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Moldy odor from air conditioners in the
residences of Japanese participants with
and without asthma

(喘息の有無と居宅内空調機由来カビ臭)

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- I got permissions for the submission of the doctoral thesis to the institutional repository of Tokai University, in addition to reuse of part of my article in my doctoral thesis.

Summary

Fungi are a major environmental allergen; exposure and sensitization to environmental fungi are associated with asthma onset, severity, and exacerbation. Mold growth is affected by temperature, relative humidity, and ventilation. Therefore, air conditioning systems are beneficial for reducing the burden of airborne fungi. However, if not properly maintained, air conditioners themselves can be contaminated with fungi and, consequently, spread fungal spores into indoor air.

Visible molds are not necessarily associated with airborne fungi or fungal components. Moldy odor derived from fungal or microbial volatile organic compounds was more closely associated with health outcomes compared to visible molds, suggesting the clinical importance of invisible fungi detectable with moldy odor. Because fungi in the interior parts of air conditioners is difficult to visualize, moldy odor from the machine may be a reasonable indicator to imply fungal contamination. We applied an online survey to examine the prevalence of moldy odors from air conditioners in the residences of healthy Japanese participants and patients with asthma and analyze the environmental factors associated with the presence of moldy air conditioners. We then analyzed whether patients with asthma were taking appropriate measures to reduce fungal contamination in the indoor environments of their residences.

Japanese adults aged ≥ 30 years registered in the database of an Internet research company, with or without asthma, were asked to participate in an online survey performed in October 2020.

Participants who answered yes to both of the following questions were regarded as having asthma and were randomly selected: 1) have you ever been diagnosed with asthma? and 2) are you currently being treated for asthma?. Those who answered no to both questions were considered non-asthmatic. The questionnaire comprised 33 questions: 12 on participant characteristics, nine on the home environment, and 12 on air conditioners.

A total of 1006 adults (aged 51.6 ± 12.0 years, 52.6% men), including 631 patients with asthma, responded to the online survey. Most of their residences (94.5%) were equipped with air conditioners, mainly in the living room (90.2%), followed by the bedrooms (50.1%). A substantial proportion of participants (37.1%) reported moldy odors from their air conditioners. This prevalence did not differ between the residences of asthmatic and non-asthmatic participants. In the non-adjusted univariable analysis, moldy odor was associated with ≥ 4 residents, living in apartments, and indoor condensation. Air conditioners ≥ 6 years of age and frequent use during the summer were related to moldy odors. In contrast, the presence of an auto-cleaning function in the air conditioner significantly reduced the moldy odor. After adjusting for age, sex, and the presence of asthma, moldy odor was associated with indoor condensation, air conditioner use ≥ 6 years, frequent use during the summer, and auto-cleaning function. Moldy odor from the air conditioner was significantly associated with cleaning using aerosol spray or a professional cleaning service, regardless of the presence of asthma. These data suggest that the presence of a moldy odor is a major motive for air conditioner cleaning. We calculated the change in the estimated probability of air conditioner moldy odors among patients with asthma before and after the removal of specific lifestyle and environmental factors. Aquariums are present in 25 asthma residences. The probability of moldy odor in these residences as deduced from our model decreased from 0.72 (median) to 0.43 (median, $P < 0.01$) when aquariums as a factor was removed

from the model.

Our survey has clarified that not only air conditioner-related factors, such as length and duration of its use, but also household condensation reflecting high indoor relative humidity were associated with the moldy odor. Asthmatic patients more frequently used air cleaners and humidifiers compared to participants without asthma, implying that they were more conscious of indoor air quality. However, the number of participants who were taking effective measures to reduce moldy odor or condensation, such as auto-cleaning function in air conditioners or 24-hour ventilation systems in residences, did not differ between patients with and without asthma. Patients with asthma in the present study were also aware of the need for air conditioner maintenance. They not only cleaned the filters but also used an aerosol spray to clean the air conditioners. However, fungal contamination is most prominent in the downstream area of the cooling coils and the blower fan of air conditioners. Therefore, spraying biocidal detergent cleaner on the front side of the AC heat exchanger has little effect. The cleaning of disassembled air conditioners with a high-pressure washer is most effective in reducing fungal load; however, <15% of patients with asthma utilized professional services for these procedures.

In conclusion, asthmatic patients do not necessarily behave appropriately to reduce indoor mold contamination, possibly due to a lack of knowledge. Physicians should provide appropriate information to patients with asthma on how to maintain an optimal indoor environment to minimize fungal contamination.

Introduction

Fungi are a major environmental allergen. Exposure and sensitization to environmental fungi are associated with asthma onset, severity, and exacerbation. Furthermore, fungi pose a risk for

the development of more severe conditions such as allergic bronchopulmonary aspergillosis/mycosis (ABPA/ABPM). An estimation of the global burden suggested that ABPA develops in approximately five million patients with asthma worldwide. As more time is spent at home in the era of the coronavirus disease 2019 (COVID-19) pandemic, appropriate maintenance of the indoor environment is essential for the health of patients with asthma. However, less is known regarding environmental interventions to reduce indoor molds and their efficacy compared to the approaches for another major indoor allergen, house dust mites.

Mold growth is affected by temperature, relative humidity, and ventilation. Therefore, heating, ventilating, and air conditioning (HVAC) systems are beneficial for reducing the burden of airborne fungi. However, if not properly maintained, air conditioners themselves can be contaminated with fungi and, consequently, spread fungal spores into indoor air. We previously reported a case of ABPM with repeated deterioration due to recurrent exposure to a contaminated air conditioner. Spontaneous resolution occurred after the environmental trigger was removed.

Moldy odors are derived from fungal or microbial volatile organic compounds (mVOCs), as mixtures of alcohols, aldehydes, acids, ethers, esters, ketones, terpenes, thiols, and their derivatives. These odors can be a sensitive indicator of the number of airborne fungal spores or β -glucan levels in indoor air. A study in daycare centers demonstrated significantly higher total fungal DNA in dust in the institutes with reported odor. In contrast, visible molds are not necessarily associated with airborne fungi or fungal components. A systematic review demonstrated that moldy odor was more closely associated with health outcomes; for example, asthma onset, compared to visible molds, suggesting the clinical importance of invisible fungi detectable with moldy odor. Moldy odor from the air conditioning systems in automobiles is also associated with fungal contamination of the systems and the vehicles. Therefore, moldy odor from

air conditioners may be a reasonable indicator to imply that fungi are a major source of contamination in residences.

We applied an online survey to examine the prevalence of moldy odors from air conditioners in the residences of healthy Japanese participants and patients with asthma and analyze the environmental factors associated with the presence of moldy air conditioners. We then analyzed whether patients with asthma were taking appropriate measures to reduce fungal contamination in the indoor environments of their residences.

Discussion

If not properly managed, air conditioners are a major site of indoor mold growth, possibly causing or worsening ABPM and hypersensitivity pneumonia. The number of airborne fungi increases by 10–10,000 fold immediately after starting a contaminated air conditioner. Moldy odors originating from air conditioners were present in more than one-third of the residences of participants with and without asthma. Not only air conditioner-related factors, such as length and duration of its use, but also household condensation reflecting high indoor relative humidity were associated with the moldy odor. Asthmatic patients more frequently used air cleaners and humidifiers compared to participants without asthma, implying that they were more conscious of indoor air quality. However, the number of participants who were taking effective measures to reduce moldy odor or condensation, such as auto-cleaning function in air conditioners or 24-hour ventilation systems in residences, did not differ between patients with and without asthma. Patients with asthma were more likely to clean air conditioners with aerosol spray, even after adjusting for moldy odor, which is the major motive to clean the air conditioners. However, less than 15% of patients with asthma had asked for professional services to clean their air

conditioners by disassembling and high-pressure washing, which effectively removes fungal contamination in the apparatus.

The dew point temperature of outdoor air, a function of temperature and relative humidity, is an important factor for microbial loads in HVAC systems of buildings in the US. Fungal loads on cooling coils are more closely correlated with dew point temperature than bacterial loads, suggesting that moisture is an important factor related to fungal growth. However, window-type (ductless mini-split) air conditioners are commonly equipped in Japanese residences, composed of an outdoor compressor/condenser and an indoor air-handling unit(s), which re-circulate cooled indoor air but do not ventilate with outdoor air. Therefore, indoor environments such as condensation are important for fungal contamination in residences with these air conditioners.

Condensation is an indicator associated with insufficient ventilation and high air humidity, sick building syndrome, asthma exacerbation, and allergic diseases. Our data confirmed that living in an apartment and the use of an aquarium increased the risk of condensation. Most Japanese apartments are reinforced concrete block buildings, which showed higher humidity and more abundant indoor fungi compared to wooden buildings. In the present study, a 24-hour ventilation system suppressed the formation of condensation. As previously discussed, the window-type air conditioners popular in Japan do not ventilate indoor air with outdoor air; therefore, the indoor dew point temperature and the indoor-to-outdoor ratio of fungal bioaerosol levels in the summer are higher in houses equipped with this type of air conditioner compared to residences with HVAC systems. A 24-hour ventilation system compensates for the shortcomings of window-type air conditioners.

Patients with asthma more frequently used air purifiers and humidifiers compared to patients without asthma. The use of humidifiers in the winter to increase indoor moisture may

prevent respiratory tract viral infections and asthma exacerbation. However, their use also promotes the growth of fungi and mites, posing a risk of asthma development and worsening. The estimated probability of moldy odor in the residences of asthmatics who use a humidifier decreased from 0.49 (median) to 0.31 (median, Table 4) if humidifier as a factor was removed from the model, further supporting the notion that patient education can reduce environmental fungal contamination and improve asthma control. Patients with asthma in the present study were also aware of the need for air conditioner maintenance. They not only cleaned the filters but also used an aerosol spray to clean the air conditioners. However, fungal contamination is most prominent in the downstream area of the cooling coils and the blower fan of air conditioners. Therefore, spraying biocidal detergent cleaner on the front side of the AC heat exchanger has little effect. The cleaning of disassembled air conditioners with a high-pressure washer is most effective in reducing fungal load; however, <15% of patients with asthma utilized professional services for these procedures. Inappropriate efforts by patients themselves to clean air conditioners may exacerbate asthma symptoms.

Online surveys based on moldy odors from air conditioners have some strength in identifying the major factors associated with indoor fungal contamination and patient behaviors regarding these conditions, as they can easily collect data from a large number of participants with variable backgrounds and lifestyles in a specific season. However, this patient- but not physician-oriented study has several limitations. First, we could not evaluate detailed clinical backgrounds and atopic status, especially sensitization status to fungal allergens. Secondly, although moldy odor is more closely associated than visible fungi with airborne fungal spores/ β -glucan levels as well as with health outcomes in patients with asthma, criticisms exist that the source of mVOCs causing “moldy odor” are not necessarily specific to fungi. Thirdly, there was a significant age dependence

in the prevalence of moldy odor: older people reported less moldy odor probably due to the deterioration of olfactory function. We, therefore, performed multivariable logistic regression analysis and analyzed the data after adjusting for age to identify the risk factors. Care is still required when using a moldy odor as a parameter of environmental fungal contamination in the elderly population. Field studies examining more detailed clinical backgrounds and environmental parameters such as frequency of air conditioner usage and ventilation can overcome these limitations, however, are limited with small number of samples. Therefore, our study with large samples and other field studies are complementary to each other to answer the questions about the role of environmental factors on health status in the patients with asthma.

Conclusion

Asthmatic patients were more conscious of indoor air quality. However, they did not necessarily behave appropriately to reduce indoor mold contamination, possibly due to a lack of knowledge. Physicians should provide appropriate information to patients with asthma on how to maintain an optimal indoor environment to minimize fungal contamination.