Air pollution is associated with elevated HPA-Axis response to stress in anxious adolescent girls

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1. Introduction

Ambient air pollution is one of the leading health risks worldwide [1]. Some of the adverse health effects of air pollution may be mediated through altered stress biology. In fact, continued exposure to air pollution and chronic psychosocial stress affect similar biological processes implicated in health [2], including hypothalamic-pituitary-adrenal (HPA) axis functioning [3]. For example, fine particulate air pollution (i.e., particulate matter <2.5; PM2.5 – air particles smaller than 2.5 μm in diameter) can be inhaled deeply into the lungs and absorbed into the bloodstream, leading to local and systemic inflammation which, in turn, can activate the HPA axis [3]. Smaller PM2.5 particles may also reach the brain via the olfactory nerve and bulb [4,5], potentially affecting neural regions such as the paraventricular nucleus (PVN) in the hypothalamus, which is important for the regulation of HPA-axis and autonomic stress response systems [6,7]. Indeed, experimental research with adults suggests that short-term PM2.5 exposure leads to increases in circulating glucocorticoids, markers of HPA-axis dysregulation [8]. Studies with animals have provided further experimental evidence that exposure to air pollution elevates HPA-axis activation [9]. Chronic or long-term exposure to air pollution may also lead to alterations in HPA-axis functioning, as recent epidemiological work has found evidence that exposure to long-term air pollution is associated with flatter diurnal cortisol slopes in adolescents [10]. Conversely, Hajat and colleagues [11] did not find a link between long-term measures of air pollution and diurnal cortisol in adults, but did find a moderate association between higher levels of nitrogen dioxide and higher cortisol awakening response. Taken together, long-term air pollution may lead to chronic activation of stress response systems [12]. Prior studies, however, have not considered whether air pollution exposure is associated with HPA-axis activation in response to psychosocial contexts that are implicated in health, such as social stress.

Examining air pollution and stress biology is particularly important for research focused on adolescence given that this is a period of both increased biological sensitivity to social stress [13] and heightened...
exposure and vulnerability to ambient air pollution [14]. To date, however, only one study has considered the association between ambient air pollution and acute responses to psychosocial stress in adolescents. Miller and colleagues [15] found that adolescents living in neighborhoods with higher concentrations of PM2.5 (based on long-term estimates of PM2.5) exhibited greater autonomic reactivity (i.e., shift to sympathetic nervous system dominance indexed by lower high-frequency heart rate variability and higher skin conductance level) in response to a social stress task. Importantly, this association was not accounted for by family- or neighborhood-level socioeconomic factors. Chronic exposure to air pollution may have systemic effects on stress biology [12]. Thus, one aim of the present study was to assess whether the association between higher PM2.5 and greater autonomic reactivity to stress in adolescents [15] would also be observed in HPA-axis reactivity to stress in an independent sample.

Although PM2.5 appears to be implicated in stress biology activation and functioning, a growing body of research suggests that some youth are more vulnerable than others to the adverse effects of PM2.5 on health [16, 17, 2, 12]. Psychological factors, particularly those related to the experience of psychosocial stress, may moderate air pollution effects. Psychosocial stress and PM2.5 affect many of the same biological pathways that lead to HPA-axis activation, and thus may compound risk for HPA-axis dysregulation [18, 12]. Indeed, prior studies focusing on other physical measures of health have found that psychosocial risk factors may exacerbate the effects of air pollution on health. For example, Dales and Cakmak [19], found that higher levels of air pollution are associated with higher blood pressure and reduced lung function in children and adolescents who reported more emotional problems. Longitudinal studies have also found evidence that long-term traffic-related air pollution exposure predicts poorer respiratory functioning and more severe asthma, primarily in children who experience more social stress [20, 21]. These findings converge with experimental research with rats suggesting that those exposed to chronic stress are more vulnerable to the adverse effects of air pollution on respiratory functioning [22]. Few studies have considered the interactive effects of air pollution and psychological factors on biological response to a stressful context. Miller and colleagues found that adolescents who reported more severe internalizing symptoms appeared to be particularly vulnerable to the effects of PM2.5 on increased autonomic reactivity to social stress [15]. We do not know, however, whether the interactive effect of PM2.5 and internalizing symptoms on stress reactivity extend to stress-related HPA-axis functioning.

In an independent sample of adolescent girls, we aimed to replicate and extend prior findings from Miller et al. [15] to HPA-axis reactivity to stress. Specifically, we examined (a) whether long-term estimates of PM2.5 are associated with HPA-axis responses to an acute psychosocial stressor; and (b) whether symptoms of anxiety moderate this association. Based on recent work implicating PM2.5 in HPA-axis activation and autonomic reactivity to stress [8, 15], we expected that PM2.5 concentrations would be positively associated with HPA-axis responsivity. Based on the growing evidence suggesting that psychosocial risk factors, including internalizing symptoms [15], may amplify the association between air pollution and pediatric health, we expected that the association between PM2.5 and HPA-axis responsivity would be significantly stronger in girls with higher levels of anxiety.

2. Methods

2.1. Participants

Participants were 130 adolescent girls from the San Francisco Bay Area (mean age = 12.27 years, SD = 1.41) who were part of a larger study (N = 200) on familial risk for depression in adolescent girls [23–25]. Half of the girls were at risk for depression due to having a mother with a history of recurrent depression; the other half of the sample had mothers with no history of depression. All girls had no current or past diagnosis of psychiatric disorder. Girls with complete data were included as participants in the current analyses. Participants were not significantly different from girls who provided incomplete data in terms of age, pubertal development, family income, or neighborhood poverty (all p > .471). This study was approved by the Stanford University Institutional Review Board and all families signed consent and assent forms to participate.

2.2. Measures

2.2.1. PM2.5

Long-term exposure to ambient PM2.5 was estimated using air quality monitoring station data made publicly available on the US Environmental Protection Agency’s Air Quality System online database (http://www.epa.gov/airs). Inverse distance-squared weighting was used to estimate PM2.5 concentrations (µg/m³) at each participant’s home address using data from monitoring stations within 30 miles [26]. These estimates were based on annual average PM2.5 concentrations from the calendar year prior to visiting the laboratory, which included data collected from 2002 to 2010.

2.2.2. Symptoms of anxiety

Miller et al. [15] used the anxious/depressed subscale of the Youth Self-Report [27] to assess the moderating role of internalizing symptoms on the association between PM2.5 and autonomic reactivity. In the current study we did not administer the YSR to participants. Instead, girls reported on their anxiety using the Multidimensional Anxiety Scale for Children (MASC) [28]. The MASC included 39 items that were rated on a 4-point scale ranging from 0 (“never true about me”) to 3 (“often true about me”). Item responses were summed to form an index of overall severity of anxiety symptoms (Cronbach’s α in this sample was .91).

2.2.3. Stress task and cortisol collection

We measured salivary cortisol in response to a social stress task. As described in Gotlib et al. [23]; participants were instructed to refrain from eating or drinking 1 h before arriving at the laboratory. Following a 30-min rest period, participants were given instructions about and participated in the stress task. Participants first completed a 3-min serial subtraction task with an experimenter present. The experimenter interrupted participants when they made a mistake and instructed them to start over. After the serial subtraction task, participants completed a 12-min semi-structured interview designed to induce stress in adolescents by having them talk about stressful situations [29]. After completing the stressor task, participants watched a 30-min neutral video intended to serve as a recovery period.

As described in Gotlib et al. [23]; participants used Sarstedt Salivettes (Sarstedt, Numbrecht, Germany) to provide saliva samples immediately before the stressor, and at 15, 30, and 45 min after the onset of the stressor. Saliva samples were stored in a freezer chest until they could be transferred to and stored in a −20 °C freezer until radioimmunoassay. Cortisol levels were assayed by luminocence immunoassay reagents using a commercial kit from Immuno-Biological Laboratories (Hamburg, Germany), and the assay sensitivity was set at 0.015 mg dl⁻¹. Samples were assayed together in large batches to control for interassay error, and control samples were included to evaluate variability. Average Intra assay coefficients of variation of three saliva pools of the low, medium, and high controls were 2.8%, 10.5%, and 4.8%, respectively. Average inter assay coefficients of the variation of the low, medium, and high controls were 10.9%, 10.5%, and 5.5%, respectively.

We calculated area under the curve with respect to ground (AUCg) and area under the curve with respect to increase (AUCi) [30] to capture total cortisol production and stressor-specific change in cortisol, respectively. AUCg represents both basal cortisol and cortisol reactivity to the stress task (sample 1 cortisol plus changes in cortisol from sample 1 to sample 4). Higher and lower AUCg values should be interpreted as higher and lower total cortisol output, respectively. AUCi represents reactive increases or decreases in cortisol to the stress task (changes in cortisol...
from sample 1 to sample 4 minus sample 1). More positive AUCI values should be interpreted as greater increases in cortisol levels in response to the stress task, whereas more negative AUCI values should be interpreted as decreasing levels of cortisol. Visual observation of the distributions of the cortisol data suggested that AUCG values were positively skewed, whereas AUCI values were more normally distributed. Extreme outlier values for AUCG and AUCI were defined as those values greater or less than the mean by 3 times the interquartile range. This is considered to be a better method for detecting outliers than is using standard deviations, which can miss outliers due to extreme values changing the sample mean and increasing the sample variance [31]. AUCG and AUCI outlier values were winsorized to the next most extreme value before analyses. This winsorization method maximizes power and accuracy by minimizing missing data points while effectively reducing the influence of outlier values [32].

2.2.4. Covariates

Previous analyses with this sample indicated that daughters of mothers with a history of recurrent depression have heightened cortisol reactivity to stress [23]. We included depression risk status as a binary covariate in regression analyses. Other covariates included age, pubertal status, family income, neighborhood-level poverty, and time of day of the first cortisol measurement (seconds since midnight). Pubertal status was assessed using self-reported Tanner stage [33]. Families reported on annual family income before taxes using a 6-point scale ranging from 0 (“less than $10,000”) to 5 (“More than $100,000”). Poverty rate at the neighborhood-level was assessed using data indicating the percent of residents within a given census tract with income less than two times the federal poverty level. The California Office of Environmental Health and Hazard Assessment (OEHHA; https://oehha.ca.gov/calenviroscreen) converted these data into percentiles representing the amount of poverty relative to other census tracts in California.

2.3. Statistical analysis

We conducted two linear regression analyses (one with AUCG and one with AUCI as the dependent variables) to examine whether PM2.5 was associated with cortisol response to stress after controlling for the covariates described above, and whether anxiety symptoms moderated this association. Taken together, each regression model included depression risk status (i.e., maternal history of recurrent depression), pubertal stage, age, time of day of the stressor task (i.e., time of first cortisol assessment), family income, neighborhood poverty, anxiety symptoms, PM2.5, and the interaction between PM2.5 and anxiety as predictors of cortisol response (either AUCG or AUCI). All continuous predictors and covariates were centered prior to forming a interaction term that was the product of PM2.5 and anxiety. Significant interactions were probed by examining the effect of PM2.5 on cortisol response at 1 SD above and below the mean of anxiety symptoms (i.e., high and low anxiety, respectively) adjusting for other covariates [34]. We included False Discovery Rate (FDR) corrected p-values within each regression model to provide more conservative estimates of statistical significance corrected for multiple comparisons [35].

3. Results

Participants (N = 130) were predominantly White (68%) and upper-middle class (mean annual family income = US $75,000-$100,000, range from US $<10,000 to >$100,000). Descriptive statistics are presented in Table 1. Zero-order correlations among predictor variables and covariates are presented in Table 2. Maternal history of recurrent depression was associated with lower family income (r = −0.35, p < .001) and higher neighborhood poverty (r = 0.22, p = .011). Adolescents from wealthier families resided in neighborhoods with less poverty (r = −0.26, p = .003). There were no statistically significant associations among socioeconomic variables, PM2.5, and cortisol metrics (all p > .098).

The full, adjusted regression models testing PM2.5 by anxiety interaction effects on AUCG and AUCI covariates are presented in Table 3. The interaction of PM2.5 and anxiety symptoms significantly predicted both AUCG (β = 0.26, p = .004, 95% CI = 0.08-0.42) and AUCI (β = 0.18, p = .049, 95% CI = 0.00-0.35). Fig. 1 presents the simple slopes of the interaction effects from the regression models adjusted for covariates (anxiety is grouped for visualization purposes). PM2.5 (μg/m³) was positively associated with AUCG and AUCI only for girls who reported more severe anxiety symptoms (i.e., 1 SD above the mean; β = 0.27, p = .023, 95% CI = 0.04-0.50) and β = 0.24, p = .045, 95% CI = 0.01-0.48 for AUCG and AUCI, respectively), but not for girls who reported anxiety symptoms at the sample mean (β = 0.02, p = .863, 95% CI = −0.16-0.19 and β = 0.07, p = .470, 95% CI = −0.12-0.25 for AUCG and AUCI, respectively), or for girls who reported less severe anxiety symptoms (I.e., 1 SD below the mean; β = −0.24, p = .072, 95% CI = −0.49-0.02, and β = −0.11, p = .415, 95% CI = −0.38-0.16 for AUCG and AUCI, respectively). As has been documented previously, daughters of mothers with a history of depression also exhibited greater HPA-axis responsivity as assessed by AUCG; no other predictor or covariate was statistically significantly associated with AUCG or AUCI. Variance inflation factor values for all predictor variables were <1.28, suggesting that our analyses did not have issues related to multicollinearity. Analyses that included neighborhood education and minority status as additional covariates did not change the findings (see Supplement).

In follow-up analyses, we investigated whether cortisol levels at specific samples were accounting for the positive associations between PM2.5 and AUC measures in girls who reported more severe anxiety symptoms. Prior to analyses, we used the same methods to detect and winsorize extreme outliers for cortisol levels that we used for AUC measures. In four linear regression models, we replaced the AUC measures with the cortisol values for sample 1 (before task), sample 2 (after 15 min), sample 3 (after 30 min), and sample 4 (after 45 min) as the dependent variables. Adjusting for covariates, the interaction between PM2.5 and anxiety was significantly associated with cortisol levels at sample 2 (β = 0.34, p = .005), sample 3 (β = 0.31, p = .011), and sample 4 (β = 0.32, p = .009). Probing these interaction effects showed that PM2.5 was positively associated with cortisol levels only for girls who reported more severe anxiety symptoms (i.e., 1 SD above the mean; β = 0.27, p = .023, β = 0.22, p = .058, and β = 0.28, p = .018 for sample 2, 3, and 4, respectively), but not for girls who reported anxiety symptoms at the sample mean (all p > .567), or for girls who reported less severe anxiety symptoms (i.e., 1 SD below the mean; all p > .078). The interaction between PM2.5 and anxiety was not significantly associated with cortisol at sample 1 (β = 0.11, p = .219). Fig. 2 presents the average cortisol

| Table 1 | Descriptive statistics. |
|---|---|---|
| M or % | SD | Range |
| Maternal history of recurrent depression (risk – 1) | 50% |
| Pubertal stage (Tanner stage) | 3.16 | 1.03 | 1.00-5.00 |
| Age (years) | 12.27 | 1.41 | 9.87-14.88 |
| Time of day of stressor task | 13:07 | 2:53 | 8:19-19:25 |
| Family income | 4.08 | 1.31 | 0.00-5.00 |
| Neighborhood poverty rate (percentile) | 17.75 | 18.17 | 0.03-88.46 |
| Anxiety | 37.78 | 15.10 | 8.00-71.00 |
| PM2.5 (μg/m³) | 10.46 | 1.38 | 6.52-14.20 |
| AUCG | 0.65 | 0.51 | 0.07-2.66 |
| AUCI | 0.01 | 0.39 | −0.95-1.05 |

Note. AUCG = area under the curve with respect to ground; AUCI = area under the curve with respect to increase; PM2.5 = particulate matter <2.5 μm. We present the descriptive statistics for time of day of stressor task in hours:minutes for the sake of clarity, but the metric of this variable is seconds since midnight. The family income mean of 4.08 corresponds to $75,000 to $100,000 per year, and the range of 0.00-5.00 corresponds to less than $10,000 per year to more than $100,000 per year.
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between PM2.5 and heightened autonomic reactivity to a social stress
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find evidence in this sample of the hypothesized overall association between PM2.5 and stress reactivity that Miller et al. [15] found for autonomic measures in an independent sample of adolescents. In addition, the previously observed effect of PM2.5 on autonomic reactivity to stress at high levels of internalizing symptoms [15] was roughly twice as strong as the effect that we observed in this study for PM2.5 and HPA-axis reactivity to stress in more anxious girls. One explanation for these inconsistencies may be that PM2.5 is implicated more strongly in autonomic than in HPA-axis functioning. Inhaled air pollutants change vagal afferent activity in the autonomic nervous system [3]. Parasympathetic neurons in the nucleus of the solitary tract (NTS) project to and can regulate corticotropin-releasing hormone (CRH) neurons in the PVN of the hypothalamus [41]. This is one path by which air pollution may alter hypothalamic functioning and activation of the HPA-axis [3], but the autonomic nervous system is more proximal to the immediate physiological changes produced by inhaled pollutants. Furthermore, autonomic activity supports rapid changes in mobilization of bodily re-

response and the estimated response (based on regression model results)
associated with high PM2.5 (1 SD above the mean) in more anxious girls.

4. Discussion

Investigators have suggested that exposure to PM2.5 adversely affects
health, in part by altering stress biology [2,3]. The majority of relevant
studies, however, assessed physiology during resting states [8,10], rather
than in psychosocial contexts that have been implicated in health, such as
social stress [36,37]. Studying adolescents, Miller et al. [15], found a link
between PM2.5 and heightened autonomic reactivity to a social stress
task, which was stronger for adolescents who reported more severe
internalizing symptoms. The current study partially replicates these
findings, providing preliminary evidence that anxious adolescent girls
are vulnerable to the effects of PM2.5 on HPA-axis responsivity to stress.
This finding was not accounted for by our family- and
neighborhood-level measures of socioeconomic status. Contrary to our
hypotheses, however, we did not find an overall association between
PM2.5 and HPA-axis responsivity.

Psychological experiences and traits, such as anxiety, may exacerbate
the biological effects of exposure to physical pollutants. Indeed, previous
work suggests that youth who experience higher levels of psychosocial
stress and mental health difficulties combined with higher levels of air
pollution are at greater risk for physical health problems [19,21]. Our
current findings and those from Miller et al. [15] extend prior studies by
demonstrating that mental health difficulties may amplify the effects of
PM2.5 on biological sensitivity to psychosocial stress contexts. The mechanisms underlying this vulnerability are still unclear. One possibility
is related to proneness to hyperarousal states and a proinflamatory phenotype that may be typical of individuals prone to internalizing symptoms [38]. For anxious adolescents, hyperarousal states characterized by increased cardiorespiratory activity may increase the amount of PM2.5 that enters the body in much the same way physical
activity increases inhalation and deposition of PM2.5 [39]; further, increased inflammatory reactivity to PM2.5 may heighten responsivity in
other stress systems, such as the HPA-axis. Administration of proinflamatory cytokines to animals has been shown to stimulate the
HPA-axis [40].

We should note, however, that the interaction effect was present only
in analyses predicting AUCg, not AUCi, when using thresholds for sta-
tistical significance corrected for multiple comparisons. In anxious girls,
long-term PM2.5 appears to be associated more robustly with total

cortisol output during and after the stress task (AUCg) than with cortisol

decreases over time (AUCi). Compared to AUCg, a measure of

HPA-axis sensitivity to the stress task, the AUCg measure may be more
closely related to, or be a product of, the chronic activation and general
dysregulation of the HPA-axis that may result from living in areas with
higher levels of PM2.5 [12].

We did not find evidence in this sample of the hypothesized overall association between PM2.5 and stress reactivity that Miller et al. [15] found for autonomic measures in an independent sample of adolescents. In addition, the previously observed effect of PM2.5 on autonomic reactivity to stress at high levels of internalizing symptoms [15] was roughly twice as strong as the effect that we observed in this study for PM2.5 and HPA-axis reactivity to stress in more anxious girls. One explanation for these inconsistencies may be that PM2.5 is implicated more strongly in autonomic than in HPA-axis functioning. Inhaled air pollutants change vagal afferent activity in the autonomic nervous system [3]. Para-
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Note. ***p < .001, **p < .01, *p < .05. AUCg = area under the curve with respect to ground; AUCi = area under the curve with respect to increase; PM2.5 = particulate matter <2.5 μm.

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Table 2
Zero-order correlations.

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Table 3
Regression models predicting HPA-Axis responsivity to stress.

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One interpretation is that the autonomic nervous system plays a role in regulating the sensitivity of the HPA-axis system to moderate levels of PM2.5, such as those observed in this study. Future studies of air pollution studies should include multiple measures of stress biology to test this possibility in adolescents and examine whether intersystem coordination is a mechanism that underlies increased vulnerability to the adverse effects of PM2.5 in adolescents who are experiencing mental health difficulties.

Inconsistencies between the current findings and those of Miller et al. [15] may also be due to study differences, such as assessing community versus at-risk samples, including boys and girls versus girls only, using different approaches in the assessment of air pollution, using similar but not identical social stress tasks, and considering self-reported anxiety versus self-reported internalizing symptoms more broadly. Conversely, these differences also reflect a strength of this research, as a similar interaction effect was observed across these methodological variations. Nonetheless, further research is needed to determine whether PM2.5 is associated with general heightened reactivity to stress, or whether this association is more specific to certain stress biology systems.

We should note several limitations of this study. First, we estimated PM2.5 concentrations at residential addresses based on data from nearby monitoring sites; we did not measure individual PM2.5 exposure directly. As a related point, we did not account for geographic factors that affect air pollution (e.g., proximity to roads, wind patterns), which may have resulted in misclassification of PM2.5 estimates. Second, although we controlled for variables that have been posited to be correlated with ambient air pollution, we cannot definitively rule out all confounds for our observed associations between PM2.5 and HPA-axis responsivity in anxious girls. It is possible that our findings are due to unmeasured factors that may be associated with air pollution and stress biology, such as noise exposure, urbanicity, or marginalization not captured by family income or census tract data. Third, our sample included only adolescent girls; future research must be conducted to examine the generalizability of these findings to other populations. Fourth, all participants resided in the same general area (i.e., within driving distance of the Bay Area in California), which may have limited variability in PM2.5 concentrations in our sample and contributed to the lack of an overall association between PM2.5 and cortisol. It is also possible that higher levels of air pollution, such as those observed in some prior epidemiological studies...
focused on PM$_{2.5}$ in more polluted regions, are required to detect the association between PM$_{2.5}$ and HPA-axis response to stress. For example, Khameiri and colleagues [44] studied the implications of long-term average PM$_{2.5}$ levels that were roughly four times as high as the average PM$_{2.5}$ in our study. It is unclear whether the findings documented in this study generalize to adolescents living in communities outside of the Bay Area that are characterized by higher (or lower) levels of long-term PM$_{2.5}$. Our sample size may have also limited our ability to detect statistically significant effects. Larger samples are necessary to have sufficient power to detect interaction effects. In addition, prior epidemiological research suggests that PM$_{2.5}$ is associated with elevated anxiety [45], but we did not observe this relation in our study. Future studies with greater statistical power, and perhaps more variability in PM$_{2.5}$, should be conducted to replicate our findings. Finally, we considered anxiety symptoms as a continuous variable rather than diagnosis of anxiety disorders based on clinical cutoffs. Although this may limit the clinical significance of these findings, it is important to note that dimensional approaches can be more useful for capturing the range of individual differences in anxiety symptom number and severity, and may align more closely with the latent structure of variability in anxiety [46,47].

In summary, we found that PM$_{2.5}$ is associated with heightened HPA-axis responsivity to social stress in anxious adolescent girls; we did not find that PM$_{2.5}$ is associated directly with HPA-axis responsivity. Thus, our findings partially replicate those of [15]; but importantly are the first to provide evidence for an association between PM$_{2.5}$ and HPA-axis activation specific to psychosocial stress in more anxious girls. Taken together with the recent findings reported by Miller et al., adolescents who experience more severe internalizing symptoms may be particularly vulnerable to the adverse effects of PM$_{2.5}$ on biological sensitivity to stress.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Appendix A. Supplementary data

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References
