Ambient Air Quality and Cardiovascular Health:
Translation of Environmental Research for Public Health and Clinical Care

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Air pollution is intuitively associated with respiratory effects, but evidence has emerged over the past few decades that the cardiovascular effects of air pollution can be much more adverse and represent a greater public health burden. In this article, we present background on the sources, exposures, and health effects of air pollution and discuss the potential for intervention strategies in the health care system to help reduce individual and population exposure and the attendant risk from the cardiovascular effects of air pollution.

Air pollution is ubiquitous and adversely affects overall population health. Most primary care practitioners are generally aware of the association between exposure to gaseous air pollutants such as ozone and sulfur dioxide (SO_2) and exacerbation of asthma among children and adults. Yet, only about 40% of physicians report ever having talked to their patients at risk from air pollutants about limiting air pollutant exposure [1]. Even fewer health care professionals discussed limiting air pollutant exposure among patients with cardiovascular disease despite the evidence emerging over the past few decades linking both short-term and long-term exposures to air particle pollution to adverse cardiovascular health effects including myocardial infarction, heart failure, stroke, and arrhythmia [2].

In 1997, the US Environmental Protection Agency (EPA) set new standards for fine particulate matter less than 2.5 μm in diameter ($PM_{2.5}$) based in part on evidence showing increased mortality and hospitalizations attributed to cardiovascular disease. At present, the evidence shows that short-term and long-term exposures to inhaled $PM_{2.5}$ cause adverse cardiovascular health effects and mortality [3]. Increasing awareness of the health effects of air pollution among health care professionals and their at-risk patients and providing actionable information to reduce exposures is likely to improve health outcomes. To this end the *Million Hearts*® Initiative, the joint effort of the US Centers for Disease Control and Prevention (CDC) and the Centers for Medicare and Medicaid Services (CMS) to prevent 1 million heart attacks and strokes, now recommends increasing awareness of the health effects of air particle pollution among health care providers and at-risk patients [4].

Sources of Air Pollution

Air pollution consists of gases and particles present in the atmosphere that are produced from many sources [5]. Motor vehicles, power plants, and industrial facilities are important sources of both gases and particles across the United States, according to EPA's National Emissions Inventory (see Table 1). Particulate matter is also generated through mechanical processes (eg, brake and tire wear) and by particle-forming chemical reactions of atmospheric gases [5]. These gases can be inorganic (eg, SO_2), organic (eg, benzene), and either anthropogenic or naturally occurring (eg, volatile organic compounds emitted from vegetation). Oxidized emissions from combustion of vegetation attendant to uncontrolled wildfires and prescribed burns are a comparatively important source of particulate matter in the southeastern United States [6], including North Carolina. The amount of burned acreage more than doubled between 1986-90 and 2011-15, and changing temperature and precipitation patterns are likely to intensify future fire seasons in many parts of the country [7]. Recent national emissions estimates indicate that wildland fires represent 15-20% of directly emitted $PM_{2.5}$ (see Table 1). Prescribed and agricultural burning accounts for approximately another 15% of direct $PM_{2.5}$ emissions [8].

While we can be proud of the reductions in emissions and improvements in US air quality since the passage of the Clean Air Act and the creation of the EPA in 1970, work remains to be done to ensure clean air for all. Source emissions have declined nationally by more than 70% since 1970, yet many communities remain affected by local sources [9]. Understanding the impact of air pollution on public health requires consideration not just of air pollution sources, but also factors that affect exposure to air pollution.

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TABLE 1.
2014 National Emissions Inventory Showing Direct Emissions of Common Air Pollutants

	Emissions, thousand tons/year					
Pollutant	**On-road vehicles**	**Power plants**	**Industrial facilities**	**Wildfire**	**Other**	**Total**
$PM_{2.5}$	163	182	577	886	4,106	5,392
PM_{10}	304	234	1,073	1,046	16,679	18,198
NO_x	4,879	1,770	2,308	119	3,519	12,596
SO_2	28	3,244	1,033	71	298	4,874
CO	24,437	731	2,951	10,487	27,040	65,646

Particulate matter, PM; nitrogen oxides, NO_x; sulfur dioxide, SO_2; carbon monoxide, CO.
Source. https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data.

Exposure to Air Pollution

People are exposed to air pollution both outdoors and indoors. Most people spend 80-90% of their time indoors, whether at home, school, or work, and outdoor exposure accounts for the majority of air pollution exposure for pollutants that do not infiltrate indoors substantially, such as ozone [10]. $PM_{2.5}$, however, does infiltrate indoors, resulting in indoor concentrations that are 50-70% of outdoor concentrations [11]. This is a substantial contribution to exposure to outdoor-generated $PM_{2.5}$. Personal activities are another factor contributing to exposure variation among individuals. For example, spending time on or near busy roadways (such as during commuting to work or school) increases exposure to traffic-related air pollution. Living near an industrial facility may also increase air pollution exposure. Exercising in polluted environments compounds exposure by increasing inhaled dose, further raising the potential for health effects.

Cardiovascular Effects of Air Pollution in North Carolina

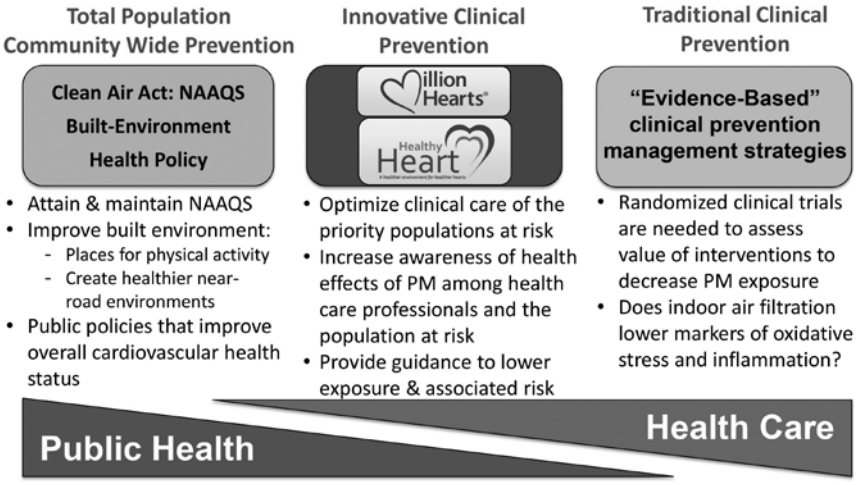
Many large epidemiology studies, along with smaller panel studies, human challenge studies, and basic toxicological research, have provided unequivocal evidence that both short-term and long-term exposure to ambient air particulate matter is associated with adverse cardiovascular health effects. Over the last several years, thousands of your patients have contributed to the state-of-the-science describing the association between air pollutant exposure and cardiovascular disease as participants in longitudinal national clinical studies such as the Women's Health Initiative (WHI), the Atherosclerosis Risk In Communities (ARIC) Study, and the Multi-Ethnic Study of Atherosclerosis and Air Pollution (MESA Air) [12-15], as well as the predominantly North Carolina-based Catheterization Genetics (CathGen) study [16-17]. Ancillary research within these parent studies investigated the impact of ambient air $PM_{2.5}$ on cardiovascular health effects, and the findings attest to the relevance of this issue to the citizens of North Carolina. The WHI study showed that long-term exposure to $PM_{2.5}$ among post-menopausal women was associated with altered glucose homeostasis, cardiovascular and cerebrovascular events, and death from cardiovascular disease [12, 13]. The ARIC study showed that residents living within 300 meters of a major road were more likely to develop coronary heart disease [14]. MESA Air measured coronary calcium, as well as other biological measures, repeatedly over a period of 10 years for the purpose of answering the question, "Is long-term exposure to air pollution associated with progression of cardiovascular disease? [15]." MESA Air showed that long-term exposure to outdoor $PM_{2.5}$ and NO_2 was associated with the accumulation of coronary artery calcium, as well as a number of other anatomic, biochemical, and physiological changes in the heart and blood vessels, a conclusion also reached by McGuinn and colleagues in the CathGen cohort who showed that long-term exposure to ambient $PM_{2.5}$ among North Carolinians is associated with the severity of coronary artery disease and the likelihood of having a myocardial infarction in the previous year [16]. Proximity of one's residence to major roads was associated with an increased risk of increased fasting plasma glucose in women, hypertension, and peripheral vascular disease [17-18].

Short-term biochemical and physiological changes have also been observed in the CathGen Cohort in response to ambient air pollution. Brief exposures to outdoor $PM_{2.5}$ and ozone were associated with metabolic changes indicating incomplete fatty acid oxidation suggesting dysfunction of the mitochondria [19].

Translating Environmental Health Research into Public Health and Clinical Action

Finding solutions to complex contemporary population health challenges such as chronic cardiovascular disease will require an integrated approach that involves public policy, state and local public health, and systems-level changes that affect communities and clinical practice [20]. Yet, largely overlooked for years has been the potential value of improving the quality of the environment as a means of decreasing the burden of cardiovascular disease. As shown in Figure 1 at the level of the population, attainment of the National Ambient Air Quality Standards as required by the Clean Air

FIGURE 1.
Intersection of Environmental and Public Health Policies with Clinical Interventions to Achieve Enhanced Clinical Prevention, Lower Exposures, and Reduced Risk



Note. Modified from [26].

Act serves as a primary and secondary prevention strategy for heart and vascular disease. Local improvements in air quality across the United States over the last several decades have resulted in increased longevity, a benefit that is largely attributed to reductions in ambient air $PM_{2.5}$ concentrations [21-24]. Through hard work and partnership with local, state, and federal agencies North Carolina has reduced emissions and improved the quality of its air. Yet, for those individuals who are particularly sensitive to the adverse health effects of air pollution—namely older adults, those with chronic heart and lung disease, and children—additional actions to avoid exposure are prudent when air quality is poor.

As recommended by the CDC and CMS in *Million Hearts®*, health care professionals can play an important role in increasing awareness among the patient populations at highest risk about actions they can take to reduce exposures [2, 25]. Such an approach represents an innovative clinical prevention program to decrease the public health burden of air particle pollution among those at highest risk (see Figure 1).

The most important aspect of the *Million Hearts®* action plan is the focus on modifying the key risk factors for heart and vascular disease. Achieving their goals will have a collateral benefit of shrinking the portion of the population at risk from the adverse effects of air pollution by improving the overall health of the population. This will entail optimizing both the number of people meeting ideal risk factor parameters and the use of evidence-based medication to prevent progression and clinical events associated with lung and heart disease.

While such recommendations to limit exposures are prudent for those at higher risk for heart attack and stroke, at the present time randomized controlled clinical trials testing whether interventions that decrease exposure—such as in-home high-efficiency particle filtering (HEPA) of indoor air or N-95 respirators that decrease clinical event rates—are lacking (see Figure 1). Yet, many studies do show that reducing exposure improves biochemical measures of inflammation and other biomarkers associated with heart disease during air pollution events. Additionally, a modeling study suggests that instituting in-home HEPA filtering among those at higher risk would reduce clinical events and be cost effective [26, 27].

Greater Engagement of the Health Care System

Increasing awareness among patients who are most likely to benefit from the avoidance of air particle pollution will require greater engagement of the many professionals who contribute to population health. Health care professionals—including health care practitioners, nurses, leaders of professional organizations, health care institutions, and health insurers who deliver health care, health education, or pay for health care and preventive services—play an important role. Increasing environmental health literacy and incorporating environmental health messages into clinical management of the at-risk individual is anticipated to support value-based health care and wellness for individuals and communities.

The 2014–2016 ConsumerStyles surveys showed health care professionals are missing the opportunity to identify and counsel those at higher risk about actions they can take to decrease exposure and potentially reduce adverse health effects of air pollution [28]. Only about one-half of US adults with chronic lung disease were aware of air quality alerts, and those with heart disease were not aware. Only 3% of patients discussed guidance to reduce exposure with a health professional [28]. The results tell us that opportunities exist to raise awareness of air quality alerts and behavior changes to reduce air pollution exposure among

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adults at risk of worsening lung and heart disease. One of the best sources of up-to-date information about air quality and health is the AirNow website. In partnership with the North Carolina Department of Environment and Natural Resources, EPA's Office of Air and Radiation supports the AirNow website (www.airnow.gov), which is the internet portal for valuable information about local air quality and educational material for public health and health care professionals. The information includes a continuing education course titled "Particle Pollution and Your Patients' Health."

Likewise health care systems and health insurers can take a more active role in increasing awareness among their patients and communities to promote healthy behaviors and avoidance of exposure among those at highest risk. Regional and city planners and city councils have opportunities to contribute through decisions made to determine the siting of housing, schools, places of business, child and eldercare facilities, as well as acute and chronic health care facilities.

Wildfire Smoke Events Highlight the Value of Translational Environmental Health Science

Extreme air pollutant events attributed to wildfires are frequent in North Carolina and contribute significantly to impaired air quality, clinical symptoms, increased health care utilization, and health care costs [29-34]. Based on the best available evidence, wildfire emissions contribute to all-cause mortality and worsen asthma, chronic lung disease, and childhood respiratory disease [33]. Wildfire smoke also exacerbates bronchitis and pneumonia [40, 44]. Less well-documented are effects on the heart, blood vessels, and birth outcomes. Some populations are more sensi-

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tive to the adverse health effects of smoke from wildfires. These include children, older adults, and those with chronic disease [33,34]. The impact of emissions from a peat fire in Eastern North Carolina provided new insights into the effects of air particle pollution on emergency department visits [31].

The public health and clinical burden of wildland fire emissions is anticipated to grow over the next 2 decades as the size of the populations vulnerable to exposure to wildland fire smoke and sensitive to the health effects of wildfire smoke grows. The growth of the at-risk population is commensurate with the changing demographics of North Carolina where over the next 2 decades the population is expected to increase by approximately 2 million, more than half of whom will be aged 65 and older [35]. Moreover, most of the growth is anticipated to be in the major urban centers, thereby bringing larger numbers of at-risk individuals into proximity with wildland fires as the wildland-urban interface increases and as forest health declines.

Recently EPA's Office of Research Development created the *Smoke Ready Toolbox for Wildfires* to facilitate communication with public health officials, health care professionals, and the public [36]. This website provides the resources health professionals can use to educate the public about the risks of smoke exposure and actions people can take to protect their health.

Conclusion

Individual health behaviors, as well as the social and economic conditions and environmental quality of one's community, strongly influence health and well-being. From its inception, the EPA has recognized the important contribu-

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tion of environmental quality to public health and produced research products informing the foundation of the National Ambient Air Quality Standards, policies, and regulations that have supported the improvement in environmental quality and population health. Yet, the complexity of contemporary environmental and health challenges necessitates greater cooperation between environmental health, public health, and the health care system. The successful collaboration among CMS, CDC, and the EPA within the *Million Hearts*® population health initiative illustrates one example of a national cross-agency effort to incorporate environmental factors into clinical medicine and prevention. NCMJ

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References

1. Mirabelli MC, Damon SA, Beavers SF, Sircar KD. Patient-provider discussion about strategies to limit air pollution exposure. Am J Prev Med. doi:10.1016/j.amepre.2018.03.018.
2. Newby DE, Mannucci PM, Tell GS, et al. Expert position paper on air pollution and cardiovascular disease. Eur Heart J. 2015;36(2):83-93b.
3. US Environmental Protection Agency. Provisional Assessment of

Recent Studies on Health Effects of Particulate Matter Exposure. Washington, DC: US Environmental Protection Agency; 2012.
4. Million Hearts. Particle Pollution and Heart Disease. Million Hearts website. https://millionhearts.hhs.gov/tools-protocols/tools/particle-pollution.html. Accessed July 7, 2018.
5. Finlayson-Pitts B, Pitts J. Chemistry of the Upper and Lower Atmosphere: Theory, Experiments, and Applications. San Diego, CA: Academic Press; 2000.
6. Liu J, Russell LM, Lee AKY, McKinney KA, Surratt JD, Ziemann PJ. Observational evidence for pollution-influenced selective uptake contributing to biogenic secondary organic aerosols in the southeastern U.S. Geophys Res Lett. 2017;44(15):8056-8064.
7. US Environmental Protection Agency. Climate Change Indicators: Wildfires. US Environmental Protection Agency website. https://www.epa.gov/climate-indicators/climate-change-indicators-wildfires. Accessed July 7, 2018.
8. US Environmental Protection Agency. Air Emissions Inventories: 2014 National Emissions Inventory (NEI) Data. US Environmental Protection Agency website. https://www.epa.gov/air-emissions-inventories/2014-national-emissions-inventory-nei-data. Accessed July 7, 2018.
9. US Environmental Protection Agency. Air Quality – National Summary. US Environmental Protection Agency website. https://www.epa.gov/air-trends/air-quality-national-summary. Accessed July 7, 2018.
10. Hazlehurst MF, Spalt EW, Curl CL, et al. Integrating data from multiple time-location measurement methods for use in exposure assessment: the multi-ethnic study of atherosclerosis and air pollution (MESA Air). J Expo Sci Environ Epidemiol. 2017;27(6):569-574.
11. Sarnat SE, Coull BA, Ruiz PA, Koutrakis P, Suh HH. The influences of ambient particle composition and size on particle infiltration in Los Angeles, CA, residences. J Air Waste Manage Assoc. 2006;56(2):186-196.
12. Miller KA, Siscovick DS, Sheppard L, et al. Long-term exposure to air pollution and incidence of cardiovascular events in women. N Engl J Med. 2007;356(5):447-458.
13. Whitsel EA, Quibrera PM, Christ SL, et al. Heart rate variability, ambient particulate matter air pollution, and glucose homeostasis: the environmental epidemiology of arrhythmogenesis in the women's health initiative. Am J Epidemiol. 2009;169(6):693-703.
14. Kan H, Heiss G, Rose KM, Whitsel EA, Lurmann F, London SJ. Prospective analysis of traffic exposure as a risk factor for heart disease: the atherosclerosis risk in communities (ARIC) study. Environ Health Perspect. 2008;116(11):1463–1468.
15. Kaufman JD, Adar AD, Barr RG, et al. Association between air pollution and coronary artery calcium in the USA (the multi-ethnic study of atherosclerosis and air pollution): a longitudinal cohort study. Lancet. 2016;388(10045):696-704.
16. McGuinn LA, Ward-Caviness CK, Neas LM, et al. Association between satellite-based estimates of long-term PM2.5 exposure and coronary artery disease. Environ Res. 2016;145:9-17.
17. Ward-Caviness CK, Kraus WE, Blach C, et al. Associations between residential proximity to traffic and vascular disease in a cardiac catheterization cohort. Arterioscler Thromb Vasc Biol. 2018;38(1):275-282.
18. Ward-Caviness CK, Kraus WE, Blach C, et al. Association of roadway proximity with fasting plasma glucose and metabolic risk factors for cardiovascular disease in a cross-sectional study of cardiac catheterization patients. Environ Health Perspect. 2015;123(10):1007-1014.
19. Breitner S, Schneider A, Devlin RB, et al. Associations among plasma metabolite levels and short-term exposure to PM2.5 and ozone in a cardiac catheterization cohort. Environ Int. 2016;97:76-84.
20. Wright JS, Wall HK, Briss PA, Schooley M. Million Hearts – Where population health and clinical practice intersect. Circ Cardiovasc Qual Outcomes. 2012;5(4):589-591.
21. Fann N, Kim SY, Olives C, Sheppard L. Estimated changes in life expectancy and adult mortality resulting from the declining PM2.5 exposure in the contiguous United States:1980-2010. Environ Health Perspect. 2017;125(9):097003-1-097003.
22. Fann N, Alman B, Broome RA, et al. The health impacts and economic value of wildland fire episodes in the U.S.: 2008-2012. Sci Total Environ. 2018;610-611:802-809.
23. Corrigan A, Becker MM, Neas LM, Cascio WE, Rappold A. Fine particulate matters: the impact of air quality standards on cardiovascular mortality. Environ Res. 2018;161:364-369.
24. Zigler CM, Choirat C, Dominici F. Impact of national ambient air quality standards nonattainment designations on particulate pollution and health. Epidemiology. 2018;29(2):165-174.
25. Ritchey MD, Loustalot F, Wall HK, et al. Million Hearts: description of the national surveillance and modeling methodology used to monitor the number of cardiovascular events prevented during 2012-2016. J Am Heart Assoc. doi: 10.1161/JAHA.117.006021.
26. Auerbach J. The 3 buckets of prevention. J Public Health Manag Pract. 2016;22(3):215-218.
27. Fisk WJ, Chan WR. Effectiveness and cost of reducing particle-related mortality with particle filtration. Indoor Air. 2017;27(5):919-920.
28. Mirabelli MC, Boehmer TK, Damon SA, et al. Air quality awareness among U.S. adults with respiratory and heart disease. Am J Prev Med. 2018;54(5):679-687.
29. Larsen AE, Reich BJ, Ruminski M, Rappold AG. Impacts of fire smoke plumes on regional air quality, 2006-2013. J Expo Sci Environ Epidemiol. 2018;28(4):319-327.
30. Fann N, Alman B, Broome RA, et al. The health impacts and economic value of wildland fire episodes in the U.S.: 2008-2012. Sci Total Environ. 2018;610-611:802-809.
31. Rappold AG, Stone SL, Cascio WE, et al. Peat bog wildfire smoke exposure in rural North Carolina is associated with cardiopulmonary emergency department visits assessed through syndromic surveillance. Environ Health Perspect. 2011;119(10):1415-1420.
32. Rappold AG, Fann NL, Crooks J, et al. Forecast-based interventions can reduce the health and economic burden of wildfires. Environ Sci Technol. 2014;48(18):10571-10579.
33. Reid CE, Brauer M, Johnson FH, Jerrett M, Balmes JR, Elliott CT. Critical review of health impacts of wildfire smoke exposure. Environ Health Perspect. 2016;124(9):1334-1243.
34. Wettstein ZS, Hoshiko S, Fahimi J, Harrison RJ, Cascio WE, Rappold AG. Cardiovascular and cerebrovascular emergency department visits associated with wildfire smoke exposure in California in 2015. J Am Heart Assoc. doi:10.1161/JAHA.117.007492. PubMed PMID: 29643111.
35. Tippett R. NC Demographic Trends Through 2035: Report to House Select Committee on Strategic Transportation Planning and Long Term Funding Solutions. Chapel Hill, NC: Carolina Demography; 2016. https://www.ncleg.net/documentsites/committees/house2015-172/2-22-16_Meeting/Demographic_Trends_through_2035.pdf. Accessed July 7, 2018.
36. US Environmental Protection Agency. Smoke Ready Toolbox for Wildfires. Washington, DC: US Environmental Protection Agency; 2018. https://www.epa.gov/sites/production/files/2018-04/documents/smoke_ready_toolbox_for_wildfires_tagged.pdf. Accessed July 7, 2018.