Editorial

Fans, Filters, or Rays? Pros and Cons of the Current Environmental Tuberculosis Control Technologies

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See also pages 686, 689, 694, 700, and 723

The Centers for Disease Control and Prevention (CDC) recently published the long-awaited draft revision of its *Guidelines for Preventing the Transmission of Tuberculosis in Health-Care Settings.*[1] The delay in publication reflects considerable honest disagreement among the various technical experts involved, and among organizations and individuals who have strong interests in the policies, procedures, and engineering interventions ultimately recommended in that document. The purpose of this editorial and of other articles[2] in this series is to discuss some of the controversies regarding technologies currently available to reduce the risk of tuberculosis (TB) transmission in institutional environments. Although the revised guidelines will address all aspects of tuberculosis control in institutions, most attention has focused on the sequestering of known or potentially infectious TB cases and high-risk procedures in well-ventilated, negative-pressure TB isolation rooms to protect other building occupants, and the use of effective personal respiratory protection for those who must enter these and other high-risk areas.

This issue features articles that discuss room filtration[3] and ultraviolet (UV) air disinfection[2]—methods considered supplemental to ventilation in the revised CDC guidelines. In this commentary, I highlight some of the pros and cons of building ventilation, filtration, and UV irradiation as primary as well as supplementary methods of air disinfection.

FANS: BUILDING VENTILATION AS AN APPROACH TO AIR DISINFECTION

Both the Macher[2] and Marier[3] articles mention some of the limitations of ventilation as a means of air disinfection. The pros of ventilation also deserve mention. Not only is mechanical ventilation available in most institutions, but its basic operating principles are familiar to most engineers. Engineers understand, for example, that airborne pathogens are less likely to escape from isolation rooms if slightly more air is exhausted than is introduced through the ventilation system, thereby drawing makeup air into the room from adjacent areas. Availability, know-how, and analogies with the control of other airborne contaminants account for the prominent place of ventilation as the engineering cornerstone of the current guidelines. In contrast, high-efficiency particle air (HEPA) filtration and ultraviolet germicidal irradiation (UVGI) are not as readily available, and most engineers are less familiar with their application for TB control.

That ventilation can dilute and remove infectious droplet nuclei and thereby reduce the probability of infection is undeniable. The dispute concerns the degree of protection ventilation provides under the actual conditions where transmission occurs, how reliable that protection is, and how practical it is to apply in existing facilities around the country. These are harder questions to answer in the absence of data from field trials, not only for ventilation, but also for

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filtration and UV air disinfection. Among the reasons why there are no field trials of any of the engineering controls, or personal respiratory protection, is the variability in infectiousness of TB cases, one from another, and over time. A TB case who is an effective disseminator has the potential to infect many contacts, and easily could skew the results of a field trial unless it were very large. Moreover, unless carefully controlled, conditions other than the intervention under study (building airflow patterns, for example) might favor transmission in one setting over another. TB infections acquired outside the intervention area are another potential confounding factor, especially in the high-prevalence areas where field trials most likely would be conducted. Fortunately, the pioneering quantitative animal exposure experiments of Wells, Ratcliffe, Lurie, and others,[4,5] done in the prechemotherapy era when TB research was a high priority, together with the experimental TB ward data of Riley et al, where guinea pigs served as quantitative air samplers for human contagion,[6] provide a solid scientific basis on which to base decisions in the absence of field trial data and to plan future research. The study of air filtration reported in this issue by Marier,[3] and previously published studies of UV air disinfection in moms by Macher,[7] highlight the importance of room experiments in determining which technologies are likely to prove useful.

Leaving for the moment the critical issue of efficacy, cost is perhaps the single most important difference in the three approaches to air disinfection under discussion. Using building ventilation to dilute and remove droplet nuclei and to ensure directional airflow from low- to high-risk areas is by far the most expensive approach available to protect occupants. Not only are major renovations often needed to produce directional airflow from corridors into isolation and procedure rooms, and to exhaust contaminated air safely outside, but substantial maintenance and monitoring expenditures are needed to assure proper performance over time, with even greater ongoing costs for energy consumed in exhausting heated or cooled air to the outside. In the case of older, naturally ventilated buildings, renovations to meet the current CDC guidelines often simply are not possible without near total building reconstruction. It is ironic that many institutions at highest risk for TB transmission (shelters for the homeless, residential drug treatment facilities, hospices for AIDS patients, and inner-city hospitals and clinics, for example) often are those least able to meet costs of ventilation system renovations and increased energy consumption. But as the entire healthcare industry is forced to reduce the costs of delivering care, the pressure from a broad spectrum of institutions to find more economical methods of air disinfection likely will grow. And as the country attempts to reduce its consumption of energy and the production of CO_2 more environmentally sound approaches to airborne infection control will be required.

High-efficiency filtration of room air, allowing recirculation, and UV air disinfection in rooms and ducts are far more economical means of air disinfection and patient isolation. A prominent Boston teaching hospital is contemplating spending a half million dollars on a new, dedicated exhaust system and other modifications to assure directional airflow into 24 isolation moms. The cost of retrofitting those rooms with a recirculating filtration system like that tested by Marier would be about 20% to 25% of that figure, and the cost of using upper room UV air disinfection in rooms and corridors together with existing ventilation would be no more than 5% to 10%, depending on how many fixtures were needed. Moreover, the yearly energy costs for direct exhaust of six air changes for 24 rooms would be staggering, roughly $40,000 per year in the Northeast, and likely to rise in the future.

Using an established mathematical model of airborne infection, incorporating actual exposure parameters of duration and intensity, it has been shown that transmission is likely even at ventilation levels at or beyond those currently recommended. For example, during a month-long exposure in an office building where outdoor air ventilation averaged a low 15 CFM per person, 27 (40%) of 67 coworkers of a person with cavitary pulmonary TB were infected. Had ventilation been an unrealistically generous 35 CFM per person, however, the model predicted that 13 workers still would have been infected.[8] Although doubling effective ventilation predictably halves the risk of infection, there are practical upper limits to how much ventilation is possible due to engineering constraints, discomfort due to drafts, and energy costs. Apart from comfort issues, increasing ventilation to dilute droplet nuclei becomes progressively less efficient as it becomes progressively more expensive. Both mathematical modeling and current ventilation recommendations assume complete room air mixing, a condition not likely to be found in real life. Air mixing and flow patterns within rooms are the greatest unknowns when engineering control theories are applied to real buildings. Room air mixing appears to be critical for effective air disinfection by all three modalities: ventilation, filtration, and upper room UV irradiation.

Another limitation of ventilation that deserves mention is reliability. Building ventilation depends on complex mechanical systems controlled by thermostats set (and reset) by humans, but highly dependent on maintenance for proper function. Even properly functioning HVAC systems deteriorate with age, with

subsequent remodeling of buildings, and as result of inadequate maintenance. According to an engineer experienced in hospital ventilation, "Hospital air-handling systems of all types-including supply and exhaust-are commonly and chronically deficient for reasons of design, construction and maintenance. These deficiencies often make difficult achieving and maintaining hospital space pressurization, the most critical element in hospital ventilation for TB infection control."[9] Another reason for the unreliability of ventilation systems is the interdependency of air pressure changes within buildings. Use of windows, doors, pharmacy exhaust hoods, elevators, and even other negative pressure isolation rooms all can influence-indeed, even reverse-directional airflow. Periodic or continuous monitoring of isolation room pressure, sealing of rooms against potential leaks, insistence that doors to isolation rooms be closed, and the use of anterooms are attempts to prevent pressures generated in other parts of buildings, or outside, from altering directional airflow. While these measures can be expected to be successful in many cases, there is little doubt that an insistence on closed doors and the use of anterooms will interfere with patient care, nursing care in particular. That reliable negative pressure isolation will prevent some nosocomial transmission is likely, but as stated earlier, the contribution of inadequate isolation to all nosocomial TB transmission is unknown.

FILTERS: LOW-PENETRATION AIR FILTRATION AS AN APPROACH TO AIR DISINFECTION

There is a long experience using HEPA filtration to remove airborne contaminants, including airborne bacteria, in laboratory hoods, clean rooms, submarines, and airliners, to name a few applications. There is every reason to believe that HEPA filters (which remove, by definition, 99.97% of particles $>0.3\ \mu m$ in diameter) will remove droplet nuclei that are believed to average 3 μm in diameter. Although HEPA filters are tested routinely with a standard particulate aerosol, Marier and Nelson[3] chose to demonstrate efficacy using artificially generated aerosols of bacteria and mycobacteria that did not penetrate the filter in their device. Their use of an ultra-low-penetration air (ULPA) filter rather than the more conventional HEPA filter is unjustifiable in theory and may add unnecessarily to cost and airflow resistance. In fact, a good argument can be made for filters somewhat less efficient than HEPA for TB control purposes. The use of germicidal UV inside their fan-filter unit is also unwarranted because the filter alone should stop 100% of droplet nuclei and because UV is not useful for surface disinfection. Nonetheless, the authors have shown that a low-penetration filtration unit can be used to remove particulates from air recirculating in a test room and to produce directional airflow into the room from a corridor or anteroom, effectively preventing leakage from the room when high flow rates were used. The advantages of this system are the tremendous savings on construction and operating expenses over using building ventilation for the same purposes. Because filtered air and outdoor air ventilation work on the same logarithmic curve of progressively increasing inefficiency, the ability to provide flow rates equivalent to 10 to 44 air changes economically via recirculated infection-free air should provide substantial room air disinfection. Moreover, because the system is self-contained, it is less likely than building ventilation to be influenced by extraneous pressure changes in the building.

One limitation of the system presented by Marier is shared with all air moving systems: the inability to move enough air to be fully protective if the source case is highly infectious. In addition, filtration systems present some unique potential problems. Because low-penetration filters offer substantial resistance to airflow, pressure build-up before the filter encourages leakage of unfiltered air. This is especially true in systems that push rather than pull air through the filter. When fans draw air through filters, the tendency for leakage is inward, although leakage around the filters is still possible. Pressure build-up and leakage is of great concern when HEPA filters are used in ventilation ducts, especially where installation and maintenance are likely to be suboptimal. HEPA filters are expensive and must be changed on a regular basis to maintain desired airflow. Systems should be tested for leaks after installation and after filter changes. Filters work best when they are close to the source of air contamination and where the room volumes are relatively small. They have been used with success, for example, in isolation booths for high-risk procedures such as pentamidine aerosol treatments and sputum induction.

ROOM AIR MIXING: A POTENTIAL LIMITATION TO ALL AIR DISINFECTION

An important concern regarding the filtration system presented by Marier and Nelson[3] is the effect of inadequate room air mixing, potentially creating regions of air stagnation where airborne droplet nuclei might persist. In the study presented, the particle counts in the room were made just in front of the fan-filter device, directly in the pathway of air streaming across the room from the louver above the door. One would expect the lowest particle counts in this region, but what of the air in other regions of the room? The authors have examined this issue on-site in

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hospital installations and report that optimal flow patterns are highly dependent on individual room configuration, including the placement of room furnishings (Nelson T, personal communication, February 1993). Conditions for optimal air disinfection must be worked out on a mom-by-room basis as units are installed, including, for example, fixing the position of furniture.

The problem of inadequate mixing potentially is much greater for portable, freestanding air filtration units that attempt to disinfect entire rooms without the advantage of the airflow patterns created in the unique Marier/Nelson ducted recirculation system. Because intake and exhaust ports must be relatively close together, portable units are likely to short-circuit, disinfecting air only in their immediate vicinity while other room air remains relatively stagnant.

A colleague tested the ability of one portable unit to capture the particulate plume generated by a smokestick (Kubica G, personal communication, March 1993). Smoke streamed into the device close-up, but at a distance of only about 18 inches away, smoke drifted up and away from the unit. The difficulty was explained to me by another colleague, an environmental engineer, who asked me to consider how easy it is to blow out a match held six inches away and how difficult it is to suck out a match even at closer range (First M, personal communication, October 1993).

Portable filtration devices attempt to suck infectious air from entire rooms, an impossible task unless flow conditions are optimal. Laminar flow rooms approximate ideal conditions, but at extraordinary cost. The air mixing problem is not unique to filtration devices. In rooms where supply air diffusers and exhaust outlets are too close together, for example, the equivalent of six air changes may enter and directly leave the room (short-circuiting) with little effect on the concentration of room air contaminants. Room air mixing is also critical to upper room ultraviolet air disinfection, as will be discussed.

Perhaps the greatest limitations of both ventilation and filtration approaches to air disinfection is that both technologies focus on the isolation or procedure room as if they clearly were the most important sources of nosocomial TB transmission. In fact, in the absence of uniform tuberculin testing of institutional employees and reporting of nosocomial infection to state or national agencies, we do not know whether the greater risk is from known or suspected TB cases that can be isolated or from unsuspected cases in emergency rooms, intensive care units, clinics, and other areas. Considerable anecdotal experience suggests, for example, that transmission is not common in tuberculosis hospitals and clinics simply because the cases are known and started on therapy.

The emergence of multidrug resistance in some parts of the country has made the institution of therapy less of an assurance against transmission, but awareness of the problem and the need for *effective* therapy before isolation ends appears to have been a large part of the solution. For some institutions—shelters and residential AIDS facilities, for example—it is the unsuspected case that is the likely source of transmission, a problem addressed neither by isolation rooms nor particulate respirators. Because unsuspected TB cases, other building occupants, and contaminated air all move within buildings, Dr. Richard Riley recently has recommended that in high-risk settings the entire building should be considered the unit for air disinfection, incorporating UV in ventilation ducts to prevent recirculation.[10]

Healthcare workers "live" in the corridors of hospitals, which are also important conduits of air and patients, but corridors are all but neglected in the current CDC guidelines. The only technology inexpensive enough, flexible enough, and potentially effective enough to be considered for the purpose of disinfecting air in corridors, waiting areas, and emergency rooms, as well as isolation rooms, is ultraviolet germicidal irradiation.

RAYS: ULTRAVIOLET GERMICIDAL IRRADIATION FOR TB CONTROL IN INSTITUTIONS

The review by Macher[2] in this issue puts into perspective the role of UV air disinfection and the other available air disinfection strategies. As noted there and above, the principal advantages of upper room UV are ease of application, relatively low cost, and potentially great efficacy. Based on room experiments done by Riley et al[11] in a naturally ventilated room into which tubercle bacilli were aerosolized, Riley and I[12] have suggested that a 30-W UV fixture adds the equivalent of 20 mom air changes of infection-free air. As recently emphasized by Permutt,[13] that statement needs to be qualified to include the requirement of good air mixing between the upper and lower room air. The number of equivalent air changes resulting from one or more UV fixtures might be lower or considerably higher than 20 room air changes, depending on air mixing and airflow patterns in the room.

Riley's experiments in a naturally ventilated test room showed good mixing by convection alone, most likely facilitated by the radiators that heated the room. In fact, small temperature gradients between the upper and lower room are the most effective way to promote mixing without noise or drafts. Further research should examine ways to have building venti-

lation systems work together with upper room UV to optimize room air mixing. Introducing warm air into the lower room or cool air into the upper room (depending on the season) would encourage air mixing, but many systems use the same ducts for both the heating and cooling cycles.

SAFETY OF UPPER ROOM UVGI

Macher touches on the safety of UVGI, but a few additional comments are warranted. Germicidal UV exposure in the lower room is safe for room occupants for the following reasons: 1) current UV exposure limits are set to prevent eye irritation because the eye is the body's most sensitive organ. 2) The current exposure limit assumes eight hours "stare time," whereas the eyes of room occupants rarely are exposed continuously. 3) Unlike the longer wavelength W in sunlight and other sources, 254 nm *UV* has little penetrating capacity. It does not reach the lens of the eye to cause cataracts, and only an estimated 5% of rays incident on the skin surface reach the uppermost living cells of the dermis.[14] Although skin cancer has been induced with 254 nm *UV* in intensely irradiated, hairless mice, a comparable dose for humans from upper room *UV* is highly unlikely. Compared with *UV* exposures in everyday life, UV exposure from germicidal lamps is almost inconsequential. Whereas four hours sunbathing can expose an individual to an estimated 740 mJ/cm^2 of more penetrating UV-A and UV-B, the maximum allowable eight-hour exposure to less penetrating UV-C is 6 mJ/cm^2.[15] Newer, louvered fixture designs effectively keep germicidal *UV* in the upper room, minimizing exposure in the lower room. However, proper hazard labeling and education to avoid accidental direct exposures by maintenance or other workers in the upper room is necessary.

The need for more economical and more effective air disinfection to prevent tuberculosis transmission in institutions is clear. The filtration system presented by Marier[3] appears to produce effective negative pressure isolation and potentially protective levels of dilutional "equivalent" ventilation at a fraction of the cost of currently recommended ventilation strategies. Upper room germicidal irradiation, as reviewed by Macher,[2] potentially can produce even higher levels of equivalent ventilation at low cost, and has the additional advantage of applicability to corridors, emergency rooms, and waiting areas-areas where unsuspected TB cases may reside. Inadequate room air mixing may prove to be the greatest barrier between potential and real protection from any of the current air disinfection technologies and is the area most urgently in need of research.

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