The Science of Health Impacts of Particulate Matter

South Asian cities record some of the highest levels of outdoor particulate pollution worldwide. Scientific research over the last two decades has demonstrated that particulate matter is the major pollutant of concern from the health perspective. Current research is focusing on questions relating to particulate matter characteristics such as size, number, and composition, and the mechanisms by which it causes health impacts. This briefing note presents the current understanding of the answers to those questions.

There is strong evidence linking urban air pollution to acute and chronic illnesses and premature death [1], and these adverse health impacts in turn carry high economic costs to society [2]. The evidence correlating air pollution and health impacts is especially strong for particulate matter (PM) [1]. Many questions still remain, however, about how PM affects human health and what makes it particularly harmful. This note, the last in a series of three notes addressing the health effects of outdoor air pollution, attempts to answer these questions based on the current understanding of the science of the health impacts of PM.

What is Particulate Matter?

Airborne particulate matter is not a single pollutant, but rather a mixture of many subclasses of pollutants—in solid and liquid forms, with each subclass containing many different chemical species. Particulate matter may be classified as primary or secondary. Primary particles are emitted directly by emission sources, whereas secondary particles are formed through the atmospheric reaction of gases, such as the reaction between ammonia and oxides of nitrogen or sulfur, that leads to the formation of PM [3].

PM is typically classified according to size. The particle size can vary from approximately 0.005 microns (0.005 x 10^-6 meters) to 100 microns in diameter (that is, from the size of a few atoms to about the thickness of a human hair). All ambient PM irrespective of size is referred to as suspended particulate matter (SPM), or total suspended particles (TSP) when a gravimetric procedure has been used for measuring mass. Particulate matter less than 10 microns in diameter is referred to as PM10, and PM less than 2.5 microns is referred to as PM2.5. The term fine PM has also come to be associated with PM2.5, ultrafine with PM less than 0.1 microns in diameter (PM0.1), and coarse with PM in the size range between 2.5 and 10 microns. Of late, the focus of PM measurement in ambient air of South Asian cities has shifted from measuring TSP to mass-based measurement of PM10.

Origin and Transport of Particulate Matter

Airborne PM has numerous sources, ranging from naturally occurring dust, sea salt, and pollen, to products of combustion such as forest fires, domestic cooking and heating, garbage burning, power generation, and mobile sources (such as vehicles and ships). Combustion processes normally contribute much more to the fine and ultrafine PM fraction, whereas noncombustion processes contribute more to larger size PM fractions [4]. For example, a study of the chemical composition of PM in Mexico City in 1997 showed that: (a) PM2.5 particle mass consisted of about 50 percent carbonaceous aerosols likely from combustion sources, followed by approximately 30 percent secondary aerosols, and 15 percent geological matter; whereas (b) PM10 particle mass consisted of about 50 percent geological matter, followed by 30 percent secondary aerosols, and 15 percent carbonaceous aerosols (about 30 percent) and secondary aerosols (less than 20 percent) [5]. Unfortunately, such detailed studies are very limited in South Asia.

Fine PM tends to be distributed uniformly over large areas, thereby making it difficult to trace it to individual sources.

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1 In India, as per the National Ambient Air Quality Monitoring standards the term respirable suspended particulate matter (RSPM or RPM) is used interchangeably with PM10.
The recent finding of the Asian brown haze, attributed primarily to combustion sources in Asia, confirms the long residence time and regional distribution of fine and ultrafine particles [6]. Larger particles, however, normally have shorter atmospheric lifetimes (minutes to hours) and do not travel long distances (less than tens of kilometers). As a result they tend to be less evenly distributed, and are usually found closer to their sources [3].

**Why is PM so Damaging to Health?**

Epidemiological studies from many different parts of the world, conducted by different groups of researchers using different data sets and analysis techniques, have generated results that confirm the magnitude of PM health impacts (see Briefing Note No. 11 [1] for more detail). While a statistical association has been found between adverse health effects and PM<sub>2.5</sub>, recent studies using PM<sub>2.5</sub> data have shown an even stronger association between health outcomes and particles in this size range. Evidence that smaller particles are more harmful is further supported by medical and toxicological research, which is increasingly focused on understanding the role of particle size (in the fine and ultrafine range) and composition in PM toxicity.

**Size and number**

Size determines how different particles deposit in different parts of the respiratory tract. Studies have shown that particles of different size vary in their respiratory tract deposition, movement, clearance, and consequent retention time in the human body. Ultrafine particles tend to behave more like gases and hence travel to the lower region of the lungs as compared to larger particles which tend to get deposited in the upper or middle region of the respiratory tract. Particles larger than about 10 microns in diameter are deposited almost exclusively in the nose and throat, whereas particles smaller than 1 micron are able to reach the lower regions of the lungs. The intermediate size range gets deposited in between these two extremes of the respiratory tract.

Ultrafine particles are highly toxic to the lungs, even when they comprise materials that are not toxic when present in larger particles. The mechanisms for toxicity of ultrafine particles are still under investigation, but several observations may be made. For a given mass, the number of particles and the total surface area increase dramatically with decreasing particle size. If toxic components are adsorbed on the surface of ultrafine particles, the level of interaction between the lungs and the surface of ultrafine particles is likely to increase with increasing surface area. It is not immediately clear, however, why the adverse impact of non-toxic particles should also increase with decreasing particle size and increasing surface area.

The above discussion suggests that the particle size and particle number may be more relevant indicators than particle mass: the smaller the particle, the greater the fraction of particles deposited in airways and lungs, and the greater the surface area available for interaction with biological systems. Most of the research, however, on the role of particle size and number has been conducted in laboratories using animals or mathematical models. In practice ambient monitoring of particle numbers is not common; rather, most of the monitoring the world over still focuses on particle mass.

**Composition**

The main components of urban PM are metals, organic compounds, materials of biological origin, secondary particulate matter (sometimes as ions), and the particle core which often forms the bulk of urban PM and is frequently composed of pure or elemental carbon. Several studies, mostly on animals, have demonstrated the effect of metallic PM on lung damage. Organic compounds are known to lead to mutations and even cause cancer. Materials of biological origin such as fungal spores and pollen are known to induce a variety of allergic responses. Sulfate and nitrate ions lead to significant impairment of the respiratory tract because of their acidic potential. Carbonaceous material in the particle core can by itself lead to lung irritation and damage after chronic exposure. In general fine and ultrafine particles are composed mainly of particles with a carbon core that contains a variety of metals, organic compounds, and secondary particulates [4]. The surface area of the elemental carbon core is considerably increased by its porous nature, greatly enhancing the adsorption probability of airborne substances such as organic compounds.

While particle composition is known to play an important role in inducing adverse health effects, much less is known about its role compared to that of particle size and mass. The strongest evidence of the role of particle composition comes from studies investigating the effects of metallic particles on health. More recently, studies have started focusing on the impact of organic compounds associated with fuel combustion, such as those contained in particles produced by diesel-powered vehicles.

A recent study by the U.S. Environmental Protection Agency (EPA) highlighted the likely cancer risk from diesel emissions [7], declaring it as a potential carcinogen. The diesel particles, many of which are smaller than 1 micron in diameter, have a carbonaceous core with a large surface area to which various organic compounds are adsorbed, including carcinogenic polycyclic and nitro-polycyclic...
hydrocarbons. Diesel particles have also been shown to adsorb allergens from grass pollen, thus potentially increasing allergen deposition in the respiratory tract [8].

The composition of PM varies with factors such as the nature of sources and/or geographical location. For example, the particle composition in the northeastern part of the United States, which has a high concentration of coal-based thermal power plants, is dominated by secondary sulfate particles linked to sulfur dioxide emissions from the power plants. As a result, the health effects of inhaled particles may also be affected by their composition. This suggests that more epidemiological studies based on PM$_{2.5}$ and smaller particles with varying composition are needed to see whether there is a significant impact of particulate composition on health.

Mechanism of Health Effects

Dose

While ambient concentrations are normally used as a proxy for linking ambient air pollution to health effects, it is the dose that actually matters. Dose is defined as the quantity of material that reaches a target. Knowledge of the dose of PM delivered to a target site or sites in the respiratory tract is important for understanding possible health effects associated with human exposure to ambient PM. The effect, however, of varying dose and potential duration of the effect are functions of the retention and clearance of particles from the respiratory tract, which in turn are affected by the characteristics of the inhaled particles (size, number, and composition) and the physical and physiological characteristics of the exposed population.

Lung defenses

The adult human lung, with a surface area of 40-120 square meters, comes in contact with between 10,000 and 20,000 liters of ambient air daily. The lung has evolved a multi-layered defense mechanism to counter inhaled particles, and it responds to particulate pollution with the same defense mechanism as it does to pollens and spores [9].

The first layer of defense is a barrier of cells and fluids that the foreign matter must penetrate before it enters the tissues of the body. Fluid secretion, such as mucus lining the airways, is an important part of the first layer that essentially traps and removes the larger particles. Coughing, activated by the presence of particles, also helps in the removal process. If the particles infiltrate the first layer of defense, “scavenger” cells come into play. These cells ingest the particles and attempt to destroy them. If the burden of foreign matter overwhelms this line of defense, as can occur in response to inhaled particles, the lung defenses may be weaker from subsequent attacks.

Specific health effects

The PM damage to lung defenses manifests itself in the form of health effects such as acute respiratory infection (both upper and lower respiratory tract infections), chronic obstructive lung disease (especially bronchitis), asthma attacks, cardiovascular disease, and lung cancer. Further, recent research has increasingly shown that particles can also affect other parts of the body, including the nervous system, by physically moving out of the airways and into the bloodstream [4]. Thus particle deposition in airways can set off a chain of events, potentially affecting parts of the body other than just the respiratory tract.

As can be expected, the changes in the body are likely to be more severe in cases where the body’s defenses are already weak or previously damaged. Hence, certain population subgroups, such as the elderly, children, and individuals with existing respiratory or cardiovascular diseases, are at increased risk from exposure to PM.

Conclusions and Policy Implications

As discussed above, the science of health impacts of particulate matter is quite complex. After more than two decades of research, however, answers to some of the key research questions regarding the science of health effects of PM are beginning to emerge.

- While a large body of studies links adverse health effects to particles less than 10 microns in diameter (PM$_{10}$), the latest evidence strongly indicates that the fine (less than 2.5 microns) and ultrafine (less than 0.1 micron) fractions of PM are most harmful because of their ability to penetrate deeply into the lungs.
- Small particles with toxic materials adsorbed onto surface are especially damaging. Ultrafine particles, however, have been found to have adverse health effects even when they comprise substances that are not harmful when present in larger particles.
- For a given mass, the surface area and particle number increase dramatically as the particle size decreases. As a result, a smaller mass of PM$_{10}$ which happens to consist primarily of ultrafine particles can be more damaging than a greater mass of PM$_{10}$ but with a significant fraction falling in the coarse range.
- Certain plausible mechanisms by which PM affects human health have been identified, strengthening evidence from epidemiological studies.

Policy decisions for reducing the health risks of PM in many countries are being made based on the current understanding of the science of PM health impacts. A review of the scientific evidence shows that the production of fine and ultrafine PM is concentrated in various combustion processes, ranging from household cooking
and garbage burning to vehicle operation and industrial processes. These findings provide a sufficient basis for an urgent need for identifying and supporting measures to reduce combustion-related emissions across these sources. Before moving to expensive control measures in a specific sector or group of sources, however, it is important to gain a better understanding of their contribution to health impacts and the effect of proposed control measures, especially if these measures also have a welfare and equity impact.

The monitoring and regulation of PM$_{2.5}$ is on its way to becoming standard across the United States and other countries. A question that clearly follows from the discussion presented in this note is whether standards for, and monitoring of, PM levels in South Asia should be revisited in favor of regulating and monitoring PM$_{2.5}$. While there is a strong case for better understanding both the ambient concentrations and sources of fine particles (and hence the need for well-designed networks for measuring these particles), it is also important to account for the complexity of measurement techniques (for more information, see references [10] and [11]). These techniques are expensive and more technically challenging than most monitoring carried out to date in South Asia. Therefore, careful consideration should be given to the pros and cons of monitoring PM$_{2.5}$, the monitoring of which is relatively new even in industrial countries, and PM$_{10}$, for which there are many well-established and proven monitoring methods with years of experience to learn from.

References

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