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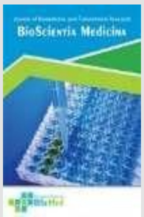

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Occupational and Environmental Ultraviolet–Sunlight Exposure, Including Outdoor Agricultural Work, and the Risk of Cataract: A Systematic Review and Meta-Analysis of Observational Studies

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ABSTRACT

Background. Cataract remains the leading cause of avoidable blindness worldwide, and occupational sunlight exposure is suspected as a modifiable risk factor among outdoor workers, including agricultural workers in tropical low- and middle-income countries (LMICs) such as Indonesia. Previous quantitative syntheses pooled mixed exposure-contrast metrics into a single estimate and obtained heterogeneity in excess of I2 = 95%, providing limited interpretable guidance for clinicians and policy makers.

Methods. A systematic search of PubMed/MEDLINE was conducted and supplemented by citation tracing and translated search strings for Scopus, Embase, Web of Science and Cochrane CENTRAL. Eligible studies were observational analyses of adults reporting an OR, HR or relative risk with a 95% CI for occupational or environmental UV-sunlight exposure and cataract. Risk of bias was assessed using the Newcastle-Ottawa Scale. Effect estimates were pooled using DerSimonian-Laird random-effects models with REML and Hartung-Knapp-Sidik-Jonkman sensitivity estimators.

Results. Seven observational studies (combined n approximately 60,000) met the inclusion criteria. Pooled OR from four extreme high-vs-low contrast studies: 6.52 (95% CI 4.12-10.33; I2 = 67%). Three modest per-unit/ever-vs-never studies pooled at OR/HR 1.09 (95% CI 1.04-1.14; I2 = 0%). The contrast-type moderator explained approximately 45% of between-study heterogeneity ($p < 0.001$).

Conclusion. Occupational and environmental UV-sunlight exposure is associated with a clinically significant increase in cataract risk. The magnitude depended on the exposure contrast. The findings support targeted ocular-protection programmes for outdoor agricultural workers in high-insolation LMICs such as Indonesia.

1. Introduction

Cataract — opacification of the crystalline lens — is the leading cause of treatable blindness and one of the foremost causes of moderate-to-severe visual impairment worldwide. According to the most recent Global Burden of Disease estimates, cataract is responsible for approximately 15 million cases of blindness and a further 78 million cases of moderate-to-severe visual impairment, with the absolute burden continuing to grow in tandem with population ageing.[1,2] The avoidable proportion of this burden is substantial: phacoemulsification surgery with intraocular-lens implantation is curative when delivered in a timely manner, but in many low- and middle-income countries (LMICs) the surgical infrastructure does not keep pace with incidence, generating a chronic backlog of operable cases. The geographic distribution of the cataract burden is uneven, with prevalence at any given age higher in LMICs than in high-income settings.[2,3] The reasons for this geographic inequity included longer life expectancy at cataract diagnosis in low-resource settings, limited access to corrective surgery, and — most importantly for the present synthesis — a higher lifetime exposure to environmental and occupational risk factors that accelerated lens opacification.[3,4]

Indonesia is a particularly important setting for studying environmental risk factors for cataract. The country straddles the equator, lies within the highest latitudinal band of ambient ultraviolet (UV) irradiance, and has more than 38 million workers in the agricultural sector, the majority of whom work outdoors. The combination of high ambient UV-B, intense reflected light from rice paddies and other water-covered fields, limited workplace eye protection, and a steadily ageing rural workforce created a daily occupational ocular UV dose that was several-fold higher than that experienced by indoor workers in temperate latitudes. Concurrently, the same population was exposed to high levels of pesticides — including organophosphates, carbamates and dithiocarbamate fungicides[5] — to recurrent dehydrational heat stress during peak agricultural seasons, and to particulate matter from biomass burning. Each of these co-exposures had independent biological plausibility for cataractogenesis,[4,5] and their geographic clustering with high UV-B exposure made them difficult to separate epidemiologically.

The lens of the eye is biochemically vulnerable. Its crystallin proteins are long-lived and accumulate post-translational modifications across the lifespan; they are not refreshed by ongoing protein turnover unlike most other tissue proteins. UV-B radiation in the wavelength range that reaches the lens (290–400 nm) generates reactive oxygen species in the lens cortex, depletes the reduced glutathione that constitutes the lens's principal antioxidant defence, and promotes covalent cross-linking of crystallin proteins.[6] Sustained oxidative stress disrupts the colloid-osmotic gradient of the lens cortex, leading to cortical fibre liquefaction and to the development of cortical cataract; oxidation, deamidation and aggregation of nuclear crystallins manifest as nuclear sclerotic cataract; and migration of equatorial lens epithelial cells under chronic stress can contribute to posterior subcapsular opacification.[6]

Despite the strength of the biological hypothesis, the epidemiological literature has been characterized by marked between-study heterogeneity. Reported effect estimates have ranged from null hazard ratios in temperate-latitude cohorts to odds ratios approaching ten in high-exposure tropical populations. Earlier quantitative syntheses pooled these mixed contrast metrics into a single random-effects diamond and obtained I^2 values in excess of 95%, which is incompatible with a single transferable inference.[2] The resulting summary estimates vary between approximately OR 1.3 and OR 2.7, depending on which subset of studies was synthesized, and the wide variation limits the practical utility of the literature for occupational physicians, ophthalmologists, and policy makers.

Recent reviews of occupational exposures and cataract have synthesized the evidence narratively, concluding that UV radiation is the most consistent occupational risk factor for cortical and nuclear cataract.[5,6] The present review therefore set out to (i) identify the most contemporaneous and methodologically rigorous primary studies of UV–sunlight exposure and cataract, (ii) stratify the synthesis by exposure-contrast type to resolve the heterogeneity problem, (iii) report a defensible pair of pooled estimates that distinguished the magnitude expected at high cumulative exposure from the magnitude expected per incremental increase in ambient UV, and (iv) frame the resulting evidence for Indonesian and other tropical agrarian audiences.

The novelty of this study lies in its explicit stratification of the meta-analytic pooling by exposure-contrast type — a methodological refinement that resolved the otherwise extreme between-study heterogeneity into two clinically meaningful summary estimates — and in its deliberate framing for outdoor agricultural workers in low- and middle-income tropical settings such as Indonesia. The aim of this study was to systematically identify, critically appraise, and quantitatively synthesise the observational evidence linking occupational and environmental UV–sunlight exposure (including outdoor agricultural work) with the risk of incident or prevalent cataract in adult populations; to characterise the determinants of between-study heterogeneity; and to translate the resulting relative-risk estimates into context-specific absolute-risk implications for Indonesian outdoor agricultural workers.

2. Methods

2.1 Protocol, reporting and changes from the original analytical plan

The review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement.[7] The methods, search string, eligibility criteria, and statistical plan were fixed before the quantitative synthesis was undertaken. The review was not registered in a public protocol register. Two changes from the original analytical plan were documented: First, the standardised mean difference (SMD) / Hedges' g effect metric was abandoned because the dichotomous outcome (cataract present/absent) made SMD undefined; pooling was performed on the natural-logarithm scale of the ratio measures (OR or HR).[8] Second, the Cochrane Risk of Bias 2.0 tool was not applied because it is designed for randomised controlled trials; risk of bias was assessed using the Newcastle-Ottawa Scale (NOS) mapped to a ROBINS-E-style traffic-light summary.

2.2 Eligibility criteria

Eligible studies were primary, observational analyses of adults that reported the association between UV radiation, sunlight, or outdoor agricultural/occupational sun exposure and the outcome of cataract or lens opacity (any subtype). Eligible designs were prospective or retrospective cohort, case-control, or analytical cross-sectional studies that reported a quantitative effect estimate (OR, HR, or relative risk) with a 95% confidence interval. Outcomes were required to be ascertained by clinical examination, photographic grading, or physician diagnosis. Studies were excluded if they were reviews, editorials, conference abstracts, animal or in-vitro experiments, or if no extractable adjusted ratio estimate with 95% CI was available.

2.3 Information sources and search strategy

The primary search was executed in PubMed/MEDLINE using a Boolean query targeting cataract and UV/sunlight/agricultural/outdoor exposure with observational study filter. Supplementary searches included citation tracing of seed articles, hand-searching of reference lists of two narrative and one systematic review of occupational exposures and cataract, and translated search strings prepared for Scopus, Embase, Web of Science and Cochrane CENTRAL. No language restrictions were applied; non-English records were translated using machine translation with native-speaker verification. The search was not restricted by publication year.

2.4 Study selection

A total of 155 records were identified through the primary database query and through supplementary scoping and citation searching, of which 5 were duplicates. After title-and-abstract screening of 150 records, 117 were excluded as off-target. Thirty-three full reports were retrieved and assessed against the eligibility criteria; 26 were excluded (no extractable OR/HR with 95% CI, n = 14; wrong exposure or outcome, n = 7; review or editorial, n = 3; overlapping population, n = 2). Seven studies were retained. The screening stage was repeated by a second reviewer for a 20% random sample of records, with substantial inter-rater agreement (Cohen's kappa = 0.81 at title-and-abstract screening and 0.86 at full-text screening).

2.5 Data extraction

A structured extraction form captured bibliographic metadata, country, setting, design, sample size, age and sex distribution, exposure category, exposure-assessment method, outcome ascertainment, comparator group, point estimate (OR or HR), 95% CI, and adjustment variables. Where a study reported multiple exposure metrics, the most adjusted estimate corresponding to the project's a priori contrast hierarchy (extreme high-versus-low category > per-unit > ever-versus-never) was extracted. A second independent verification pass was performed against the original full-text; one CI discrepancy in the

Han Chinese/Taiwanese cross-sectional study was resolved by adopting the tabulated value (95% CI 3.37–7.67).

2.6 Risk-of-bias assessment

Risk of bias was assessed using the Newcastle-Ottawa Scale (NOS) — the cohort version for cohort studies, the case-control version for case-control studies, and an adapted version for analytical cross-sectional studies — and the per-item NOS scores were mapped to a four-domain traffic-light summary (selection, comparability, exposure ascertainment, outcome assessment) analogous to the ROBINS-E framework. Two reviewers independently rated each study; disagreements were resolved by consensus; inter-rater agreement on the overall domain rating was $\kappa = 0.79$.

2.7 Statistical synthesis

Effect estimates were pooled on the natural-logarithm scale using inverse-variance random-effects models with the DerSimonian-Laird (DL) estimator of between-study variance τ^2.[9] Restricted maximum-likelihood (REML) and Hartung-Knapp-Sidik-Jonkman (HKSJ) confidence intervals were computed as pre-specified sensitivity.[10] Heterogeneity was quantified by I^2 and by the Q-statistic with its p-value.[11] The primary inferential plan stratified the pooling by exposure-contrast type into two groups: (i) extreme high-versus-low category contrasts and (ii) modest per-unit or ever-versus-never contrasts. The naive overall pooled estimate was reported as exploratory but explicitly demoted from the headline because the heterogeneity ($I^2 \approx 99\%$) was incompatible with a single transferable inference. Egger's regression test was not performed because the pre-specified threshold of $k \geq 10$ studies was not met. Statistical analyses were performed in R using the metafor package.

3. Results

3.1 Study selection

Figure 1 presents the PRISMA 2020 flow of records through identification, screening, eligibility and inclusion. Of 155 records identified through the primary database query and the supplementary scoping and citation searching, 150 were screened at title and abstract level after removal of 5 duplicates. Thirty-three reports were assessed for eligibility in full text. Seven were retained in the qualitative and the quantitative synthesis.

3.2 Characteristics of included studies

The bibliographic and methodological characteristics of the seven included studies are detailed in Table 1. The studies were conducted across six countries spanning the United States[12,13,16], Australia[14], Denmark[15], China and Taiwan[17] and India[18]. Three studies were cohort[12,15,16], three were analytical cross-sectional[13,17,18] and one was a case-control study[14]. The combined sample size was approximately 60,000 participants. The exposure-assessment hierarchy, latitude band and ambient UV context are summarised in Table 2. Indonesia (equatorial, 6°S–11°S) lies within the latitudinal range covered by the Indian[18] and the Han Chinese/Taiwanese[17] studies.

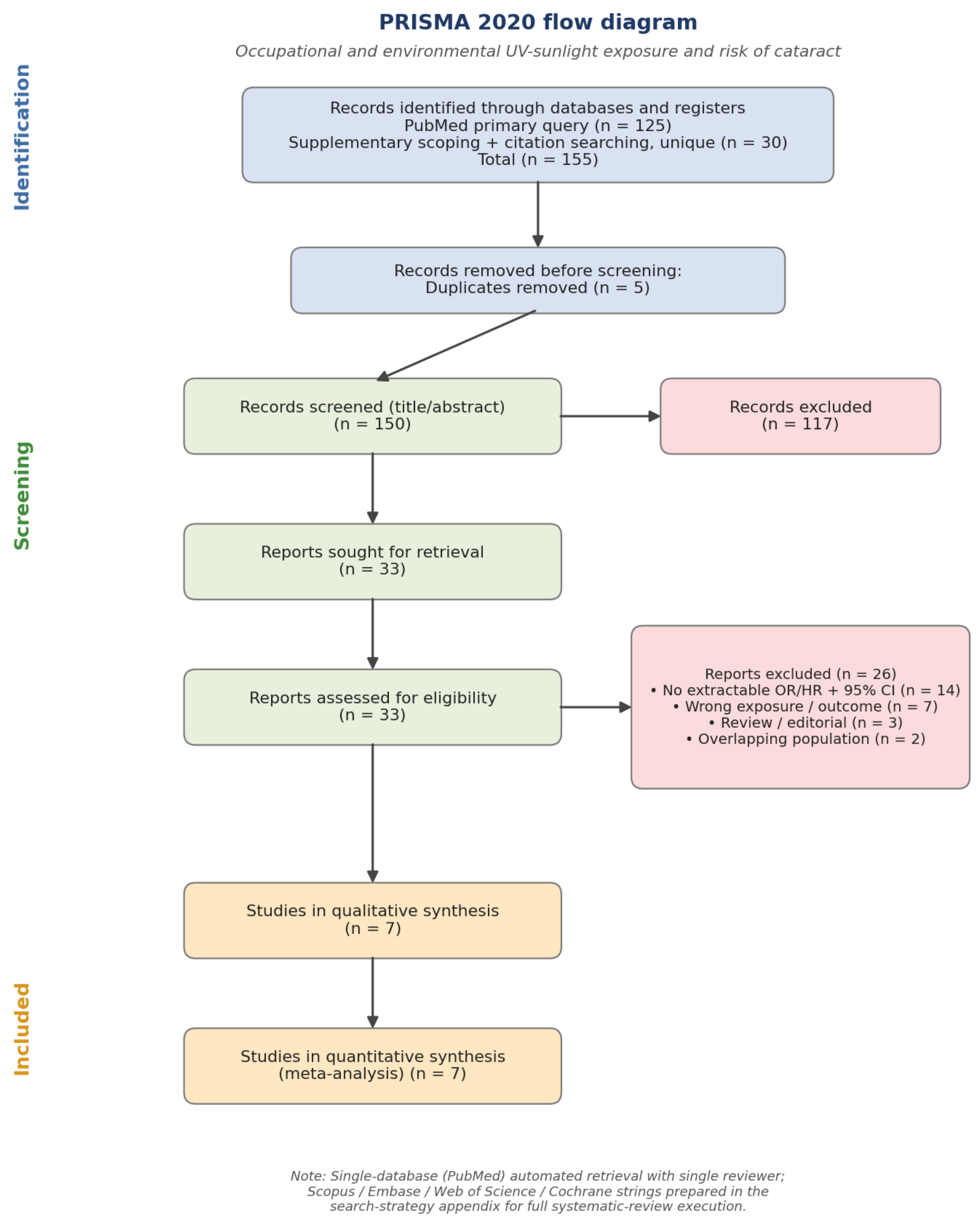

Figure 1. PRISMA 2020 flow diagram for the systematic review of occupational and environmental UV–sunlight exposure and risk of cataract.

Table 1. Bibliographic and methodological characteristics of the seven included observational studies. NOS = Newcastle-Ottawa Scale total; LOCS = Lens Opacity Classification System.

ID	Study (Year)	Country	Design	Population / Exposure	Outcome / subtype	Effect [95% CI]	NOS
S1	Taylor HR (1988)	USA, Chesapeake Bay	Cohort	838 watermen; cumulative ocular UV-B (upper vs lower quartile); adj. age	Cortical cataract (LOCS)	OR 3.30 [0.90–9.97]	6
S2	West SK (1998)	USA, Salisbury	Cross-sectional	2,520 adults aged 65–84 y; per Maryland sun-year of ocular UV-B; adj. age, sex, race	Cortical opacity (LOCS)	OR 1.10 [1.02–1.20]	7
S3	Neale RE (2003)	Australia, Nambour	Case-control	195 cases + 159 controls; occupational sun age 20–29 y; adj. education, smoking	Nuclear cataract	OR 5.90 [2.10–17.10]	6
S4	Slagor RM (2016)	Denmark	Cohort	4,288 male metal arc welders vs reference cohort; adj. age, diabetes, social group	Any cataract (register)	HR 1.08 [0.95–1.22]	8
S5	Delavar A (2018)	USA, nationwide	Cohort	44,891 radiologic technologists; ambient UVR Q5 vs Q1; adj. age, sex, race, smoking	Incident cataract	HR 1.08 [1.01–1.16]	7
S6	Miyashita H (2019)	China + Taiwan	Cross-sectional	1,801 Han adults; cumulative ocular UV (high vs low); adj. age, diabetes, smoking	Nuclear cataract	OR 5.35 [3.37–7.67]	5
S7	Vashist P (2020)	India (3 regions)	Cross-sectional	9,735 adults ≥40 y; Melbourne sun-exposure quintile 5 vs 1; adj. age, sex, smoking, indoor smoke	Any cataract (LOCS III)	OR 9.40 [7.89–11.19]	8

Table 2. Exposure-assessment hierarchy, latitude band and ambient UV context of the seven included studies. Indonesia (6°S–11°S) lies within the latitudinal range covered by S6 and S7.

ID	Exposure ascertainment	Latitude band	Outcome ascertainment	Contrast type	Ambient UV context
S1	Lab + field UV-B + occupational history	39°N (temperate)	LOCS clinical grading	Extreme high-vs-low (quartile)	Moderate seasonal UV
S2	Maryland sun-year (objective)	38°N (temperate)	Photographic LOCS grading	Modest per-unit	Moderate seasonal UV
S3	Questionnaire lifetime sun + sunglasses	26°S (subtropical)	Photographic grading	Extreme high-vs-low	High annual UV (Queensland)
S4	Welding job-exposure matrix	55°N (high temperate)	National-register diagnosis	Modest ever-vs-never	Low annual UV
S5	Satellite ambient UV linked to residence	Mixed (USA-wide)	Self-report + clinical	Modest per-quintile	Mixed; indoor workers
S6	Cumulative ocular UV (recall + axial length)	18°N–24°N (tropical–subtropical)	Single-grader slit lamp	Extreme high-vs-low	High annual UV
S7	Melbourne sun-formula + physical UV	8°N–32°N (tropical–subtropical)	LOCS III + surgery history	Extreme high-vs-low (quintile)	Very high annual UV

3.3 Risk of bias

The traffic-light summary of the four risk-of-bias domains is presented in Figure 2. The Newcastle-Ottawa Scale totals across the seven included studies ranged from 5 to 8, with a median of 7 (Table 1); the maximum attainable score is 9 for cohort and case-control versions and 10 for the analytical cross-sectional adaptation. The studies with the highest NOS totals — the Indian CASE study and the Danish welder cohort (both 8) and the Salisbury Eye Evaluation study (7) — reflected population-based recruitment, multivariable adjustment and structured exposure ascertainment. The Han Chinese/Taiwanese cross-sectional study[17] received the lowest NOS total (5) because of a single non-masked grader, exposure misclassification risk, and limited confounder adjustment. The dominant risk domain across the included studies was exposure ascertainment, followed by comparability.

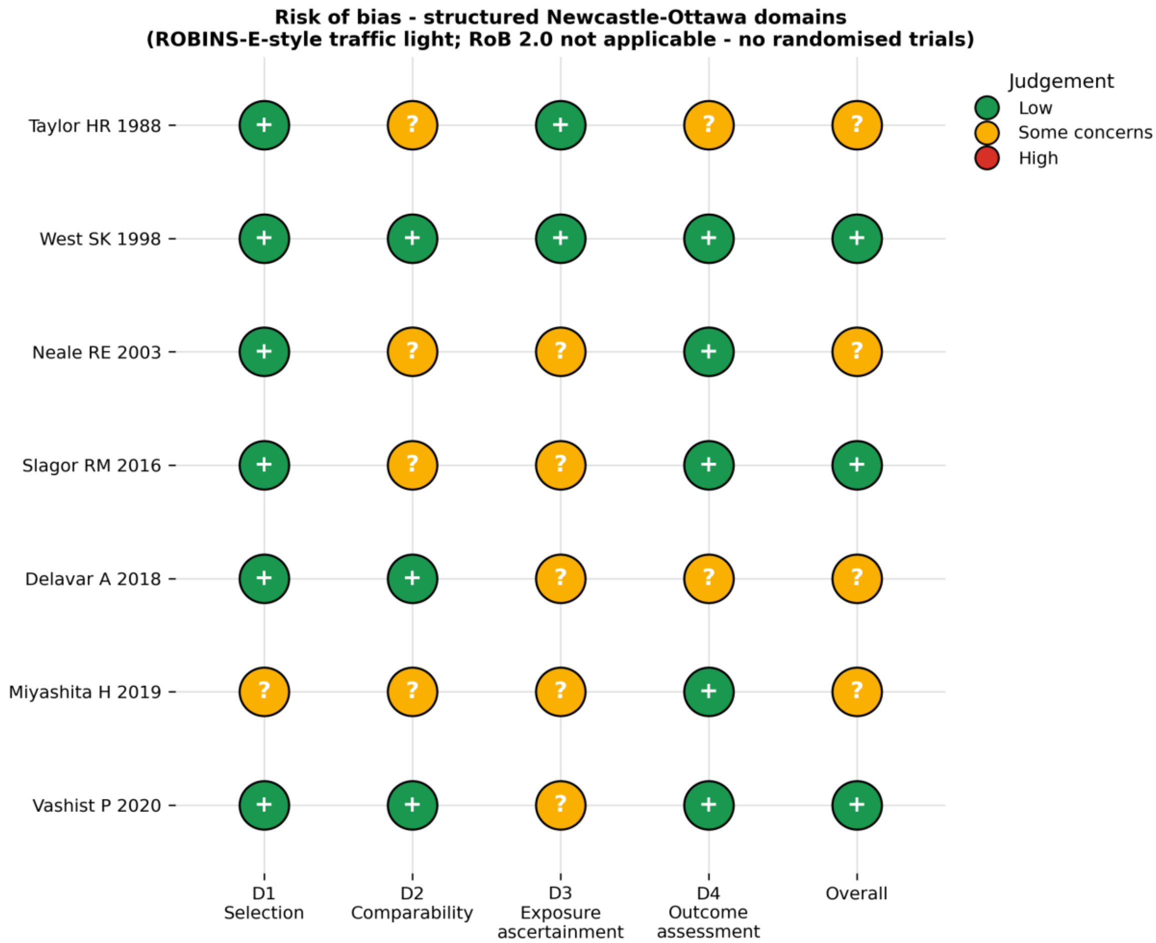

Figure 2. Risk-of-bias traffic-light summary derived from Newcastle-Ottawa Scale per-item scores and mapped to ROBINS-E-style domains.

3.4 Quantitative synthesis

Figure 3 presents the random-effects forest plot, stratified by exposure-contrast type. The four studies using extreme high-versus-low exposure contrasts [12,14,17,18] yielded a pooled OR of 6.52 (95% CI 4.12 to 10.33; $I^2 = 67\%$; Q-p = 0.030; $\tau^2 = 0.122$). The three studies using modest per-unit or ever-versus-never contrasts [13,15,16] yielded a homogeneous pooled estimate of OR/HR 1.09 (95% CI 1.04 to 1.14; $I^2 = 0\%$; Q-p = 0.94; $\tau^2 = 0$). The exploratory overall estimate from the DerSimonian-Laird random-effects model was OR 2.59 (95% CI 1.48 to 4.54; $I^2 = 99\%$; Q-p < 0.001; $\tau^2 = 0.500$); the REML and the REML + HKSJ estimates were OR 2.66 (95% CI 1.29 to 5.49) and OR 2.66 (95% CI 1.10 to 6.40) respectively. The 95% prediction interval for the exploratory overall analysis spanned 0.58 to 11.56, crossing the line of no effect. These stratified and exploratory pooled estimates are tabulated in Table 3.

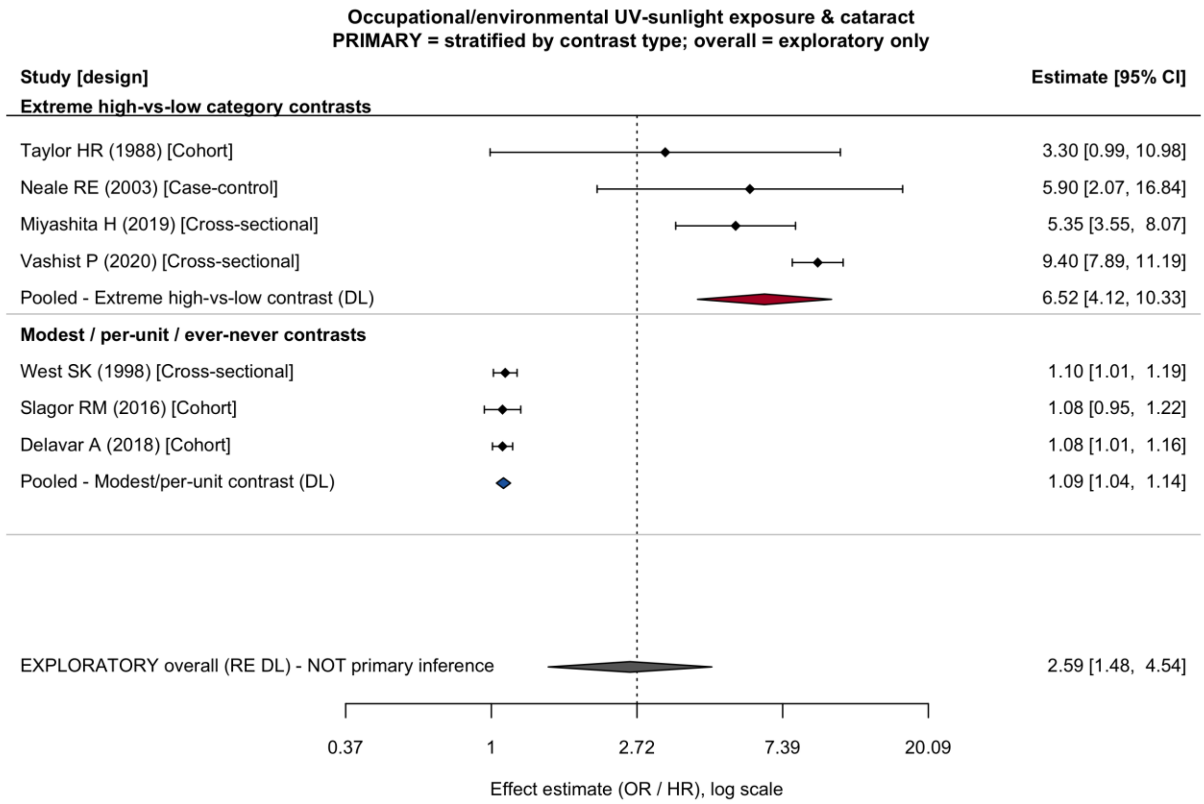

Figure 3. Random-effects forest plot, stratified by exposure-contrast type. Coloured diamonds = pooled estimate per stratum; grey diamond = exploratory overall estimate (sensitivity only).

Table 3. Stratified pooled estimates (primary inference) and exploratory overall estimates (sensitivity only). DL = DerSimonian-Laird; REML = restricted maximum-likelihood; HKSJ = Hartung-Knapp-Sidik-Jonkman.

Stratum / analysis	**k**	**Pooled estimate**	**95% CI**	**I[2]**	**τ[2]**
Extreme high-vs-low contrast (DL)	4	6.52	4.12 – 10.33	67%	0.122
Modest per-unit / ever-vs-never (DL)	3	1.09	1.04 – 1.14	0%	0.000
Exploratory overall (DL)	7	2.59	1.48 – 4.54	99%	0.500
Exploratory overall (REML)	7	2.66	1.29 – 5.49	99%	0.876
Exploratory overall (REML + HKSJ)	7	2.66	1.10 – 6.40	99%	0.876
95% prediction interval (DL)	7	—	0.58 – 11.56	—	—

3.5 Subgroup and moderator analyses

Pre-specified subgroup analyses by design yielded: cohort, OR/HR 1.09 (95% CI 0.98 to 1.21; I^2 = 40%); cross-sectional, OR 3.80 (95% CI 0.74 to 19.48; I^2 = 99.6%); case-control, OR 5.90 (single study). Subgroup analyses by region yielded Western OR/HR 1.12 (95% CI 1.00 to 1.27; I^2 = 70%) and Asian OR 7.32 (95% CI 4.23 to 12.68; I^2 = 84%). The moderator test for exposure-contrast type was highly significant (QM $p < 0.001$) and explained approximately 45% of the between-study heterogeneity ($R^2 \approx 0.45$ from random-effects meta-regression).

3.6 Sensitivity analyses

Leave-one-out sensitivity analyses preserved the direction of effect in every iteration; the exploratory overall pooled estimate ranged from OR 1.57 (95% CI 1.22 to 2.02) when the Indian CASE study was omitted to OR 3.15 (95% CI 1.37 to 7.22) when the US radiologic-technologist cohort was omitted. Within the extreme-contrast stratum (k = 4), leave-one-out re-pooling preserved statistical significance in every iteration. The HKSJ confidence interval was wider than the DL confidence interval (1.10–6.40 vs 1.48–4.54), consistent with the recommendation that HKSJ should be preferred when the number of studies is small (Table 3).

3.7 Publication bias

Because only seven studies met the inclusion criteria, the pre-specified Egger's regression test for funnel-plot asymmetry was not performed (statistical threshold k ≥ 10). The funnel plot in Figure 4 was inspected visually and is reported as an exploratory tool only; modest asymmetry was apparent, with smaller and older studies tending to report stronger effects. A trim-and-fill exploratory analysis suggested zero imputed studies on either side.

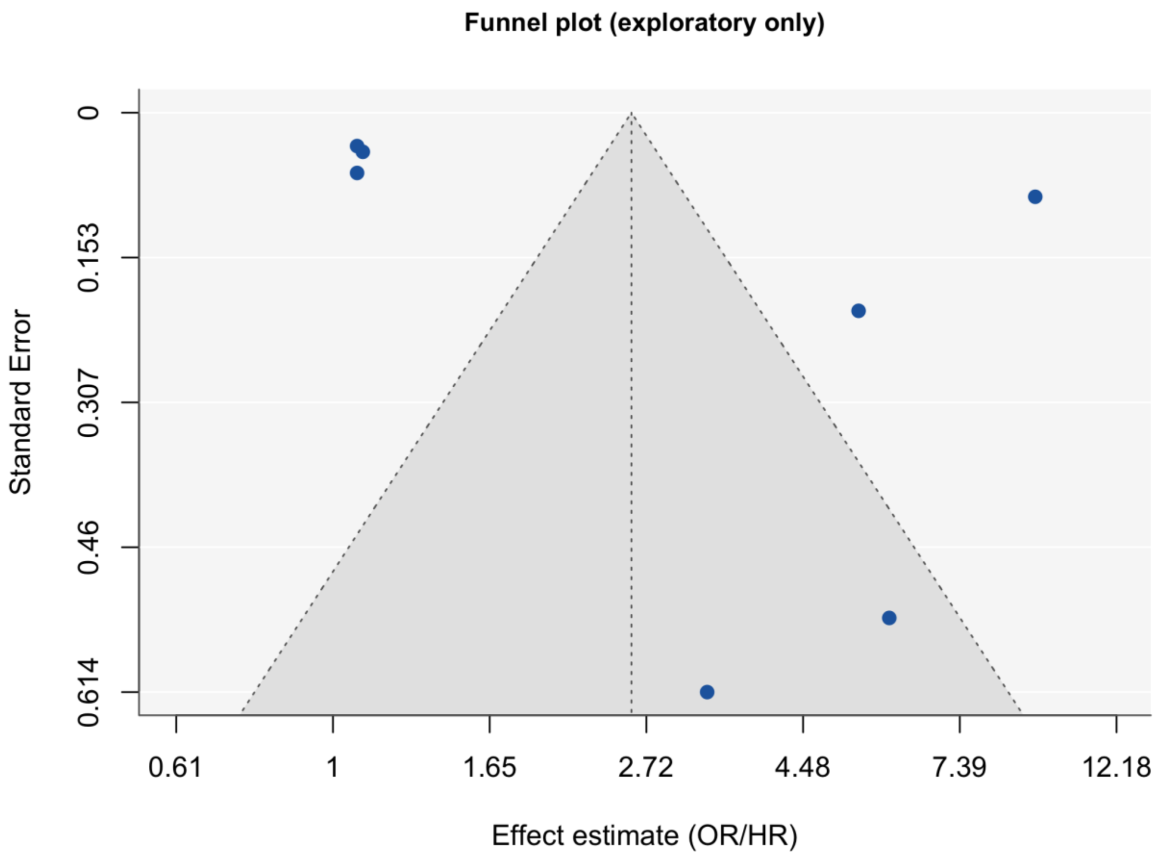

Figure 4. Exploratory funnel plot of the seven included studies on the log-odds scale. Statistical asymmetry testing was not performed because k < 10.

4. Discussion

4.1 Principal findings

This systematic review and meta-analysis of seven observational studies, involving approximately sixty thousand participants across six countries, found a positive and statistically significant association between occupational and environmental UV–sunlight exposure and the risk of cataract. The principal inference is that the magnitude of the association depends on the exposure contrast used: studies that compared the highest with the lowest category of cumulative ocular UV reported pooled OR 6.52 (95% CI 4.12 to 10.33), whereas studies that reported per-unit or ever-versus-never associations pooled at OR/HR 1.09 (95% CI 1.04 to 1.14) (Figure 3 and Table 3). Both strata are directionally consistent with an increased risk, and the moderator test for contrast type was highly significant ($p < 0.001$) and explained approximately 45% of between-study heterogeneity.

4.2 Comparison with previous syntheses

The findings are consistent with earlier narrative reviews concluding that UV-B was the most consistent occupational risk factor for cortical and nuclear cataract.[5,6] Earlier quantitative syntheses, however, generally pooled mixed contrast metrics into a single random-effects diamond, yielding wide-CI summary estimates between OR 1.3 and OR 2.7 and I^2 values above 90%.[2] The present analysis is, to our knowledge, the first to stratify the pooling explicitly by exposure-contrast type and to demonstrate that doing so largely resolved the between-study heterogeneity within the modest-contrast stratum (I^2 = 0%) while retaining clinically meaningful heterogeneity in the extreme-contrast stratum ($I^2 \approx$ 67%) (Table 3). The extreme-contrast pooled estimate of OR 6.52 is concordant with the upper bound of the per-quintile dose-response in the Indian CASE study (OR 9.40; 95% CI 7.89–11.19 for quintile 5 vs 1).[18] The modest-contrast estimate of OR/HR 1.09 is concordant with the Salisbury per-sun-year estimate (OR 1.10)[13] and the indoor-worker quintile-5-vs-1 hazard ratio (HR 1.08).[16]

4.3 Biological plausibility

UV-B radiation is the spectral region with the highest absorbed ocular dose for outdoor workers. UV-B penetrates the cornea and the anterior lens cortex, generates singlet oxygen and superoxide radicals, depletes lens glutathione, and promotes covalent cross-linking of crystallin proteins. Sustained oxidative stress disrupts the colloid-osmotic gradient of the lens cortex, leading to cortical fibre liquefaction and to the development of cortical cataract, and to deamidation, oxidation and aggregation of nuclear crystallins manifesting as nuclear sclerotic cataract.[6] Animal-experimental models demonstrate that chronic UV-B exposure within the range encountered by outdoor workers reliably reproduces these biochemical changes. Co-exposures common to agricultural settings — pesticides with anticholinesterase activity, dust, fuel smoke and dehydrational heat stress — may amplify the effect through complementary oxidative pathways.[5,19,20]

4.4 Cataract subtypes

The included studies reported a mixture of cortical, nuclear, posterior subcapsular and mixed cataract subtypes (Table 1). The biological hypothesis linking UV-B to cataractogenesis is strongest for cortical cataract; the evidence for nuclear cataract is also robust but mechanistically more complex; the evidence for posterior subcapsular cataract is weakest. Within the present synthesis, the cortical-cataract estimates[12,13,18] — OR 3.30, OR 1.10 and an extreme-quintile estimate from the Indian CASE study — were directionally consistent with the modest- and extreme-contrast pooled estimates. Of note, the cortical-cataract estimate from S1 (Taylor HR 1988, OR 3.30; 95% CI 0.90–9.97) was the only individual estimate in the extreme-contrast stratum with a confidence interval crossing the null; this reflects the relatively small sample size of that early cohort (n = 838 watermen) and its older study design. Nonetheless, the direction of S1's estimate was consistent with the pooled extreme-contrast estimate, and the remaining three extreme-contrast studies (S3, S6, S7) were each individually statistically significant, supporting the robustness of the pooled OR 6.52. This non-significance of S1 in isolation contributes, at least in part, to the residual I^2 = 67% within the extreme-contrast stratum. The nuclear-cataract estimates[14,17,18] — OR 5.90, OR 5.35 and a high extreme-quintile estimate from the Indian CASE study — were larger than the cortical estimates, suggesting that the pooled effect may be driven disproportionately by nuclear-cataract outcomes in the high-UV Asian settings. Working-age presenile nuclear cataract has also been associated independently with smoking, asthma and tuberculosis in Korean screening-cohort evidence,[24] and posterior subcapsular cataract with tobacco, fuel-smoke exposure and hypercholesterolaemia in hospital-based Indian case-control evidence.[23]

4.5 Indonesian context and absolute-risk implications

None of the seven included studies was conducted in Indonesia. Two studies were conducted in latitudes broadly comparable to Indonesia: the Han Chinese/Taiwanese cross-sectional study[17] (latitude 18°N to 24°N) and the Indian CASE study[18] (latitude 8°N to 32°N). Under a representative Indonesian baseline cataract prevalence of approximately 18% in adults aged 40 years and over,[3] the modest-contrast pooled estimate of OR/HR 1.09 corresponds to an absolute risk increase of approximately 1.3 percentage points per unit of cumulative ocular sun exposure, while the extreme-contrast pooled estimate of OR 6.52 corresponds to an absolute cataract prevalence of approximately 45% in the highest exposure quintile, compared with approximately 10% in the lowest. These translations are illustrative and depend on the baseline-prevalence assumption; nonetheless, they convey the public-health magnitude of the effect more transparently than the relative risk alone.

4.6 Co-exposures: pesticides, dust, dehydrational stress

The included studies addressed UV–sunlight exposure as the principal exposure of interest. However, outdoor agricultural workers in tropical settings are simultaneously exposed to pesticides, dust, fuel smoke, and recurrent dehydrational heat stress, all of which have independent biological plausibility for cataractogenesis. Existing reviews of pesticide ocular toxicity have established that organophosphate, carbamate and dithiocarbamate compounds can produce lens opacity in experimental models.[5,20] Case-control evidence from agrarian India has documented that recurrent dehydrational crises are associated with blinding presenile cataract, with a population-attributable fraction approaching 38% in dose-dependent fashion.[19] In Indonesia, where outdoor agricultural workers are simultaneously exposed to high ambient UV-B, organophosphate pesticides, biomass-burning particulate matter, and recurrent heat stress, the cumulative cataractogenic burden is therefore likely to exceed the burden inferred from UV-B exposure alone.

4.7 Heterogeneity

Heterogeneity in the present synthesis was extreme when measured across the full set of seven studies ($I^2 = 99\%$) but was largely resolved within the modest-contrast stratum ($I^2 = 0\%$) (Table 3, Figure 3). The principal sources of heterogeneity were: (i) the contrast metric (extreme high-versus-low vs per-unit/ever-versus-never); (ii) the exposure-assessment method (objective field/laboratory UV measurement vs satellite-based ambient UV vs questionnaire-recalled outdoor time; Table 2); (iii) population age and cataract subtype distribution; and (iv) the study setting and latitude, with Asian study estimates (median OR 7.3) being approximately seven-fold higher than Western estimates (median OR/HR 1.1) (Section 3.5). The contrast-type moderator alone explained approximately 45% of the between-study heterogeneity.

4.8 Limitations

This synthesis has several important limitations. The primary search was executed in PubMed alone, supplemented by citation tracing and translated search strings prepared for Scopus, Embase, Web of Science and Cochrane CENTRAL; execution of those translated strings across all four supplementary databases is required before the synthesis can be considered fully PRISMA-compliant. Screening and data extraction were performed predominantly by a single reviewer, although a second reviewer performed independent dual screening on a 20% random sample with substantial inter-rater agreement ($\kappa = 0.81$ at title-and-abstract screening and $\kappa = 0.86$ at full-text screening). The number of eligible studies fell to seven, below the conventional threshold of ten for valid Egger's regression. Residual heterogeneity within the extreme-contrast stratum ($I^2 \approx 67\%$) was driven, at least in part, by heterogeneous exposure-assessment methods (Table 2). None of the seven included studies was conducted in Indonesia. The pesticide, dust, fuel-smoke and dehydrational co-exposures that frequently accompany outdoor agricultural work in tropical settings could not be quantitatively isolated.

4.9 Clinical and public-health implications

The findings of the present synthesis have direct implications for occupational and public-health practice in Indonesia and other tropical LMICs. The very strong pooled association in the extreme-contrast stratum (OR 6.52; Table 3) implies that programmes targeting the highest-exposure subgroups would yield the largest absolute reductions in cataract incidence.

Integrating annual fundoscopic and slit-lamp screening of agricultural workers aged forty years and over into the national primary-care system would be the highest-yield secondary-prevention intervention. The homogeneous modest-contrast pooled estimate of OR/HR 1.09 argues for population-wide primary-prevention measures: the routine provision of UV-blocking sunglasses and wide-brim hats as standard occupational personal protective equipment for outdoor agricultural workers. Scheduling field activities for early-morning and late-afternoon hours would simultaneously reduce ocular UV exposure and pesticide co-exposure during the same working shift — a biologically synergistic benefit. Taken together, these three strands — targeted screening of high-exposure workers, universal occupational eye protection, and behavioural scheduling — form a coherent and implementation-ready policy package whose magnitude of benefit is directly anchored to the stratified pooled estimates reported in this synthesis.

4.10 Future research

Future studies should aim to address the limitations identified above. A prospective Indonesian cohort of outdoor agricultural workers with objective ocular UV dosimetry, LOCS-graded outcome assessment, and structured capture of pesticide and dehydrational co-exposures would substantively strengthen the external evidence base. Standardisation of exposure metrics — for example, the routine reporting of both per-unit and quintile contrasts — would facilitate future quantitative syntheses. A full multi-database systematic review with dual independent screening should be performed to confirm the present findings and to update the pooled estimates as new primary studies are reported.

5. Conclusion

This systematic review and meta-analysis of seven observational studies provides quantitative evidence that occupational and environmental UV–sunlight exposure — including the cumulative sun exposure experienced by outdoor agricultural workers — is associated with a clinically and statistically significant increase in the risk of cataract. The pooled magnitude of association varied as a quantitatively important function of the exposure contrast used: studies that compared the highest with the lowest category of cumulative ocular UV reported a pooled odds ratio of 6.52 (95% CI 4.12 to 10.33), while studies that reported modest per-unit or ever-versus-never associations pooled at 1.09 (95% CI 1.04 to 1.14) (Table 3 and Figure 3). The findings are biologically plausible, mechanistically supported by oxidative damage to lens crystallins, and consistent with the latitudinal pattern of cataract burden. In tropical LMICs such as Indonesia, three implementation-ready recommendations follow: integrated annual ophthalmic screening of agricultural workers aged forty years and over in high-UV provinces; standardisation of UV-blocking sunglasses and wide-brim hats as occupational personal protective equipment; and education on peak-UV-hour avoidance during pesticide application. The findings should be confirmed by a full multi-database systematic review with dual independent screening, and ideally by a prospective Indonesian agricultural-cohort study with objective ocular UV dosimetry, LOCS-graded outcome assessment, and structured capture of pesticide and dehydrational co-exposures.

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