National Institute for Health and Care Excellence

Guideline version (Draft)

Indoor air quality at home

[3.3] Evidence review for ventilation design and use

NICE guideline <number>

Evidence review

June 2019

Draft for Consultation

These evidence reviews were developed by Public Health Internal Guideline Development team

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Contents

Design and use of ventilation to prevent or reduce the health impacts of poor indoor air quality at home

Review question

How can ventilation in homes be designed or used to prevent or reduce the health impacts of poor indoor air quality whilst maintaining adequate energy and thermal performance?

Introduction

People spend up to 90% of their lives indoors and 60% of that time at home. Exposure to indoor air pollutants including nitrogen dioxide (NO2), carbon monoxide (CO), particulate matter (PM), biological agents and volatile organic compounds (VOCs) is widespread. These pollutants are associated with respiratory and other diseases and premature death.

There are competing needs for increased ventilation, adequate heating, sufficient indoor environmental quality and the drive for energy efficiency. This review aims to provide evidence on how these competing needs can be addressed.

PICO table

Table 1: Population, intervention, comparator, outcomes table

Field	Content
Population	People in all dwellings
Interventions	Strategies including any (or combinations) of the following • Mechanical ventilation • Passive ventilation • Heating • draught proofing
Comparator(s)/control	Another strategy or do nothing
Outcomes	• Respiratory health effects o Changes in pulmonary function measured as a reduction in e.g. FEV1, PEF o Respiratory symptoms for example cough, wheeze, phlegm, sore throat, nasal congestion, runny nose, sneezing o Respiratory infection for example Pneumonia, alveolitis, bronchitis • COPD • Asthma • Allergic diseases for example o Allergic asthma o Allergic alveolitis o Allergic rhinoconjuctivitis o Allergic rhinitis o Allergic dermatitis • Pregnancy related health effects for example

Field	Content
	○ Low birthweight, perinatal mortality (still births and deaths in the first week of life) • Cardiovascular health effects. For example ○ Ischaemic heart disease, stroke • Quality adjusted life years (QALYs)

Methods and process

This evidence review was developed using the methods and process described in Developing NICE guidelines: the manual. Methods specific to this review question are described in the review protocol in Appendix A:

Respiratory conditions were reported differently within and across studies. Due to the myriad of respiratory conditions reported, the committee agreed that:

- Where 2 or more respiratory conditions are reported, to use the most sensitive outcome. For example, using Forced expiratory volume - 1 second (FEV1) over peak expiratory flow (PEF) or
- Where 2 or more respiratory conditions are reported, to use the one reported as the primary outcome for which the trial was powered. For example, reporting wheeze powered for study over cough.

Declarations of interest were recorded according to NICE's 2018 conflicts of interest policy.

Public health evidence

8,122 references were identified from literature searches outlined in Appendix B. An additional 5 references were identified from other sources. 12 papers were ordered and retrieved in full-text. 2 modelling studies, covered in 4 articles, and 2 RCTs covered in 3 articles, met the inclusion criteria outlined in the review protocol.

Included studies

We included 2 modelling studies (Asikainen 2016, Hamilton 2015) and 2 randomised controlled trials (RCTs) (Lajoie 2015, Woodfine 2011) in this review. We identified the modelling studies (Asikainen 2016, Hamilton 2015) and 1 RCT (Woodfine 2011) from the search strategy screening. We identified the other RCT (Lajoie 2015) from research question (RQ) 3.1.

The 2 modelling studies estimate the health impact of home ventilation. One model has a European-wide perspective providing country specific results. The other model is specific to the English housing stock. Both models focus on retrofits rather than new builds. Each model compares three real world scenarios, though the modelling approaches differ in structure, input variables, and model assumptions. For example, one model considered heat loss while the other considered indoor-outdoor air mass balance exchange (the transfer and transformation of pollutant in the environment).

The 2 RCTs contribute information of the effectiveness of ventilation strategies on improving health outcomes. The studies include children with asthma, a population at risk of health impact from poor indoor air quality. One study was conducted in Canada while the other was conducted in the UK. The authors reported on different health outcomes including asthma, respiratory health, atopic disease, and quality of life.

See Appendix D: for more details of the included studies.

Excluded studies

We excluded 5 studies from this review (See Appendix K: for full list of studies excluded with the reasons for exclusion)

Summary of public health studies included in the evidence review

Using a health impact analysis with a 50-year horizon span, Hamilton *et al.* 2015 assessed the potential public health impacts of retrofitting current English housing stock to provide improvements in energy efficiency (through loft insulation, cavity wall insulation, solid wall insulation, double glazing installation, condensation boiler installation, gas central heating installation and draught proofing) with three different policies applied to alterations in ventilation. The three ventilation policies considered were 1) wide scale regulated improvements with installation/refurbishment of extractor fans and trickle vents (‘regulated’) 2) improvements with installation/refurbishment of extractor fans and trickle vents changes but only in homes where installers felt there was a problem with damp or mould and (‘installer discretion’) 3) repair only of existing ventilation (‘no added ventilation’).

The authors used a validated multi-zone airflow and pollutant transport simulation tool (CONTAMv2.4c). They modelled 5 indoor air pollutants: PM2.5 from internal sources, PM2.5 from external sources, radon, second-hand tobacco smoke (STS), and mould (as a precursor for mould). The model predicted the concentration of the pollutants every 15 minutes over 1 year.

The authors modelled mortality and morbidity for excess winter cardiovascular events (for temperature), CVA and MI (for second hand smoke), cardiopulmonary events and lung cancer (for PM2.5) and lung cancer (for radon). Additionally, they modelled morbidity for mental health (for temperature) and asthma admissions, primary care consultations and symptoms (for mould).

The exposure-response relationships were from published literature.

They used Life Table methods for modelling mortality, WHO Global Burden of Disease data to assess morbidity for the same diseases (by application of age-specific and cause specific ratios of years of healthy life lost to the overall years of life lost to the disease) and estimated morbidity impacts from published estimates of disease prevalence.

Additionally, the authors applied a number of assumptions regarding life tables, mortality and morbidity impact. These included that mortality rates vary only with age and sex; baseline prevalence is not dependent on age- or sex; baseline population disease prevalence is assumed to represent an individual’s probability of having the disease; and a fixed ratio exists between mortality and morbidity impacts at the population level (indirect estimates).

The results showed that regulated ventilation retrofits in addition to energy efficiency in all homes could gain 2,241 QALYs per 10,000 people over 50 years compared to no action. Implementation of only ‘installer discretion’ ventilation changes in addition to energy efficiency could lead to a loss of 539 QALYs over a 50 year period (--) and, in the case of ‘no added ventilation’ to a loss of 739 QALYs (-).

Asikainen *et al.* 2016 developed a health impact model to estimate the long-term health impact of poor indoor air quality. The authors compared three ventilation scenarios and their impact on health over a 1-year period. The scenarios are: ventilation at health-based optimum level ventilation rate (3.2 litres per second per person); ventilation with ventilation rate of 5 litres per second per person and filtration of intake air; ventilation with Europe-wide minimum ventilation rate (4 litres per second per person) and source control of pollutants. When modelling source control, the authors defined hypothetical but technically feasible maximum reductions in pollutant levels. They also provided explanation on how such reductions could be achieved. For example, use of new low VOC-emitting products and a wider use of comprehensive labelling systems could achieve a 50% VOCs.

The authors used an outdoor-indoor mass-balance model. The model included 7 indoor air pollutants: particulate matter (PM2.5), radon, second hand smoke exposure, home dampness, outdoor bioaerosols, volatile organic compounds (VOCs), and carbon monoxide (CO).

The model incorporates 7 health outcomes (asthma, lung cancer, cardiovascular disease, COPD, acute CO poisoning, respiratory infection, and ischaemic heart disease) which the authors linked to specific pollutants based on published literature. The authors modelled the health outcomes using risk functions based on published epidemiological evidence. They calculated relative risk-based population attributable fraction and used WHO estimates as input for the background disease burden.

The results showed that Europe-wide minimum ventilation rate (4 litres per second per person) as well as source control of pollutants is the dominant scenario. It could save 1,651 DALYs per 1 million people over 1 year (baseline 3,456 DALYs versus intervention 1,805 DALYs) compared to ventilation at health-based optimum level ventilation rate (3.2 litres per second per person); or ventilation with ventilation rate of 5 litres per second per person as well as filtration of intake air (869 DALYs saved and 1,445 DALYs saved respectively.

The publication by Asikainen *et al.* 2016 is part of the HealthVent guideline project that developed health-based ventilation guidelines.

1 **Table 2: Summary of included studies**

Study	Population	Intervention	Comparator	Outcome used	Risk of bias or limitation
Modelling studies					
Asikainen 2016 (Europe)	European household population	Dilution with health-based optimum level ventilation	Filtration of intake air OR Source control and minimum ventilation	Disability adjusted life years (DALYs)	Serious limitations[1, 2]
Hamilton 2015 (UK)	English household population	Fabric and ventilation retrofits	Fabric retrofits and ventilation retrofits but only for homes at risk of poor ventilation OR Fabric retrofits no ventilation	Quality adjusted life years (QALYs)	Serious limitations[1, 3]
Randomised controlled trials					
Woodfine 2011 (UK)	Children with asthma	Ventilation system installation	Delayed intervention	Quality of life	Low
Lajoie 2015 (Canada)	Children with asthma	Heat Recovery Ventilator (HRV) or Energy Recovery Ventilator (ERV)	Placebo heat recovery ventilation	Respiratory health Rhinitis	Low

[1]We used Philips checklist to assess study limitations; Philips Z, Ginnelly L, Sculpher M, *et al.* 2004 Review of guidelines for good practice in decision-analytic modelling in health technology assessment. Health Technol Assess. 2004 8(36):iii-iv, ix-xi, 1-158.
[2]Lack of assessing methodological and structural uncertainties, lack of data quality assessment, used data distributions not explained
[3]Lack of assessing methodological uncertainty, lack of data quality assessment, unclear how QALYs were derived

2 See Appendix D: for full evidence tables.

3

Economic evidence

For the review of published cost effectiveness evidence see Evidence reviews for indoor air quality at home:

Economic model

For the results of the economic analysis see Indoor Air Quality at Home Economic Model Report and Community Health Worker Appendix.

Evidence statements

- One directly applicable European health-impact modelling study with potentially serious limitations showed that source control with minimum ventilation was most effective in reducing the health impact of poor indoor air quality compared to ventilation only or filtration of intake air (reduction of 1,651 versus 1,445 and 869 DALYs per million population, respectively).
- One directly applicable UK health-impact modelling study with potentially serious limitations showed that the combination of fabric and ventilation retrofits were most effective in improving the health impact of poor indoor air quality compared to fabric retrofits with selected ventilation retrofits or fabric retrofits alone (2,241 95% CI 2,085 to 2,397 QALYs gained per 10,000 persons per 50 years versus -539 95% CI -678 to -399 and -728 95% CI -864 to -592 respectively).
- High quality evidence from 1 RCT with a follow up of 12 months on children with asthma showed significant improvement in asthma-related quality of life with the use of roof-space installed ventilation system to prevent/reduce exposure to poor indoor air compared to the control group (n=180; MD 7.19 95% CI 2.91 to 11.47). Subgroup analysis for households in need of only ventilation retrofit also showed a significant improvement (n=139; MD 6.8 95% CI 2.14 to 11.46; high quality evidence). Subgroup analysis for households in need of both ventilation retrofit and central heating retrofit showed no improvement (n=38; MD 9.3 95% CI -1.57 to 20.17; high quality evidence).
- High quality evidence from 1 RCT with a follow up of 2 years on children with asthma showed no difference in asthma symptoms with the use of Heat Recovery Ventilator (HRV) or Energy Recovery Ventilator (ERV) to prevent/reduce poor indoor air exposure compared to the control group (n=75; MD 0.2 95% CI -2.16 to 2.56).
- Moderate quality evidence from 1 RCT with a follow up of 2 years on children with asthma showed no difference in respiratory health with the use of Heat Recovery Ventilator (HRV) or Energy Recovery Ventilator (ERV) to prevent/reduce poor indoor air exposure compared to the control group (n=41; MD -14.4 95% CI -109.26 to 80.46).
- Moderate quality evidence from 1 RCT with a follow up of 2 years on children with asthma showed no difference in atopic disease with the use of Heat Recovery Ventilator (HRV) or Energy Recovery Ventilator (ERV) to prevent/reduce poor indoor air exposure compared to the control group (n=82; MD -5.8 95% CI -32.83 to 21.23).

Recommendations

Research recommendations

What is the minimum air exchange rate to maintain good indoor air quality in residential properties? See PICO in appendix L.1.1

Rationale and impact

Link to be added

The committee's discussion of the evidence

Interpreting the evidence

The outcomes that matter most

The committee agreed that the presented outcomes, quality adjusted life years (QALYs) and disability adjusted life years (DALYs) are of equal importance as they reflect similar concepts. QALYs are a measure of the state of health of a person and DALYs are a measure of overall disease burden. Both encompass a multitude of health outcomes.

The quality of the evidence

The committee noted the lack of evidence on people with low income, older people, people with disabilities and pregnant women. There was also limited evidence on children and young people while the majority of studies included people with asthma.

The committee acknowledged the certainty of the evidence from modelling studies. But they also noted that any modelling study is built around available evidence (data) and relies on a number of assumptions to fill any gaps in the evidence. The authors of the modelling studies used non-RCT data to develop their models. This is different from the evidence base for interventions, which relies on data arising from RCTs. The committee agreed that the authors of the modelling studies made appropriate assumptions which are well explained and justified. Therefore, the committee was happy to consider the model results during decision making.

The committee acknowledged that as per protocol the evidence for review question 3.3 focused on modelling studies. However, they agreed to include evidence from 2 RCTs within the evidence review. These RCTs investigated the effectiveness of ventilation on health outcomes compared to control (do nothing). They were identified in review question 3.1. One RCT from the UK provided evidence on self-reported disease-specific quality of life using a validated instrument. The committee agreed that the results of this RCT directly validated the results of the modelling studies.

The committee also noted that the second RCT contributed little to the discussion. This RCT was based in Canada and did not focus on quality of life.

Benefits and harms

The committee discussed the clarity of the results from the modelling studies. They agreed that ventilation can contribute to improving poor indoor quality. The committee were aware of the balance between source control and ventilation and the delicate equilibrium between the two. The committee were mindful that any interventions aimed to improve indoor air quality could have positive and negative consequences. They impact on indoor air quality but also heating and energy efficiency and might increase the entry of outdoor air pollutants to the indoor environment.

The committee discussed the clarity of the results from the modelling studies. They agreed that source control is an important first step in reducing indoor air pollutant levels. Ventilation can improve indoor air quality even further particularly when energy efficient retrofits and builds get more prevalent. The committee agreed that there needs to be a holistic approach to balance between the drive for energy efficiency to reduce energy use and carbon footprint, and ventilation to improve indoor air quality. They appreciated, that both can have positive and negative unintended consequences. Improving energy efficiency through airtightness reduces the energy use but also the natural airflow and therefore might lead to increased moisture indoors leading to damp and mould. This could be offset by additional ventilation. Ventilation might prevent moisture build up and decrease the level of indoor air pollutants. But it also increases the demand for heating and the entry of outdoor air pollutants.

Cost effectiveness and resource use

The committee noted the paucity of health economic literature on ventilation systems. It also noted that the studies which had been identified were only partially applicable and of low quality. Even so, the committee were mindful that these studies suggest that ventilation systems and carbon filters used alongside ventilation systems could be cost effective and in certain circumstances cost saving. Similarly, the economic model suggested that interventions to reduce exposure to indoor air pollution could be cost saving. However, the committee are aware that some interventions may have little or no cost (e.g. opening a window) whereas others could be costly (e.g. installing a ventilation system). It was particularly noteworthy therefore that the main driver of the cost savings was the excess risk profile of dwellings which is a combination of physical (building) risk and personal baseline risk. For example, a dwelling with a low risk function and an intervention that is effective in reducing the prevalence of asthma (by 5%) is unlikely to be cost-saving unless the cost of implementation per dwelling is £50 or lower whereas, for an extreme risk dwelling the cost-saving threshold rises to £150 at a 5% effectiveness. A key limitation of the model is that there were no data on the explicit link between indoor air quality and health outcomes in general, and specifically for any of the interventions of interest to the committee. Some identified benefits could not be quantified for example, the benefits that an intervention may bring to someone with comorbidities, suggesting that the overall benefits are likely to have been underestimated. The committee concluded that interventions could offer good value for money in certain scenarios.

Other factors the committee took into account

Committee noted that affordability may be a barrier to effective and efficient heating and ventilation. Heating systems should be designed in ways that exposure to particulate matter is minimised. For example, heating systems that include open solid fuels should be avoided or converted to other safe heating sources. Builders should be aware of funding/grants that may be available to help to achieve such conversion.

While there was no evidence on the best way to balance ventilation, insulation and heating, the committee agreed, based on their experience, that this was best practice to maintain good indoor air quality at home. The committee heard expert testimony from the author of the key included study (Hamilton 2015). The expert explained in detail the sources of data behind the modelling study and the assumptions made and provided more detail that was available in the published paper. The committee agreed that these were acceptable and noted that the take home message was that renovating properties for energy or thermal efficiency had substantial benefit to health as long as ventilation if not reduced. The committee also noted that if regulations on ventilation are not complied with the this would have a negative impact on health,

The committee highlighted that those on low incomes may not be able to afford to heat their homes adequately. This may result in making homes airtight which will in turn affect ventilation. To this end, the committee agreed that local authority strategies, architects and designers should ensure a holistic approach to heating and ventilation.

The committee noted that there was no set standard as regard adequate ventilation level in homes and so drafted a research recommendation to examine this issue. the committee were aware of standards for schools (outlined in Building Bulletin BB 101: Ventilation, thermal comfort and indoor air quality 2018). They agreed that local authorities could extrapolate from the minimum ventilation rates outlined in this document for use in dwellings.

Appendices

Appendix A: **Review protocols**

Review protocol for design and use of ventilation

Field	Content
Review question	How can the ventilation in homes be designed or used to prevent or reduce the health impacts of poor indoor air quality whilst maintaining adequate energy and thermal performance (for example, balancing the cost of heating against opening the windows for ventilation)?
Type of review question	Decision analysis or prediction (health impact) model
Objective of the review	To identify strategies by which homes can be designed and used to reduce or prevent poor indoor air quality by the provision of adequate ventilation without compromising energy efficiency or causing other unintended consequences such as thermal discomfort, excessive cost or external nuisances
Eligibility criteria – population/disease/condition/issue/domain	People in all dwellings
Eligibility criteria – intervention(s)	Strategies including any (or combinations) of the following • Mechanical ventilation • Passive ventilation • Heating • Draught proofing
Eligibility criteria – comparator(s)/control	• Another strategy • Do nothing
Outcomes and prioritisation	Respiratory health effects • Changes in pulmonary function measured as a reduction in e.g. FEV1, PEF • Respiratory symptoms for example cough, wheeze, phlegm, sore throat, nasal congestion, runny nose, sneezing • Respiratory infection for example Pneumonia, alveolitis, bronchitis • COPD • Asthma • Allergic diseases for example • Allergic asthma • Allergic alveolitis • Allergic rhinoconjuctivitis • Allergic rhinitis • Allergic dermatitis • Pregnancy related health effects for example • Low birthweight, perinatal mortality (still births and deaths in the first week of life)

Field	Content
	• Cardiovascular health effects. For example Ischaemic heart disease, stroke • QALYs
Eligibility criteria – study design	Decision-analytic models: • Studies on cost-consequence analyses • Value-based models • Studies on cost-effectiveness • Studies on cost-benefit • Decision trees • Health impact models • Prediction models
Other inclusion exclusion criteria	Inclusion: • English language only • Published peer-reviewed studies only • Studies conducted in developed economies similar to the UK • Studies conducted from 1970 onwards Exclusion: • Conference abstract, letter, opinion piece, review articles
Proposed sensitivity/sub-group analysis, or meta-regression	Where evidence allows, pre-specified sub-group analysis will be conducted to include those at increased risk of poor indoor air quality: Subgroup • People on low income • Older people • People with disabilities • Pregnant women • Children and young people • People with conditions associated with or exacerbated by indoor air pollution, such as stroke, heart disease, allergic disease and asthma
Selection process – duplicate screening/selection/analysis	All abstracts will be duplicate screened as a reliability check. Any disagreement will be resolved by discussion, or if necessary, a third independent reviewer. Data extraction and critical appraisal will be checked by a second reviewer. Any disagreements will be resolved by the two reviewers, and escalated to a third reviewer if agreement cannot be reached. The inclusion list will be double checked with PHAC to ensure no studies are excluded inappropriately
Information sources – databases	A systematic search of relevant databases will be carried out to identify relevant studies and evidence. Appropriate limits will be applied. Database functionality will be used, where available, to exclude:

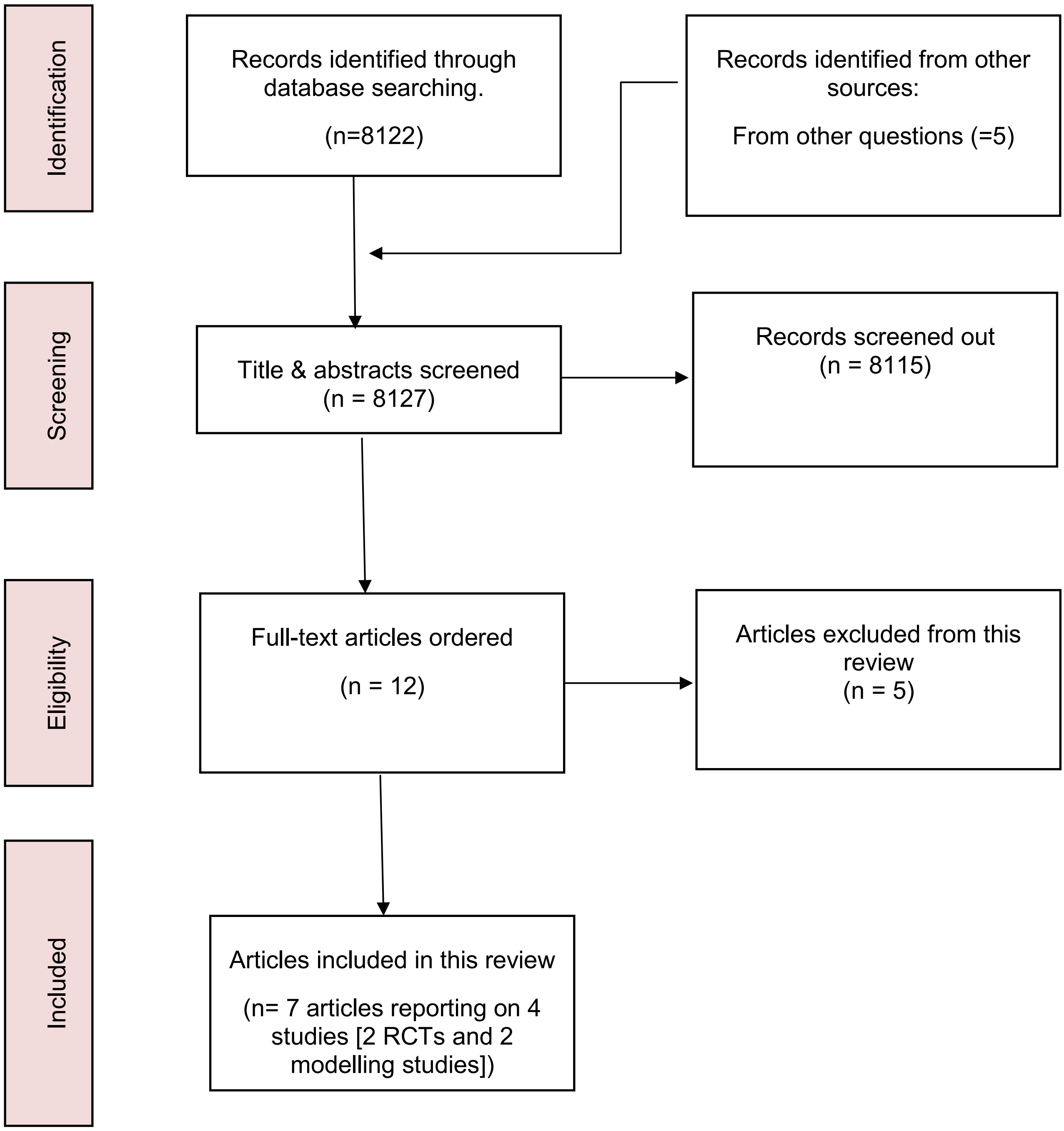
Field	Content
	• Non-English language papers • Animal studies • Editorials, letters, news items and commentaries • Conference abstracts and posters • Theses and dissertations • Duplicates Websites will be browsed or searched to focus on relevant evidence. The bibliographies of relevant reports and findings may also be used to capture evidence. The following databases will be searched: • MEDLINE and MEDLINE in Process (OVID) • Embase (OVID) • Health Management Information Consortium (HMIC) (OVID) • Social Policy and Practice (OVID) • CENTRAL (Wiley) • Cochrane Database of Systematic Reviews (Wiley) • DARE (Wiley) • Greenfile (EBSCO) • NHS EED (legacy database) (Wiley) • EconLit (OVID) • OpenGrey • Web of Science The following websites will be searched: Google and Google scholar (with appropriate limits and looking specifically for reports or evaluations of interventions related to indoor air quality)
Data management (software)	Where feasible data management will be undertaken using EPPI-reviewer software. Data will be summarised using an appropriate qualitative synthesis approach, for example, narrative synthesis. We don't anticipate pairwise meta-analyses for this review question.
Methods for assessing bias at outcome/study level	Standard study checklists were used to critically appraise individual studies. For details please see section 6.2 of Developing NICE guidelines: the manual Where appropriate qualitative data will be summarised using an appropriate qualitative synthesis approach, for example, narrative synthesis. The risk of bias across all available evidence will be evaluated for each outcome using an adaptation of the 'GRADE toolbox' developed by the international

Field	Content
	GRADE working group http://www.gradeworkinggroup.org/
Criteria for evidence synthesis	Data from studies meeting our inclusion criteria above are extracted for inclusion in evidence tables. For details please see section 6.4 of Developing NICE guidelines: the manual
Methods of analysis – combining studies and exploring (in)consistency	We do not expect to meta-analyse (combine) studies or explore inconsistency for this review question. Study results will be reported narratively.

Appendix B: **Literature search strategies**

Please see search strategies here

Appendix C: **Public health evidence study selection**



Appendix D: **Public health evidence tables**

D.1 Modelling studies

Asikainen 2016

Study, population, country and quality	Data sources	Other comments	Health outcomes	Conclusions	Uncertainty
Asikainen 2016 European household population Europe Direct applicable[1] Serious limitations[2]	Building characteristics: • Not specified • Estimate of ventilation rate used Health impact: • Estimated using risk model • National burden of disease data estimated by WHO • Published data for pollutant specific diseases (outlined in Table 3 of publication) Ventilation rate: • Estimated using regression model and Bayesian subjectivity probability approaches;	Model type: Health impact model, outdoor-indoor mass-balance model Model horizon: 1 year Model created in: not provided The model includes 3 scenarios: 1. Dilution with health-based optimum level ventilation (3.2 litres per second per person). 2. Ventilation (5 litres per second per person) and filtration of intake air. 3. Source control and minimum ventilation (4 litres per second per person). Pollutants included: • particulate matter (PM2.5)	UK results total DALYs/million including indoor and outdoor DALYs Scenario Base-line | 1 | 2 | 3 3,456 | 2,587 | 2,011 | 1,805	The authors concluded that (i) there is a substantial burden of disease associated with exposures taking place indoors and that (ii) these risks can substantially be reduced by range of control actions affecting indoor pollution sources, infiltration of outdoor pollutants, and	The authors conducted sensitivity analysis to estimate the effectiveness of source control. They analysed 2 scenarios • lower source control capabilities (reduction of 80 % for radon, CO and SHS; and 25 % for, PM2.5, VOC and dampness • higher were source control capabilities (reduction of 100 % of radon, CO and SHS,

Study, population, country and quality	Data sources	Other comments	Health outcomes				Conclusions	Uncertainty
	authors accounted for climatological and economical differences of European countries • Estimated using information from existing measurements, national legislation and building codes	• outdoor bioaerosols • volatile organic compounds (VOCs) • carbon monoxide (CO) • radon • home dampness • second hand smoke exposure. Health conditions included: • asthma • lung cancer • cardiovascular disease • COPD • acute toxication caused by carbon monoxide • respiratory infection • ischaemic heart disease					ventilation levels.	and 75 % of PM2.5, VOC and dampness)

[1]European study also using UK data and presenting UK results

[2]Lack of assessing methodological and structural uncertainties, lack of data quality assessment, used data distributions not explained

Main publication

Asikainen A, Carrer P, Kephalopoulos S, et al (2016) Reducing burden of disease from residential indoor air exposures in Europe (HEALTHVENT project). Environmental health : a global access science source 15 Suppl 1, 35

Additional publications:

Carrer P, de Oliveira Fernandes E, Santos H, Hänninen O, Kephalopoulos S, Wargocki P. (2018) On the Development of Health-Based Ventilation Guidelines: Principles and Framework. Int J Environ Res Public Health. 15(7).

Study, population, country and quality	Data sources	Other comments	Health outcomes	Conclusions	Uncertainty
Haenninen O, Asikainen A. (2014) Efficient reduction of indoor exposures – Health benefits from optimizing ventilation, filtration and indoor source controls. Report National institute for health and welfare					

Hamilton 2015

Study, population, country and quality	Data sources	Other comments	Health outcomes	Conclusions	Uncertainty
Hamilton 2015 English household population UK Direct applicable[1] Serious limitations[2]	Building characteristics: • 2010 English Housing Survey (EHS) • Dwelling energy performance was calculated as a notional heat loss value Health impact: • Life table methods based on the Institute of occupational medicine (IOM) LIFET model applied to EHS data • Life tables were set up using 2010 age-specific population and (disease-specific and all-cause) mortality	Model type: Health impact modelling study Model horizon: 50 years. Model created in: CONTAMv2.4c, a validated multi-zone airflow and pollutant transport simulation tool Health Impact of Domestic Energy Efficiency Model (HIDEEM) an exposure-determinant and health impact comprising of 2 components: • A building physics model based on Previous validated building physics and airflow models • Health impact model	QALYs gained/lost per 10,000 persons per 50 years Scenario 1: 2,241 (95% CI 2,085 to 2,397) 2: -539 (95% CI -678 to -399) 3: -728 (95% CI -864 to -592)	The authors concluded that energy efficiency retrofits can improve health by reducing exposure to cold and air pollutant if implemented alongside ventilation	Uncertainty: Authors used Monte Carlo simulation to assess parametric uncertainty in the health impact estimates associated with the determinant of the exposure change (meaning the change in heat loss and air tightness due to each intervention), the exposure-response relationships and the utility weights

Study, population, country and quality	Data sources	Other comments	Health outcomes	Conclusions	Uncertainty
	data for England and Wales from the Office for National Statistics (ONS), with separate life tables set up for males and females • Impacts on morbidity for these same outcomes were estimated from the mortality estimates by applying age-specific and cause-specific ratios of years of healthy life lost due to disability (YLD) to the overall years of life lost (YLL) derived from WHO Global Burden of Disease data • Utility values: source unclear	The model includes 3 retrofit scenarios: 1. Fabric and ventilation retrofits (extractor vents and trickle vents) installed 2. Fabric retrofits and ventilation retrofits (extractor vents and trickle vents) but only for homes at risk of poor ventilation 3. Fabric retrofits no ventilation retrofits Pollutants included: • particulate matter (PM2.5) • radon • mould • second hand smoke exposure • temperature. Health conditions included: • asthma (children) • lung cancer • cardiovascular (winter) • heart attack • stroke • cardiopulmonary			for each health outcome Uncertainty analysis for scenario 2 for changes in the proportion of the population in the group assumed to be at high risk for cardiovascular events (100% equivalent to whole population equally at risk) 100% -538.6 (95% CI -677.9 to -399.3); 10% -575.2 (95% CI -706.5 to -443.9); 1% -595.5 (95% CI -724.2 to -466.7); 0.1% -602.2 (95% CI -729.6 to -474.8)

Study, population, country and quality	Data sources	Other comments	Health outcomes			Conclusions	Uncertainty
		• common mental disorder					

[1]UK study
[2]Lack of assessing methodological uncertainty, lack of data quality assessment, unclear how QALYs were derived

Main publication
Hamilton I, Milner J, Chalabi Z, et al (2015) Health effects of home energy efficiency interventions in England: a modelling study. BMJ open 5(4), e007298

D.2 Randomised control trials

Woodfine 2011

Bibliographic reference	**Woodfine L, Neal RD, Bruce N et.al. 2011. Enhancing ventilation in homes of children with asthma: pragmatic randomised controlled trial. The British journal of general practice: the journal of the Royal College of General Practitioners 61(592):e724-32.**		
Registration	Not reported		
Study type	Cluster randomised controlled study		
Study dates	June 2005 to winter of 2007		
Objective	Pragmatic trial design to decide whether to invest in ventilation systems, rather than to test scientific hypotheses under laboratory conditions		
Country/ Setting	United Kingdom		
Number of participants	192 children		
Participant characteristics	**Demographic characteristics**	Intervention group (n=96)	Control group (n=96)
		n (%)	n (%)
	Age (years) Mean (SD)	9.59 (2.95)	9.57 (2.95)
	Sex (Female)	42 (44)	43 (45)
	Ethnicity	Not reported	Not reported
	Socio-economic status (Age parent left full-time education, years)		
	16 and under	49 (51)	54 (56)
	17 to 19	34 (35)	21 (22)
	20 and over, or still in full-time education	13 (14)	21 (22)
	Building characteristics		
	Council	25 (26)	23 (24)
	Owner occupier	63 (66)	68 (71)
	Housing association or private landlord	8 (8)	5 (5)
	Existing health condition		
	Family history of asthma	53.71 (94)	54.02 (94)
Exposure	Mould		
Inclusion criteria	Children were eligible to take part if • They were aged between 5 and 14 years, • Resident in Wrexham (in any type of housing), and registered with a participating general practice • Had received three or more prescriptions for corticosteroid inhalers		
Exclusion criteria	Not reported		
Intervention	TIDieR Checklist criteria	Paper/Location	Details

Bibliographic reference	**Woodfine L, Neal RD, Bruce N et.al. 2011. Enhancing ventilation in homes of children with asthma: pragmatic randomised controlled trial. The British journal of general practice: the journal of the Royal College of General Practitioners 61(592):e724-32.**		
	Brief Name	Pe724	Enhancing ventilation in homes of children with asthma
	Rationale/theory/Goal	Pe724	Pragmatic trial design to decide whether to invest in ventilation systems
	Materials used	Pe725	Home ventilation system
	Procedures used	Pe725	Local authority installed in the roof space of each house a Vent-Axia® HR200XL ventilation system. This comprises two insulated flexible pipes: one delivers fresh air from outside the house through a cleaning filter to first-floor bedrooms; the other removes stale air from the house, and warms the fresh air. If necessary, contractors also improved or replaced central heating systems to bring them to the standard defined by the housing officer
	Provider	–	Not applicable
	Method of delivery	–	Not applicable
	Location	Pe725	Intervention delivered at home
	Duration	Pe727	12 months
	Intensity	–	Not applicable
	Tailoring/adaptation	–	Not applicable
	Modifications	–	Not applicable
	Planned treatment fidelity	–	Not applicable
	Actual treatment fidelity	–	Not applicable
	Other details	–	None
Comparison	TIDieR Checklist criteria	Paper/Location	Details
	Brief Name	Pe724	Enhancing ventilation in homes of children with asthma
	Rationale/theory/Goal	Pe724	Pragmatic trial design to decide whether to invest in ventilation systems
	Materials used	Pe726	Delayed intervention
	Procedures used	–	Not applicable
	Provider	–	Not applicable
	Method of delivery	–	Not applicable
	Location	Pe725	Intervention delivered at home
	Duration	Pe727	12 months
	Intensity	–	Not applicable

Bibliographic reference	**Woodfine L, Neal RD, Bruce N et.al. 2011. Enhancing ventilation in homes of children with asthma: pragmatic randomised controlled trial. The British journal of general practice: the journal of the Royal College of General Practitioners 61(592):e724-32.**		
	Tailoring/adaptation	–	Not applicable
	Modifications	–	Not applicable
	Planned treatment fidelity	–	Not applicable
	Actual treatment fidelity	–	Not applicable
	Other details	–	None
Follow up	12 months		
Study Methods	Method of randomisation	Dynamic randomisation	
	Method of allocation concealment	Not reported	
	Statistical method(s) used to analyse data	Analysis of covariance was used to adjust reported outcomes, notably for any differences between groups in corresponding scores at baseline.	
	Unit of allocation	Individual	
	Unit of analysis	Individual	
	Attrition	Number of participants completing the study: 177	Reasons for not completing the study: Participants did not respond to questionnaire
Outcomes measures and effect size.	Effect of heating intervention on parent reported health outcomes in children		
	Health outcome	Mean difference (95% CI) adjusted for baseline at 4 months	Mean difference (95% CI) adjusted for baseline at 12 months
	Paediatric scale Quality of life (PedsQL) intervention (n=88) versus control (n=89) group		
	Overall asthma scale	6.3 (2.1 to 10.4)	7.1 (2.8 to 11.4)
	Physical scale	7.2 (2.6 to 11.8)	4.5 (-0.2 to 9.1)
	Overall psychosocial scale	3.0 (-1.3 to 7.2)	2.2 (-1.9 to 6.4)
	Paediatric scale Quality of life (PedsQL) intervention versus control group for homes in need of ventilation only (n=69 intervention group, n=70 control group)		
	Overall asthma scale	Not reported	6.8 (2.1 to 11.5)
	Physical scale	Not reported	3.7 (-1.8 to 9.1)
	Overall psychosocial scale	Not reported	2.7 (-1.8 to 7.2)
	Paediatric scale Quality of life (PedsQL) across intervention and control group for homes in need of ventilation and central heating (n=19 intervention group, n=19 control group)		
	Overall asthma scale	Not reported	9.3 (-1.9 to 20.6)
	Physical scale	Not reported	10.3 (-1.7 to 22.4)
	Overall psychosocial scale	Not reported	0.6 (-10.1 to 11.3)

Bibliographic reference	**Woodfine L, Neal RD, Bruce N et.al. 2011. Enhancing ventilation in homes of children with asthma: pragmatic randomised controlled trial. The British journal of general practice: the journal of the Royal College of General Practitioners 61(592):e724-32.**		
Risk of bias (ROB)	**Outcome**	**Judgement**	**Comments**
	Random sequence generation	Low	Dynamic randomisation conducted
	Allocation concealment	Unclear	Not reported
	Blinding of participants and personnel	Unclear	Not possible to blind the participants to their allocation
	Blinding of outcome assessment	Low	Researchers who undertook analysis were blind to children's allocation
	Incomplete outcome data	Low	8 % total loss to follow up. Loss unlikely to affect estimate
	Selective reporting	Low	Pre-specified outcomes reported in analysis
	Other sources of bias	None	None
Overall ROB	Low		
Source of funding	Housing modifications were provided and administered by Wrexham County Borough Council (WCBC). Resources to run the study were provided by the National Public Health Service for Wales (NPHSW). Authors received small research grants from the Chief Medical Officer for Wales Research Grant Scheme (CMOWRGS), the North Wales Research Committee (NWRC), Npower, and Wrexham Local Health Alliance.		
Comments	Edwards R T, Neal R D, Linck P et.al 2011. "Enhancing ventilation in homes of children with asthma: cost-effectiveness study alongside randomised controlled trial". The British journal of general practice: the journal of the Royal College of General Practitioners 61(592):e733-41.		

Lajoie 2015

Bibliographic reference	**Lajoie P, Aubin D, Gingras V et.al 2015. The IVAIRE project--a randomized controlled study of the impact of ventilation on indoor air quality and the respiratory symptoms of asthmatic children in single family homes. Indoor air 25(6):582-97.**		
Registration	Not reported		
Study type	Randomised controlled study		
Study dates	From October 2008 to June 2011		
Objective	To evaluate the effect of Heat recovery ventilators (HRVs) on the respiratory health of young Inuit children in Qikiqtaaluk Region		
Country/ Setting	Canada		
Number of participants	83 children with asthma		
Participant characteristics	**Demographic characteristics**	Intervention group (n=43)	Control group (n=40)
		n (%)	n (%)
	Age (years) Mean (SE)	5.5 (2.0)	6.5 (2.9)
	Sex (male)	28 (65)	27 (68)

Bibliographic reference	**Lajoie P, Aubin D, Gingras V et.al 2015. The IVAIRE project--a randomized controlled study of the impact of ventilation on indoor air quality and the respiratory symptoms of asthmatic children in single family homes. Indoor air 25(6):582-97.**		
	Ethnicity	Not reported	Not reported
	Socio-economic status (education)		
	Parent's level of educational (college or university)	18 (44)	22 (56)
	Building characteristics		
	Age (years) mean (SE)	21.2 (3.1)	24.6 (2.8)
	Attached garage	16 (37.2)	2 (5.0)
	Woodstove	16 (37.2)	20 (50.0)
	Heating system (electric)	36 (83.7)	27 (67.5)
	Airtightness (<3 ACH50)	17 (39.5)	10 (25.0)
	Existing health condition		
	Days with asthma-related symptoms per 14 days, mean (SE)	5.7 (0.5)	5.6 (0.6)
Exposure	Chemical parameters: CO_2, VOCs, semi-volatile organic compounds (SVOCs), NO_2, and formaldehyde		

Inclusion criteria	• Children aged 3 to 12 years
	• Asthma diagnosed by a physician at the Mother Child Centre
	• Family living in the Greater Quebec Area up to 45 min by car from downtown Quebec City
	• Single family home: bungalow, cottage, twin, duplex, triplex, quadruplex.
	• Family has lived in the home for the previous 12 months at least.
	• Following measured ventilation rates:
	  ○ 2 PFT or SF_6 results smaller than 0.30 ACH
	  ○ 1 PFT or SF_6 result smaller than 0.25 ACH.		

Exclusion criteria	• Very unstable asthma or family context not suitable for full participation based on a physician's advice • Significant other lung comorbidity (e.g., cystic fibrosis) • Child expected to be away from the home more than 21 days during November through March • Child lives in another home on a regular basis (more than 8 nights per month) • Significant environmental contamination of the building (water damage, mould, unsanitary conditions, etc.) requiring immediate remediation • Parents do not own the house • Major work planned in the dwelling during the study period that may modify isolation and ventilation • Commercial services offered to the public in the home (hair styling, kindergarten, others) • Move planned within the next 3 years		

Bibliographic reference	**Lajoie P, Aubin D, Gingras V et.al 2015. The IVAIRE project--a randomized controlled study of the impact of ventilation on indoor air quality and the respiratory symptoms of asthmatic children in single family homes. Indoor air 25(6):582-97.**		
Intervention	TIDieR Checklist criteria	Paper/Location	Details
	Brief Name	P582	Impact of ventilation on indoor air quality and the respiratory symptoms of asthmatic children
	Rationale/theory/Goal	P583	To evaluate the effectiveness of improved ventilation in single family homes of children with asthma on indoor air quality and their respiratory health
	Materials used	P582	Heat Recovery Ventilator (HRV) or Energy Recovery Ventilator (ERV)
	Procedures used	P582	Installation of either a Heat Recovery Ventilator (HRV) or Energy Recovery Ventilator (ERV).
	Provider	–	Not reported
	Method of delivery	–	Not applicable
	Location	P583	Intervention delivered at home
	Duration	P592	2 years
	Intensity	–	Not applicable
	Tailoring/adaptation	–	Not applicable
	Modifications	–	Not applicable
	Planned treatment fidelity	–	Not applicable
	Actual treatment fidelity	–	Not applicable
	Other details	–	None
Comparison	TIDieR Checklist criteria	Paper/Location	Details
	Brief Name	P582	Impact of ventilation on indoor air quality and the respiratory symptoms of asthmatic children
	Rationale/theory/Goal	P583	To evaluate the effectiveness of improved ventilation in single family homes of children with asthma on indoor air quality and their respiratory health
	Materials used	–	Not reported
	Procedures used	–	Not reported
	Provider	–	Not reported
	Method of delivery	–	Not applicable
	Location	P583	Intervention delivered at home
	Duration	P592	2 years
	Intensity	–	Not applicable

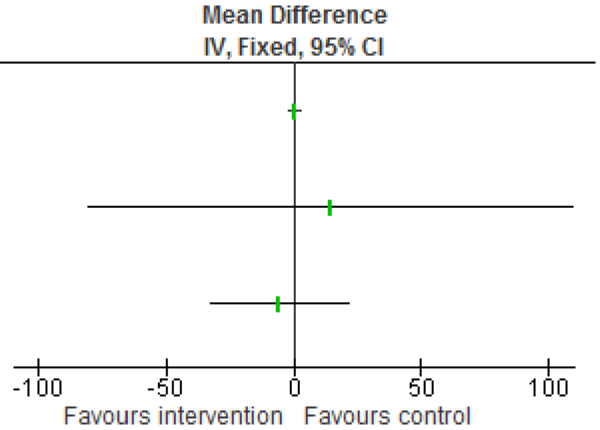
Bibliographic reference	**Lajoie P, Aubin D, Gingras V et.al 2015. The IVAIRE project--a randomized controlled study of the impact of ventilation on indoor air quality and the respiratory symptoms of asthmatic children in single family homes. Indoor air 25(6):582-97.**		
	Tailoring/adaptation	–	Not applicable
	Modifications	–	Not applicable
	Planned treatment fidelity	–	Not applicable
	Actual treatment fidelity	–	Not applicable
	Other details	–	None
Follow up	2 years		
Study Methods	Method of randomisation	Not reported	
	Method of allocation concealment	A computer-generated list of random numbers was used for allocation. Participants allocated using a personal identification code for each participant.	
	Statistical method(s) used to analyse data	Mixed linear models with repeated measures were used to evaluate the impact of the intervention on the change from Year 1 to Year 2 in environmental and health variables in the intervention group compared with the control group after adjustment for confounding variables	
	Unit of allocation	Individual	
	Unit of analysis	Individual	
	Attrition	Number of participants completing the study: 82	Reasons for not completing the study: 1 abandoned study
Health outcomes measures and effect size.	Effects of ventilation intervention on asthma symptoms and PEFR. Means (95% CI) adjusted for age, gender, parents' level of education and eczema. • Primary outcome – mean number of days with symptoms per 14 days • Secondary outcomes – proportion of children with occurrence of at least one episode of wheezing during the previous 12 months measured by ISAAC questionnaire; mean number of months with asthma control measured with the Asthma Quiz, mean number of days with use of relief medication as well as the mean peak expiratory flow rate (liters/minute) measured twice daily using the Truzone peakflow meter		
	Health outcome	**Intervention group**	**Control group**
	Asthma (number of days with symptoms per 14 days) mean (SE) baseline	5.7 (0.5) n=43	5.6 (0.6) n=40
	Asthma (number of days with symptoms per 14 days) mean (SE) 2 years	4.4 (0.8) n=37	4.1 (0.9) n=32

Bibliographic reference	**Lajoie P, Aubin D, Gingras V et.al 2015. The IVAIRE project--a randomized controlled study of the impact of ventilation on indoor air quality and the respiratory symptoms of asthmatic children in single family homes. Indoor air 25(6):582-97.**		
	Rhinitis (children with symptoms) % (SE)	78.8 (9.5) n=43	84.6 (10.0) n=39
	Peak expiratory flow rate (PEFR) (L/min) mean (SE)	232.1 (32.9) n=20	246.5 (35.5) n=21
Risk of bias (ROB)	**Outcome**	**Judgement**	**Comments**
	Random sequence generation	Unclear	Not reported
	Allocation concealment	Low	Computer-generated list of random numbers was used for allocation
	Blinding of participants and personnel	High	Unblinded randomised controlled trial
	Blinding of outcome assessment	Low	Environmental and clinical data were captured blind by two research assistants
	Incomplete outcome data	Low	1.2% total loss to follow up. Loss unlikely to affect estimate
	Selective reporting	Low	Pre-specified outcomes reported
	Other sources of bias	None	None
Overall ROB	Low		
Source of funding	Financial support for this study was provided by the National Research Council of Canada through the Government of Canada's Clean Air Agenda, the Ministere de la sante et des services sociaux du Quebec, the Canada Mortgage and Housing Corporation and Health Canada.		
Comments	None		

Appendix E: **Forest plots**

E.1 Asthma, respiratory health, and atopic disease (rhinitis)*

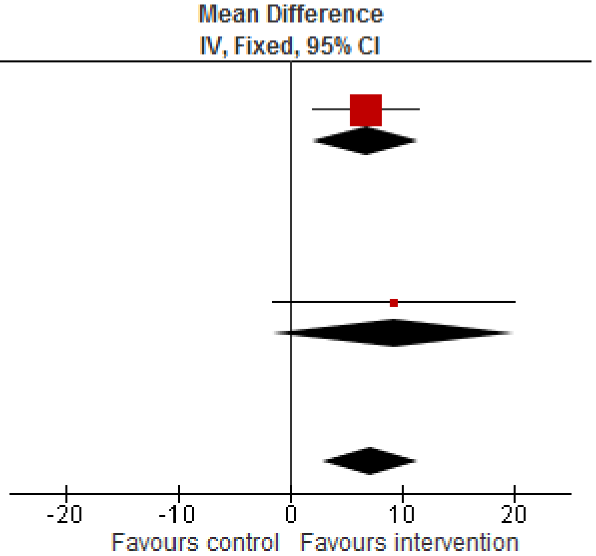
Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Mean Difference IV, Fixed, 95% CI
1.2.1 Asthma (mean symptom days per 14 day)							
Lajoie 2015 (heat recovery ventilator)	-1.3	4.86621	37	-1.5	5.091169	32	0.20 [-2.16, 2.56]
1.2.2 Respiratory health (PEFR)							
Lajoie 2015 (heat recovery ventilator)	-232.1	147.1333	20	-246.5	162.6814	21	14.40 [-80.46, 109.26]
1.2.3 Rhinitis							
Lajoie 2015 (heat recovery ventilator)	78.8	62.3	43	84.6	62.45	39	-5.80 [-32.83, 21.23]



*Lower values favour intervention; we sign inverted values for respiratory health to plot on the same graph

E.2 Health related quality of life (asthma related)

Study or Subgroup	Mean Difference	SE	Weight	Mean Difference IV, Fixed, 95% CI
1.5.1 In need of ventilation only				
Woodfine 2011 (air vent system)	6.8	2.3768	84.5%	6.80 [2.14, 11.46]
Subtotal (95% CI)			**84.5%**	**6.80 [2.14, 11.46]**
Heterogeneity: Not applicable				
Test for overall effect: Z = 2.86 (P = 0.004)				
1.5.2 In need of ventilation and central heating				
Woodfine 2011 (air vent system)	9.3	5.54708016	15.5%	9.30 [-1.57, 20.17]
Subtotal (95% CI)			**15.5%**	**9.30 [-1.57, 20.17]**
Heterogeneity: Not applicable				
Test for overall effect: Z = 1.68 (P = 0.09)				
Total (95% CI)			**100.0%**	**7.19 [2.91, 11.47]**
Heterogeneity: Chi² = 0.17, df = 1 (P = 0.68); I² = 0%				
Test for overall effect: Z = 3.29 (P = 0.001)				
Test for subgroup differences: Chi² = 0.17, df = 1 (P = 0.68), I² = 0%				



Appendix F: **GRADE profiles**

Quality assessment							No of people		Effect		Quality
No of studies	**Design**	**Risk of bias**	**Inconsistency**	**Indirectness**	**Imprecision**	**Other considerations**	**Ventilation versus control**	**Control**	**Relative (95% CI)**	**Absolute**	
HRQoL - overall asthma scale group specific (follow-up 12 months; Better indicated by higher values)											
Woodfine 2011	randomised trials	no serious risk of bias[1]	no serious inconsistency[2]	no serious indirectness[3]	no serious imprecision[4]	none	88	92	-	MD 7.19 higher (2.91 to 11.47 higher)	HIGH
HRQoL - overall asthma scale group specific - In need of ventilation only (follow-up 12 months; Better indicated by higher values)											
Woodfine 2011	randomised trials	no serious risk of bias[1]	no serious inconsistency[2]	no serious indirectness[3]	no serious imprecision[4]	none	69	70	-	MD 6.8 higher (2.14 to 11.46 higher)	HIGH
HRQoL - overall asthma scale group specific - In need of ventilation and central heating (follow-up 12 months; Better indicated by higher values)											
Woodfine 2011	randomised trials	no serious risk of bias[1]	no serious inconsistency[2]	no serious indirectness[3]	serious[5]	none	19	19	-	MD 9.3 higher (1.57 lower to 20.17 higher)	MODERATE
Asthma (mean symptom days per 14 days) (follow-up 2 years; Better indicated by lower values)											
Lajoie 2015	randomised trials	no serious risk of bias[1]	no serious inconsistency[2]	no serious indirectness[3]	no serious imprecision[4]	none	43	32	-	MD 0.2 higher (2.16 lower to 2.56 higher)	HIGH
Respiratory health (PEFR) (follow-up 2 years; Better indicated by higher values)											
Lajoie 2015	randomised trials	no serious risk of bias	no serious inconsistency[2]	no serious indirectness[3]	serious[6]	none	20	21	-	MD 14.4 lower (109.26 lower to 80.46 higher)	MODERATE
Rhinitis (% children) (follow-up 2 years; Better indicated by lower values)											
Lajoie 2015	randomised trials	no serious risk of bias[1]	no serious inconsistency[2]	no serious indirectness[3]	serious[7]	none	43	39	-	MD 5.8 lower (32.83 lower to 21.23 higher)	MODERATE

[1] Not downgraded - study judged low risk of bias
[2] Not applicable - single study
[3] Not downgraded - study met eligibility criteria as per protocol
[4] Not downgraded - confidence interval is precise does not cross lines of appreciable benefit or harm (0.5 SD of control either side; default minimal important difference for mean difference)
[5] Downgraded once - the higher confidence interval crosses the line of appreciable benefit of 2.8 (0.5 SD of control; default minimal important difference for mean difference)
[6] Downgraded once - the lower confidence interval crosses the line of appreciable benefit of 81.3 (0.5 SD of control; default minimal important difference for mean difference)
[7] Downgraded once - the lower confidence interval crosses the line of appreciable benefit of 31.2 (0.5 SD of control; default minimal important difference for mean difference)

Appendix G: **Health economic evidence study selection**

Please see cost-effectiveness review

Appendix H: **Health economic evidence tables**

Please see cost-effectiveness review

Appendix I: **Health economic evidence profiles**

Please see cost-effectiveness review

Appendix J: **Health economic analysis**

Please see cost-effectiveness review

Appendix K: **Excluded studies**

K.1 Public health studies

	Bibliography	Reason for exclusion
1	Francisco PW, Jacobs DE, Targos L, Dixon SL, Breysse J, Rose W, and Cali S (2017) Ventilation, indoor air quality, and health in homes undergoing weatherization. Indoor air 27(2), 463-477	Study does not contain any of the outcomes of interest
2	Marsik Tom, and Johnson Ron (2008) Use of Simulink to evaluate the air-quality and energy performance of HRV-equipped residences in Fairbanks, Alaska. Energy & Buildings 40(8), 1605-1613	Study setting – study conducted in Alaska, objective to evaluate intervention in very cold climate
3	Perino M, and Heiselberg P (2009) Short-term airing by natural ventilation - modeling and control strategies. Indoor air 19(5), 357-80	Study does not contain any of the outcomes of interest
4	Sharpe Richard A, Thornton Christopher R, Nikolaou Vasilis, and Osborne Nicholas J (2015) Fuel poverty increases risk of mould contamination, regardless of adult risk perception & ventilation in social housing properties. Environment international 79, 115-29	Study does not contain any of the outcomes of interest - Reported outcomes visible mould and mould odour
5	Underhill L J, Fabian M P, Vermeer K, Sandel M, Adamkiewicz G, Leibler J H, and Levy J I (2018) Modeling the resiliency of energy-efficient retrofits in low-income multifamily housing. Indoor air 28(3), 459-468	Study does not contain any of the outcomes of interest - Reported outcomes PM2.5, and NO2

K.2 Economic studies

Please see cost effectiveness review

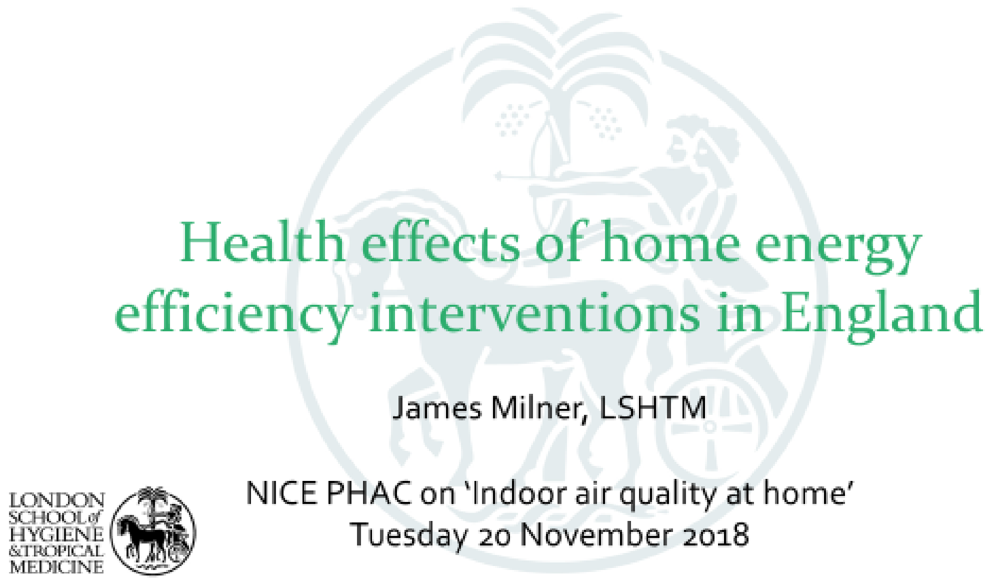
Appendix L: **Research recommendations**

L.1.1 Air exchange rate and the quality of indoor air at home

Population	Homes
Intervention	Different air exchange rates
Comparison	No intervention
Outcomes	Levels of indoor air pollutants such as particulate matter, nitrogen dioxide, VOCs and PAHs
Study design	Before and after study
Time frame	At least 6 months

Rationale: evidence reviews showed the importance of ventilation as a means to reduce exposure to indoor air pollutants and associated health problems. However, the focus on draught proofing homes and making them energy efficient has reduced ventilation. Evidence about the benefits and harms of different air exchange rates would improve understanding of minimum thresholds that would inform designers and builders.

Appendix M: **Expert testimony**



Context

Housing is responsible for roughly a quarter of UK CO_2 emissions

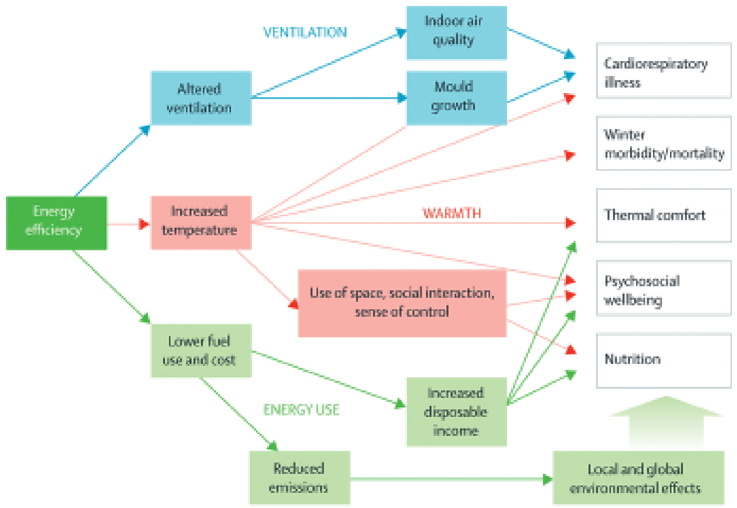
UK committed to improving energy efficiency of nearly all dwellings by 2030

There is evidence that this may improve population health (↓ ambient air pollution, ↑ winter temperature)

However, there is also potential for adverse effects (↑ indoor-generated pollutants)

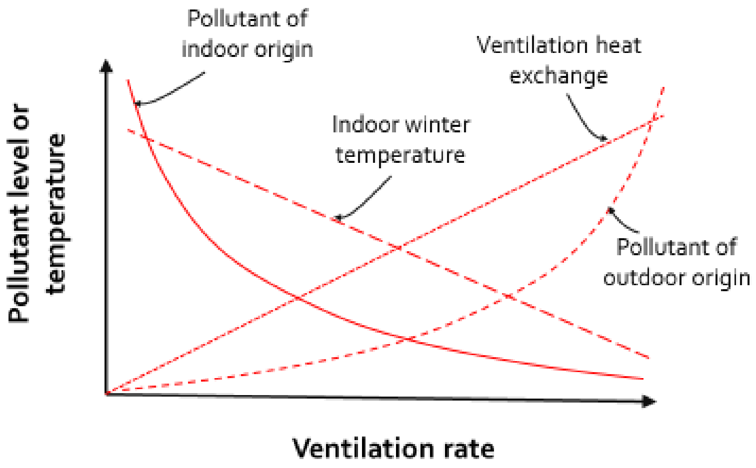
There is currently little guidance for installers on provision of adequate ventilation

Energy efficiency and health



Energy, energy efficiency, and the built environment. Wilkinson et al 2007

Housing energy and health 'trade-offs'



Background to the work

Collaboration between LSHTM and UCL (lead author: Ian Hamilton)

Based on the 'Health Impact of Domestic Energy Efficiency Model' (HIDEEM)

Aim: To assess potential public health impacts of changes to indoor air quality and temperature due to energy efficiency retrofits in English dwellings to meet 2030 carbon reduction targets.

Open Access | Research

BMJ Open **Health effects of home energy efficiency interventions in England: a modelling study**

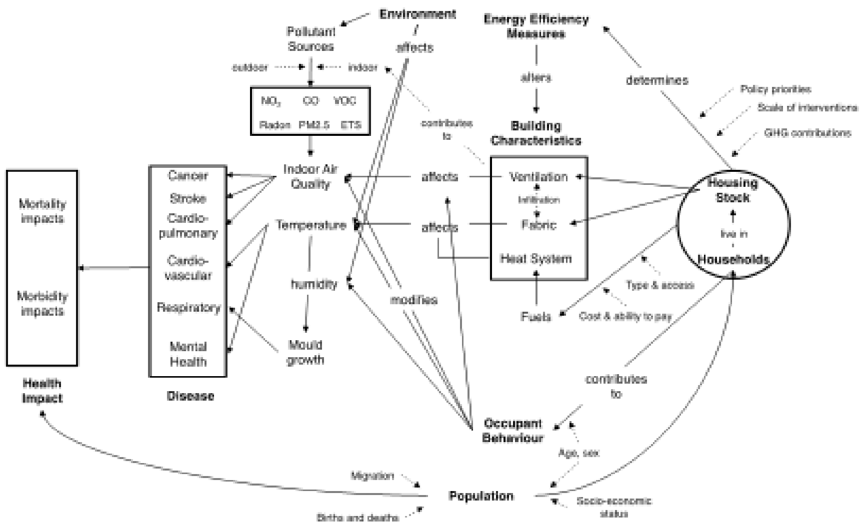
Ian Hamilton,[1] James Milner,[2] Zaid Chalabi,[2] Payel Das,[3] Benjamin Jones,[4] Clive Shrubsole,[3] Mike Davies,[3] Paul Wilkinson[2]

The HIDEEM model

- Model originally developed for DECC (now BEIS)
- Now linked to the National Household Model
- Used for economic modelling to support NICE guidance on 'Excess winter deaths and illness and the health risks associated with cold homes'

- Based on the English Housing Survey (EHS)
- Assesses the impacts of user-specified home energy efficiency interventions
- Two main components: (1) building physics model, (2) health impact model
- Also includes costs (intervention, energy savings, health care)

The HIDEEM model



The HIDEEM model

Building physics model:

- Indoor exposures based on CONTAM modelling
  - Particulate air pollution ($PM_{2.5}$)
  - Secondhand tobacco smoke (STS)
  - Radon
  - Mould
- Cold (standardized internal temperature, SIT) based on empirical relationship with E-value
- Energy
  - Fabric- and ventilation-related heat losses
  - Demand for space heating

The HIDEEM model

Health impact model:

- Mortality impacts based on life tables (but applied to each individual)
- Morbidity based on simpler methods:
  - YLD using Global Burden of Disease data
  - changes in disease prevalence
- Exposure-response functions from literature
- Time lags included where appropriate
- Outputs are changes in quality-adjusted life years (QALYs)

Methods

- Home energy efficiency measures installed where needed:
  - Loft insulation (5.3 million)
  - Cavity wall insulation (6.6 million)
  - Solid wall insulation (5.7 million)
  - Double glazing (2.4 million)
  - Condensing boilers (10.7 million)
  - Gas central heating (0.3 million)
  - Draught proofing (3.9 million)

- Broadly consistent with UK's 2030 targets
- Interventions installed instantaneously
- 50 year follow-up period

Scenarios

Three scenarios:

1. **Regulation:** fabric (insulation etc) and ventilation (trickle vents, extract fans) retrofits installed assuming building regulations are met

2. **Installer discretion:** as scenario (1) but with additional ventilation only for homes at risk of poor ventilation

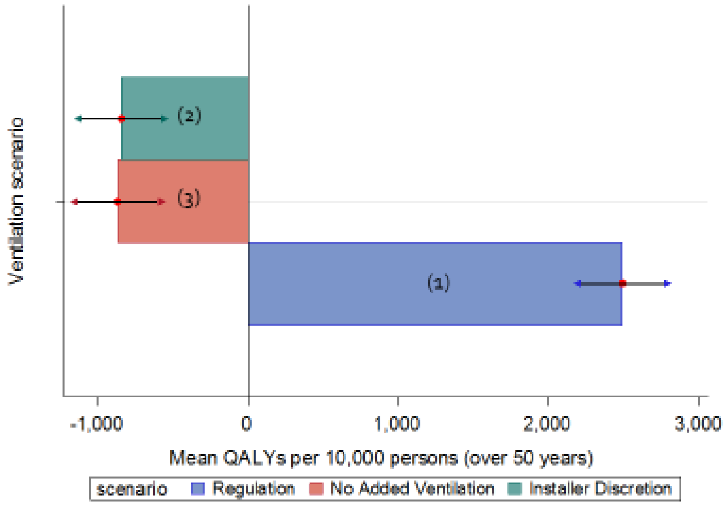
3. **No added ventilation:** as scenario (1) but with no additional ventilation to illustrate the potential risk of weak regulations and non-compliance

Results

Exposure	Baseline	Regulation (1)	Installer discretion (2)	No added ventilation (3)
SIT (°C)	17.8	18.1	18.1	18.1
STS*	0.5	0.5	0.7	0.7
Indoor PM2.5 (µg m-3)	9.4	4.6	10.6	11.0
Outdoor PM2.5 (µg m-3)	6.2	6.8	5.9	5.8
Radon (Bq m-3)	22.9	22.4	34.2	35.0
Mould (% with MSI>1)	14.9	12.3	18.5	18.8

*STS: 1 = average for smoking household

Results



Results

The **Regulation** scenario (1) had positive net effects on mortality and morbidity of 2,241 QALYs per 10,000 persons over 50 years due to improved temperatures and reduced exposure to indoor pollutants, but increased exposure to outdoor–generated PM2.5.

The **Installer discretion** scenario (2) resulted in -539 QALYs per 10,000 persons due to an increase in indoor exposures despite targeting

The **No added ventilation** scenario (3) resulted in -728 QALYs per 10,000 persons due to an overall increase in indoor pollutant exposures

Summary of main findings

Substantial benefits to health as long as ventilation is not reduced (i.e. Building Regulations are met)

There is potential for large adverse impacts on indoor air quality and health without additional ventilation

Targeting only homes at risk of poor ventilation is not enough to mitigate these impacts

Key modelling uncertainties

- Toxicity of particles from indoor sources
  - Epidemiological evidence mostly based on ambient $PM_{2.5}$ exposure
  - Toxicity assumptions critical to balance of risks and benefits

- Cold-related deaths
  - Epidemiological evidence mostly based on short-term (time series) studies
  - Vulnerable people likely to have shorter life expectancy than average
  - Therefore, life table-based estimates of cold impacts likely to be overestimated

Conclusions

If properly implemented, increasing home energy efficiency is likely to be net beneficial for health

But there are potential adverse health impacts if compensatory purpose-provided ventilation is not provided

Maximising health benefits requires careful understanding of the balance of changes in pollutant exposures

Results highlight the importance of ventilation to mitigate the risk of poor indoor air quality

Limitations

The study attempted to combine validated models and the best available evidence

But important limitations, eg...

- Epidemiological evidence of varying certainty
- No changes in future mortality rates
- No future reductions of ambient $PM_{2.5}$

Results should be viewed as indicative

Thank you

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Hamilton I, Milner J, Chalabi Z, et al. Health effects of home energy efficiency interventions in England: a modelling study. BMJ Open 2015;5:e007298. doi:10.1136/bmjopen-2014-007298