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ABSTRACT

While a growing body of scientific literature describes the population health impacts of fossil fuel production and burning via climate and air pollution pathways, less is known about the health impacts of indoor combustion. This paper summarizes the results of studies from the last two decades that investigated the association between exposure to sources of unvented combustion pollutants in homes and a range of health outcomes. We found gas combustion to be associated with 6-28% (95% confidence intervals) increased odds of asthma symptoms, 4-51% increased odds of systemic symptoms, 7-81% increased odds of asthma medication use, and 3-12% increased risk of mortality. These findings can be used to improve public health, for example, by informing requirements for improved ventilation and source control, justifying switching to vented appliances, better regulation of device emissions and quantifying the benefits of electrification of end-uses. Dose-response relationships between human health, NO_2 exposure, and other by-products of combustion are not characterized with a high degree of precision. However, there is clear evidence of a wide range of health effects, even at low levels of exposure. Despite the various designs, geographic sites, length of follow-up, and study dates, we noted a level of consistency between the studies within the current meta-analysis, and with previous ones, which strengthens the level of confidence in our findings.

Keywords
Health; gas combustion; gas cooking; gas heating; meta-analysis

1. Introduction

The primary consumers of fossil fuels in homes are: heating, hot water, cooking and clothes drying. Except for cooking and unvented heaters, these end-uses are required to have a vent to outside and only contaminate indoor air if their venting system fails. While venting combustion products contributes to outside air pollution that can then enter a home, in this paper we will focus on direct indoor sources only.

It is well established that the inhalation of fossil fuel combustion products leads to a range of adverse population health effects. Cooking and unvented heating are main indoor sources of NO_2, ultrafine particles, and volatile organic compounds (VOCs) if not vented to outdoors (Lewis et al., 2023). A previous literature review (Less et al. 2022) discussing home energy performance provided a high-level summary of a few indoor air quality studies related to indoor combustion, but did into provide the in-depth health analysis that is the focus of this paper.

NO_2 is an irritant to the respiratory tract. Even short-term exposures can irritate the airways, drive inflammation, and lead to acute and chronic disease, especially among those with asthma (Barck et al., 2005; Vardoulakis et al., 2020; Lim et al., 2022). While particles are the most important contaminant of concern for health impacts, at least from Disability Adjusted Life Year (DALY) perspective (Logue et al., 2012; Morantes et al., 2022), most particle exposure is from non-residential sources such as transport, agriculture and industry. Therefore, in this review will focus on the next important contaminant of concern, i.e., NO_2. A meta-analysis done by (Faustini et al., 2014) confirms that the effect of NO_2 was independent from PM, suggesting that NO_2 can drive health effects on its own. In addition, when the levels of NO_2 in a home are below the threshold limits, (< 15 ppb), it becomes challenging to observe any potential health effects.

Although the strong toxicological evidence for NO_2 is compelling enough to spur population health protective action, the toxicology is borne out in a number of epidemiological studies. Meta-analyses by (Khreis et al., 2017) and (Gruenwald et al., 2022) of epidemiological studies showed clear relationships with asthma development and have enabled modelling studies estimating the broader population impacts of reducing NO_2 exposures (e.g., (Knibbs et al., 2018; Achakulwisut et al., 2019; Jacobs et al., 2019; Hu et al., 2022). (Lin et al., 2013) synthesized the available literature on gas stove use and found correlations with the two health outcomes they studied, asthma development and wheeze in children. This paper provides a 10-year update to Lin et al, to build on existing dose-response findings through the inclusion of studies published through April 2023 that reported on a broader set of potential adverse health effects like hospitalization, asthma symptoms and medication use.

2. Methodology

This study reviews research since the year 2000 on the health impacts associated with exposure to combustion-related contaminants in homes. We grounded the evaluation using literature related to interventions where gas combustion appliances were replaced, or effective engineering controls were implemented, including those where measured NO_2 was taken as the main exposure variable. We grounded the review in the landmark intervention studies conducted in Australia and New Zealand (Pilotto et al., 2004; Howden-Chapman et al., 2008; Marks et al., 2010; Gillespie-Bennett et al., 2011), and a comprehensive meta-analysis focused on gas stove effects on cough and wheeze (Lin et al., 2013). We used Google Scholar to identify works citing these studies. We then applied inclusion and exclusion criteria to narrow the search to epidemiological studies that provide dose-response relationships between home combustion appliances and health outcomes.

We assessed study relevance and quality, leading to a final set of manuscripts. We included studies that used epidemiologic methods to investigate associations between health outcomes and the presence or use of unvented gas combustion appliances and/or measured NO_2 with results presented as effect estimates with confidence intervals. Studies were excluded that did not involve data collection post-2000, that did not focus on residential exposure, that had effect estimates that were already included by Lin and colleagues, and that did not include gas or oil-based cooking or heating sources. Wood burning was considered beyond the scope of this analysis, as were effect estimates of lung function. We considered meta-analyses that used pooled estimates from studies with lower risk of bias as evaluated by the WHO or other similar methodology.

In this study, the health outcomes primarily were associated with acute exposures. We categorized the health outcomes into 12 distinct categories.: 1) asthma symptoms including wheeze, cough, shortness of breath, chest tightness, respiratory symptoms, nasal symptoms, and difficulty breathing; 2) asthma symptom scores including ordinal scores 0-3 (3 as the most severe and 0 as no symptom) for wheeze, cough, overall asthma symptoms, upper respiratory, and lower respiratory symptoms; 3) systemic symptoms including poor/fair health, diarrhea, vomiting, ear infection stomach ache, eczema, sensitization, allergies, nighttime waking, and steroid use; 4) healthcare visits that were not hospitalizations or emergency room visits or changes to asthma management; 5) hospitalization or emergency room visits, 6) medication use including asthma preventer and reliever use; 7) nonpharmaceutical interventions including limiting activity; 8) neurological disease development including schizophrenia; 9) absences from school; 10) all-cause mortality; 11) cardiovascular mortality; 12) respiratory mortality.

We converted effect estimates with continuous, independent variables to effects per 20 ppb increase in NO_2. We converted intervention studies to consider control groups as the numerator in effect estimate ratios. We used effect estimates that adjusted for confounders when available. We stratified pooled estimates by health outcome, categorical or continuous exposure, and effect estimate type (odds ratios (OR), risk ratios (RR), incident rate ratios (IRR)). We computed random effect pooled estimates where there were at least four effect estimates, accounting for variation in study populations, differences in study design, and a variety of health outcomes considered. For example, the outcome of "asthma symptoms" included effect estimates for cough, wheeze, respiratory symptoms, and others. Statistics and forest plots were generated by *R v.4.2.1* with packages *meta* and *metafor.* The data and code for reproducibility can be found at https://gitlab.com/jacobbueno/zapdos.

3. Results

The search yielded 29 studies including 10 meta-analyses, 12 observational studies and 7 randomized controlled trials (RCTs) or quasi-experimental studies. In total, these included 184 effect estimates for a variety of health outcomes. Eleven of the studies focused exclusively on children with asthma, as part of randomized controlled trials or observational studies. An additional study included over 80% children with asthma. RCTs and observational studies often focused on unvented exposures from unvented gas heat and gas cooking. In contrast, the meta-analyses mostly focused on residential indoor NO_2 exposure from multi-year indoor air pollution monitoring. Intervention studies examined changes in exposure to combustion contaminants and associated health effects. Intervention activities included installing exhaust ventilation for combustion appliances or electric alternatives like heat pumps (Pilotto et al., 2004; Howden-Chapman et al., 2008; Free et al., 2010; Barnard et al., 2011; Gillespie-Bennett et al., 2011), a gas scrubber (Gent et al., 2022) or comparing homes with gas and appliances (Belanger et al., 2006; Willers et al., 2006; Boulic, 2012; Rice et al., 2020).

Average NO_2 level changes for unvented gas heat at home were reported in residences at 3.8 ppb (Howden-Chapman et al., 2008; Free et al., 2010), and in schools at 14.1 ppb (Marks et al., 2010), and 31.5 ppb (Pilotto et al., 2004). Belanger et al, showed an increase in average NO_2 of 17.3 ppb (Belanger et al., 2006), Comparing gas ranges with electric ranges in both multifamily and single-family homes. (Hansel et al., 2008) found that the presence of a gas stove, as well as the use of stove/oven and space heater for heat, is linked to higher indoor levels of NO_2, which suggests modifiable sources of exposure. Those with gas stoves had 15.7 ppb (95% CI 6.9-24.6) times the NO2 concentration and those with gas heaters had 4.4 ppb (95% CI -2.8-11.6) times the NO2 concentration. In 24 high performance California homes, (B. Less et al., 2015) measured NO2 in kitchens that used gas and electric cooking equipment and found average 6-day integrated NO_2 concentrations of 6.6 vs. 17.9 ppb in electric and gas cooking kitchens respectively. The California Healthy Homes Indoor Air Quality Study of 2011–2013 (Mullen et al., 2016), measured combustion contaminants for 6-day periods in 352 existing California dwellings (including the homes in Less et al.). They found that kitchen NO_2 concentrations were not significantly impacted by vented combustion appliances (6.5 vs. 7.6 ppb), while unvented gas cooking with and without other vented gas appliances led to significantly higher indoor concentrations (18 and 22 ppb, respectively). Similarly, Belanger et al 2006 found clear increases in NO_2 concentration in homes with gas versus electric cooking.

We considered NO_2 to be a main toxicant produced by indoor gas combustion (compared with electric appliances) or an indicator chemical of the combustion air pollution—including PM and VOCs—that could be related to health effects via inhalation exposure. Meta-analyses focused on indoor NO_2 concentrations found consistent relationships with all mortality with a 95% CIs of 3-12%, while a 10-year Danish birth cohort quantified risk of schizophrenia development at 2.18 (95% CI 1.69-2.85) times higher for each 20 ppb NO_2 increase (Horsdal et al., 2019). The range of health effects consistently associated with indoor, residential gas combustion over the last two decades shows that at population scale, substituting gas appliances for electric ones should reduce some adverse health effects, with associated health, economic, and social benefits. The studies highlight the elevated risk of symptoms and associated health problems for those with asthma, but also show that combustion appliance exposure could lead to asthma development and other cardiovascular, respiratory, and neurological diseases.

Samet and colleagues tracked daily symptoms in over 1,200 infants through 18 months of age and found that measured NO_2 concentrations at home, mostly below 20 ppb, were not associated with respiratory symptoms (Samet et al., 1993), suggesting there may be little risk for infants with low to modest NO_2 exposure, or among populations that are not already susceptible to respiratory health risks (e.g., those with asthma, or bronchopulmonary dysplasia). However, this study did not examine other health impacts such as respiratory infections, asthma exacerbation or initiation. Other studies included in our meta-analysis included infant populations along with older children, with mixed results (Belanger et al., 2006; Willers et al., 2006; Barnard et al., 2011; Rice et al., 2020). The 8-year prospective birth cohort by Willers et al reported a positive relationship between gas cooking and nasal symptoms, and a trend toward a positive relationship with asthma prevalence, but not eczema, wheeze, or sensitization (Willers et al., 2006). A cross-sectional study of children 12 years old or younger revealed strong, positive associations between gas stove use and wheeze, chest tightness, and shortness of breath, particularly among multi-family as opposed to single-family residences (Belanger et al., 2006). Barnard et al showed a slight risk of hospitalization associated with gas heating in a population inclusive of all ages, and Rice et al showed a nearly 600% increase in odds of hospitalization among children with bronchopulmonary dysplasia on respiratory support (Barnard et al., 2011; Rice et al., 2020). The detectable risk increases associated with indoor combustion sources appear to be modified by existing health vulnerability including asthma. The likelihood of increased risks with cumulative exposures raises concerns about health risks for communities already facing disproportionate burdens of toxic exposures, especially where there are already higher rates of asthma and other illnesses or vulnerability due to environmental exposures. Overall, the effect estimates trended toward a positive relationship between residential gas combustion, NO_2 exposure, and adverse health outcomes. There were no effect estimates with 95% CIs completely below the null, which would have been indicative of a statistically significant protective effect of the exposures on health risks.

Asthma Symptoms and Symptom Scores. The presence of gas versus electric appliances, mediated by whether the gas appliances were vented (e.g., flue for gas heater), was associated with 1.16 times the odds of reporting asthma symptoms (95% CI 1.06-1.28). There was little difference in the magnitude of effect between observational studies and RCTs, although there was greater precision among the observational studies. Table 1 summarizes odds ratios for a 20 ppb increase in average NO_2 exposure linked with combustion cooking and/or unvented heating. Each 20 ppb increase in NO_2 exposure linked with gas combustion was associated with 1.55 (95% CI 1.41-1.71) and 1.21 (95% CI 1.06-1.37) times higher odds of asthma symptoms, for RCTs and observational studies, respectively. The pooled OR of 1.33 (95% CI 1.19-1.49) may not be reliable given the lack of overlap in confidence intervals for RCTs and observational studies, yet the confidence interval ranges demonstrate a consistent, positive association with asthma symptom risk.

Fifteen effect estimates from two RCTs (Pilotto et al., 2004; Howden-Chapman et al., 2008) showed 1.38 (95% CI 1.19-1.61) times higher risk of asthma symptoms with gas appliance exposure. A prospective cohort with six months of follow up showed that measured NO_2 at home was associated with elevated incidence rates of a range of asthma symptoms including wheeze, cough, chest tightness, limited speech, and greater correlation of these symptoms with exercise. A pooled effects model of the six effect estimates in (Hansel et al., 2008), gave an 11% (95% CI 7-15) incident rate increase per 20 ppb increase in NO_2. For each 20 ppb increase in measured indoor NO_2 level, another study reported 2.86 (95% CI

1.03-8.35) times higher odds of a unit increase in asthma symptom score (Belanger et al., 2013), and yet another (Gillespie-Bennett et al., 2011) reported 1.62 (95% CI 1.52-1.73) and 1.12 (95% CI 1.00-1.20) times higher odds of lower and upper respiratory symptoms, respectively. (Schachter et al., 2020) showed that the presence of a gas stove was associated with 2.82 (95% CI 1.10-7.24) times greater odds of an increased wintertime cough and wheeze score.

Two studies considered asthma incidence (Lin et al., 2013; Khreis et al., 2017). Pooled effect estimates and confidence intervals from Kreis and colleagues spanned above one and reached 2.08 (95% CI 1.45-2.94) for children less than 6 years of age. Lin et al., 2013 showed 32% (18-48%) and 12% (-12%-43%) increased odds of asthma incidence for presence of residential gas stove and 15 ppb NO_2 increase, respectively. Meta-analyses by Zheng and colleagues showed consistent but mild increases in emergency room visits or hospitalizations with increases in indoor NO_2 (Zheng et al., 2015, 2021). The 2015 study gave pooled risk ratios for asthma-related emergency room visits or hospitalizations of 1.07 (95% CI 1.05-1.09) for all ages. The 2021 study pooled risk ratios for the same outcome of 1.00 (95% CI 0.88-1.13) and 1.04 (95% CI 1.03-1.05) for increases in 1-hr maximum NO_2 and 24-hr average NO_2 concentrations.

It should be noted that a few studies showed no or weak associations between gas combustion or NO_2 exposure and health outcomes under study in their respective investigations. The quasi-experimental study that was included used a retrospective matched cohort for nearly 1 million New Zealanders of all ages, mostly without asthma, for 3 years of follow up and found a very slight trend toward an increase in hospitalization rate for asthma, circulatory disease, respiratory disease, or RSV among homes without a heat pump, pellet burner, or flued gas heat intervention (IRR 1.04 95% CI 1.00-1.09) (Barnard et al., 2011). The same study failed to detect an effect for hospitalization for congestive heart failure or for mortality among those hospitalized for cardiovascular or respiratory disease. A prospective cohort study with 12 weeks of follow-up in Adelaide, Australia tracked NO_2 exposure at home and in school and showed mostly weak, non-statistically significant effects (Nitschke et al., 2006). They reported some mild effects for night-time breathing difficulty and night-time asthma attacks (RR 1.06 [1.02-1.10] and 1.08 [1.00-1.14]). An intervention trial with 5 weeks of particle filtration and NO_2 scrubbing showed only marginal reductions in measured NO_2 levels and no effect between NO_2 level and asthma symptom days during the final two weeks of treatment (Gent et al., 2022).

Gas stoves and unvented gas heaters can readily produce increases in NO_2 concentration associated with adverse health effects. Relationships between gas stove use and NO_2 levels reported by Hansel et al (2008), and Belanger et al (2006), are consistent with the work of others including (Simoni et al., 2004) who examined relationships between gas stove use time and pollutant levels. We note that exhaust ventilation can reduce but not eliminate gas stove emissions and relies upon consistent and proper operation, which is generally low (Sun & Singer, 2023). Many inner-city households are known to have gas stoves, often without exhaust ventilation (Breysse et al., 2005; Diette et al., 2007). The Baltimore home cohort conducted by Hansel et al, identified 14% of homes using gas stoves for heat, underscoring the intersection of environmental and energy injustice (Hansel et al., 2008). The higher magnitude of effects per unit increase in NO_2, reported by Belanger et al (2006), for multi-family versus single-family housing suggests that the size of the health risk may be greater at higher exposure levels associated with greater gas stove use. Field studies in homes (e.g., (Francisco et al., 2010), and IAQ analyses

(Sherman et al., 2022)), have shown that NO_2 from unvented gas heaters regularly exceeds health guidelines, including spaces that meet minimum ventilation standards.

<u>Systemic symptoms</u>. We found evidence of a trend toward increased odds of systemic symptoms with gas combustion exposure, with a pooled OR of 1.25 (95% CI 1.04-1.51). The RCT effect estimates drove this trend in the pooled regression. Studies that reported effects as a function of continuous NO_2 exposure found similar results with OR of asthma medication use of 1.61 (95% CI 1.01-2.56) for each 20 ppb NO_2 increase.

<u>Hospitalization, healthcare utilization and medication use</u>. A number of other observational studies and RCTs reported on risks associated with residential gas combustion. A cross sectional study with a 2-month prospective of survey data in Maryland showed a consistent, elevated trend toward higher risk of emergency room visit or hospitalization among children with bronchopulmonary dysplasia (Rice et al., 2020). Among those with respiratory support, the odds of hospitalization were 5.95 (95% CI 1.08-32.76) times greater for homes with gas combustion. Pooled analysis of studies evaluating the use of asthma medication showed 1.39 (95% CI 1.07-1.81) times higher odds with gas combustion exposure compared with electric appliance use or the addition of exhaust ventilation.

Study	Follow-up length	Combustion	Outcome	Age	Subgroup	N participants	% with asthma	Odds Ratio	OR	95%-CI	Weight
design_type = RCT											
gillespie-bennet_2011	4 months	heat	nighttime cough	6-13	.	344	100		1.73	[1.52; 2.03]	6.4%
gillespie-bennet_2011	4 months	heat	daytime cough	6-13	.	358	100		1.52	[1.33; 1.73]	6.5%
gillespie-bennet_2011	4 months	heat	cough with waking	6-13	.	344	100		1.73	[1.47; 1.96]	6.4%
gillespie-bennet_2011	4 months	heat	nighttime wheeze	6-13	.	343	100		1.52	[1.24; 1.90]	5.7%
gillespie-bennet_2011	4 months	heat	daytime wheeze	6-13	.	365	100		1.24	[1.04; 1.52]	5.9%
gillespie-bennet_2011	4 months	heat	wheeze with waking	6-13	.	343	100		1.52	[1.24; 1.85]	5.8%
Random effects model									1.55	[1.41; 1.71]	36.7%
Heterogeneity: $I^2 = 49\%$, $\tau^2 = 0.0070$, $p = 0.08$											
design_type = observational											
belanger_2006	2 weeks	stove	wheeze	0-12	multifamily	242	100		1.52	[1.04; 2.21]	4.0%
belanger_2006	2 weeks	stove	persistent cough	0-12	multifamily	242	100		1.06	[0.75; 1.49]	4.3%
belanger_2006	2 weeks	stove	shortness of breath	0-12	multifamily	242	100		1.28	[0.85; 1.91]	3.7%
belanger_2006	2 weeks	stove	chest tightness	0-12	multifamily	242	100		1.61	[1.04; 2.49]	3.4%
belanger_2006	2 weeks	stove	wheeze	0-12	singlefamily	486	100		1.33	[1.05; 1.68]	5.4%
belanger_2006	2 weeks	stove	persistent cough	0-12	singlefamily	486	100		1.07	[0.84; 1.35]	5.4%
belanger_2006	2 weeks	stove	shortness of breath	0-12	singlefamily	486	100		1.23	[0.95; 1.59]	5.2%
belanger_2006	2 weeks	stove	chest tightness	0-12	singlefamily	486	100		1.61	[1.04; 2.49]	3.4%
belanger_2013	4 months	stove	wheeze	5-10	.	1342	100		3.78	[1.33; 10.59]	1.0%
belanger_2013	4 months	stove	nighttime asthma symptoms	5-10	.	1342	100		4.04	[1.64; 10.08]	1.3%
permaul_2020	5 years	both	days of asthma symptoms	4-13	obese	97	100		3.46	[1.32; 9.12]	1.1%
permaul_2020	5 years	both	wheeze, cough, or chest tightness	4-13	obese	97	100		2.02	[0.77; 5.20]	1.2%
permaul_2020	5 years	both	nighttime asthma symptoms	4-13	obese	97	100		0.96	[0.85; 1.08]	6.6%
permaul_2020	5 years	both	days of asthma symptoms	4-13	overweight	41	100		0.61	[0.10; 3.76]	0.4%
permaul_2020	5 years	both	wheeze, cough, or chest tightness	4-13	overweight	41	100		0.36	[0.07; 1.85]	0.4%
permaul_2020	5 years	both	nighttime asthma symptoms	4-13	overweight	41	100		0.94	[0.86; 1.02]	6.9%
permaul_2020	5 years	both	days of asthma symptoms	4-13	normalweight	133	100		0.81	[0.32; 2.02]	1.2%
permaul_2020	5 years	both	wheeze, cough, or chest tightness	4-13	normalweight	133	100		0.77	[0.32; 1.85]	1.3%
permaul_2020	5 years	both	nighttime asthma symptoms	4-13	normalweight	133	100		1.02	[0.96; 1.06]	7.1%
Random effects model									1.21	[1.06; 1.37]	63.3%
Heterogeneity: $I^2 = 65\%$, $\tau^2 = 0.0354$, $p < 0.01$											
Random effects model									**1.33**	**[1.19; 1.49]**	**100.0%**
Heterogeneity: $I^2 = 86\%$, $\tau^2 = 0.0457$, $p < 0.01$											
Test for subgroup differences: $\chi^2_1 = 9.42$, df = 1 ($p < 0.01$)											

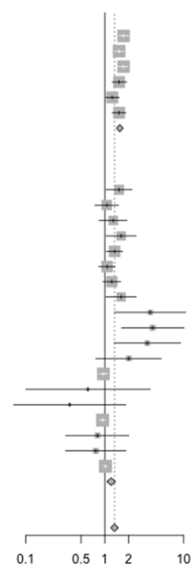

Table 1. Odds ratios for a 20 ppb increase in average NO_2 exposure linked with combustion cooking and/or heating.

A number of studies examined relationships between residential-level indoor NO_2 and population health risks. These are mostly summarized by meta-analyses, however we also included a Danish birth cohort following over 23,000 children for 10 years, which showed a 2.18 (95% CI 1.69-2.85) times higher risk for schizophrenia development for each 20 ppb increase in NO_2 (Horsdal et al., 2019). Meta-analyses mostly used a continuous NO_2 exposure variable to evaluate risk of mortality, asthma incidence, emergency room visits, and hospitalizations. The risk of mortality was consistently elevated, with 95% CIs ranging up to 39% above the null (Table 2). The ozone-adjusted model from (Orellano et al., 2020) gave similar results to the PM-adjusted model and both were not substantially different from pooled estimates that did not adjust for co-pollutant measurements. Similarly, the effect of NO_2 was independent from PM in the meta-analysis done by (Faustini et al., 2014) according to their subset of studies that adjusted for multiple pollutants (n=7), suggesting that NO_2 can drive health effects on its own.

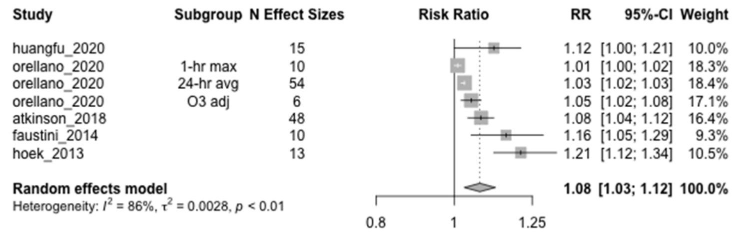

Table 2. Pooled meta-analysis all-cause mortality risk ratios for 20 ppb increases in indoor NO_2.

4. Discussion

We reviewed the literature investigating associations between unvented residential gas combustion for cooking and unvented heating and potential health outcomes and found that observational studies, RCTs, and meta-analyses showed consistent increased risks for asthma symptoms, asthma development, school absence, hospitalization, and emergency room visits. Overall the health outcome with the most effect estimates for pooled analysis was the risk of asthma symptoms. The pooled estimates shows a 6-28% (95% CI) increase in risk of symptoms for unvented gas heating or presence of gas stoves compared with flued heating or electric heat or stoves. For each 20 ppb increase NO_2 concentration, the odds of asthma symptoms increased 19-49% We observed elevated odds of asthma medication use across RCTs and observational studies with a pooled confidence interval of 7-81% higher odds with the presence of gas appliances.

Our results are consistent with a large body of scientific work in this area spanning decades. (Hasselblad et al., 1992) conducted a meta-analysis of the studies from the 1970's-1980's of indoor NO_2 exposure associated with gas stoves reported 20% increased odds of respiratory illness in children for each 16 ppb increase in NO_2 (Hasselblad et al., 1992). Lin et al considered studies through 2013 and found 6% (95% CI -1-3%) and 16% (95% CI 5-29%) increased odds of wheeze incidence with presence of residential gas stove and 15 ppb NO_2 increase, respectively. Our findings, using even more recent studies through 2023, were consistent with both of these previous meta-analyses.

Dose-response relationships between human health, NO_2 exposure, and other by-products of combustion are not well characterized. Furthermore, these relationships are mediated by numerous factors both inside and outside the built environment, including the presence and use of exhaust ventilation, the duration and types of food preparation, psychosocial stressors, and pre-existing health conditions. However, there is clear evidence of a wide range of health effects, even at low levels of exposure. A four-month prospective cohort by Belanger and colleagues showed a dose-response relationship between NO_2 exposure and wheeze, asthma symptoms, and asthma reliever medication use, with effects seen above a threshold of 6 ppb NO_2 (Belanger et al., 2013). Similarly, the year-long follow-up study by Boulic found that a 2-8 ppb increase was associated with a range of respiratory health outcomes. Perhaps it is not surprising then, that the underpowered trial by Gent and colleagues found little relationship between health outcomes and the average 3-4 ppb NO_2 reductions, that were observed in dwellings already below health effects threshold limits.

The effect estimates, and confidence intervals presented here provide a window of reasonable risk levels for a variety of health outcomes and mortality, which can be used to extrapolate the health benefits of widespread measures to reduce the impacts of unvented combustion, including improved ventilation and source control, switching to vented appliances, better regulation of device emissions, and quantifying the benefits of electrification of end-uses. Despite the various designs, geographic sites, length of follow-up, and study dates, we noted a level of consistency between the studies within the current meta-analysis, and with previous ones, which strengthens the level of confidence in our findings. Studies were generally rigorously conducted, and variables were collected to allow for appropriate covariable adjustment. Given the small sample sizes, the pooled effect estimates are sensitive to the addition of new studies, given the small sample size. However, the reported confidence intervals are likely to be robust and provide perhaps a more helpful quantitative measure of risk given the inherent uncertainties and limitations of the epidemiologic studies required to detect population health effects in real-world conditions (Atkinson et al., 2018). New studies may be able to reduce sources of bias revealing even higher effect estimates and/or greater precision. Residential unvented combustion appliances pose a variety of serious health risks to people of all ages, but especially to children with asthma or other respiratory conditions.

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