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Indoor temperature and humidity in New York City apartments during winter

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Abstract

Background—Concerns about indoor residential humidity have largely centered on dampness prevention. Overly dry air, however, may favor the survival of some viruses and hence respiratory infections. Many residents employ portable humidifiers to humidify their home environment, yet the effect of these humidifiers on indoor humidity is not known.

Methods—We monitored indoor temperature and humidity in 34 apartments in New York City during winter 2014–2015. We combined information from the monitors with surveyed information on building, household, and apartment-level factors and with information on household humidifier use. Using multilevel regression models, we investigated the role of these factors on indoor absolute humidity levels during the winter.

Results—Mean indoor vapor pressure (a measure of absolute humidity) was 6.7mb in the surveyed homes during the winter season. Ownership of a humidifier was not associated with higher indoor humidity levels; however, larger building size (above 100 units) was significantly associated with lower humidity. The presence of a radiator heating system was non-significantly associated with higher humidity.

Conclusions—The wintertime indoor environment in this sample of New York City apartments is dry. Future research is needed to evaluate the effectiveness of portable humidifiers in the home and to clarify the relationship between dry indoor air and the transmission of viral infections.

Graphical Abstract

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Keywords

Humidity; Housing; Indoor air; Humidifier; Respiratory infection; Influenza

1. Introduction

Many major cities, including New York City (NYC), regulate a minimum level of heat that must be maintained in multifamily residential buildings during the winter months as a matter of public health policy (NYC Department of Housing Preservation and Development). To our knowledge, no policies exist in any major city to regulate levels of humidity in the winter months. Concerns about humidity in the residential environment have tended to focus on the relationship between high humidity/lack of ventilation and the adverse health consequences of mold proliferation (Arena et al. 2010; Baughman and Arens 1996; Krieger and Higgins 2002; World Health Organization 1990), with much less attention being paid to the health effects of an overly dry environment.

A dry environment, however, may promote the survival and transmission of respiratory viral infections such as influenza, which pose a major health risk during the winter season in temperate parts of the world (Thompson et al. 2003). Low humidity has been associated with influenza infections observationally (Hajat et al. 2004; Mäkinen et al. 2009; Mourtzoukou and Falagas 2007) and via experiments in humans (Johnson and Eccles 2005) and in animals (Lowen et al. 2007; Shaman and Kohn 2009). Humidity affects both the rate of inactivation of the virus and the rates of evaporation and settling of aerosol particles containing the virus (Noti et al. 2013; Yang and Marr 2011), and absolute, rather than relative, humidity seems to be the best environmental predictor of influenza survival and transmission (Shaman et al. 2010; Shaman and Kohn 2009; te Beest et al. 2013; Yaari et al. 2013). A longitudinal study of 30 years of data across 359 urban U.S. counties suggests that approximately half of seasonal mortality from influenza could be attributable to variations in absolute humidity (Barreca and Shimshack 2012).

It is thus possible that the environmental conditions created by residential winter heating without supplemental humidification provide a robust environment for respiratory virus survival, and for the transmission of respiratory infections between susceptible hosts. If this theory holds, humidification of indoor air could reduce disease risk: an experiment in a classroom setting has estimated that 1-h influenza virus survival rates could be reduced from a wintertime maximum of 75% at to about 35–45% via humidification (Koepp et al. 2013).

Currently, the amount of measured data about temperature and humidity in the residential environment is very limited (Arena et al. 2010). There are only a few studies that have monitored wintertime temperature and humidity inside homes in the United States (Arena et al. 2010; Nguyen et al. 2013; Tamerius et al. 2013). Particularly, with few exceptions (Myatt et al. 2010) there have been almost no studies that have investigated the effectiveness of attempts to humidify the wintertime residential environment.

Here, we report findings from a study of the temperature and humidity conditions in 34 occupied apartments in New York City over the winter season 2014–2015. The aim of the study is to ascertain the levels of absolute humidity in these homes in the wintertime and to determine the building-level and apartment-level factors that may modify these humidity levels.

2. Methods

2.1. Recruitment and ethical approval

Recruitment for this study was done via email and personal outreach by Columbia's NIEHS Center for Environmental Health in Northern Manhattan and by We ACT for Environmental Justice, an environmental justice organization located in Harlem, NYC. Any household in the boroughs of Manhattan, Brooklyn, and the Bronx was eligible to participate if the head of household was over 18 years of age, the family did not plan to be away from their NYC residence for more than three weeks during the winter, and the main family contact had an active email account. The study protocols and procedures were approved by the Institutional Review Board of Columbia University's Medical Center.

2.2. Indoor temperature and humidity measurements

Indoor temperature and humidity readings were captured using Maxim Integrated DS1923 Hygrochron iButton sensors. These loggers record temperature measurements with an accuracy of ± 0.5 °C within the range of -10 °C– 65 °C, and relative humidity (RH) measurements with an accuracy of 0.6% within the range 0–100%. Two to four iButtons were installed in each participant's home, depending on the size of the residence. At a minimum, one sensor was installed in the home's main living room and another in the main bedroom. The sensors were programmed to log measurements every hour, and were attached to walls or furniture at a height of approximately 1.5 m, away from windows and heating devices and out of direct sunlight. The loggers remained in the residences for approximately 5–6 months, at which time they were removed and the data downloaded. These relatively low-cost data loggers cannot be calibrated by the user, but they were purchased immediately

prior to study initiation and kept in the field for a maximum of 1 year, reducing the likelihood of sensor drift over time.

2.3. Outdoor temperature and humidity measurements

Hourly outdoor temperature and dew point temperature readings were obtained from the National Oceanic and Atmospheric Association (NOAA) for New York City's Central Park weather station, the closest NOAA weather station to the homes in this study.

2.4. Baseline health and housing information

At an initial home visit, data were collected on variables including: number and ages of household members, approximate hours spent at home, respiratory or cardiovascular diagnoses in the household, number of rooms, bedrooms, and windows in the residence, floor level of residence, type of heating system, humidifier ownership, and building size and age.

2.5. Data analysis

The unit we used for our humidity analyses is vapor pressure (VP), a measure of absolute humidity. Hourly VP levels were calculated from recorded indoor temperature and relative humidity conditions using the Clausius-Clayperon equation (Wallace and Hobbs 2006):

$$e_s(T) = 6.11 \times \exp \left\{ 5.42 \times 10^3 \times \left(\frac{1}{273} - \frac{1}{T} \right) \right\}; \quad (1)$$

where $e_s(T)$ is the saturation vapor pressure of water at temperature T in degrees Kelvin.

Vapor pressure was calculated as follows:

$$VP = e_s(T) \times \frac{RH}{100\%} \quad (2)$$

Internal moisture excess refers to the difference between indoor and outdoor humidity (Geving and Holme 2012). We investigated the diurnal patterns of VP by taking the mean of the internal moisture excess by hour of the day.

To test the factors influencing indoor VP, we built multilevel linear regression models with a random intercept to account for the spatial clustering of observations for sensors nested within households. Hourly indoor VP was the dependent variable. Predictors we included in our models a priori were outdoor VP and humidifier ownership. We tested the following building- and household-level factors for inclusion in the models: number of rooms in the home, type of room (bedroom vs. other room), floor of building, building size, year of construction, number of persons in the household, and type of heating system. We retained variables in the final model if they were significant at $p < 0.05$ or if the beta coefficient for a predictor was > 0.3 , as a rough indicator of a “strong” influence on VP. In our final model, only building size and heat type met these criteria and were retained in the model.

Our final models were fit using a three-level random-intercept multilevel regression model, as follows:

$$y_{ijk} = \alpha_{jk[i]} + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} + \varepsilon_i \quad (3)$$

$$\alpha_{jk} = a + b_2 U_{j2} + b_3 U_{k3} + \eta_{jk} \quad (4)$$

Where:

- The outcome variable, y_{ijk} , represents hourly observations of indoor vapor pressure (VP) for hour i in room j within household k .
- The vector X_1 represents a matrix of covariates that vary at the same level as the individual VP observations (Level 1); that is, in time. In this case X_1 represents a matrix of outdoor VP variables: 1-h-lagged and 24-h-lagged outdoor VP.
- The vector X_2 represents a matrix of covariates varying at the location of individual temperature/humidity loggers (the “room” level of the home, Level 2): presence of humidifier, and bedroom versus other room.
- The vector X_3 represents a matrix of covariates that vary at the household level (Level 3): heat type and building size.
- ε_i is the within-household variation not explained by the predictors X_1 , X_2 , and X_3 .
- The intercept, α_{jk} , incorporates error terms U_j and U_k that allow it to vary by room and household.

Lastly, we fit the models with a first-order autocorrelation structure to account for temporal autocorrelation in the time series data.

3. Results

3.1. Study period and overall climate

The winter study season was defined as November 1, 2014–March 30, 2015. Outdoor temperature during this period was on average 2.0 °C, which is 2 °C cooler than the 30-year average of 4.0 °C for temperature recorded at the Central Park weather station between November and March 1981–2010 (Fig. 1).

The indoor monitoring season was defined as the time span within the winter season when active monitoring occurred within at least 80% of the households enrolled; the monitoring season started on November 27, 2014 and ended on March 24, 2015.

3.2. Participating households

34 households participated in the study. An overall description of their characteristics is provided in Table 1. The mean number of individuals per household was 2.3, with mean age

31.2 years. The apartments were all in multistory buildings, with an average height of 14 floors. 88% of the apartments were in buildings with >20 dwellings. Three-quarters of the households rented their homes, and the predominant heating system was radiator heat (62% of the homes), with less common heating systems including forced air heat and electric heat. The majority of the participants could turn their home's heat on and off, but few had thermostats to control the temperature (only 9 homes). Approximately one-third (35%) of the households reported ownership of at least one humidifier.

3.3. Indoor and outdoor temperature and humidity

As can be seen in Fig. 2a, indoor temperature was relatively constant throughout the winter season despite fluctuations in outdoor temperature. The seasonal average temperature indoors was 23.3 °C, with very little variability from month to month (Table 2). The Spearman's correlation coefficient between indoor and outdoor temperature was 0.45. Indoor VP, on the other hand, tracked outdoor VP closely, with a Spearman's correlation coefficient of 0.92 (Fig. 2b). Indoor VP averaged 6.7 mb over the winter season, which was 2.7 mb higher than the outdoor average of 4.0 mb. VP was slightly higher during December and March, and lowest during January and February (Fig. 2 and Table 2).

Heat regulations for New York City housing (NYC Housing Preservation and Development), which cover the winter period only (October–May), require indoor temperature to be at least 68 °F (20 °C) during daytime hours (6:00 am to 10:00 pm) when the outside temperature falls below 55 °F (12.8 °C), and require an indoor nighttime temperature of at least 55 °F when the outside temperature falls below 40 °F (4.4 °C) between 10:00 pm and 6:00 am. In this sample, nighttime indoor temperatures only dropped below these criteria levels 0.2% of the time (range among households: 0–4.4%), while daytime indoor temperatures were below these criteria levels more often (7.3% of the time, range among households: 0–35.8%). This pattern, however, may be indicative of occupancy patterns, as many of the participants were working professionals and were regularly out of their homes during the day. It is possible that the heat was not turned on during some of these daytime hours.

On an hourly basis, outdoor vapor pressure on average reached its peak during the evening hours (approximately 15:00 to 22:00, Fig. 3a and b). As expected by occupancy patterns, indoor vapor pressure was at its highest during the nighttime hours, when the majority of our participants reported they were usually at home (Fig. 3c and d). The highest internal moisture excess levels (the difference between indoor and outdoor vapor pressure) were also observed during the nighttime hours. The diurnal pattern was particularly striking for bedrooms, where we observed the most internal moisture excess between the hours of midnight and 10 am. Other rooms of the residences were also most humid at night; however, there were peaks during the daytime hours as well, which could correspond with behaviors such as bathing and cooking, that add moisture to the environment (Fig. 3c and d).

In initial exploratory bivariate models, the presence of a humidifier in a room was significantly associated with slightly increased humidity (0.24 mb higher in rooms with a humidifier); however, the effect of a room being a bedroom, where people are present at night, was associated with nearly the same increase in humidity (Table 3, Model 2). When both humidifier presence and room type (bedroom vs. other) were included in the same

model (Table 3, Model 3), the effect of being a bedroom was larger than the effect for humidifier presence, suggesting that the type of room was more important to mean nightly humidity levels than the presence of a humidifier (coefficient for bedroom = 0.27 [95% CI: 0.22, 0.31], for humidifier presence = 0.08 [95% CI: 0.01, 0.15]).

To investigate whether this finding could be explained by the possibility that homes with humidifiers started out drier than homes without humidifiers, prompting humidifier acquisition. For this analysis, we examined only those rooms with no humidifiers present, across households that owned humidifiers and those that did not (Table 3, Model 4). We found that ownership of a humidifier was not significantly associated with mean nightly VP in these unhumidified rooms (coefficient for humidifier ownership = 0.15 [95% CI: -0.81, 1.11]).

In our multivariable model results (Fig. 4), we found that humidifier presence was not significantly associated with indoor VP levels (coefficient = 0.06, p -value = 0.2). Larger buildings were significantly drier than smaller buildings (coefficient = -1.3, p -value = 0.003, while a radiator heating system was non-significantly associated with higher humidity levels. The contribution of outdoor humidity levels to indoor humidity levels was slightly positive and significant.

Further analyses that use time-of-day stratification to investigate the influence of interactions between time-use patterning and humidifier ownership can be found in the Supplemental Material, Fig. S1. These analyses largely corroborated our main finding that humidifier ownership was not associated with significant increases in indoor humidity levels.

In Fig. 5 we show the distribution of indoor absolute humidity and temperature by four strata defined by the two building-level factors in our model: building size (small = under 100 units; large = 100 or more units) and heating type (radiator heat vs. electric/forced air/other heat). Small buildings with radiator heat were significantly more humid than all the other building/heat combinations. Large buildings with radiator heating systems were significantly warmer than other building/heat combinations.

4. Discussion

This study demonstrates that in this sample of 34 New York City apartments, there is relatively good management of indoor temperature during winter, but an absence of such management for indoor humidity. We demonstrated a strong correlation between indoor and outdoor absolute humidity during the winter season, as has been reported previously (Nguyen et al. 2013; Tamerius et al. 2013). We found, as well, that indoor wintertime environments are consistently about 2.8 mb (2.1 g/m³) more humid than the corresponding outdoor environment. This figure is fairly consistent with existing reports of internal moisture excess in countries with cold winters: for example 2.1 g/m³ in Norwegian living rooms, 2.9 g/m³ in multifamily houses in Sweden, and 3.3 g/m³ in historic wooden apartment buildings in Estonia (Arumägi et al. 2015; Geving and Holme 2012). We also found that occupancy impacted the diurnal cycle of indoor humidity, with bedrooms more

humid during nighttime hours. This is presumably due to the contribution of human respiration and perspiration (Geving and Holme 2012).

The mean wintertime indoor humidity level in this set of homes was 6.7 mb. This was slightly drier than the wintertime indoor VP observed in a previous study of detached single-family homes in the “cold northeast” region of the US, where December to March indoor VP averaged 8.1 mb, (Arena et al. 2010). On average, humidity in the apartments in this study remained at levels below 10mb for over three months during the winter, below 5 mb for almost a month, and reached very low levels (below 3mb) for about 7 days during the winter. We found that homes in larger buildings (containing over 100 apartments) were significantly drier than homes in smaller buildings, and observed that homes with radiator heat were more humid than homes with other types of heat, although this association did not reach statistical significance.

Our hypothesis that humidifier presence would be associated with higher levels of indoor humidity was not supported by the data. This finding was in contrast to a few prior studies that have suggested that room humidification is effective at increasing absolute humidity levels in indoor environments. For example, a modeling exercise based on a two-story home in the Boston area suggested that a single humidifier turned on overnight in a bedroom could increase indoor VP from a baseline level of 7.5 mb to 10.4 mb (radiant heat model) or from 8.2 mb to 9.4mb (forced air heat model), corresponding to an estimated influenza virus survival decrease of 17.5–31.6% in the room with the humidifier operating (Myatt et al. 2010). Further, an experiment in a Minnesota grade-school environment found that commercially available home humidification equipment was effective in raising the levels of humidity in classrooms, and could potentially reduce 1-h influenza virus survival rates from a maximum of 75% at low levels of humidity to about 35–45% using humidification (Koep et al. 2013).

A lingering question presented by the current study, then, concerns why we did not see a significant effect of humidifier ownership on indoor absolute humidity levels during the winter. There are several possible explanations for this finding. First, as we only had data on humidifier ownership and presence in the home but not on actual humidifier use, it is possible that the residents were not actually using their humidifiers, or using them infrequently. Second, we did not have information on the size or capacity of the humidifiers, and it is possible that their moisture generation capability was smaller than in the models used in prior experiments. It is also possible that the effect of the humidifiers was extremely localized (e.g. humidifying the air in a small region near a bed) and did not sufficiently mix into the air to make a difference in the levels of humidity being recorded by the stationary monitors. Further, we did not collect data on other household behaviors that add moisture to the environment, such as cooking, bathing, and breathing. The effect of these moisture-generating activities might have diluted the humidity signal provided by the humidifiers. Lastly, because this was an observational study, it is possible that those households who report owning humidifiers are those whose indoor air tended to be drier. We tried to examine this hypothesis by comparing the humidity in rooms with no humidifiers (across households that reported owning humidifiers and those that did not), and did not find any significant difference in humidity in the non-humidified rooms.

Previous studies have demonstrated the effectiveness of commercially available humidifiers on humidity levels under experimental conditions. What emerges from this study, however, is the observation that ownership of humidifiers under non-experimental conditions (i.e., under conditions of normal residential behavior) is not associated with increased moisture levels in homes. As home humidification is an intervention that is relatively simple and accessible to most households, this finding warrants further research into the optimal operation of humidifiers in occupied households.

5. Conclusions

Wintertime indoor conditions in this sample of New York City apartments are dry, with levels of absolute humidity that have been seen to correlate with increased influenza virus survival in laboratory experiments. In this study, humidifier ownership was not associated with increased levels of indoor humidity. Future research is needed to clarify the potential association of excessive indoor dryness with transmission of respiratory infections, and to evaluate the effectiveness of humidifiers in the residential environment.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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HIGHLIGHTS

- Wintertime air in New York City apartments is very dry.
- Levels of humidity seen here are consistent with increased influenza virus survival.
- Humidifier ownership was not associated with increased indoor humidity.
- Additional research is required to determine how humidifiers can be used effectively.

Winter 2014–2015 Outdoor Temperatures at Central Park Station, New York

Fig. 1.
Outdoor climate 2014–2015 compared to 30-year average.

Fig. 2.
Indoor and outdoor temperature and humidity, winter 2014–2015.

Fig. 3.
a) Mean indoor and outdoor vapor pressure by hour of day, bedrooms. b) same as a, for non-bedrooms. c) internal moisture excess (indoor VP – outdoor VP) by hour of day, bedrooms. d) same as c, for non-bedrooms.

Fig. 4. Forest plot of the beta coefficients (in mb) and 95% confidence intervals from linear regression models of indoor VP during winter 2014–2015. Covariates are presence of humidifier in room (humidifier), radiator heating system vs other heating system (radiator heat), large vs small building size, bedroom vs. other room, one-hour-lagged outdoor VP, and 24-h-lagged outdoor VP. Green diamonds: statistically significant at $p < 0.05$. Black lines: 95% confidence interval for the coefficient. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

* p -value < 0.05 from a bivariate multilevel regression model of VP or temperature predicted by stratum of building size/heating type.

Fig. 5. Distribution of wintertime hourly indoor VP and temperature by building size and heating type. * p -value < 0.05 from a bivariate multilevel regression model of VP or temperature predicted by stratum of building size/heating type.

Table 1

Descriptive characteristics of 34 households.

	Mean (range)
Total household members	2.3 (1–5)
Age of household members	31.2 (2–90)
Rooms in home	3.7 (1–9)
Bedrooms in home	1.9 (1–4)
Floors in building	14.2 (3–34)
Year of construction	1945 (1870–2012)
	Count (percent)
Rent vs. own	
Rent	26 (76%)
Own	8 (24%)
Units in building	
2–4	3 (9%)
10–19	1 (3%)
20–99	15 (44%)
100+	15 (44%)
Heat type	
Radiators	21 (62%)
Forced air	7 (21%)
Electric	5 (15%)
Other	1 (3%)
Can turn heat on and off	
Yes	24 (71%)
No	10 (29%)
Have a thermostat	
Yes	9 (26%)
No	25 (74%)
Own humidifier(s)	
Yes	12 (35%)
No	20 (59%)
NA	2 (6%)

Table 2

Mean [SD] monthly indoor and outdoor temperature and VP.

	Temperature (°C)		Vapor pressure (mb)	
	Indoor	Outdoor	Indoor	Outdoor
December	23.2 [2.8]	4.6 [3.8]	8.6 [2.4]	5.7 [2.4]
January	23.0 [3.4]	−1.1 [4.7]	6.2 [2.2]	3.3 [1.9]
February	23.1 [3.1]	−4.3 [4.8]	5.3 [2.0]	2.6 [1.4]
March	23.5 [2.7]	2.8 [5.0]	6.5 [2.1]	4.1 [2.3]
Winter overall	23.3 [3.1]	0.6 [5.7]	6.7 [2.5]	4.0 [2.4]

Table 3

Results of multilevel regression models for the effect of having a humidifier on winter nightly mean vapor pressure ($n = 79$ rooms in 34 homes; 14 rooms in 12 homes had humidifiers).

Model	Data	Predictor(s)	Coefficient for effect of predictor on nightly mean vapor pressure (mb) [95% CI]
1	All rooms	Room_has_humidifier: TRUE	0.24 [0.17, 0.31] ***
2	All rooms	Is_bedroom	0.21 [0.17, 0.25] ***
3	All rooms	Is_bedroom	0.27 [0.22, 0.31] ***
		Room_has_humidifier: TRUE	0.08 [0.01, 0.15] *
4	Only rooms with no humidifiers	Home_has_humidifier: TRUE	0.15 [−0.81, 1.11]