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Impact of smoke-free policies in outdoor areas and (semi-)private places on children's tobacco smoke exposure and respiratory health: a systematic review and meta-analysis

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Summary

Background: Smoke-free policies in outdoor areas and (semi-)private places (e.g. cars) may lower health harms caused by tobacco smoke exposure (TSE). We aimed to review studies reporting the impact of such policies on children's TSE and respiratory health.

Methods: We conducted a systematic review and meta-analysis and searched 13 electronic databases until January 29, 2021. Eligible for the main analysis were (non)-randomised trials, interrupted time series and controlled before-after studies. Primary outcomes were: TSE in places covered by the policy, and hospital attendance for wheezing/asthma, and for respiratory tract infections (RTIs) in children aged <17 years. Risk-of-bias was assessed on a 4-point scale ranging from low to critical using ROBINS-I. Random-effects meta-analysis was conducted where appropriate. PROSPERO: CRD42020190563.

Findings: Seven of the 11 identified studies fit pre-specified robustness criteria. These assessed smoke-free cars (n=5), schools (n=1), and a comprehensive policy covering multiple areas (n=1). Risk-of-bias was low to moderate in six studies and critical in one. In meta-analysis of ten effect estimates from four studies, smoke-free car policies were associated with an immediate TSE reduction in cars (risk ratio [RR] 0·69, 95% CI: 0·55 to 0·87; n=161,466). One study reported a gradual TSE decrease in cars. Individual studies found TSE reductions in school grounds following a smoke-free school policy and in hospital attendances for RTI following a comprehensive smoke-free policy.

Interpretation: Smoke-free car policies are associated with reductions in reported child TSE in cars, which could translate in health benefits. Very few studies assessed policies regulating smoking in outdoor areas and semi-private places.

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Research in context

Evidence before this study

Environmental tobacco smoke exposure (TSE) remains a major burden to child health globally. TSE during childhood increases the risk of respiratory tract infections, wheezing and asthma exacerbations. Children generally have very little control over their level of TSE. Smoke-free policies can help protect children from TSE and, through doing so, can contribute to achieving the United Nations Sustainable Development Goal 3 to improve child health and well-being.

A review published in 2017 provided strong evidence that comprehensive smoke-free legislation covering enclosed public places and workplaces is associated with substantial reductions in preterm births, hospital attendances for asthma and respiratory tract infections among children. Local and national governments are increasingly expanding the scope of policies to include outside areas and (semi-)private places that are frequently visited by children, but uncertainty remains about their effects on TSE and health outcomes. Compared to existing measures that prohibit smoking in enclosed public places in many countries, these novel policies might face more complex enforcement and compliance challenges. Moreover, such policies can potentially contribute to declines in TSE in other areas via norm-spreading. In January 2020, we searched PubMed and PROSPERO using the terms (systematic review OR meta-analysis) AND smok* AND (polic* OR regulation* OR legislation OR law) AND child* for published or planned reviews on this topic, but did not find any.

Added value of this study

Following a published protocol we systematically reviewed published studies assessing the effects of smoke-free policies for outside areas and (semi-)private places on TSE and respiratory health in children. Through a systematic search across 13 electronic databases, we identified 11 studies of which seven used robust methodologies as recommended by the Cochrane Effective Practice and Organization of Care group. Five studies evaluated smoke-free car policies. We were able to pool ten effect estimates from four studies in meta-analysis, which indicated that smoke-free car policies were followed by an immediate reduction in children's TSE in cars. Additional individual studies demonstrated reductions in child TSE following a smoke-free school ground policy and in paediatric hospital attendance for lower respiratory tract infections following a city-wide smoke-free policy covering indoor public, (semi-)private, and outside areas. Whereas the health benefits of indoor smoke-free policies are already well established, this is the first systematic assessment of the impact of policies regulating smoking in outdoor and (semi-)private areas. With policy-makers now increasingly considering implementing such regulations, our work fills an important knowledge gap on the potential effectiveness of these next steps that can be taken in protecting people, and particularly children, from the harmful effects of TSE. At the same time, it highlights the need for additional robust evaluations of such policies, particularly those regulating smoking in outdoor areas and (semi-)private places other than cars.

Implications of all the available evidence

Previous work has found that comprehensive smoke-free legislation covering enclosed public places is a powerful tool to reduce the adverse health effects of TSE in children. The additional evidence from this review, based on a small number of studies indicates that smoke-free car policies can be effective in further reducing TSE in children. We identified very few evaluations of smoke-free policies in outdoor places. Although these indicated potential benefits, more robust studies are clearly needed to corroborate this finding.

Introduction

Environmental tobacco smoke exposure (TSE) resulting from second-hand smoke (i.e. inhalation of emitted smoke) and potentially also from third-hand smoke (i.e. the uptake of tobacco smoke residuals from polluted surfaces) is known to cause a major burden on children's health.[1-3] Each year, second-hand smoke is responsible for an estimated 56,000 deaths in children under ten years of age globally[1] and for 35,633 disability-adjusted life years (DALYs) among children in the European Union.[2] TSE has been linked to a range of adverse respiratory health outcomes in children, including respiratory tract infections (RTIs), wheezing, and asthma.[4,5] Governmental action to protect children from these deleterious effects of TSE is urgently needed, as children are not able to control their level of exposure.[6] Smoke-free policies have been identified as a key instrument to achieve the United Nations Sustainable Development Goal 3 to improve child health and well-being.[7,8]

Solid evidence indicates that smoke-free policies covering enclosed public places can effectively reduce adverse respiratory health outcomes in children, including decreasing hospital attendance for asthma exacerbations by –10% [95% confidence interval (CI) –17 to –3] and hospital attendance for lower RTIs by –18% [95% CI –33 to –4].[5] These health benefits are likely mediated via a reduction in TSE from second- and possibly also third-hand smoke. Smoke-free policies covering enclosed public areas can decrease child TSE in places covered by the policy, but also – via norm spreading – in places not covered including private places, such as cars or homes.[9-13]

In recent years, an increasing number of jurisdictions have expanded smoke-free policies to encompass outdoor areas (e.g. school grounds, playgrounds and parks),[14] semi-private places (e.g. shared housing), and private places (e.g. privately owned cars).[15] Many of these places are frequented by children and therefore contribute to TSE during childhood. Estimates of the effectiveness of these 'novel smoke-free policies' cannot be easily extrapolated from earlier evidence on smoke-free indoor areas, for example, given the dilution of TSE in outdoor places, and enforcement issues regarding policies covering private areas.[15] Besides, it is unclear whether such policies affect TSE exposure in other places either negatively (i.e. via displacement of smoking) or positively (i.e. via norm spreading).[15]

In order to inform policy, we sought to systematically review evidence on the impact of smoke-free policies covering outdoor areas or (semi-)private places on TSE and respiratory health in children.

Methods

Protocol and registration

This systematic review and meta-analysis was conducted according to a published peer-reviewed protocol with PROSPERO registration (CRD42020190563).[16] We used PRISMA guidelines to report our findings.[17] Ethical approval was not required for this study.

Eligibility criteria

Studies were eligible for inclusion if they evaluated the association between implementation of policies restricting smoking in designated (semi-)private places or any outdoor areas, and TSE and/or respiratory health outcomes in children. In line with earlier systematic reviews,[5,18] we included studies in which at least 50% of the study population was aged <17 years to ensure that we would not exclude studies that included a high proportion of children. Studies reporting the effect of a smoke-free policy covering indoor private places (e.g. cars), indoor semi-private places (e.g. multi-unit housing), outdoor (semi-)private places (e.g. shared gardens), and outdoor public places (e.g. parks, school grounds, beaches, hospital grounds) introduced at any governmental or institutional level were considered eligible. Moreover, studies reporting on such policies which were simultaneously introduced with other tobacco control measures were also eligible. We excluded studies evaluating smoke-free policies covering only enclosed public places. Primary outcomes were: 1. TSE in places covered by the policy; 2. unplanned hospital attendance for wheezing/asthma; and 3. unplanned hospital attendance for RTIs. We defined unplanned hospital attendance as acute presentations to an emergency department as well as hospital admissions. Secondary outcomes were 1. TSE in places of which only some were covered by the policy or in unspecified places; 2. TSE in places not covered by the policy; 3. cotinine or other biomarkers of TSE; 4. TSE assessed by wearable devices; 5. incidence of wheezing/asthma; 6. incidence of RTIs; 7. otitis media with effusion (OME); 8. chronic cough; 9. lung function parameters. Studies reporting on exposure assessment not specific to tobacco smoke (e.g. particulate matter) or changes in smoking behaviour per se without assessing changes in children's exposure were excluded. Following the methodological recommendations of the Cochrane Effective Practice and Organization of Care (EPOC) group,[19] we selected studies with the most robust study designs for our main analyses, namely: (non-)randomised trials, interrupted time series, and controlled before-after studies. In sensitivity analyses, we also included studies that did not meet the EPOC criteria: prospective cohort studies, retrospective cohort studies, and uncontrolled before-after studies.

Information sources and study selection

To identify eligible studies our research team, including an information specialist specialised in search strategy optimisation, searched, from date of inception until 29 January 2021, 13 electronic databases (see search strategies in appendix pp 2-4). No restrictions were imposed for the observational period, publication date, or language. To identify additional relevant studies including grey literature, we hand-searched reference lists and citations of included studies and consulted with experts in the field (appendix p 5). All identified records were extracted into an EndNote Library. Following automatic deduplication, two out of the three reviewers (MKR, FJMM, and LEHW) independently screened each record's title and abstract, manually identifying and removing any remaining duplicates, and thereafter the full-texts, to identify eligible studies. Disagreement was resolved through discussion or by involving an adjudicator (JVB).

Data collection and risk of bias assessment

Two of the three reviewers (MKR, FJMM, and LEHW) independently extracted data including adjusted test statistics from each study using a pre-specified form (appendix pp 6-8) and assessed risk of bias for effect estimates from each study using the *Risk of Bias in Non-Randomised Studies of Interventions* (ROBINS-I) tool.[20] From studies that reported multiple effect estimates for overlapping study samples, we extracted one estimate based on the following hierarchy; (1) the most adjusted model, (2) the longest observation period, (3) the most comprehensive policy, or (4) the largest intervention group. Again, disagreements were resolved through discussion or by involving an adjudicator (JVB). If relevant data were missing, we contacted the corresponding author. We extracted from the included studies any additional information that could provide further insight on the robustness of the findings (i.e. use of an alternative comparison group, neutral outcomes, or alternative method) and on the mechanism of how policies might have impacted the outcomes of interest, following the United Kingdom (UK) Medical Research Council guidance on natural experiments.[21]

Summary measures

Point estimates and 95% CIs are reported in tabular form. For dichotomous outcomes, we harmonised effect estimates into relative risk (RR). When a study reported odds ratios (ORs) instead, we contacted the corresponding author to request the RR. In case this could not be provided, we applied the following formula to approximate RR based on OR:

$$RR = \frac{OR}{(1 - EER) + (EER \times OR)}$$

where EER is the expected event rate or prevalence in the control group.[22] If EER was not available in interrupted time series studies, the overall event rate of the study population was used instead. Regarding outcomes that could occur multiple times with the same individual (e.g. hospital attendance), we analysed incidence rate ratios (IRRs).

Statistical analysis

We performed random-effects meta-analyses to derive pooled effect estimates when at least two studies evaluated policies that regulated smoking in similar places and reported on the same outcome. Based on a one-sided log-likelihood-ratio test, we assessed whether a three-level meta-analysis instead of a two-level meta-analysis would be needed to account for dependency of observations for estimates of similar policies implemented in different regions within a country. Step changes (immediate changes) and slope changes (gradual changes) were pooled in separate models.

We conducted sensitivity analysis including studies with a less robust design.[16,19] A priori, we planned a number of other sensitivity and subgroup analyses that we could not conduct due to the low number of eligible studies.[16] We presented findings on effect modification by socioeconomic status when it was reported. In addition to quantitative study findings, we narratively describe additional elements from individual studies that may support causal inference.

As we anticipated that most studies would have evaluated TSE rather than health outcomes, we planned an additional health impact assessment to estimate the potential impact of any observed changes in TSE following the introduction of smoke-free policies. We calculated the potential impact fraction (PIF) which captures the change in health outcomes attributable to the change in TSE following the policy implementation, as follows:[23]

$$PIF = \frac{(P_0 - P_1) \times (RR - 1)}{P_0 \times (RR - 1) + 1}$$

where P_0 is the prevalence of TSE before policy implementation, P_1 is the prevalence of TSE after policy implementation, and RR the relative risk of respiratory disease of children exposed to TSE over unexposed children. To capture the sensitivity of PIFs to varying parameters, we calculated PIFs given a plausible range of TSE baseline levels, and associations between exposure and outcome. Based on studies identified in the review, this analysis was only possible for smoke-free car policies. In these studies, TSE before implementation ranged from 6% in the UK[24] to 43% in Canadian provinces.[25] Therefore, we modelled scenarios varying the baseline TSE levels between 5 and 45%. As a reference value of the strength of the association between TSE in cars and asthma diagnosis, we used the associations presented by one included study (i.e. RR 1·12 (95% CI 0·98 to 1·28) for children with 1 to 2 days per week of TSE in cars as compared to children with no TSE in cars, and RR 1·19 (95% CI 1·02 to 1·38) for children with 3 to 7 days per week of TSE in cars.[26]

All analyses were conducted in R version 3.4.1 using the metafor package for the meta-analyses.

Role of the funding source

The funders of this study had no role in study design, data collection, analysis, data interpretation, or writing of the report. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Results

We identified 5,745 records and after de-duplication, 2,831 records were screened on title and abstract. From 204 full-text articles assessed, 11 eligible studies were identified (Figure 1). No ongoing or unpublished studies were found.

Seven studies meeting EPOC criteria were included: four controlled before-after studies,[24,25,27,28] and three interrupted time series studies (appendix pp 9-13).[15,26,29] Overall, risk of bias was low in three studies,[15,25,26] moderate in three,[24,27,28] and critical in one study (appendix pp 14-15). Table 1 shows the primary and secondary outcomes that were assessed in the identified studies. Information on the evaluated policies and enforcement is presented in Table 2. Five studies evaluated smoke-free car policies, of which two focussed on the national policy in England (UK),[15,24] two on various policies across Canadian provinces,[25,27] and one in California (US).[26] One study assessed a smoke-free school policy in Canada,[28] and another evaluated a comprehensive smoke-free policy covering enclosed public, (semi-)private, and outside areas in Hong Kong.[29] Four of the 11 eligible studies did not meet EPOC criteria, and are discussed separately.[30-32]

In two-level meta-analysis, smoke-free car policies were associated with an immediate risk reduction in child TSE in cars (RR 0·69, 95%CI: 0·55 to 0·87; ten effect estimates from four studies, 161,466 participants) (Figure 2). A one-sided log-likelihood-ratio test favoured two-level over three-level meta-analysis (P-value: 0·38) (appendix p 17). One additional study from California (US) found that the smoke-free car policy was followed by an annual reduction in child TSE in cars (RR 0·95/year, 95%CI: 0·94 to 0·97; 151,074 participants), with no significant temporal trend in TSE in the pre-intervention period.[26]

Two studies reported on secondary TSE outcomes (appendix pp 18-19).[15,25] One study from England found a relative increase in the proportion of children having detectable salivary cotinine levels (RR 1·22, 95% CI 1·06 to 1·38; 7,858 participants).[15] Although TSE at home or other people's homes appeared to increase following the policy in this study, this was not statistically significant. One Canadian study found that the smoke-free car policy was not associated with significant changes in TSE at places other than cars, including bus stops and shelters, parks and sidewalks, and inside restaurants.[25]

Regarding health outcomes, one study from England found no significant change in the incidence of childhood wheezing or asthma following the smoke-free car policy (RR: 0·82 [95% CI 0·63 to 1·05]; 13,369 participants) (appendix pp 18-19).[15]

Among studies assessing other policies, a controlled before-after study from Canada found a reduction in TSE among high school students on school property following a smoke-free school policy (RR 0·89, 95%CI: 0·83 to 0·95; 20,388 participants) (Table 3).[28] No health outcomes were assessed.

An interrupted time series study from Hong Kong found that a comprehensive smoke-free policy covering (semi-)private, and outside areas in addition to enclosed public spaces was associated with an immediate drop in unplanned hospital attendances for RTIs among children (RR 0·66, 95% CI: 0·63 to 0·69; n=75,870 hospital attendance) and an additional annual decrease over the first six years following the new policy (RR 0·86/year, 95%CI: 0·84 to 0·88).[29]

Four studies did not meet EPOC criteria, and all had a critical risk of bias (appendix pp 20-23). One uncontrolled before-after study evaluated a comprehensive smoke-free policy covering cars and outside areas in Quebec (Canada).[33] The results indicated an immediate reduction in child TSE in cars (RR 0·42, 95% CI: 0·30 to 0·57) (appendix pp 24-26), and a decline in child TSE at home (RR 0·55, 95% CI: 0·41 to 0·73). Including this estimate in the meta-analysis did not materially change the overall effect estimate of smoke-free car policies on child TSE (RR 0·66, 95% CI: 0·53 to 0·83) (appendix p 27).

We identified three uncontrolled before-after studies that evaluated the same comprehensive smoke-free city-wide policy in Hong Kong (appendix pp 20-23).[30-32] Meta-analysis of these studies was not possible since study populations overlapped, or outcomes could not be harmonised. One study found that the policy was followed by a significant increase in TSE in places covered by the policy and in TSE overall (appendix pp 24-26).[30] Two other studies using parental-reported outcomes did not assess TSE in places covered by the policy, but found a significant decrease in child TSE at home.[31,32]

Using effect estimates from the meta-analysis, we estimated the proportion of respiratory disease that could potentially be prevented by the observed TSE reductions following smoke-free car policies. Assuming an arbitrarily chosen but plausible baseline level of TSE in cars of 20% and using the association between TSE for 1-2 days a week and asthma (RR=1·12), we estimate that 2·3% (95% CI: –0·4 to 5·3) of asthma diagnoses are attributable to TSE in cars. Based on the effect estimate of our meta-analysis, the PIF indicated that the proportion of asthma diagnoses would decrease by –0·7 percent (95% CI: –1·1 to –0·4) by implementing a smoke-free car policy at this baseline TSE level (Figure 3). In the appendix (p 28), we show different scenarios indicating that the proportion of asthma cases among children that could potentially be prevented by smoke-free car policies ranged between –0·2% and –2·4%, depending on a plausible range of baseline TSE. PIFs were not calculated for policies covering outdoor areas, since meta-analysis on the effect of these policies on TSE was not possible.

One study assessed socioeconomic inequalities in TSE following the implementation of a comprehensive smoke-free policy including outside areas and cars in Quebec (Canada).[33] Findings suggested that child TSE in cars and at home decreased in each education and income group, but that the relative inequalities remained unchanged.

Some studies provided further information supporting robustness of the findings (appendix pp 29-30).[34] Three studies found that results were robust to different specifications of comparison groups.[15,24,27] A Canadian study did not correct for a pre-legislation trend in their main analysis, but additionally showed that TSE in cars did not decline before the policy was introduced.[25] The US study on smoke-free cars showed that the change in TSE in cars in California could not be explained by secular trends at the national level.[26] Some studies reported further information on the underlying mechanism that may explain the change in outcomes. A study from England found that the implementation of the smoke-free car policy did not significantly change active smoking or TSE in cars among adults, possibly explaining the null findings for TSE in cars among children in that study.[15] A study evaluating the smoke-free car policy in Canada did not find a significant change in smoking at home among smokers, suggesting that no significant displacement of TSE or norm spreading towards other private areas occurred.[25] Furthermore, the policy impact was restricted to children whose parents had a car, supporting causality of the findings.[25]

Discussion

This systematic review and meta-analysis found that smoke-free car policies were associated with substantial reductions in TSE among children in cars. We estimate that such changes may translate into an estimated –0·2 to –2·4% decrease in asthma diagnoses. Additionally, a very limited number of studies indicated that smoke-free policies covering school grounds and a comprehensive smoke-free policy covering indoor public, (semi-)private, and outside areas may reduce TSE and improve health outcomes in children. Although based on a small number of studies, the evidence identified suggests that extending smoke-free policies to private and outdoor settings may help protect children from TSE-related harms and may provide additional health benefits.

To our knowledge, this is the first systematic assessment of the impact of smoke-free policies covering outdoor and (semi-)private places on children's TSE and respiratory health. Whereas the link between smoke-free policies in enclosed public places and child health benefits is already well established,[5,18] the effect of smoke-free policies in other locations was unclear. To ensure that all relevant studies were identified, we used a comprehensive search strategy including screening 13 electronic databases, checking references and citations, and consulting experts to identify additional studies. Moreover, we followed EPOC guidelines for including studies using methodologically robust designs in the main analysis.[19] We also extracted supportive information from the included studies to facilitate causal reasoning.

Evidence on the effectiveness of smoke-free policies, similar to most large-scale public health interventions, was derived from quasi-experimental studies. Although such methodologies have a risk of bias,[34] this was assessed to be low to moderate in six out of seven studies in our primary analyses, strengthening confidence in our results. Due to the small number of eligible studies, we could not conduct our pre-planned meta-regression and subgroup analyses, nor assess potential publication bias. Our findings need to be supported with future additional studies, and at present need to be interpreted with caution. Further, our findings must be interpreted in the light of the observational nature of the available evidence, the fact that findings from systematic reviews and meta-analyses are inherently dependent on the quality of the underlying studies (which is why we limited our primary analyses to EPOC-approved designs), and on heterogeneity of the estimated effects.[35,36] All TSE outcomes were child- or parent-reported. Although these measures might be subject to desirability bias, previous studies support their validity in quantifying actual exposure.[37,38] Biomarkers for exposure were evaluated in some studies,[15,32] but these cannot discern between TSE in various locations. Further, TSE presents different risks in different settings. For example, TSE in cars will likely be more harmful to child health than TSE in outside areas.[39,40] A formula suggested by the Cochrane Handbook was used to compute RR when only OR was available, however, the conversion may be biased in situations with a high level of confounding.[41]

Our review builds on solid existing evidence indicating child health benefits of smoke-free policies.[5] Based on the current meta-analysis, we estimated that smoke-free car policies may contribute to a moderate reduction in the number of asthma diagnoses in children, ranging from –0·2% in the most conservative scenario with low baseline levels of TSE in cars, to –2·4% in the most favourable scenario. It is important to note that these calculations assumed that there was no change in TSE in other places than cars, which needs further substantiation in future research as the current evidence-base on this is rather limited.[15] Despite the relatively modest reductions, more widespread implementation of smoke-free car policies might translate to important health benefits given the substantial global burden of asthma.[42,43]

All evidence in this review was derived from countries with an already existing and well-enforced comprehensive smoke-free legislation covering enclosed public places. Thus, countries may derive substantial additional benefits by implementing an even more comprehensive measure covering indoor enclosed places,[5] as well as private and outdoor areas. Moreover, the comprehensive smoke-free policy in Hong Kong covering indoor public, (semi-)private, and outside areas was associated with large reductions in hospital attendances for lower RTIs in children. Although it is not possible to disentangle the relative contributions of the various spaces covered by this smoke-free policy, the effect sizes were much larger than those from other studies which assessed the impact of policies covering enclosed public places only on child RTIs,[44-46] suggesting that part of the impact may be from its additional coverage of (semi-)private and outdoor areas.

Previous studies indicated that part of the positive health impact of smoke-free policies covering indoor public places may be mediated via reducing TSE in cars and homes through norm spreading.[13] At present, there is limited insight on whether norm spreading also occurs following smoke-free policies covering outdoor or private places, or whether displacement of smoking to areas not covered by the policy may occur.[47] In our review, there was mixed evidence on the impact of smoke-free policies covering private or outdoor areas on TSE in areas not covered by the policy. One study found that salivary cotinine levels increased in children following the smoke-free car policy in England, indicating that overall TSE may have increased.[15] In contrast, there was no evidence of displacement of smoking to outside areas or restaurants using surveys following the Canadian smoke-free car policy. Another Canadian study showed that TSE at home was reduced following a comprehensive policy including outdoor areas and cars.[33] Two studies found that the comprehensive city-wide smoke-free policy in Hong Kong was associated with a reduction in TSE in areas which were not covered by the policy,[31,32] however, one study found the opposite.[30] This inconsistency could derive from the fact that the latter study was based on child reports, whereas the other two studies relied on parent-reported outcomes which could be subject to higher desirability bias. Further, substantial displacement of TSE is unlikely in Hong Kong given the observed reduction in hospital attendances for RTIs.[29] We are unaware of any evidence from other studies on whether smoke-free policies in (semi-)private or outdoor areas had an impact on smoking behaviour in places not covered by the policy.

Compliance is essential for smoke-free policies to be effective, and enforcement of policies covering private or outdoor places can be challenging.[48-51] Despite these challenges, which were also noted in the included studies, health benefits could be demonstrated, and these may increase with more widespread adoption and acceptability. Several measures could be taken to improve policy compliance such as penalties,[48,51] smoke-free signages,[52,53] or information campaigns,[49,54] which can carry additional child health benefits.[55] In general, the reviewed policies were positively perceived by the general population which can foster effective policy implementation.[56] Smoke-free policies introduced in public enclosed areas often gain support after implementation as they become customary.[57-60] We are currently conducting a related review to assess determinants of public support for smoke-free policies covering private and outdoor places.[61]

Our review provides the first meta-analysis assessing the effectiveness of smoke-free car policies on TSE among children. More studies are needed to further substantiate findings for smoke-free policies in outdoor areas and should cover a wider range of areas. No eligible studies assessing policies for private homes, outdoor hospital grounds, or parks were identified even though these policies could potentially have a great impact on children's health. Previous studies found that such policies can decrease TSE among adults and cross-sectional studies also supported the potential child health benefits of these policies.[40,62-66] We did not identify any study exploring the differential effects of novel smoke-free policies in low-income countries. This is worthy of future investigation as previous studies have observed that population-level tobacco control policies might produce greater health benefits in low-income populations.[15,67]

To conclude, although the health burden associated with TSE has declined over past decades around the world, there is still considerable scope to further reduce this preventable harm to children.[68] To realise this goal, comprehensive smoke-free policies are needed and our review, albeit based on a small number of studies, suggests that including private and outdoor places in national tobacco control policies may produce additional benefits. The majority of studies identified evaluated smoke-free car policies, and when taken together, these suggest that such policies can help reduce children's TSE in cars. Based on informed estimations, we demonstrate that this may translate into small improvements in respiratory health. We found limited evidence indicating that policies covering other private or outdoor areas may also reduce TSE and offer additional respiratory health benefits. All children around the world should have the right to breathe clean air in private, public, indoor and outdoor areas.

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Declaration of interests

We declare no competing interests.

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Authors contributions

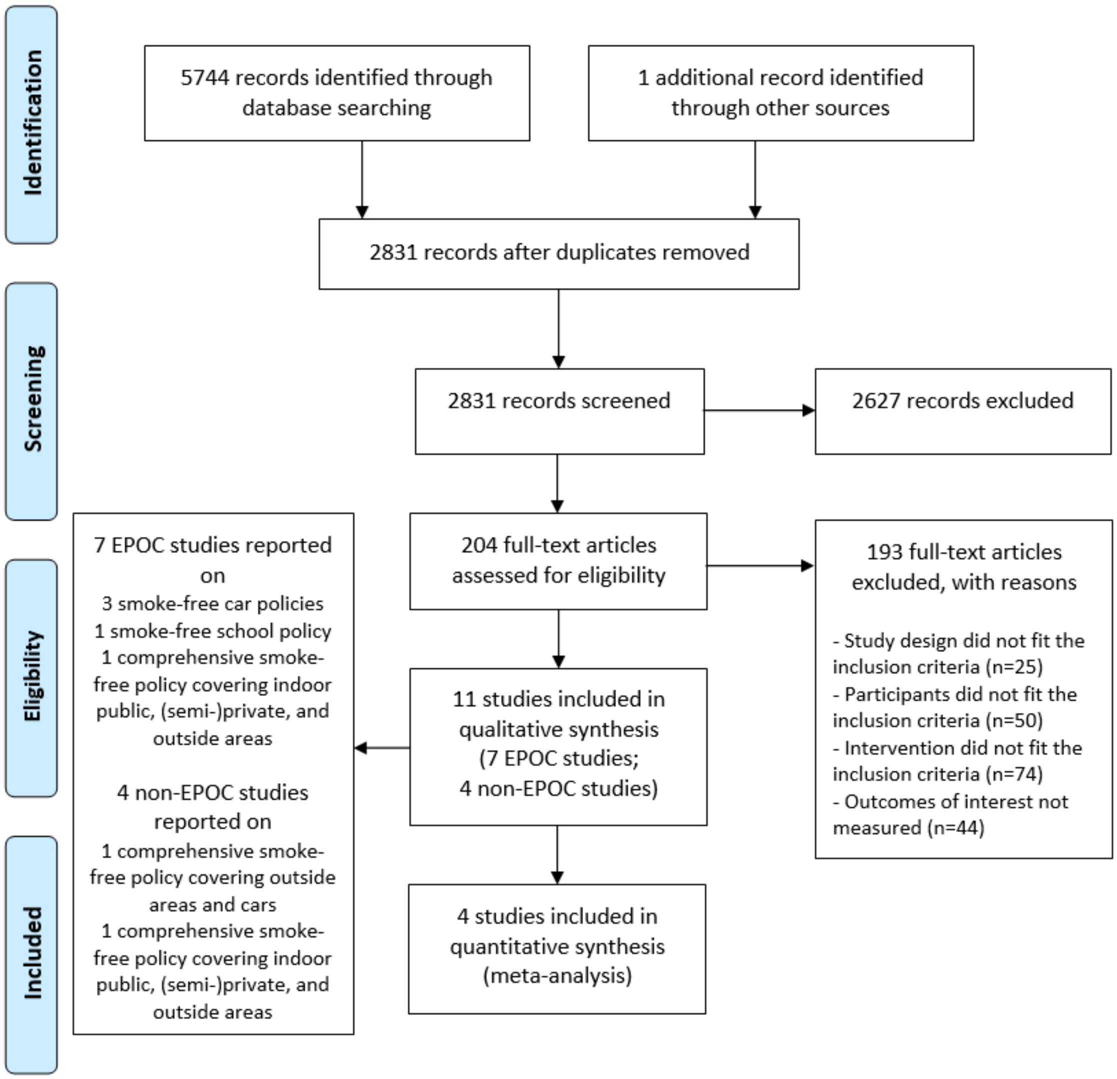
JVB secured funding for this work. MKR, FJMM, AS, CM, AB, FJL, and JVB designed the study and wrote the protocol. MKR, FJMM and LEHW contributed to the study search, study selection, data extraction, and risk of bias assessment. JVB supervised all the steps in the review process. MKR and FJMM did the data analysis and created the figures. All authors interpreted the findings. MKR, FJMM, LEHW, and JVB drafted the manuscript and appendix. AS, CM, AB, and FJL provided feedback. All authors had access to the underlying data. MKR, FJMM and JVB verified the underlying data. All authors read and approved the final manuscript. MKR and FJMM contributed equally to this work.

Data sharing

All datasets generated and analyses are available in the article and appendix.

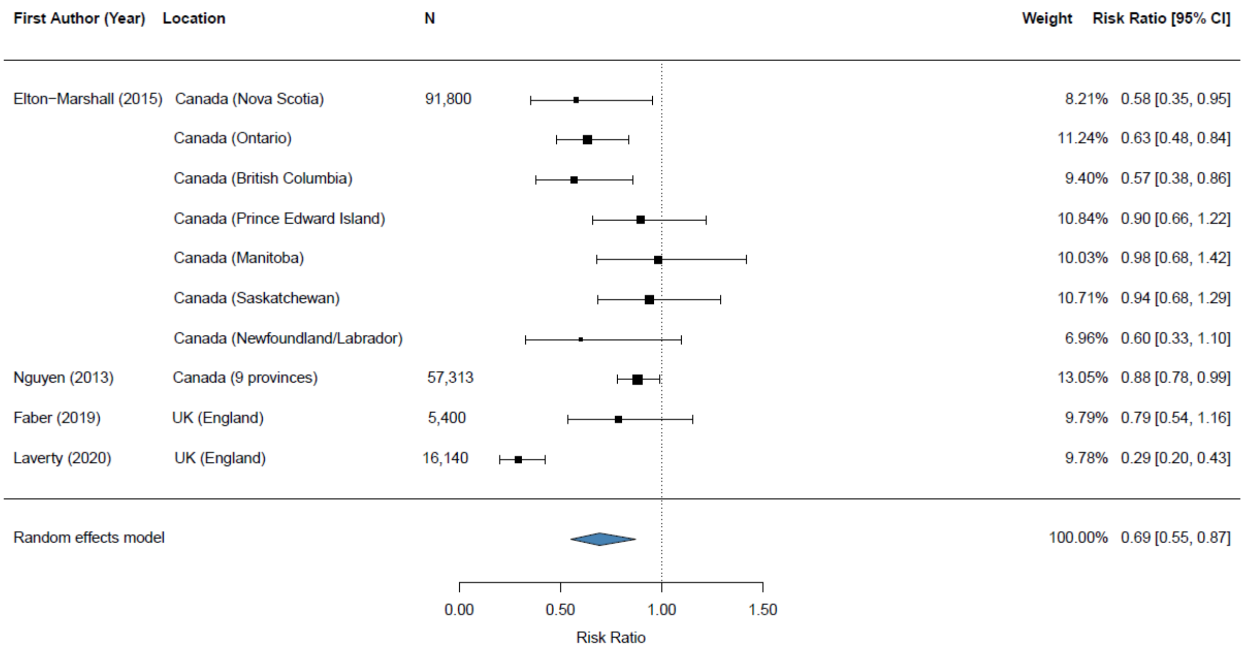
Figures

Figure 1: PRISMA flow diagram



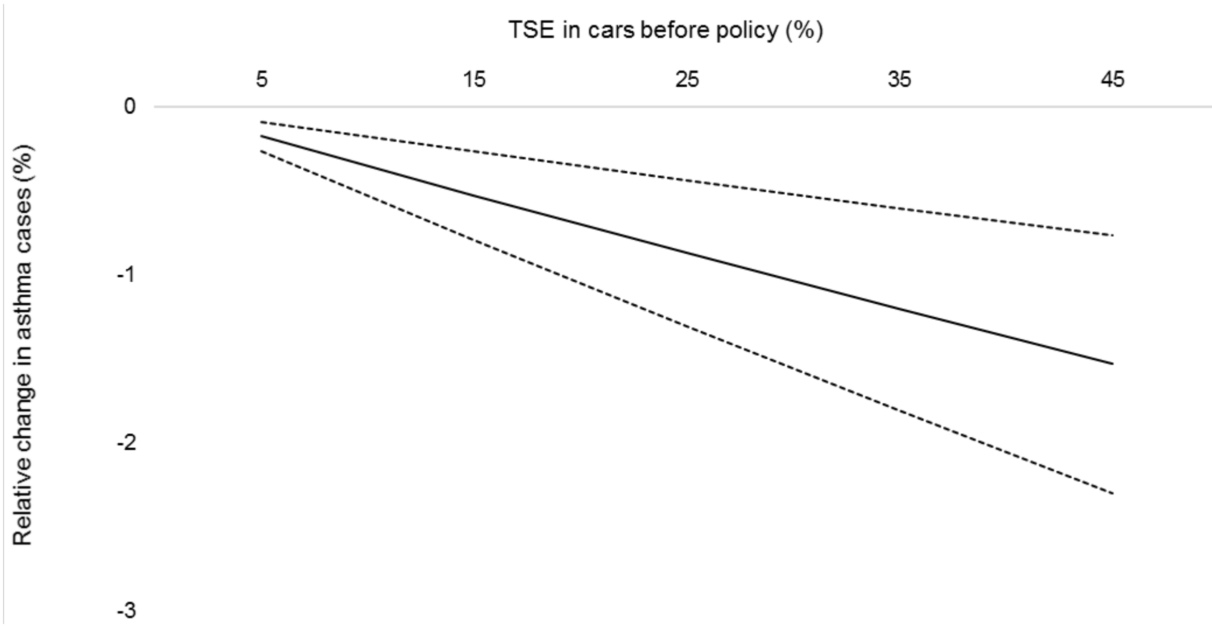
Abbreviations: EPOC = Effective Practice and Organization of Care

Figure 2: Meta-analysis of relative risk of child tobacco smoke exposure in cars before and after implementation of smoke-free car policy



Black squares indicate the point estimate for each policy, with the horizontal lines representing the 95% confidence intervals. The pooled effect of the ten estimates was obtained using a random-effects meta-analysis, with the effect of each event weighted by the inverse of its variance. The pooled effect is indicated with the diamond, and the width of the diamond corresponds with the 95% confidence intervals of the pooled effect. N refers to the number of participants in the given study.

Figure 3: Estimated proportion of asthma cases in children that could be prevented by introducing smoke-free car policies for varying baseline levels of tobacco smoke exposure in cars.



The relative change in asthma cases was estimated by calculating the potential impact fraction, which captures the change in asthma cases attributable to the change in tobacco smoke exposure following the implementation of smoke-free car policies.
The solid line represents the average effect, dotted lines represent 95% confidence interval
Abbreviations: TSE=tobacco smoke exposure

Tables

Table 1 – Primary and secondary outcomes that were reported in included studies on smoke-free policies

First author (year of publication)	Meeting EPOC criteria	TSE outcome				Health outcome		
		Primary: TSE in places covered by the policy	Secondary: TSE in unspecified places	Secondary: TSE in places not covered by the policy	Secondary: biomarker of TSE	Primary: unplanned hospital attendance for RTIs	Secondary: incidence of wheezing/ asthma	Secondary: chronic coug
Smoke-free car policy								
Elton-Marshall (2015)[27]	Yes	X						
Faber (2019)[15]	Yes	X		X	X		X	
Laverty (2020)[24]	Yes	X						
Nguyen (2013)[25]	Yes	X		X				
Patel (2018)[26]	Yes	X						
Comprehensive smoke-free policy covering outside areas and cars								
Gagné (2020)[33]	No	X		X				
Smoke-free school ground policy								
Azagba (2016)[28]	Yes	X						
Comprehensive smoke-free policy covering indoor public, (semi-)private, and outside areas								
Lee (2016)[29]	Yes					X		
Chan (2011)[31]	No		X	X			X	
Chan (2014)[32]	No		X	X	X			
Ho (2010)[30]	No	X	X	X				X

Abbreviations: TSE = tobacco smoke exposure; RTI = respiratory tract infection; EPOC= Cochrane Effective Practice and Organization of Care

Note: ‘X’ denotes that the certain study included the given outcome

Table 2– Description of the novel smoke-free policies evaluated in eligible studies[a]

First author (year)	Country (region)	Description	Level of enforcement	Timing of implementation	Enforcement	Actual enforcement
Smoke-free car policy						
Nguyen (2013)[25]; Elton-Marshall (2015)[27]	Canada (nine provinces)	Smoke-free car policy prohibiting smoking in private vehicles with anyone aged ≤15 years present (≤18 years for Nova Scotia and Prince Edward Island)	Province	Nova Scotia April 1, 2008; Ontario January 21, 2009; British Columbia April 7, 2009; Prince Edward Island September 1, 2009; New Brunswick January 1, 2010; Manitoba July 15, 2010; Saskatchewan October 1, 2010; Newfoundland May 31, 2011; Alberta January 1, 2013.	Law enforcement agencies were authorised to issue fines or warnings to those who do not comply with the ban. Fines vary across provinces (maximum fines stated in the provincial Tobacco Control Act for any offences, but no specific guideline for violating smoke-free car policy).	A few fine tickets were issued in the initial periods which mainly relied on the deterrence effect and educating the value of the policy.
Faber (2019)[15]; Laverty (2020)[24]	United Kingdom (England)	Smoke-free car policy prohibiting smoking in private vehicles with anyone aged ≤18 years present. Exceptions apply for convertible cars with the roof completely down and for e-cigarettes	Country	October 1, 2015	The driver and smokers who break this policy risk a £50 (i.e. US$60) fine each. Before the policy came into force, police had announced that they were not planning to actively enforce the policy.	One year after the policy was imposed, only one single penalty was issued in England. Other cases were dealt with by verbal warnings.
Patel (2018)[26]	United States of America (California)	Smoke-free car policy prohibiting smoking in a motor vehicle with anyone aged ≤17 years present	State	January 1, 2008	Police was not authorised to stop a vehicle for a smoking violation alone; it must have been secondary to another infraction. Violators of the policy can be fined up to US$100.	Not reported
Comprehensive smoke-free policy covering outside areas and cars						
Gagné (2020)[33]	Canada (Quebec)	A comprehensive smoke-free policy	Province	November 2015	Police services may stop a motor vehicle if the member	Not reported

		covering bar and restaurant patios, playgrounds, within 9 metres from building entrances and in vehicles with youth under the age of 16. Furthermore, it permitted landlords to enforce a smoke-free policy in multi-unit apartment buildings.			has reasonable grounds to believe that a person is smoking in the vehicle while a minor under 16 years of age is present in it. Furthermore, smoking in a prohibited place is fined (US$40 to US$600), and repeated offences are higher (US$80 to $1200).	
Smoke-free school policy						
Azagba (2016)[28]	Canada (four provinces)	Smoke-free school policy (not further specified)	Province	Quebec May 2006; British Colombia March 2008; Prince Edward Island September 2009; Saskatchewan August 2010.	Law enforcement agencies were authorised to issue fines or warnings for any smoke-free policy offences. Fines vary across provinces (maximum fines stated in the provincial Tobacco Control Act for any smoke-free policy offences, but no specific guideline for violating smoke-free school policy).	Not reported
Comprehensive smoke-free policy covering indoor public, (semi-)private, and outside areas						
Ho (2010)[30]; Chan (2011)[31]; Chan (2014)[32]; Lee (2016)[29]	Hong Kong	A comprehensive smoke-free policy covering indoor public, (semi-)private, and outside areas (i.e. public playgrounds, parks, beaches, barbecue sites, public swimming pools and areas of public housing estates)	City	January 1, 2007	Policy was enforced by the Tobacco Control Office. The budget for policy enforcement increased from the US $0·9 million in 2006 (pre-legislation) to US$3 million in 2007 (post legislation). Penalty points are allotted to households for smoking and other offences, with the ultimate punishment being the termination of tenancy.	The policy was effectively enforced. In two years, 11085 penalties were issued against smoking offences (outside or inside areas).

[a] A list of additional sources used to extract information on the policies is available in appendix 4 (p 16)

Table 3 – Findings from studies meeting EPOC criteria reporting the association between implementation of novel smoke-free policies and primary outcomes

First author (year)	Country (region)	Intervention population	Sample size	Observational period	Outcome eligibility	Outcome	Reported intervention effect	Summary of findings
Smoke-free car policy								
Elton-Marshall (2015)[27]	Canada (Nova Scotia)	Children aged 11-14 years	91800 (without missing values 83331)	2004-2012	Primary: TSE in places covered by the policy	Child-reported TSE in cars in the past seven days (any vs none)	OR: 0·47 (0·25 to 0·89)	Smoke-free car policy in Nova Scotia was associated with a reduction in TSE in cars
	Canada (Ontario)				Primary: TSE in places covered by the policy	Child-reported TSE in cars in the past seven days (any vs none)	OR: 0·58 (0·42 to 0·80)	Smoke-free car policy in Ontario was associated with a reduction in TSE in cars
	Canada (British Columbia)				Primary: TSE in places covered by the policy	Child-reported TSE in cars in the past seven days (any vs none)	OR: 0·51 (0·32 to 0·82)	Smoke-free car policy in British Colombia was associated with a reduction in TSE in cars
	Canada (Prince Edward Island)				Primary: TSE in places covered by the policy	Child-reported TSE in cars in the past seven days (any vs none)	OR: 0·87 (0·59 to 1.30)	Smoke-free car policy in Prince Edward Island was not associated with significant changes in TSE in cars
	Canada (Manitoba)				Primary: TSE in places covered by the policy	Child-reported TSE in cars in the past seven days (any vs none)	OR: 0·98 (0·62 to 1.54)	Smoke-free car policy in Manitoba was not associated with significant changes in TSE in cars

First author (year)	Country (region)	Intervention population	Sample size	Observational period	Outcome eligibility	Outcome	Reported intervention effect	Summary of findings
	Canada (Saskatchewan)				Primary: TSE in places covered by the policy	Child-reported TSE in cars in the past seven days (any vs none)	OR: 0·91 (0·56 to 1.48)	Smoke-free car policy in Saskatchewan was not associated with significant changes in TSE in cars
	Canada (Newfoundland/ Labrador)				Primary: TSE in places covered by the policy	Child-reported TSE in cars in the past seven days (any vs none)	OR: 0·53 (0·26 to 1.09)	Smoke-free car policy in Newfoundland/Labrador was not associated with significant changes in TSE in cars
Faber (2019)[15]	United Kingdom (England)	Children aged 8-15 years	5400 (without missing values 5399)	2008-2017	Primary: TSE in places covered by the policy	Child-reported TSE in cars in the past days (any vs none)	OR: 0·77 (0·51 to 1.17)	Smoke-free car policy in England was not associated with significant changes in TSE in cars
Laverty (2020)[24]	United Kingdom (England)	Children aged 13-15 years	16140 (missing values unknown)	2012-2016	Primary: TSE in places covered by the policy	Child-reported TSE in cars in the past seven days (regular exposure vs non/occasional)	OR: 0·28 (0·21 to 0·37) Absolute difference (percentage points): -4 (-3 to -2)	Smoke-free car policy in England was associated with a reduction in TSE in cars

First author (year)	Country (region)	Intervention population	Sample size	Observational period	Outcome eligibility	Outcome	Reported intervention effect	Summary of findings
Nguyen (2013)[25]	Canada (Prince Edward Island, Nova Scotia, New Brunswick, Ontario, Manitoba, Saskatchewan, British Columbia)	Children aged 15-16 years, except for Nova Scotia and Prince Edward Island where children were aged 15-19 years	57313 (without missing values 56596)	2005-2010	Primary: TSE in places covered by the policy	Child-reported TSE in cars in the past month (any vs none)	Absolute difference (percentage points): -5·1 (-9·8 to -1·0)	Smoke-free car policy in seven Canadian provinces was associated with an overall reduction in TSE in cars
Patel (2018)[26]	United States of America (California)	Children aged 11-18 years	151074 (missing values unknown)	2001-2012	Primary: TSE in places covered by the policy	Child-reported TSE in cars in the past month (any vs none)	Pre-intervention annual trend (percentage points): -0·3/year (-0·6 to 0·7) Post-intervention annual trend, (percentage points): -1·2/year (-1·5 to -0·8)	The smoke-free car policy in California was followed by an annual decline in TSE in cars, whereas there was no significant temporal trend in the pre-intervention period. Step or slope changes were not formally tested.
Smoke-free school policy								
Azagba (2016)[28]	Canada (Quebec, British Columbia, Prince Edward Island, Saskatchewan)	Children aged 15-18 years	20388 (missing values unknown)	2005-2012	Primary: TSE in places covered by the policy	Child-reported TSE on a school property in the past month (any vs none)	Absolute difference (percentage points): -6·5 (-10·0 to -3·0)	Smoke-free school policy in four Canadian provinces was associated with an overall reduction in TSE on a school property
Comprehensive smoke-free policy covering indoor public, (semi-)private, and outside areas								

First author (year)	Country (region)	Intervention population	Sample size	Observational period	Outcome eligibility	Outcome	Reported intervention effect	Summary of findings
Lee (2016)[29]	Hong Kong	Children aged 0-18 years	75870 (missing values unknown)	2004-2012	Primary: unplanned hospital attendances for RTIs	Unplanned hospital admissions for lower RTI (yes vs no)	Immediate change: OR: 0·66 (0·63 to 0·69) Gradual change: OR: 0·86/year (0·84 to 0·88)	Comprehensive smoke-free policy in Hong Kong was associated with an immediate reduction in hospital admissions for lower RTI, followed by an additional reduction per year

Abbreviations: OR = odds ratio (95% confidence interval); TSE = tobacco smoke exposure; RTI = respiratory tract infection.

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