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Indoor Climate and the Performance of Ventilation in Finnish Residences

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Abstract

The purpose of the study was to gather information about the actual ventilation and indoor air quality and to evaluate the differences between houses and apartments with different ventilation systems. A sample of 242 dwellings in the Helsinki metropolitan area was studied over periods of two weeks during the 1988-1989 heating season. The mean air-exchange rates had a high variation (average 0.52 1/h, range 0.07-1.55 1/h). The ASHRAE minimum value of 0.35 1/h was not achieved in 28% of the dwellings. The air-exchange rates were significantly lower in the houses than in the apartments (averages 0.45 / 0.64 1/h, $p < 0.001$); in the natural ventilation systems they were slightly lower than in the mechanical systems. The average temperature in the bedrooms was approximately 22 °C (range 18-27 °C), slightly but significantly higher in the apartments than in the houses. The average dust depositions were higher in the balanced ventilation systems than in the other systems. The median radon concentration was 82 Bq/m³ (range 5-866 Bq/m³); the Finnish target value of 200 Bq/m³ was exceeded in 17% of the houses but in none of the apartments. The measurements indicate that the indoor air quality in Finnish dwellings is not always satisfactory with reference to human health and comfort.

KEY WORDS:
Ventilation, Indoor air quality, Dwellings, Ventilation systems, Air-exchange rate

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Introduction

Many indoor air pollutants in residences can cause adverse health effects, annoyance to occupants or damage to the building fabric. The main pollutants are environmental tobacco smoke, combustion products, organic materials, radon, body odour and water vapour (International Energy Agency, 1987). Ventilation decreases the indoor pollutant concentration by dilution with the outside air. The ventilation system itself has been criticized for such adverse conditions as draught, noise and dust in the occupancy zone. Mechanical ventilation and air conditioning in large office buildings have been associated with the sick building syndrome (Finnegan et al., 1984; Hedge, 1984; Robertson et al., 1985; Burge et al., 1987; Harrison et al., 1987; Robertson 1989; Mendell and Smith, 1990). On the other hand ventilation has a significant effect on the energy consumption of buildings. Ventilation and air infiltration account for approximately 40 per cent of the total heat consumption in Finnish residential buildings (Tampere University of Technology, 1985). However, very little is known about the actual magnitude of ventilation in residences.

This technical part of the Finnish Housing Epidemiology Study was carried out in order to obtain information about the actual ventilation and indoor air quality in Finnish residences. The prevalence of the problem of low air-exchange rates was revealed. The objective of the study was to evaluate the differences in the ventilation and indoor air quality between houses and apartments with different ventilation systems.

Methods

A sample of 242 residences in the Helsinki metropolitan area was selected from lists of service companies. The residences represent typical Finnish architecture and construction technology. The sample

Table 1 Characteristics of the 242 residences studied.

	Houses								Apartments								Total	
	Nat. vent.		Mech. exh.		Bal. vent.		Total		Nat. vent.		Mech. exh.		Bal. vent.		Total			
	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%
Total	56		56		43		155		20		46		21		87		242	
Heating system																		
Hot water radiators	47	**84**	39	**70**	8	**19**	94	**61**	9	**45**	46	**100**	21	**100**	76	**87**	170	**70**
Electrical	8	**14**	16	**29**	2	**5**	26	**17**	0	**0**	0	**0**	0	**0**	0	**0**	26	**11**
Floor heating	0	**0**	0	**0**	1	**2**	1	**1**	11	**55**	0	**0**	0	**0**	11	**13**	12	**5**
Radiant ceiling h.	1	**2**	1	**2**	9	**21**	11	**7**	0	**0**	0	**0**	0	**0**	0	**0**	11	**5**
Warm air heating	0	**0**	0	**0**	23	**53**	23	**15**	0	**0**	0	**0**	0	**0**	0	**0**	23	**10**
Year of construction																		
-1960	2	**4**	0	**0**	0	**0**	2	**1**	14	**74**	3	**7**	0	**0**	17	**21**	19	**8**
1961-1975	21	**39**	4	**7**	0	**0**	25	**17**	5	**26**	15	**34**	0	**0**	20	**25**	45	**19**
1976-1980	19	**35**	15	**27**	5	**12**	39	**26**	0	**0**	4	**9**	0	**0**	4	**5**	43	**19**
1981-	12	**22**	36	**65**	37	**88**	85	**56**	0	**0**	22	**50**	17	**100**	39	**49**	124	**54**
Data missing	2		1		1		4		1		2		4		7		11	
Number of occupants																		
1	1	**2**	1	**2**	0	**0**	2	**1**	8	**40**	11	**24**	8	**38**	27	**31**	29	**12**
2	19	**34**	14	**25**	9	**21**	42	**27**	12	**60**	19	**41**	4	**19**	35	**40**	77	**32**
3	13	**23**	16	**29**	13	**30**	42	**27**	0	**0**	6	**13**	1	**5**	7	**8**	49	**20**
4	17	**30**	21	**37**	14	**33**	52	**34**	0	**0**	7	**15**	5	**24**	12	**14**	64	**26**
5-	6	**11**	4	**7**	7	**16**	17	**11**	0	**0**	3	**7**	3	**14**	6	**7**	23	**10**
Floor area (m²)																		
- 60	3	**5**	3	**5**	0	**0**	6	**4**	13	**65**	25	**54**	9	**43**	47	**54**	53	**22**
61- 80	13	**23**	4	**7**	2	**5**	19	**12**	6	**30**	14	**30**	6	**29**	26	**30**	45	**19**
81-100	20	**36**	23	**41**	23	**53**	66	**43**	1	**5**	7	**15**	6	**29**	14	**16**	80	**33**
101-120	12	**21**	12	**21**	11	**26**	35	**23**	0	**0**	0	**0**	0	**0**	0	**0**	35	**14**
121-	8	**14**	14	**25**	7	**16**	29	**19**	0	**0**	0	**0**	0	**0**	0	**0**	29	**12**
Volume/person (m³/p.)																		
-< 50	8	**14**	4	**7**	2	**5**	14	**9**	0	**0**	11	**24**	6	**29**	17	**20**	31	**13**
50-< 70	14	**25**	18	**32**	14	**33**	46	**30**	3	**15**	14	**30**	4	**19**	21	**24**	67	**28**
70-< 90	11	**20**	13	**23**	11	**26**	35	**23**	9	**45**	8	**17**	5	**24**	22	**25**	57	**24**
90-<110	13	**23**	9	**16**	8	**19**	30	**19**	1	**5**	8	**17**	1	**5**	10	**11**	40	**17**
110-	10	**18**	12	**21**	8	**19**	30	**19**	7	**35**	5	**11**	5	**24**	17	**20**	47	**19**

consisted of 155 residences in detached or semi-detached houses and 87 residences in blocks of flats (Table 1). The ventilation systems in these residences were natural ventilation (76 residences), mechanical exhaust (102 residences) and balanced ventilation (mechanical supply and exhaust, 64 residences).

Measurements of the ventilation and indoor air quality were made between November 1988 and April 1989. The measurement period in each dwelling was two weeks. The following measurements were carried out in the dwellings:

- the mean air-exchange rate using an integrating constant tracer flow technique (PFT-technique);
- the temperature and relative humidity;
- the dust deposition and radon concentration.

During the measurements the ventilation system was operated in the normal way and the occupants were allowed to open the windows as usual. After the two-week measurement period the occupants were asked to fill in a questionnaire inquiring into their health and their perception of the indoor air quality. The occurrence of symptoms and the ratings for perceived air quality based on the questionnaire are reported elsewhere (Ruotsalainen et al., 1991).

Measurement Techniques

Total outdoor airflows (m³/h) were measured using an integrating constant tracer flow technique (PFT-technique). The mean air-exchange rate of a dwelling (1/h) was calculated by dividing the total outdoor airflow by the volume of the dwelling (m³). The local air-exchange indicators in the bedroom zone were also calculated, the results being reported by

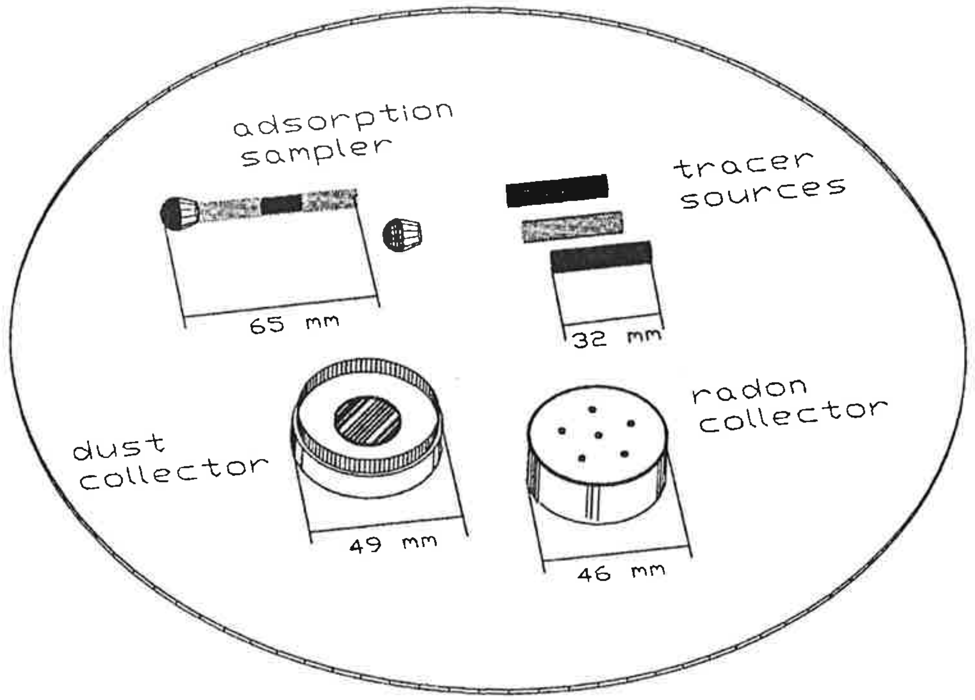

Fig. 1 Field measurement instruments.

Säteri et al. (1991). Miniature permeation tubes were used to create a constant injection of up to three different perfluorocarbon tracer gases. An integrating adsorption sampler measured the average concentration of each tracer (Figure 1). The samplers were analysed in a laboratory using an ECD gaschromatograph. The reliability of the PFT-method is ±20% (Säteri et al., 1989).

The temperature and relative humidity of the indoor air were measured and recorded by the occupants. Calibrated instruments were distributed to the master bedroom of each dwelling. A standard thermometer with a scale from 0 to 40 °C at 1 °C intervals was used. The relative humidity was measured with a hygrometer, scale from 0% to 100% of relative humidity at 1% intervals. The data were recorded twice a day, in the morning and in the evening.

Dust depositions in the dwellings were measured using a deposition method where a sample is collected passively as the airborne dust particles settle on the greasy surface (area 4.9 cm^2) of the collector (Figure 1). This technique measures dust particles of all sizes. The dust collector was placed horizontally in the master bedroom, approximately 1.4 m above the floor. Dust depositions equivalent to 100 hours' exposure were calculated (Kulmala et al., 1986).

Radon concentrations in the dwellings were measured using passive integrating solid state nuclear track detectors (Figure 1). Two detectors were placed in the dwelling, one in the master bedroom and one in the living room (Arvela, 1990).

Statistical Methods

Distributions of air-exchange rates and air quality parameters were compared in houses and apartments with different ventilation systems. Stratified analyses were carried out to assess the effect of different distributions of heating system, year of construction and size of dwellings. The statistical significance of the differences was assessed by using a t-test or Wilcoxon rank sum test (Armitage, 1971).

Results

Ventilation

The air-exchange rates over a two-week period were measured in 242 dwellings. The mean air-exchange rates had a high variation, from 0.07 to 1.55 1/h (ACH), but in the majority of the dwellings (73%) the rates were between 0.2 and 0.7 1/h. The distribution of the rates was within the limits of normal distribution (skewness 1.05, kurtosis 1.42) (Figure 2). The average value for all the dwellings was 0.52 1/h (12 L/s per person) and standard deviation 0.27 1/h. The recommended Finnish value (0.5 1/h) was achieved in less than half of the dwellings (48%).

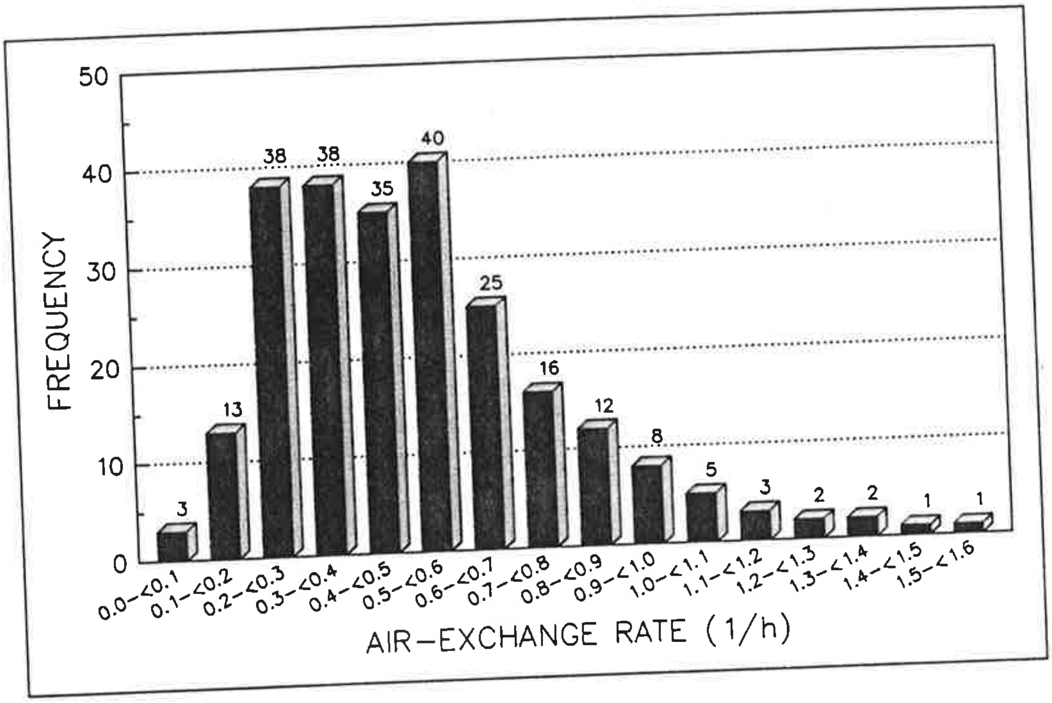

Fig. 2 The distribution of the mean air-exchange rates in the dwellings (n = 242).

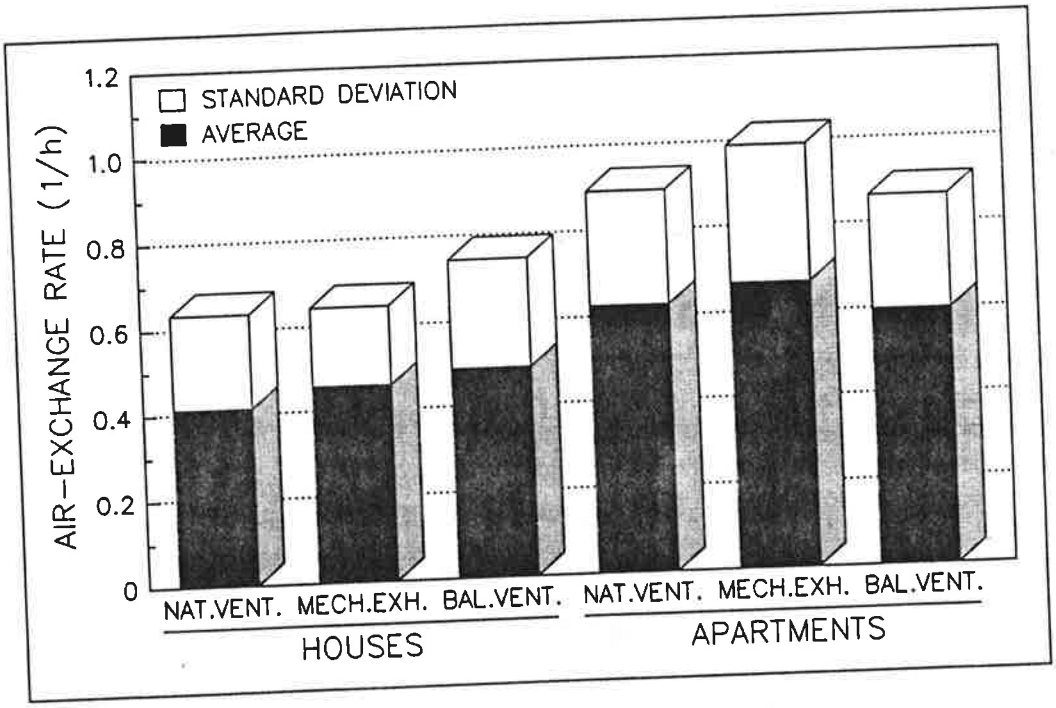

Fig. 3 The average air-exchange rates and standard deviations by building type and ventilation system (n = 242).

The air-exchange rates were on average higher in the apartments (average 0.64 l/h, standard deviation 0.30 l/h) than in the houses (average 0.45 l/h, standard deviation 0.22 l/h) (Figure 3). The difference was statistically significant ($p < 0.001$, unpaired t-test and Wilcoxon rank sum test). Comparison of the different ventilation systems did not reveal any great differences (Figure 3). In houses with natural ventilation (average 0.41 l/h, standard deviation 0.22 l/h) the air-exchange rates were on average slightly but statistically non-significantly lower than in houses with mechanical systems (averages 0.46 and 0.49 l/h, standard deviations 0.19 and 0.26 l/h). Although the lowest air-exchange rates appeared in natural ventilation systems, there were also some quite high air-exchange rates among the natural ventilation systems.

Low air-exchange rates were more common in the houses than in the apartments. ASHRAE's outdoor air requirement for ventilation in dwellings,

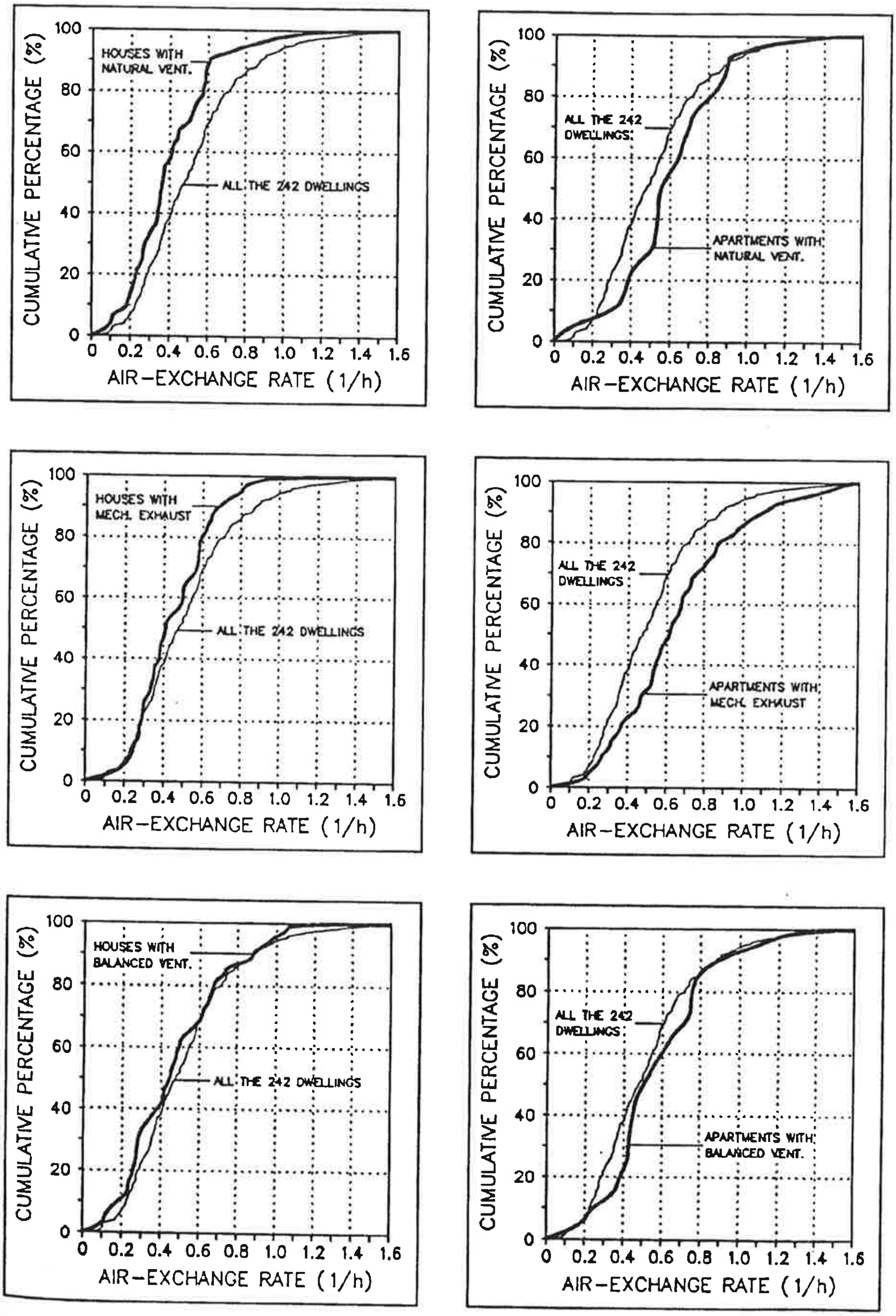

Fig. 4 The cumulative distribution of the air-exchange rates in the houses and apartments with different ventilation systems (n = 242).

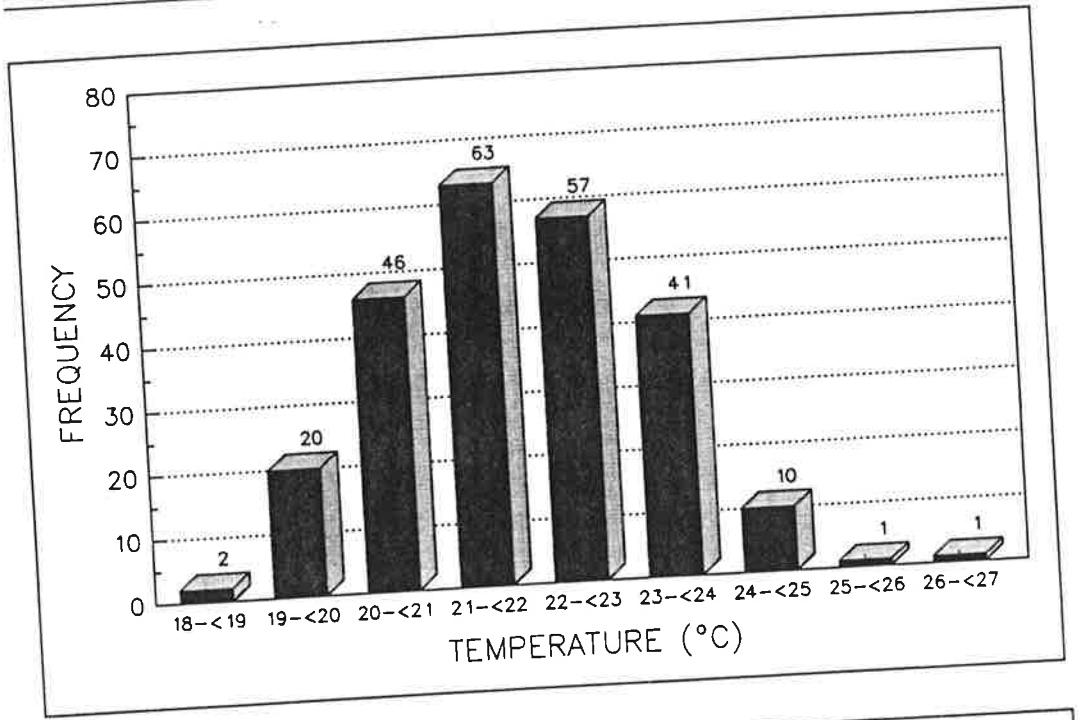

Fig. 5 The distribution of the mean temperatures in the dwellings (n = 241).

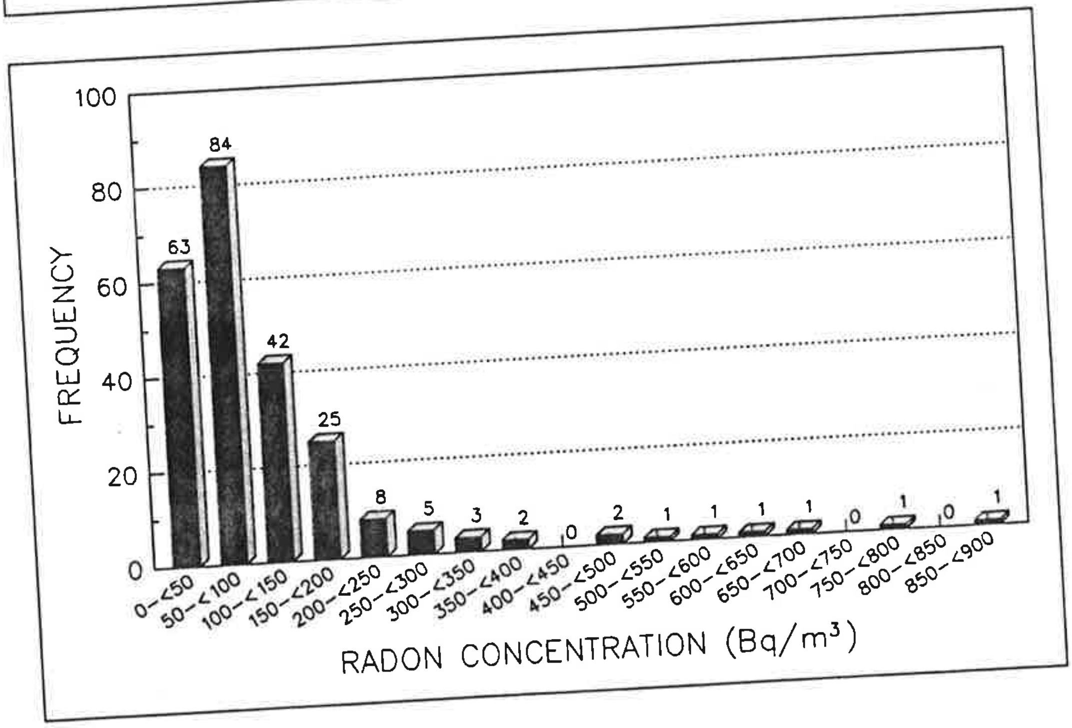

Fig. 6 The distribution of the mean radon concentrations in the dwellings (n = 240).

0.35 l/h (ACH) (ASHRAE, 1989), was not achieved in 36% of the houses and 13% of the apartments. In the houses with natural ventilation the low air-exchange rates were slightly more common (41%) than in the houses with mechanical ventilation (mechanical exhaust 32%, balanced ventilation 35%). In the apartments air-exchange rates below 0.35 l/h were more common with mechanical exhaust (15%, natural and balanced ventilation 10%). The cumulative distributions of the air-exchange rates in the houses and apartments with different ventilation systems are presented in Figure 4.

Temperature and Humidity

The temperature and relative humidity of the bedroom air were measured over a two-week period in 242 dwellings. The mean temperatures, following normal distribution, varied remarkably from 18 to 27 °C and the average was 21.8 °C (standard deviation 1.4 °C). In half the dwellings (50%) the mean temperature was between 21 and 23 °C (Figure 5). On average the temperatures were slightly but statistically significantly higher in the apartments than in the houses (averages 22.2 / 21.7 °C, standard deviations 1.3 / 1.4 °C, $p < 0.01$, unpaired t-test and Wilcoxon rank sum test). The differences were smaller between the different types of ventilation systems.

The mean relative humidities varied from 21% to 65% and the average was 36.7% (standard deviation 7.0%). In over half the dwellings (60%) the mean humidity was between 30% and 40%. Variations between the building types and ventilation systems were small. Observing the results, it must be considered that the study period, winter season 1988-1989, was exceptionally warm and indoor air humidities were strongly weather-induced, thus the indoor humidities were higher than normal; in 37% of the dwellings an air humidifier was used at least occasionally.

Dust Deposition

The dust depositions of the bedroom air were measured over a two-week period in 242 dwellings. The dust depositions varied from 1 to 80 μg/100h and the median was 13.4 μg/100h. The distribution was lognormal. Both in houses and apartments, buildings with natural ventilation had on average lower dust deposition than those with mechanical systems. Buildings with balanced ventilation had the highest dust depositions. The average dust deposition in the apartments with balanced ventilation was statistically significantly higher than in the naturally ventilated apartments (22.2 vs. 13.3 μg/100h, $p < 0.05$, Wilcoxon rank sum test).

Radon Concentration

The radon concentrations were measured over a two-week period in 242 dwellings. The mean radon concentrations varied from 5 to 866 Bq/m^3 and the median was 82 Bq/m^3 (quartiles of 25%: 49 Bq/m^3 and 75%: 130 Bq/m^3) (Figure 6). The Finnish target value of 200 Bq/m^3 was exceeded in 11% of the dwellings. The mean indoor radon concentration in the Helsinki area is lower than the mean level in Finnish dwellings. On average the concentrations were over twice as high in the houses (average 142 Bq/m^3) as in the apartments (average 63 Bq/m^3). The difference was statistically significant ($p < 0.001$, Wilcoxon rank sum test). In the houses with natural ventilation (average 127 Bq/m^3), the concentrations were on average slightly lower than in the houses with mechanical exhaust (average 144 Bq/m^3) or balanced ventilation (average 156 Bq/m^3). These differences can be explained by variations in the radon influx from the ground, the radon diffused from building materials and the operation of the ventilation system. According to the analysis made by the Finnish Centre for Radiation and Nuclear Safety, significant factors affecting the indoor radon concentration were house substructure, building materials and air-exchange rate (Arvela, 1990).

Discussion

The ventilation and indoor air quality were measured in houses and apartments with different types of ventilation systems. The comparison was made in order to find the type of residences with the greatest problems.

The mean air-exchange rates had a high variation, but the average of 0.52 1/h (ACH) was close to the recommended Finnish value of 0.5 1/h. 28% of the dwellings failed to meet the ASHRAE minimum value of 0.35 1/h. There were no significant differences between the different ventilation systems, neither in the houses nor in the apartments, but in the natural ventilation systems the air-exchange rates were on average slightly lower than in the mechanical systems. There were greater differences between the house types; on average the air-exchange rates were significantly lower in the houses than in the apartments. Different heating systems, age and size distributions did not explain the differences. The higher air-exchange rates in the apartments may partly be explained by more frequent airing through the windows. For natural ventilation systems the difference between the building types can be caused by higher stacks in the blocks of flats. For mechanical systems the differences are partly due to irregular use (or misuse) of the ventilation system in the houses. In 46% of the houses with mechanical exhaust the fans were operated only during cooking and bathing. Low ventilation can cause health problems and complaints of poor indoor air quality by increasing indoor pollutants. Among Finnish office workers the occurrence of symptoms of the sick building syndrome was higher in offices with air-exchange rates below 10 L/s per person (Jaakkola et al., 1991). Similar findings have been reported from a large office environment study in Sweden (Sundell et al., 1991). High ventilation increases the energy consumption unnecessarily and can cause draught and low humidity.

The mean temperatures of the bedroom air varied remarkably; the average was approximately 22 °C. The temperatures were on average slightly higher in the apartments than in the houses. A room temperature above 22 °C has been associated with excess symptoms of the sick building syndrome in a Finnish and a British cross-sectional study of office workers (Jaakkola et al., 1989; Hedge et al., 1989).

The average dust deposition of the bedroom air was approximately 17 µg/100h, but the variation was high. The dust depositions were on average highest in buildings with balanced ventilation systems and lowest in buildings with natural ventilation. This may be due to the fact that supply jets induce settled dust from surfaces to the air. No significant correlation was found between the air-exchange rates and the dust depositions. The indoor air concentrations of respirable dust (range 8-24 µg/m³) in 14 Swedish primary schools were associated with the occurrence of eye symptoms among workers (Norbäck et al., 1990).

The median radon concentration was 82 Bq/m³, but in 11% of the dwellings the Finnish target value of 200 Bq/m³ was exceeded. The radon concentrations were on average twice as high in the houses as in the apartments. Several epidemiological studies carried out in Nordic countries have associated an indoor radon exposure of similar magnitude with lung cancer incidence (Axelson et al., 1979; Edling et al., 1982 and 1984; Stranden, 1986; Svensson et al., 1987; Axelson et al., 1988). However, some studies have observed no such association (Castrén et al., 1985; Damber and Larsson, 1987). In a recent Finnish case-control study the results were inconclusive, though they did not refute the hypothesis (Ruosteenoja, 1991). Exposure to indoor radon concentrations of more than 80 Bq/m³ accounted for 13% of the cases of lung cancer (95% CI 1-24%), representing an excess of about 300 lung cancer cases a year in Finland (Ruosteenoja, 1991).

There is a high degree of variation in ventilation rates and indoor air quality in Finnish dwellings. Thus the indoor air in some buildings may cause adverse health effects. The control of ventilation, temperature and humidity are important determinants on which to concentrate.

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