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Higher measured moisture in California homes with qualitative evidence of dampness

Abstract Relationships between measured moisture and qualitative dampness indicators (mold odor, visible mold, visible water damage, or peeling paint) were evaluated using data collected from California homes in a prospective birth cohort study when the infants were 6 or 12 months of age (737 home visits). For repeated visits, agreement between observation of the presence/absence of each qualitative indicator at both visits was high (71–87%, $P < 0.0001$). Among individual indicators, musty odor and visible mold were most strongly correlated with elevated moisture readings. Measured moisture differed significantly between repeated visits in opposite seasons ($P < 0.0001$), and dampness increased with the number of indicators in a home. Linear mixed-effect models showed that 10-unit increases in maximum measured moisture were associated with the presence of 0.5 additional dampness indicators ($P < 0.001$). Bedroom (BR) walls were damper than living room (LR) walls in the same homes ($P < 0.0001$), although both average and maximum readings were positively correlated across room type ($r = 0.75$ and 0.67 , respectively, both $P < 0.0001$). Exterior walls were significantly damper than interior walls ($P < 0.0001$ in both LRs and BRs), but no differences were observed between maximum wall readings and measurements at either window corners or sites of suspected dampness.

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Key words: Measured moisture; Dampness; Dampness indicators; Moisture location; Mold odor; Visible mold.

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Practical Implications

The more indicators of dampness or mold present in a home (especially musty odor and visible mold), the damper the walls were likely to be. In our study, the consistency of dampness indicators over time suggests that one-time, qualitative assessments of dampness and mold have value in identifying moisture problems. However, the seasonal variation seen in measured wall moisture suggests that quantitative measurements repeated at different times of year may be necessary to identify transient moisture problems. Therefore, moisture measurements may be most informative when assessed along with dampness indicators, some of which consistently have been associated with increased risks of respiratory disease, for example, mold odor, visible mold, and water damage.

Introduction

Qualitative and quantitative dampness indicators and health

Many epidemiological studies have shown consistent associations between respiratory or allergic outcomes and *qualitative* indicators of indoor dampness or fungal growth, for example, water damage, dampness, visible mold, or mold odor (Mendell et al., 2011; Quansah et al., 2012; WHO, 2009). However, the evidence linking health effects with *quantitatively* measured microbial factors, such as concentrations of bacteria,

fungi, or marker compounds, is equivocal, with only suggestive and often inconsistent associations between health effects and specific agents (Behbod et al., 2015; Dannemiller et al., 2014; Mendell et al., 2011; Sharpe et al., 2015). Thus, the specific dampness-related factors that cause health effects have not yet have been sufficiently characterized. In considering health risks related to dampness or mold in buildings, the World Health Organization defined dampness as 'any visible, measurable or perceived outcome of excess moisture that causes problems in buildings, such as mould, leaks

or material degradation, mould odor or directly measured excess moisture [in terms of relative humidity or moisture content (MC)] or microbial growth' (WHO, 2009). Because moisture is the limiting factor determining the ability of fungi to grow in buildings, the WHO concluded that 'the health risks of biological contaminants of indoor air could thus be addressed by considering *dampness* as the risk indicator' (WHO, 2009), emphasis added. Therefore, objective, quantitative assessments of building dampness, such as measured moisture, may be useful additions to the qualitative dampness indicators used to date in many epidemiologic studies to assess moisture-related health risks.

One objective measurement of dampness is MC, a measurement of the amount of water in a building material, usually expressed as a percentage of the mass of an oven-dried material. Moisture content can be measured in the field with electrical resistance moisture meters, which are designed to measure the MC of wood. When used on other materials, the unit of measurement for a moisture meter is 'percentage wood moisture equivalent' (%WME), the theoretical percentage MC that a piece of wood would attain when in moisture equilibrium with the measured material.

While the measured dampness of building materials is often used to identify water damage to guide remediation (Haverinen-Shaughnessy et al., 2008; NIOSH, 2012), quantitative moisture assessments have been used less often than subjective assessments in epidemiological studies. To our knowledge, only two studies have assessed the relationships between health effects and home dampness as quantified with moisture meters (Mendell et al., 2014). These studies, both in the UK and using different versions of the same two-pin, conductance moisture meter, reported statistically significant, dose-related increases in health effects with increasing residential dampness. Williamson et al. (1997) found associations with asthma severity and predicted FEV₁ in 102 patients with diagnosed asthma and 196 controls aged 5–44 years; and Venn et al. (2003) found associations with daytime wheeze, nighttime wheeze, and persistent wheeze in 193 children with persistent wheezing illness and 223 controls aged 9–11 years. Williamson et al. (1997) used moisture readings of 17 and 20 %WME as cutpoints to identify homes with any and severe dampness, respectively; and Venn et al. (2003) used 10, 15, and 20 %WME as cutpoints for low, medium, and high dampness, respectively. Both studies also examined the association of qualitative dampness indicators with health but did not compare the qualitative evidence with their quantitative moisture measurements.

In this study, we analyzed relationships between qualitative and quantitative assessments of home dampness in the Center for the Health Assessment of Mothers and Children of Salinas (CHAMACOS), a birth cohort study of low-income, predominantly Mexican-immigrant

families residing in the Salinas Valley, an agricultural region in Monterey County, California. CHAMACOS is a Community–University partnership studying pesticide and allergen exposures to pregnant women and their children and the potential effects of these exposures on growth, neurodevelopment, and respiratory disease (Eskenazi et al., 2003). Moisture measurements and observations of dampness indicators were made to categorically classify the dampness of residences to study potential risks of respiratory disease in infants.

This study extends an earlier description of the housing quality of the CHAMACOS population (Bradman et al., 2005) as well as prior analyses of associations of qualitative dampness indicators with indoor air concentrations of fungal spores (Chang et al., 2012) and relationships between the fungal microbiome in house dust and the development of childhood asthma (Dannemiller et al., 2014). The current paper was motivated by research linking health with qualitative (Mendell et al., 2011; Quansah et al., 2012; WHO, 2009) as well as quantitative dampness indicators (Venn et al., 2003; Williamson et al., 1997). We hypothesized that measured moisture would be higher in homes with indicators of dampness and that measured moisture would increase with the number of indicators present; that perimeter walls would be damper than interior walls; that walls next to rooms with plumbing would be damper than other interior walls; and that readings at window corners or sites of suspected dampness would be higher than readings at prescribed wall locations.

Materials and methods

Home visits and moisture meter measurements

Inspectors, trained by the Monterey County Health Department, inspected homes during 737 home visits (HVs) conducted approximately 6 or 12 months after a child's birth (376 and 361 HVs, respectively; September 2000 to December 2002) (Bradman et al., 2005). One of two teams, each composed of a male and a female inspector, conducted both HVs. Moisture measurements were made with a pinless, dielectric moisture meter (Model CT100; Electrophysics, Dutton, ON, Canada; calibrated reading range: 0–30; 1% accuracy; 2.5-cm sensing depth; 4 × 5-cm sensor pad). The density dial on the meter was set to 0.5, the manufacturer's recommendation for gypsum wallboard, the most common interior finish for residential and commercial walls and ceilings (Greenwell and Menetrez, 2008). The manufacturer calibrated the meter at 20°C with Douglas fir, which has a density of ~0.5 g/cm³ when dried to a MC of 12% (Lachenbruch et al., 2010).

The male inspector of each HV team systematically conducted moisture measurements in the main living area (living room, LR) and the child's sleeping area (bedroom, BR) in the following order until three

measurements were taken for each room: first, on all perimeter (exterior) walls that faced the outdoors; second, on all inside (interior) walls next to bathrooms, kitchens, or laundry rooms; and third, if necessary, on interior walls next to BRs, LRs, or dining rooms (Lowenthal et al., 2002). These ‘systematic’ measurements were made 45–60 cm above the floor at the horizontal midpoint of a wall (Bradman et al., 2005). If a desired location was blocked by furniture, the measurement was taken as close as possible to the prescribed location. Wall measurements were not made if a home did not have a common living area, the inspectors were not allowed into a LR or BR, or the meter did not operate correctly. The inspector took up to three additional ‘targeted’ measurements in each room at sites of suspected dampness, that is, areas with a musty odor or visible water damage, mold, or condensation. The suspected sites were recorded as exterior walls, interior walls, floors, or other. At the 12-month HV, an additional systematic wall measurement was made at the lower corner of a window in each room (next to the window frame or 5 cm from the corner if frameless).

Dampness indicators

The female inspector of each HV team obtained descriptive information from a parent or other occupant and also conducted an independent visual examination noting qualitative indications of dampness throughout the home. For training on the first 10 HVs for each team, a supervisor made a duplicate walk-through, compared findings with those of the HV inspector, and resolved any discrepancies. Thereafter, a comparison was made for every 10th HV. For these analyses, each qualitative indicator (visible mold, visible water damage, musty odor, interior peeling paint, interior rotting wood, and leak under the kitchen sink) was coded as present or absent at each HV. We defined mold as present if there was moderate to extensive visible mold (i.e., growth visible, but covering $<1 \text{ m}^2$ of wall area, to growth covering $\geq 1 \text{ m}^2$ or very thick in several places, respectively) and as absent if there was none or only minimal mold (i.e., no visible mold or mold only in crevices or covering small areas, respectively). The inspectors recorded mold in the bathroom, LR, mother’s sleeping area, child’s sleeping area, and elsewhere in the house; for the purpose of these analyses, the most extensive mold growth in any room other than a bathroom was used to represent the level of visible mold in the home. The other indicators applied to kitchens (sink leak) or all occupied areas of the participants’ homes (water damage, musty odor, peeling paint, and rotting wood).

Data analysis

Average and maximum moisture readings for multiple measurements were calculated to characterize home

dampness (ASTM D7438-13, 2013): room-specific averages and maxima of the systematic wall measurements; the wall maximum for a home; room-specific averages and maxima for targeted measurements at sites of suspected dampness; and the overall maximum for each home, which included the systematic wall and window readings as well as the targeted measurements at sites of suspected dampness. Geometric means (GM) and standard deviations (GSD) of moisture readings were reported because the data were closer to log-normally than normally distributed and the moisture meter scale may not have been linear (ASTM D7438-13, 2013). The qualitative dampness indicators were evaluated individually for their associations with measured moisture; and for indicators that were consistently associated with higher measured moisture, their associations with dampness also were evaluated in combination. Only HVs with complete data at prescribed wall locations (i.e., three systematic measurements in both the LR and the BR) were considered for the comparisons of moisture levels in the two rooms and of homes with different numbers of dampness indicators.

We used nonparametric tests of significance because the moisture readings were not normally distributed. Sample correlation coefficients (Pearson’s product-moment correlation coefficient, r) and two-sided Wilcoxon signed-rank tests were used to compare paired moisture readings, that is, measurements at the 6- and 12-month HVs, measurements in LR and BRs in the same homes, as well as measurements at prescribed wall locations and sites of suspected dampness or the corners of windows in the same rooms. Two-sided Mann–Whitney U -tests were used for other comparisons, that is, measurements in homes with and without qualitative dampness indicators, measurements on exterior and interior walls, and measurements made for different reasons for suspecting dampness. Finally, we used generalized linear mixed-effects models to determine how strongly maximum measured wall moisture was associated with the number of indicators present, combining 6- and 12-month HV data, in separate models for the two rooms. The dependent variable in the models was the number of dampness indicators, and the independent variable was measured moisture (%WME). We did not adjust for other covariates in the models. Moisture readings were analyzed as a continuous variable and also were dichotomized at the approximate median of 11 %WME.

Results

CHAMACOS housing stock

Nearly all participants were renters (Bradman et al., 2005). For 643 homes inspected at a pre-natal or 6-month HV, 45% were multi-unit apartment buildings (three or more apartments), 43% were detached

homes, 7% were other (e.g., a garage or trailer), and 5% were duplexes (two adjacent apartments) (Bradman et al., 2005). Some apartments were in non-profit or low-income housing developments, and single-family houses were often shared. The homes were estimated to be 20–40 years old, but the exact age of the homes was not determined. In 2000, 56% of the overall Salinas housing stock was in this age range (many of these residences were built to house workers after closure of farm labor camps when growers stopped providing housing near their fields), 10% was older, and 34% was newer (City of Salinas, 2015). The homes were predominantly wood frame with stucco exteriors. An estimated $\geq 95\%$ of the interior finish material in the CHAMACOS homes was 1.3-cm gypsum wall-board, but the presence of wall insulation was not determined.

Distributions of moisture readings in LR and BRs

Approximately three-quarters of the 12-month HVs were in the same homes as the 6-month HVs. However, moisture readings for the two HVs differed significantly ($P < 0.0001$), for both those who had and those who had not moved, likely because the measurements were made in different seasons. The 5171 moisture readings had a skewed distribution with a mode at 10 %WME and few wall readings exceeded 30 %WME (Figure 1). In homes with three wall measurements at prescribed locations in both LR and BRs, both average and maximum readings were highly correlated across rooms (Table 1). However, BR wall readings were significantly higher than LR readings (Table 1).

Comparison of qualitative indicators of dampness

Agreement rates for the presence or absence of the dampness indicators at both HVs were similar for families that had not and those that had moved, but were consistently higher if determined in the same homes (agreement rate: 86% and 82% for musty odor, 71% and 57% for mold, 74% and 70% for water damage, 79% and 65% for peeling paint, 87% and 80% for rotting wood, and 84% and 75% for leaks, respectively). The most common qualitative indicators of dampness were peeling paint and visible mold, which were seen in 68% and 42% of HVs, respectively. Less common were water damage (21%), a leaking kitchen sink (14%), a musty odor (11%), or rotting wood (9%). Homes were consistently damper in both rooms if a musty odor, visible water damage, visible mold, or peeling paint was present ($P \leq 0.05$; Table 2).

Considering the four qualitative dampness indicators that were consistently associated with higher measured moisture in both LR and BRs (i.e., musty odor, visible mold, visible water damage, and peeling paint;

Fig. 1 Frequency distributions of systematic moisture meter readings at prescribed wall locations in two rooms

Table 1 Comparisons of the averages and maxima of three systematic moisture measurements at prescribed wall locations in the BR and LR of the same residences (restricted to the 621 home visits with three measurements in both rooms)

BR vs. LR	Average moisture readings (%WME)	Maximum moisture readings (%WME)
GM (GSD)	12.4 (1.3) vs. 11.7 (1.3)	14.1 (1.4) vs. 12.9 (1.4)
Ratio of GMs, (BR GM)/(LR GM)	1.06	1.09
Wilcoxon signed-rank test	$P < 0.0001$	$P < 0.0001$
Correlation (<i>r</i>)	0.75, $P < 0.0001$	0.67, $P < 0.0001$

P-values in bold statistically significant ($P < 0.05$).

GM, geometric means; GSD, geometric standard deviation; LR, living room; BR, bedroom.

Table 2), the more indicators observed in a home, the higher the maximum wall moisture reading (Figure 2; see Figure S1 for the averages of the three wall readings per room). The inspectors observed no qualitative dampness indicators in 112 (15%) of the HVs. All four indicators were observed in only 2% of the HVs, but these were among the dampest homes (overall GM: 21.0 %WME) and were similar to homes with the combination of visible mold and water damage (overall GM: 21.3 %WME) or the combination of musty odor, visible mold, and peeling paint (overall GM: 20.8 %WME) (Table S2). A musty odor as the only indicator was infrequent (<1% of 330 HVs with only one indicator); however, homes with musty odors were the dampest among homes with single indicators (overall GM: 18.0 %WME) followed by those with visible mold (overall GM: 15.8 %WME) (Table S2). Moisture levels in homes with two indicators (overall GM: 17.1–21.3 %WME) and three indicators (overall

Table 2 Comparisons of maximum systematic living room (LR) and bedroom (BR) moisture readings at prescribed wall locations in homes with qualitative indicators of dampness [see Table S1 for comparisons of average readings and the geometric standard deviations of all all geometric means (GMs)]

Indicator	Maximum LR moisture readings (%WME) (<i>N</i> = 653 home visits)				Maximum BR moisture readings (%WME) (<i>N</i> = 714 home visits)			
	GM indicator present	GM indicator absent	Ratio of GMs ^a	<i>P</i> -value ^b	GM indicator present	GM indicator absent	Ratio of GMs ^a	<i>P</i> -value ^b
Musty odor	14.9	12.7	1.17	0.02	17.0	13.8	1.23	0.0001
Visible mold	14.0	12.2	1.15	0.0002	15.7	13.1	1.20	<0.0001
Rotting wood	14.9	12.7	1.17	0.04	15.9	13.9	1.14	0.08
Water damage	14.3	12.6	1.13	0.002	15.3	13.8	1.11	0.05
Peeling paint	13.4	12.1	1.11	0.002	14.4	13.4	1.07	0.003
Kitchen leak	13.2	12.9	1.02	0.11	14.6	14.0	1.04	0.08

P-values in bold statistically significant ($P < 0.05$).

^aRatio = (GM if indicator present)/(GM if indicator absent).

^bMann–Whitney *U*-test.

Fig. 2 Maximum moisture meter readings at prescribed wall locations by number of qualitative dampness indicators (i.e., musty odor, visible mold, visible water damage, or peeling paint); the percentages at the top of the figure are the respective increases relative to the same room type in homes with no indicators; *N* = number of home visits

GM: 17.6–20.8 %WME) were approximately similar for all combinations except that of peeling paint and water damage (overall GM: 15.6 %WME).

Using mixed-effects models with combined data from the 6- and 12-month HVs, separately for LR and BR data, we found that maximum LR and maximum BR moisture readings, as continuous variables, were both associated with a significant increase in the number of dampness indicators observed in a home ($P < 0.001$). Each 10-unit increase in measured moisture in either location was associated with an increase

of approximately 0.5 dampness indicators. Maximum LR and BR moisture each explained approximately 10% of the overall variance, and if included in a single model together explained approximately 13%. From the models with dichotomized moisture readings, a high LR reading (>11 %WME) was associated with an increase of approximately 0.4 dampness indicators ($P < 0.0001$) and explained approximately 6% of the overall variance, but high BR readings were associated with a smaller increase, not statistically significant.

Comparison of interior and exterior walls

The only interior walls next to plumbing on which moisture measurements were made were adjacent to bathrooms (interior/bath). Exterior walls were significantly damper than both interior walls and interior/bath walls, but no differences were observed between readings on interior and interior/bath walls (Figure 3; see Table S3 for ratios and GSDs). A total of 455 targeted moisture measurements were made at sites of suspected dampness during 321 (44%) of the HVs. Unlike the systematic wall measurements, these typically were single measurements per room. Almost all sites of suspected dampness were on exterior walls (LRs and BRs: 91% and 83%, respectively) (Table S4), and none were on walls next to bathrooms, kitchens, or laundry rooms. Only 6% and 11% of suspected sites were on interior walls in LR and BRs, respectively; 2% and 6% were at other, unspecified, sites, respectively; and 1% and 0% were on floors, respectively. In contrast with the findings for the systematic wall measurements (Figure 3; Table S3), there were no statistically significant differences between measurements made at suspected sites on exterior walls, interior walls, or other locations (Table S4).

Comparison of walls, sites of suspected dampness, and the corners of windows

Readings at prescribed wall locations and sites of suspected dampness in the same rooms were significantly

Fig. 3 Systematic moisture readings at prescribed locations for exterior, interior/bath, and interior walls (error bars above and below each column represent the geometric mean for that location multiplied and divided, respectively, by one geometric standard deviation for the location)

positively correlated ($r = 0.74\text{--}0.85$, $P < 0.0001$); that is, systematic readings at walls tended to be higher in homes with higher readings at suspected sites (Figure S2, Table S5). A comparison of the averages of readings at walls and suspected sites in the same rooms identified significant differences for both rooms (averages of readings at suspected sites in LR and BR: GM = 15.2 and 16.0 %WME, respectively; Wilcoxon tests of paired suspected and prescribed measurements = $P < 0.0001$ and $P < 0.0001$, respectively; and ratios of suspected and prescribed measurements = 1.15 and 1.17, respectively) (Table S5). This difference persisted for maximum BR but not LR wall readings, but was small (Figure S2; Table S5). Maximum readings for walls and suspected sites were identical for 64% and 62% of LR and BR readings, respectively; the wall maximum exceeded the suspected site maximum for 21% and 16% of LR and BRs, respectively; and vice versa for 15% and 22% of LR and BRs, respectively.

A total of 627 moisture measurements were made at the corners of windows during the 12-month HVs (Figure S2). One landlord did not allow a window measurement because of visible condensation. Overall, condensation was reported for <3% of HVs, but condensation around a window frame was reported more often for the 12- than the 6-month HV: 3.9% and 1.3%, respectively). Wall and window readings in the same rooms were significantly positively correlated

($r = 0.73\text{--}0.80$, $P < 0.0001$) (Figure S2, Table S6); that is, systematic readings at walls were higher in homes with higher readings at the corners of windows. Again, a comparison of paired wall and window measurements identified significant differences in both rooms if the single window reading was compared with the average of multiple wall readings but not if it was compared with the maximum wall reading (Figure S2; Table S6). Window and maximum wall readings were identical for 28% and 20% of LR and BRs, respectively; the wall maximum exceeded the window reading for 34% and 36% of LR and BRs, respectively; and vice versa for 39% and 43% of LR and BRs, respectively.

Window readings and measurements at suspected sites in the same rooms also were positively correlated ($r = 0.72\text{--}0.87$, $P < 0.0001$) (Table S7). However, neither the averages nor the maxima of the readings at sites of suspected dampness were higher than measurements at the corners of windows in the same rooms (Figure S2, Table S7). For moisture thresholds of 15, 17, and 20 %WME, only 8%, 5%, and 3% of all wall measurements exceeded these levels, respectively ($n = 4089$), as compared with 39%, 30%, and 22% of measurements at suspected sites, respectively ($n = 455$), and 37%, 28%, and 16% of measurements at window corners, respectively ($n = 627$).

Reasons for making targeted measurements at sites of suspected dampness

Visible mold was the most frequent reason for taking a targeted measurement for suspected dampness, especially in LR (LR and BR: 71% and 58% of all reasons, respectively) (Figure 4; Table S8). In BRs, a musty odor was the second most frequent cause for suspecting dampness (22% of all reasons), but odor was much less often a suspicion in LR (7% of all reasons) (Figure 4; Table S8). The inspectors occasionally reported multiple reasons for suspecting dampness (LR and BR: 13% and 11% of all reasons, respectively) (Figure 4; Table S8). Fewer than 10% of measurements at suspected sites were made because of condensation, visible water damage, or a missing reason.

Additional measurements made for two or more reasons for suspecting dampness were significantly higher than measurements taken for a musty odor or visible mold alone, the former only in BRs (Figure 4; Table S8). Moisture measurements made because of a musty odor did not differ from those made because of visible mold, and no other statistically significant differences were identified among reasons.

Discussion

In our study, wall moisture measurements in LR and BRs were positively correlated, but BRs were damper

Fig. 4 Targeted moisture readings (%WME) at sites suspected of dampness for different reasons (error bars above and below each column represent the geometric mean for that reason multiplied and divided, respectively, by one geometric standard deviation for the reason)

than LR. Norbäck et al. (2011) postulated that their finding of an association between lung function and damp spots only in BRs was due to the longer time people spend sleeping and the smaller size and poorer ventilation of BRs relative to other parts of homes. In children, visible mold or dampness in a home also has been associated with sleep problems (Tiesler et al., 2014). Infants may spend even more time than other family members in their BRs, and the finding that BR walls were damper than LR walls suggested potentially greater exposure of these infants to dampness-related agents in the first year of life.

Four of six dampness indicators were consistently positively associated with higher measured moisture, and measured moisture was significantly higher with increasing numbers of dampness indicators in a home. Likewise, readings at sites measured for two or more reasons for suspecting dampness were higher than readings at sites measured solely because there was visible mold or a musty odor. Visible mold, visible water damage, and mold odor have been associated with respiratory and allergic outcomes (Jaakkola et al., 2013; Mendell et al., 2011; Quansah et al., 2012; WHO, 2009). Norbäck et al. (2011) looked at the co-occurrence of dampness indicators and found only partial overlap. Their interpretation was that water leaks, visible dampness, and visible mold were different aspects

of dampness that may lead to unique exposures with separate impacts on respiratory health. Cho et al. (2015) found that observational dampness scores in three school buildings were positively associated with higher levels of fungal and bacterial contamination in floor dust. However, their measurements of the MC of building materials were uncorrelated or weakly negatively correlated with microbial presence, and there was no association between measured moisture and dampness score in these schools. In the CHAMACOS homes, we previously found a positive association between measured moisture (dichotomized at 17 %WME) and the concentration of airborne fungal spores, in particular, the group *Aspergillus/Penicillium* species (Chang et al., 2012), genera that have been associated with respiratory health risks (Behbod et al., 2015; Sharpe et al., 2015). We also found that exposure to low fungal richness in house dust was associated with an increased risk of asthma development in CHAMACOS children, especially low richness within the genus *Cryptococcus* (Dannemiller et al., 2014).

The CHAMACOS protocol prioritized measurements on perimeter walls facing the outdoors (exterior walls, ~50% of systematic wall measurements), and our hypothesis that exterior walls would be damper than walls facing other indoor spaces (interior walls) was confirmed (Figure 3). However, we did not see the expected difference between measurements on interior walls next to bathrooms and interior walls next to rooms without plumbing, perhaps because there were too few measurements (<10%) on interior walls next to bathrooms (Figure 3). That almost 90% of sites of suspected dampness were on exterior walls provided further evidence that the perimeters of these homes may have been more susceptible to water damage than the interiors, for example, from condensation of water vapor on cooler exterior walls and windows or from wetting by rain, roof runoff, or flooding. Higher indoor humidity and the risk for condensation are related to the number of occupants in a home. The CHAMACOS population had much higher resident density compared with national data (39% of CHAMACOS homes had ≥1.5 persons per room as compared with 3% of Hispanic and 0.5% of all US households), and high density (>1 person per room) was associated with higher odds of having peeling paint, water damage, or visible mold (Bradman et al., 2005).

Homes with higher readings at prescribed wall locations tended to have higher readings at sites of suspected dampness and at window corners ($r = 0.73-0.85$), but readings were statistically significantly higher at suspected sites or windows only when compared with average not maximum wall readings. This difference may be attributed to more measurements at walls than at suspected sites or windows and dilution of the contribution of one or more high readings when averaged. Averaging may be appropriate when the goal of

making moisture measurements is to determine the overall MC of a piece of lumber or other building material (ASTM D7438-13, 2013). However, this metric may not be appropriate when seeking to identify damp homes susceptible to microbial growth or material change that may increase occupant health risks.

Maximum wall dampness equaled or exceeded that measured at sites of suspected dampness in 85% of LR's and 78% of BR's, but walls equaled or exceeded window corners in only 61% and 57%, respectively. Therefore, the overall home maximum more often increased because of a higher window reading than for one at a suspected site. Measurements at prescribed wall locations and window corners are defined and repeatable, whereas the recognition of suspicious sites and the number of such measurements made might vary by inspector and by the time available to make additional targeted measurements if there are multiple suspicious sites in a home.

Williamson et al. (1997) measured moisture in every room in a home just above the skirting boards (baseboards) at three points on each wall (usually the center and either end). Venn et al. (2003) measured moisture in LR's, BR's, and kitchens primarily on outside walls as we did, and the authors reported the height of their measurements (30 cm above the skirting board) but not the horizontal position. The CHAMACOS systematic wall measurements were made only in LR's and BR's at a height of 45–60 cm and near the centers of walls. Measuring near the floor was convenient, and one might assume that gravity would draw water from leaks toward the bottom of a wall, and also that with rising damp a wall would be wetter closer to the floor. The UK studies successfully found associations between health and measured moisture using only wall measurements near the floor. However, systematic measurements in the centers of walls and at the lower edges of windows would miss dampness near or on ceilings, in corners, and above or to the sides of windows. The distribution of dampness in typical homes and the ability of systematic measurements to characterize dampness need to be determined.

In Scotland, Williamson et al. (1997) found excess moisture and severe dampness (>17 and >20 %WME) in 51% and 19% of homes, respectively; much higher than the frequencies of these levels on walls in CHAMACOS homes (5% and 3%, respectively); the average monthly rainfall in the Glasgow region for the 2 years of their study was 118 mm (1992 and 1993; range: 22–285 mm per month) (Alexander and Jones, 2000) whereas that in Salinas for 2001 and 2002 was 18 mm (range: 0–75 mm per month) (Daly et al., 2000). In England, Venn et al. (2003) found medium and high moisture (15.1–20 and >20 %WME) in 19% and 13% of LR's, respectively; also higher than the frequencies of these levels in California (8% and 3%, respectively); average monthly rainfall in the Notting-

ham region for the 2 years of their study was 62 mm (1998 and 1999; range: 10–111 mm per month) (Alexander and Jones, 2000). However, readings at suspected sites and window corners approached the frequencies observed on walls in the UK populations. The dampness thresholds for which the two UK studies found increased symptoms on gypsum plaster may not be predictive of the health risks for the California subjects because the meters, wall materials, and climates differed and fewer wall readings exceeded the UK thresholds. In fact, analyses of multiple respiratory health outcomes have not found any associations with measured moisture in the CHAMACOS data (M. J. Mendell and T. Fong, unpublished data), either because the CHAMACOS homes were not excessively damp or because of the low incidence of asthma in this population (Hunninghake et al., 2006).

The manufacturer of the meter used in this study warned that the dampness of walls with rough surfaces may be underestimated because of poor contact between an uneven surface and the pinless meter's flat sensing pad. Moisture meters also may give falsely high readings if measurements are made over conducting metal or if surface moisture is present. Other factors that may affect the accuracy of moisture measurements include the density and thickness of wall materials. A density setting of 0.5 g/cm³ was used for all measurements in the CHAMACOS study on the determination that gypsum board of this density was the most prevalent type of interior wall finish. The difference between readings based on correct material density and the default 0.5 g/cm³ density needs to be determined, as does the relationship between MC and water activity (an absolute measurement of dampness that is independent of material and is directly relevant to microbial growth) for the most common types of building materials (Flannigan and Miller, 2011). Although water activity is a better means of determining the risk of microbial growth, building investigators seldom can determine water activity in a non-destructive manner in the field and instead rely on convenient, direct-reading moisture meter measurements.

The pinless moisture meter was designed to measure the MC of wood up to a depth of 2.5 cm, and the manufacturer recommended correcting readings for thicker and thinner materials. Gypsum wallboard typically is 1.3 cm thick, but no corrections were made to the CHAMACOS readings because actual wall thickness was not known. Surface temperature also can affect meter performance, and the manufacturer recommended correcting readings for temperatures other than the calibration temperature, but neither air nor surface temperature was measured during HV's. The meter should read 00 when held in the air and 14 when in contact with a copper calibration plate. Both settings can be corrected before use; however, we checked only the first setting in the field. In future studies, the

type of wall material should be determined when making moisture measurements, surface temperature should be measured as well as indoor and outdoor air temperature and relative humidity, and the meter's calibration also should be checked before each use and corrected if needed. Such changes to the home assessment protocol would increase the likelihood that future epidemiological studies will lead to a better understanding of the relationships between indoor dampness and health. Likewise, the model results may be improved by inclusion of covariates that may affect measured moisture or the presence of dampness indicators, for example, housing age and type and use of heating, cooling, and ventilation equipment.

Moisture meter measurements were continuous, and we evaluated them as both continuous measurements and dichotomized at the median for the mixed-effects modeling. We dichotomized all dampness indicators to present or absent even if originally recorded in more detail. Alternatively, indicators could be graded on scales, for example, strength of mold odor and area of visible mold or water damage, although categories may be difficult to standardize. Pirinen (2006) found that approximately two-thirds of moisture problems could be found by non-destructive methods, such as careful visual inspection, while the remaining third were hidden and were detected only with comprehensive investigations.

Trained inspectors conducted our home evaluations to avoid bias that building occupants may introduce if an assessment is based on self-reporting (WHO, 2009). However, no confirmations were made that what an inspector determined was mold was in fact fungal growth rather than discoloration or surface material that the inspector mistook for fungi (Anagnost, 2007; Miller, 2011). Nor was the history or cause explored for mold odor, visible water damage, peeling paint, rotting wood, or a sink leak. Errors in these determinations could skew the results toward over-reporting of damp conditions, whereas failure to notice moisture indicators during brief HVs and failure to recognize dampness that had been disguised (e.g., painted over) would skew the results toward underreporting. Supervisors confirmed reports of moisture indicators and resolved discrepancies to train the inspectors and ensure consistency between the two teams, but neither supervisors nor inspectors repeated moisture measurements. Therefore, both false-positive and false-negative associations between evident dampness and measured moisture may have occurred.

Inspector-derived data have the advantages of being more objective and providing more standardized evaluations of dampness than self reports. For example, Park et al. (2004) compared two teams that independently cross-classified eight rooms in water-damaged buildings and found agreement rates of 100% for moisture (based on touch and presence of visible water),

88% for water stain, 75% for mold odor, and 63% for visible mold. Nevertheless, a home inspection is often a single snapshot that may lack the longer perspective that a building occupant could provide (WHO, 2009). Engman et al. (2007) found good agreement between inspector observations and occupant responses about technical parameters related to a dwelling, for example, type of house and ventilation system, but poor agreement for dampness indicators and mold odor, although the stronger the odor the higher the level of agreement. Therefore, using qualitative dampness indicators, some of which may persist in a home over time, in combination with currently measured moisture, which may vary with season, may be a more reliable means to accurately identify damp spaces than either alone. The high agreement between presence and absence of indicators for families in the same homes for both HVs suggested that the indicators seldom changed within the ~6-month periods between visits. Possible explanations are that further moisture problems did not occur during these intervals in this relatively dry region of California or that residential moisture problems were long standing in this cohort of low-income, Latino families in an agricultural community. However, such persistence of dampness evidence would not be expected in all climates and for all populations.

Conclusions

Positive associations were seen between moisture measured on walls and the presence of qualitative dampness indicators, in particular mold odor and visible mold, as well as with the number of indicators present in a home. Bedroom walls were damper than LR walls, and exterior walls were damper than interior walls, whether or not the latter were next to bathrooms. No differences were observed between maximum wall readings and additional systematic measurements at the corners of windows, between walls and targeted measurements at sites of suspected dampness, or between suspected sites and window corners. Qualitative dampness indicators (mold odor, visible mold, water damage, and peeling paint) changed little between repeated HVs approximately 6 months apart. However, measured moisture differed significantly because the two visits were made in opposite seasons. Therefore, moisture measurements may be most informative when assessed along with dampness indicators, some of which consistently have been associated with increased risks of respiratory disease, for example, mold odor, visible mold, and water damage.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Comparison of systematic living room (LR) and bedroom (BR) moisture readings at prescribed wall locations in homes with vs. those without specific qualitative indicators of dampness for the averages and maxima of multiple measurements.

Table S2. Frequencies of observing four selected dampness indicators associated with higher measured moisture in both living rooms (LRs), and bedrooms (BRs) ($N = 737$ home visits, HVs).

Table S3. Comparison of systematic living room (LR) and bedroom (BR) moisture readings at prescribed locations on perimeter walls facing the outdoors (Exterior) and walls next to other rooms (Interior or Interior/Bath).

Table S4. Comparison of targeted living room (LR) and bedroom (BR) moisture readings at sites of suspected dampness on perimeter walls facing the outdoors (Exterior), on walls next to other rooms (Interior), and at other locations (Other).

Table S5. Comparison of targeted living room (LR) and bedroom (BR) moisture readings at sites of suspected dampness (Suspected) and systematic readings at prescribed wall locations (Wall) in the same rooms for the averages and maxima of multiple measurements if more than one.

Table S6. Comparison of systematic living room (LR) and bedroom (BR) moisture readings at the corners of windows (Window; single measurements) and at prescribed wall locations (Wall; averages and maxima of multiple measurements) in the same rooms.

Table S7. Comparison of targeted living room (LR) and bedroom (BR) moisture readings at sites of suspected dampness (Suspected; averages and maxima of multiple measurements if more than one) and systematic measurements at the corners of windows (Window; single measurements) in the same rooms.

Table S8. Comparison of targeted living room (LR) and bedroom (BR) moisture readings made for different reasons for suspecting dampness.

Figure S1. GMs of average and maximum moisture meter readings at prescribed wall locations in homes with different total numbers of qualitative dampness indicators (i.e., musty odor, visible water damage, visible mold, and peeling paint; % in box = percentage of home visits, restricted to the 621 with three systematic measurements in both rooms).

Figure S2. Maximum targeted moisture readings at sites of suspected dampness (suspect) and systematic readings at prescribed wall locations (wall) and the corners of windows (window) in the same rooms (r = correlation coefficient; error bars above and below each column represent the GM for that type of measurement multiplied and divided, respectively, by one GSD for the measurement type).

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