

# Housing Interventions and Control of Health-Related Chemical Agents: A Review of the Evidence

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Subject matter experts systematically reviewed evidence on the effectiveness of housing interventions that affect health outcomes associated with exposure to chemical agents, such as pesticides, lead, volatile organic compounds, as well as the radon gas. Particulates were also examined, and the role of ventilation on exposures was assessed. The review included both published literature and peer-reviewed reports from the US Environmental Protection Agency. Four of the 14 interventions reviewed had sufficient evidence to demonstrate their effectiveness and are ready for implementation: radon air mitigation by using active soil depressurization systems, integrated pest management to reduce exposures to pesticides, smoke-free home policies making indoor areas smoke-free (ie, no smoking allowed anywhere at any time), and residential lead hazard control. Four interventions needed more field evaluation, 3 needed formative research, and 3 either had no sufficient evidence of effectiveness or had evidence the interventions were ineffective. This evidence review shows that housing improvements are likely to help reduce radon-induced lung cancer, cardiovascular mortality related to secondhand smoke, and neurological effects from exposure to pesticides and lead paint. Investing in housing interventions may yield important savings from reduced disease and injury from avoidable exposures to chemical agents.

**KEY WORDS:** chemicals, housing, integrated pest management, lead poisoning, radon, secondhand smoke, ventilation

Exposure to indoor chemical agents has been associated with neurotoxicity and developmental disorders, asthma and other respiratory illnesses, and cancer.<sup>1-9</sup> Exposure to high levels of some indoor chemical agents has been associated with fatalities. Indoor chemical agents include lead, pesticides, secondhand smoke (SHS) from cigarettes or other combusted tobacco products, volatile organic compounds (VOCs), and the radioactive radon gas.

Structural deficiencies, pest infestations, gas stoves, and introduction of source materials that off-gas or otherwise release toxic agents are all housing factors that can increase the presence of chemical agents in or around a dwelling. Because most homes in the United States do not have a planned supply of fresh air delivered to the building space and, instead, rely

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on operation of windows and intermittent or inadequate building leakage, indoor airborne contaminants can increase. The absence of easily cleanable surfaces can also contribute to increases in pesticide residues, lead-contaminated house dust, and other accumulated toxicants.<sup>10</sup>

## ● Lead

Lead is one of the best studied toxic substances. Its toxicity affects the brain, neurodevelopment processes, and many other organ systems.<sup>11,12</sup> Some of its effects are irreversible, and no safe level of lead exposure has been identified.<sup>4,5,7,13,14</sup> Over the past several decades, children's blood lead levels have declined, yet about 250 000 children younger than 6 years have elevated blood lead levels ( $\geq 10 \mu\text{g}/\text{dL}$ ).<sup>15</sup> Low-income children and black and Hispanic children are at higher risk.<sup>16</sup> On the basis of results from the National Survey of Lead and Allergens in Housing, approximately 40% of housing units (38 million) in the United States contain lead-based paint and of those 24 million have significant lead-based paint hazards, such as deteriorated lead-based paint and lead-contaminated house dust and bare soil.<sup>17,18</sup> This study's panel of subject matter experts did not review the effectiveness of lead hazard control, but a summary is included in the following text.

## ● Secondhand Smoke

Secondhand smoke causes approximately 3000 lung cancer deaths in nonsmokers each year.<sup>19</sup> Fetal and infant exposure to tobacco smoke has also been associated with prematurity, low birth weight, low Apgar scores, poor early growth of infants, and dysfunctional behavior.<sup>20-23</sup> Secondhand smoke exposure and cognitive abilities among US children and adolescents aged 6 to 16 years have been found to be inversely associated, even at extremely low levels of exposure.<sup>24</sup> The Institute of Medicine (IOM) found sufficient evidence for a causal relationship between SHS exposure and the exacerbation of asthma in preschool-aged children and an association between SHS exposure and the development of asthma in younger children.<sup>2</sup> The 2006 Surgeon General's report, *The Health Consequences of Involuntary Exposure to Tobacco Smoke*, concluded that the scientific evidence indicates that there is no risk-free level of exposure to SHS. The report also found that the home is the major setting where children are exposed to SHS.<sup>25</sup> A 2009 report by the IOM, *Secondhand Smoke Exposure and Cardiovascular Effects*, concluded that the evidence is consistent with a causal relationship between SHS exposure and acute coronary events, including myocardial infarctions.<sup>26</sup>

## ● Pesticides

Pesticides are any agent used to suppress pests such as insects, rodents, weeds, fungi, and bacteria. Pesticides can affect the nervous system, and exposure to multiple pesticides may have a cumulative risk.<sup>27,28</sup> The health effects of chronic exposure are not well understood.<sup>28-30</sup> The IOM report on asthma found inadequate evidence of an association between residential pesticide exposure and the development or exacerbation of asthma.

Exposure to pesticides occurs through diet, dermal absorption, and inhalation of airborne pesticides either as an aerosol or adsorbed on dust particles.<sup>2</sup> In 2000, 75% of US households used at least 1 pesticide indoors during the past year and 80% of most people's exposure to pesticides occurred indoors.<sup>31</sup> Pesticides can remain in a home for years after their use has stopped and have been found in indoor air and carpet dust and on settled dust surfaces.

## ● Volatile Organic Compounds

The health effects of VOCs are varied. The IOM report found insufficient evidence of an association between indoor residential VOC exposures and the development or exacerbation of asthma.<sup>2</sup> At higher levels of exposure, however, the threat of sensitization, cancer, and respiratory and other problems can be pronounced.<sup>32</sup> Common household items that can release VOCs include paint, varnish, and wax, as well as cleaning, disinfecting, cosmetic, and degreasing products; products containing particle board and plywood; so-called air fresheners; and hobby products. Formaldehyde is a VOC that is a component of some building materials, such as particle board and plywood adhesives, and may be found at high levels in many new buildings; however, levels decline over time because of off-gassing.<sup>32</sup>

## ● Radon Gas

Exposure to radon gas is the leading cause of lung cancer among nonsmokers and the second leading cause of lung cancer overall, causing 21 000 deaths annually in the United States.<sup>33</sup> Combined data from several previous residential studies show definitive evidence of an association between residential radon gas exposure and lung cancer.<sup>6,8,34</sup>

A decay product of uranium, radon is a colorless, odorless radioactive gas that occurs naturally in soil and rock. It moves through fractures and porous substrates in the foundations of buildings and can collect

in high concentrations in certain areas. Radon may also enter a house through water systems in communities where groundwater is the main water supply. This occurrence is most common in small public systems and private wells that are typically closed systems that do not allow radon to escape. Housing with high radon concentrations is more prevalent in certain regions of the country, but any house, regardless of region, can contain dangerous or unhealthy levels of radon; the US Environmental Protection Agency (EPA) has mapped high-risk radon areas.<sup>1</sup>

## ● Interventions Reviewed

The methods article by Jacobs et al<sup>35</sup> in this issue describes the literature search and review process in detail. In addition to these methods, the study team also acquired literature on radon interventions that had been peer-reviewed by the EPA but had not been published in the peer-reviewed literature and was, therefore, not available for previous systematic review. These paper reports have now been scanned and are available electronically from the National Center for Healthy Housing (<http://www.nchh.org/Search.aspx?Source=3&SearchIn=5&Name=radon&Status=0,1&Audience=&Principle=&Keywords=random&Author=&Journal=&From=&To=>). This review of evidence on the effectiveness of interventions did not involve human subjects.

The review of evidence on carbon monoxide exposure was considered by the panel evaluating interventions addressing structural deficiencies and is reported by DiGuseppi et al<sup>36</sup> in this issue. In reviewing the literature, this study's panel of subject matter experts defined the scope of interventions to control chemical exposure in the home to include the following:

- active radon air mitigation,
- passive radon air mitigation,
- radon in drinking water mitigation,
- integrated pest management (IPM) (as pesticide exposure reduction),
- smoke-free policies,
- particulate air cleaners,
- particulate control by envelope sealing,
- attached garage sealing,
- residential ventilation,
- reductions of VOCs,
- air cleaners using or releasing ozone,
- portable air cleaners to reduce SHS or gases,
- single professional cleaning to control lead exposure, and
- residential lead hazard control.

## ● Results

Of the 14 interventions reviewed, 4 are ready for implementation and have been shown to be effective, 4 need more field testing but are promising, 3 need formative research, and 3 are either had evidence proving them to be ineffective or have no sufficient evidence of effectiveness.

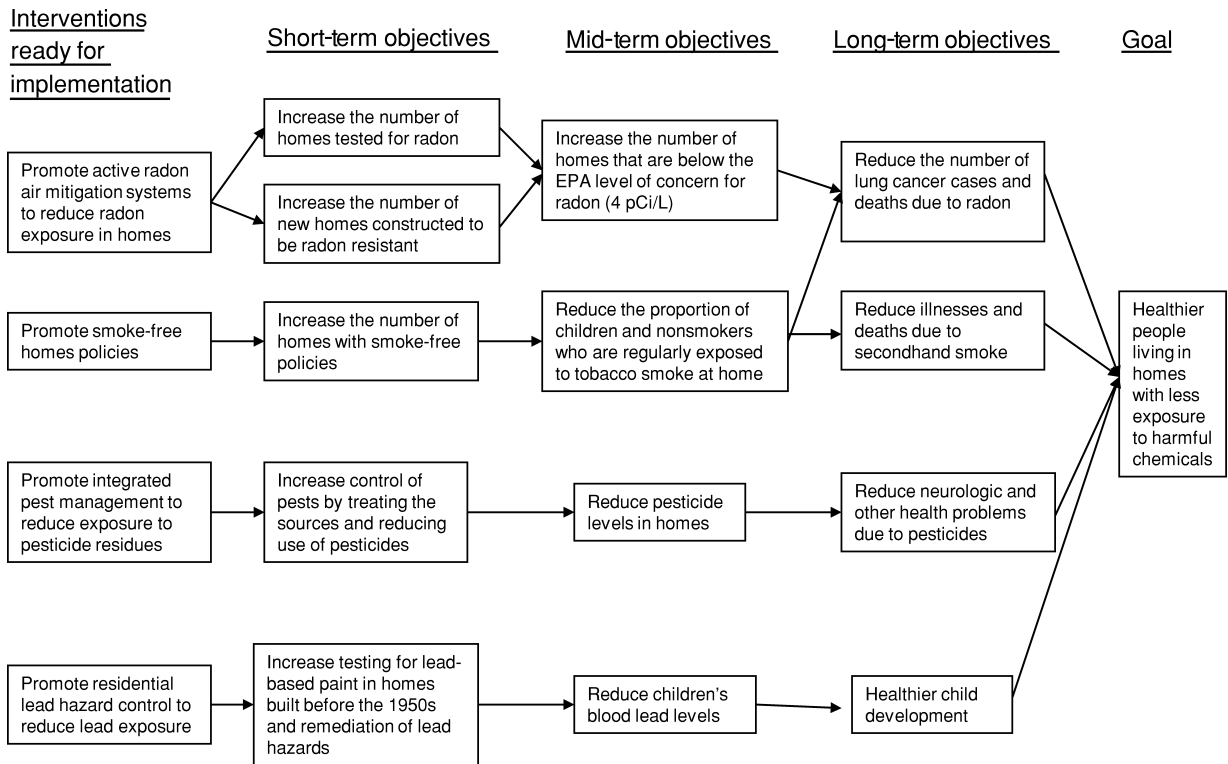
### Sufficient evidence

The panel found that 4 of the interventions reviewed had sufficient evidence and were shown to be effective. The Figure is a logic model for evaluating the effectiveness of the interventions listed in improving housing-related health outcomes.

#### *Radon air mitigation through active soil depressurization*

The panel found that active radon mitigation strategies are effective in reducing exposure to radon in air to less than 4 pCi/L. The evidence for this finding comes from 7 studies.<sup>37-43</sup> Each of these studies enrolled a relatively large number of housing units, ranging from 73 to 238 units. Active soil depressurization is the creation of a negative pressure zone under the foundation so that soil gases are exhausted through the roof instead of entering the building. The exposure level established by the EPA to protect health is 4 pCi/L of air.

In particular, the studies of Groves-Kirkby et al and Burkhardt and Kladder had well-characterized control groups and could demonstrate significantly reduced radon exposures by using active soil depressurization systems. The study of Groves-Kirkby et al<sup>43</sup> showed that active soil depressurization systems were far more effective than installation of membranes during construction. An EPA review concluded that 97% of houses with high baseline radon levels (76% had baseline radon levels  $\geq 10$  pCi/L) could be remediated with active soil depressurization systems to less than 4 pCi/L.<sup>37</sup> The study of Brodhead,<sup>41</sup> which was a national survey, showed that 95% of homes were remediated to less than 4 pCi/L and 69% were actually remediated to less than 2 pCi/L ( $n = 238$  houses). The durability of these active systems has been assessed in relatively small studies, with the exception of the large study of Dehmel,<sup>38</sup> which showed that 95% of houses were remediated to less than 4 pCi/L 18 months after installation. Kladder and Jelinek<sup>39</sup> found that 11 of 13 houses evaluated were remediated to less than 4 pCi/L 2 years after installation. The evidence shows that active radon mitigation is an effective housing intervention. As mentioned earlier, some of radon literature used to evaluate the effectiveness of the active soil depressurization was not published, and we acknowledge the importance of this unpublished literature here.

**FIGURE 1 ● Housing Interventions to Control Chemical Agents Ready for Implementation**

### ***Integrated pest management for pesticide exposure reduction***

The panel found that IPM is effective in reducing exposure to pesticide residues. Integrated Pest Management is a system that controls pests through denial of access, harborage, food, water, resident education, and use of least toxic pesticides. The evidence for this finding comes from the study of Williams et al,<sup>44</sup> which showed that both cockroach infestations and levels of pyrethroid insecticides in indoor air samples decreased significantly ( $P = .016$ ) in the intervention group. In addition, pesticides were not detected in the maternal blood samples in the intervention group and were either significantly different ( $P = .008$ ) or of borderline significance ( $P = .1$ ) when comparing the intervention and control groups. The efficacy of IPM in controlling exposure to pests and their allergens is discussed in a companion article in this series by Krieger et al.<sup>45</sup> This research provides further evidence that IPM is an effective intervention.

### ***Smoke-free policies***

The panel found that 100% smoke-free policies or rules are effective in reducing exposure to SHS. The evidence for this finding comes from 4 studies of nonresidential smoke-free policies<sup>46-49</sup> and 2009 reports from the IOM<sup>26</sup> and the International Agency for Research on Cancer.<sup>50</sup>

The IOM found sufficient evidence for a causal relationship between smoke-free laws and decreases in acute coronary events.<sup>26</sup> It further concluded that eliminating smoking in indoor spaces fully protects nonsmokers from SHS exposure. Separating smokers from nonsmokers, cleaning the air, and ventilating buildings cannot eliminate exposures of nonsmokers to SHS.

The 2009 International Agency for Research on Cancer report, *Evaluating the Effectiveness of Smoke-free Policies*, reviewed the available evidence on the effects of interventions to reduce SHS exposure in the home. The report concludes that there is sufficient evidence that smoke-free home policies reduce exposure of children to SHS and reduce adult smoking. There is strong evidence that smoke-free home policies reduce youth smoking.<sup>50</sup>

### ***Lead hazard control***

The evidence that extensive residential lead hazard control is effective in reducing environmental lead contamination comes from numerous studies, which have been reviewed extensively elsewhere.<sup>51-53</sup>

The largest study on lead hazard control occurred in 14 jurisdictions and covered nearly 3000 housing units enrolled in the lead hazard control program funded by the US Department of Housing and Urban Development. The results demonstrated that dust lead levels

declined by 78% to 95% over a 3-year period after lead hazard control.<sup>54</sup> Further declines in dust lead levels on both floors and window sills occurred in a representative subset of homes selected for follow-up 6 years after hazard control.<sup>10</sup> Although this study could control for a number of confounding influences and was nationwide in scope, one of its weaknesses was that constructing a control or comparison group was not feasible.

However, similar declines in dust lead levels have been observed in a number of other smaller studies following lead hazard control work where control or comparison groups were feasible.<sup>55,56</sup> For example, one such study that did have comparison groups showed that median dust lead levels following hazard control declined to more than 98%.<sup>57</sup> Yet, another study showed that dust lead loadings 1.5 to 3.5 years postabatement were only 16%, 10%, and 4% of preabatement levels for floors, window sills, and window wells, respectively.<sup>58</sup>

The specific interventions for lead hazard control are multifactorial and include a combination of building component replacement, paint stabilization, enclosure, encapsulation, education, and limited paint removal, followed by specialized cleaning and clearance testing. These interventions for lead hazard control have been published and adopted for federally assisted housing and in many local jurisdictions.<sup>59</sup>

The extent of residential lead hazard control necessary to reduce blood lead levels in children whose blood lead levels are elevated (ie,  $>10\mu\text{g}/\text{dL}$ ) is less clear. A number of randomized, controlled trials of lower-level interventions, such as education only or modest dust control, have found modest declines or no statistically significant decline in the blood lead levels of children.<sup>60-64</sup> Some researchers have postulated that modest declines in blood lead levels after dust control alone are most likely because of the release of significant amounts of lead from endogenous bone lead stores in children whose exogenous lead exposure source has been controlled. This occurrence may limit the ability of lead hazard intervention to detect a reduction in blood lead levels in chronically exposed children.<sup>65</sup>

Dust lead and blood lead levels following lead hazard control have been extensively reviewed elsewhere.<sup>53</sup> Because dust lead is known to be highly correlated with blood lead, dust lead levels may be a more useful metric of the effectiveness of interventions on paint, dust, and soil.<sup>52</sup> Furthermore, in at least 1 study, residential lead hazard control was found to significantly reduce the likelihood of subsequent lead poisoning cases in buildings where children had been poisoned in the past, indicating that lead hazard control is an effective prevention strategy.<sup>64</sup>

## Promising interventions that need more field evaluation

The panel found that 4 of the interventions reviewed were promising but need more field evaluation.

### *Radon mitigation for drinking water by using activated charcoal and aeration*

The study of Mose et al<sup>66</sup> showed that large reductions of radon in drinking water, which can sometimes be quite high, are achievable through filtration and aeration, or a combination of both. However, the study also showed that even after filtration and aeration, radon can still be at levels exceeding the proposed EPA maximum contaminant level of 300 pCi/L. Anecdotal evidence suggests that significant improvements have been made in reducing radon levels in drinking water, and the associated contribution to radon in air, since the study of Mose appeared. However, these improvements do not appear to have been published in the peer-reviewed literature, which suggests that this promising method needs further evaluation.

### *Portable HEPA air cleaners for indoor particulate control*

The ability of air cleaners to remove particulate matter of certain size ranges from air is well established. Specifically, air cleaners are known to be able to achieve a 30% to 70% reduction in the half-life of airborne particulate matter between 0.3 and 1  $\mu\text{m}$ .<sup>67</sup>

However, that study also showed that the air cleaners did not reduce larger airborne particles between 1 and 5  $\mu\text{m}$ . Air cleaners are less effective as the particle size increases, probably because the larger particles settle out of the air more quickly than do smaller ones. In addition, air cleaners have not been demonstrated to reduce nonparticulate gases, such as VOCs, or other gases such as carbon monoxide, oxides of nitrogen, and others.<sup>68</sup> This finding led the IOM to conclude that only limited evidence shows that air cleaners are effective in reducing asthma,<sup>2</sup> probably because many allergens may be concentrated in the larger particle size ranges.

Nevertheless, the fact that air cleaners can reduce small airborne particles shows that this intervention is a promising one requiring further field study. A recently published study that appeared after the panel's deliberations showed that portable HEPA air cleaning devices could greatly reduce very small particles in the indoor environment during forest fires and wood burning,<sup>69</sup> adding further support to the position that this intervention is promising and requires further work.

Reducing exposure to indoor particulate matter and gaseous pollutants is always more effectively achieved by removing the sources of pollutants.<sup>68</sup> Given the

current published peer-reviewed literature, the panel feels there is not sufficient evidence for portable air filtration systems to adequately protect people exposed to SHS from a wide range of adverse effects. Elimination of smoking indoors is by far the most effective strategy to prevent exposure to the complex mixture of gaseous and particulate pollutants in SHS.

#### ***Garage sealing to reduce benzene and other VOC exposures***

The study of Batterman et al<sup>70</sup> showed that nearly all of the indoor exposure to benzene and other VOCs in the houses studied was due to VOC migration from attached garages into the living space. Another study found that the risk of asthma tripled for every 10-unit increase in benzene exposure.<sup>71</sup> Possible interventions include sealing the garage, maintaining a negative pressure in the garage with respect to the indoor living space, sealing penetrations from the living area into the garage, taking administrative measures (eg, parking the car outside), and perhaps others.

The effect of such interventions on indoor exposures to benzene and other VOCs has yet to be demonstrated consistently. However, because attached garages account for much of the indoor exposure to VOCs, sealing such garages is a promising intervention. Housing construction guidelines that separate garages from houses are also potential effective interventions but need further review to ensure elimination of exposure.

#### ***Particulate intrusion reduction and improved ventilation***

A study of a single home showed that the building shell was not effective at preventing infiltration of small particulate matter, such as from air pollution from traffic.<sup>72</sup> However, earlier studies that did not account for re-suspension in indoor air suggested that the building envelope had a filtering effect.<sup>73</sup> Although a building envelope likely reduces the number of larger particles that infiltrate, the effectiveness of differing building envelopes in filtering smaller particles requires further field investigation and cannot be recommended on the basis of a single home study.

### **Interventions in need of formative research**

The panel found that 3 of the interventions reviewed need formative research.

#### ***Radon mitigation by using passive systems***

Several studies demonstrate that mitigation of airborne radon levels by using passive systems (ie, no exhaust fan) does not consistently reduce indoor radon levels adequately or consistently over time.<sup>43,74-77</sup> Although

they are not as effective as active systems (those with exhaust fans), passive radon mitigation systems can be effective in many cases and can serve as a cost-effective initial phase of an active mitigation system, should one be needed, especially in radon-resistant new construction. However, both effectiveness of passive systems alone and their cost-effectiveness as part of active systems depend on proper installation of the system components according to available technical guidance and maintenance over time. The panel recommended further formative research to better formulate the standards of the intervention.

#### ***Improved residential ventilation***

Although ventilation standards have been developed,<sup>73,78</sup> and compliance with such standards is quite likely to be beneficial, too little is known about how ventilation levels affect both short- and long-term health. Ventilation systems can be varied and may consist of nothing more than building leakage for supply of fresh air. Many single family housing units and low-rise units in the United States do not have a planned fresh air supply system, and multi-family buildings may have unbalanced or otherwise inadequate air supply systems. Ventilation rates can be expressed as volumetric air supply (cubic feet per minute), air exchanges per hour, air velocity, pressure differentials, and other metrics, which also need to include filtration and distribution requirements.

Despite the complexity involved, compelling evidence shows that inadequate ventilation adversely affects health. For example, one large study showed that the odds of bronchial obstructions were higher in people living in housing with lower air exchange rates.<sup>79</sup> Another multilevel intervention study in new home construction showed that increasing the fresh air supply, coupled with heat recovery systems for the exhaust air, produced statistically significant improvements in the number of days free from asthma symptoms, quality of life, urgent clinical care, and asthma trigger exposure.<sup>80</sup> Inadequate ventilation is also associated with moisture problems,<sup>81</sup> and studies show that improved ventilation can help control moisture and mold problems.<sup>45</sup> Finally, the increasing emphasis on energy conservation requires further research to understand how such energy conservation measures affect indoor air quality and health and the precise levels of fresh air supply and distribution that are needed to protect health.

#### ***Volatile organic compound interventions other than garage sealing***

The effectiveness of avoiding building materials containing VOCs, baking out VOCs following new

construction by using short-term higher ventilation and temperature levels, or using both practices has not been adequately demonstrated to show a positive health effect. Further study is needed to demonstrate the potential health benefits of product avoidance, ventilation, or a combination of both.

One notable exception to this finding is avoiding the use of particle board containing formaldehyde and urea/formaldehyde insulation and other similar products until new, independent studies are completed demonstrating their safety. Recent studies of Federal Emergency Management Agency trailers in the Gulf Coast region show that exposures to formaldehyde in closed trailers can be quite high.<sup>82</sup> Finally, no peer-reviewed literature was found demonstrating that sealing particle board with coatings or laminates sufficiently reduces formaldehyde emissions. This result suggests that building materials containing added formaldehyde should be avoided until coatings or laminates have been shown to be effective.

Finally, many other classes of organic compounds are in house dust, including persistent organic pollutants, polybrominated diphenyl ethers, benzo(a)pyrene, and others. Exposures to these other compounds may also be reduced by intensive cleaning and source control, as is the case for lead, but no articles were identified indicating that such procedures were effective for this class of chemicals.

### No evidence/ineffective interventions

The panel found that 3 of the interventions reviewed had no evidence of effectiveness or were ineffective.

#### Portable air cleaning filtration systems for SHS or gases

Portable air cleaning filtration systems are ineffective in controlling exposures to SHS or formaldehyde to levels safe for human exposure, although some modest decline in exposure may occur. For example, the Surgeon General concluded that cleaning the air cannot eliminate exposures of nonsmokers to SHS.<sup>25</sup> In a 2008 position document, The American Society of Heating, Refrigerating and Air Conditioning Engineers stated that no engineering approaches, including current and advanced dilution ventilation or air cleaning technologies, have been demonstrated or should be relied upon to control health risks from SHS exposure in spaces where smoking occurs.<sup>83</sup> Source control through voluntary smoke-free household rules, and, in the case of formaldehyde, product substitution, has been shown to be much more effective and should be implemented instead.

#### Ionizers or other air cleaners

Ionizers or other air cleaners that produce large amounts of ozone should not be used because they result in increased exposure to ozone, which is associated with asthma morbidity.<sup>84</sup> Because there is an unknown benefit to these machines and a known hazard related to creating ozone from such devices have on removing indoor airborne particulate matter,<sup>85</sup> their use is not recommended.

#### Single professional cleaning

A single professional cleaning of dust and debris without addressing potential sources of lead dust (such as deteriorated lead-based paint) is unlikely to result in significant and sustained reductions in dust lead loadings. More extensive interventions that address deteriorated lead-based paint, although more expensive, are likely to provide longer-term reductions in dust lead loadings.<sup>86</sup>

## ● Conclusion

Many chemical exposures exist that can adversely affect human health. Sufficient evidence suggests that certain chemical exposures in the home can be decreased by housing interventions, which will likely reduce rates of radon-induced lung cancer and poorer neurodevelopment in children that is associated with exposure to pesticides and lead. Such interventions should be implemented and may yield important savings associated with reduced disease and injury connected with avoidable exposures to chemical agents.

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