The history and science behind airborne infections and the use of ultraviolet irradiation for disinfecting indoor air

Part one of an interview with Dr. Ed Nardell

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Dr. Edward Nardell has dedicated close to a half century of his life to the study and examination of airborne infections such as tuberculosis and the use of ultraviolet irradiation for disinfecting indoor air. After completing his pulmonary medical training at Massachusetts General Hospital in 1977, he began working for the Boston Department of Public Health.

Two events in the mid-80s, an outbreak of TB among Haitian immigrants in Cambridge and then the resurgence of TB reinfections at the Pine Street Inn homeless shelter in Boston, shaped Nardell's life-focus in its current direction. In considering how he could stop TB, he recalled a lecture by famed pulmonologist and TB expert Dr. Richard Riley, who had recently retired. Riley had explained that ultraviolet (UV) germicidal irradiation was very efficient at killing airborne bacteria and viruses.

Nardell contacted Riley, who guided him on the installation of upper room UV fixtures (near or at ceiling level). The collaboration led to a life-long professional relationship until Riley's death in 2001. Nardell has continued the legacy left behind by famed Harvard sanitary engineer, William Wells, and his successor Riley, through his extensive work in countries where the burden of TB is high. He has also analyzed air purification systems which use ventilation principles. These are good at providing comfort in indoor spaces but are less effective at addressing the risks associated with airborne pathogens.

As Dr. Nardell has noted, "Lighting experts may know about UV irradiation, but they are not involved in public health issues. UV irradiation technology is not taught to engineers, so it really has fallen between disciplines, and a lot of people don't know about it." The COVID-19 pandemic has brought these issues to the fore in public health discussions. The World Socialist Web Site *reached out to Dr. Nardell, and he graciously consented to an interview which was conducted in early January 2023.*

The discussion was critical in the drafting of the two-part series on ultraviolet irradiation recently published on the web site and available here: Part 1 and Part 2.

Benjamin Mateus: Dr. Nardell, thank you for speaking with me. It is a real pleasure.

Edward Nardell: Thank you. Of course.

BM: We have recently been reviewing Far UVC [lamps] and the use of UV [ultraviolet] as a germicidal for disinfecting indoor air and surfaces, and its history and development going back more than 100 years. In particular, the contributions made by William F. Wells and his student, Dr. Richard Riley, and then your work over the last four decades, have been seminal in this field. We have also addressed the important contributions made by Columbia University, specifically Dr. David Brenner and his team on Far UVC.

EN: Technically when you say, "going back a 100 years," we're using Far UV—some people don't like the term—to refer specifically to 222-nanometer (nm) or 206 nm wavelengths. Whereas what was used a 100 years ago, of course, was all UVC, but at 254 nm, which was the natural output of mercury lamps.

BM: Correct. So, maybe as by way of introduction, you can tell us who you are and speak to the work that you do on the topic of air disinfection and ultraviolet irradiation. This should help ground our discussion.

EN: Sure. My name is Ed Nardell. I'm a professor at Harvard Medical School and Department of Medicine Global Health and in pulmonary medicine as well as at the Harvard School of Public Health.

My interest in airborne transmission began in the early eighties when I was put in charge of tuberculosis (TB) for Boston initially. And then I eventually served about 18 years as a TB officer for Massachusetts. TB is an exclusively airborne disease. It's the prototype, one of the prototype airborne infections, and there was an outbreak at a homeless shelter back in the early eighties. I contacted Richard Riley, who had just recently retired from Hopkins and was living in Petersham, Massachusetts. We developed a professional relationship and personal friendship that lasted also about 18 years until he died in 2001.

At any rate, I learned an awful lot from him about germicidal UV. He had worked with Wells when he was a medical student at Harvard, and then later in life when Wells left Penn and joined him at Johns Hopkins. And they did some … Wells conceived of, and Riley carried out pioneering studies on airborne transmission and germicidal ultraviolet.

We've repeated or gone beyond some of those Baltimore studies in South Africa using the same human to guinea pig transmission model that Wells envisioned and Riley carried out in the fifties and sixties in Baltimore. For the past 40 years I've been very much involved in studying airborne transmission, initially TB, and now COVID, and how we can best control it—ventilation, air filtration and UV.

BM: When you first heard of COVID, given the extensive work that you've done with airborne transmission, what came to mind? Just to be clear, I'm asking about the airborne nature of COVID transmission and perhaps the reluctance of the World Health Organization [WHO] and the CDC [Centers for Disease Control and Prevention] to accept this mode of transmission as the primary source of spreading.

EN: To be fair to the WHO, while I do think they were late in recognizing airborne transmission, there's been a lot of controversy over many different pathogens and to what extent they were airborne or spread by larger droplets. For instance, influenza was highly controversial for many years. SARS-CoV-1 as well.

And it comes down to the basic question of do we need full respiratory protection—respirators versus face masks. And the ball went back and forth on whether or not face masks were protective against influenza H1N1 or SARS-CoV-1. And if not, then you need respirators.

I was of an open mind to begin with until the Washington state outbreak in a choir where they knew about SARS-CoV-2, and they took all precautions to avoid contact. You were not supposed to be symptomatic to go to that rehearsal. Everyone kept their distance from each other and contact precautions were in place. And still there was widespread transmission and several deaths that resulted from those early cases of COVID, which was very strongly suggestive of airborne transmission.

Dr. Harvey Fineberg, who was on the National Academy of Sciences and Engineering's Epidemic Response Committee (I believe), contacted me, and with him and experts, I wrote a response to a request from the White House on how COVID was spread—a white paper. That was requested from the White House—ironic, because this was the Trump White House—which is not remembered for its reliance on science. But on the question of whether or not we thought COVID was airborne, we came down firmly very early on that this was an airborne infection, or at least partially airborne, as far as we could tell, and suggested air disinfection as an approach.

BM: If I may interrupt … how did they respond to your report?

EN: I am not aware of a White House response. Apparently, the American Academy of Science, Engineering, and Medicine is the place that the White House routinely turns to for science advice.

This was a rapid response request done without an elaborate meeting and parsing of evidence. Dr. Fineberg called together by Zoom several like-minded experts to draft, edit and approve a response to the request and submit [it] to the White House. It is a formal process, and it was published in the Federal Register, I believe. I do not believe a White House response was expected. How or why the White House request for a rapid response from the academies was made under that administration is unclear, but I suspect some official protocol was followed.

BM: Thank you. Please continue …

EN: Well, it wasn't only the WHO and CDC with regards to their position against airborne transmission. Even the head of infection control at the Brigham, my institution here in Boston, Dr. Mike Klompas, was firmly in the belief that this was a contact droplet spread infection—meaning the concept of droplet transmission was pervasive. I had a long talk with him about germicidal UV and he was not willing to go that route. Now, he's changed his opinion, I believe. Not in terms of UV, but just in how the virus is spread. And it took quite a few people a while to get there.

BM: Who is using this technology now and where is it being applied? And perhaps you might know more about this. The Air Force, I think in 2020, conducted a large study …

EN: I know Boeing's been studying Far UV and I know the Air Force has purchased it through PG Piper's [CEO and founder of the] company called Far UV Technologies. Their Far UV 222-nm wavelength fixtures are in some of their medical facilities. And I believe Piper was able to get some of this into the Pentagon in some critical areas.

BM: And there are a few pictures we have found on social media that show Dr. Ashish Jha using these UVC lamps positioned behind him while giving talks unmasked. And I raise this issue because there was this recent indoor air quality summit and, I believe, one of your colleagues from Harvard, Joe Allen, delivered the keynote address. And he said we need to think about how to design buildings to disinfect the air, improve the air quality, but there was no mention of the use of ultraviolet technology.

EN: What is the saying? "If the only tool you have is a hammer, everything looks like a nail." (Mark Twain)

I have discussed this topic with Joe Allen. His work has focused on ventilation and filtration, funded in part, I believe, by the large ventilation company, United Technologies. He has talked about nothing but ventilation and filtration despite the fact that I've challenged his rationale more than once. I have reminded him that there is simply not even one convincing reported case of COVID room-to-room transmission through a mechanical ventilation system without any other contact. If SARS-CoV-2 virus is not being recirculated, the role of high-retention air filters in ventilation ducts is questionable as a primary mitigation strategy—although air filtration is important for other reasons. And other colleagues in the area who are even more attentive to this question than I am have agreed the observation that proof of viral transmission through ventilation ducts is lacking. [*United Technologies was an American multinational conglomerate that did research, development and manufacturing in areas of aircraft engines, aerospace systems, HVAC, building automation and industrial products. In April 2020 it merged with Raytheon Corporation to form Raytheon Technologies. In 2018, it ranked 51 in the Fortune 500 list of the largest US corporation by total revenue.*]

Now, I think it's possible [for such a room-to-room mode of transmission]. Measles can go through air ventilation systems. TB goes through ventilation systems and so on. With TB and measles there are reports of people in different parts of a building who get infected who didn't have any in-room contact. That's not happened with COVID-19, or, more accurately, has not been reported. And you would think more than two years after the pandemic, with this being the center of attention for a very long time, that people would be reporting this scary possibility if it were a common event—or even an uncommon event.

There are two cases: One from SARS-CoV-1 and one from SARS-CoV-2 of COVID traveling up toilet ventilation ducts.

That's a little different. It's not forced air, it's a passive ventilation duct. There is little dilution and not much air turbulence—factors that may explain the lack of COVID-19 transmission through ventilation ducts. And concentrations in wastewater may have been particularly high. With the toilet vent cases there were people on different floors who got infected, and there's these studies that show that. But not through ventilation systems, interestingly.

So, for me to recommend that schools primarily focus on increasing filtration to MERV 13 with absolutely no evidence that this is going through the ventilation system is really missing the boat. In the *Time* magazine article that I wrote on this I played on the popular musical Hamilton and basically said it's "in the room where it happened."

[Quote from his article: *While it is often difficult to discern among several airborne infection transmission pathways, the apparent paucity of reports of transmission through ventilation ducts likely reflects the well-known fragility of envelope viruses, such as SARS-CoV-2, although dilution in rooms and ventilation ducts to concentrations below infectious dose could also be playing a role. Importantly, if air recirculation in ventilation ducts is not contributing importantly to COVID-19 transmission in buildings, the value of high-efficiency filters or germicidal UV in recirculating ventilation ducts for preventing spread is speculative and limited at best. Moreover, to a person sharing air in a room with someone with infectious COVID-19, there is little comfort in knowing that the air will be decontaminated only after they leave the room. A more effective air disinfection strategy is to rapidly decontaminate the air within the room where person-to-person transmission occurs.*]

It's what's happening in the room that matters. And, so, COVID is spread from person to person in reasonable proximity or at least following air currents within the room. And the strategies we have must be based on what's happening in the room. That leaves us with mechanical ventilation, room air filtration, and germicidal UV. As an aside—filtration in ductwork and in rooms both involve filters, but they are different.

A factor that is often left out is that the amount of ventilation you need for protection is not only dependent on the level of protection that you'd

like. It's also dependent on the source strength of the infection—the rate at which infectious agents (doses) are being generated. In other words, if a virus particle is released in very high numbers, simple calculations will show what happens when you apply six, 12 or 30 air exchanges because of this principle called *target theory*. This applies to all disinfection apparently, which is to say that each application of a *disinfectant* or application of a room *air exchange* removes a *fixed fraction of the risk*. And the next application removes a fraction of what remains, and so on. It's always about the same fraction, and so the remaining risk is always going down incrementally, but never gets down to zero.

And every room air exchange in classic, well-mixed ventilation models, 63 percent of the pollutants, contaminants, odors or whatever are removed. And the next air change removes 63 percent of what's left, and so on. But that is also dependent on what the concentration is to start with and importantly what's being produced continuously.

For instance, for measles, I have a 1991 paper called *Building Ventilation: The Theoretical Limits of Protection for Airborne Infection*, and it argued that building ventilation is optimally designed for comfort. It removes enough carbon dioxide and odors and provides enough oxygen per person, per room to ensure people in that room are comfortable. Ventilation is not designed for, and not always able to adequately reduce the risk of airborne infection. We adjust to levels of odor that are not noticeable, but not to levels of airborne infectious particles that remain dangerous. Riley would say "ventilate for comfort but irradiate for infection control" because only germicidal UV can get you to the 20, 30, 40 equivalent air changes per hour that a truly a highly infectious source case requires for good protection.

You simply can't do it with mechanical ventilation because of flow limitations, costs, etc. And unless you're recirculating all the air, you are going to have to cool or heat the outside air, dehumidify it. If it's a room air cleaner, the noise level to achieve 20 equivalent air changes per hour just becomes problematic, especially in classrooms where the students won't be able to hear the teacher speak, and people will end up turning them off.

BM: I'm very interested to hear you speak on the history of your relationship with Riley and Wells and discussing that period. You wrote a paper with Riley back in 1989 titled *Clearing the Air: The Theory and Application of Ultraviolet Air Disinfection*, which is profound in the sense that this was more than 30 years ago when you were raising this issue, which has come to dominate so much of the conversation on the COVID pandemic. [First sentence in the abstract: *In the 1940s and 1950s, both the potential and the problems of interrupting transmission of airborne infection with ultraviolet (UV) light were demonstrated. William F. Wells first introduced the concept of droplet nuclei as the vehicles of airborne transmission and later showed that these nearly naked, suspended organisms were highly susceptible to inactivation by UV light of 254 nm wavelength*.]

Maybe you can speak about their work hypothesizing that respiratory viruses were airborne. I can't help but think it was a major missed opportunity in public health.

EN: We can go back a little bit earlier. You may know at one point in medical history there were these theories about miasmas and night air and the idea that lots of things spread through the air. And as a reaction to that, there was a view in the late 19th century that nothing spread by air. Infection transmission required direct contact.

There was a public health officer in Providence, Rhode Island, Charles Chapin, who wrote a book called *The Sources and Modes of Infection* and argued that really no infections (maybe tuberculosis) were spread by the airborne route. And it was almost a direct rebuttal to that, that Wells responded with his research and writings. My understanding of Wells was that he was in the military at one time [World War I] and was a sanitary engineer—had no advanced degree—but Riley, nonetheless, called him a mad genius. He did in fact die with a bit of insanity. He was paranoid schizophrenic I think, or at least paranoid.

At any rate, Wells developed an air centrifuge which was able to pull bacteria out of the air—I don't think they were able to do viruses then. And back in the 1930s, the Massachusetts Department of Public Health contacted him. There were a lot of textile mills in Massachusetts and people were getting sick in what are called the charting rooms. Now, I don't know enough about how cotton and cloths were made to exactly know the details, but suffice it to say that there was a lot of dust. And to keep the dust down, they would spray water into the air to try to encourage the dust to settle. Well, the water came from thoroughly stagnant pools and people were getting sick.

Wells took his air centrifuge to these mills with Riley in tow, who was a medical student at the time. How Riley got involved with Wells is that his brother, Ed Riley, worked for Wells as an engineer at the Harvard School of Public Health and he happened to get his younger brother a job as an assistant to Wells. And, so, Richard Riley and Wells did this study at these textile mills and were able to isolate the same bacteria out of the air that was in the stagnant water.

From that they came up with the *droplet nucleus hypothesis* that water droplet particles in air evaporate to the point that they become buoyant, no longer settling and, instead, moving with and through the air. They called these dried residua of larger droplets "droplet nuclei." And from the environmental source they jumped to the next step by hypothesizing that maybe [respiratory] particles generated by infected people before they hit the ground can evaporate into [aerosol] droplet nuclei that might spread disease from person to person.

Frankly, even though in this country we have credited Wells and Riley with the droplet nucleus hypothesis, a colleague of mine from South Africa, a retired pediatrician named Peter Donald, became very interested in the history of airborne infection and went back to Europe to do research on the subject—he was comfortable in French and German—and went through a lot of the older literature. He found there was a lot of discussion on this in Europe over large droplets versus small droplets and using animals to receive infection.

I will send you some of these papers I hope you find interesting.

BM: Can I link to these articles for the interview?

EN: Yes, that's fine. On theoretical limits, you should also quote the early paper suggesting that ventilation alone is insufficient for what we now call "superspreader events" or very highly infectious organisms, of which measles is considered the most infectious airborne organism. [Excerpt: *According to the model, the index case (of TB) added approximately 13 infectious doses (quanta) per hour (qph) to the office air during the exposure period, 10 times the average infectiousness reported in a large series of tuberculosis cases. Further modeling predicted that as infectiousness rises, ventilation would offer progressively less protection. We conclude that outdoor air ventilation that is inadequate for comfort may contribute to airborne infection but that the protection afforded to building occupants by ventilation above comfort levels may be inherently limited, especially when the level of exposure to infection is high*.]

And that's the paper I use the Wells-Riley equation—first used on a school outbreak that Ed Riley had studied and came up with the *Wells-Riley equation*. It is not widely appreciated that the *Riley* in the *Wells-Riley equation* is not *Richard Riley*, but his brother *Ed Riley*. And they came up with a source strength of 5,000 infectious particles per hour for measles in that outbreak. Whereas with TB we talk about anywhere from one to 13 to the highest we've seen of 250. Orders of magnitude more infectious particles generated with measles than TB, for example. So, very different implications for what it takes to prevent infection. SARS-CoV-2 virus, especially the Omicron and subsequent variants, more closely resemble measles than TB in terms of infectiousness and the rates of ventilation or equivalent ventilation needed

for control.

Perhaps an explanation of equivalent ventilation is in order.

Ventilation refers to building ventilation, natural or mechanical. In either case, when a volume of air equal to the room volume enters the room, one air change (AC) has occurred. But not all air is exchanged. New air mixes with old air and if good mixing is assumed, only 63 percent of room contaminants are removed after one AC. Most buildings without mechanical ventilation with windows closed in winter have no more than one air change per hour (ACH) through passive infiltration of air through the building envelope.

Mechanically ventilated rooms should have more, perhaps two to four ACH, but only a fraction comes from outside air depending on the system and outdoor conditions—the rest is recirculated air. Hospital infection isolation rooms have six to 12 ACH—all outdoor air. Outdoor air is often limited intentionally due to the cost of heating, cooling, dehumidifying and filtering outdoor air.

When UV inactivates 63 percent of airborne infectious agents—one equivalent AC has occurred—now being called eACH (equivalent air change per hour). If a room air cleaner removes 63 percent of infectious agents, likewise, one eACH has occurred. Note that eACH is "equivalent" only from an infection risk perspective—CO2 is not removed, nor oxygen added. That is, eACH do not entirely replace the need for comfort-level which require two to four real ACH.

BM: Just to clarify, are you saying that there is a certain threshold concentration of infectious particles necessary in a room where it makes another person more susceptible to getting the disease?

EN: That's an infectious dose concept. And that's another interesting historical note. Wells, again, a brilliant guy, said that for the guinea pig, they were pretty sure that one infectious TB droplet nucleus (one to a few bacteria) could do it. If they made an aerosol so dilute that by chance a guinea pig would only likely inhale one particle, it would still get infected.

Perhaps more than you need to know, guinea pigs were initially used by Robert Koch himself and were subsequently shown by Wells and Radcliff to be so susceptible to human TB that one culture forming unit in air detected by culture on a settling plate—i.e., one infectious droplet nuclei—led to one lesion in the lung of a guinea pig. Riley called this "parity," suggesting that the guinea pig was fully vulnerable to TB—compared to mice and rats, for example.

Rabbits were ultimately bred that were both susceptible and resistant by Lurie in Philadelphia, resulting in his book on resistance to TB. Some compared guinea pig susceptibility to a human infant or HIV-compromised human host.

However, in our AIR studies we found that many guinea pigs get infected but do not stay infected and do not progress to TB—demonstrating that even the guinea pig has some innate resistance to low dose (naturally inhaled) TB—as do even newborns and immunocompromised humans. Still, in the past, injecting a guinea pig with a clinical sample was considered the ultimate test of whether TB was present or not.

Now, the way they knew how many particles were in it, they exposed culture plates to the same aerosol, count the colonies, and then they would count the infections in the lungs of guinea pigs. One infection lesion in a guinea pig was equivalent to one colony-forming unit. We knew in that case that the guinea pig infectious dose seemed to be one particle.

What we didn't know is that for other infections than TB and other hosts than guinea pigs there are other particles in the air that don't infect and don't result in culture being positive. Wells did not know how many infectious particles of TB it takes to infect a human. Humans have been exposed to TB for thousands of years. They have some resistance to the organism, and it varies greatly from population to population in terms of historical exposure to TB and genetically innate resistance. So, Wells side-stepped the problem, calling whatever that unknown number is of particles for any given infection *an infectious dose*. And using a term that refers to the smallest dose of anything, Wells called that a *quantum.* So, Wells talks about "quanta" of infection.

I've used that term and others have as well, although some people are really hung up on it because they want to know how many infectious organisms there are and not how many quanta. But what's nice about a quantum is that you can say that if you have a room and 50 out of a hundred people get infected, you can say that in that volume of air there were 50 quanta of infection. In other words, enough organisms that 50 [infectious] doses were there.

Now some people get two doses, and you can't measure that second dose, and some people don't get any, which is by chance. So, the Wells-Riley equation and the whole concept of airborne infection is a probabilistic concept and quanta is a part of it. Some people think "quanta" is an archaic term. Other people, me included, think it's still quite useful.

BM: At least from what I read on the guinea pig studies and the work done by Wells and Riley, they proved two things. First, that these respiratory pathogens are airborne. But the second is that by using UV to prove the airborne nature of these infections, they also proved UV can prevent their transmission. [*Guinea pigs were considered an excellent model for studying TB transmission. Two groups of these animals were caged above a TB treatment facility and their only contact with infected patients was via ventilation ducts. The experimental group had UV lamps placed in the ventilation ducts leading to their cages while the control had no such device. Only the guinea pigs in the control group became infected with TB.*]

EN: Have you heard of the name Matthew Luckiesh? [*A physicist and director of General Electric's (GE) Lighting Research Laboratory at its facility in Cleveland, Ohio.*] He was at GE and wrote 20 some books on light. But he also wrote a book in 1946 titled *Applications of Germicidal, Erythemal, and Infrared Energy*. And in that book the pictures of UV fixtures were not that different in concept and application to everything we had done [with mercury lamps] until we started using LEDs and low wavelength UV.

By the time Wells was doing his work UV Germicidal was well known. It wasn't widely applied and there was still some skepticism. So, initially, this experiment [for transmission of TB] from human to Guinea pig, which Wells conceived, and Riley carried out in the late fifties, early sixties, was designed to prove airborne. [Excerpt from Riley's 2001 report, "How it Really Happened." *In 1954 Wells and I spent many hours at the (New VA Hospital in Baltimore) hospital ensuring that organisms from the research ward could not escape into the rest of the building, installing in the penthouse an exposure chamber designed by Wells to house 150 guinea pigs, getting the amount of fresh air make-up to the room ventilating system controlled and measured, performing preliminary experiments to show that rabbits in a patient's room could be infected with bovine TB atomized into the ventilating system, and satisfying all concerned that we were ready to start studying human patients.*]

By way of some explanation, there was no contact between the TB patients and the guinea pigs other than the air [in the ventilation ducts]. Two years later, Wells published a paper demonstrating the guinea pigs were being infected at a certain rate consistent with their theoretical modeling. But critiques questioned if the animal handlers could have been carrying infection to the animals. There was only one exposure chamber.

So, for the second two years, they established two chambers. In the ducts leading to the second chamber, they put intense UV lamps. They could have put filters, but they decided to put UV. Not to test UV but to demonstrate that the rate of transmission in the treated air was the same as in the first two years. But there was zero transmission in the treated air, meaning that all the infection was coming off the ward. The handlers were not introducing infection. It was the last nail that had to be nailed down. But it meant that they spent another two years, four years altogether doing

this experiment.

By that time the VA hospital wanted its ward back. And when Riley had come back from a trip to India, they told him it was done—no more! He intended to study Upper Room Germicidal UV but never did. He used a chamber with culture techniques, but he was never able to do the full UV study.

To be continued