ABSTRACT
In North America, there are ~140 million homes and 4 million public buildings. More than one fifth of the energy use in Canada is used to condition air whether from the cold in much of Canada or provide cooling and heating where summers are hot and humid and winters are cold. To reduce greenhouse gases and improve housing affordability, this energy use needs to be reduced. In 1981, the Federal and Provincial governments understood that science was needed to inform building codes in relation to occupant health. Ventilation standards used in North America were developed during the late 19th century from studies done mainly in schools. Modern studies of ventilation rate and health effects in public buildings indicate that relative risk for increased respiratory disease and absenteeism becomes significant around 14 L/s per person. Most of this work has been done in public buildings. In Canada, there has been interest in ventilation questions for residential housing in relation to comfort, disease transmission and relationships of ventilation to dampness and pollutants mainly derived from vehicle traffic as well as endotoxin. Considering new homes with heat recovery ventilators, occupants reported improvement over 1 year in the symptoms of throat irritation, cough, fatigue, and irritability in comparison with control new home occupants. Homes that have low per person ventilation rates, and, those that are air leaky are prone to dampness with the associated increased risks of asthma and upper respiratory disease. In the most under-ventilated homes in Canada (in the far north), increased infectious disease has been observed in infants. Lastly, both gaseous and particulate air contaminants infiltrate homes. This is affected by ventilation and other aspects of system design and appears to modulate allergic responses. New studies are needed on the effect of ventilation on health to prevent negative effects on population health consequent to changes in energy codes for residential homes.

KEYWORDS
ventilation, health, indoor air pollution, outdoor air pollution

INTRODUCTION
The North American jurisdictions that adhere to the AHSRAE standard have incorporated a multi-stakeholder process to advance ventilation standards for public buildings (the origin of this work is briefly discussed below). For residential homes, ventilation was not a major issue because the houses were well constructed to resist moisture but were considerably air leaky. In response to the energy crisis of the 1970s many governments subsidized the installation of better insulation and windows. As a generalization, the programs did not provide tools to determine whether this tightening of the house would affect indoor air quality, health and comfort. This came to be recognized as unwise as occupant complaints increased and health effects began to be associated with inappropriate levels of ventilation. In 1981, the Federal and Provincial governments initiated a science-based process to develop information that would inform building codes in relation to occupant health. The intent was "to develop
guidelines of selected contaminants of indoor air, taking into account such factors as the sensitivity of
groups and special risk and the sources and mechanisms of action of the contaminants” (Wylie and
Armstrong 1986). The committee recognized that public education and influencing product
specifications might be better tools than guidelines. Guideline development and voluntary processes to
improve products has proceeded well since 1987 (the publication of the first guidelines). This was done
for a large number of chemicals and for microbials in a series of guidelines in a process that continues
to this day. In contrast, the objective to determine health based ventilation rates (Wylie and Armstrong
1986) has not received attention. The prevailing view was that a house needed a ventilation system
that “would be able to deliver enough outdoor air to meet the probable maximum needs of the
household”. It would also be capable of modulating delivery so that it did not deliver more outdoor air
than required at times of reduced need (Haysom et al. 1998).

In the US and Canada, ventilation codes have been at best rudimentary because of the high natural
rate of ventilation. It was only recently that ASHRAE developed and approved a ventilation standard for
homes (Sherman 2004). In Canada, excepting R2000 homes, ventilation codes for the construction of
new homes evolved slowly, because the houses had high rates of natural ventilation and remain mainly
tied to moisture management than health. The 2005 Canadian National Building Code requires a
ventilation capacity of 2-3 L/s per room. The Provinces and Municipalities across Canada choose which
if any provisions in the national building code and there is little or no inspection. By 2003, Canadian
officials involved in the major energy conservation research initiative in Canada (Program of Energy
Research and Development), recognized that energy conservation measures must now be shown to be
health neutral or health positive. Further, if necessary, health studies needed to be conducted to
demonstrate the impact of a new technology on health.

HISTORICAL STUDIES

Although it has been known since the Biblical times that indoor air quality affected occupant health, it
was not until the early 17th century that it was recognized that “want of ventilation” resulted in increased
rates of infectious disease. The first guidelines for ventilation rate probably appeared in the UK and
were intended for ventilating deep mines in Cornwall. In 1836, an estimate of acceptable ventilation
rate was made by a mining engineer based on the known rates of human-generated moisture and CO2
of 2 L/s per person (Janssen 1999). This estimate was possibly the minimum needed for metabolic
needs but did not deal with infectious diseases, odour control or comfort. By the late 19th century,
fairly sophisticated experiments were conducted on the effect of ventilation on disease (Sundell 2004).
Perhaps most notable of these studies was by Carnelly et al. (1887). They measured CO2, airborne
mold and bacteria and total organic material in housing, schools, factories and a hospital in the Dundee
area as well as in outdoor air [noting carefully wind and general weather conditions]. They found that
concentrations of all these parameters were proportional to occupants per room. One of the co-authors
was the Medical Officer of Health and, in conjunction with the several registrars of death, compiled an
annual death rate for each neighbourhood. Deaths from TB, acute bronchitis, pneumonia were strongly
influenced by crowding. Deaths from what we now know as water-borne diseases did not relate to
crowding.

During the US Civil War, it was observed that there was a greater and faster spread of disease in
hospitals with low per person ventilation rates. Col J.S. Billings MD served in the medical core of US
Army, served in the Civil War and wrote a number of important books on public health including the
influential “Ventilation and Health” in 1893 (Janssen 1999). Dr. Billings estimated that 28 L/s per person
of outdoor air were necessary for prevention of disease and 14 L/s per person were necessary for
comfort. The latter value was written into Massachusetts statutes for large buildings. Studies were done
in Chicago and New York on acceptable ventilation rates in heated school buildings based on
respiratory disease rates. In cities where ventilation by open windows was not acceptable because of noise and air pollution, mechanical ventilation systems supplied the necessary supply air. The 14L/s rate became the practice in States or Provinces with large cities usually by law. Modern studies of ventilation rate and health effects in public buildings indicate that relative risk for increased respiratory disease and absenteeism becomes significant around 14 L/s per person (Milton et al. 2000; Seppanen & Fisk 2004)

Advances in heating and air-conditioning technology permitted the development of larger buildings where supplied air was intended to dominate. In a time where it was uncommon to bathe more than weekly, ventilation researchers moved beyond infection control to odour control and comfort. By the late 1930’s very careful studies had been completed on the ventilation rates needed to satisfy the majority of occupants. These were done with children and adults from a variety of circumstances indicated that the rate that Col Billings suggested in 1893 as necessary for comfort (~5 L/s per person) was appropriate, something confirmed by studies conducted in the 1980’s (Janssen 1999). The lessons of the past were forgotten and thus the mechanical ventilation rates were lowered. This worked because buildings still had very large rates of natural ventilation. The third wave of ventilation research and health had to do with acceptable relative humidity in indoor air. In colder areas with high natural ventilation rates, indoor relative humidity is low in the winter. Unsurprisingly, this was reported in Canada where studies in the 1960s related low indoor RH values to increased rates of infectious disease (Green 1975). The implication was drawn that this was because the survival of some viruses on surfaces is greater at lower RH values (Arundel et al. 1986).

STUDIES IN CANADIAN HOMES

Most of the work discussed so far was drawn from studies of public buildings. The former are pertinent to single family dwellings because the ventilation rates in Canadian homes have been based on the ASHRAE standard for large buildings (Haysom et al. 1998). Residential ventilation rates became an issue for public health and public policy by 1980. The association of lung cancers with radon prompted their measurements indoors (McGregor et al. 1980) and required attention particularly to basement ventilation in existing houses. In new housing, high concentrations of formaldehyde arising from some building materials became a major issue and large scale surveys were conducted using methods developed for that specific purpose (Shirtliffe et al. 1985). Changes in product formulations have reduced the concentrations of formaldehyde and other volatiles over the last 25 years in Canadian homes (Gilbert et al. 2005). Canadian houses built prior to the 1960’s had high natural air change rates and almost all were heated by combustion, both of which generally produced adequate ventilation (Hayson & Reardon 1998). Tighter construction and the large increase in use of radiant electrical heating meant more Canadians lived in homes with much reduced per person ventilation rates compared to their parents. By the late 1980’s perhaps 70% of homes had ventilation rates below that indicated by the Canadian standard (Haysom et al. 1990). Under these circumstances, all pollutants produced indoors –whether from occupants or the building- increase in concentration. One of the contaminants that accumulated, moisture, led to increases in concentrations of biological contaminants, particularly house dust mites and fungal growth. Epidemiological studies began by Health Canada in 1989 led to the observation that mold and dampness was associated with increased rates of asthma and upper respiratory disease in both children and adults (Dales et al. 1991a, b). It is known that house dust mite allergen causes asthma and that mold is associated with exacerbation of asthma and upper respiratory disease (NAS 2004). Approximately 10% of Canadian homes have material dampness problems, the prevalence of which varies according to region to region, and, economic circumstance.
There have been a number of multi-pollutant studies in Canadian houses where some measurement of ventilation rate has been obtained. A study of 52 homes in several cities conducted in 1985 indicated the presence of relatively high concentrations of molds and volatiles. Although 75% of the homes had air change rates higher than 1 per hour, the majority also had high moisture source strength despite having air change rates (Miller et al. 1988). The Wallaceburg study was conducted consequent to the findings of Dales et al. noted above. Just over 400 homes in the community were intensively studied for a broad array of contaminants along with studies of the children and this has been the subject of many publications. In this study, mold remained a risk factor for upper respiratory disease when adjusted for the unusual variables as well as house dust mite allergens and endotoxin (Dales & Miller 1999). We found that children living in more versus less mold contaminated housing had significant differences in particular lymphocyte subpopulations (Dales et al. 1998). This study was done in 1994-95 approximately 10 years after the 52 home study. These houses had air change rates less than one. The homes classified as moldy had higher air change rates than the less moldy homes (Lawton et al. 1998) which reflects that air leakiness can sometimes also mean water leakiness. In 1998, Health Canada began a prospective study on housing and infant health in Prince Edward Island (Dales et al. 2006). Air change per hour values in these homes (collected from 1998 to 2003) were similar to those of the Wallaceburg homes (Ruest et al., unpublished data) as were values from a study in Ottawa, Ontario (Miller et al. 2007).

Formaldehyde is an example of an air pollutant where concentrations in Canadian homes are generally higher in homes with lower ventilation rates (Gilbert et al. 2006), albeit still much lower than 20 years ago (Shirliffe et al. 1985).

Ventilation has another important impact on namely the penetration of outdoor air contaminants indoors. This includes particles from traffic and soil as well as gases. There are data on the health effects of particles from outdoors penetrating indoors (Miller et al. 2007 and references cited therein). These are known to have health effects and improving air filtration on buildings may result in a material reduction in the resulting effects on population health (Hanninen et al. 2005). In Canadian homes, naturally ventilated homes will have large infiltration of particles from outdoors. This can be reduced in spring, summer, and fall by pressurizing the house with filtered supply air. HEPA filters on the air intakes will be most effective. Using HEPA filters on the intakes of balanced systems will also result in low particle infiltration, when compared to natural ventilation (Fugler 2003). In Ottawa homes sampled in the winter, the weekend median indoor black carbon value was higher than the weekday mainly reflecting higher values between 5 and 8 PM on Saturday (p > 0.0001). The time-activity reports were compared to graphs of the measured black carbon values. This revealed no association between the use of fireplaces, woodstoves or other household activities with black carbon, suggesting that traffic emissions comprised the majority of the signal as can be the case in some US cities. The time-activity reports of wood burning, cooking or the use of candles did not account for the greater weekend values of black carbon. The explanation appeared to be the neighbourhood effect of wood burning which is more common on the weekend in Ottawa (Miller et al. 2007).

The 19th century studies of ventilation noted above indicated that at very low per person ventilation rates, rates of some infectious diseases increased. Most housing in Canada and the US has relatively high per person ventilation rates because of large houses and small families. An exception is in aboriginal housing in the far north. The rate of hospitalization for severe lower respiratory tract infection (LRTI), including bronchiolitis and LRTI due to Respiratory Syncytial Virus, in Inuit children in North America appears to be markedly elevated, with rates of 306 per 1000 infants in Baffin Region, Nunavut and 249 per 1000 in the Yukon-Kuskokwim Delta region of Alaska. In a pilot study of houses of Inuit infants and toddlers below 2 years of age in Cape Dorset a number of parameters were measured including air change rates, indoor nitrogen dioxide (NO2), particulate, and carbon dioxide.
concentrations, airborne nicotine concentrations, and settled dust fungal and dust mite concentrations. The infants had a median age of 13 months and 25% had been hospitalized for a chest illness. Houses were very small, and had a median of 6 occupants per home. A large percentage the houses (41%) had a calculated natural air change rate less than 0.35 air changes per hour. Excepting environmental tobacco smoke, the pollutants were in acceptable ranges and fungi and dust mites were not present. It appeared that reduced air exchange and environmental tobacco smoke exposure were potential risk factors for viral LRTI in (Kovesi et al. 2006).

In a subsequent study, ventilation was measured in 49 homes of Inuit children below 5 years of age in Qikiqtaaluk (Baffin) Region, Nunavut. The mean ventilation rate per person was 5.6 L/s/person and 80% of houses had rates below the recommended rate of 7.5 L/s/person. The mean indoor carbon dioxide (CO2) concentration was 1358 ppm. Smokers were present in 93.9% (46/49) of houses. Reported LRTI was significantly associated with mean CO2 (Odds Ratio (OR) = 2.85 per 500 ppm increase in mean indoor CO2) and occupancy (OR = 1.81 for each additional occupant). Reduced ventilation and crowding may be one cause of the observed increase in LRTI among Inuit children (Kovesi et al. 2007). A ventilation intervention study is under way.

Such studies were not possible in homes until the advent of affordable devices for balanced ventilation of homes came available, homes either had no additional ventilation measures beyond windows, air pulled into the house consequent to the use of combustion for heating and some exhaust ventilation. In Canada, this began with the development of the R-2000™ programme in the 1980’s. As a result, it was more or less impossible in the past to conduct a reliable analysis of the effect of ventilation on health in detached houses and the studies that have been done date have been of limited interpretability and statistical power.

In Sweden, 30 mechanically ventilated energy-efficient homes studied after 5 and 15 months were shown to have decreased house-dust mite concentrations (Wickman et al.1994). In a study done in the U.K., 14 asthmatics in similar houses were shown to have decreased medication use and symptom scores over the same time periods (Warner et al. 2000). These studies focused on dust mite control as the principal benefit but humidity control may also influence mold concentrations. If there is indeed a health benefit to case homes the most likely mechanism is through control of dampness, which has been shown to affect symptoms in occupants (NAS 2004).

Leech et al. (2004) examined reported changes in health status by questionnaire in occupants of case homes at about 1 year after occupancy in comparison with health status in the year before occupancy and to control new home occupants’ reported health changes over the same period of time. The test group or cases was 52 R-2000 homes (128 occupants) built to preset and certified criteria for energy efficient ventilation and construction practices. The control group were 53 new homes (149 occupants) built in the same year in the same geographic area and price range. R-2000 homes are registered with Natural Resources Canada, the developer of this housing type. Consecutive registrants with the R-2000 program were identified in 1997 and 1998 in New Brunswick and Nova Scotia, Canada. Control new homes were identified in the same geographic. Analyzed by household, case occupants’ summative symptom scores improved significantly over the year of occupancy (Wilcoxon rank sum test, P < 0.006). Analysis of variance of individuals’ total symptom scores showed a significant effect of the type of house (P < 0.0001), with lower change of scores in case buildings, but not of age or sex. In comparison with control homes, occupants of case homes reported more improvement in throat irritation (P < 0.004), cough (P < 0.002), fatigue (P < 0.009) and irritability (P < 0.002) with the main change in symptom category being from “sometimes” to “never”. New occupants of energy efficient homes with heat recovery ventilators reported improvement over 1 year in the symptoms of throat irritation, cough, fatigue, and irritability in comparison with control new home occupants.
These studies need to be repeated on a much larger scale to permit them to be used to form public policy. The houses studies were new houses which is a small percentage of the overall housing stock. New designs and new equipment as well as training of contractors would be needed to deal with the existing housing stock.

CONCLUSIONS

For environmental and economic reasons, the more attention is needed to the cost of the energy to condition air. This needs to be done respecting the principle that each intervention, particularly in the existing housing stock needs to be health positive or health neutral. Aside from the obvious need for building scientists and architects to work together to achieve these goals, more research is needed on the population health effects of ventilation interventions, including increased air tightness, particularly for the existing housing stock. There are compelling reasons to do this work and to do it quickly. Using cost data from a large tract home builder in the Greater Toronto Area, Gray et al. (2005) compared the costs and associated energy savings of meeting the minimum code with the costs and associated energy savings of building to the R2000 standard. Designing to the R2000 standard produced an internal rate of return in the range of 7% and 14%. It is essential that the very wide application of these design approaches include be soundly based from a health perspective and to get started on this work now.

ACKNOWLEDGEMENTS

I thank colleagues at Health Canada and Canada Mortgage and Housing Corporation for the interactions in studies of residential housing and health conducted since 1984 and the Natural Sciences and Engineering Research Council for funding.

REFERENCES


