



Environmental risk factors and cardiovascular health

A clinical consensus statement of the European Society of Cardiology

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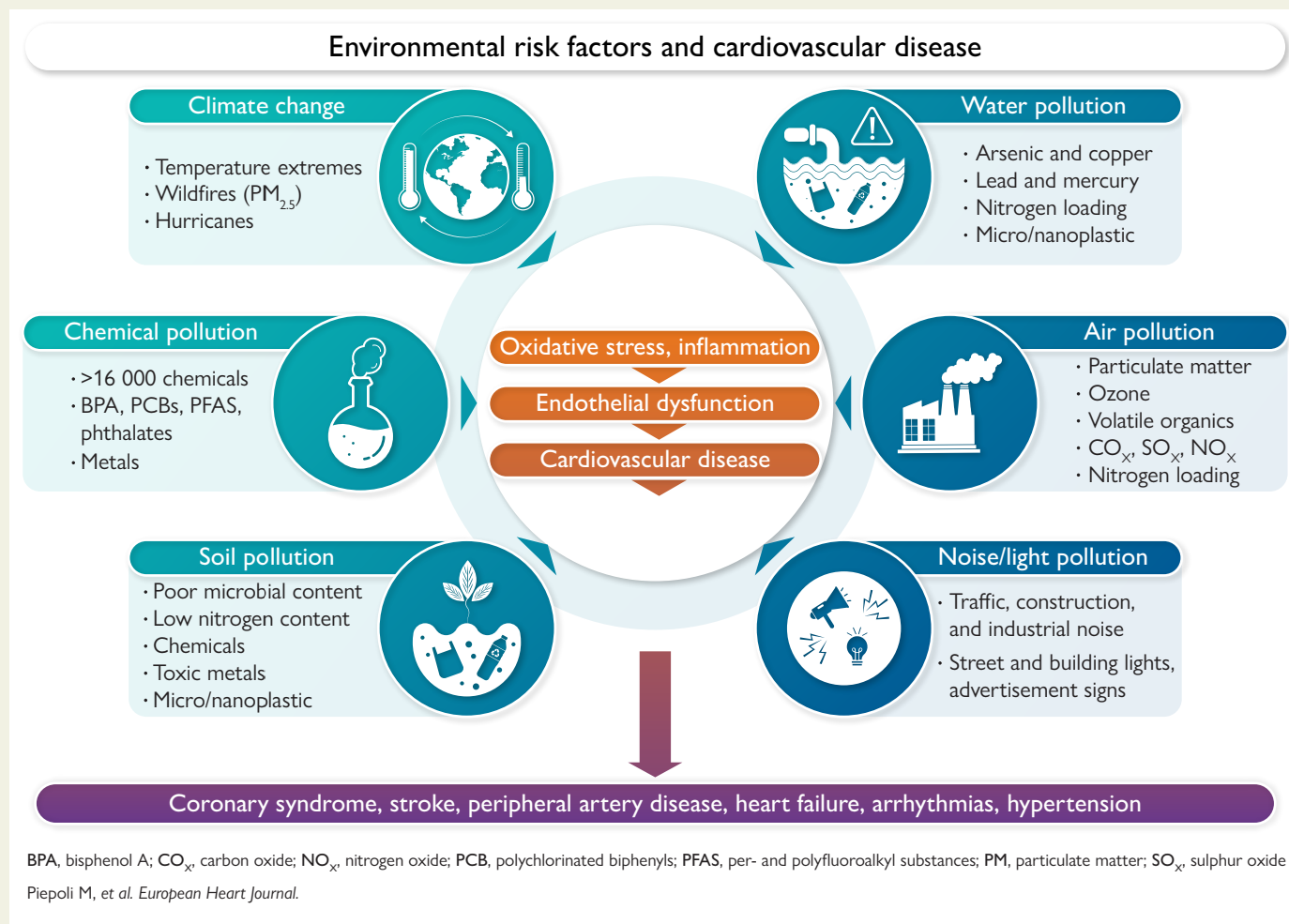
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Abstract

Environmental risk factors—air pollution, noise, heat, chemical contamination, and light pollution—are increasingly recognized as key contributors to cardiovascular disease but remain underrepresented in clinical guidelines and public health strategies. This comprehensive review, developed under the auspices of the European Society of Cardiology (ESC), synthesizes current evidence on the cardiovascular consequences of environmental exposures. Building on prior ESC recommendations on air pollution, the consensus statement extends the focus to include climate change, urban heat islands, chemical pollutants, noise, and light pollution, highlighting their shared pathophysiological mechanisms: oxidative stress, inflammation, endothelial dysfunction, and circadian disruption. Epidemiological and experimental studies confirm that these exposures exacerbate the incidence of coronary artery disease, stroke, heart failure, arrhythmias, and hypertension—even at levels below existing regulatory thresholds. It is proposed the exposome framework as a conceptual tool to understand the cumulative lifetime impact of environmental hazards on cardiovascular health. Special attention is given to vulnerable populations, including children, the elderly, socioeconomically disadvantaged groups, and patients with pre-existing cardiovascular disease. The document outlines urgent research needs, such as the need for high-resolution exposure data, exploration of gene–environment interactions and molecular pathways, and the development of real-world and mechanistic studies assessing interventions. Mitigation strategies are discussed across individual, clinical, and policy levels, with a call for heart-healthy urban design, stricter emissions legislation, and equitable access to clean environments. Cardiologists are uniquely positioned to advocate for environmental cardiovascular health, bridging the gap between science, clinical care, and policy. This statement aims to accelerate that translation by raising awareness and promoting action across disciplines.

Graphical Abstract



Environmental Stressors Driving Cardiovascular Disease. Environmental determinants of cardiovascular disease: mechanistic pathways and clinical consequences. This graphical abstract illustrates the multifaceted contribution of environmental stressors to cardiovascular pathology. Climate change (e.g. temperature extremes, wildfires, hurricanes), air pollution (e.g. PM_{2.5}, ozone, nitrogen dioxide), chemical pollution (e.g. PFAS, PCBs, BPA), soil pollution (e.g. toxic metals, microplastics, low microbial content), water pollution (e.g. heavy metals, nitrogen loading), and noise/light pollution (e.g. traffic noise, artificial lighting) act via common pathophysiological mechanisms, including oxidative stress, inflammation, and endothelial dysfunction. These processes contribute to the development and exacerbation of cardiovascular disease, manifesting clinically as hypertension, acute and chronic coronary syndromes, heart failure, stroke, and arrhythmias. The central image emphasizes the human health burden, linking environmental exposures directly to major adverse cardiovascular events. BPA, bisphenol A; COx, carbon oxides; NOx, nitrogen oxides; PCB, polychlorinated biphenyls; PFAS, per- and polyfluoroalkyl substances; PM, particulate matter; SOx, sulphur oxides.

Keywords

Environment • Environmental risk factors • Air pollution • Particulate matter • Climate change • Non-optimal temperature • Noise pollution • Light pollution • Chemical pollution • Cardiovascular disease

Introduction and objectives

The association between environmental risk exposures and cardiovascular diseases (CVDs) has long been established, yet it continues to receive limited public awareness and inadequate policy attention.¹ The impact of increases in ambient temperature and exposure to air pollution on human health has raised concerns among professionals who care for patients with cardiovascular (CV) conditions, as documented by a survey conducted among the presidents of National Cardiac Societies of the European Society of Cardiology (ESC) at the ESC Spring Summit 2024. The same survey has highlighted the need to enhance awareness among all healthcare providers. Air pollution, noise, and urban heat islands can negatively impact CV health and are described as environmental '*cardiac hazards*' by the World Health Organization (WHO). Cardiologists are at the forefront of managing CV death, so it is vital that they understand and address environmental factors. By increasing awareness of environmental risk factors, they can better advise patients on how to reduce their exposure and adopt healthier lifestyles, thereby helping to mitigate the effects of these risks on heart health.² In addition, cardiologists can play an important role at policy and community levels by providing expert advice that supports population-wide interventions to reduce environmental exposures and improve CV health.

Thus, following a previous ESC document specifically oriented on air pollution¹ the present consensus statement summarizes current knowledge on how all environmental risk factors impact CV health and the associated pathophysiological mechanisms. The statement also covers groups that are more vulnerable or susceptible to environmental exposures, research priorities, and strategies that can mitigate these risks. Furthermore, this work provides an overview of the current state of the field, supplemented with selected evidence to illustrate the key points, while directing readers to focused reviews for a more comprehensive examination of specific issues.

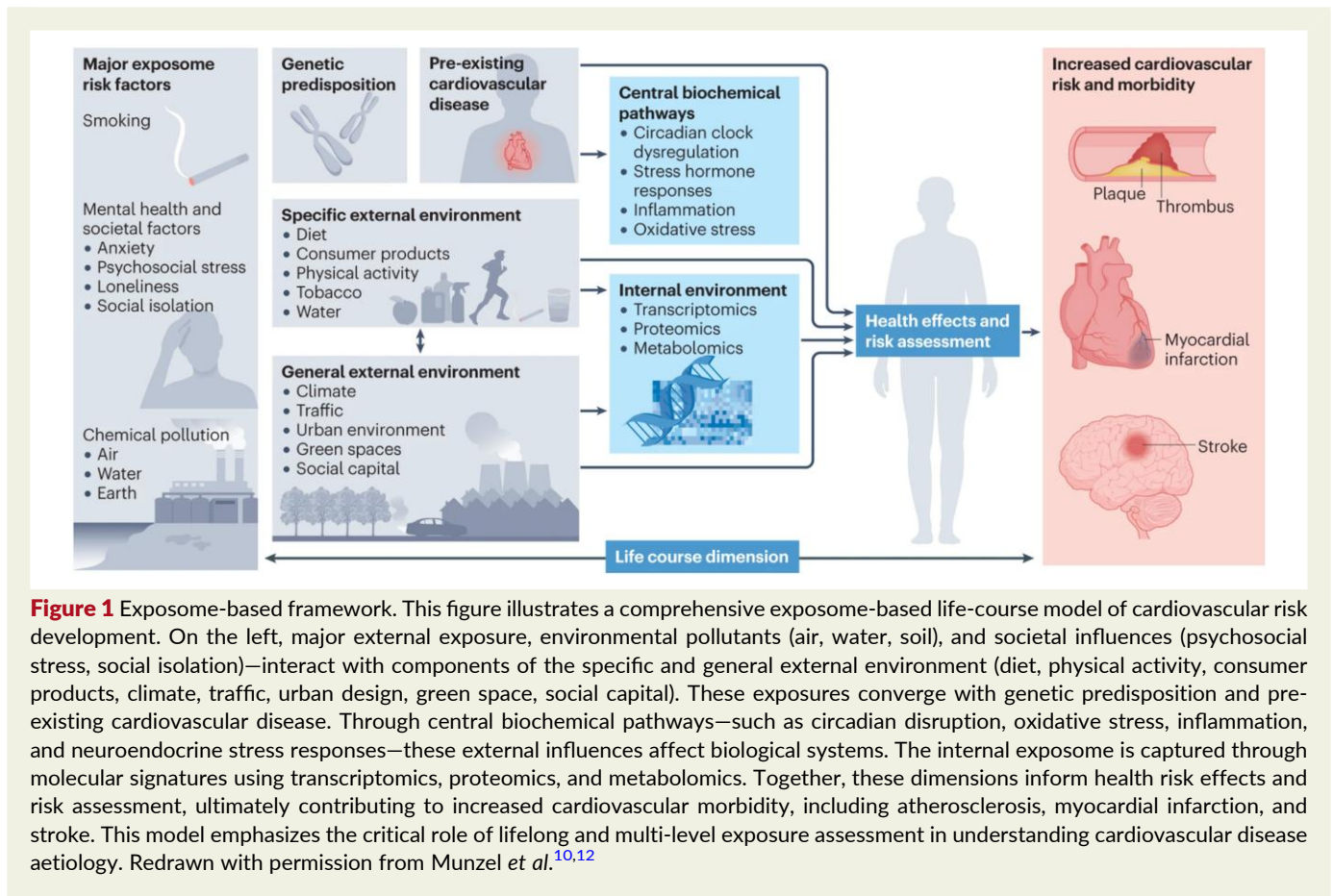
Disease burden and the exposome

Over the last decades, the global burden of disease has shifted from communicable to non-communicable diseases (NCDs), such as CVDs, cancer, respiratory diseases, and cardiometabolic conditions. This shift has been driven by (i) the prevention and

treatment of communicable diseases (through, e.g. improved sanitation, vaccination, and antibiotic use) and (ii) the rise in NCDs, driven also by environmental factors.³

The interplay between genetic predisposition and environmental exposures is crucial in addressing the growing burden of NCDs.⁴ The Lancet Commission on pollution and health identified chemical pollution as the most significant environmental cause of disease and premature death, responsible for an estimated 9 million premature deaths in 2015 (i.e. 16% of all deaths). Major chemical pollutants in the air, soil, water, and in occupational settings are linked to CVD.⁵ Surprisingly, the Global Action Plan for NCDs of the WHO overlooks many environmental risk factors, especially non-chemical ones. Poor urban design, such as the reliance on travel by vehicles relying on fossil fuel energy and the absence of green infrastructure in cities, contributes to environmental risks.⁶ A 2021 study estimated that meeting WHO recommendations for green space access could prevent a significant number of deaths.⁷ Climate change, associated with increased CV deaths due to an increased number and length of heat waves, poses a significant environmental risk, leading to more casualties than any other extreme weather event.⁸

In 2005, Wild introduced the exposome concept,⁹ which refers to the total environmental exposures an individual experiences throughout the lifetime, from conception to death.¹⁰ Unlike the static genome, the dynamic exposome evolves with changing internal and external factors, including all environmental exposures, physical stressors, social and psychological factors, lifestyle choices, and the body's biological make up, including epigenetic changes induced by the exposome. In line with the classification proposed by Vermeulen *et al.*¹¹ the exposome can be conceptualized as encompassing three interconnected domains: (i) the general external exposome (e.g. climate, pollution, waste, socioeconomic status); (ii) the specific external exposome (e.g. diet, physical activity, specific consumer products exposure); and (iii) the internal exposome, which involves biological responses like hormonal stress reactions, circadian rhythm disruption, inflammation, and oxidative stress and epigenetic changes associated with it.¹⁰ The exposome offers a promising approach to describe the complex relationships between environmental exposures and health outcomes integrating external exposures with internal biological responses to provide a holistic view of lifetime CV risk (*Figure 1*). The



following paragraphs will review the different risk factors linked to the environment with their consequences on CVDs and the putative pathophysiological mechanisms (*Graphical Abstract*).

Air pollution

Background

Air pollution represents a complex mix of hundreds to thousands of different chemicals, broadly categorized as gases and particles. While gases such as nitrogen dioxide (NO₂), ozone (O₃), sulphur dioxide (SO₂) and carbon monoxide (CO) are all linked to adverse CV effects, the strongest associations are found with the particles in air pollution. Airborne particulate matter (PM) varies in size and composition depending on source and atmospheric conditions. PM is categorized by size as PM₁₀ (PM with an aerodynamic diameter ≤10 μm) and PM_{2.5} (aerodynamic diameter ≤2.5 μm). Fossil oil, gas and coal combustion, and road traffic (fuel combustion, but much also from road/tyre/breakpad wear) are major sources of PM_{2.5}, the air pollutant most closely associated with short-term adverse CV effects. Smaller ultrafine PM (diameter ≤100 nm) may have especially prominent effects on the CV system. This PM size is not routinely measured by monitoring networks, limiting epidemiological data sets. Ultrafine PM can arise from many origins, mainly from combustion. Vehicle exhaust, such as diesel exhaust, is especially rich in ultrafine particles, having a complex composition with many toxic constituents.

Links with cardiovascular disease

The link between outdoor ambient air pollution and CVD both in the short (*Table 1*)^{13–18} and long term (*Table 2*)^{17,19–21,24–27} is well established. Worldwide, CV conditions—specifically coronary artery disease (CAD) and stroke—account for ~70% of mortality attributed to air pollution.² World Heart Federation data from 2019 suggest that, annually, PM_{2.5} is responsible for 1.9 million premature deaths from CAD and 900 000 from annual stroke.² Ambient outdoor air pollution is estimated to reduce average life expectancy in Europe by 2.2 years, with CV events being the dominant cause of premature mortality.²⁸ The relationship between PM_{2.5} concentration and CVD varies depending on the specific type of CV condition. While earlier reports described this association as approximately linear at concentrations commonly observed in Europe,²⁹ multiple epidemiological analyses—including landmark studies demonstrating supralinear exposure–response curves^{30,31}—have shown that increases in CVD risk are proportionally greater at lower PM_{2.5} levels. Recent large-scale studies have demonstrated that air pollution increases the risk of CV deaths at PM_{2.5} concentrations below the already stringent WHO guidelines.³² Moreover, emerging evidence suggests that the chemical composition of PM influences its cardiotoxicity. Particles enriched in metals and acidic sulphates appear to exert stronger CV effects, including increased risk of myocardial infarction (MI) and arrhythmias, highlighting that not all PM_{2.5} is equally harmful and that targeting specific particle sources may optimize public health interventions.³³

Table 1 Selected meta-analyses of short-term exposure (<1 month) to air pollutants and cardiovascular mortality and morbidity

Cardiovascular condition	Pollutant	Studies/subjects included	% increase in risk	Reference
Cardiovascular/circulatory mortality	PM ₁₀	196 studies, global	0.6% per 10 µg/m ³	Orellano <i>et al.</i> , 2020 ¹³
	PM _{2.5}		0.9% per 10 µg/m ³	
	NO ₂		0.7% per 10 ppb	
	O ₃		0.4% per 10 ppb	
Myocardial infarction	PM ₁₀	33 studies, global	1.1% per 10 µg/m ³	Cai <i>et al.</i> , 2016 ¹⁴
	PM _{2.5}		2.4% per 10 µg/m ³	
Heart failure	PM ₁₀	7.56 million patients	1.3% per 10 µg/m ³	Yang <i>et al.</i> , 2022 ¹⁵
	PM _{2.5}		1.3% per 10 µg/m ³	
	NO ₂		2.1% per 10 ppb	
	O ₃		1.0% per 10 ppb	
Stroke	PM ₁₀	103 studies, global	1.1% per 10 µg/m ³	Shah <i>et al.</i> , 2015 ¹⁶
	PM _{2.5}		0.3% per 10 µg/m ³	
	NO ₂		1.4% per 10 ppb	
	O ₃		0.1% per 10 ppb	
Arrhythmia	PM ₁₀	13 studies, Asia, Europe, USA	1.1% per 10 µg/m ³	Chen <i>et al.</i> , 2021 ¹⁷
	PM _{2.5}		1.8% per 10 µg/m ³	
	NO ₂		3.2% per 10 µg/m ³	
	O ₃		0.5% per 10 µg/m ³	
Hypertension	PM ₁₀	6 studies, global	2.4% per 10 µg/m ³	Cai <i>et al.</i> , 2016 ¹⁸

Table 2. Selected meta-analyses of long-term exposure (>1 month) to air pollutants and cardiovascular mortality and morbidity^{17,19-23}

Cardiovascular condition	Pollutant	Studies/subjects included	% increase in risk	Reference
Cardiovascular/circulatory mortality	PM _{2.5}	42 studies, global	13% per 10 µg/m ³	Orellano <i>et al.</i> , 2024 ²⁴
	PM ₁₀	26 studies, global	8% per 10 µg/m ³	
Coronary artery disease	NO ₂	137 148 European subjects	4% per 10 µg/m ³	Wolf <i>et al.</i> , 2021 ¹⁹
Ischaemic heart disease	PM _{2.5}	34 studies, global	14% per 10 µg/m ³	Orellano <i>et al.</i> , 2024 ²⁴
	PM ₁₀	16 studies, global	6% per 10 µg/m ³	
Myocardial infarction	PM _{2.5}	47 studies, global	13% per 10 µg/m ³	Forastiere <i>et al.</i> , 2024 ²⁵
Heart failure	PM _{2.5}	22 000 subjects, Denmark	1.2% per 5 µg/m ³	Lim <i>et al.</i> , 2021 ²⁰
	NO ₂		1.1% per 9 µg/m ³	
Stroke	PM _{2.5}	28 studies, global	15% per 10 µg/m ³	Orellano <i>et al.</i> , 2024 ²⁴
	PM ₁₀	15 studies, global	5% per 10 µg/m ³	
	NO ₂	137 148 European	8% per 10 µg/m ³	
Arrhythmia	PM ₁₀	6 studies, Asia, Europe, USA	3.4% per 10 µg/m ³	Chen <i>et al.</i> , 2021 ¹⁷
	PM _{2.5}		11.6% per 10 µg/m ³	
	NO ₂		1.7% per 10 µg/m ³	
	O ₃		0.7% per 10 µg/m ³	
Hypertension	PM ₁₀	53 studies, global	4% per 10 µg/m ³	Qin <i>et al.</i> , 2021 ²¹
	PM _{2.5}	47 studies, global	17% per 10 µg/m ³	
	NO ₂		No association	

Coronary artery disease

There is a large body of robust evidence linking exposure to air pollution and CAD, in terms of both hospital admissions and mortality, especially for PM_{2.5}.³⁴ Air pollutants contribute to

atherosclerotic plaque development and vulnerability (see below), increasing the risk of acute events such as acute coronary syndromes (ACS) (Figure 2).³⁴⁻³⁷ Moreover, in case of ST-elevation MI, the impact of PM_{2.5}, SO₂, and NO₂ was more

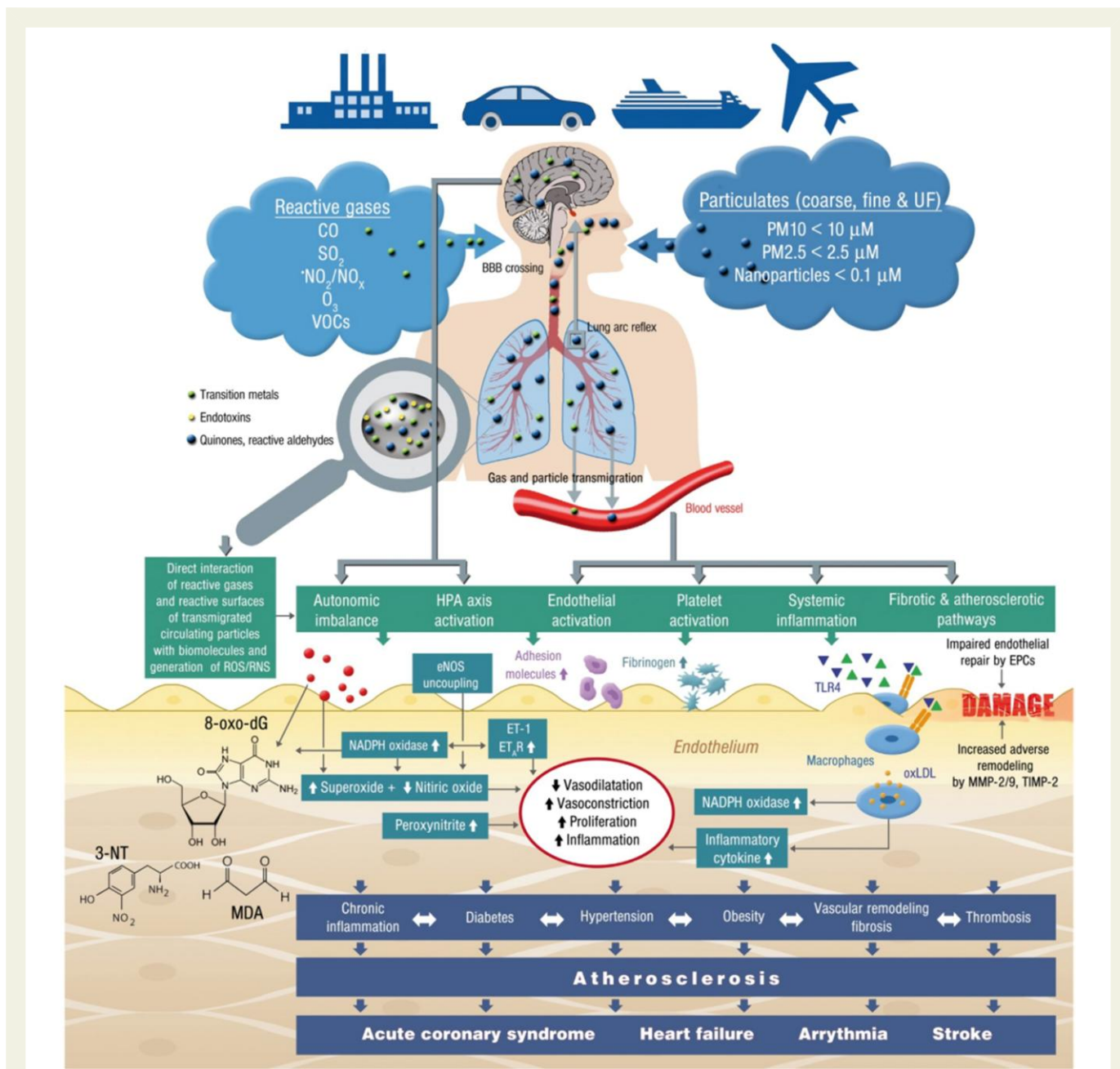


Figure 2 Mechanistic pathways linking air pollution to cardiovascular disease. This figure illustrates how inhaled air pollutants—reactive gases (CO, SO₂, NO_x, O₃, and VOCs) and particulate matter (PM₁₀, PM_{2.5}, ultrafine particles <0.1 μm)—lead to cardiovascular injury. After lung uptake, pollutants enter the bloodstream or trigger neural reflexes, initiating systemic effects. The magnified particle composition (bottom left) reveals a complex mix of toxic components, including *transition metals*, *endotoxins*, *quinones*, and *reactive aldehydes*, all of which interact with biomolecules to generate reactive oxygen and nitrogen species (ROS/RNS). These interactions drive *oxidative and nitrosative stress* (e.g. superoxide, peroxyntirite, 8-oxo-dG, 3-nitrotyrosine), leading to autonomic imbalance, HPA axis activation, endothelial dysfunction (eNOS uncoupling, ET-1, adhesion molecules), platelet activation (↑ fibrinogen), and systemic inflammation (via cytokines, TLR4 activation). In parallel, oxidized LDL and impaired endothelial progenitor cell (EPC) repair promote *fibrotic and atherosclerotic remodelling*, mediated by MMPs and TIMPs. These processes accelerate chronic inflammation, diabetes, obesity, and hypertension, ultimately promoting *atherosclerosis* and its clinical endpoints: acute coronary syndrome, heart failure, arrhythmia, stroke, and thrombosis. Adapted with permission from Munzel et al.³⁵

pronounced in populations with a higher prevalence of classical risk factors, such as smoking, diabetes, and hypertension.³⁸ Exposure to ultrafine PM from traffic is especially concerning. Seminal studies showed that individuals presenting with MI

were significantly more likely to have been exposed to traffic exhaust in previous hours before acute cardiac event.³⁹ Ultrafine particle exposure (as assessed by surrogates) is associated with MI.⁴⁰ Seminal work by Kunzli et al. demonstrated the link

between air pollution and morphological measures of atherosclerosis.⁴¹ Importantly, several studies, including the Multi-Ethnic Study of Atherosclerosis cohort, have shown that long-term exposure to PM_{2.5} is associated with increased coronary artery calcium scores, providing direct evidence that air pollution contributes to coronary calcification, a well-established marker of atherosclerotic burden.⁴² More recently, a retrospective cohort study in Seoul (South Korea) of ~3200 adults found a correlation between cumulative PM_{2.5} exposure and an increased coronary artery calcium score over 53 months.⁴³ Furthermore, PM_{2.5} exposure was associated with high-risk plaque formation, including fibro-fatty or necrotic cores in new plaques or plaque volume increase in pre-existing ones.⁴⁴

Cerebrovascular disease/stroke

Evidence from observational and interventional studies suggests that short-term exposure to air pollution can induce cerebrovascular incidents and, in the medium and long term, increase the risk of future events.⁴⁵ Air pollution directly affects cerebral vascular haemodynamics by increasing vascular resistance and decreasing blood flow.⁴⁶ It also increases indirectly cerebrovascular risk by promoting stroke risk factors like atrial fibrillation (AF) and hypertension.³⁴ Epidemiological studies show an increase in ischaemic strokes after short-term exposure to various air pollutants, even at low or moderate concentrations. A meta-analysis linked stroke incidence and mortality to increased concentrations of NO₂, SO₂, O₃, and PMs.¹⁶ More substantial and consistent associations are observed in ischaemic stroke than in haemorrhagic stroke.⁴⁷ There are interactions with other CV risk factors; for instance, residents of regions in Poland with higher alcohol and tobacco consumption were at higher risk of ischaemic stroke associated with exposure to PM_{2.5} and SO₂.⁴⁸ Sources of large PM above 10 µm, e.g. from sand and dust storms, can increase cerebrovascular disease risk.⁴⁹

Peripheral artery disease

Long-term air pollution is associated with a higher incidence of peripheral artery disease (PAD).⁵⁰ The main evidence stems from a longitudinal study carried out in the metropolitan area of Rome in Italy in a population at risk, which comprised 1 719 475 citizens aged 30 years or more.⁵¹ A total number of 14 629 incident cases were identified. Levels of PM_{2.5}, NO₂ and black carbon were associated with the incidence of PAD. The association with these pollutants was stronger for NO₂ and dose-response curves showed a higher increased risk even at low concentrations of pollutants. There was also an association with male sex and lower socioeconomic status. Comorbidities such as diabetes, hypertension, and dyslipidaemia did not modify the PAD-air pollution association.⁵¹

Heart failure

A strong association exists between short- and long-term exposure to air pollution and heart failure (HF).⁵² A meta-analysis of 35 studies showed that short-term exposure to air pollutants (e.g. PM₁₀, PM_{2.5}, NO₂, and O₃) increases the risk of HF hospitalizations. The impact of air pollution on HF occurs on the same day as PM elevation in the environment, and also on the following days.⁵³ For short-term exposure, each 10 µg/m³ increment in PM_{2.5} and PM₁₀ increased HF risk by 1.8% and 1.6%,

respectively, with stronger associations observed with exposure over the previous 2 days. These effects were more pronounced in low- and middle-income countries (LMICs). Even in areas with very low air pollution, such as Tasmania (Australia), acute PM exposure has been associated with increased HF incidence.⁵⁴ As regards long-term exposure, the risk of HF was significantly associated with each 10 µg/m³ increase in PM_{2.5} [odds ratio (OR) 1.20, 95% confidence interval (CI) 1.08–1.33], PM₁₀ (OR 1.19, 95% CI 1.05–1.36), and NO₂ (OR 1.07, 95% CI 1.03–1.12).⁵³ In Ontario, Canada, long-term exposure to air pollutants, such as O₃, was associated with increased HF admissions.⁵⁵ A prospective analysis in the UK reported a 31% higher risk of incident HF with long-term pollutant exposure, even after adjustment for possible confounders. Traffic-related air pollution has been associated with an increased incidence of HF. Genetic factors may modify these effects by promoting left ventricular hypertrophy and inflammation.⁵⁶

Arrhythmias

Air pollution is linked to increased arrhythmic events. In a meta-analysis, long-term exposure to 10 µg/m³ PM_{2.5} increased the risk of AF by 0.89%.^{37,57–59} A systematic review by Pallikadavath *et al.* found that in patients experiencing the acute phase of MI, air pollution could trigger arrhythmias⁵⁷ and also impact sudden cardiac death risk. A nationwide study in Poland demonstrated exposure-response functions with steeper slopes of the pollutant-AF occurrence associations in the lower ranges of exposures, far below WHO air quality guideline norms.⁶⁰

Cardiovascular risk factors

Exposure to air pollution, especially PM, promotes CV risk factors like hypertension⁴⁵ and metabolic disorders.^{61,62} Risk ratios can be high with long-term exposure, but even where the size of effect is smaller (e.g. 1–2 mmHg per interquartile range increase of pollutant), given the ubiquity of exposure, this may translate to a large number of CV events across the population as a result. Air pollutants may promote obesity through interactions with lipids⁶³ and diabetes mellitus through oxidative stress⁶² and insulin resistance.⁶⁴ In addition, there is growing evidence that PM_{2.5} exposure is associated with higher body mass index (BMI) and increased adiposity. In the China-PAR cohort, long-term exposure to PM_{2.5} was associated with incremental increases in BMI and a higher risk of overweight/obesity.⁶⁵ Genetic evidence from a Mendelian randomization study in individuals of European ancestry also supports a causal association between PM_{2.5} and obesity, in particular visceral fat accumulation.⁶⁶ Moreover, in midlife women, increases in PM_{2.5} exposure were associated with higher fat mass and proportion fat mass, and lower lean mass as measured by dual-energy X-ray absorptiometry.⁶⁷

Venous thromboembolism

An association of dysregulated coagulation and air pollution is supported by large meta-analysis and systematic reviews.^{34,68} A large cohort study found a significant correlation between elevated PM_{2.5} levels and venous thromboembolism (VTE).⁶⁹ Similarly, higher NO₂ levels, mainly from traffic emissions, have been linked to increased VTE risk in urban areas. Although the evidence for SO₂ and O₃ is less definitive, some studies suggest a possible association with VTE.^{70,71}

Mechanisms

The mechanistic underpinnings of the CV effects of air pollution are now well established.⁷² Oxidative stress and inflammation are hallmark responses to air pollution exposure at multiple levels of the pathological process. Several pathways link pulmonary inhalation to the CV system, including the passage of pollutants (especially ultrafine particles) and in turn release of inflammatory and oxidative mediators into the circulation leading to an acute phase response, changes to the autonomic nervous system influencing cardiac function and alterations in endocrine pathways mediated alterations in the central nervous system.⁷³ There are also emerging mechanisms such as changes in the gut microbiota and circulating micro-RNAs. At the level of the CV system itself, air pollution causes endothelial dysfunction and in turn vasoconstriction, increased arterial stiffness, raised blood pressure (BP) and reduced heart rate variability, increases the susceptibility of the heart to injurious stimuli, promotes blood clotting and impairs fibrinolysis. Because of this raft of insults, exposure to air pollution has been found to exacerbate almost all CV conditions⁷² (Figure 2).

Climate change and non-optimal temperatures

Background

Industrialization and urbanization of societies across the world have had the unintended consequences of increasing air pollution and adverse impacts on global climate. This anthropogenic climate change has led to higher global temperatures and more erratic weather patterns, leading indirectly to further consequences for population health, including reduced food security and water quality, flooding, inhabitable areas, migration, poverty, infectious diseases, among others.⁷⁴ Global heating caused by greenhouse gases (such as CO₂) has driven an increase in the number and scale of wildfire, that release yet more CO₂ (a positive feedback loop), and also combustion-derived particulate matter. Climate-related environmental changes (e.g. air pollution from wildfires and dust, potential for greater mould and pollen exposure; extreme heat and cold; increased incidence of hurricanes, floods, and droughts) represent a hazard to the CV system.⁷⁵ Although the evidence base remains limited, droughts may also contribute to CV vulnerability through mechanisms such as water scarcity, food insecurity, and increased airborne particulate concentrations. These combinations of climatic effects are particularly apparent and detrimental in LMICs, especially as they rapidly develop and industrialize.⁷⁴

Links with cardiovascular disease

Rising temperatures cause excessive heat exposure, which is associated with increased CV stress and thrombogenicity. This, in turn, fosters intravascular thrombus formation secondary to inflammation, reduced circulatory volume, and vasodilatation, causing reflex increases in heart rate and contractility.⁷⁶ The associations between extreme heat and CV mortality and hospitalization are well established.⁷⁷ Unphysiological temperatures have been associated with an increased risk of sudden cardiac death in a U-shaped manner, with stronger associations in older individuals, particularly at low temperatures.^{78,79}

The pathophysiological effects of air pollution and heat may be additive or synergistic and inevitably lead to increased risks of adverse CV events (Figure 3)⁸⁰; for instance, CV mortality increases by 2.1% for every 1°C rise in temperature.⁸¹

As a consequence, climate change accounted for an estimated 93 000 CV deaths worldwide in 2019.^{82,83} Exposure to wildfire smoke is associated with CVD mortality (16% to 30%).⁸⁴

Coronary artery disease

In a large study looking at a dataset from 27 countries, with periods ranging from 1979–2019, extreme heat was associated with a 7% increase in ischaemic heart disease mortality.⁸ In one of the largest meta-analyses on temperature–CVD studies, there was a positive relationship between increasing temperature and CAD with a 2.8% increased risk for every 1°C increase in temperature above reference temperatures.⁸¹ Several other smaller studies have reported statistically significant increases in CAD-related hospitalizations and emergency department visits during exposure to heat wave.^{85,86}

Cerebrovascular disease/stroke

Extreme temperatures, characteristic of climate change, increase the risk of stroke and stroke death, with immediate effects.^{8,87} Weather phenomena like hurricanes, floods wildfires, and cyclones also raise stroke risk, in part due to emotional trauma.^{88,89}

Heart failure

Most studies evaluating the relationship between HF admissions and climate have focused on seasonality rather than temperature extremes.⁹⁰ A greater diurnal temperature range has been linked to greater HF admissions, even after adjusting for seasonality, mean temperature levels, humidity, and air pollution. Alahmad *et al.* found similar results in a cohort from 567 cities in 27 countries linking extreme heat (99th percentile) to a higher risk of CV deaths, including HF.⁸ Wildfire smoke is also associated with more emergency visits for HF: specifically, patients with a history of hypertrophic cardiomyopathy or with HF with reduced or preserved ejection fraction, left ventricular hypertrophy and diastolic dysfunction are more vulnerable to high temperatures.⁹¹

Arrhythmias

For AF, previous studies suggested a protective effect of heat and an adverse effect of cold, possibly indirectly through sympathetic activation with higher BP and vascular resistance. However, seasonal variations in AF hospital admissions were not observed in a nationwide US quality improvement registry.⁹² Wildfire smoke is also associated with more emergency visits for arrhythmias.⁹¹

Cardiovascular risk factors

Weather-related conditions, particularly seasonal temperature changes, influence BP, with lower BPs at higher temperatures and higher BPs at lower temperatures.⁹³ This phenomenon affects both sexes, all age groups, and both normotensive and hypertensive individuals. Notably, BP reduction in hot weather has been associated with an increased incidence of syncope. Vice versa, BP increase in cold weather has been linked to a higher incidence of major CV events and mortality.⁹⁴ Wildfire smoke is also associated with diabetes and hypertensive crises.^{91,95}

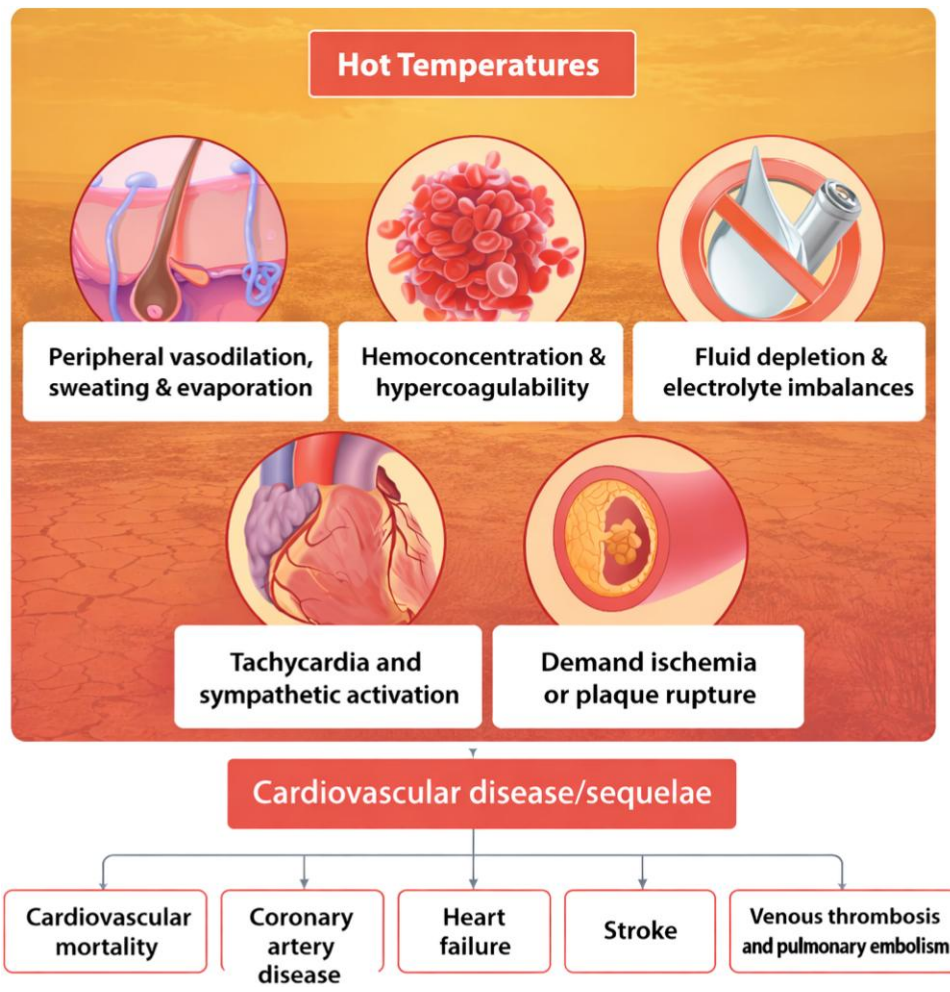


Figure 3 Cardiovascular effects of heat. This figure illustrates how exposure to extreme heat contributes to cardiovascular disease. High temperatures cause peripheral vasodilation, sweating, dehydration and haemoconcentration, and electrolyte imbalance—resulting in sympathetic activation, tachycardia, and increased risk of myocardial ischaemia or plaque rupture, especially in patients with left ventricle hypertrophy. These pathways elevate the risk of cardiovascular mortality, coronary artery disease, heart failure, stroke, and venous thromboembolism. The stressor burden from heat represents a growing environmental threat to cardiovascular health. (Redrawn with permission from Munzel *et al.*⁸⁰)

Mechanisms

Rising temperatures and excessive heat exposure are associated with increased thrombogenicity secondary to oxidative stress, inflammation, reduced circulatory volume and vasodilatation causing reflex increases in heart rate and cardiac contractility, and thrombosis (Figure 4).^{76,80,96} Similar to vehicle-derived air pollution, wildfire smoke exposure causes potential adverse mechanisms include oxidative stress, inflammation, atherosclerotic disease, and cardiac dysfunction.⁹⁷

Noise pollution

Background

Noise is defined as an unwanted and/or harmful sound; it is a frequent and often overlooked environmental pollutant, posing

serious health risks, particularly in urban areas where exposure to high levels of noise and air pollution is common. Despite this, the evidence of the health impacts of noise pollution is less established compared to air pollution. Estimations show that at least 20% of the population in the European Union (EU) is exposed to harmful levels of transportation noise, contributing substantially to the CV health burden. In Europe, noise exposure above the WHO guideline values causes 66 000 premature deaths, 50 000 new cases of CVDs, 22 000 cases of diabetes, which together with noise-induced sleep disturbances and annoyance, account for 1.3 million disability-adjusted life years.⁹⁸ A key challenge in studies of transportation noise is confounding by air pollution, since traffic is a common source of both exposures. Reviews and cohort studies indicate that associations between noise and CV outcomes generally persist after adjustment for NO₂ or PM_{2.5}, with mutual confounding typically small (<10%).^{99–101}

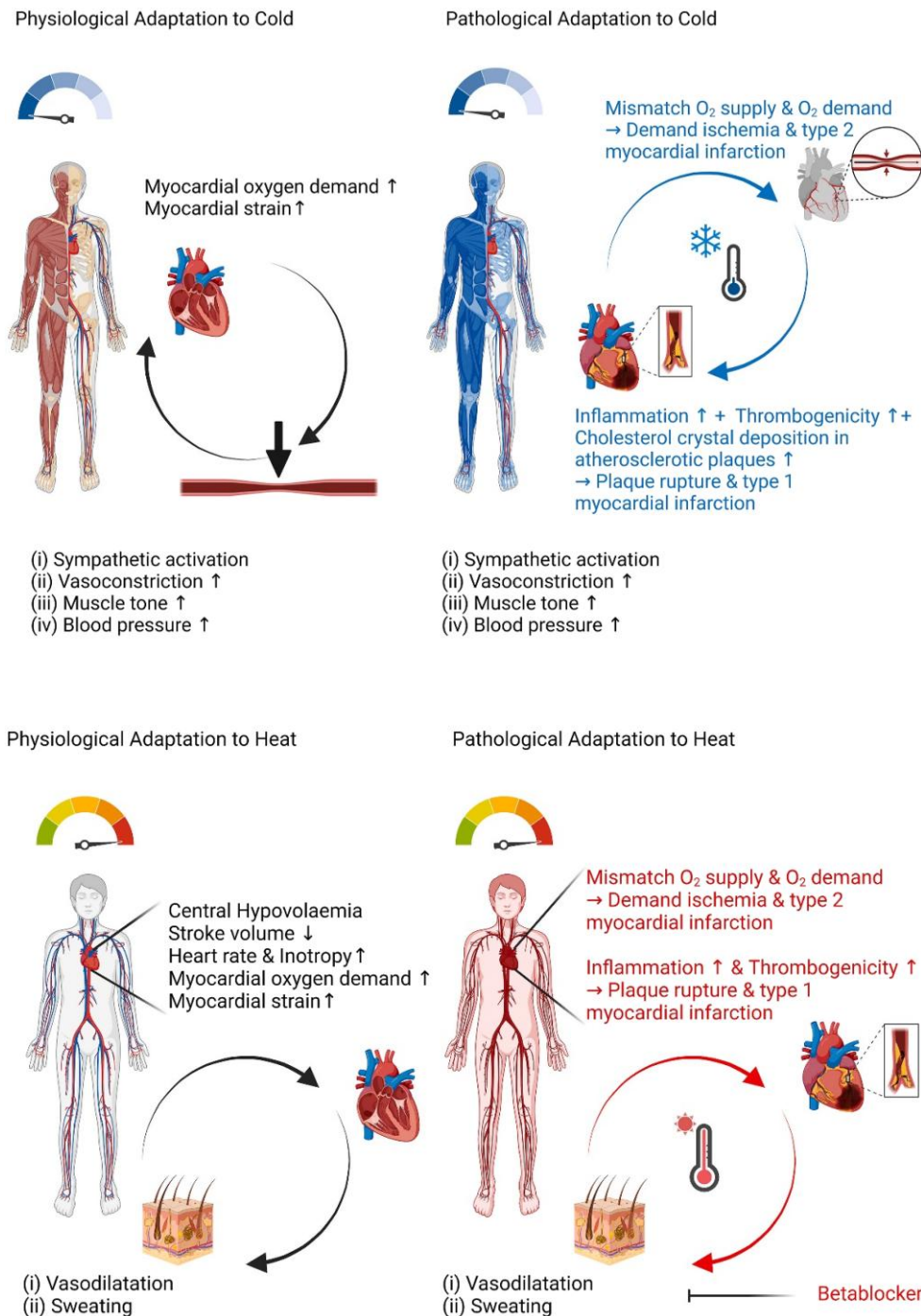


Figure 4 Physiological and pathological cardiovascular adaptations to thermal stress. (Panel A) illustrates the body's response to heat. Under physiological conditions (left), heat exposure triggers cutaneous vasodilatation and sweating to promote thermoregulation. These responses result in central hypovolemia, reduced stroke volume, and compensatory increases in heart rate, inotropy, myocardial oxygen demand, and cardiac strain. If adaptive mechanisms are overwhelmed (right), pathological responses ensue: a mismatch between myocardial oxygen supply and demand leads to demand ischaemia and type 2 myocardial infarction. Additionally, systemic inflammation and thrombogenicity are enhanced, promoting plaque vulnerability, rupture, and type 1 myocardial infarction. (Panel B) shows the response to cold exposure. Physiologically (left), cold induces sympathetic activation, peripheral vasoconstriction, increased muscle tone, and elevated blood pressure. These adaptations increase myocardial oxygen demand and strain. Under pathological conditions (right), cold stress exacerbates inflammation and thrombotic potential, increases vasoconstriction, and contributes to cholesterol crystal formation within plaques. These processes promote atherothrombosis and type 1 myocardial infarction, particularly in individuals with pre-existing cardiovascular disease. Both heat and cold extremes pose serious cardiovascular risks through distinct but converging mechanisms involving myocardial oxygen imbalance, inflammation, and plaque destabilization. Adapted from Ni et al.⁹⁶

Links with cardiovascular disease

A 2024 Umbrella+ review (i.e. a research synthesis of multiple systematic reviews and meta-analyses) reported that road traffic noise was associated with CVD.¹² The effects of noise from trains and aircraft have been less investigated, and the results are thus less clear.

Coronary artery disease

The 2024 Umbrella+ review associated road traffic noise with a 4.1% higher risk of CAD per 10 dB.^{12,102} In a large retrospective Canadian cohort, noise levels as 24 and 8 h nighttime average A-weighted decibels were modelled. Each interquartile range increase was associated with a 7% increase in acute MI incidence.¹⁰³

Cerebrovascular disease/stroke

Exposure to road traffic noise was found associated with a 4.6% higher risk of stroke per 10 dB increase.^{12,102}

Heart failure

Road traffic noise was related to 4.4% higher risk of HF per 10 dB.^{12,102} In a Canadian cohort study, each interquartile range increase was associated with a 6% rise in HF incidence.¹⁰³

Arrhythmias

Arrhythmias have been related to transportation and industry noise exposure, particularly from aircraft. The 2024 Umbrella+ review suggested a link between road traffic noise and arrhythmias.^{12,102} Others found that road traffic noise was indeed associated with AF, with a hazard ratio (HR) of 1.02 (95% CI 1.00–1.04) per 10-dB of 5-year mean time-weighted exposure. The association between road traffic noise and AF appeared most vigorous in women and overweight or obese participants.^{104,105}

Cardiovascular risk factors

The non-auditory effects of noise are linked with various cardiometabolic conditions, such as noise-induced arterial hypertension, obesity, and diabetes.^{12,106} Chronic exposure to transportation or railway or aircraft noise was associated with elevated BP, with nighttime noise particularly detrimental for CV health.^{107,108} Repeated nocturnal awakening and sleep fragmentation due to nighttime traffic noise may induce neurohormonal activation, preventing the regular nocturnal decline in BP, leading to alterations in circadian BP profiles and elevations in nighttime BP levels, with significant prognostic relevance for CV health.^{12,106} A WHO review of over 35 cross-sectional studies of different scientific quality on transportation noise and hypertension estimated a 10 dB(A) increase in day-evening-night noise level (L_{den}) to be related to an increase in relative CV risk of 1.05 (95% CI 1.02–1.08).¹⁰⁷ Stress and sleep disturbances are key pathways linking noise to CV and metabolic changes.^{12,106} For the development of diabetes, a meta-analysis found a relative risk of 1.11 (95% CI 1.08–1.15) per 10 dB(A) L_{den} increase for road traffic noise and 1.20 (95% CI 0.88–1.63) for aircraft noise exposure.¹⁰⁹ Traffic noise has also been linked to central obesity, possibly due to increased cortisol levels, which are particularly elevated in primary central obesity. Moreover, urban noise and

traffic are indirectly associated with unhealthy lifestyles, including reduced physical activity, further exacerbating CV risk.¹⁰⁶

Mechanisms

Translational and experimental studies have provided insights into the biological pathways underlying noise-induced CV alterations, which are activated through the impacts of noise on stress and sleep (Figure 5). Research in healthy subjects has shown that nighttime noise impairs vascular function, increases stress hormone levels, and triggers inflammation and oxidative stress. These effects are particularly pronounced in individuals with pre-existing CV conditions.¹⁰⁶ Animal studies have corroborated these findings, showing that noise exposure leads to endothelial dysfunction, increased BP, and oxidative stress, driven by molecular mechanisms like those of traditional CV risk factors, including NO activation. Noise-induced activation of the sympathetic nervous system and endocrine stress responses can destabilize coronary plaques and, in turn, trigger ACS.¹⁰⁶ AF and hypertension may further contribute to the total CV effects of noise,¹² although no relation of noise with hypertension has been reported.¹¹⁰

Light pollution

Background

Light pollution is a novel, ubiquitous environmental risk factor, defined by the changes in natural nighttime sky brightness induced by anthropogenic light sources,¹¹¹ which is most evident in urban areas. Today, 83% of the world's population and more than 99% of the US and European populations live under light-polluted skies.¹¹¹ Artificial outdoor light at night represents an understudied urban environmental risk factor that may lead to cumulative risk increases in multi-exposure settings.

Links with cardiovascular disease

Light pollution disrupts the circadian rhythm similarly to shift work, which is an accepted CV risk factor. In an observational nationwide study in China, higher exposure to light at night increased the relative risk of all-cause mortality, including cancer, respiratory disease, and CVDs.¹¹²

Coronary artery disease

Disruption of the circadian rhythm by excessive artificial light at night, increases BP and the risk of CAD and ACS. In older adults in Hong Kong,¹¹³ nocturnal light pollution has been observed to be associated with an increased risk of hospitalizations (HR 1.11; 95% CI 1.03–1.18) and cardiac deaths (HR 1.10; 95% CI 1.00–1.22), even after multivariable adjustment.¹¹³ Longitudinal studies have indicated that greater exposure to residential nighttime light increases the risk of CV events.¹¹³

Heart failure

A cohort study reported a non-linear (J-shaped) trend between nocturnal light time and HF risk: participants with <1.0 h or >2.5 h of light time had a higher risk after the model was adjusted for age and sex [<1.0 h: HR 1.27 (95% CI 1.18–1.36); >2.5 h: HR 1.11 (95% CI 1.07–1.15)] suggesting that a moderate exposure to outdoor light may be a prevention strategy for HF.¹¹⁴

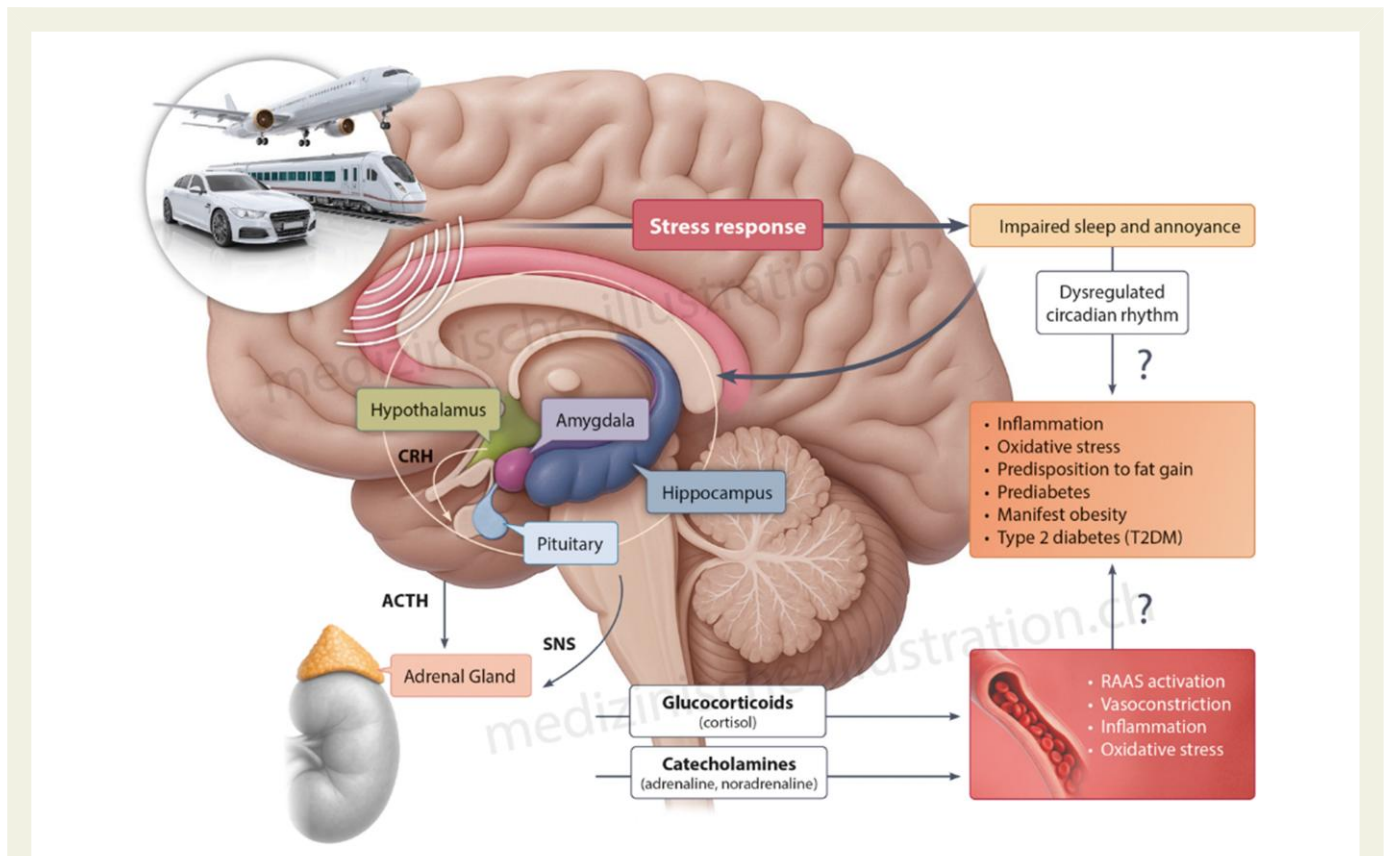


Figure 5 The noise-stress-CVD concept. Schematic representation of the neuroendocrine and cardiometabolic effects of transportation noise exposure. Environmental noise emitted by aircraft, road traffic, and trains activates the central auditory pathway and limbic structures—particularly the amygdala—leading to hypothalamic stimulation and initiation of the stress response. The hypothalamic–pituitary–adrenal (HPA) axis is activated via corticotropin-releasing hormone (CRH), stimulating adrenocorticotropic hormone (ACTH) release from the pituitary and subsequent cortisol secretion from the adrenal cortex. In parallel, the sympathetic nervous system (SNS) is activated, resulting in the release of catecholamines (adrenaline and noradrenaline). These neurohormonal responses contribute to vascular dysfunction via oxidative stress, inflammation, and activation of the renin–angiotensin–aldosterone system (RAAS), promoting vasoconstriction and endothelial damage. Chronic noise exposure also disrupts hippocampal and prefrontal regulation of the HPA axis and impairs sleep architecture and circadian rhythm regulation, leading to metabolic consequences such as insulin resistance, fat accumulation, prediabetes, and type 2 diabetes mellitus (T2DM). The figure highlights both direct and indirect pathways linking noise-induced stress to cardiometabolic disease, including vascular inflammation, oxidative stress, and metabolic dysregulation

Arrhythmias and cerebrovascular disease

Emerging nationwide studies also suggest that artificial light at night may be linked to cerebrovascular events and AF, although the evidence remains limited and heterogeneous and further high-quality studies are needed.

Cardiovascular risk factors

Artificial nocturnal light exposure may disrupt circadian rhythms, inducing neuro-hormonal activation, which increased nighttime BP.^{115,116} In addition, an increase in systolic BP by 4.3 mmHg was observed in elderly Japanese subjects for every 5 lux increase [1 lux = 1 lumen/m²; 1 lumen is equivalent to approx. 0.1 W (bulb) or 0.01 W (LED) in outdoor nighttime light pollution].⁶ Prolonged day length decreases the uptake of fatty acids from triglyceride-rich lipoproteins and glucose from plasma. Longer daily light exposure also affects body adiposity by attenuating brown adipose tissue activity and decreasing sympathetic input. Misalignment in circadian rhythm due to

altered gene expression of the cellular and peripheral clock components promotes obesity, hyperglycaemia, and defective beta-cell function, all of which ultimately lead to insulin resistance, impaired glucose metabolism, and type 2 diabetes mellitus.¹¹⁷

Mechanisms

Light pollution has a major impact on fauna, flora and human disease, primarily due to a disrupted circadian rhythm and impaired sleep.¹¹⁶ The circadian clock is an evolutionarily conserved mechanism that controls 10%–15% of our genes and plays a central role in physiology, regulation of stress hormone release.¹¹⁵ Meta-analysis data show that artificial light at night increases the risk of allergic diseases, such as asthma, allergic rhinitis, and skin allergies (HR 1.36; 95% CI 1.16–1.60),¹¹⁸ all of which are positively correlated with a higher incidence of CVDs. Additionally, chronic light pollution is strongly associated with poor sleep quality, which increases the risk of hypertension, AF, and other cardiac conditions.¹¹⁹

Chemical pollution (including water and soil pollution)

Background

Healthy soil and clean water are essential for human health, supporting food production, ecosystems, and water storage. Soil is crucial in providing safe, nutritious food and is also a vital carbon sink, helping mitigate climate change. However, approximately 3.2 billion people are affected by soil degradation,¹²⁰ and over 2 billion people lived in water-stressed countries in 2021;¹²¹ these numbers are expected to rise due to climate change and population growth. However, chemical pollution in water and soil is rarely addressed in global health strategies focused on NCD prevention. Metals, pesticides, and synthetic chemicals are the primary pollutants contaminating soil and water, with devastating consequences for human health.¹²² Contaminants like lead, cadmium, arsenic, copper, and zinc commonly found in polluted soils and water supplies, are associated with increased risk of CVDs.¹²³ Pesticides disrupt endocrine functions, leading to chronic conditions such as diabetes and arterial hypertension. Despite these alarming numbers, in 2020 alone, 208 million tonnes of harmful chemicals were produced in the EU, with no decrease since 2004.¹²⁴ Developing countries and newly industrialized regions bear the brunt of chemical pollution, accounting for over 90% of pollution-related deaths. Research is frequently finding associations between specific chemical exposures and health conditions, at levels below recommended guidelines.¹²⁵ For example, Lead pollution alone is not simply a soil issue, but involves multiple exposure routes—including air, water, food, and legacy infrastructure (e.g. pipes)—as highlighted by Lanphear *et al.*¹²⁶ who emphasize that lead remains a complex and globally pervasive contaminant, with toxic effects even at very low blood levels.¹²⁷

Plastic waste

A growing concern is the impact of plastic waste, especially micro- and nanoplastics (MNPs), on soil and water systems, entering the food chain.¹²⁸ Plastics persist in the environment and slowly break down into smaller particles, which may have toxic effects, although current evidence on human health impacts remains limited. Global plastic production has increased exponentially in the past seven decades, from <2 million tons in 1950 to 500 million tons in 2024, with production expected to double by 2040 and triple by 2060.¹²⁸

Links with cardiovascular disease

A WHO document reported that lead pollution alone was associated with 21.7 million years of life lost due to disability and death and 4.6% of the global burden of CVD.¹²⁷ Recent work further underscores the global significance of lead exposure: Larsen and Sánchez-Triana¹²⁹ estimated millions of CV deaths worldwide attributable to lead, highlighting both hypertension-mediated and non-hypertension-mediated pathways. The American Heart Association also issued a scientific statement recognizing lead, cadmium, and arsenic as important risk factors for CVD via mechanisms, including oxidative stress, endothelial dysfunction, and myocardial toxicity.¹³⁰ Lanphear *et al.*¹²⁶ emphasized that even low-level chronic lead exposure

can increase BP, promote atherosclerosis, and elevate CV mortality, confirming the need to consider multiple exposure routes.

Coronary artery disease

A strong link between exposure to chemicals, metals, and pesticides and the development of atherosclerosis was described.¹²² Lead exposure increases the risk of carotid atherosclerosis and CV mortality, even at low blood levels. Cadmium is associated with arterial stiffness, PAD, and greater carotid intima-media thickness.¹³¹ Arsenic promotes endothelial dysfunction, oxidative stress, and inflammation, fostering plaque formation.¹³² Mercury, particularly methylmercury, has been associated with accelerated atherosclerosis and increased carotid artery thickness; however, epidemiologic evidence is complex and often confounded by seafood intake, which provides protective omega-3 fatty acids, making causal inference challenging.¹³³ Pesticides and endocrine-disrupting chemicals also contribute to vascular disease. Organophosphate pesticides induce oxidative stress, endothelial dysfunction, and inflammation, promoting arterial plaque progression.¹³⁴ Per- and polyfluoroalkyl substances (PFAS) are associated with elevated cholesterol and carotid atherosclerosis.¹³⁵ Bisphenol A (BPA) and polychlorinated biphenyls (PCBs) correlate with arterial plaque formation and increased vascular inflammation.^{136,137}

Clinical studies concerned with the proatherosclerotic effects of MNPs are beginning to emerge. MNPs can induce oxidative stress, inflammation, and pyroptosis, which would be expected to exacerbate atherosclerosis.¹²² A pivotal 2024 multicentre observational study examined the link between MNP exposure and CV events in patients with carotid artery stenosis.¹³⁸ Among 257 patients, polyethylene was detected in 58% carotid plaques and polyvinyl chloride in 12%. Patients with plaques containing MNPs had a 4.5-fold increased risk of MI, stroke, or all-cause mortality. These findings suggest that MNPs may accumulate in human vasculature in similar ways to other inhaled nanoparticles, potentially exacerbating CVD risk.⁷³ However, given the cross-sectional design of these studies and limited prospective evidence, reverse causality cannot be excluded. It is possible that MNPs become trapped within pre-existing atherosclerotic plaques without contributing directly to plaque development or progression. Experimental challenges remain in regards to the detection and identification of MNPs in biological specimens, as well as the source of exposure of MNPs.¹³⁹

Heart failure

Metallic pollutants (arsenic, lead, cadmium, copper, and mercury)^{134,140} as well as endocrine-disrupting and persistent chemicals can indirectly contribute to HF by inducing ischaemic damage, arrhythmias, diabetes, or hypertension.¹²² In the Strong Heart Family Study, urinary arsenic was associated with an increase in left ventricular wall thickness and left ventricular hypertrophy, both conditions associated with HF development.¹⁴¹ Higher urinary cadmium was positively associated with HF incidence in patients who participated to the Strong Heart Study (HR 1.39; 95% CI 1.01–1.94),¹⁴² and among the non-smokers of the Danish Diet, Cancer and Health cohort study (HR 1.5; 95% CI 1.2–1.9).¹⁴³

Cardiovascular risk factors

Arsenic and methylmercury impair endothelial function, increasing the risk of diabetes and hypertension.¹²² Cadmium promotes insulin resistance, and obesity.^{131,144} Organophosphate pesticides interfere with glucose metabolism, promoting obesity, and type 2 diabetes.¹²² BPA, phthalates, and PFAS disrupt hormone function, contributing to hypertension and dyslipidaemia.¹²²

Mechanisms

Exposure to various chemicals, metals, and pesticides significantly contribute to hypertension, obesity, and diabetes through oxidative stress, inflammation, and metabolic disruption.¹²² Metals such as lead, cadmium, arsenic, mercury, as well as essential trace metals like copper and zinc, interfere with vascular and metabolic functions. Alterations in copper and zinc homeostasis have been linked to oxidative stress, inflammation, impaired lipid metabolism, and endothelial dysfunction, potentially contributing to atherosclerosis and other CV outcomes. Lead exposure is linked to hypertension by disrupting calcium signalling and endothelial function.¹²² Contaminants like lead, cadmium, and arsenic, commonly found in polluted soils, food and water supplies, lead to endothelial dysfunction, oxidative stress, and inflammation, significantly increasing the risk of CVD.¹²² Many of these pollutants impact circadian rhythms, increasing the risk of CVD.^{137,145} Microplastics can accumulate in the body, triggering oxidative stress and inflammation linked to heart disease and other chronic illnesses.¹²²

Special consideration for vulnerable and susceptible communities

Children and the elderly

The Lancet Commission on pollution and health reported that children and the elderly are specifically vulnerable (i.e. greater exposure) or susceptible (i.e. biological susceptibility) to chemical pollution in the soil, water, and air by displaying increased patterns of disability-adjusted life years and deaths during young and old age for the different pollution sources.⁵ The underlying reasons can be the rapidly developing organ systems, the insufficient defence capacity and higher exposure to body mass ratio for infants, the accumulation of damage over lifetime, and the decline of defence capacity during the ageing process in the elderly.¹⁰

Patients with cardiovascular disease

Patients with CVD are particularly vulnerable to environmental risk factors, such as air pollution, noise, and heat, due to pathophysiological changes and disrupted biological pathways.¹⁴⁶ In balance, so far, only few studies reported an incremental CV risk, e.g. a steeper increase in risk of recurrent events/complications by noise exposure in patients with established CAD.¹⁴⁷ An additive effect was observed for endothelial dysfunction by noise in CVD patients.¹⁴⁸ Pallikadavath's review showed that ischaemic patients appear to have the strongest association with ventricular arrhythmias for both gaseous and particulate pollution. Results in the general population or in patients with implantable cardioverter defibrillator were less consistent.⁵⁷

Sex

Environmental risks exhibit sex and gender differences related to physiologic, cultural, and socioeconomic factors. Women, especially those with lower socio-economic status, show a higher disease burden due to climate change.¹⁴⁹ Overall, women are more likely to experience fatal CAD because of PM exposure¹⁵⁰ and show more pronounced arterial wall thickening related to ambient PM levels.⁴¹ In terms of air pollution and stroke incidence, while most studies report similar outcomes for men and women, a Swedish study showed that women had a higher risk (HR 2.16; 95% CI 1.15–4.06)¹⁵¹ and a Polish study suggested younger women were particularly susceptible.⁴⁸ Several studies have demonstrated that women, especially older women, are at greater risk of dying in heat waves. Speculatively, this evidence might be related to the fact that older women often present either with more pronounced arterial hypertension or with a left ventricular phenotype characterized by smaller cavity size and hypertrophy and are therefore at greater risk during heat waves.¹⁵²

Of note, particularly women in LMICs spend more time at home, where indoor air pollution from solid fuel burning is common, especially in settings without adequate ventilation and where cooking is often performed over open fires or gas stoves. On the other hand, also certain male-dominated occupations may lead to greater exposure (e.g. taxi drivers, truck drivers, outside workers, coal mine workers among others).

Pregnancy

Pregnancy is a critical window of susceptibility, during which environmental exposures can have both immediate and long-term effects on maternal and child health, potentially mediated by epigenetic modifications. Air pollution, especially fine PM and traffic-related emissions, has been associated with low birth weight, preterm birth, and impaired placental function.^{153,154} Similarly, chronic exposure to environmental noise—such as road and aircraft noise—can increase maternal stress and BP, potentially affecting foetal development.¹⁵⁵

Extreme heat exposure during pregnancy, increasingly frequent due to climate change, has been linked to increased risks of preterm birth, stillbirth, and low birth weight (odds ratio per 1°C ~1.05 for pre-term, per meta-analysis).¹⁵⁶ Mechanisms may include maternal dehydration, systemic inflammation, oxidative stress, and impaired placental perfusion. Contaminated soil and water, particularly with metals such as lead or arsenic, pose established risks for maternal hypertension, neurodevelopmental deficits in the child, and other pregnancy complications. In addition, chemicals including endocrine-disrupting compounds (e.g. BPA, phthalates, PFAS) have been associated with gestational diabetes, pre-eclampsia, altered foetal growth patterns, and potential long-term metabolic programming in offspring. Also, paternal lead exposure increases the risk of congenital anomalies, linking reproductive health to the socioeconomic status.¹⁵⁶

Socio-economically disadvantaged regions and populations

Environmental stressors play a crucial role in underprivileged communities, including minority groups.¹⁵⁷ Low-income communities often face disproportionate exposure to toxins, air

pollution, poor water quality, excessive noise, overcrowding, inadequate housing and educational facilities, and unhealthy work and food environments, all of which are linked to a higher incidence of CVD.^{158,159}

Lifestyle-related CV risk factors add to environmental risk, particularly in populations of low socio-economic status.¹⁶⁰

Moreover, chronic stress from economic insecurity, war time exposure, violence, unstable employment, and poor living conditions contributes to high BP, higher serum cholesterol,¹⁶¹ and greater body mass index¹⁶¹—all major CV risk factors. Historical evidence from studies on World War II Resistance veterans further supports this link, showing that exposure to extreme trauma was associated with a high prevalence of posttraumatic stress disorder as well as an excess of CV risk factors, particularly vital exhaustion and adverse living conditions.¹⁶² These findings suggest that early-life psychosocial stressors can heighten sensitivity to environmental stressors and contribute to long-term CV vulnerability. In line with this, an ongoing study in Ukrainian female refugees is testing the hypothesis that trauma exposure and psychological stress may accelerate BP elevation and the progression of CVD.¹⁶³

Similarly, adults with a history of sexual violence have been shown to carry a higher risk of CVD compared with those without such experiences, underlining the need to integrate sexual violence prevention and support into CV risk reduction strategies.¹⁶⁴

Finally, socioeconomic status profoundly shapes mental health, with conditions such as anxiety and depression further amplifying CV risk.¹⁶⁵ These factors make disadvantaged populations more susceptible to environmental risk due to depleted defence mechanisms and limited access or financial constraints to adequate healthcare and prevention strategies. Depleted defence mechanisms refer to the physiological and psychological erosion of stress-buffering systems, including chronic inflammation, impaired immune responses, reduced antioxidant capacity, and dysregulated activity of the hypothalamic–pituitary–adrenal axis. These biological alterations heighten susceptibility to air pollution, noise, heat, and chemical exposures.^{166,167} Nationwide analysis showed that long-term exposure to ambient air pollution increased CV mortality, while greater greenness, more favourable socioeconomic conditions and higher utilization of mental health care mitigated pollution-related risks, underscoring the joint impact of environmental and social determinants on CV vulnerability.¹⁶⁸

The role of gene–environment interactions in cardiovascular health

Gene–environment interplay represents a central axis in CV pathobiology, whereby genetic susceptibility interacts with social and environmental exposures to shape CV health and the risk of CVD. (Figure 1) Social determinants of health (SDOH)—including socioeconomic adversity, structural racism, psychosocial stress, and environmental toxicants—modulate biological pathways through both direct gene–environment interactions and epigenomic reprogramming.^{4,10} Among epigenetic mechanisms, DNA methylation (DNAm) constitutes the most extensively characterized regulatory layer: exposure-dependent alterations in cytosine and guanine site methylation influence transcriptional activity in pathways critical to inflammation, vascular remodelling, neuroendocrine stress responses, and cardiometabolic regulation. DNAm reliably captures cumulative exposures, such as smoking, chronic

stress, and neighbourhood deprivation, and emerging evidence indicates that DNAm risk scores may refine CVD risk stratification by integrating long-term environmental and genetic influences. In addition to DNAm, histone modifications and non-coding RNAs (including microRNAs and long non-coding RNAs) have been implicated as key regulatory layers through which environmental exposures modulate inflammatory, vascular, and cardiometabolic pathways, with some changes potentially persisting across generations. However, despite these advances, current knowledge remains constrained by profound underrepresentation of global populations in genomic and epigenomic datasets, limiting the portability and accuracy of polygenic and DNAm-based risk models. Furthermore, the absence of longitudinal, repeated-measures designs restricts the ability to elucidate temporal dynamics, causal mechanisms, and life-course-sensitive periods through which SDOH shape the epigenome and CVD risk.¹⁶⁹

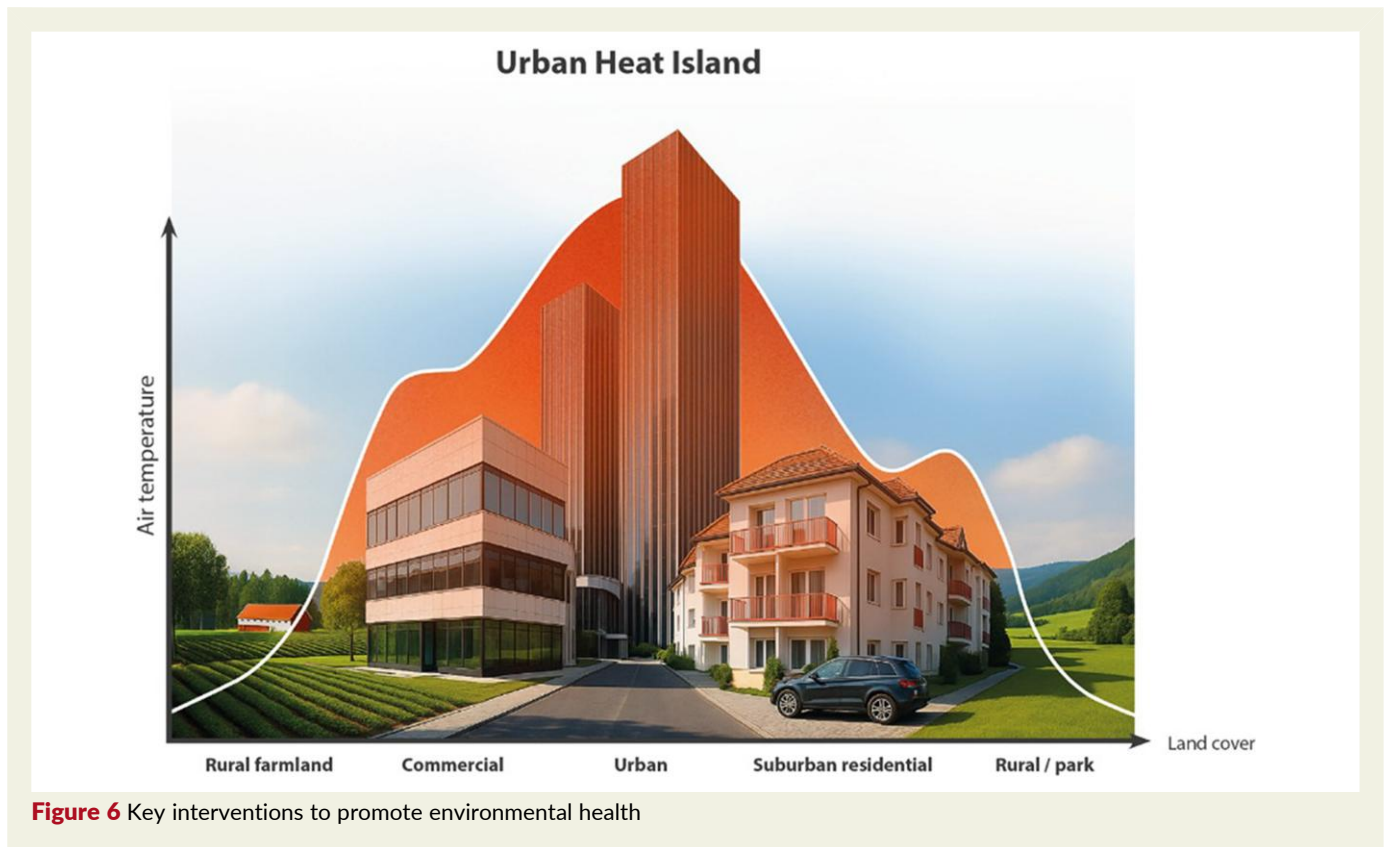
Interventions to mitigate environmental risk factors on cardiovascular health

Despite the amount of available evidence, there is only one CV guideline that provides recommendations with levels of evidence regarding air pollution: the 2021 ESC Guidelines on CVD prevention in clinical practice. These Guidelines state: ‘Recommendations for policy interventions at the population level: putting in place measures to reduce air pollution, including reducing PM emissions and gaseous pollutants, reducing the use of fossil fuels, and limiting carbon dioxide emissions, are recommended to reduce CVD mortality and morbidity (Class I, Level C)’.¹⁷⁰ To reduce environmental CVD risk mitigation measures have high priority such as emission regulation and cross-sectoral urban planning. Reducing lifestyle risks has a benefit on their own and may also help to modify environmental risk (Figure 6).

European legislation providing setting-based (structural) prevention

Clean air regulation urgently requires political action to ensure healthier living environments. While substantial steps have been taken, including the setting of air pollutant limit and target values by EU in 2008, much more remains to be done to protect population health. In 2021, the WHO published new Global Air Quality Guidelines with substantially more stringent values to reflect the current evidence demonstrating health effects below previous reference values.¹⁷¹ In October 2024, the EU finally adopted a revised Ambient Air Quality Directive with stricter pollutant limits expected to be met by 2030.¹⁷² Other provisions include access to justice for all Europeans and the possibility of compensation for health damage resulting from non-compliance with regulatory limits.

To meet these ambitious goals, structural prevention must extend beyond legal thresholds to encompass transport, industry, agriculture, and indoor environments. Among transport-related measures, Euro 6/7 engine standards have played a central role in reducing vehicular nitrogen oxides and particulate emissions. Yet, real-world driving emissions, especially from diesel vehicles, often exceed laboratory test values, calling for tighter on-road



compliance enforcement and accelerated electrification of vehicle fleets.¹⁷³

Urban interventions such as low emission zones (LEZs) have proven effective in improving air quality and reducing CV hospital admissions. When combined with investments in public transport, walking, and cycling infrastructure, LEZs can deliver substantial health and climate benefits.¹⁷⁴

On a global scale, the proposed Fossil Fuel Non-Proliferation Treaty aims to phase out fossil fuel production just and equitably. Such a transition would bring significant air quality gains, especially in cities and industrial regions, and help mitigate CV risks related to pollution exposure.¹⁷⁵ However, current EU regulation lags behind emerging air pollution threats. For example, ammonia emissions from agriculture contribute to secondary particulate matter formation but remain poorly regulated. Likewise, indoor sources of air pollution—such as cooking fumes, cleaning products, flame retardants, and microplastics—are not adequately addressed, despite growing evidence of their health impacts.¹⁷⁶ Policies must evolve to consider cumulative exposures across settings, particularly in disadvantaged populations.

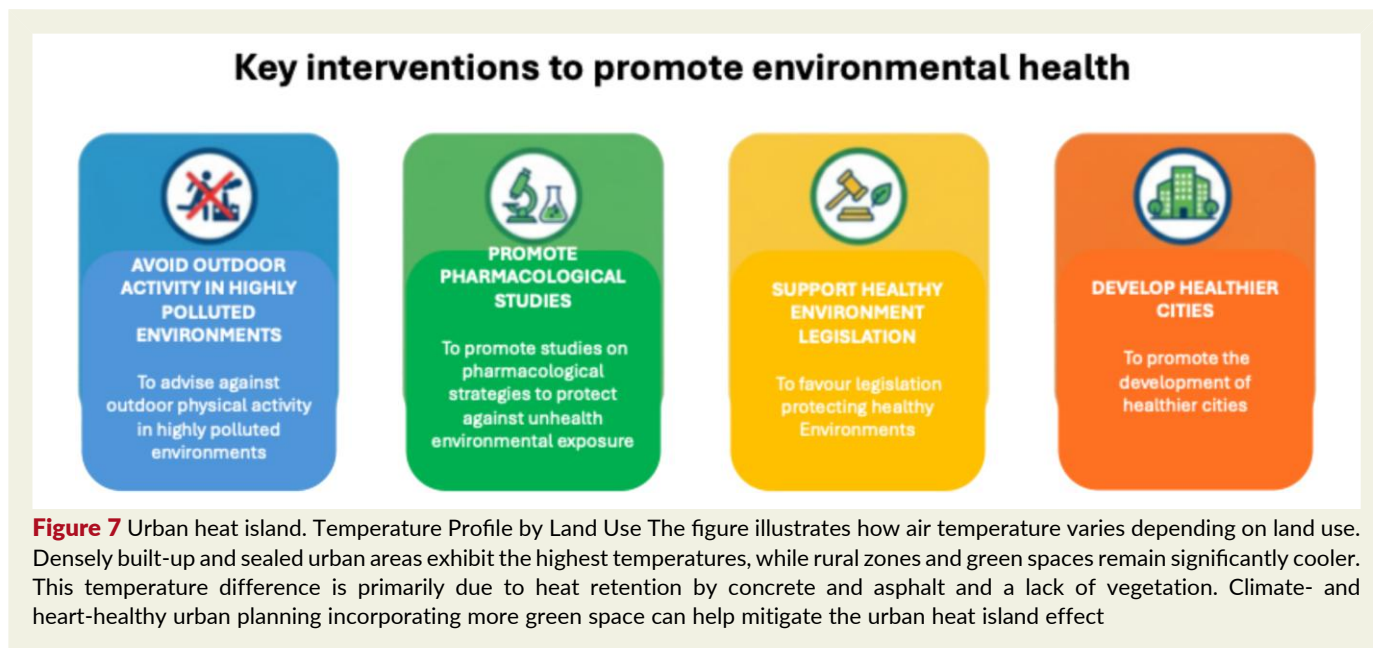
Furthermore, while environmental guidelines exist for metals (e.g. lead, cadmium) and chemicals like PFAS, phthalates, and BPA, these frameworks are often fragmented, outdated, or weakly enforced. A more coherent, precautionary approach to chemical regulation is urgently needed, ensuring protection across the lifespan and across exposure routes.¹⁷⁷

Finally, structural prevention must not ignore global health equity. In many LMICs, indoor air pollution from the use of solid fuels, such as wood, charcoal, or dung, remains a major yet preventable cause of CVD. Chronic exposure to household smoke

contributes to systemic inflammation, hypertension, and stroke, especially among women and children. Fortunately, cost-effective interventions such as clean cookstoves and improved ventilation exist and could dramatically reduce the burden of disease—if backed by international policy and funding mechanisms.

Physical activity

The ESC Guidelines on CVD prevention in clinical practice recommends 150–300 min of moderate or 75–150 min of vigorous-aerobic physical activity per week for adults.^{170,178} Sustained physical activity yields the most significant benefits for heart function, circulation, and stress reduction. However, increased physical activity increases breathing rate and depth, therefore, physical exercise, such as jogging, soccer, tennis, and alike, in areas of high air pollution could increase the amount of air pollution delivered to the alveoli. Accordingly, research suggests that the benefits of physical exercise could be reduced in highly polluted environments.¹⁷⁹ Furthermore, two different studies examining commuting by walking or cycling found that exposure to low PM_{2.5} levels reduced the risks of CAD and cerebrovascular disease.^{180,181} However, these protective effects disappeared at high PM_{2.5} levels (>54 µg/m³). Similar findings were observed among outdoor workers, such as farmers, who experienced increased cerebrovascular disease risk in areas with high air pollution.¹⁸² Recommendations to temporarily lower exertion levels, or move physical activity indoors, on high-pollution days or away from pollution sources should be balanced with the need to encourage exercise when and where air quality is favourable.^{183,184}



Pharmacological mitigation

Most research focuses on air pollution, where several agents could prevent or reverse CV effects. While few in number, studies in animals have shown preventive effects of natural antioxidants or inflammatory compounds, beta-blockers, statins, and angiotensin-converting enzyme inhibitors.¹⁸⁵ Clinical studies have also explored interventions aimed at reducing CV damage from environmental exposures. For example, metal chelation therapy has been investigated in the TACT2 trial,¹⁸⁶ and folic acid supplementation has been studied to mitigate the effects of air pollution on CV outcomes.¹⁸⁷ While results have been mixed and often show limited clinical benefit, these trials provide important insights into potential pharmacological strategies.

For other environmental stressors, AMP-kinase activation with exercise, fasting, and pharmacological interventions may reduce the CV effects for noise exposure in a mouse model.¹⁸⁸ Use of β_1 -selective beta-blockers and antiplatelet drugs may mitigate heat exposure effects,¹⁸⁹ although a study also reported that in patients with CVD, particularly those with HF who take diuretics and beta-blockers, heat might result in severe volume depletion and, potentially, syncope, and cardiogenic shock.⁸ Pharmacological agents used in emergencies, such as accidental occupational exposure, have not been considered for preventing chronic environmental exposure. The evidence remains limited and inconsistent, requiring broader studies across various exposures, therapies, and CV outcomes.

Heart-healthy cities

Currently, 55% of the world's population lives in cities, which is projected to rise to 68% by 2050 according to the United Nations.¹⁹⁰ While urban living has health benefits, including better access to healthcare and public services,¹⁹¹ it also increases exposure to high temperature, air, soil, and water pollutants (Figure 7) due to concentrated industry, traffic, and waste.⁶ Improved urban design can reduce climate change impacts¹⁹² and improve CV health.

Dense urban areas with limited green spaces often suffer from poor air quality¹⁹³ due to more sources of emissions, and lesser removal by foliage. Not only do trees and plants help filter air pollutants but also they absorb CO₂ and reduce environmental temperature. Urban 'heat islands', characterized by vast concrete areas and limited vegetation, can lead to premature mortality and heat-related illnesses, including CAD, stroke, and poor mental health, particularly among the vulnerable ones. Urban design often prioritizes vehicles over pedestrians and cyclists, contributing to sedentary lifestyles promoting CVD, in addition to the production of pollutants from the vehicles themselves.^{6,194} Additionally, dense urban areas have higher noise pollution, overcrowding increases stress, and urban runoff contaminates water sources.¹⁹⁵

Urban planners should address these issues by promoting sustainable, zero-pollution and health-conscious cities.¹⁹⁶ Strategies include expanding green spaces, improving public transport, promoting pedestrian and cycling infrastructure, and implementing stricter pollution controls.¹⁹⁶ Active transport (walking and cycling) instead of powered transport has a double benefit—it reduces particulate production and brings health benefits. Furthermore, innovative models like car-free zones, the '15-minute city' (all essential services are within a 15-min walk or bike ride), and 'superblocks' aim to reduce pollution and promote physical activity.⁶ The Heart-Healthy City reduces CV risk by promoting green spaces, improving air quality, encouraging walking and cycling, and reducing car dependence and transportation noise. Tackling health inequalities must be central to sustainable urban development, particularly in LMICs. With targeted international funding and policy support, millions of CV deaths could be prevented globally.¹⁹⁷

Limitations of current evidence

Despite the growing body of research linking environmental risk factors to CVD, significant limitations remain. Most evidence obtained in healthy subjects, patients with CVD or the population

at large is based on associative and epidemiological studies reporting associations between environmental exposures and adverse CV outcomes. Instead, direct causality is seldom established outside of experimental settings. A major challenge is the difficulty in separating simple associations from genuine causal mechanisms, given the complexity and overlap of environmental exposures and biological pathways. Well-designed longitudinal studies and robust causal-inference methods are therefore needed to better clarify temporal relationships and underlying mechanisms. Animal and *in vitro* experiments provide insights that not necessarily translate to human health, especially in terms of concentration of pollutants and exposure levels used. In many epidemiological studies, identification of which pollutant/stressor out of the mixture/exposome is driving adverse effects is challenging. This can be addressed by toxicological studies in laboratory models and controlled human exposures, although sourcing individual chemical exposures that are relevant to real-world scenarios hinders progress. Counter to this, many studies also fail to consider simultaneous exposure to multiple environmental stressors, which likely act synergistically. Another limitation is the reliance on estimates and modelling. Exposure assessments, such as satellite-based air pollution measurements and noise modelling, are subject to uncertainties that may bias risk estimates. For example, quantifying a single air pollutant in an environment with dozens of coexisting and correlated pollutants can be challenging, and measurement errors may lead to misclassification, attenuated risk estimates and inaccurate causal interpretation. Recently, it was demonstrated that the bias in epidemiological studies related to assessing long-term exposure at the residential address only is likely small although improvements in exposure assessment especially for large populations was deemed to be useful.¹⁹⁸ The advantage of geospatial environmental exposure modelling is the fact that differential misclassification is unlikely. Using sophisticated personal exposure measurements instead of modelling may, however, introduce high random variability and confounding if not carefully designed.¹⁹⁹

Global burden assessments often depend on complex statistical models rather than direct observational data, leading to potential inaccuracies in risk quantification. Study heterogeneity also further complicates interpretation. Geographic, socioeconomic, and genetic differences, along with varied methodologies, hinder generalizability. Longitudinal data remain scarce, making it difficult to assess cumulative lifetime exposure effects. Even where they do exist, the volume and complexity of data can make interpretation challenging (e.g. what time point of exposure does represent the greatest period of susceptibility for CVD that manifest only to many years later in the future?).

Gaps in knowledge and research needs

- (1) It is currently unclear what level of evidence exists for each environmental risk factor related to CVDs. Introducing a gradient or ranking of evidence robustness would better identify existing knowledge gaps and future research needs.
- (2) There is a limited understanding of the specific mechanistic pathways through which many environmental factors influence specific CVDs. While air pollution is currently mentioned in some clinical guidelines (albeit briefly), noise

pollution is not yet accepted as a CV risk factor in current guidelines, nor are many of the other environmental risk factors discussed. Mechanistic investigation is needed to support specific public health questions such as which specific stressors are most harmful, who is most at risk and how to develop/assess targeted interventions. Specifically, natural experiments are largely missing and could provide an important research need.

- (3) Current methodologies may not capture individual variability or cumulative multi-stressor effects. Repeated assessments of exposure to environmental stressors throughout an individual's lifespan would be advantageous. Continuous tracking via wearable sensors and mobile applications offers potential, but integrating this data into meaningful health insights remains challenging.²⁰⁰
- (4) More research is needed to elucidate further the additive or synergistic effects of exposures, as well as in vulnerable groups, such as children, women, the elderly, and those with acute or chronic diseases.
- (5) While genetic predisposition plays a role in CV risk, the interaction between genetic factors and environmental exposures has barely been explored, and could enhance our ability to identify high-risk populations and tailor preventive strategies.^{4,201} Statistical challenges further complicate CV exposome research to address the cumulative effects of multiple co-exposures common in urban environments. Recent work on the Danish National Cohort shows that lack of green space, and exposure to fine and ultrafine PM as well as traffic noise can result in cumulative risk increase for diabetes,²⁰² stroke,²⁰³ and MI.²⁰⁴ Improved statistical techniques are needed to better reflect real-world multi-stressor scenarios.¹⁰
- (6) High-resolution exposure maps for traffic noise are lacking in most countries,^{10,205} and even air pollution monitoring by ground-measurement stations is surprisingly limited, especially in low- or middle-income continents, such as Latin America, Asia, and Africa, among others.²⁰⁶
- (7) There is a need for clinical and epidemiological studies mimicking of randomized controlled trials (RCTs) of different exposures, and the ability of interventions that may alleviate the CV effects of environmental exposures. Even where such studies exist (e.g. assessment of the ability of facemasks or air purifiers to prevent the CV effects of air pollution²⁰⁷) the studies tend to be small and use only 'subclinical' measures of CV parameters such as BP and heart rate variabilities, rather than 'hard' CV endpoints like mortality or hospital admissions. Such studies are logistically and financially demanding to perform at sufficient scale to have the power to detect long-term effects on these endpoints. However, if realized they would provide the compelling support for the causality of epidemiological associations, aid development of clinically relevant CV guidelines for environmentally relevant exposures, as well as the all-important assessment of the efficacy of the intervention itself. At present there is compelling evidence that fossil fuels should be prioritized, as these represents one of the foremost air quality strategies, which could save 5.1 million lives/year, as well as have benefits for climate change.²⁶ However, it is clear that multiple interventions across all sectors are required to reduce the toll of air pollution and, most likely, other environmental stressors. Given the difficulties in performing RCTs in this field, also analysis

of real-world data (RWD) could be considered. Accumulating evidence suggests that appropriately conducted RWD studies have the potential to support regulatory decisions in the absence of RCT data. Further work may be needed to better illustrate the settings in which RWD analyses can robustly and consistently match the results of RCTs and the settings in which they cannot match them.

- (8) Emerging data indicate that CV healthcare activities—including cardiac imaging, pharmaceutical prescribing, and in-hospital care such as cardiac surgery—generate substantial environmental impacts in terms of CO₂ emissions.²⁷ However, systematic and comparable assessments of the carbon footprint of common CV procedures are largely lacking. Methodologically robust studies are required to quantify these impacts, identify major emission drivers, and evaluate mitigation strategies, with the ultimate aim of integrating sustainability considerations into clinical pathways without compromising effectiveness or patient safety.

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Supplementary data

Supplementary data are not available at [European Heart Journal](#) online.

Declarations

Disclosure of Interest

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Data Availability

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