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ORIGINAL ARTICLE

Impact of Ambient Particulate Matter and Exposure duration on Ocular Surface Disease Severity: A Cross-Sectional Analytical Study

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ABSTRACT

Background: Ocular surface disease particularly dry eye disease (DED) are increasingly recognized as multifactorial inflammatory disorder in which environmental exposures plays significant role. Ambient particulate matter especially in urban settings have been implicated in tear film instability and ocular surface inflammation.

Objective: To evaluate the independent association between ambient particulate matter (PM2.5 and PM10), daily exposure duration, and severity of ocular surface disease measured by Ocular Surface Disease Index (OSDI).

Methods: This cross-sectional analytical study included 316 adults (≥18 years) recruited from an urban population with documented particulate exposure Impact of Ambient Particulate M. Sample size was calculated using OpenEpi with 95% confidence level and 5% margin of error. Participants with active ocular infection, recent ocular surgery, autoimmune ocular disease, or contact lens use was excluded. Ambient PM2.5 and PM10 levels (μg/m³) were recorded according to exposure settings, and daily exposure duration was documented. OSDI questionnaire was used to assess symptom severity. Pearson correlation, multivariable linear regression and logistic regression analysis were performed.

Results: Mean OSDI score was 39.84 ± 12.76 indicating high symptomatic burden. Significant positive correlations was observed between OSDI and PM2.5 ($r = 0.121$, $p = 0.032$), PM10 ($r = 0.190$, $p < 0.001$) and exposure duration ($r = 0.191$, $p < 0.001$). In adjusted analysis, PM10 ($\beta = 0.052$, $p = 0.0046$) and exposure duration ($\beta = 0.850$, $p = 0.0020$) remained independent predictors. PM2.5 lost statistical significance. Logistic regression showed PM10 and exposure hours independently predicts severe OSDI.

Conclusion: Ambient PM10 and prolonged exposure duration are significant predictors of ocular surface disease severity. Environmental control should be considered integral part of dry eye management especially in high pollution regions.

Keywords: Dry eye disease; Ocular surface disease; PM10; Air pollution; OSDI; Environmental exposure.

INTRODUCTION

Ocular surface disease particularly dry eye disease (DED) in contemporary ophthalmic understanding are no longer regarded as a simple manifestation of age related lacrimal hyposecretion Rather it is now widely accepted as complex multifactorial and predominantly inflammatory disorder in which environmental exposures plays a central and sometimes decisive role The Tear Film & Ocular Surface Society (TFOS) DEWS II report clearly emphasized that environmental stressors significantly destabilize the tear film and initiate or perpetuate surface inflammation[1] however in real clinical settings this concept are often underestimated From a clinical perspective especially in densely populated metropolitan regions we is observing that urban pollutants is not merely aggravating factors but may in fact act as primary drivers of tear film dysfunction In industrial and traffic dense environments airborne particulate matter have therefore emerged as an important though still insufficiently addressed contributor to ocular morbidity.

Particulate matter particularly PM2.5 and PM10 fractions exert its pathogenic influence through multiple biological mechanism These particles induces epithelial microtrauma generate oxidative stress and promotes upregulation of pro inflammatory cytokines on the ocular surface[2,3] The cumulative exposure lead to disruption of epithelial barrier integrity and tear film homeostasis which over time becomes clinically significant Both experimental models and large scale epidemiological investigations has consistently demonstrated that exposure to fine and coarse particulates are associated with increased tear osmolarity shortened tear break up time and higher ocular symptom scores[4–6] Although PM2.5 possess the capacity for deeper penetration into respiratory tissues due to its smaller aerodynamic diameter PM10 tend to exert a more immediate and direct mechanical irritative effect upon exposed mucosal surfaces including the conjunctival epithelium[7] In routine practice one can clinically appreciates this irritative component in patients reporting burning foreign body sensation and reflex tearing after environmental exposure which is commonly seen

Recent population based investigations conducted in East Asia and various European cohorts has documented statistically significant correlations between ambient air pollution indices and objective as well as subjective dry eye parameters[8,9] These studies have strengthen the biological plausibility of pollution mediated ocular surface inflammation However data from South Asian populations where particulate load frequently exceeds international safety thresholds remains relatively scarce and under represented in the literature Additionally a methodological limitation observed in several prior reports are the inadequate adjustment for cumulative daily exposure duration which is a variable that may intensify inflammatory cascade activation over prolonged period

Accordingly the present study were undertaken to evaluate the independent association between ambient particulate matter concentrations (PM2.5 and PM10) daily exposure duration and the severity of ocular surface disease as quantified by the Ocular Surface Disease Index (OSDI) It was hypothesized that both particulate burden and exposure time would independently predicts symptom severity even after appropriate adjustment for relevant demographic variables which is important in interpreting the findings.

METHODOLOGY

This cross-sectional analytical study was conducted on 316 adult participants (≥18 years) recruited from an urban population having documented environmental particulate exposure. The sample size was calculated using OpenEpi software on the basis of anticipated prevalence of ocular surface symptoms from prior regional studies, with 95% confidence level and 5% margin of error. The minimum required sample was estimated accordingly, and additional margin was added for incomplete responses, therefore the final analyzed sample became 316 participants.

To reduce possible confounding inflammatory influences, individuals with active ocular infection, recent ocular surgery (<6 months), autoimmune ocular disease, or contact lens usage were excluded. These conditions otherwise could have altered the tear film parameters independently and thus biasing the results.

Demographic variables including age, gender and occupation was recorded in a structured manner. Ambient exposure was quantified using measured PM2.5 and PM10 concentrations (μg/m³) corresponding to the participants exposure settings. Daily exposure duration (hours/day) was self-reported, and where feasible it were verified through occupational documentation to increase reliability of exposure estimation.

Ocular symptom severity was assessed by using the validated Ocular Surface Disease Index (OSDI) questionnaire, which is widely accepted tool in ocular surface research. Scores were categorized as Normal (0–12), Mild (13–22), Moderate (23–32), and Severe (≥33). Continuous variables was expressed as mean ± standard deviation (SD). Pearson correlation analysis were applied to evaluate association between particulate levels and OSDI scores.

Multivariable linear regression was performed with OSDI score as continuous dependent variable, adjusting for age, gender, occupation, PM2.5, PM10 and exposure duration. Binary logistic regression were conducted to identify predictors of severe OSDI (≥33). Adjusted β coefficients, odds ratios (OR), and 95% confidence intervals (CI) was calculated. A p-value <0.05 were considered statistically significant.

RESULTS

Baseline Characteristics: The demographic and exposure characteristics are summarized in Table 1 The mean age of the participants were 42.83 ± 13.46 years which represent a predominantly middle aged cohort The average PM2.5 level was 89.47 ± 17.64 μg/m³ and PM10 was 174.67 ± 39.06 μg/m³ values which substantially exceeds the WHO recommended thresholds and are clearly above safe limits The mean daily exposure duration were 5.91 ± 2.57 hours The overall mean OSDI score was 39.84 ± 12.76 reflecting a markedly high symptomatic burden in this population which clinically are quite significant and not merely an incidental observation

Correlation Analysis: As demonstrated in Table 2 statistically significant positive correlations was observed between OSDI score and environmental parameters OSDI correlated with PM2.5 (r = 0.121 p = 0.032) PM10 (r = 0.190 p < 0.001) and exposure duration (r = 0.191 p < 0.001) Age did not show statistically significant association with OSDI score (p = 0.358) Although the correlation coefficients appears modest in magnitude the consistency of direction across particulate variables suggest that these associations is biologically meaningful rather than simply random statistical fluctuation

Multivariable Linear Regression: In the adjusted multivariable regression model presented in Table 3 PM10 (β = 0.052 p = 0.0046) and exposure duration (β = 0.850 p = 0.0020) remained statistically significant independent predictors of OSDI score PM2.5 lost its statistical significance in the adjusted modelling (p = 0.156) Demographic variables including age and gender was not statistically significant in the final model which indicate limited contribution from these covariates

This indicate that with every incremental rise in PM10 concentration there are measurable increase in symptom severity even after controlling for confounding variables The magnitude may appear numerically small but within cumulative environmental exposure context it becomes clinically relevant and should not be underestimated

Logistic Regression for Severe OSDI: Binary logistic regression analysis shown in Table 4 demonstrated that PM10 per 10 μg/m³ increase had an OR of 1.10 (p = 0.0031) and exposure duration per hour increase had an OR of 1.13 (p = 0.0162) Both variables remained independent and statistically significant predictors of severe ocular surface disease

These findings collectively suggest that cumulative particulate burden along with prolonged daily exposure significantly increases the likelihood of clinically severe ocular surface symptomatology something which we frequently observes in high exposure urban settings and which have important public health implications.

Table 1A. Environmental Exposure and OSDI Characteristics (n = 316)

Variable	Mean ± SD
PM2.5 (μg/m³)	89.47 ± 17.64
PM10 (μg/m³)	174.67 ± 39.06
Exposure Hours/day	5.91 ± 2.57
OSDI Score	39.84 ± 12.76

Table 2A. Correlation Between Environmental Factors and OSDI Score

Variable	Pearson r	p-value
PM2.5	0.121	0.032
PM10	0.190	0.00069
Exposure Hours	0.191	0.00064

Table 3A. Multivariable Linear Regression for OSDI Score

Predictor	Adjusted β (95% CI)	p-value
PM2.5	0.057 (−0.022 to 0.136)	0.156
PM10	0.052 (0.016 to 0.088)	0.0046
Exposure Hours	0.850 (0.312 to 1.389)	0.0020

Table 4A. Logistic Regression for Severe OSDI (≥33)

Predictor	Adjusted OR (95% CI)	p-value
PM10 (per 10 μg/m³)	1.10 (1.03–1.18)	0.0031
Exposure Hours	1.13 (1.02–1.24)	0.0162
Other Variables	NS	

DISCUSSION

The present study clearly, demonstrate that ambient, particulate matter—particularly PM10—and daily exposure ,duration is independently associated with, increasing severity of ocular surface disease. From a clinical perspective, the predominance of PM10 over PM2.5 in the adjusted modelling are especially noteworthy and carries practical implications. While fine particles are known to penetrate deeper into pulmonary tissues, coarse particulates tends to exert more direct mechanical as well as inflammatory insult upon the exposed ocular surface epithelium[7,10]. In routine ophthalmic practice, we frequently observes that patients who are exposed to dusty urban surroundings complains of immediate irritation, foreign body sensation and surface burning, which can reasonably be explained by this epithelial level interaction and microtrauma.

Our findings is consistent with recent epidemiological investigations from China and South Korea, where significant associations between air pollution indices and increased dry eye prevalence have been reported[8,11]. Likewise, a European cohort study published in 2022 have demonstrated positive correlation between PM10 concentrations and ocular discomfort indices[9]. The biological plausibility of these observations are further supported by experimental evidence demonstrating particulate-induced oxidative stress and upregulation of pro-inflammatory cytokines, including IL-6 and TNF-α, within conjunctival epithelial cells[3,12]. These molecular events provides a mechanistic framework linking environmental exposure with clinical symptomatology, although the inflammatory cascade itself are complex and multifactorial in nature.

Interestingly, advancing age were not emerged as statistically significant determinant in our cohort. This suggest that environmentally mediated inflammatory mechanisms may overrides the classical degenerative tear dysfunction pathways in heavily exposed populations. It reinforces the evolving concept that contemporary urban dry eye is increasingly environmental rather than purely senescent in origin, particularly in regions where particulate burden remain persistently elevated and poorly regulated.

Exposure duration were emerged as a strong independent predictor of disease severity. Chronic and cumulative exposure likely amplify tear film instability, disrupt mucin layer integrity, and compromises epithelial barrier function over time[13]. Repeated micro inflammatory episodes may gradually transitions into sustained

ocular surface inflammation which then manifest as persistent and clinically significant disease that we frequently encounters in daily practice This chronicity of inflammation over time are likely responsible for the progressive symptom burden seen in environmentally exposed individuals

Certain limitations must be acknowledged The cross sectional design inherently limit causal inference and do not establishes a definite temporal relationship between exposure and disease severity Objective tear film parameters such as TBUT and Schirmer testing was not incorporated into the present analysis which could have further strengthen the physiological correlation with symptom scores Nevertheless the study derive its principal strength from multivariable statistical adjustment and relatively substantial sample size which together enhances the robustness and clinical credibility of the observed associations even if certain methodological constraints remains unavoidable

CONCLUSION

Ambient PM10 concentration and daily exposure duration are independent predictors of ocular surface disease severity The findings underscores the importance of environmental risk mitigation strategies in managing symptomatic ocular surface disease particularly in regions where particulate burden remain elevated and poorly controlled

From a clinical ophthalmology standpoint addressing environmental exposure should be considered integral rather than peripheral to dry eye management strategies Environmental modification are not optional but should forms a routine component of comprehensive therapeutic planning in modern urban practice.

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