

Window pane condensation and high indoor vapour contribution – markers of an unhealthy indoor climate?

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Summary

Objective The aim of this study was to investigate whether window pane condensation and indoor vapour contribution $\geq 3 \text{ g/m}^3$ could be used as indicators of defective air change rate, high indoor humidity and high mite allergen concentration in mattress dust.

Methods Actual ventilation rate, indoor temperature, air humidity (AIH/RH) and concentrations of mite allergen were measured in 59 houses and compared with received outdoor temperatures and air humidity. Indoor vapour contribution defined as the difference between the indoor and the outdoor vapour concentration was calculated. Sensitivity, specificity, predictive values and accuracy were calculated for window pane condensation and high vapour contribution ($\geq 3 \text{ g/m}^3$), as indicators of defective ventilation ($< 0.5 \text{ ACH}$), high indoor humidity ($\geq 7 \text{ g/kg}$ and $\geq 45\% \text{ RH}$) and high mite allergen concentration in mattress dust ($\geq 2 \mu\text{g/g}$).

Results All houses with high humidity and high mite allergen concentrations were positive for the two indicators (high sensitivity), but with a specificity of only 50% so that half of the houses with reported condensation and high vapour contribution turned out to be low pollution houses with adequate high ventilation levels. Both indicators had high negative predictive values and absence of the two indicators almost certainly (97–100%) excluded high indoor pollution with high humidity and high mite concentrations. Overall more than 70% of the dwellings were correctly classified by the two indicators.

Conclusion Absence of window pane condensation on double-glazed windows and low indoor vapour contribution ($< 3 \text{ g/m}^3$) during the winter are true markers of a dwelling without high indoor air humidity and without high mite allergen concentrations in mattress dust in houses in a cold temperate climate with subzero outdoor temperatures. The presence of the two indicators is associated with a 18–45% risk of high humidity and mite allergen concentrations so in this latter group further measurements are needed for correct classification.

Keywords: air quality, allergens, humidity, indoor, mites, ventilation

Clinical and Experimental Allergy, Vol. 30, pp. 418–425. Submitted 31 December 1998; revised 11 March 1999; accepted 12 July 1999.

Introduction

In several studies a relationship has been found between 'damp buildings' and adverse health effects [1–9]. In general 'damp buildings', besides houses with water

damage, are considered as houses with a reduced defective ventilation. As defective ventilation increases levels of the pollutants produced indoors with, for example, high indoor humidity levels and consequent mite growth, it has been hypothesized that this may promote adverse health effects [10].

Humidity is the most decisive limiting factor for mite growth. Domestic mites are dependent on a high indoor air

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Table 1. Calculated inside surface temperatures on three different window types with three different outdoor air temperatures in winter. From the resulting inside surface temperature it is calculated whether or not water vapour condensation take place with an absolute indoor air humidity of 7.0 g/kg at indoor temperatures of 20 °C and lastly critical dewpoint indoor air relative humidities at indoor temperatures of 20 °C are given

Window type glazes	Outdoor air temperature (°C)	Indoor air temperature (°C)	Heat transmission through window (W/m ² °C)	Inside surface temperature (°C)	Cond at 7.0 g/kg and 20 °C (corr. 48%Rh)	Window dewpoint indoor air relative humidity percentage
Single	0	20	6.5	3.2	Yes	27
Double	0	20	3.2	11.7	Yes/no	55
Triple	0	20	2.1	14.5	No	70
Single	-10	20	6.5	-5.3	Yes	16
Double	-10	20	3.2	7.5	Yes	43
Triple	-10	20	2.1	11.8	Yes/no	55
Single	-20	20	6.5	-13.8	Yes	10
Double	-20	20	3.2	3.4	Yes	33
Triple	-20	20	2.1	9.1	Yes	48

humidity for survival and reproduction and they do not tolerate an absolute indoor air humidity below 7 g/kg air for more than a few months [11,12]. Reduced ventilation in modern, highly insulated and tight houses, but also tight insulation in older buildings, has been considered important factors in raising indoor humidity levels above 7 g/kg in regions with a cold temperate climate, despite a long heating season [1]. In contrast, an adequate ventilation in dwellings in winter will reduce indoor air humidity levels in houses and thereby prevent house dust mite infestation [10]. As such, the evaluation of ventilation and humidity conditions in houses becomes clinically interesting for treating doctors and nurses. For practical and economical reasons, however, it is difficult to estimate the air exchange rate in homes of mite-sensitized individuals in routine clinical settings. Therefore, it is relevant to find markers or indicators to identify hazardous dwellings with reduced ventilation (<0.5 ACH), high indoor humidity (>7 g water/kg dry air) and high mite infestation.

In winter with an outside temperature of 0 °C or below and indoor temperature ~20 °C, the temperature on the interior surface of the building envelope will depend on the insulation capacity of individual components – the lower the insulation capacity the lower the interior surface temperature will occur. Different types of windows with corresponding different thermal insulation capacity will accordingly have different interior surface temperatures – single-glazed windows will reach an interior surface temperature of 3 °C, double-glazed windows likewise an inside surface temperature of 12 °C and lastly triple-glazed windows an inside temperature around 15 °C (Table 1). As such windows in winter act as cold surfaces where water vapour condensation takes place whenever the indoor air humidity

exceeds the point where cooling of indoor air to the level of interior surface temperature increases the relative humidity to 100% (dew-point). Table 1 shows the critical level of indoor air relative humidity above which the dew-point is reached on the three different types of windows. In relation to the critical level of indoor air humidity of 45% RH at 20 °C or absolute humidity of 7 g/kg it is evident that vapour condensation on the inside of double-glazed windows, with below zero outside temperature, imply an indoor air humidity above 45% RH (Table 1). The observation of the family reporting inside window condensation in winter in their home could thus be a valuable clinical indication of reduced ventilation with high humidity and increased exposure to mite allergen and other pollutants predominantly produced indoors. Earlier studies performed in the Stockholm area indicate that window pane condensation might be a sign of a 'damp' indoor environment with reduced air exchange rate just as condensation is a risk factor for mite growth [1,13].

The purpose of this study was to investigate 'owner-reported window pane condensation' and the occurrence of 'indoor water vapour contribution $\geq 3 \text{ g/m}^3$ ' as markers of inadequate air exchange rate (<0.5 ACH), high indoor air humidity ($\geq 7 \text{ g/kg}$) and high concentrations of house dust mite allergen in mattress dust ($\geq 2 \text{ } \mu\text{g/g}$ dust).

Materials and methods

Fifty-nine one-storey single-dwelling houses, within a small residential area outside Stockholm, were included. The houses have been identified in an earlier study [13]. The residential area consisted of 250 houses with similar design, built in two stages between 1968 and 1970. All houses were originally designed for natural ventilation. The first stage

was built with walls of lightweight concrete on crawl space foundations, the second stage consisted of timber-frame houses with facing bricks and concrete slab foundations.

The inclusion criteria were set in the original study as: family size ≥ 2 persons, restoration of ventilation system only, and no allergen avoidance measures undertaken [13]. Habitation by the same family in the house since the original study was also an inclusion criteria. The same mattress/bed that was originally vacuumed in the first study should be present in the house and in use. Fifty-nine of the original 70 houses were included: 20 houses built during stage one and 39 houses from stage two.

The included house owners answered a questionnaire about living habits in the house and details of building construction, which included questions about vapour condensation on the inside of window panes in bedrooms and living rooms in the winter season. The wording of the question on window pane condensation was: 'Does window pane condensation (> 2 cm from bottom) occur on the interior surface of windows in bedrooms and living room during the winter season (heating period)'.

During a 14-day period in late winter the ventilation rate, temperature, indoor air humidity and VOC were measured simultaneously in all houses. Mattress dust was collected for analysis of mite allergen.

Measurement of the air exchange rate (ACH) was performed using a passive tracer gas technique [14].

The temperature was registered continuously in two rooms of each house (living room and one bedroom) with an electronic device (GTM20, Mitec, Säfte, Sweden).

The relative indoor air humidity (RH) was also measured continuously using diffusion sampling tubes with lithium chloride hydrate ($\text{LiCl} \cdot \text{H}_2\text{O}$) as an absorption substance. The absolute indoor air humidity (AIH) was calculated as vapour ratio with a Mollier-diagram, from the recorded temperature and average relative air humidity levels, and expressed in grams per kilogram (g/kg) of dry air. Data on outdoor air temperature and humidity during the study period, were received from the Swedish Meteorological and Hydrological Institute. Furthermore, outdoor as well as indoor water vapour concentration expressed as grams of water per cubic meter of air (g/m^3) were calculated from data on relative humidity and temperature during the period of investigation. The difference between outdoor and indoor vapour concentrations constitute the indoor vapour contribution.

Indoor Volatile Organic Compounds (VOC) were measured using diffusion samplers with Tenax TA as an adsorbent (Chemik Lab AB, Norrtälje, Sweden).

Dust from bedroom mattresses from each home was collected in a standardized fashion by one of the authors using a nozzle attached to the hose of a vacuum cleaner (Volta Lite U1840, Volta, Sweden). Separate filter cassettes

were used for each of the mattresses. Dust samples were analysed for group I allergen concentrations of the house dust mite species (*Dermatophagoides pteronyssinus* [Der p 1], *D. farinae* [Der f 1] and *D. microceras* [Der m 1]) by an enzyme-linked immunosorbent assay (ELISA; ALK, Hørsholm, Denmark) and expressed as micrograms per gram of dust [15]. The detection limit was $0.007 \mu\text{g/g}$ dust.

The technical measurements have previously been described in details [10].

Statistical analysis

Chi-square test was used for statistical analysis. Discussed risk levels or, whenever applicable, stipulate national building codes were used in comparisons between different groups.

To assess to what extent 'owner-reported window pane condensation' and 'indoor water vapour contribution $\geq 3 \text{ g/m}^3$ ' can be used as markers of reduced ventilation (< 0.5 ACH), high indoor air humidity ($\geq 7 \text{ g/kg}$) and high mite allergen concentrations in mattress dust ($\geq 2 \mu\text{g/g}$ dust), sensitivity *, specificity **, predictive values *** and accuracy **** for those parameters were calculated (Appendix 1).

Results

The average outdoor temperature for the period was 3.5°C and the mean relative humidity 66.4%, equivalent to an outdoor vapour concentration of 4.1 g/m^3 and vapour ratio of 3.2 g/kg , respectively. Measured mean indoor temperature for all houses was 20.9°C (min–max 18.5 – 22.4 , median 21.0). At this temperature saturated vapour ratio is 15.6 g/kg (13.3 – 17.1) and saturated vapour concentration 18.3 g/m^3 (15.7 – 19.9). Measured indoor median humidity for all houses during the period was AIH 5.5 g/kg (4.3 – 7.7 , mean 5.7) and RH 36.5% (27.5% [at $21.5^\circ\text{C} \rightarrow \text{AIH } 5.3 \text{ g/kg}$] – 53.5% [at $19.7^\circ\text{C} \rightarrow \text{AIH } 7.5 \text{ g/kg}$]). Mean measured indoor vapour contribution for all houses was 2.8 g/m^3 (1.1 – 5.1 , median 2.6).

In dwellings with reported window pane condensation and/or a measured vapour contribution $\geq 3 \text{ g/m}^3$, ACH was significantly lower and indoor humidity, mite allergen levels as well as TVOC levels significantly higher, when compared with dwellings without the occurrence of these markers (Table 2).

In 36 of the 59 houses the air flow was below 0.5 ACH. In 27 of the 36 houses with an specific air flow < 0.5 ACH window pane condensation was reported, compared with seven of 23 in houses with a specific air flow ≥ 0.5 ACH, $P < 0.001$ (Table 2).

In 21 of the houses with ventilation < 0.5 ACH the vapour contribution exceeded 3 g/m^3 , compared with one

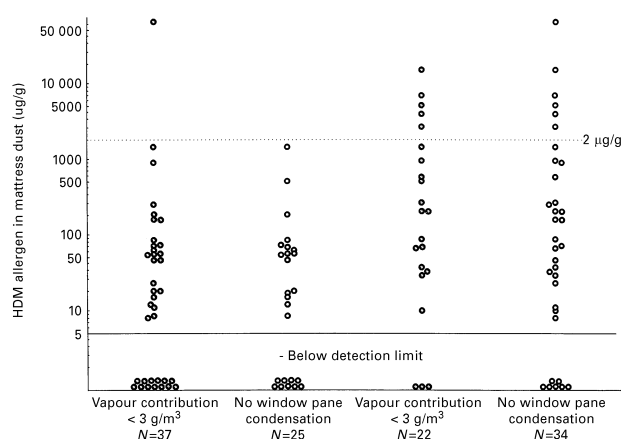
Table 2. *P*-levels for association between different indoor variables

	Total <i>n</i>	Window pane condensation					Indoor vapour contribution $\geq 3 \text{ g/m}^3$				
		<i>n</i>	%	Diff. %	95% CI	<i>P</i> -value	<i>n</i>	%	Diff. %	95% CI	<i>P</i> -value
ACH < 0.5	36	27	75.0	44.6	21.0–68.1	< 0.001	18	50.0	45.6	27.3–64.0	< 0.001
ACH ≥ 0.5	23	7	30.4				1	4.4			
AIH $\geq 7 \text{ g/kg}$	10	10	100	51.0	37.0–65.0	0.003	10	100	62.5	43.1–89.9	< 0.001
AIH < 7 g/kg	49	24	49				9	37.5			
RH $\geq 45\%$	10	10	100	51.0	37.0–65.0	0.003	10	100	62.5	43.1–89.9	< 0.001
RH < 45%	49	24	49				9	37.5			
Vapour contr. $\geq 3 \text{ g/m}^3$	19	18	94.7	54.7	36.5–72.9	< 0.001	–	–	–	–	–
Vapour contr. < 3 g/m ³	40	16	40.7								
Mite allergen $\geq 2 \mu\text{g/g}$	6	6	100	47.2	33.7–60.6	0.027	5	83.3	56.9	24.8–89.0	0.005
Mite allergen < 2 $\mu\text{g/g}$	53	28	52.8				14	26.4			
TVOC $\geq 200 \mu\text{g/m}^3$	34	24	70.6	34.2	8.9–59.5	0.011	16	47.0	33.4	11.4–55.5	0.010
TVOC < 200 $\mu\text{g/m}^3$	22	8	36.4				14	26.4			

out of 23 houses with a specific flow ≥ 0.5 ACH, $P < 0.001$ (Table 2).

Owner-reported window pane condensation was associated with an absolute indoor air humidity (AIH) $\geq 7 \text{ g/m}^3$ as well as a relative humidity (RH) $\geq 45\%$. In 10 of the 34 houses with owner-reported window pane condensation both AIH and RH exceeded $\geq 7 \text{ g/m}^3$ and $\geq 45\%$, respectively, compared with none of the 25 houses without reported condensation, $P = 0.003$ for both parameters (Table 2).

Furthermore, in 10 out of 10 houses with an AIH $\geq 7 \text{ g/m}^3$ ($\approx 45\%$ RH at 21°C) the indoor vapour contribution exceeded $\geq 3 \text{ g/m}^3$, compared with nine out of 40 houses with lower AIH, $P < 0.0001$ (Table 2).

**Fig. 1.** Concentrations of mite allergen in mattress dust in relation to window pane condensation and indoor vapour contribution, respectively

When comparing mite allergen concentrations in mattress dust in houses with and without reported window pane condensation and vapour contribution $\geq 3 \text{ g/m}^3$, respectively, they were also significantly associated. Concentrations of mite allergen in mattress dust $\geq 2 \mu\text{g/g}$ occurred in six of the 34 houses with owner-reported window pane condensation, compared with none of the 25 houses without such condensation ($P = 0.03$). For vapour contribution the corresponding data was one of 37 houses with vapour contribution below 3 g/m^3 , compared with five out of 22 houses exceeding 3 g/m^3 , $P = 0.02$ (Table 2, Fig. 1).

Levels of TVOC were significantly higher in houses with a vapour contribution $< 3 \text{ g/m}^3$, compared with houses with a vapour contribution $\geq 3 \text{ g/m}^3$ (median level $207 \mu\text{g/m}^3$ and $470 \mu\text{g/m}^3$, respectively), $P = 0.010$.

TVOC levels were also higher in dwellings with owner-reported window pane condensation, compared with dwellings without such condensation (median level 178 and $305 \mu\text{g/m}^3$, respectively), $P = 0.011$.

High sensitivity was found for condensation vs ACH, high indoor humidity, vapour contribution and mite infestation as well as for vapour contribution vs indoor humidity and mite allergen (Table 3). High vapour contribution as a marker of reduced ventilation revealed both high specificity and a high positive predictive value (Tables 3 and 4). High negative predictive values were found for condensation vs indoor humidity and mite infestation as well as for indoor vapour contribution vs indoor humidity and mite infestation (Table 4).

There was a marked difference (Table 4) between the positive and negative predictive value for condensation with an average low (30–50%) positive predictive value (except for ACH) and in contrast high (90–100%) values for

	Sensitivity (%)	Specificity (%)	Accuracy (%)
Condensation*/ACH < 0.5	75	70	73
Condensation/AIH $\geq$ 7g/kg	100	51	59
Condensation/RH $\geq$ 45%g	100	51	59
Condensation/Mites† > 2 µg/g	100	47	53
Condensation/Mites† > 0.5 µg/g	83	49	56
Condensation/Mites† > 0.1 µg/g	84	55	64
Condensation/Vapour contribution $\geq$ 3 g/m ³	91	62	73
Vapour contribution $\geq$ 3 g/m ³ /ACH < 0.5	56	91	70
Vapour contribution/AIH $\geq$ 7g/kg	100	76	80
Vapour contribution/RH $\geq$ 45%g	100	76	80
Vapour contribution/Mites† > 2 µg/g	83	68	69
Vapour contribution/Mites† > 0.5 µg/g	75	72	73
Vapour contribution/Mites† > 0.1 µg/g	63	75	71

*Window pane condensation on the interior surface of double-glazed windows. †Concentrations of mite allergen in mattress dust.

negative predictive values. Thus, owner-reported condensation imply a 30–50% risk of increased indoor air humidity and occurrence of mites. In contrast when the owners failed to report condensation during the winter this was a reliable (>90%) sign of low indoor air humidity and absence of mite allergen in mattress dust. The same appears for sensitivity and specificity where (sensitivity) all (100%) owners living in houses with high humidity and high mite allergen concentrations reported window condensation in winter, while

(specificity) only 50% of the owners living in houses with low humidity and low allergen levels failed to report condensation (Table 4).

In total, 73 and 70% of the buildings, respectively, were correctly classified in relation to ACH when the investigated markers were used as indicators of reduced ventilation (Table 3).

When data on indoor vapour contribution from the two study occasions (October and March) were compared, a strong positive correlation was found, $r = 0.80$, $P < 0.0001$ (Fig. 2).

Table 4. Positive and negative predictive values of condensation and indoor vapour contribution ≥ 3 g/m³ as markers for different indoor variables

	Positive predictive value		Negative predictive value	
	<i>n</i>	%	<i>n</i>	%
Condensation*/ACH < 0.5	27/34	80	16/25	64
Condensation/AIH $\geq$ 7g/kg	10/34	29	25/25	100
Condensation/RH $\geq$ 45%g	10/34	30	25/25	100
Condensation/Mites† > 2 µg/g	6/34	18	25/25	100
Condensation/Mites† > 0.5 µg/g	10/34	29	23/25	92
Condensation/Mites† > 0.1 µg/g	16/34	47	22/25	88
Condensation/Vapour contribution ≥ 3 g/m ³	20/34	59	23/25	92
Vapour contribution ≥ 3 g/m ³ /ACH < 0.5	20/22	91	21/37	57
Vapour contribution/AIH $\geq$ 7g/kg	10/22	45	37/37	100
Vapour contribution/RH $\geq$ 45%g	10/22	45	37/37	100
Vapour contribution/Mites† > 2 µg/g	5/22	23	36/37	97
Vapour contribution/Mites† > 0.5 µg/g	9/22	41	34/37	92
Vapour contribution/Mites† > 0.1 µg/g	12/22	55	30/37	81

*Window pane condensation on the interior surface of double-glazed windows. †Concentrations of mite allergen in mattress dust.

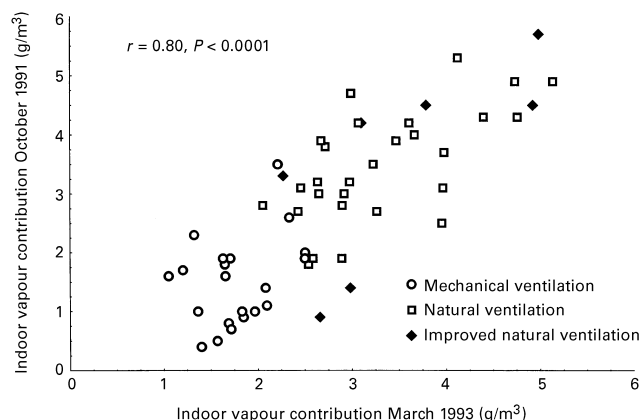


Fig. 2. Correlation between the indoor vapour contribution measured on two occasions, October and March, respectively, in 59 single-dwelling houses outside Stockholm, Sweden

Discussion

This study focused on simple indoor markers as window pane condensation on the inside of double-glazed windows and an indoor water vapour contribution $\geq 3 \text{ g/m}^3$, as indicators of reduced ventilation, increased humidity levels and mite infestation in dwellings.

In general the resulting concentration of a given pollutant in indoor air are determined by three principal factors: rate of production indoors, the volume of distribution in indoor air, and the rate of elimination by exchange of clean outdoor air with polluted indoor air. As such the air exchange rate is only one in three factors determining the resulting concentration of a pollutant. In this study 75% of the houses with a reduced ventilation level below 0.5 ACH had owner-reported window pane condensation while, on the other hand, the failure to report condensation still implied a 25% (9/36) risk of low ventilation levels in the houses. In contrast 100% of the houses with measured high humidity and mite allergen concentrations had owner-reported window pane condensation while, on the other hand, the failure to report condensation implied a 0% risk of both high indoor air humidity (0/10) and high mite allergen concentrations (0/6). As such indoor indicators of the combined effect of pollutant production, dilution and elimination, i.e. indoor air humidity and mite concentrations are superior to individual elements as for example elimination, i.e. actual ventilation levels. This result suggests that definition of minimum ventilation levels would improve if parameters of productions and dilution are included as for example by definition of minimum ventilation as a function of population density in a given house.

In relation to the dynamic parameters of indoor air pollution (water vapour, mites and organic gases) both

condensation and vapour contribution for indoor sources were in all cases significant predictors. There was a marked difference between the positive and negative predictive value of owners report of condensation. In houses where the owners did not report condensation this was a reliable (100%) predictor of low indoor air humidity and concentration of mite allergen below $2 \mu\text{g/g}$. A report of condensation only implied a 20–30% risk of high indoor air humidity and high mite allergen concentrations. This probably reflects that condensation is reported and does take place in homes where the indoor air humidity is low and where the concentration of mite antigen is low. One likely explanation is that the houses all are located in the Stockholm area where outdoor temperatures as low as -20°C occur several days every winter. With an outdoor temperature of -20°C surface temperature on the inside of double-glazed windows is 4°C and condensation will take place with indoor relative humidity as low as 33% (Table 1). The question to residents on window condensation could possibly improve in predictive value by further asking about frequency of condensation on the interior surface of windows.

The results of condensation suggest that in common practice the failure to report condensation on the interior surface of double-glazed windows in winter, is a reliable indicator of low indoor humidity and low occurrence of mite antigen, where almost none are mis-classified. In contrast affirmative answers to questions on condensation imply a 20–30% risk of actual high indoor air pollution with high humidity and mite antigen, which have been shown to be risk factors for asthma and bronchial hyperreactivity by others [1–4]. Where clinically relevant problems exist, this group of patients should be further investigated with, for example, measurement of actual mite exposure or humidity measurements.

It is important to realize that the results on window condensation in winter only apply to geographical areas with average winter outdoor temperatures at or below 0°C simply because no condensation occurs at critical humidities with higher outdoor temperatures. The results thus apply for example to northern and central parts of Europe but not to southern parts of Europe. Likewise the results presume that no condensation on other interior building components takes place as with non- or insufficiently insulated outer walls or roofs, which very rarely occurs in Scandinavia.

According to the Swedish guidelines the vapour contribution in dwellings are suggested to be $< 3 \text{ g/m}^3$ as higher vapour contribution, mostly occur in dwellings as a result of defective ventilation. This relation between ACH and vapour contribution could be confirmed by our study. High vapour contribution also increases the risk of condensation on cold surfaces other than windows, for instance outer wall/basement constructions as well as

condensation in the external wall and roof construction caused by water vapour convection. This in turn may induce water damages in the building, which is another well-established indoor risk factor for adverse health effects which can be prevented [5–9].

Conclusion

The report of no window pane condensation on the interior surface of double-glazed windows in winter and a measurement of a vapour contribution below 3 g/m^3 are both reliable (90–100%) markers of low indoor air humidity and low mite allergen concentrations in mattress dust. When condensation is reported there is a 20–30% risk of high indoor air humidity. Affirmative information of window pane condensation and high vapour contribution in Sweden only implies a 18–45% risk of the occurrence of high levels of indoor pollutants. In this latter group further investigations are needed for correct classification. Furthermore, VOC levels were significantly higher in dwellings with condensation problems, compared with dwellings without condensation. This again indicates houses with a risk of reduced ventilation and consequently a possible increase in the level of all indoor air pollutants whose production is predominantly indoors as VOCs, formaldehyde, CO_2 , particulate matter, tobacco smoke, etc.

The results further suggest that a dynamic definition of minimum ventilation levels in relation to production and dilution factors is superior to a universal static value of 0.5 ACH in all circumstances.

In households with very low production of moisture, absence of condensation and vapour contribution $< 3 \text{ g/m}^3$, might not exclude the risk of a poor ventilation, which may be taken into consideration.

Acknowledgements

We would like to thank Carl Axel Boman and Hans Stymne at the former Swedish Institute for Building Research and Jan Kristensson, Chemik lab AB, Norrtälje, Sweden, for technical assistance.

The work presented in this paper has received economic support from the National Board of Building Research and The Swedish Asthma and Allergy Association.

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Appendix 1. Definitions

$$** \text{ Sensitivity } \% = \frac{\text{True positive} \times 100}{(\text{True positive} + \text{False negative})}$$

$$** \text{ Specificity } \% = \frac{\text{True negative} \times 100}{(\text{True negative} + \text{False positive})}$$

$$*** \text{ Positive predictive value } \% = \frac{\text{True Positive} \times 100}{(\text{True positive} + \text{False positive})}$$

$$\text{Negative predictive value } \% = \frac{\text{True negative} \times 100}{(\text{True negative} + \text{False negative})}$$

$$**** \text{ Accuracy } \% = \frac{(\text{True positive} + \text{True negative}) \times 100}{\text{True positive} + \text{True negative} + \text{False positive} + \text{False negative}}$$