fibre dusts. Once inside the alveolus, macrophages also try to ingest undissolved fibres. Our current understanding is that macrophages can deal with fibres in a similar way to particles only if the fibre is either short enough or flexible enough to be completely taken up, see Figure 20. Whereas for fibres that are long and rigid this phagocytosis cannot be completed: The phagosome cannot be closed, the macrophage leaches, initiates the inflammatory signalling cascade and eventually dies. This can cause chronic inflammation leading to fibrosis, asbestosis or lung cancer. Because a single biodurable fibre that persists in the lung tissue may kill several generations of macrophages, occupational exposure limits for fibres are set as fibre number concentrations, not mass concentrations as in case of particle dusts. Measurement strategies for nanoscale fibre exposure have been developed (Meyer-Plath et al. 2020) that use automated correlative microscopic techniques for morphological classification and substance identification of dust constituents.

As the incubation period for fatal mesothelioma carcinomas can reach 30-40 years, it has taken several decades to epidemiologically correlate the delayed deaths of workers with occupational fibre exposure (Furuya et al. 2018). With the availability of a wide range of newly developed high-performance fibre

materials, we must not wait for epidemiological evidence, but raise awareness for the fibre pathological paradigm. We propose to extend the paradigm by flexural rigidity (bending stiffness) (Fortini et al. 2020). The paradigm then states that the length and rigidity of respirable low-soluble fibres are carcinogenic principles. Fibres less than 3 µm in diameter are considered respirable. Fibres longer than 5 µm should be considered critical.

Toxicological studies on carbon nanotubes suggest that the flexural rigidity of fibres can already exceed critical limits at diameters above 37 nm (Rittinghausen et al. 2014)[2]. These findings motivate that fibres with a rigidity greater than about 1 N·nm² should be considered critical (Broßell et al. 2020). As rigidity scales linearly with elastic modulus but to the fourth power of diameter, critical diameters of other materials should be in a neighbouring range. However, fibres below a critical rigidity value may still cause fibre-toxic effects if they form fibre bundles that are collectively stiffer than the individual fibre, see Figure 21. Similarly, fibres shorter than 5 µm can form bundles that exceed this critical length threshold.

As a consequence, inhalation exposure to respirable biodurable particles and especially fibres must not only be minimised but kept below safe concentrations. This requires estimates of release rates and to assess the effectiveness of protective measures, including containment, safe maintenance and spill protocols, exhaust ventilation, personal protection.

It must be considered that the number of fibres released during handling or processing of dry powders can vary over several orders of magnitude. It depends on the process, the mass and agglomeration state of the fibres as well as their morphological and mechanical characteristics (Broßell et al. 2019). Similarly, the release of individual or still (partially) embedded fibres during synthesis or machining of composites depends on many processing details and must be assessed. Also a fibre-shaped fragment released from a biodurable (matrix) material should be considered as an inhalation risk (Meyer-Plath et al. 2023).

All products containing materials that consist of or form potentially hazardous fibres must be safe throughout their life cycle. The information necessary to protect consumers, professional users, dismantlers and recyclers from exposure must be adequately communicated along the supply chain.

[2] Further toxicological results on carbonaceous fibre materials, including carbon fibre fragments, are expected to be published in 2024.

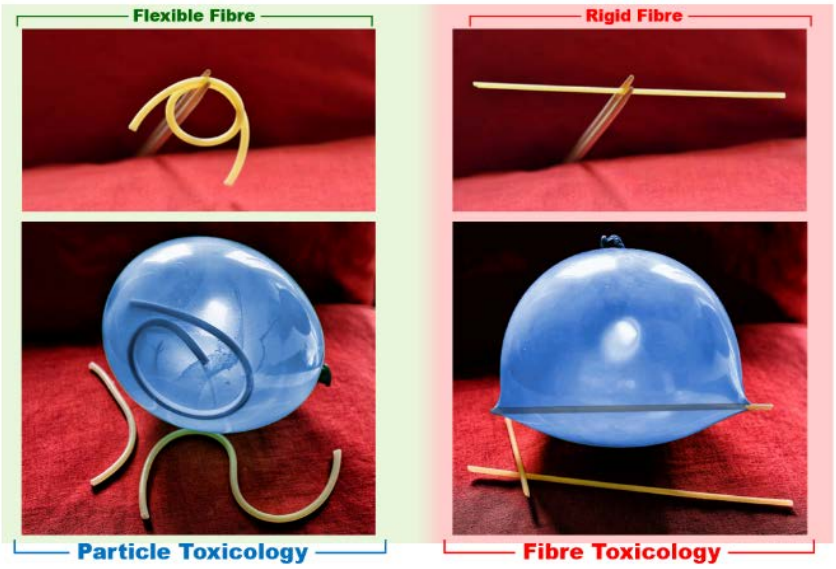

Figure 20: Humans perform the "al dente" test before serving cooked spaghetti. Alveolar macrophages miss such a test. They may die from ingesting long fibres that turn out to be harmfully rigid. The difference between particle and fibre toxicity is illustrated here with a balloon and tubular spaghetti (maccheroni).

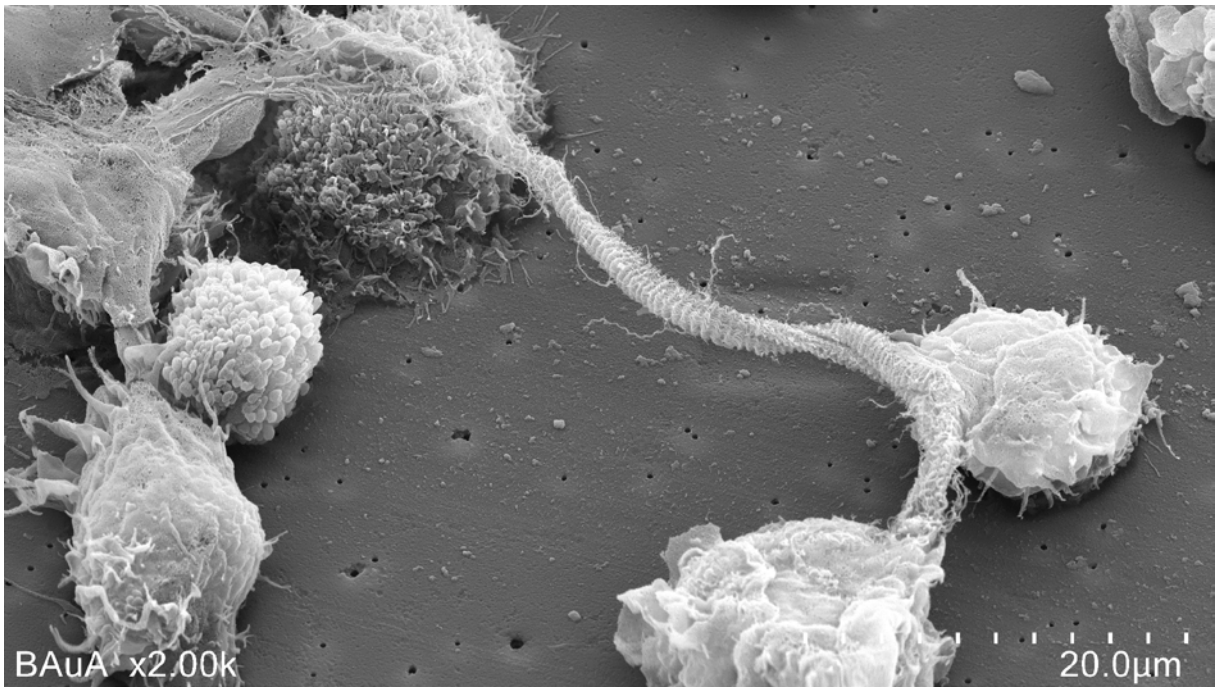

Figure 21: A cell culture of rat macrophages was exposed to dust containing multi-walled carbon nanotubes. Critical point-drying for SEM imaging preserved the moment a group of macrophages was trying to ingest a nanotube bundle.