Association of Secondhand Smoke Exposure with Pediatric Invasive Bacterial Disease and Bacterial Carriage: A Systematic Review and Meta-analysis

Chien-Chang Lee1,2, Nicole A. Middaugh1, Stephen R. C. Howie3, Majid Ezzati4,5,6,7*

1 Department of Epidemiology, Harvard School of Public Health, Boston, Massachusetts, United States of America, 2 Department of Emergency Medicine, National Taiwan University Hospital, Taipei, Taiwan, 3 Bacterial Diseases Programme, Medical Research Council (UK) Laboratories, Fajara, The Gambia, 4 Department of Global Health and Population, Harvard School of Public Health, Boston, Massachusetts, United States of America, 5 Department of Environmental Health, Harvard School of Public Health, Boston, Massachusetts, United States of America, 6 Department of Epidemiology and Biostatistics, School of Public Health, Imperial College, London, United Kingdom, 7 MRC-HPA Center for Environment and Health, Imperial College, London, United Kingdom

Abstract

Background: A number of epidemiologic studies have observed an association between secondhand smoke (SHS) exposure and pediatric invasive bacterial disease (IBD) but the evidence has not been systematically reviewed. We carried out a systematic review and meta-analysis of SHS exposure and two outcomes, IBD and pharyngeal carriage of bacteria, for Neisseria meningitidis (N. meningitidis), Haemophilus influenzae type B (Hib), and Streptococcus pneumoniae (S. pneumoniae).

Methods and Findings: Two independent reviewers searched Medline, EMBASE, and selected other databases, and screened articles for inclusion and exclusion criteria. We identified 30 case-control studies on SHS and IBD, and 12 cross-sectional studies on SHS and bacterial carriage. Weighted summary odds ratios (ORs) were calculated for each outcome and for studies with specific design and quality characteristics. Compared with those unexposed to SHS, summary OR for SHS exposure was 2.02 (95% confidence interval [CI] 1.52–2.69) for invasive meningococcal disease, 1.21 (95% CI 0.69–2.14) for invasive pneumococcal disease, and 1.22 (95% CI 0.93–1.62) for invasive Hib disease. For pharyngeal carriage, summary OR was 1.68 (95% CI 1.19–2.36) for N. meningitidis, 1.66 (95% CI 1.33–2.07) for S. pneumoniae, and 0.96 (95% CI 0.48–1.95) for Hib. The association between SHS exposure and invasive meningococcal and Hib diseases was consistent regardless of outcome definitions, age groups, study designs, and publication year. The effect estimates were larger in studies among children younger than 6 years of age for all three IBDs, and in studies with the more rigorous laboratory-confirmed diagnosis for invasive meningococcal disease (summary OR 3.24; 95% CI 1.72–6.13).

Conclusions: When considered together with evidence from direct smoking and biological mechanisms, our systematic review and meta-analysis indicates that SHS exposure may be associated with invasive meningococcal disease. The epidemiologic evidence is currently insufficient to show an association between SHS and invasive Hib disease or pneumococcal disease. Because the burden of IBD is highest in developing countries where SHS is increasing, there is a need for high-quality studies to confirm these results, and for interventions to reduce exposure of children to SHS.

Please see later in the article for the Editors’ Summary.


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Abbreviations: CI, confidence interval; Hib, Haemophilus influenzae type B; IBD, invasive bacterial disease; MeSH, medical subject heading; SHS, secondhand smoke; tw, text word

* E-mail: majid.ezzati@imperial.ac.uk
Introduction

Invasive bacterial disease (IBD) is an important cause of child mortality in developing and developed countries [1–7], accounting for at least as many child deaths as HIV/AIDS and malaria combined [6–8]. The organisms responsible for most pediatric IBD cases are S. pneumoniae, Haemophilus influenzae type B (Hib), and N. meningitidis [1,2,4,6,7,9]. In 2000, there were an estimated 14.5 million cases and 826,000 deaths from pneumococcal disease in children under 5 with estimated incidence ranging from 544 per 100,000 in the Americas to 1,778 per 100,000 in Africa [6]. The burden of Hib was estimated at 8.13 million cases and 371,000 deaths with estimated incidence ranging from 504 per 100,000 in Europe to 3,627 per 100,000 in Africa [7]. While there are currently no analyses of global invasive meningococcal disease burden, regional estimates of incidence range from 0.3 to 4 cases per 100,000 in North America to as high as 1,000 cases per 100,000 in the so-called “meningitis belt” in sub-Saharan Africa [9].

Secondhand smoke (SHS; also referred to as involuntary smoking, passive smoking, or environmental tobacco smoke [ETS]) has been shown to increase the risk of several adverse outcomes in children, including lower respiratory tract infections, middle ear infection, asthma, and sudden infant death syndrome [10,11]. Since the 1980s, epidemiologic studies have also found an association between SHS exposure and IBD or bacterial carriage, including those related to N. meningitidis, Hib, and S. pneumoniae, which suggests that SHS might be an independent risk factor for IBD. Given the persistent or growing exposure and IBD or bacterial carriage, including those related to N. meningitidis, Hib, and S. pneumoniae in pediatric populations, aged 1 mo to 19 y, i.e. infants, children, and adolescents. We included the effects of SHS exposure on pharyngeal carriage of these three bacteria because asymptomatic carriage is also associated with clinical disease [12–16].

Methods

Search Strategy


We used manual restriction by age and study type (versus using automated methods in PubMed) to avoid unnecessarily eliminating any articles relevant to the search. A similar search strategy and search terms were used in EMBASE. The searches and studies included were not limited by publication date, country, or language. PubMed and EMBASE searches were conducted independently by two authors (C-CL and NAM). To ensure comprehensive acquisition of literature, independent supplemental manual searches were performed on the reference lists of relevant articles and other minor databases, including Web of Science, Cochrane databases, Centers for Disease Control and Prevention Smoking and Health Database, China National Knowledge Infrastructures (CNKI), Latin American and Caribbean Health Sciences Information System (LILACS), and African Index Medicus (AIM). Medical Subject Heading (MeSH) and EMBase TREE tool (EMTREE) were used to guide the choice of appropriate search terms in other databases.

Inclusion and Exclusion

Two reviewers independently identified articles eligible for in-depth examination using the following inclusion and exclusion criteria. Studies were included if at least one of the following outcomes was analyzed: invasive S. pneumoniae disease, invasive Hib disease, invasive N. meningitidis disease, and noso- or oropharyngeal carriage of any of the above three bacteria. IBD was defined as bacterial meningitis, bacterial epiglottitis, bacteremia, or microbiologically documented infection at other normally sterile sites with relevant clinical syndrome. Relevant exposures were defined as SHS or ETS exposure, parental smoking, household smoking or presence of household smoker(s), and regular contact with smokers. We excluded studies in which active smoking was the only exposure, active smoking was not distinguished from passive smoking, or studies that also included prenatal exposure. Study types included were cohort, case-control, and cross-sectional surveys, whereas case reports, review articles, editorials, and clinical guidelines were excluded. We included studies on human participants aged 1 mo to 19 y, i.e., infants, children, and adolescents. We excluded the neonatal period because of its established epidemiologic and pathophysiologic distinction from the post-neonatal period [17]. We included adolescents because age-specific N. meningitidis incidence peaks in childhood as well as adolescence; while S. pneumoniae incidence peaks in childhood and infancy, this disease may also occur in adolescents [4,6,9]. Studies on immunocompromised populations were excluded. When multiple articles reported on the same study population, we included only the most detailed publication that met the inclusion criteria. Any discrepancies on articles meriting inclusion between reviewers were resolved by a consensus meeting of three authors (C-CL, NAM, and ME). Study selection is summarized in Figure 1.

Data Extraction and Synthesis

Data were extracted on study location, setting (e.g., community, school, hospital, etc.), population characteristics including age range and sex ratio, number of participants, definition of exposure and diagnosis of outcome, crude and adjusted effect sizes as available, and confidence intervals (CIs). We also recorded quality indicators of study design including presence of appropriate controls and covariates used for adjustment in multivariate analysis. We conducted separate analyses on IBD and bacterial carriage. When studies were identified as containing pertinent data not included in the published article (e.g., when they did not differentiate between pediatric and adult participants), we contacted the authors to obtain the missing data. When a response was not provided and raw data were provided in the article, we manually calculated the unadjusted odds ratio (OR) for inclusion in the meta-analysis. Otherwise, such articles were excluded.
were considered statistically significant.

models were used for heterogeneity across studies [19,20]. The value of the I², which describes the variation of effect size that is attributable to

$p$-values $<0.05$ and quantified with the $F$ statistic, which describes the variation of effect size that is attributable to heterogeneity across studies [19,20]. The value of the $I^2$ statistic was used to select the appropriate pooling model: fixed-effects models were used for $F<50\%$ and random-effects models for $F \geq 50\%$ [19,20]. CIs of $F$ were calculated by the methods suggested by Higgins et al. [21]. Pooled ORs were summarized with Mantel–Haenszel method for fixed-effect models and DerSimonian and Laird method for random effect models [20]. Gaibrath plots were used to visualize the impact of individual studies on the overall homogeneity test statistic [22]. Meta-regression was used to evaluate whether effect size estimates were significantly different by specific study characteristics and quality factors, particularly those of adjustment for covariates and whether IBD diagnosis was only the more rigorous laboratory-confirmed or a mix of clinical-only and laboratory-confirmed diagnosis. We defined a study as having laboratory-confirmed diagnosis as the primary outcome if the study had more than 80% of cases confirmed by a positive culture, rapid antigen test, or PCR-based identification. In subgroup analyses, the association was larger in studies that included a total of 412 cases and 842 controls (Table 1) [25–41]. When the results from all studies were combined, SHS exposure was associated with an increased risk of invasive meningococcal disease (pooled OR 2.02, 95% CI 1.52–2.69; test of heterogeneity $p=0.001$, $I^2=68.5\%$) (Figure 2A). Gaibrath plots showed that two studies from Australia and Ghana were potential sources of heterogeneity [30,37]. The effect estimate excluding these two studies was slightly reduced compared with the overall effect estimate (OR 1.79, 95% CI 1.56–2.05).

Meta-regression analysis did not show any significant effect size modification by the specific study characteristics considered, possibly because of a relatively small number of studies (Table 2). In subgroup analyses, the association was larger in studies that used laboratory-confirmed cases (OR 3.24, 95% CI 1.72–6.13) [27,28,31–33,39]. Subgroup analysis of studies with different covariate adjustment generally found similar magnitude and direction of ORs compared with the overall effect size (Table 2) [25–28,30–34,36–40]. When the analysis was restricted to the three studies on preschool children (age $\leq 6$ y), the association was stronger but nonsignificant (OR 3.04, 95% CI 0.89–10.47) [28,33,39].

Invasive pneumococcal disease. The four case-control studies on SHS exposure and invasive pneumococcal disease included a total of 412 cases and 842 controls (Table 1) [35,36,42,43]. Combined results from all studies yielded a nonsignificant association (pooled OR 1.21, 95% CI 0.69–2.14; test of heterogeneity $p=0.098$, $I^2=52.3\%$) (Figure 2B). Once again, meta-regression did not show any significant effect size modification by specific study characteristics considered (Table 2).
Table 1. Summary of studies of the association between SHS exposure and IBD or pharyngeal bacterial carriage.

<table>
<thead>
<tr>
<th>Study (Location, Year)</th>
<th>Design</th>
<th>Setting and Study Population</th>
<th>Sample Size</th>
<th>Exposure*</th>
<th>Case Ascertainment**</th>
<th>Adjustment in Multivariate Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Invasive meningococcal disease</strong></td>
<td></td>
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</tr>
<tr>
<td>Haneberg et al. (Norway, 1983) [29]</td>
<td>Case-control</td>
<td>Population-based, younger than 12 y</td>
<td>469 (case 115)</td>
<td>Parental or household smoking</td>
<td>Laboratory-confirmed and/or clinical diagnosis</td>
<td>Only unadjusted ORs reported</td>
</tr>
<tr>
<td>Stuart et al. (UK, 1988) [40]</td>
<td>Case-control</td>
<td>Population-based, younger than 12 y</td>
<td>140 (case 70)</td>
<td>Household smoking</td>
<td>Laboratory-confirmed and/or clinical diagnosis</td>
<td>Only unadjusted ORs reported</td>
</tr>
<tr>
<td>Stanwell-Smith et al. (UK, 1994) [39]</td>
<td>Case-control</td>
<td>Population-based, younger than 5 y</td>
<td>152 (case 38)</td>
<td>Household smoking</td>
<td>Laboratory-confirmed diagnosis</td>
<td>Only unadjusted ORs reported</td>
</tr>
<tr>
<td>Fischer et al. (US, 1997) [27]</td>
<td>Case-control</td>
<td>Population-based, younger than 18 y</td>
<td>259 (case 84)</td>
<td>Maternal smoking at home</td>
<td>Laboratory-confirmed diagnosis</td>
<td>Age, location, maternal education, lack of primary care physician, household member density, school children density, humidifier use, church attendance</td>
</tr>
<tr>
<td>Moodley et al. (South Africa, 1999) [34]</td>
<td>Case-control</td>
<td>Population-based, younger than 14 y</td>
<td>280 (case 70)</td>
<td>Two or more household smokers</td>
<td>Laboratory-confirmed and/or clinical diagnosis</td>
<td>Age, breastfeeding, crowding index, recent respiratory tract infection, weight for age z-score</td>
</tr>
<tr>
<td>Baker et al. (New Zealand, 2000) [25]</td>
<td>Case-control</td>
<td>Population-based, younger than 8 y</td>
<td>515 (case 202)</td>
<td>Household smoking</td>
<td>Laboratory-confirmed and/or clinical diagnosis</td>
<td>Number of household members, analgesic use, attendance of social gathering, food sharing, household member respiratory tract infection symptom, recent respiratory tract infection, bed sharing</td>
</tr>
<tr>
<td>Kriz et al. (Czech Republic, 2000) [32]</td>
<td>Case-control</td>
<td>Population-based, younger than 15 y</td>
<td>203 (case 68)</td>
<td>Number of cigarettes smoked in the house in multiples of 20</td>
<td>Laboratory-confirmed diagnosis</td>
<td>Mother’s and father’s education, ownership of car and cottage, crowding</td>
</tr>
<tr>
<td>Hodgson A. et al. (Ghana, 2001) [30]</td>
<td>Case-control</td>
<td>Population-based, younger than 15 y</td>
<td>398 (case 201)</td>
<td>Compound (household) smoking</td>
<td>Laboratory-confirmed and/or clinical diagnosis</td>
<td>Only unadjusted ORs reported</td>
</tr>
<tr>
<td>Robinson et al. (Australia, 2001) [37]</td>
<td>Case-control</td>
<td>Population-based, younger than 16 y</td>
<td>141 (case 47)</td>
<td>Parent or partner smoking</td>
<td>Laboratory-confirmed and/or clinical diagnosis</td>
<td>Contact with dust, shared bedroom, any illness in prior 2 wk, oral muscle tone deficiency</td>
</tr>
<tr>
<td>Grein et al. (Ireland, 2001) [28]</td>
<td>Case-control</td>
<td>Population-based, younger than 6 y</td>
<td>354 (case 87)</td>
<td>Household smoking</td>
<td>Laboratory-confirmed diagnosis</td>
<td>Daycare attendance, number of children under 6 y old in household, number of adults in household, crowding index</td>
</tr>
<tr>
<td>Sorensen et al. (Denmark, 2004) [38]</td>
<td>Nested case-control</td>
<td>Nationwide population-based, younger than 18 y</td>
<td>9,702 (case 462)</td>
<td>Maternal smoking at home</td>
<td>ICD-8 and ICD-10 codes (treated as laboratory-confirmed and/or clinical diagnosis)</td>
<td>Low birth weight and prematurity, family income, crowding index</td>
</tr>
<tr>
<td>McCauley et al. (Australia, 2004) [33]</td>
<td>Case-control</td>
<td>Population-based, younger than 6 y</td>
<td>49 (case 21)</td>
<td>Household smoking</td>
<td>Laboratory-confirmed diagnosis</td>
<td>Breastfeeding, room sharing, daycare attendance</td>
</tr>
<tr>
<td>Pereiro et al. (Spain, 2004) [36]</td>
<td>Case-control</td>
<td>Hospital-based, younger than 15 y</td>
<td>424 (case 181)</td>
<td>Household smoking (≥60 cigarettes/day)*</td>
<td>Laboratory-confirmed diagnosis and/or clinical diagnosis</td>
<td>More than four household members, meningococcal vaccination</td>
</tr>
<tr>
<td>Coen et al. (England, 2005) [26]</td>
<td>Case-control</td>
<td>Population-based, 19 y</td>
<td>15–288 (case 144)</td>
<td>Latent variable for SHS exposure based on 7 variables</td>
<td>Laboratory-confirmed diagnosis and/or clinical diagnosis</td>
<td>Socioeconomic status, individual’s occupation, meningococcal vaccination status</td>
</tr>
<tr>
<td>Tully et al. (UK, 2005) [41]</td>
<td>Case-control</td>
<td>Population-based, 19 y</td>
<td>15–228 (case 114)</td>
<td>Close contacts with smokers</td>
<td>Laboratory-confirmed diagnosis and/or clinical diagnosis</td>
<td>Only unadjusted ORs reported</td>
</tr>
<tr>
<td>Honish et al. (Canada, 2008) [31]</td>
<td>Case-control</td>
<td>Population-based, 19 y</td>
<td>15–132 (case 44)</td>
<td>Maternal smoking</td>
<td>Laboratory-confirmed diagnosis</td>
<td>Use of humidifier, attended rave, bar visits, maternal education, visit to places where smoking was allowed, vaccination status</td>
</tr>
</tbody>
</table>

<p>| <strong>Meningococcal carriage</strong> |        |                               |             |           |                      |                                     |
| Stuart et al. (UK, 1989) [58] | Cross-sectional survey | Population-based, 5–19 y | 224 (case 112) | Household smoking | Nasopharyngeal carriage | Only unadjusted ORs reported |</p>
<table>
<thead>
<tr>
<th>Study (Location, Year)</th>
<th>Design</th>
<th>Setting and Study Population</th>
<th>Sample Size</th>
<th>Exposure*</th>
<th>Case Ascertainmentb</th>
<th>Adjustment in Multivariate Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kremastinou et al. (Greece, 1994) [55]</td>
<td>Cross-sectional survey</td>
<td>Population-based, 5–19 y</td>
<td>742 (case 44)</td>
<td>Maternal or other caretaker smoking</td>
<td>Oropharyngeal carriage, saliva</td>
<td>Only unadjusted ORs reported</td>
</tr>
<tr>
<td>Davies AL, et al. (UK, 1996) [54]</td>
<td>Cross-sectional survey</td>
<td>School contacts of index case, 11–18 y</td>
<td>114 (case 18)</td>
<td>Household smoking</td>
<td>Nasopharyngeal carriage</td>
<td>Only unadjusted ORs reported</td>
</tr>
<tr>
<td>Kremastinou et al. (Greece, 1999) [56]</td>
<td>Cross-sectional survey</td>
<td>Russian immigrants, 6–15 y</td>
<td>625 (case 82)</td>
<td>Parental smoking</td>
<td>Oropharyngeal carriage</td>
<td>Only unadjusted ORs reported</td>
</tr>
<tr>
<td>MacLennan et al. (UK, 2006) [57]</td>
<td>Cross-sectional survey</td>
<td>Population-based, 15–19 y</td>
<td>13,919 (case 2,319)</td>
<td>Household smoking</td>
<td>Oropharyngeal carriage</td>
<td>Age, active smoking, intimate kissing, pub attendance, number of people in the bedroom, household member density, recent antibiotic use, school type, school size, study sites</td>
</tr>
<tr>
<td>Invasive pneumococcal disease</td>
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<tr>
<td>Takala et al. (Finland, 1995) [43]</td>
<td>Case-control</td>
<td>Population-based, &lt;15 y</td>
<td>433 (case 149)</td>
<td>Parental smoking at home</td>
<td>Laboratory-confirmed diagnosis</td>
<td>Only unadjusted ORs reported</td>
</tr>
<tr>
<td>O’Dempsey et al. (Gambia, 1996) [35]</td>
<td>Case-control</td>
<td>Population-based, 4–14.2 mo</td>
<td>239 (case 80)</td>
<td>Paternal or other household smoking</td>
<td>Laboratory-confirmed and/or clinical diagnosis</td>
<td>Mother has income, cooking smoke exposure, weight for age z-score, illness in past month, significant illness in past 6 mo</td>
</tr>
<tr>
<td>Pereiro et al. (Spain, 2004) [36]</td>
<td>Case-control</td>
<td>Hospital-based, younger than 15 y</td>
<td>306 (case 63)</td>
<td>Household smoking (≥60 cigarettes/day)c</td>
<td>Laboratory-confirmed diagnosis</td>
<td>Only unadjusted ORs reported</td>
</tr>
<tr>
<td>Haddad et al. (USA, 2008) [42]</td>
<td>Case-control</td>
<td>Population-based, younger than 59 mo</td>
<td>276 (case 120)</td>
<td>Tobacoo exposure (no specific definition provided)</td>
<td>Laboratory-confirmed diagnosis</td>
<td>Only unadjusted ORs reported</td>
</tr>
<tr>
<td>Pneumococcal carriage</td>
<td></td>
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<tr>
<td>Sung et al. (Hong Kong, 1995) [63]</td>
<td>Cross-sectional survey</td>
<td>Population-based, 2 mo to 5 y</td>
<td>921 (case 234)</td>
<td>Household smoking</td>
<td>Nasopharyngeal carriage</td>
<td>Only unadjusted ORs reported</td>
</tr>
<tr>
<td>Coles et al. (India, 2001) [60]</td>
<td>Cross-sectional survey</td>
<td>South India endemic area population, 6 mo</td>
<td>464 (case 400)</td>
<td>20 or more cigarettes per day were smoked in the household</td>
<td>Nasopharyngeal carriage</td>
<td>Sex, fed with colostrums, history of night blindness during pregnancy, fuel used for cooking, season, maternal education, transportation with bicycle, number of siblings younger than 5 y, vitamin A supplementation</td>
</tr>
<tr>
<td>Greenberg et al. (Israel, 2006) [61]</td>
<td>Cross-sectional survey</td>
<td>Population-based, 1–59 mo</td>
<td>208 (case 143)</td>
<td>Parental smoking at home</td>
<td>Nasopharyngeal carriage</td>
<td>Only unadjusted ORs reported</td>
</tr>
<tr>
<td>Cardozo et al. (Brazil, 2008) [59]</td>
<td>Cross-sectional survey</td>
<td>Population-based, 19 y</td>
<td>10–1,013 (case 83)</td>
<td>Household smoking</td>
<td>Nasopharyngeal carriage</td>
<td>Age, sex, presence of siblings younger than 5 y of age, upper respiratory tract infection, acute asthma</td>
</tr>
<tr>
<td>Labout et al. (Netherlands, 2008) [62]</td>
<td>Cross-sectional survey</td>
<td>Population-based, 1.5 mo</td>
<td>757 (case 337)</td>
<td>Maternal smoking at home</td>
<td>Nasopharyngeal carriage</td>
<td>Birth weight, gestational age, parity, sex, maternal education, having siblings</td>
</tr>
<tr>
<td>Invasive Hib disease</td>
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<tr>
<td>Cochi et al. (USA, 1986) [45]</td>
<td>Case-control</td>
<td>Population-based, younger than 5 y</td>
<td>619 (case 89)</td>
<td>Parental smoking</td>
<td>Laboratory-confirmed and/or clinical diagnosis</td>
<td>Only unadjusted ORs reported</td>
</tr>
<tr>
<td>Harrison et al. (USA, 1989) [3]</td>
<td>Case-control</td>
<td>Population-based, younger than 5 y</td>
<td>201 (Case 74)</td>
<td>Parental smoking</td>
<td>Laboratory-confirmed diagnosis</td>
<td>Sex, race, income, age, maternal education, number of rooms in house, breastfeeding</td>
</tr>
<tr>
<td>Takala et al. (Finland, 1989) [46]</td>
<td>Case-control</td>
<td>Population-based, 1 month to 6 y</td>
<td>342 (case 117)</td>
<td>Parental smoking</td>
<td>Laboratory-confirmed diagnosis</td>
<td>Only unadjusted ORs reported</td>
</tr>
<tr>
<td>Vadheim et al. (USA, 1992) [47]</td>
<td>Case-control</td>
<td>Population-based, 18–60 mo</td>
<td>300 (case 79)</td>
<td>Two or more household smokers</td>
<td>Laboratory-confirmed diagnosis</td>
<td>Age, month of diagnosis, Hib vaccine status, household size, annual household income, number of children under 5 y old, household density breastfeeding, ethnicity, daycare attendance</td>
</tr>
</tbody>
</table>
In the case of adjustment, there was only one adjusted study that had a large but imprecise effect estimate (OR 2.99, 95% CI 1.10–8.14) [35]. In subgroup analysis, the three studies with laboratory-confirmed diagnosis had a null effect size of 0.93 (95% CI 0.62–1.41). The association was stronger in studies on preschool children was statistically significant (Table 2). In subgroup analysis, studies with laboratory-confirmed diagnosis had a similar effect size of 1.24 (95% CI 0.86–1.78), whereas adjusted studies yielded a lower and nonsignificant effect size (OR 1.10, 95% CI 0.80–1.51) [3,36,44,46–53]. Studies on preschool children had a significant positive association (OR 1.46, 95% CI 1.19–1.81) (Table 2) [3,36,47,49,52,53]. Studies before 1990, when Hib vaccine was not yet commonly available, had a stronger effect size (OR 2.99, 95% CI 1.10–8.14) (Table 2) [3,36,44–47,49,52,53]. Studies before 2000, when pneumococcal vaccines (including the 7-valent pneumococcal conjugate vaccine) were not widely available, also showed a stronger but nonsignificant association (OR 1.75, 95% CI 1.00–3.04) [49]. Studies on preschool children had a significant positive association (OR 1.46, 95% CI 1.19–1.81) (Table 2) [3,36,44,47,49,52,53]. Studies before 1990, when Hib vaccine was not yet commonly available, had a stronger effect size.
Figure 2. ORs for invasive bacterial disease for exposure to secondhand smoke compared to nonexposure: (A) meningococcal disease, (B) pneumococcal disease, (C) Hib disease.
doi:10.1371/journal.pmed.1000374.g002
positive association (OR 1.49, 95% CI 1.16–1.93) than the overall analysis [3,44–47].

SHS Exposure and Pharyngeal Bacterial Carriage

**N. meningitidis carriage.** We identified a total of five cross-sectional surveys on pharyngeal carriage of *N. meningitidis* comprising 2,575 carriers and 15,624 noncarriers (Table 1) [54–58]. The pooled OR for all studies showed a significant positive association between SHS exposure and pharyngeal *N. meningitidis* carriage (pooled OR 1.67, 95% CI 1.12–2.52; test of heterogeneity \( p = 0.034, I^2 = 61.6\% \)) [54–58] (Figure 3A). Studies with multivariate adjustment had an OR smaller than the overall analysis, but their pooled effect size remained significant (1.17 [1.05–1.30]) (Table 2) [57]. However, meta-regression analysis indicated that the difference between adjusted and crude effect sizes had borderline statistical significance (\( p = 0.061 \)).

**S. pneumoniae carriage.** There were five cross-sectional surveys on SHS exposure and pharyngeal carriage of *S. pneumoniae*...
with a total of 860 carriers and 1,746 noncarriers (Table 1) [59–63]. The pooled result from all studies showed a significant positive association (pooled OR 1.66, 95% CI 1.33–2.07; test of heterogeneity $p = 0.48, I^2 = 0\%$) (Figure 3B). Adjustment or study characteristics did not significantly modify the effect size in meta-regression analysis (Table 2). Subgroup analysis on the three studies with multivariate

Figure 3. ORs for pharyngeal carriage of bacteria for exposure to secondhand smoke compared to nonexposure: (A) *N. meningitidis*, (B) *S. pneumoniae*, (C) Hib.

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SHS and Pediatric Invasive Bacterial Disease

adjustment yielded a similar association with borderline significance (OR 1.48, 95% CI 1.01–2.16) [59,60,62]. Studies on preschool children also had a significant association of similar magnitude (OR 1.63, 95% CI 1.27–2.10) (Table 1) [64,65]. The pooled association was nonsignificant (OR 0.96, 95% CI 0.48–1.95; test of heterogeneity p = 0.56, I² = 0%) (Figure 3C). The study population did not include the most vulnerable age group, i.e., preschool children.

Hib carriage. There were only two cross-sectional studies on SHS exposure and childhood pharyngeal carriage of Hib that included a total of 38 cases and 945 controls (Table 1) [64,65]. The pooled association was nonsignificant (OR 0.96, 95% CI 0.48–1.95; test of heterogeneity p = 0.56, I² = 0%) (Figure 3C). The study population did not include the most vulnerable age group, i.e., preschool children.

Dose-Response Relationships

Dose-response relationships were examined in four invasive meningococcal disease studies [28,32,36,39], three invasive Hib disease studies [47,50,51], and one invasive pneumococcal disease study [36]. The studies had used different metrics to measure exposure and dose including number of cigarettes smoked per day and number of household smokers. The absence of a consistent definition of exposure meant that a pooled analysis of the dose-response relationship was not possible. Broadly, with the exception of the pneumococcal study and one Hib study, there was a dose-response relationship with the number of cigarettes smoked per day or the number of smokers in the household [28,32,36,39,47,50,51].

Publication Bias

The test for publication bias was significant in three of the six outcomes, namely invasive meningococcal and pneumococcal diseases and N. meningitidis carriage (Table 3). The trim-and-fill ORs for meningococcal disease and N. meningitidis carriage were lower but the former remained statistically significant. The positive, but nonsignificant, OR of 1.21 (95% CI 0.69–2.14) for pneumococcal disease was replaced by a trim-and-fill OR of 0.83 (95% CI 0.45–1.53).

Discussion

This systematic review and meta-analysis of studies on the association between SHS exposure and IBD or pharyngeal carriage of pathogenic bacteria in pediatric populations revealed a consistent and positive association between SHS exposure and invasive meningococcal disease and pharyngeal carriage of N. meningitidis, as well as a positive association with S. pneumoniae carriage. There was also a positive but not statistically significant association with invasive pneumococcal and Hib diseases. The association with Hib carriage was based on only two studies and was null. When subanalyses could be conducted, the pooled effect sizes with and without adjustment for important risk factors were generally similar, becoming slightly smaller for meningococcal and pneumococcal carriage and for invasive Hib disease, and larger for invasive meningococcal and pneumococcal diseases. Studies with laboratory-confirmed diagnosis, the more rigorous outcome, had large and statistically significant effect sizes for meningococcal disease but not for pneumococcal and Hib diseases.

The nonsignificant associations with invasive pneumococcal disease may have been partially due to the relatively small pooled sample sizes (412 cases), whereas that of Hib disease is less likely to be due to sample size (1,228 cases). For Hib disease, studies on the most vulnerable ages (≤6 y old) had larger and significant effect estimates. A factor that may have contributed to the insignificant effects may be the increasing use of Hib vaccine (since 1990) and pneumococcal conjugate vaccines (since 2000). Studies before the vaccine era had larger effect sizes for both Hib and pneumococcal diseases, but these were only statistically significant for Hib. These factors, and the strong association that has been observed between active smoking and invasive pneumococcal disease [66], should motivate additional high-quality studies with large sample sizes to clarify the role of SHS in the etiology of invasive pneumococcal disease.

There are plausible mechanisms for the effects of SHS on bacterial diseases. Both in vivo and in vitro experimental studies have found that SHS exposure may induce structural changes in the respiratory tract including peribronchiolar inflammation and fibrosis, increased mucosal permeability, and impairment of the mucociliary clearance [67,68]. It may also decrease immune defenses, e.g., a decreased level and depressed responses of circulating immunoglobulins, decreased CD4+ lymphocyte counts and increased CD8+ lymphocyte counts, depressed phagocyte activity, and decreased release of proinflammatory cytokines [68–72]. All these mechanisms might increase the risk of bacterial invasion and subsequent infection. The significant findings here regarding the association of SHS exposure with bacterial carriage also support a plausible etiological role for SHS in invasive bacterial disease, because asymptomatic carriage is an intermediate step towards invasive disease [12,13,15,16]. Asymptomatic carriage itself has a public health implication because it is important in population transmission of infectious bacteria [12,15].

Strengths and Limitations

This systematic review has strengths and limitations. To the best of our knowledge, this is the first systematic review of the epidemiologic evidence on the association between SHS exposure and pediatric IBD. We were able to include clinical invasive disease as well as the etiologically and epidemiologically important intermediate stage of asymptomatic bacterial carriage. As far as possible, we assessed sensitivity to important methodological

Table 3. Tests for publication bias and trim-and-fill ORs.

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Begg ρ-Value</th>
<th>Egger ρ-Value</th>
<th>Original OR (95% CI)</th>
<th>Trim and Fill OR (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invasive meningococcal disease</td>
<td>0.015</td>
<td>0.060</td>
<td>2.02 (1.52–2.69)</td>
<td>1.66 (1.22–2.24)</td>
</tr>
<tr>
<td>Meningococcal carriage</td>
<td>0.624</td>
<td>0.065</td>
<td>1.67 (1.12–2.32)</td>
<td>1.32 (0.91–1.92)</td>
</tr>
<tr>
<td>Invasive pneumococcal disease</td>
<td>0.042</td>
<td>0.012</td>
<td>1.21 (0.69–2.14)</td>
<td>0.83 (0.45–1.53)</td>
</tr>
<tr>
<td>Pneumococcal carriage</td>
<td>0.327</td>
<td>0.255</td>
<td>1.66 (1.33–2.07)</td>
<td>NA</td>
</tr>
<tr>
<td>Invasive Hib disease</td>
<td>0.537</td>
<td>0.777</td>
<td>1.22 (0.93–1.62)</td>
<td>NA</td>
</tr>
<tr>
<td>Hib carriage</td>
<td>0.317</td>
<td>NA</td>
<td>0.96 (0.48–1.95)</td>
<td>NA</td>
</tr>
</tbody>
</table>

Trim-and-fill ORs were calculated when publication bias tests were statistically significant.

*From Figure 2.

NA, not applicable.

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design and quality characteristics using meta-regression and subgroup analysis. Our search covered multiple databases without language limitation.

A key limitation of our study was the relatively small number of studies, specifically from developing countries in which the IBD burden is the largest, smoking, increasing SHS and vaccination coverage may be lower. Notably, two African studies had a nonsignificant effect size for invasive meningococcal disease [30,34]. One of these studies was from northern Ghana, where more than 93% of participants were exposed to fuelwood smoke [30]. In addition, negative residual confounding (due to the potential negative association of household smoking with economic status) cannot be ruled out as a source of the nonsignificant negative finding. The second study, from urban South Africa, had included an interaction term between recent upper respiratory tract infection (URTI) and SHS exposure in the multivariate analysis, which had an OR of 3.6 (95% CI 1.4–7.5) [34]. If recent URTI itself was caused by SHS and can increase the risk of IBD, then this adjustment would attenuate the true effect of the SHS term. A third African study from The Gambia had an OR of 2.99 (95% CI 1.10–8.14) for pneumococcal disease [35]. The limited number of studies from developing countries makes it difficult to assess the role of factors such as background incidence rate, nutritional status, vaccination, and coexposure to wood smoke on the ORs for SHS-IBD association. A second potential limitation is that both the exposure and outcome measurements may have been subject to error, which is likely to have biased our results towards the null and reduced its significance. Third, heterogeneity of effect sizes across studies restricts our ability and confidence to generalize the results of this pooled data analysis to all populations. Fourth, the studies on association with bacterial carriage were distinct from those on IBD and no SHS-IBD studies had assessed carriage at baseline. As a result, we were not able to assess whether SHS exposure only increases the risk for colonization, or increases the risk of subsequent infection, or both. Fifth, because IBD is a complex disease with multiple causes, there is potential for residual confounding in the observational studies included in our analysis. This is especially relevant given that the currently available SHS-IBD studies were case-control or nested case-control studies and those on SHS-bacterial carriage were cross-sectional studies. Our findings on the potential causal associations should motivate new prospective studies. Sixth, our study focused on pediatric SHS exposure and did not assess studies on perinatal SHS exposure as a risk factor for IBD, with some of the effect possibly mediated through low birth weight. [73,74]. Finally, while we assessed the potential for publication bias and report trim-and-fill ORs, the latter estimates are themselves subject to methodologic limitations especially when the number of studies is small [73].

Despite the limitations of current epidemiologic studies, our meta-analysis provides some evidence of an association between SHS and IBD and pharyngeal carriage, especially in preschool children. Although there are efficacious vaccines against all three pathogens assessed in this study, many children in low-income countries are not covered in routine immunizations and have limited access to case management [76–80]. Vaccine pricing remains an obstacle to uptake, while waning immunity and serotype replacement may undermine long-term vaccine effectiveness [78,81–83]. Thus scaling up vaccine coverage and case management must be accompanied by nonvaccine interventions, such as environmental interventions, to address the large burden of IBDs. Tobacco smoking and SHS exposure have increased in low-income and middle-income countries, making SHS exposure a global problem [84,85]. While public smoking bans have been effective in reducing adult SHS exposure and adverse health effects [86,87], children’s exposure to SHS may occur at home, where bans may be difficult to enforce [11]. An estimated 700 million children worldwide are exposed to SHS at home [84]. If the observed effects are causal, our results indicate that in a population where 25% of young children are exposed to SHS (e.g., Brazil or South Africa), 5%–20% of IBD cases may be attributable to this risk factor; the attributable fraction would be 10%–34% in populations where exposure is 50% (e.g., Egypt or Indonesia). Effects of such magnitude should motivate a number of research and intervention steps specifically related to SHS and pediatric IBD: Firstly, there should be well-designed prospective studies with high-quality measurement of exposure, outcome, and potential confounders to overcome the limitations of the current studies. Secondly, interventions that specifically focus on reducing children’s exposure at home, schools, and other environments should be pursued. These two directions are particularly important in developing countries where the IBD burden is high and exposure to SHS is high or increasing. Finally, the effects of other combustion pollutant sources that are common in developing countries, especially smoke from wood and animal dung fuels, on IBD should be subject to research.

Supporting Information

Text S1 PRISMA checklist.

Found at: doi:10.1371/journal.pmed.1000374.s001 (0.07 MB DOC)

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Author Contributions

ICMJE criteria for authorship read and met: CCL NAM SRCH ME. Agree with the manuscript’s results and conclusions: CCL NAM SRCH ME. Designed the experiments/the study: CCL ME. Analyzed the data: CCL NAM SRCH. Collected data/did experiments for the study: CCL NAM. Wrote the first draft of the paper: CCL ME. Contributed to the writing of the paper: NAM SRCH. Developed research concept and oversaw research: ME.

References


Editors’ Summary

Background. The deleterious health effects of smoking on smokers are well established, but smoking also seriously damages the health of nonsmokers. Secondhand smoke (SHS), which is released by burning cigarettes and exhaled by smokers, contains hundreds of toxic chemicals that increase the risk of adults developing lung cancer and heart disease. Children, however, are particularly vulnerable to the effects of SHS exposure (also known as passive smoking) because they are still developing physically. In addition, children have little control over their indoor environment and thus can be heavily exposed to SHS. Exposure to SHS increases the risk of ear infections, asthma, respiratory symptoms (coughing, sneezing, and breathlessness), and lung infections such as pneumonia and bronchitis in young children and the risk of sudden infant death syndrome during the first year of life.

Why Was This Study Done? Several studies have also shown an association between SHS exposure (which damages the lining of the mouth, throat, and lungs and decreases immune defenses) and potentially fatal invasive bacterial disease (IBD) in children. In IBD, bacteria invade the body and grow in normally sterile sites such as the blood (bacteremia) and the covering of the brain (meningitis). Three organisms are mainly responsible for IBD in children—Streptococcus pneumoniae, Haemophilus influenzae type B (Hib), and Neisseria meningitidis. In 2000, S. pneumonia (pneumococcal disease) alone killed nearly one million children. Here, the researchers undertake a systematic review and meta-analysis of the association between SHS exposure in children and two outcomes—IBD and the presence of IBD-causing organisms in the nose and throat (bacterial carriage). A systematic review uses predefined criteria to identify all the research on a given topic; meta-analysis is a statistical method that combines the results of several studies. By combining data, it is possible to get a clearer view of the causes of a disease than is possible from individual studies.

What Did the Researchers Do and Find? The researchers identified 30 case-control studies that compared the occurrence of IBD over time in children exposed to SHS with its occurrence in children not exposed to SHS. They also identified 12 cross-sectional studies that measured bacterial carriage at a single time point in children exposed and not exposed to SHS. The researchers used the data from these studies to calculate a “summary odds ratio” (OR) for each outcome—a measure of how SHS exposure affected the likelihood of each outcome. Compared with children unexposed to SHS, exposure to SHS doubled the likelihood of invasive meningococcal disease (a summary OR for SHS exposure of 2.02), Summary ORs for invasive pneumococcal disease and Hib diseases were 1.21 and 1.22, respectively. However, these small increases in the risk of developing these IBDs were not statistically significant unlike the increase in the risk of developing meningococcal disease. That is, they might have occurred by chance. For bacterial carriage, summary ORs for SHS exposure were 1.68 for N. meningitidis, 1.66 for S. pneumonia (both these ORs were statistically significant), and 0.96 for Hib (a nonsignificant decrease in risk).

What Do These Findings Mean? These findings indicate that SHS exposure is significantly associated with invasive meningococcal disease among children. However, the evidence that SHS exposure is associated with invasive pneumococcal and Hib disease is only suggestive. These findings also indicate that exposure to SHS is associated with an increased carriage of N. meningitidis and S. pneumonia. The accuracy and generalizability of these findings is limited by the small number of studies identified, by the lack of studies from developing countries where SHS exposure is increasing and the burden of IBD is high, and by large variations between the studies in how SHS exposure was measured and IBD diagnosed. Nevertheless, they suggest that, by reducing children’s exposure to SHS (by, for example, persuading parents not to smoke at home), the illness and death caused by IBDs among children could be greatly reduced. Such a reduction would be particularly welcome in developing countries where vaccination against IBDs is low.

Additional Information. Please access these Web sites via the online version of this summary at http://dx.doi.org/10.1371/journal.pmed.1000374.

- The US Centers for Disease Control and Prevention provides information on secondhand smoke, on children and secondhand smoke exposure, on meningitis, and on Hib infection
- The US Environmental Protection Agency also provides information on the health effects of exposure to secondhand smoke (in English and Spanish) and a leaflet (also in English and Spanish) entitled Secondhand Tobacco Smoke and the Health of Your Family
- The US Office of the Surgeon General provides information on the health consequences of involuntary exposure to tobacco smoke
- The World Health Organization provides a range of information on the global tobacco epidemic
- The World Health Organization has information on meningococcal disease (in English only) and on Hib (in several languages)
- The US National Foundation for Infectious Diseases provides a fact sheet on pneumococcal disease