Air Pollution Increases Depression Risk among Young Women: Possible Natural World Resiliencies

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Abstract

Air pollution may contribute to depression risk, but prospective incidence studies of risks and resiliencies for young women have not been undertaken. We analyzed prospective cohort data from the Australian Longitudinal Study on Women's Health combined with air pollution exposure data from the National Pollutant Inventory. We followed 7,804 women without baseline depression who were aged 21-26 at baseline for up to 14 years. Cox proportional hazards regression models were used to examine associations between greater air pollution exposures and incident depression controlling for covariates. Air pollutants included carbon monoxide, nitrogen oxides, particulate matter (PM2.5 and PM10) and sulphur dioxide, measured in inverse-distance weighted exposures in kilograms occurring within 10 kilometers of participants' residences. Results showed that total air pollution exposure decile was significantly associated with incident depression (HR=1.039, 95% CI 1.018-1.060). Exposures were also significantly related to depression when total exposure, and each of the five individual air pollutants, was measured in quartile. Multiple other sociodemographic and behavioral variables were independently associated with depression. Women who possessed behavioral resiliencies (non-smokers and non-obese) or socioeconomic resiliencies (higher education and adequate income) were not at elevated depression risk when exposed to high amounts of air pollution. Multiple depression risks, and the presence of behavioral and socioeconomic resiliencies, suggest multiple leverage points to reduce depression risk among young women with air pollution exposures, including effects to improve air quality and improve human connection to the natural environment, especially for women who experience lifestyle or socioeconomic disadvantages.

Key words: depression; air pollution; women; resiliency

INTRODUCTION

Depression is an illness with serious personal and societal consequences. Depression increases risk of suicide and other premature death, increases health services utilization and costs, impairs functional ability, and increases risks for subsequent illnesses such as diabetes, cancer and heart disease (McLaughlin, 2011). The prevalence of depression is higher among adults aged 20-59 compared to older adults, with the highest rates among women during this age period (Brody, Pratt, & Hughes, 2018). In Australia, the prevalence of affective disorders including depression peaks at ages 25 through 44 (ABS, 2007).

Mental well-being or illness is determined by multiple interacting genetic, biological, social and psychological forces (Chang, Pan, Kawachi, & Okereke, 2016; Herrman, Saxena, Moodie, & Walker, 2005). Among young women, risks or correlates of depression include poor socioeconomic conditions, life stress, sleep disturbance, early motherhood and being a single parent, childhood trauma, drug use, domestic violence, poor physical health, and genetic influences (Galea et al., 2007; Gladka, Rymaszewska, & Zatonski, 2018; Herrman et al., 2005; Jackson, Sztendur, Diamond, Byles, & Bruck, 2014; Kendler, Gardner, Neale, & Prescott, 2001; Maercker, Michael, Fehm, Becker, & Margraf, 2004; Melchior et al., 2007; Patton et al., 2002; Powers, Duffy, Burns, & Loxton, 2016). Smoking might be a consequence of depression, but can also contribute to depression through its physiological impacts (Fluharty, Taylor, Grabski, & Munafo, 2107; Taylor et al., 2014). Similarly, the relationship between obesity and depression may be bi-directional (Jung et al., 2017; Martin-Rodriguez, Guillen-Grima, Auba, Marti, & Brugos-Larumbe, 2016; Tyrrell et al., 2018).

Exposure to environmental pollutants has also been recognized as a contributing factor to depression. Previous studies have found associations between air pollution and depression but results have been inconsistent (Gladka et al., 2018; Xue, Zhu, Zheng, & Zhang, 2019). There are few prospective cohort studies of depression onset in association with air pollution, and most studies have focused on older adults (Kioumourtzoglou et al., 2017). Importantly, no prospective study of incident depression in association with air pollution has been conducted with young women, despite high rates of depression onset in this population.

The link between air pollution and depression is thought to operate through oxidative stress and pro-inflammatory mechanisms (Baithwaite, Zhang, Kirkbride, Osborn, & Hayes, 2019; Mohankumar, Campbell, Block, & Veronesi, 2008). Inflammation contributes to chronic activation of the hypothalamic-pituitary-adrenal axis which is linked to depression (Liu, Ho, & Mak, 2012). Pro-inflammatory cytokines may also directly impair central nervous system function (Liu, Ho, & Mak, 2012). Particulate matter air pollution also induces oxidative stress with subsequent neurotoxic effects that may increase depression risk (Mohankumar, Campbell, Block, & Veronesi, 2008). Beyond its direct physiological impacts, air pollution may serve as a marker of environments with greater disconnection from the natural world (e.g., more industrialized, less green space); these natural connections have themselves been linked to reduced depression risks (Beyer et al.; 2014; Korpela, Stengard, & Jussila, 2016.)

The current study has two primary objectives. The first is to provide a prospective examination of whether exposure to air pollution increases risk of incident self-reported depression among young women with control for covariates. The second is to examine whether air pollution-depression associations are mitigated by the presence of other favorable characteristics, or whether air pollution-depression associations are robust to countervailing influences. We are interested in examining favorable influences that are potentially modifiable through behavior change or policy intervention. Behaviorally, we focus on smoking and weight control because of evidence of their contributions to depression risk. From a policy perspective, we focus on education and income because poor socioeconomic conditions also contribute to depression risk. If mitigating effects are present, they may serve as leverage points for efforts to reduce the impacts of air pollution under circumstances where the pollution itself is unavoidable, including leverage points that attend to improvements in the quantity, quality, and accessibility of the natural world.

METHODS

Design

The design of the study was a prospective cohort analysis that combined data from the Australian Longitudinal Study on Women's Health (ALSWH) with National Pollutant Inventory (NPI) data on air pollutants. Five air pollutants were examined including carbon monoxide (CO), nitrogen oxides (NOx), particulate matter with aerodynamic diameter <2.5 μ/m^3 (PM2.5) and <10 μ/m^3 (PM10), and sulphur dioxide (SO_2). Survey items from the ALSWH measured self-reported diagnosed depression and covariates as described below.

Participants

Women were recruited to participate in a long-term prospective study of women's health in Australia (Brown & Dobson, 2000). The current study was limited to women in a cohort born in the years 1973-1978, who were age 18-23 at recruitment and age 21-26 when baseline for the current study was established as described below. Women were randomly selected from the national Medicare database, which covers the entire Australian population, with over-selection for rural and remote areas. About 41.5% of women in the current study cohort who were invited to take part agreed (ALSWH, 2018). Response rates to follow-up surveys varied from 57-69%

(ALSWH, 2018). Participants were demographically similar to the general age-specific Australian population but over-represented women who were married, employed or had higher education, and under-represented immigrant women (ALSWH, 2019). Surveys were conducted by mail, with the addition of an online option beginning in 2013. Ongoing efforts were made to encourage continued participation through telephone and email contacts. The study was approved by the university institutional review boards and all women gave written informed consent to participate.

Women were followed every three years for seven total survey administrations. We established the baseline for the current study with the second survey in the young cohort because that is when participants were first queried about the presence or absence of diagnosed depression. The item used to identify baseline depression was, "Have you ever been told by a doctor that you have depression (not postnatal) in the last four years?" with responses of yes or no. Women who said 'yes' to this item at the second survey were excluded from analysis. All baseline covariates were also measured at the second survey.

The sample numbered 9,688 at the second survey when depression was first queried. Women were excluded if they provided no data over the follow-up surveys (N=765) resulting in a sample of 8,923. Of these, 1,028 women were excluded because they reported baseline depression or had missing data (N=91) on the depression item, resulting in a final baseline sample of 7,804 women without depression. The mean length of follow-up was 10.9 years (SD=4.1) with a maximum of 14 years.

Outcome

The outcome was first occurrence of a self-report of doctor-diagnosed depression in surveys 3 through 7. The item used was, "In the past three years, have you been diagnosed or treated for depression (not postnatal)?” with responses of yes or no. Self-reported depression has been shown to have adequate agreement with clinical interview, with sensitivity of 74% and specificity of 81% (Sanchez-Villegas, et al. 2008).

Exposures

Pollution emission data were taken from the National Pollutant Inventory (NPI). This is a publicly available database maintained by the Australian Department of the Environment and Energy (NPI, 2018). The raw data provide kilograms (kg) of chemical emissions from each of thousands of individual facilities across the country for each year 1998 to 2018. Sites are coded as to latitude and longitude. There are a total of 93 pollutants included in the NPI. The current study was limited to five common air pollutants (CO, NOx, PM2.5, PM10, and SO_2). Air pollution emissions included point emissions, fugitive emissions and total (point plus fugitive) emissions. Fugitive emissions are releases not confined to a stack, duct or vent, including equipment leaks, emissions from bulk handling or processing, windblown dust and other industrial processes (NPI, 2012). Point emissions and total air emissions were highly correlated and we limited our analysis to total emissions. Emissions were measured via direct sampling or measurement, mass balance calculations, fuel analysis or other engineering calculations, or production-based emissions factors.

We found the total kg release over time at each facility for each pollutant. Next, we measured the distances between the latitudes and longitudes of each facility site for each site that was located within 10 kilometers (km) of the latitude and longitude of each ALSWH survey respondent’s residence. These calculations might change from one survey administration to the next for a given survey participant if she moved, or if sites became active or inactive. We weighted each exposure by inverse distance by dividing the kg amount of the release by the km distance between the survey respondent residence and the site. For each person we then found the sum inverse distance-weighted kg of their exposure to each pollutant across years and sites. Emissions originating greater than 10 km from the participant were not included in the exposure estimates. To maintain participant confidentiality requirements, we categorized each exposure measure into percentiles such that each exposure category for each pollutant had 10 or more participant observations.

Percentiles were converted to deciles for the proportional hazards models to make interpretation easier. Exposure was expressed as deciles and quartiles in alternative analyses. We also examined quartiles of exposures for each pollutant separately.

Covariates

Other exposure variables were based on status at survey 2: married or in a de facto relationship (yes/no); education (less than 12 years, 12 years, some post-high school training, or university degree or higher); income adequacy (difficulty getting by with available income, yes/no); body mass index (BMI) category (kg/m^2 grouped into normal (<25), overweight (25 to <30), or obese (30 or more)); smoking category (never, former, levels of current smoking <10, 10-19, or 20 or more cigarettes per day); physical activity (lowest quartile vs higher based on amounts of walking, moderate activity and vigorous activity converted to metabolic equivalents); alcohol consumption (none or low drinker with less than weekly bingeing vs risky drinking or more frequent bingeing); other drug use (yes/no); life events based on yes/no responses to 37 items describing events the participant had experienced within the last 12 months (divided into low/high at the 75th percentile); perceived stress (none, low, or moderate/high based on a reliable and valid 10-item scale categorized into three previously established stress levels (Harris et al., 2017)); single mom (participants who reported not having a partner and having children living at home); and physical health measured by physical component standardized score (PCS from the SF-36 (RAND, 2019), grouped into lowest quartile vs higher).

Analysis

Descriptive statistics for the sample were calculated. We compared characteristics between participants who developed self-reported depression compared to those who did not, testing differences using chi-square for categorical variables and unpaired two-tailed t-tests for continuous variables.

Cox proportional hazards regression models were then used to examine the association between air pollution exposures and incident depression controlling for covariates. Women were followed until the first occurrence of reported depression, loss to follow-up, or the end of follow-up, whichever came first. Missing observations on categorical covariates were retained by including missing as a category. We examined alternative specifications of exposure (decile, quartile, dichotomized). We also conducted a spline analysis to examine possible non-linear associations, using the total pollution exposure score with knots at the 2^{nd}, 4^{th}, 6^{th} and 8^{th} deciles.

We explored the effects of two possible mitigating factors on air pollution-depression associations. Each of these two factors was examined using two of the covariates. One factor was behavioral – weight control and smoking. The other addressed socioeconomic (SES) conditions – education and income. We examined whether air pollution associations were robust to behavioral and SES conditions, or whether the negative associations between air pollution and depression were rendered non-significant by favorable circumstances in the other factors. We did this by dichotomizing each of the exposures (air pollution at the 25^{th} percentile, current smoking (yes/no), obesity (yes/no), income difficulties (yes/no) and university or higher education (yes/no)). The variables were expressed this way so that all exposures for the stratification analyses could be treated dichotomously with higher scores being positive. Then, keeping the dichotomized air pollution measure in each Cox model, along with other covariates not part of the stratification, we stratified by the presence or absence of the possible mitigating factors jointly (non-smoking and non-obese; high education and adequate income) or singly. Analyses were conducted using SAS Software version 9.4.

RESULTS

Sample characteristics are presented in Table 1. Over the follow-up, 1,685 (21.6%) women reported incidence of diagnosed depression. Women who reported depression, compared to those who did not, were more likely to be married at age 21-26, be a single parent, have low education, greater income difficulties, higher stress and more life events, heavier smoking, drug use other than alcohol, higher BMI, less physical activity, lower physical health component score, and greater air pollution exposure.

With control for covariates in the Cox proportional hazards regression model, air pollutants (CO, NOx, PM2.5, PM10, SO2) combined into a single exposure score in deciles was significantly associated with incident depression (HR=1.039, 95% CI 1.018-1.060). Table 2 shows results for the full model when the total air pollution exposure score was measured in quartiles. Air pollution HRs increased with increasing exposure and were significant for the third and fourth quartiles relative to the first quartile referent. Other significant associations with depression included married at baseline or marital status missing, being a single mom, obesity, heavy baseline smoking, low physical activity, stressful life events, higher perceived stress, drug use, and poor physical health. Higher alcohol consumption, university or higher education, and higher income were associated with lower depression risk.

Table 3 shows effects of each of the five individual pollutants in quartile. All were significantly associated with depression risk. Compared to the low exposure quartile referent, PM10 was significant for all 3 quartiles, NOx for the third and fourth quartiles, and all others for the fourth quartile.

When we examined mitigating factors via the stratification analyses, we first confirmed that the air pollution exposure score was still significantly associated with incident depression when it was expressed as better air quality and dichotomized into the lowest three quartiles of exposure versus the top quartile (HR=0.84, 95% CI=0.76-0.94). The stratification results showed that higher air pollution exposure was not significantly associated with depression if the participant was both a non-smoker and non-obese (HR=0.92, 95% CI=0.80-1.06) (Table 4). Being a non-smoker by itself, or being non-obese by itself, did not render the air pollution associations non-significant. Having both high education and adequate income also rendered the air pollution association non-significant (HR=0.89, 95% CI=0.69-1.15), as did having high education by itself, but having adequate income by itself did not.

The spline analysis of non-linear associations indicated that the linear term was strongly significant (chi-square=14.3, df=3, $p<.003$), and the non-linear term was not (chi-square=0.8, df=2, $p<.66$). A graph of the spline analysis is provided in Figure 1; visual examination of the graph suggests that exposure effects might be stronger in the upper deciles, but only the linear term was significant.

DISCUSSION

The results of the study indicated that women aged 21-26 without reported baseline depression were at significantly higher risk of developing depression over an average 10.9 year follow-up period in association with greater air pollution. Significant associations were observed for total air pollution exposures expressed in deciles and quartiles, and in quartiles of exposures for each of five individual pollutants including CO, NOx, PM2.5, PM10 and SO_2.

Stratification analyses with selected covariates suggested that the risk of depression could be substantially reduced even under conditions of high air pollution exposures when women had other positive countervailing influences. Specifically, women who did not smoke and maintained healthier weight, and women with better income and educational resources, did not have significantly elevated depression risk when exposed to higher air pollution.

The observation that depression in young women resulted from numerous exposures indicates that multiple intervention points may reduce risk. We should endeavour to improve air quality to improve mental health in addition to the demonstrated physical health benefits of cleaner ambient air (Ancona et al., 2015; Lipfert, 2018; Schraufnagel et al., 2019; Turner et al., 2011). But other interventions may be considered to reduce depression in this high risk population such as educational support programs, providing support for young moms, stress management, promoting healthy lifestyles (smoking prevention, diet and exercise), and drug use prevention.

Furthermore, interventions directed to natural environments may be fruitful. By these interventions we refer to efforts to improve the breadth, quality, and accessibility of natural places, especially for most vulnerable members of society. We also refer to improved design of built environments in ways that create less air pollution by reducing reliance on fossil fuel use while also promoting greater human contact with the natural world (e.g., biking and walking trails) (Samet, 2011). Such interventions may have double benefits of improving physical environmental quality and mental health (Sullivan & Chang, 2011). Interactions with nature allow us to more fully experience and actualize ourselves, and provide for us a sense of aliveness, belonging and peace (Davis, 2004). Perhaps ironically, it is our connections to the ‘more-than-human’ world that help to make us more fully human. These powerful emotions and states of being must be in large measure incompatible with simultaneous experiences of depression.

Regarding other variables included in the study, we observed that being married or in a de facto relationship by age 21-26 was associated with greater reported depression risk. Being married generally has been recognized as protective against mental health problems (Frech & Williams, 2007; Thomeer, Umberson, & Pudrovska, 2013), but being married at a young age may serve as a proxy indicator for other psychological, social or economic vulnerabilities that increase depression risk. The lowest levels of marital satisfaction for women occur when women are relatively younger during higher-stress childbearing years (Hirschberger, Srivastava, Marsh, Cowan, & Cowan, 2009), such that marital correlates to depression across longer timespans may yield different findings.

We also observed that greater alcohol use was protective against subsequent depression, contrary to some other research that has identified alcohol use as a risk for depression in young people (Galaif, Sussman, Newcomb, & Locke, 2007). A review by Pedrelli et al. (2016) concluded that young adults with alcohol use disorder, but not other drinking behaviors, had higher risk of major depression. Although alcohol use was associated with reduced depression risk in our study, other forms of drug use were significantly associated with increased risk. Alcohol use among the young adults of legal drinking age in our study may be a reflection of normative, pro-social behavior.

The sources of air pollution considered in the current study included point sources only, not mobile sources. Other research using the National Pollutant Inventory identified the primary sources of air pollution as originating from fossil fuel electricity generating power plants, various forms of mining, and other industrial processes (Tang & Mudd, 2015). In fact, there are hundreds of unique industrial classifications, and thousands of individual sites, that contributed to air pollution (NPI, 2018). Efforts to improve air quality may target major contributors such as fossil fuel power plants, but the findings highlight the role that co-exposures play within the larger exposome concept (Wild, 2012). People in daily life are not exposed to a single chemical or a single pollution source, but face multiple environmental exposures simultaneously and in the context of other social and behavioral risks and resiliencies. Research to understand those complexities holds promise to help guide future policy or behavioral strategies to reduce risks for depression or other illnesses.

Limitations of the study include that depression was based on self-report rather than confirmed diagnosis, although self-report has been found to be reasonably accurate compared to other independent assessments (Holden et al., 2013; Sanchez-Villegas et al., 2008; Smith et al., 2008). Other variables were also based on self-report such as physical activity, smoking and BMI. Covariates were measured at baseline and we did not capture changes that may have occurred after baseline and before depression. Exposures were not measured exactly with respect to surveys conducted at three-year intervals, to the extent that women may have moved early or late in the interval, or more than once; earlier exposures during these intervals will thus be somewhat underweighted and later exposures overweighted, although it is difficult to know if this variation will be random or somehow systematic.

In addition, the five individual measured air pollutants have correlated exposures: a participant exposed to high levels of one pollutant was likely exposed to high levels of others, and we cannot determine which specific pollutant had greater impacts on development of depression, although the results from the quartile analysis suggested that effects from PM10 exposure may have been most telling. PM2.5 was added to the NPI only in 2007 and its effects may be underestimated. Air pollution exposures were averaged over time and we cannot isolate effects from earlier or later exposure. The study was limited to young women in Australia and may not generalize to other populations.

Despite these limitations, the study provides the first prospective cohort analysis of incident depression in association with air pollution exposures in young women. Results are consistent with other research indicating that air pollution is a risk for depression (Gladka et al., 2018; Kioumourtzoglou et al., 2017). Results also suggest that air pollution risks can be attenuated when women possess other resiliencies such as adequate socioeconomic resources or engagement in healthy behaviors. This is not to excuse the negative impacts of air pollution, as many women, especially those in more vulnerable circumstances, do not possess these resources. But they do suggest that other positive steps, including development of green space and promotion of our experience with it, may be taken to reduce depression risk when air quality conditions are not possible for an individual to control.

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Author Disclosure Statement

No competing financial interests exist for any of the authors of the study.

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Figure 1. Spline analysis for association between total air pollution exposure and depression.