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ORIGINAL ARTICLE

Evidence of Airborne Transmission of the Severe Acute Respiratory Syndrome Virus

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ABSTRACT

BACKGROUND

There is uncertainty about the mode of transmission of the severe acute respiratory syndrome (SARS) virus. We analyzed the temporal and spatial distributions of cases in a large community outbreak of SARS in Hong Kong and examined the correlation of these data with the three-dimensional spread of a virus-laden aerosol plume that was modeled using studies of airflow dynamics.

METHODS

We determined the distribution of the initial 187 cases of SARS in the Amoy Gardens housing complex in 2003 according to the date of onset and location of residence. We then studied the association between the location (building, floor, and direction the apartment unit faced) and the probability of infection using logistic regression. The spread of the airborne, virus-laden aerosols generated by the index patient was modeled with the use of airflow-dynamics studies, including studies performed with the use of computational fluid-dynamics and multizone modeling.

RESULTS

The curves of the epidemic suggested a common source of the outbreak. All but 5 patients lived in seven buildings (A to G), and the index patient and more than half the other patients with SARS (99 patients) lived in building E. Residents of the floors at the middle and upper levels in building E were at a significantly higher risk than residents on lower floors; this finding is consistent with a rising plume of contaminated warm air in the air shaft generated from a middle-level apartment unit. The risks for the different units matched the virus concentrations predicted with the use of multizone modeling. The distribution of risk in buildings B, C, and D corresponded well with the three-dimensional spread of virus-laden aerosols predicted with the use of computational fluid-dynamics modeling.

CONCLUSIONS

Airborne spread of the virus appears to explain this large community outbreak of SARS, and future efforts at prevention and control must take into consideration the potential for airborne spread of this virus.

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HONG KONG WAS THE HARDEST-HIT area during the worldwide epidemic of infection with the severe acute respiratory syndrome (SARS) virus in 2003, with the highest incidence rate (1755 cases in a population of 6.7 million) and a high case fatality rate of 17 percent (299 deaths).[1] In fact, the infection in Hong Kong was believed to be the source of the spread of the disease to many other countries.[2] A series of case clusters that occurred during the epidemic in Hong Kong[2-6] suggested that environmental factors might have been involved in the spread of the virus.

The large community outbreak in the Amoy Gardens housing complex affected more than 300 residents of this private housing estate. The index patient infected with the SARS virus visited unit 7 on a middle floor of building E on March 14 and again on March 19 and used the toilet; the patient had diarrhea. Subsequent cases of SARS (categorized according to apartment unit) were located in clusters in four buildings and at certain floor levels.[6] Previously available reports have not provided a satisfactory explanation of the features of the outbreak in the Amoy Gardens housing complex.[7-9]

We analyzed the available data with reference to the spatial distribution of the cases in this outbreak and used models based on airflow dynamics to investigate the possibility of airborne transmission of the SARS virus.

METHODS

EPIDEMIOLOGIC ANALYSIS

We studied data with regard to the date of onset of symptoms and the location of the residences of the persons with SARS virus infection in the initial phase of the outbreak (most of these were probably secondary cases). Residences were characterized according to building (A through S, for a total of 19 buildings), floor (4th to 36th), and apartment unit (apartment unit 1 to apartment unit 8, with eight units on each floor). We then determined the distribution of cases according to date of onset and location of residence.

We used the probability of infection for each apartment unit (not each resident) as the dependent variable and applied the logistic-regression model to explore the association between location (i.e., apartment unit and floor in each building) and the probability of infection.[10] Because each unit had two bedrooms and all units were roughly equal in size, we assumed that each unit housed four persons, which was the largest number of infected persons in any one unit in the data. The observed probability of infection for an individual apartment unit could therefore be 0, 0.25, 0.5, 0.75, or 1. Because the airflow dynamics involved in the spread of the SARS virus in building E (the suspected location of the source of infection) were obviously different from the dynamics in the other buildings, the analyses for building E were performed separately from the analyses for the other buildings.

The floors of the buildings were grouped into three categories according to height (lower, middle, and upper) so as to provide sufficient numbers for analysis. The criteria for the cutoff points were chosen to minimize the deviance in the logistic-regression models.[10] Unit numbers (1 to 8) were recoded to reflect the directions of the bedroom windows (front facing) and living room windows (side facing) in every apartment unit (Fig. 1). In the resultant eight directional codes (Ab, Ad, Ba, Bc, Cb, Cd, Da, Dc, where A is southeast, B southwest, C northwest, and D northeast) that were used in place of the eight unit numbers, uppercase letters indicate the front-facing window direction and lowercase letters indicate the side-facing window direction. The lower floors and apartment unit Cb were used as reference categories in the regression analyses. To examine the possibility of contamination of the analysis by tertiary cases, we repeated the analyses after excluding late-onset cases and used different cutoff dates, beginning with March 26. The fitted models were compared with the use of the maximum rescaled R^2 and C statistics.[11-13]

COMPUTATIONAL FLUID-DYNAMICS ANALYSIS AND MULTIZONE MODELING

A detailed site plan, floor plans, and the layout of the drainage system in the Amoy Gardens complex were obtained from the Buildings Department of the Hong Kong Special Administrative Region. Hourly meteorologic data for the area of Amoy Gardens during March were obtained from the Hong Kong Observatory.

Analysis with the use of computational fluid dynamics (CFD) allowed us to make a reasonably accurate prediction of the detailed airflow pattern in the air shafts (reentrant areas) and around the buildings in the housing complex. Similar airflow models have been used for the study of foot-and-mouth disease[14] and the Sverdlovsk anthrax outbreak of

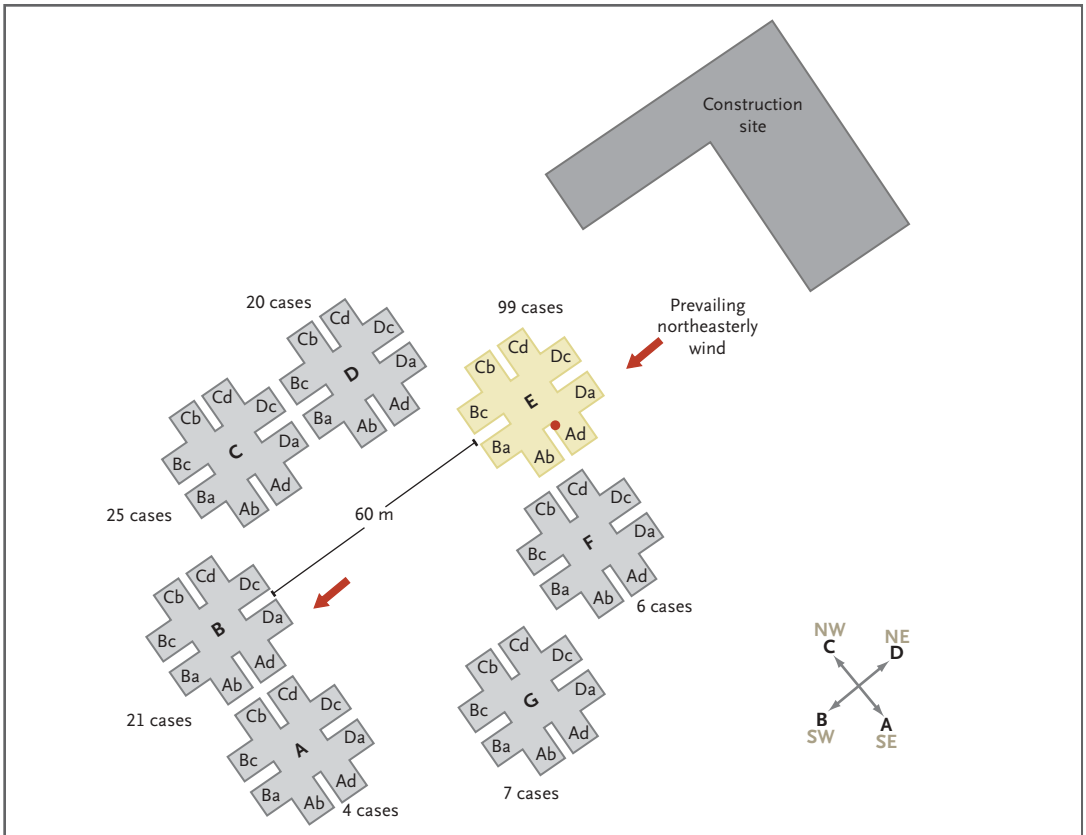

Figure 1. Distribution of Cases of SARS Infection in Buildings A to G in the Amoy Gardens Housing Estate.

The prevailing wind (red arrows) during the period of possible exposure was northeasterly, or roughly perpendicular to the exterior walls of apartment units Dc and Da in building E. The distance between buildings E and B is 60 m. The direction from which the wind blew shifted from nearly north to east and even southeast. The red dot in building E indicates the unit that the index patient visited. The directional indicator for the units at the lower right-hand corner indicates the direction each unit faced. In the directional code (Ab, Ad, Ba, Bc, Cb, Cd, Da, Dc) used to designate an apartment unit, uppercase letters denote front-facing windows and lowercase letters side-facing windows.

1979.[15] In the application of such a modeling tool, turbulence models, numerical methods, and the user's experience can introduce substantial errors.[16] Hence, proper evaluation of the results is essential. Two software packages were used for CFD, Fluent (Fluent) and Airpak (Fluent). Fluent is a three-dimensional, general-purpose CFD software package for modeling fluid flows.[17] We used the basic-renormalization-group (RNG) turbulence model and the Reynolds stress model in Fluent to model the effects of turbulence on airflow and the dispersion of pollutants. The virus-laden water droplets generated from the apartment unit that the index patient visited[6,7] were found to evaporate rapidly (after a few seconds in air) when we modeled the virus-laden plume in the air shaft. For most of the simulations, we approximated the droplet nuclei as passive scalars, and the deposition effect was therefore neglected. Airpak is a three-dimensional CFD software package that was developed for modeling airflow in and around buildings.[18] We used the RNG turbulence model in Airpak to carry out CFD simulations of both the plume flow in the air shaft and the aerosol spread between buildings.

Multizone methods[19] allowed us to calculate the hourly rates of airflow between the apartment units — also called zones for this calculation — and the concentrations of virus-laden aerosols in each unit in building E. These zones were connected by flow paths, such as windows, doors, gaps around closed

windows and doors, and elevator lobbies, to form a flow network. For closed windows and doors, the effective leakage area was calculated on the basis of data from Orme et al.[20] Flow rates through doorways and windows (closed and open) were assumed to be dependent on differences in air pressure. Differences in air temperature and winds, as well as the exhaust from fans, could introduce driving pressures. We used the software program MIX, which was developed by Li et al.,[21] to model the airflows between apartment units in building E, on the assumption that the contamination started from a source inside the air shaft between units 7 and 8.

RESULTS

Adequate data for our analysis of the spread of the SARS virus in Amoy Gardens were available for the first 187 confirmed cases (involving persons in 142 apartment units) of a total of 321 cases (up to April 15, 2003) that were investigated by the Department of Health[6] and that accounted for approximately 70 percent of all cases that occurred on or before April 1. The dates of onset of the first symptoms are shown in Figure 2. The epidemic started on March 21, 2003, and in the majority of cases among residents in all buildings, the onset of symptoms occurred during three days, March 24 to 26, with the peak (mode) on March 24. The shape of the epidemic curve was consistent with an outbreak with a common source. Data with reference to building E alone produced a pattern very similar to that of the epidemic curve for all buildings, and the peak on March 24 was obvious. As shown in Figure 2, in building D, the epidemic started on March 22 and also peaked on March 24; in building C, it started on March 24 and peaked on March 26; and in building B, the first cases occurred on March 23, and there was no clear peak.

The floors in the buildings were categorized by level as lower (floors 4 to 13), middle (floors 14 to 23), or upper (floors 24 to 36). All but 5 patients with SARS (97 percent) lived in the seven buildings (A to G) that form a ring (Fig. 1), and more than half the cases (99) occurred in building E. In buildings A, F, and G, there were fewer than 10 cases each, and hence those buildings were excluded from further regression analyses. In buildings B, C, and D, there were 20 to 25 cases each, and those buildings were included in the stratified analyses.

The fit was very similar in the different models in which various cutoff dates were used for building E. The maximum rescaled R^2 (the proportion of variation explained by the model) ranged from 0.23 to 0.24, and the C statistic was between 0.80 and 0.82. The results of the logistic-regression models without cutoff dates are shown in Table 1. For building E, apartment units (not persons) on the middle and upper floors had higher probabilities of infection than did units on lower floors, with an odds ratio of 5.15 (95 percent confidence interval, 2.6 to 10.3; $P<0.001$) for the middle floors and 3.1 (95 percent confidence interval, 1.6 to 6.2; $P<0.01$) for the upper floors. The risk of infection was highest (odds ratio, 14.5; 95 percent confidence interval, 5.5 to 38.4) for units that faced direction Ab (unit 8 on each floor), and it was also significantly elevated in apartment units that faced direction Ad (unit 7) (Table 1). The units that faced directions Da (unit 6) and Dc (unit 5) appeared to have a slightly lower risk of infection than the other units. Results of the test for heterogeneity were statistically significant ($P<0.001$) for both floor level and direction.

For buildings B, C, and D, the variation among the three categories of floor level was statistically significant ($P=0.01$), but the variation among the eight directions was of only borderline significance ($P=0.06$). For middle-level floors and for directions Ad, Ba, and Da there was a significantly higher risk of infection than on the lower floors and in direction Cb, respectively. In the analyses stratified according to building, only the model for building C showed significant heterogeneity among floor levels and directions. The odds ratios for the middle-level floors (16.3) and for apartment units coded Da (9.9) were statistically significant, whereas those for the upper-level floors (7.2) and for units coded Ad (6.4) were of borderline significance. Location (floor level and direction) was not statistically significant for buildings B and D. However, in building B, all apartment units with windows that faced direction D (either at the front or the side) — that is, the direction from which the wind blew from building E — had high odds ratios, between 3.0 and 5.2; in building D, two directions the windows faced were of borderline significance — namely, Ab (odds ratio, 6.3) and Ba (odds ratio, 6.3). We repeated the modeling assuming five or six residents in each unit and obtained similar results (data not shown).

Figure 3 shows CFD modeling for the vertical

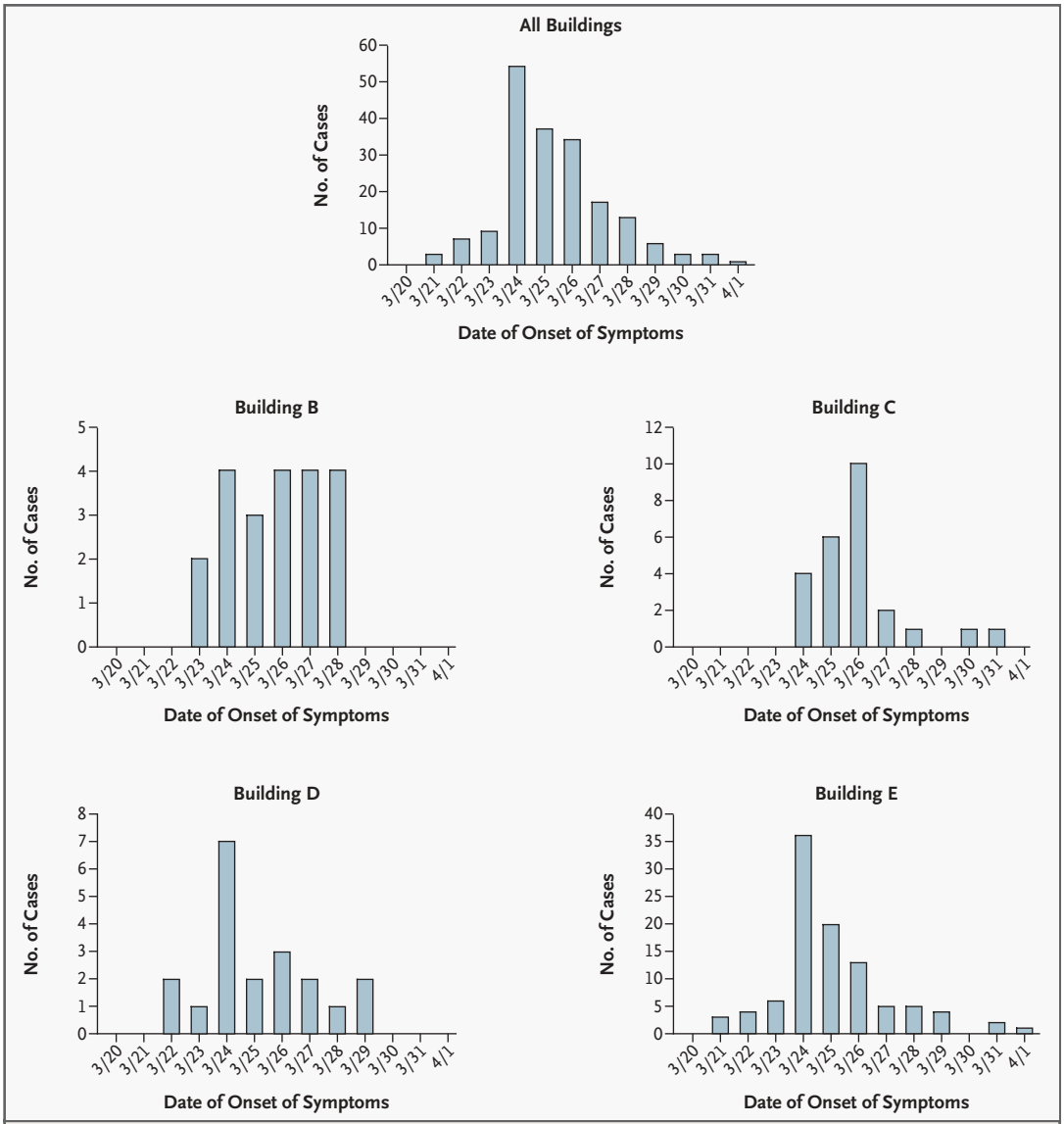

Figure 2. **Epidemic Curves for All Buildings and for Buildings B, C, D, and E.**

movement of contaminated air in the air shaft between unit 7 (Ad) and unit 8 (Ab) in building E and the three-dimensional spread of the viral plume to buildings B, C, and D. Moist, warm air flowed from the bathroom of the index unit (unit 7 in building E, with windows facing direction Ad) and established a plume in the air shaft that spread the airborne virus upward. The predicted decay in the concentration of the contaminated aerosols in the plume was 25 percent at the top of the air shaft where a northeasterly wind was blowing at the velocity of 2 m per second. On reaching the top of the building, the contaminated air was carried by this northeasterly wind toward other buildings. A substantial amount of the contaminated air passed between buildings C and D at the height of the middle-level floors.

The analysis performed with multizone methods showed that horizontal airflows between apartment units in building E, from unit 7 (Ad) and unit 8 (Ab) toward units 1 to 6, were driven mainly by wind pressure and by exhaust fans in the bathrooms or kitchens in units 1 to 6 (Fig. 4). The "normalized" con-

Table 1. Location as a Risk Factor for Infection with the SARS Virus among Residents of Housing Units in Amoy Gardens.

Location	Building E		Buildings B, C, and D	
	Risk*	Odds Ratio (95% CI)†	Risk*	Odds Ratio (95% CI)†
	no./total no.		*no./total no.*	
Floor‡				
Lower	12/320	1.00	11/960	1.00
Middle	46/320	5.15 (2.58–10.29)§	30/960	2.80 (1.39–5.62)¶
Upper	41/416	3.12 (1.57–6.22)¶	25/1248	1.77 (0.86–3.61)
Direction‖				
Cb	5/132	1.00	2/396	1.00
Ab	45/132	14.49 (5.46–38.44)§	8/396	4.07 (0.86–19.30)
Ad	17/132	3.86 (1.37–10.88)**	11/396	5.65 (1.24–25.66)**
Ba	8/132	1.65 (0.52–5.22)	12/396	6.18 (1.37–27.81)**
Bc	9/132	1.88 (0.61–5.79)	5/396	2.52 (0.49–13.08)
Cd	9/132	1.88 (0.61–5.79)	5/396	2.52 (0.49–13.08)
Da	4/132	0.79 (0.21–3.04)	15/396	7.79 (1.77–34.33)**
Dc	2/132	0.39 (0.07–2.05)	8/396	4.07 (0.86–19.30)

* Risk was calculated as the number of cases divided by the assumed number of residents.
† The odds ratios for the risk of infection with the SARS virus at different floor levels compare middle and upper levels with lower levels (the reference category). The odds ratios for the risk of infection with windows facing various directions are compared with units facing direction Cb (the reference category). CI denotes confidence interval.
‡ Floors were categorized according to level as lower (floors 4 to 13), middle (floors 14 to 23), and upper (floors 24 to 36).
§ P<0.001.
¶ P<0.01.
‖ Directions were coded on the basis of the directions each unit faced. Upper-case letters denote front-facing windows and lower-case letters side-facing windows.
**P<0.05.

centration of the hypothetical infectious aerosols was highest in units 7 and 8 (the referent) and lowest in units 5 and 6.

DISCUSSION

Various hypotheses have been proposed to explain the spread of the SARS virus in the Amoy Gardens outbreak. The investigation by the government of the Hong Kong Special Administrative Region suggested that the index patient infected a small group of residents in building E and that the infection subsequently spread to the other residents in that building through the sewage-disposal system, person-to-person contact, and the use of communal facilities such as elevators and staircases. These infected residents subsequently transmitted the disease to others both within and outside building E through person-to-person contact and by contaminating the environment.

An investigative team from the World Health Organization (WHO) found that traps in the floor drains in many of the housing units seemed not to have been filled with water for long periods; the seals in the traps thus dried out, and as a result, a connection was opened to the vertical soil stack (drainage pipe).[7] The investigative team suggested that an exhaust fan that was running behind a closed door in the bathroom could have drawn fine droplets or aerosols from the soil stack into the bathroom through the unsealed floor drain and thereby contaminated the bathroom. The exhaust fan could have transported contaminated droplets or aerosols from the bathroom into the air shaft. These contaminated droplets or aerosols could have been carried upward by the natural air current and could have entered other apartment units, even units several floors away from the source of infection, if the virus-laden aerosols had reached an open window. The WHO report did not provide an explanation for the spread of the infection from building E to the other buildings.

We concur with the WHO hypothesis regarding the source of infection and the mechanism of the initial spread of the virus-contaminated aerosols. With the use of a mock-up of the drainage system in experimental studies at the Hydraulics Laboratory of the University of Hong Kong, we found that huge numbers of aerosols were generated by the hydraulic action in vertical soil stacks when toilets were flushed. The drainage pipes for various units within a single building were not directly connected, and the drainage pipes for all the buildings were not connected until they met underground. Hence, the spread of infection through the sewage system, which was suggested in the government's report, could explain only cases that developed in unit 7 of building E but not cases that developed in other units in that building and in other buildings.

Cases of infection began to occur in buildings B, C, and D only one to three days after the first cases occurred in building E. In the majority of the cases in buildings C and D, the first symptoms appeared within a period of three days (March 24 to 26), coinciding with the peak of the epidemic in building E. This finding suggested that these cases were more likely to have developed from exposure to a common source than from person-to-person contact, as was suggested in the government report.[6] Riley et al.

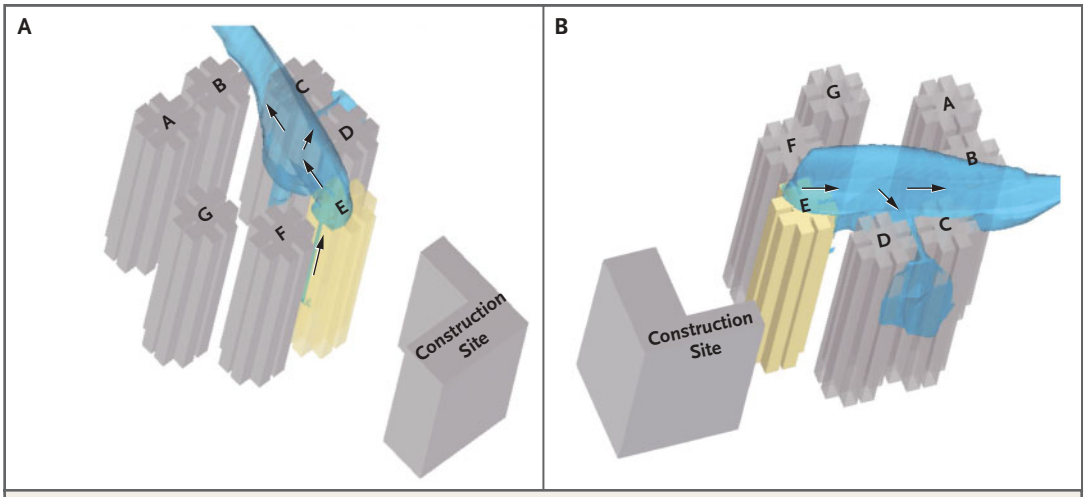

Figure 3. Model of the Movement of the Virus-Laden Plume.

According to our computational fluid-dynamics modeling, the buoyant plume (blue) rose from the air shaft between two housing units in building E (yellow) and was carried by a northeasterly wind toward the middle-level floors in buildings C and D. The L-shape structure (Panels A and B) was a nearby construction site that blocked the wind flowing toward lower-level floors in buildings E, C, and D. The wake flow of the construction site created a region of negative air pressure in the space between buildings E, C, and D (Panel B) that caused the plume to bend downward, toward buildings C and D.

showed that the persons who became ill in the outbreak were likely to have been infected during a very short period (±1 day) around March 19, 2003.[22] Our analysis also showed that the peak exposure would have occurred on approximately March 19 and 20, if a modal incubation period of about four to five days was assumed.[23]

Members of the management and security staff of Amoy Gardens, who worked on the ground floor in each building 24 hours a day and would probably have had frequent person-to-person contact with the residents, were not affected by the virus. Likewise, there were no cases reported among staff members in the large shopping center in the Amoy Gardens estate. The spatial distribution of the affected apartment units (in which there were cases of infection) could not be explained by random person-to-person contact. We believe that such contact probably occurred in the latter part of the epidemic and that the number of cases and therefore the number of units affected by this means was likely to have been small.

Ng put forward the theory that roof rats were both amplifiers and distributors of the SARS-associated coronavirus,[9] but this theory is not supported by the epidemiologic distribution of cases; the middle-level floors were affected more than the upper floors, and certain units were affected more than others in the same building. Roof rats are by nature territorial, and they therefore could not be responsible for the rapid and efficient spread of the infection from a single building, building E, to other buildings. The main flaw in this hypothesis is that it does not explain the steep decline in the epidemic curve after the peak, because there was no sudden disappearance of roof rats or massive deaths among them.

The epidemic curve supports the hypothesis of a common source of the outbreak in Amoy Gardens, and the spatial distribution of the cases conformed to the hypothesis that virus-laden aerosols spread from a single source (the index apartment unit), as shown in our model made with the use of airflow-dynamics data. The delay of one to three days in the onset of the epidemic in buildings B, C, and D might be explained by a lower effective viral load in the aerosols as the plume became progressively diluted. A delay in the onset of symptoms was also observed among cases in the apartment units of building E that did not border the index air shaft. With regard to cases with an onset of symptoms within the first three days of the outbreak, all except one occurred in unit 7 (Ad) and unit 8 (Ab), which lined the air shaft nearest the index unit. The predominant direction of the wind blowing from unit 7 toward unit 8 could explain why residents in unit 8 on

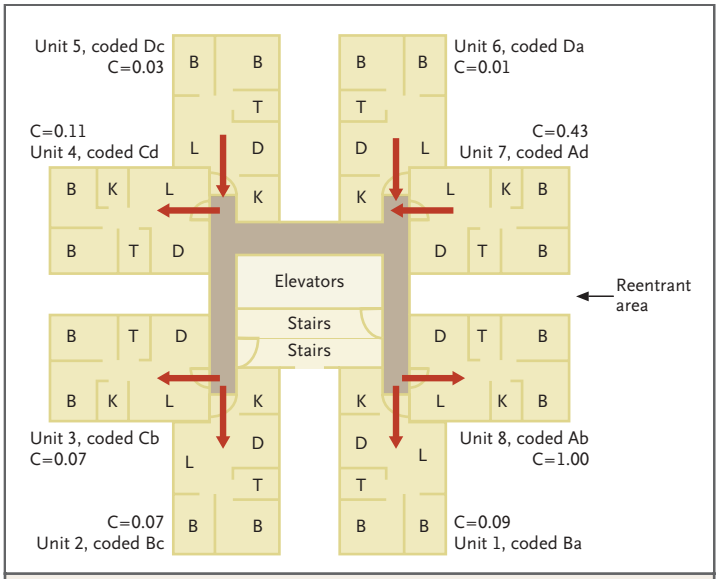

Figure 4. Predicted, Time-Averaged, "Normalized" Concentration of Virus-Laden Aerosols in Apartment Units 1 to 8 in Building E.

The direction of the prevailing airflow (arrows) was modeled through the front door of each unit. For the directional codes for the apartment units, see the legend to Figure 1. B denotes bedroom, D dining area, K kitchen, L living room, and T toilet (bathroom). C denotes normalized calculated concentration of virus-laden aerosols.

the various floors were more affected than those in unit 7.

The dilution of the viral load as the plume traveled upward might explain why residents on the middle floors were more affected than those on the upper floors. In apartment unit 5 (Dc) and unit 6 (Da) there were fewer cases of infection, because these units were upwind of the index air shaft and therefore received the lowest normalized viral concentrations. The unit directions (i.e., the directions the front and side windows faced) and floor levels that were associated with higher risk in buildings C and D corresponded well to the results of the airflow modeling, which showed the contaminated plume passing through the space between buildings C and D at middle-level floors. For building B, apartment units that faced building E appeared to have a higher risk of infection.

The extremely high concentrations of the SARS-associated coronavirus found in the feces and urine of the index patient, coupled with the aerosolization due to hydraulic action inside the drainage pipes (vertical soil stacks), most likely generated huge numbers of virus-laden aerosols. The concentration of the aerosols decayed as the plume traveled away from the source, and the decay corresponded to lower attack rates (and, possibly, to a longer incubation period) in other apartment units of building E and in other buildings. The concentration of virus in respiratory secretions was found to be much lower than the concentrations in urine and stool, and this difference might explain the need for close contact with the index cases in some nosocomial outbreaks of SARS.[24]

In summary, our epidemiologic analysis, experimental studies, and airflow simulations support the probability of an airborne spread of the SARS virus in the outbreak in Amoy Gardens. Virus-laden aerosols generated in the vertical soil stack of unit 7 in building E returned to the bathroom through the dried-up seals of the floor-drain traps and then entered the air shaft, probably by means of suction created by an exhaust fan. The aerosols moved upward owing to the buoyancy of the warm, humid air within the air shaft and could enter apartment units that bordered the air shaft on the upper floors because of the negative pressure created by the exhaust fans or the action of wind flows around the building. The horizontal spread of infection to other units in building E was by movement of the air between apartment units. After the plume reached the top of the air shaft in building E, the virus was spread to some units at certain heights in buildings B, C, and D by the action of a predominant northeasterly wind.

Our hypothesis adequately explains the temporal and spatial distribution of cases of SARS. This hypothesis remains to be confirmed by further analytic epidemiologic, environmental, and experimental studies and should have important public health implications for the prevention and control of SARS, should the disease recur.

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