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

Márta K Radó, Famke J M Mölenberg*, Lauren E H Westenberg, Aziz Sheikh, Christopher Millett, Alex Burdorf, Frank J van Lenthe, Jasper V Been*

Summary

Background Smoke-free policies in outdoor areas and semi-private and private places (eg, cars) might reduce the health harms caused by tobacco smoke exposure (TSE). We aimed to investigate the effect of smoke-free policies covering outdoor areas or semi-private and private places on TSE and respiratory health in children, to inform policy.

Methods In this systematic review and meta-analysis, we searched 13 electronic databases from date of inception to Jan 29, 2021, for published studies that assessed the effects of smoke-free policies in outdoor areas or semi-private or private places on TSE, respiratory health outcomes, or both, in children. Non-randomised and randomised trials, interrupted time series, and controlled before–after studies, without restrictions to the observational period, publication date, or language, were eligible for the main analysis. Two reviewers independently extracted data, including adjusted test statistics from each study using a prespecified form, and assessed risk of bias for effect estimates from each study using the Risk of Bias in Non-Randomised Studies of Interventions tool. Primary outcomes were TSE in places covered by the policy, unplanned hospital attendance for wheezing or asthma, and unplanned hospital attendance for respiratory tract infections, in children younger than 17 years. Random-effects meta-analyses were done when at least two studies evaluated policies that regulated smoking in similar places and reported on the same outcome. This study is registered with PROSPERO, CRD42020190563.

Findings We identified 5745 records and assessed 204 full-text articles for eligibility, of which 11 studies met the inclusion criteria and were included in the qualitative synthesis. Of these studies, seven fit prespecified robustness criteria as recommended by the Cochrane Effective Practice and Organization of Care group, assessing smoke-free cars (n=5), schools (n=1), and a comprehensive policy covering multiple areas (n=1). Risk of bias was low in three studies, moderate in three, and critical in one. In the meta-analysis of ten effect estimates from four studies, smoke-free car policies were associated with an immediate TSE reduction in cars (risk ratio 0·69, 95% CI 0·55–0·87; 161 466 participants); heterogeneity was substantial (I^2 80·7%; p<0·0001). One additional study reported a gradual TSE decrease in cars annually. Individual studies found TSE reductions on school grounds, following a smoke-free school policy, and in hospital attendances for respiratory tract infection, following a comprehensive smoke-free policy.

Interpretation Smoke-free car policies are associated with reductions in reported child TSE in cars, which could translate into respiratory health benefits. Few additional studies assessed the effect of policies regulating smoking in outdoor areas and semi-private and private places on children's TSE or health outcomes. On the basis of these findings, governments should consider including private cars in comprehensive smoke-free policies to protect child health.

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*Contributed equally

Division of Neonatology, Department of Paediatrics, Erasmus MC Sophia Children's Hospital (M K Radó PhD, L E H Westenberg MD, J V Been PhD) **and Department of Public Health, Erasmus MC** (M K Radó, F J M Mölenberg PhD, Prof A Burdorf PhD, Prof F J van Lenthe PhD, J V Been)**, University Medical Center Rotterdam, Rotterdam, Netherlands; Asthma UK Centre for Applied Research** (Prof A Sheikh MD, J V Been) **and Centre for Medical Informatics** (Prof A Sheikh)**, Usher Institute, University of Edinburgh, Edinburgh, UK; Division of General Internal Medicine and Primary Care, Brigham and Women's Hospital, Harvard Medical School, Boston, MA, USA** (Prof A Sheikh)**; Department of Medicine, Harvard Medical School, Boston, MA, USA** (Prof A Sheikh)**; Public Health Policy Evaluation Unit, School of Public Health, Imperial College London, London, UK** (Prof C Millett PhD)

Correspondence to: Dr Jasper V Been, Division of Neonatology, Department of Paediatrics, Erasmus MC Sophia Children's Hospital, University Medical Center Rotterdam, Rotterdam 3000 CB, Netherlands **j.been@erasmusmc.nl**

Introduction

Environmental tobacco smoke exposure (TSE) resulting from second-hand smoke (ie, inhalation of emitted smoke) and potentially from third-hand smoke (ie, the uptake of tobacco smoke residuals from polluted surfaces) is known to be a major burden on children's health.[1–3] Each year, second-hand smoke is responsible for an estimated 56 000 deaths globally in children younger than 10 years[1] and for 35 633 disability-adjusted life-years among children in the EU.[2] TSE has been linked to various adverse respiratory health outcomes in children, including respiratory tract infections, wheezing, and asthma.[4,5] Governmental action to protect children from these deleterious effects of TSE is urgently needed, given that children are not able to control their degree of exposure.[6] Smoke-free policies have been identified as a key component in achieving the UN Sustainable Development Goal 3 to improve child health and wellbeing.[7,8]

Solid evidence indicates that smoke-free policies covering enclosed public places can effectively reduce

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 little control over their amount of TSE. Smoke-free policies can help to protect children from TSE and, through doing so, can contribute to achieving the UN Sustainable Development Goal 3 to improve child health and wellbeing. A systematic 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 and private places that are frequently visited by children; however, uncertainty still remains about their effects on TSE and health outcomes. Compared with existing measures that prohibit smoking in enclosed public places in many countries, these novel policies might face more complex enforcement and compliance challenges. Furthermore, such policies can potentially contribute to decreases in TSE in other areas via norm spreading (ie, refraining from smoking in the vicinity of others in places not covered by the policy, including private places [eg, cars and homes]). To identify any existing or planned systematic reviews on this topic, we searched PubMed and PROSPERO on Jan 29, 2020, using the terms (“systematic review” OR “meta-analysis”) AND “smok*” AND (“polic*” OR “regulation*” OR “legislation” OR “law”) AND “child*”. No systematic reviews were identified.

Added value of this study

We systematically reviewed published studies that assessed the effects of smoke-free policies in semi-private and private places and outside areas on TSE, respiratory health outcomes, or both, in children. We identified 11 studies, of which seven used robust methodologies as recommended by the Cochrane Effective Practice and Organization of Care group, and pooled ten effect estimates from four studies in the meta-analysis, which indicated that smoke-free car policies were followed by an immediate reduction in children’s TSE in cars. Despite the health benefits of indoor smoke-free policies being already well established, this is the first systematic assessment of the effect of policies regulating smoking in semi-private, private, and outdoor 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, this review highlights the need for additional robust evaluations of such policies, particularly those regulating smoking in outdoor, semi-private, and 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 systematic 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 few evaluations of smoke-free policies in outdoor places. Although these evaluations indicated potential benefits, more robust studies are clearly needed to corroborate this finding.

adverse respiratory health outcomes in children, including decreases in hospital attendance for asthma exacerbations by 10% (95% CI 3–17) and for lower respiratory tract infections by 18% (4–33).[5] These health benefits are likely to be mediated via a reduction in TSE from second-hand and possibly third-hand smoke. Smoke-free policies covering enclosed public areas can decrease child TSE not only in places included in the policy but also via norm spreading (ie, refraining from smoking in the vicinity of others in places not covered by the policy, including private places [eg, cars and homes]).[9–13]

Over the past two decades, an increasing number of jurisdictions have expanded smoke-free policies to encompass outdoor areas (eg, school grounds, play-grounds, and parks),[14] semi-private places (eg, shared housing), and private places (eg, 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 (ie, via displacement of smoking) or positively (ie, via norm spreading).[15]

We did a systematic review and meta-analysis to investigate the effect of smoke-free policies covering outdoor areas or semi-private and private places on TSE and respiratory health in children, to inform policy making in jurisdictions that do not yet have such policies in place.

Methods

Search strategy and selection criteria

This systematic review and meta-analysis was done in accordance with our peer-reviewed, published protocol,[16] and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) reporting guidelines.[17]

Our research team (MKR, FJMM, LEHW, and JVB), including an information specialist in search strategy optimisation, searched 13 electronic databases (Embase, MEDLINE Ovid, Web of Science, PsycINFO Ovid, CINAHL EBSCOhost, Google Scholar, IndMED, KoreaMed, EconLit, WHO Global Health Library [including African Index Medicus, Latin America and the Caribbean Literature on Health Sciences, Index Medicus for the Eastern Mediterranean Region, Index Medicus for South-East Asia Region, Western Pacific Region Index Medicus], WHO Library Database, Scientific Electronic Library Online, and Paediatric Economic Database Evaluation) for studies published from the date of database inception to Jan 29, 2021, exploring the association between implementation of policies restricting smoking in designated outdoor areas or semi-private and private places, and TSE, respiratory health outcomes, or both, in children. A full list of search terms is provided in the appendix (pp 2–4). No restrictions were applied for the observational period, publication date, or language; studies were translated if they were in a language not spoken by the research team. 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 de-duplication, two 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).

Eligibility assessment

In line with earlier systematic reviews,[5,18] we included studies in which at least 50% of the study population was younger than 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 (eg, cars), indoor semi-private places (eg, multi-unit housing), outdoor semi-private or private places (eg, shared gardens), and outdoor public places (eg, parks, school grounds, beaches, hospital grounds) introduced at any governmental or institutional level were considered eligible. Additionally, studies reporting on such policies that were simultaneously introduced with other tobacco control measures were also eligible. We excluded studies reporting smoke-free policies covering enclosed public places only, exposure assessment not specific to tobacco smoke (eg, particulate matter), or changes in smoking behaviour per se without assessing changes in children's exposure.

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 and randomised trials, interrupted time series, and controlled before–after studies. Effect estimates from studies that met EPOC criteria and assessed the effects of similar policies on the same outcome were eligible for the meta-analysis. In the sensitivity analyses, we also included studies that did not meet the EPOC criteria: prospective cohort studies, retrospective cohort studies, and uncontrolled before–after studies.

Outcomes

There were three primary outcomes: TSE in places covered by the policy, as reported by the child, parent or primary caregiver, or both; unplanned hospital attendance for wheezing or asthma; and unplanned hospital attendance for respiratory tract infections, in children younger than 17 years. We defined unplanned hospital attendance as acute presentations to an emergency department, as well as hospital admissions. There were nine secondary outcomes: TSE in places where only some areas were covered by the policy, or in unspecified places; TSE in places not covered by the policy; cotinine or other biomarkers of TSE; TSE assessed by wearable devices; incidence of wheezing or asthma; incidence of respiratory tract infections; otitis media with effusion; chronic cough; and lung function parameters.

See Online for appendix

Data analysis 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 prespecified 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 tool.[20] From studies that reported multiple effect estimates for overlapping study samples, we extracted one estimate on the basis of 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 (ie, use of an alternative comparison group, neutral outcomes, or alternative method) and on the mechanism of how policies might have affected the outcomes of interest, following the UK Medical Research Council guidance on natural experiments.[21] All variables for which data were extracted are outlined in the prespecified form in the appendix (pp 6–8).

Summary measures

We recorded point estimates and 95% CIs in tabular form. For dichotomous outcomes, we harmonised effect

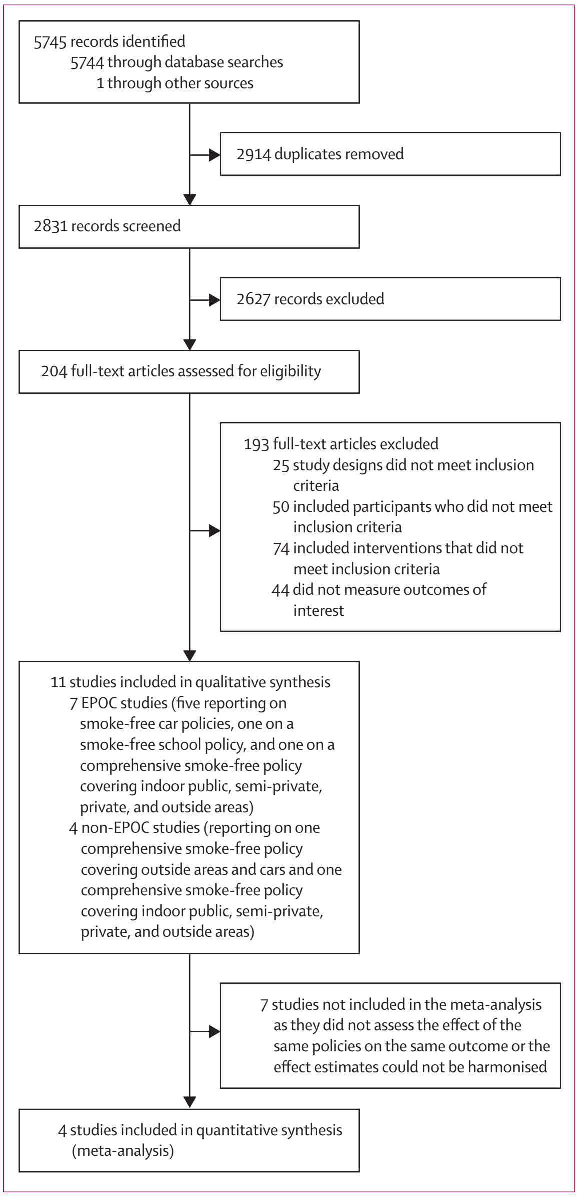

Figure 1: **Study selection**
EPOC=Cochrane Effective Practice and Organization of Care.

estimates into risk ratios (RRs). When a study reported odds ratios (ORs) instead, we contacted the corresponding author to request the RR. In cases in which RR 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 as an approximation instead. Regarding outcomes that could occur multiple times within the same individual (eg, hospital attendance), we analysed incidence rate ratios.

Statistical analysis

Heterogeneity between studies was assessed using the Cochran's Q, I^2, and H statistics (total heterogeneity/total variability), with an I^2 of more than 75% indicating substantial heterogeneity.[23] We did 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. On the basis of a one-sided log-likelihood-ratio test, we assessed whether a three-level 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 did a 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 complete due to the low number of eligible studies.[16] We present 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 might 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 effect 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:[24]

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

where P_0 is the prevalence of TSE before policy implementation, P_1 is the prevalence of TSE after policy implementation, and RR is the relative risk of respiratory disease of children exposed to TSE over children not exposed. To capture the sensitivity of PIFs to varying parameters, we calculated PIFs given a plausible range of baseline TSE, and associations between exposure and outcome.

All analyses were done in R (version 3.4.1) using the metafor package for the meta-analyses. This study is registered on PROSPERO, CRD42020190563.

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.

	Study meets EPOC criteria	TSE outcome				Health outcome		
		Primary	Secondary			Primary	Secondary	
		TSE in places covered by the policy	TSE in unspecified places	TSE in places not covered by the policy	Biomarker of TSE	Unplanned hospital attendance for RTIs	Incidence of wheezing or asthma	Chronic cough
Smoke-free car policy								
Elton-Marshall et al (2015)[28]	✓	✓	✗	✗	✗	✗	✗	✗
Faber et al (2019)[15]	✓	✓	✗	✓	✓	✗	✓	✗
Laverty et al (2020)[25]	✓	✓	✗	✗	✗	✗	✗	✗
Nguyen (2013)[26]	✓	✓	✗	✓	✗	✗	✗	✗
Patel et al (2018)[27]	✓	✓	✗	✗	✗	✗	✗	✗
Comprehensive smoke-free policy covering outside areas and cars								
Gagné et al (2020)[34]	✗	✓	✗	✓	✗	✗	✗	✗
Smoke-free school policy								
Azagba et al (2016)[29]	✓	✓	✗	✗	✗	✗	✗	✗
Comprehensive smoke-free policy covering indoor public, semi-private, private, and outside areas								
Lee et al (2016)[30]	✓	✗	✗	✗	✗	✓	✗	✗
Chan et al (2011)[32]	✗	✗	✓	✓	✗	✗	✓	✗
Chan et al (2014)[33]	✗	✗	✓	✓	✓	✗	✗	✗
Ho et al (2010)[31]	✗	✓	✓	✓	✗	✗	✗	✓

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

Table 1: **Primary and secondary outcomes reported in included studies on smoke-free policies**

Results

We identified 5745 records and after de-duplication, 2831 records were screened on title and abstract. From 204 full-text articles assessed for eligibility, 11 eligible studies were included in the qualitative synthesis (figure 1).[15,25–34] No ongoing or unpublished studies were found.

Of the 11 eligible studies, seven met EPOC criteria: four controlled before–after studies[25,26,28,29] and three interrupted time series studies (appendix pp 9–13).[15,27,30] Overall, risk of bias was low in three studies,[15,26,27] moderate in three,[25,28,29] and critical in one[30] (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 focused on the national policy in England, UK,[15,25] two on various policies across Canadian provinces,[26,28] and one in California, USA.[27] One study assessed a smoke-free school policy in Canada,[29] and another evaluated a comprehensive smoke-free policy covering enclosed public, semi-private, private, and outside areas in Hong Kong.[30] Four of the 11 eligible studies did not meet EPOC criteria (figure 1).[31–34]

Ten effect estimates from four studies evaluating the effects of smoke-free car policies on child TSE in cars could be meta-analysed given that they assessed the immediate effects of similar policies on the same outcome.[15,25,26,28] In the two-level meta-analysis of these estimates, smoke-free car policies were associated with an immediate risk reduction in child TSE in cars (RR 0·69, 95% CI 0·55–0·87; 161 466 participants; figure 2). A one-sided log-likelihood-ratio test favoured a two-level over three-level meta-analysis (p=0·38; appendix p 17). Heterogeneity (I^2) was 80·7%, indicating substantial heterogeneity between studies (p<0·0001). One additional study from California, which could not be included in the meta-analysis, found that the smoke-free car policy was followed by an annual reduction in child TSE in cars (0·95 per year, 0·94–0·97; 151 074 participants), with no significant temporal trend in TSE in the period before the intervention.[27]

Two studies assessing smoke-free car policies reported on secondary TSE outcomes (appendix pp 18–19).[15,26] One study from England found a relative increase in the proportion of children having detectable salivary cotinine concentrations after introduction of the policy (1·22, 1·06–1·38; 7858 participants).[15] Although TSE at home or in other people's homes appeared to increase following the policy in this study, this increase 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, such as bus stops and shelters, parks and sidewalks, and inside restaurants.[26]

	Country (region)	Description	Level of enforcement	Date of implementation	Enforcement	Actual enforcement
Smoke-free car policy						
Nguyen (2013);[26] Elton-Marshall et al (2015)[28]	Canada (BC, MB, NL, NS, ON, PE, SK)	Smoke-free car policy prohibiting smoking in private vehicles with anyone aged ≤15 years present (≤18 years in NS and PE)	Province	April 1, 2008, in NS; Jan 21, 2009, in ON; April 7, 2009, in BC; Sept 1, 2009, in PE; July 15, 2010, in MB; Oct 1, 2010, in SK; May 31, 2011, in NL	Law enforcement agencies were authorised to issue fines or warnings to individuals not complying 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; the fines were mainly issued for deterrence and educative reasons
Faber et al (2019);[15] Laverty et al (2020)[25]	UK (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 electronic cigarettes	Country	Oct 1, 2015	Drivers and smokers who break this policy risk a £50 (US$60) fine each; before the policy came into force, police had announced that they were not planning to actively enforce the policy	1 year after the policy was imposed, only one single penalty had been issued in England; other cases were dealt with by verbal warnings
Patel et al (2018)[27]	USA (California)	Smoke-free car policy prohibiting smoking in a motor vehicle with anyone aged ≤17 years present	State	Jan 1, 2008	Police were not authorised to stop a vehicle for a smoking violation alone; it must have been secondary to another infraction; violators can be fined <US$100	Not reported
Comprehensive smoke-free policy covering outside areas and cars						
Gagné et al (2020)[34]	Canada (QC)	A comprehensive smoke-free policy covering bar and restaurant patios, playgrounds, areas within 9 m from building entrances, and in vehicles with anyone aged <16 years; permitted landlords to enforce a smoke-free policy in multi-unit apartment buildings	Province	November, 2015	Police services could stop a motor vehicle if they had reasonable grounds to believe that a person was smoking in the vehicle with someone aged <16 years present; smoking in a prohibited place is fined (CA$250–750 [US$170–510]), as are repeated offences (CA$500–1500 [US$340–1020])	Not reported
Smoke-free school policy						
Azagba et al (2016)[29]	Canada (BC, QC, PE, SK)	Smoke-free school policy (not further specified)	Province	May, 2006, in QC; March, 2008, in BC; September, 2009, in PE; August, 2010, in SK	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, private, and outside areas						
Ho et al (2010);[31] Chan et al (2011);[32] Chan et al (2014);[33] Lee et al (2016)[30]	Hong Kong	A comprehensive smoke-free policy covering indoor public, semi-private, private, and outside areas (eg, public playgrounds, parks, beaches, barbecue sites, public swimming pools, and areas of public housing estates)	City	Jan 1, 2007	Policy enforced by the Tobacco Control Office; the budget for policy enforcement increased from HK$7·8 million (US$0·9 million) in 2006 (before legislation) to HK$23·4 million (US$3·0 million) in 2007 (after legislation); penalty points allotted to households for smoking and other offences, with the ultimate punishment being termination of tenancy	The policy was effectively enforced; in 2 years, 11 085 penalties were issued against smoking offences (outside or inside areas)

A list of additional sources used to extract information on the policies is available in the appendix (p 16). BC=British Columbia. MB=Manitoba. NL=Newfoundland and Labrador. NS=Nova Scotia. ON=Ontario. PE=Prince Edward Island. QC=Quebec. SK=Saskatchewan.

Table 2: **Description of the novel smoke-free policies evaluated in eligible studies**

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 (0·82, 0·63–1·05; 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 (0·89, 0·83–0·95;

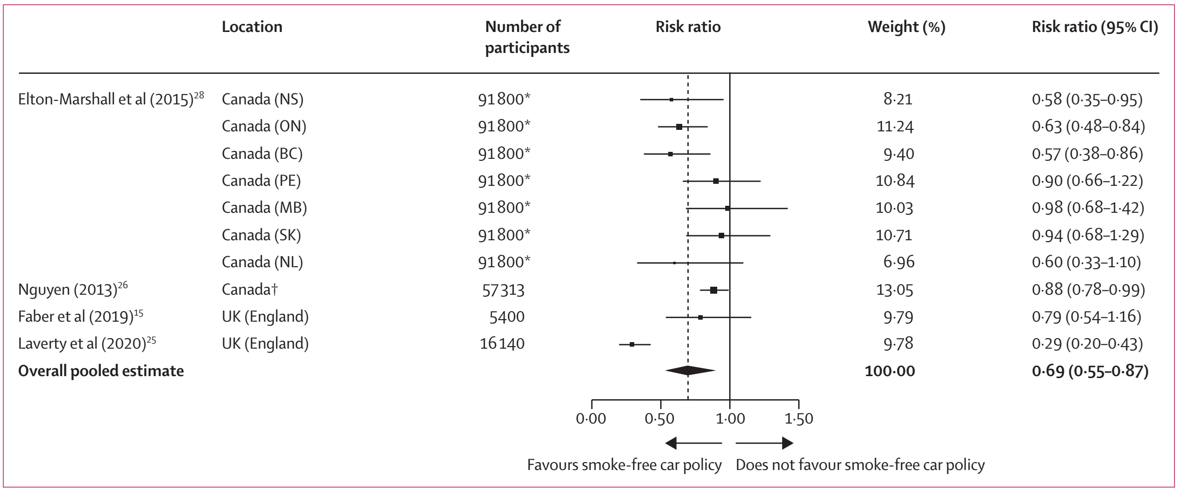

Figure 2: **Meta-analysis of relative risk of child tobacco smoke exposure in cars before and after implementation of smoke-free car policy**
The pooled effect of the ten estimates was calculated with a random-effects meta-analysis, with the effect of each event weighted by the inverse of its variance. BC=British Columbia. MB=Manitoba. NB=New Brunswick. NL=Newfoundland and Labrador. NS=Nova Scotia. ON=Ontario. PE=Prince Edward Island. SK=Saskatchewan. *Total number of participants reported across whole study, rather than by province. †BC, MB, NB, NS, PE, ON, SK.

20 388 participants; table 3).[29] No health outcomes were assessed.

An interrupted time series study from Hong Kong found that a comprehensive smoke-free policy covering semi-private, private, and outside areas, in addition to enclosed public spaces, was associated with an immediate drop in unplanned hospital attendances for respiratory tract infections among children (0·66, 0·63–0·69; 75 870 hospital attendances) and an additional annual decrease over the first 6 years following the new policy (0·86 per year, 0·84–0·88).[29]

Of the four studies that did not meet EPOC criteria,[30–33] 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 (0·42, 0·30–0·57; appendix pp 24–26), and at home (0·55, 0·41–0·73). Including this estimate in the meta-analysis did not substantially change the overall effect estimate of smoke-free car policies on child TSE (0·66, 0·53–0·83; 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] A meta-analysis of these studies was not possible because either 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] The two other studies, using parent-reported outcomes, did not assess TSE in places covered by the policy, but found a significant decrease in child TSE at home.[31,32]

On the basis of studies identified in the review, our planned health impact assessment 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 baseline TSE amounts between 5% and 45% (appendix p 28). As a reference value of the strength of the association between TSE in cars and asthma diagnosis, we used the RRs presented by one included study for children with 1–2 days per week of TSE in cars (RR 1·12, 95% CI 0·98 to 1·28), and 3–7 days per week of TSE in cars (1·19, 1·02 to 1·38), compared with children with no TSE in cars.[26] Using effect estimates from the meta-analysis, we estimated the proportion of asthma diagnoses that could potentially be prevented by the observed TSE reductions following smoke-free car policies. Assuming an arbitrarily chosen but plausible baseline prevalence of TSE in cars of 20% and using the association between TSE for 1–2 days a week and asthma (RR 1·12, 95% CI 0·98 to 1·28), we estimate that 2·3% (–0·4 to 5·3) of asthma diagnoses are attributable to TSE in cars. On the basis of the effect estimate of our meta-analysis, the PIF indicated that the proportion of asthma diagnoses would change by –0·7% (–1·1 to –0·4) by implementing a smoke-free car policy at a baseline TSE prevalence of 20% (figure 3). Different scenarios indicated that the percentage change in asthma diagnoses among children that could potentially be associated with smoke-free car policies ranged between –0·2% and –2·4% (appendix p 28). PIFs were not calculated for policies covering outdoor areas, given that a meta-analysis on the effect of these policies on TSE was not possible.

The uncontrolled before–after study in Quebec, Canada, also assessed socioeconomic inequalities in TSE following the implementation of a comprehensive smoke-free policy that included outside areas and cars.[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.

	Intervention population	Sample size	Observational period	Primary outcome eligibility	Primary outcome	Reported intervention effect*	Summary of findings
Smoke-free car policy							
Elton-Marshall et al (2015)[28]							
Canada (NS)	Children aged 11–14 years	91 800 (83 331 without missing values)†	2004–12	TSE in places covered by the policy	Child-reported TSE in cars in the past 7 days (any *vs* none)	OR 0·47 (0·25 to 0·89)	Policy associated with a reduction in TSE in cars
Canada (ON)	Children aged 11–14 years	91 800 (83 331 without missing values)†	2004–12	TSE in places covered by the policy	Child-reported TSE in cars in the past 7 days (any *vs* none)	OR 0·58 (0·42 to 0·80)	Policy associated with a reduction in TSE in cars
Canada (BC)	Children aged 11–14 years	91 800 (83 331 without missing values)†	2004–12	TSE in places covered by the policy	Child-reported TSE in cars in the past 7 days (any *vs* none)	OR 0·51 (0·32 to 0·82)	Policy associated with a reduction in TSE in cars
Canada (PE)	Children aged 11–14 years	91 800 (83 331 without missing values)†	2004–12	TSE in places covered by the policy	Child-reported TSE in cars in the past 7 days (any *vs* none)	OR 0·87 (0·59 to 1·30)	Policy not associated with a reduction in TSE in cars
Canada (MB)	Children aged 11–14 years	91 800 (83 331 without missing values)†	2004–12	TSE in places covered by the policy	Child-reported TSE in cars in the past 7 days (any *vs* none)	OR 0·98 (0·62 to 1·54)	Policy not associated with a reduction in TSE in cars
Canada (SK)	Children aged 11–14 years	91 800 (83 331 without missing values)†	2004–12	TSE in places covered by the policy	Child-reported TSE in cars in the past 7 days (any *vs* none)	OR 0·91 (0·56 to 1·48)	Policy not associated with a reduction in TSE in cars
Canada (NL)	Children aged 11–14 years	91 800 (83 331 without missing values)†	2004–12	TSE in places covered by the policy	Child-reported TSE in cars in the past 7 days (any *vs* none)	OR 0·53 (0·26 to 1·09)	Policy not associated with a reduction in TSE in cars
Faber et al (2019)[15]							
UK (England)	Children aged 8–15 years	5400 (5399 without missing values)	2008–17	TSE in places covered by the policy	Regular child-reported TSE in cars (unspecified timeframe; any *vs* none)	OR 0·77 (0·51 to 1·17)	Policy not associated with a reduction in TSE in cars
Laverty et al (2020)[25]							
UK (England)	Children aged 13–15 years	16 140 (missing values unknown)	2012–16	TSE in places covered by the policy	Child-reported TSE in cars in the past 7 days (regular exposure *vs* no exposure or occasional exposure)	OR 0·28 (0·21 to 0·37); absolute difference –4 percentage points (–3 to –2)	Policy associated with a reduction in TSE in cars
Nguyen (2013)[26]							
Canada‡	Children aged 15–16 years (15–19 years in NS and PE)	57 313 (56 596 without missing values)	2005–10	TSE in places covered by the policy	Child-reported TSE in cars in the past month (any *vs* none)	Absolute difference –5·1 percentage points (–9·8 to –1·0)	Policy associated with a reduction in TSE in cars
Patel et al (2018)[27]							
USA (California)	Children aged 11–18 years	151 074 (missing values unknown)	2001–12	TSE in places covered by the policy	Child-reported TSE in cars in the past month (any *vs* none)	Pre-intervention annual trend –0·3 percentage points per year (–0·6 to 0·7); post-intervention annual trend –1·2 percentage points per year (–1·5 to –0·8)	Policy was followed by an annual decrease in TSE in cars, whereas there was no significant temporal trend in the pre-intervention period; step or slope changes were not formally tested

(Table 3 continues on next page)

Some studies provided further information supporting the robustness of the findings (appendix pp 29–30). 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 change in TSE in cars in their main analysis, but additionally showed that TSE in cars did not decrease 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 might 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 the study.[15] A study evaluating smoke-free car policies 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.[26] Furthermore, the policy effect was restricted to children whose parents had a car, supporting causality of the findings.[26]

	Intervention population	Sample size	Observational period	Primary outcome eligibility	Primary outcome	Reported intervention effect*	Summary of findings
(Continued from previous page)							
Smoke-free school policy							
Azagba et al (2016)[29]							
Canada§	Children aged 15–18 years	20 388 (missing values unknown)	2005–12	TSE in places covered by the policy	Child-reported TSE on a school property in the past month (any *vs* none)	Absolute difference –6·5 percentage points (–10·0 to –3·0)	Policy associated with a reduction in TSE on school property
Comprehensive smoke-free policy covering indoor public, semi-private, private, and outside areas							
Lee et al (2016)[30]							
Hong Kong	Children aged ≤18 years	75 870 (missing values unknown)	2004–12	Unplanned hospital admission 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 per year (0·84 to 0·88)	Policy associated with an immediate reduction in hospital admissions for lower RTI, followed by an additional reduction per year

BC=British Columbia. EPOC=Cochrane Effective Practice and Organization of Care. MB=Manitoba. NB=New Brunswick. NL=Newfoundland and Labrador. NS=Nova Scotia. ON=Ontario. OR=odds ratio. PE=Prince Edward Island. QC=Quebec. RTI=respiratory tract infection. SK=Saskatchewan. TSE=tobacco smoke exposure. *Data are OR (95% CI), absolute difference in percentage points (95% CI), or annual trend in percentage points (95% CI). †Total number of participants reported across the whole study, rather than by province. ‡PE, NS, NB, ON, MB, SK, and BC. §QC, BC, PE, and SK.

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

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 could translate into an estimated 0·2–2·4% decrease in asthma diagnoses. Additionally, a few studies indicated that smoke-free policies covering school grounds and a comprehensive smoke-free policy covering indoor public, semi-private, private, and outside areas might 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 might help to protect children from TSE-related harm and provide additional health benefits.

To our knowledge, this is the first systematic assessment of the effect of smoke-free policies covering outdoor areas and semi-private and private places on children's TSE and respiratory health. The link between smoke-free policies in enclosed public places and health benefits in children was already well established,[5,18] but 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. Furthermore, 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,[35] this was assessed to be low to moderate in six of seven studies in our primary analyses, strengthening confidence in our results. Due to the small number of eligible studies, we could not do 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. Additionally, our findings must be interpreted in the light of the observational nature of the available evidence. For example, 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 designs approved by EPOC), and on the heterogeneity of the estimated effects.[36–38] All TSE outcomes were reported by children or parents. Although these measures might be subject to desirability bias, previous studies support their validity in quantifying actual exposure.[39,40] Biomarkers for exposure were evaluated in some studies,[15,33] but these cannot discern between TSE in various locations. Furthermore, TSE presents different risks in different settings. For example, TSE in cars is likely to be more harmful to child health than is TSE in outside areas.[41,42] We used a formula suggested by the *Cochrane Handbook* to compute RR when only OR was available; however, the conversion might be biased in situations with a high level of confounding.[43]

Our systematic review builds on solid existing evidence indicating health benefits of smoke-free policies in children.[5] On the basis of this meta-analysis, we estimated that smoke-free car policies might contribute to a moderate reduction in the number of asthma diagnoses in children, ranging from a decrease of 0·2% in the most conservative scenario with a low baseline prevalence of TSE in cars, to a decrease of 2·4% in the most favourable scenario. It is important to note that

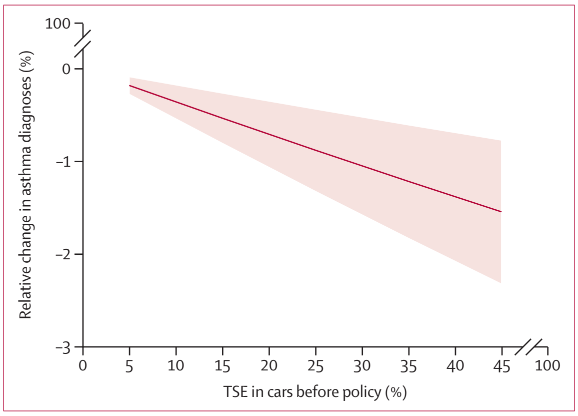

***Figure 3:* Estimated proportion of asthma diagnoses in children that could be prevented by introducing smoke-free car policies for varying baseline prevalence of TSE in cars**
The relative change in asthma cases was estimated by calculating the potential impact fraction, which captures the change in asthma cases attributable to the change in TSE following the implementation of smoke-free car policies. The solid line represents the average effect; shading represents 95% CI. TSE=tobacco smoke exposure.

these calculations assumed that there was no change in TSE in places other than cars, which needs further substantiation in future research as the current evidence base on this assumption is scarce.[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.[44,45]

All evidence in this systematic review was derived from countries with an already existing and well enforced, comprehensive smoke-free legislation covering enclosed public places. Thus, countries might derive substantial additional benefits by implementing an even more comprehensive measure covering indoor enclosed places,[5] as well as private and outdoor areas. Additionally, the comprehensive smoke-free policy in Hong Kong covering indoor public, semi-private, private, and outside areas was associated with large reductions in hospital attendances for lower respiratory tract infections 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 were those from other studies that assessed the effect of policies covering enclosed public places only on child respiratory tract infections,[46–48] suggesting that part of the effect could be from its additional coverage of semi-private, private, and outdoor areas.

Previous studies indicated that part of the positive health effect of smoke-free policies covering indoor public places could be mediated by reducing TSE in cars and homes through norm spreading.[13] At present, there is little 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 might occur.[49] In our review, there was mixed evidence on the effect of smoke-free policies covering private or outdoor areas on TSE in areas not covered by the policy. One study found that salivary cotinine concentrations increased in children following the smoke-free car policy in England, indicating that overall TSE might have increased.[15] By contrast, there was no evidence of displacement of smoking to outside areas or restaurants as measured by surveys, following the Canadian smoke-free car policy. Another Canadian study showed that TSE at home was reduced following a comprehensive policy that included outdoor areas and cars.[34] Two studies found that the comprehensive, city-wide smoke-free policy in Hong Kong was associated with a reduction in TSE in areas that were not covered by the policy;[32,33] however, one study found the opposite.[31] This inconsistency could derive from the fact that the study by Ho and colleagues[31] was based on child reports, whereas the other two studies relied on parent-reported outcomes, which could be subject to increased desirability bias. Furthermore, substantial displacement of TSE is unlikely in Hong Kong given the observed reduction in hospital attendances for respiratory tract infections.[30] We are unaware of any evidence from other studies on whether smoke-free policies in outdoor areas or semi-private and private places had an effect 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.[50–53] Despite these challenges, which were also noted in the included studies, health benefits could be seen, and these benefits might increase with more widespread adoption and acceptability. Several measures could be taken to improve policy compliance, such as penalties,[50,53] smoke-free signages,[54,55] or information campaigns,[51,56] which can carry additional child health benefits.[57] In general, the reviewed policies were positively perceived by the general population, which can foster effective policy implementation.[58] Smoke-free policies introduced in enclosed public areas often gain support after implementation as they become customary.[59–62] We are currently completing a related review to assess determinants of public support for smoke-free policies covering private and outdoor places.[63]

This systematic review provides the first meta-analysis assessing the effect 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. Several studies have found that such policies can decrease TSE among adults, and cross-sectional studies have also supported the potential health benefits of these policies in children.[42,64–68] We did not identify any study exploring the differential effects of novel smoke-free policies in low-income countries. This consideration is worthy of future investigation because previous studies have observed that population-level tobacco control policies could produce greater health benefits in low-income populations than in high-income populations.[15,69,70]

To conclude, although the health burden associated with TSE has decreased over past decades around the world, there is still considerable scope to further reduce this preventable harm to children.[71] To achieve this goal, comprehensive smoke-free policies are needed and this systematic review and meta-analysis, albeit based on a small number of studies, suggests that including private and outdoor places in national tobacco control policies could produce additional benefits. Most of the studies identified evaluated smoke-free car policies and, when taken together, these suggest that such policies can help to reduce children's TSE in cars. On the basis of informed estimations, we show that this reduction might translate into small improvements in respiratory health. We found scarce evidence indicating that policies covering other private or outdoor areas might also reduce TSE and offer additional respiratory health benefits. All children worldwide should have the right to breathe clean air in private, public, indoor, and outdoor areas.

Contributors

JVB secured funding for this work. MKR, FJMM, AS, CM, AB, FJvL, 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 FJvL provided feedback. MKR, FJMM, and JVB verified the underlying data. All authors read and approved the final manuscript. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Declaration of interests

We declare no competing interests.

Data sharing

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

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