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The Ventilation Rate of 344 Oslo Residences

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Abstract The ventilation in Norwegian residences was studied with respect to the effect of new standards, construction techniques adopted, and energy conservation measures implemented. This was compared to residential ventilation performance in other countries with a similar climate. The effective total air change rate (h^{-1}) in 344 residences was measured with a passive tracer gas method known as the perfluorocarbon tracer gas method (PFT-method). The measurements were performed over a 14-day integrated sampling period. Overall, 36% of all residences had lower air change rates than the national building code requirement of 0.5 h^{-1}. In spite of similar construction techniques and building codes in the Nordic countries, Norwegian residences seem to be better ventilated in general than residences in other Nordic countries. However, the common belief of a gradual reduction of ventilation rates in Norwegian buildings as the date of construction becomes more recent is supported by our findings which show a linear reduction (slope $\beta=-0.002$, $P<0.05$) of ventilation until the revision of the national building codes in 1987. Consequently, our results provide evidence supporting the hypothesis that the introduction of new building standards and construction techniques, and the implementation of energy conservation measures, have decreased the effective total air change rates in Norwegian residences until 1987.

Key words Indoor climate; Ventilation; Air change rate; Passive tracer gas technique; Perfluorocarbon; Residences.

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Introduction

The home environment has changed considerably during the past decades because of the rapid advancements in building technology. Residences have become more tightly sealed as amended residential building standards have been adopted and energy conservation measures have been implemented. The potentially negative impact on indoor air quality from some of these measures is a matter of concern. Especially in cold climates like in Norway, efforts were put into m imizing transmission and air infiltration losses means of facade insulation, better insulated windo and careful sealing of the building structure. In the ginning of the 1980s, the negative effect of greatly duced outdoor air intake was discovered in term elevated humidity (IEA, 1991; Korsgaard, 19 Studies of inhabitant behavior with respect to ve lation revealed that the level of outdoor air infiltrat the tightness of the building structure, and the siz the residence has not influenced the ventilation beh ior of the occupants (Dubrul, 1988; Lundqvist Revsbech, 1986; Lundqvist, 1985; Dale and Smith, 1 Brundrett, 1977). This means that the ventilation havior of the occupants does not respond to the ergy-conserving efforts carried out. As a result technical development and the environmental po requirements seem to have changed too rapidly created a conflict between energy-saving and ve lation.

Even though efforts have been made in Norwa reduce outdoor air infiltration, the effect in term reduced actual ventilation rates in residences is documented. It is a common belief that national bu ing regulations and new building technology have to more air-tight buildings, and therefore lower ve lation rates, but this has not, to our knowledge, b verified for the Norwegian building stock. In 1993 new national building code regulations quantifie minimum air change rate in residences of 0.5 h^{-1} (N wegian Building Authorities, 1993). The actual ve lation in existing Norwegian residences, and the d ation from the new building code, is not known. objectives of this study were to determine the ac ventilation in Norwegian residences and to com this to the national building code, the actual ventila of residences in other Nordic countries, and the e of building regulations and new building technolo

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Methods

Study Design

The results presented in this paper are elaborated from our main study on the role of building characteristics as risk factors for development of obstructive respiratory symptoms in early childhood (Nafstad et al., 1997). In brief, a matched case-control study was carried out based on a cohort of 3,754 children born in Oslo in 1992/93, and followed-up for two years. The case series consisted of 251 children with bronchial obstruction, defined as two or more episodes or one episode lasting one month or more. The control series was one-to-one matched by the date of birth. Details of the recruitment and follow up of the cohort are presented elsewhere (Nafstad et al., 1997a; Nafstad et al., 1996).

Data Collection

The aim of this study was to determine the effective total air change rate (ACH (h^{-1})) of residences. Two trained persons assessed exposures and interviewed parents during site inspections. The measurements were performed in the same two-week period for the matched case-control pairs. When a case was defined, an age-matched control was immediately selected for parallel visits. The families were urged not to perform any interventions before the visit, which usually was conducted within one week after the first contact. A detailed evaluation of building characteristics was conducted, including type of building, main construction material, type of ventilation system, opening of grills, kitchen range hood, home volume, type of primary heating source and crowdedness (m^2 per occupant). Data on ambient weather conditions (outdoor temperature, relative humidity, wind speed and precipitation) were provided by the Norwegian Meteorological Institute.

Assessment of Residential Ventilation

The effective total ACH (h^{-1}) in the residences was measured with a passive tracer gas method, utilizing perfluorocarbon tracers (PFT) (Stymne and Eliasson, 1991). The measurements were performed over a 14-day integrated sampling period. The occupants were instructed to behave as they normally would with respect to ventilation. All equipment was installed and dismantled by the project staff and the occupants were never involved in the handling of the equipment. The validation showed no difference in air change rates between residences measured by the two investigators when controlled for season, type of building and ventilation system. Stymne et al. (1994) have estimated the technical error to 11.1%. All measurements were performed during the period May 1992 to May 1995, excluding the summer months of June, July and August due to the presumed dominating effect of airing.

The experimental layout of this study was similar to the one described by Stymne et al. (1994) in a national survey of ventilation in Swedish residences. There were, however, minor modifications. In the present study, passive sources with two different types of tracer compounds were distributed in the residences, one type being positioned in the child's bedroom, the other type (1–3 sources) distributed in the other rooms in the residence. Five diffusive passive samplers containing a charcoal adsorbent were also distributed in the residence: one in the child's bedroom; one in the living room; and the others in vicinity of identifiable air extract points (i.e., close to kitchen range hood and just outside bath and toilet rooms).

The total ventilation flow rate was computed from the tracer emission rates, the analyzed amounts of tracer compounds in the samplers, and the exposure time. A two zone approach was used whenever possible, otherwise a single zone approximation was used. Errors were estimated from a combination of technical error and the standard diviation from the mean of analyzed amounts in the different samplers.

In contrast to the Swedish study (Stymne et al., 1994), the present study used capillary tracer gas sources equipped with a tracer gas permeable silicone polymer plug at the outlet. This plug was intended to eliminate a tendency of increased emission rate due to rapid temperature variations. The combination of the presence of this polymer plug and an unfortunate storage of tracer gas sources in closed containers (20–30 in each) when not in use resulted in an increased initial emission rate when positioned in the residence. This increased emission rate was due to a saturation effect in the silicone polymer plug, in which the tracer gas is partly soluble. After measurement in 216 residences, this effect was observed and the tracer gas sources were changed to a new improved type of capillary source for the rest of the study. When analyzing the results, there was a marked and systematic difference in the distribution of calculated ACH with respect to season, type and size of residence and type of ventilation system between measurements performed before and after the change of tracer gas sources. From the observed difference in distribution functions a correction factor of 1.56 for the emission rates of the old sources was empirically estimated. After correction, no systematic differences in the ACH distribution functions could be observed. The correction factor was further validated experimentally through reconstruction of the saturation situation, followed by measuring the decay of emission rates until steady state was reached. The experiment validated the empirical correction factor and hence it is believed that the used correction factor fully compensate for the systematic error of the first 216 measurements.

Due to the temperature dependence of the tracer gas emission rates, it was necessary to input the indoor air temperature into the calculation of ACH. The indoor air temperature was therefore continuously logged and registered as the mean of the 14-day measuring period using a simple battery-driven electronic device (MTM-11; Wilberg a.s., Oslo, Norway). Inaccuracy for the indoor air temperature measurement was specified to ±0.2°C.

Statistical Methods

Univariate analysis was used to study the association between ACH (h^{-1}) and type of building and ventilation. Further a multivariate analysis (stepwise linear regression), with logarithm of ACH as the dependent variable, was used to identify the degree of effect each independent variable has on residential ACH (SPSS for Windows, 1994). The independent variables tried in the model were: type of building, main construction material, type of ventilation system, opening of grills, ki chen range hood, home volume, type of primary hea ing source, crowdedness (m^2 per occupant) and amb ent weather conditions (outdoor temperature, relativ humidity, wind speed and precipitation). The variable on weather conditions were averaged over the exa same 14-day integrated PFT sampling period (± hours).

The time trend in residential ACH was studied i retrospect using the year of construction as the inde pendent variable. To display changes of ACH ove time, major changes in construction techniques and/o adoption of new standards or national regulation were used to categorize homogeneous time interval using similar construction techniques and standards In addition, the hypothesis that ACH in Norwegia residences has not changed over time was tested usin linear regression with ACH as the dependent variabl and year of construction (continuous) as independen variable.

Results

A total of 304 children from the Oslo Birth Cohort wer diagnosed as having bronchial obstruction. Of these

Table 1 Distribution of Building Characteristics in Cases and Controls

Building Characteristics	Cases (N=172)		Controls (N=172)	
	%	95% CI	%	95% CI
Type of building				
Single family house	20	14–26	24	18–31
Detached and semi-detached house	27	20–34	27	20–33
Apartment building	53	46–61	49	41–56
Main construction material				
Wood	49	42–57	48	41–56
Concrete	38	31–46	31	24–38
Brick*	11	6–15	19	13–24
Other	2	0–4	2	0–4
Type of ventilation				
Natural	66	59–73	67	60–74
Mechanical exhaust	34	27–41	31	24–38
Balanced	0	0–0	1	0–3
Opening of ventilation grills in living room, child's bedroom and kitchen				
Open in 0 of 3 rooms	14	9–19	12	7–17
Open in 1 of 3 rooms	15	9–20	16	10–21
Open in 2 of 3 rooms	27	20–33	33	26–40
Open in 3 of 3 rooms	45	37–52	39	32–46
Kitchen range hood (exhaust)	51	44–59	58	51–66
Home volume (m^3)				
<150	14	9–19	13	8–18
150–300	59	51–66	58	50–65
>300	27	21–34	29	22–36
Primary heating source				
Electrical convection heaters	68	61–75	64	57–71
Radiators	27	20–34	32	25–40
Other	5	2–9	4	1–6
Crowdedness (<20 m^2 per inhabitant)	24	18–31	21	15–27

* Chi-square test: $P<0.05$ in comparison between cases and controls

256 children were still living in Oslo at the time of the diagnosis and thereby candidates for the case-control study. A total of five pairs were lost: the parents of three cases were unwilling to have home visits and the homes of two pairs were not visited by mistake. Building characteristics are presented separately for the cases and controls in Table 1. There were few differences between the cases and the controls, in terms of the type of building, ventilation system, opening of ventilation grills, the presence of kitchen range hood, home volume, primary heating source and crowdedness. The use of brick as the main construction material was more common among controls than cases.

ACH measurements were halted due to economic reasons after measuring in the residences of 172 (67%) case-control pairs, i.e., in total 344 residences. Comparison of home characteristics between cases with and without ACH measurements did not reveal significant differences (figures not given).

Distribution of Effective Total Air Change Rate Compared to the National Building Code

Figure 1 shows the cumulative distribution of the ventilation in the 172 residences expressed as effective total ACH separated according to type of building. The differences in ACH between types of building were small. 40% of the single family houses, 40% of the apartments, and 29% of the detached and semi-detached houses have ventilation rates $<0.5\ h^{-1}$. ACH between types of ventilation system did not show substantial differences either. Overall 36% of all residences have lower ventilation than the national building code of $0.5\ h^{-1}$.

For comparison with other Nordic countries, residential ventilation is also presented as ventilation in liters per second and square meter, separated as to type of building and ventilation system (Table 2). Norwegian residences seem, in general, to be better ventilated than residences in other Nordic countries. The one exception is apartment buildings with exhaust ventilation where the figures are similar in all Nordic countries.

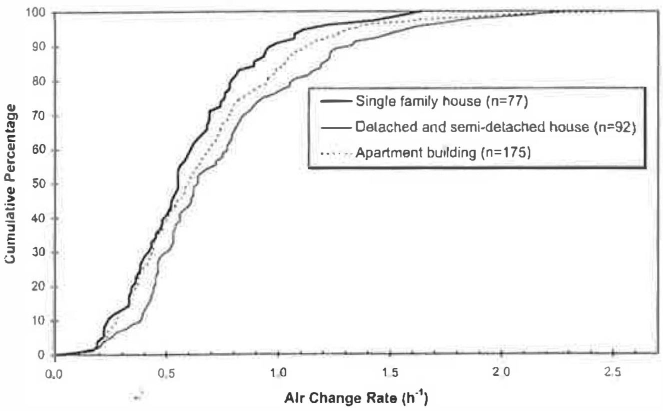

Fig. 1 Cumulative frequency distribution of the air change rate for different types of building.

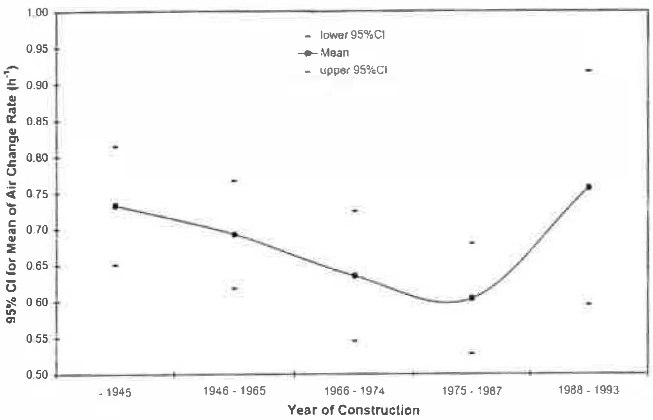

Fig. 2 Air change rate (h^{-1}) mean and 95% confidence intervals (CI) of mean according to year of construction.

Effective Total Air Change Rate According to Year of Construction

Historically, national building codes on ventilation have periodically changed and construction techniques have improved. Based on major changes in national building codes and/or building technique, or other events with expected influence on the residential ventilation rate, the houses were categorized into intervals based on year of construction. Changes in building regulations and/or building technique are not likely to generate continuous interventions in the housing stock, but more likely to induce stepwise changes responding to the new regulation and/or building techniques.

A historical review of building regulations and major changes in building technique reveals that 1945, 1965, 1974 and 1987 were major turning points for expected direct or indirect impact on residential ventilation rate. At the end of World War Two in 1945, the need for renewal of the national building stock was great because of war damage and general conservation during the years of war. In 1955, the insulation codes were sharpened and the use of mineral wool as a construction material increased. This probably led to more air-tight buildings. In 1965, a major change in the building codes was implemented. Instead of describing accepted building techniques, the building code was reformulated as performance demands, further sharpening areas with direct and indirect influence on ventilation performance. As a consequence of the energy crises in the mid-seventies, energy conservation dra-

Table 2 Mean ventilation in litres per second and square meters (l/s, m²) in Nordic residences separated by type of building a ventilation system

Type of building and ventilation system	Ventilation (l/s, m²)			
	Sweden (n=1143)	Finland (n=242)	Denmark (n=123)	Norway (n=344)
Single family houses, detached and semi-detached houses				
natural ventilation	0.23	0.28	0.24	0.47
exhaust ventilation	0.24	0.31	0.38	0.44
balanced ventilation	0.29	0.35	–	–
Apartment building				
natural ventilation	0.33	0.43	–	0.51
exhaust ventilation	0.39	0.47	0.40	0.42
balanced ventilation	0.40	0.42	–	–

Table 3 Linear stepwise regression of logarithm of air change rate*

Independent Variables	Parameter Estimate	Partial R^2	P-value
Logarithm of home volume (m³)	−0.1742	0.023	0.0049
Average outdoor temperature (°C)	0.0070	0.020	0.0022
Electrical convection heaters as primary heat source	−0.0525	0.009	0.0492

* Only independent variables with P-value <0.05 are included in the table

matically changed and building techniques were directed towards more air-tight buildings, but this was usually not followed by enhanced mechanical ventilation, and probably resulted in lower effective ventilation rates in buildings in general, especially in residences. In the 1980s the indoor air quality problems became more pronounced, and public awareness was raised. This was recognized in the new building codes of 1987 with minimum requirements of extract ventilation from kitchen and bathrooms. In 1993, a new guideline (Norwegian Building Authorities, 1993) for the building code of 1987 formulated a minimum ACH in the residence of 0.5 h^{-1}.

The common belief of a gradual reduction of ventilation rates in Norwegian buildings is supported by Figure 2, showing a reduction of ventilation until the revision of national building codes in 1987. A linear regression, with ACH (h^{-1}) as the dependent variable and construction year (continuous) as the independent variable, shows a linear trend with slope β=-0.002 ($P<0.05$) until 1987. Our study population shows a tendency towards improved ventilation in newer residences (built after 1987), but due to the relative small number in this group (n=33), the post–1987 improvement shown in Figure 2 is not significant (β=0.065, P=0.24).

Multivariate Analysis

To study the degree of effect each independent variable has on effective total ACH, a multivariate analysis (stepwise linear regression) was used. The regressi results are summarized in Table 3. Three independe variables produced a total model R^2=0.06. Home v ume has the most explanatory power for ACH, wh the presence of electrical convection heaters as the p mary heat source has the least explanatory power a significance. Variables tried in the model but witho explanatory power were type of building, main co struction material, type of ventilation system, openi of grills, kitchen range hood, crowdedness (m² per o cupant) and the ambient weather conditions relati humidity, wind speed and precipitation.

Discussion

Ventilation

The actual ventilation in the parts of the Norwegi building stock was studied, and shows that 36% of a residences have lower ventilation than the nation building code of 0.5 h^{-1}. The differences in ACH b tween types of building and types of ventilation sy tem were small. In Table 2, the study is compared to large Swedish national survey (Stymne et al., 1994), random sample of residences in the metropolitan ar of Helsinki in Finland (Ruotsalainen et al., 1992), an a random sample of newer single family houses, d tached or semi-detached houses (built in 1983–86) o the island Sjælland in Denmark (Bergsøe, 1991). I spite of similar construction techniques and buildi codes in the Nordic countries, Norwegian residenc seem in general to be better ventilated than residences in the other Nordic countries. One exception is apartment buildings with exhaust ventilation where the figures are similar in all Nordic countries. However, it is known that inhabitant behavior with respect to ventilation is a strong determinant for effective total ACH (Dubrul, 1988) and this may explain the difference observed. In this comparison the Swedish study is the only national survey, and thus the lack of generalization in the other studies could bias the comparison. This study is not a national survey and may not be representative for the Norwegian building stock. However, the distribution of ACH among controls only produced similar results and therefore our study seems to be representative for homes in Oslo inhabited by families with small children.

Validity of Results

The integrated 2-week measurements of air change rate could be expected to vary with the weather conditions even though the summer season was excluded. However, little is known about the quantitative effect of weather conditions in Norway. The 344 measurements were fairly evenly distributed over all seasons (32% in winter (December to February); 29% in spring (March to May); 39% in autumn (September to November)) and hence averaging out any seasonal effect.

Side by side duplicate samplers were not used because experience shows that analysis of such samplers usually differ less than 8% (Stymne et al., 1994). Neither were duplicate tracer gases with different flavors used, but two different tracer gases were used to permit a two zone calculation. The total ventilation rate in the dwellings was usually calculated with the two zone approach. However, because two different tracer gases were used, it was also possible to perform two independent single zone calculations. When the two zone calculation failed due to unreasonable interzonal flows, a weighted average of the two one zone calculations was reported (Styme et al., 1994). When mixing within a dwelling was good, as seen from even tracer gas concentrations, the two one zone calculations were consistent. The two zone approach gave the most reliable results in 140 houses. In the rest of the houses a single zone approached was used to calculate ACH. On a regular basis blind blanks were analyzed to check for contamination. No contamination problems other than the saturation of the permeable silicone polymer plug in the PFT sources were observed. The saturation problem was taken into consideration as described in the methods and should not bias the results.

Effect of Adoption of New Construction Techniques and/or Building Codes

Although it has not been verified, there is a common belief that ventilation rates in Norwegian buildings have decreased due to tightly sealed buildings enforced by the adoption of new construction techniques and/or building codes. There are, to our knowledge, only scattered and non-review publications on air tightness of houses in Norway from 1945 to present. Our findings support this common belief showing a linear trend of decreasing ACH until the mid-eighties when the ACHs again seem to increase. The increase is consistent with the growing concern for indoor climate in the 1980s and the national response to this in 1987 when a new building code was implemented, in which indoor climate was emphasized, and in 1993 when a new national guideline (Norwegian Building Authorities, 1993) sharpened the interpretation of this building code.

Modeling of Residential Air Change Rate

It is difficult to model effective total residential ACH due to the human behavioral effects which can be observed from the relationship between ACH and the outdoor temperature (Dubrul, 1988). People open their doors and windows more often when ambient air temperature is temperate and keep their homes more tightly closed when temperatures are colder. The difficulties in modeling residential ACH is obvious from the multivariate analysis, which produced an R^2 of only 0.06. Consequently, our model can not be used to predict residential ACH. Nevertheless, home volume, outdoor temperature and the presence of electrical convection heaters as the primary heat source, all are shown to have a statistically significant influence on residential ACH. As can be seen from Table 3, the presence of electrical convection heaters as the primary heat source has a negative association to ACH, i.e., the air change is higher among those who do not have electrical convection heaters as the primary heat source. Those who do not have electrical convection heaters as the primary heat source mainly have radiators (see Table 1).

Concluding Remarks

In conclusion, our results provide evidence supporting the hypothesis that the introduction of new building standards and construction techniques, and the implementation of energy conservation measures, have decreased the effective total air change rates in Norwegian residences. The actual residential ventilation in Norway seems to be better than in our Nordic neighbors, but still one-third of the residences are underventilated according to the current national building code. Due to the inability to predict human behavioral effects, it would be difficult to model residential ACH even if sufficient data were available on house shell leakage area and on weather parameters. However, home volume, outdoor temperature and the presence of electrical convection heaters as the primary heat source, are identified as factors that influence the residential ACH.

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