Original Contribution

Refined Estimate of the Incubation Period of Severe Acute Respiratory Syndrome and Related Influencing Factors

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Received for publication November 5, 2004; accepted for publication September 7, 2005.

Many epidemiologists have agreed that a refined estimate of the incubation period of severe acute respiratory syndrome (SARS) would need a sample size of about 200 cases and appropriate statistical methods enabling the inclusion of cases with defined periods of exposure. However, no such studies have been reported so far. Besides, determinants of the SARS incubation period remain unclear. In this study, 209 probable SARS cases with documented episodes of exposure between March 1 and May 31, 2003, in mainland China were included. A nonparametric method was used to analyze these data with defined periods of exposure to obtain the refined estimate of the SARS incubation period. Furthermore, the authors also explored the influence of various factors on the SARS incubation period by analysis of variance, linear regression analysis, and analysis of covariance. The estimates of mean and variance of the SARS incubation period were 5.29 days and 12.33 days², respectively; 90% of patients would have an incubation period of less than 11.58 days with a probability of 0.8, and 99% of patients would have an incubation of less than 22.22 days with a probability of 0.9. The affected area showed a highly significant effect on the incubation period (p < 0.001), but the contact pattern, occupation, gender, and age did not.

Abbreviations: CI, confidence interval; SARS, severe acute respiratory syndrome.

An “incubation period” is defined as the time from infection to onset of clinical symptoms of disease (1). Accurate estimates of important parameters characterizing the incubation period of severe acute respiratory syndrome (SARS) are of great importance in preventing and controlling outbreaks of SARS, given their significance to the duration of quarantine and to contact tracing. Because many SARS patients had multiple contact dates before the onset of symptoms, their actual dates of infection appeared as interval-censored data, and so did the observations of their incubation periods. The most reliable estimates of SARS incubation periods up to now were based on studies of cases having a single documented exposure to a known case (2–6). However, the sample sizes of these studies were not large enough (usually fewer than 60 cases). In addition, the SARS cases arising...
from a single exposure may not be representative of all SARS cases. At a global conference on SARS epidemiology sponsored by the World Health Organization, epidemiologists agreed that a refined estimate of the SARS incubation period would need a sample size of about 200 cases, and that appropriate statistical methods should be developed to enable the inclusion of cases with defined periods of exposure rather than a single-point exposure alone in order to be more representative (7). To our knowledge, no such studies have been reported so far. The present study provides such a refined estimate.

The length of the incubation period of an infectious disease is likely to be affected by various factors, including virulence of infection, route of infection, host resistance, and dose of the invading organism (8). For example, Miner (9) reported a difference in the incubation period of typhoid fever following infection by food or by water, which he interpreted as reflecting variation in the virulence of the infection. Fenner (10) explained the difference in incubation periods between the naturally occurring disease and that following intravenous inoculation in terms of the time necessary for the proliferation of the organism in the primary lesion and in the regional lymph nodes, which two stages were eliminated when intravenous inoculation was the mode of infection. Stillerman and Thalhimer (11) ascribed differences in the length of the incubation period of measles to variations in host resistance. In an outbreak investigation of food-borne hepatitis A, Istré and Hopkins (12) reported that the incubation period of hepatitis A was inversely related to the dose of virus consumed. Identification of determinants of the incubation period can provide insight into the mechanisms of disease progression (13). However, it remains unclear which factors influence the SARS incubation period (7). The present study also did such an exploration.

MATERIALS AND METHODS

Study population

A total of 220 probable SARS cases with documented episodes of exposure between March 1 and May 31, 2003, were initially identified and screened by individual survey databases of probable SARS cases and close contacts, main transmission chains of SARS in important affected areas such as Beijing, and medical records of SARS cases in some designated hospitals. All data were from the mainland of China in 2003. The criteria for SARS diagnosis were consistent with the criteria for diagnosing infectious atypical pneumonia from the Ministry of Health of the People’s Republic of China. The histories of close contacts and possible factors influencing the incubation period, including age, gender, occupation, affected area, and contact pattern, were investigated through telephone interviews. All interviews were tape recorded and checked by quality control staff to monitor the quality of the interview data. Of the 220 probable SARS cases, 11 cases (5 percent) were excluded from the present study for no reliable exposure information, and 209 cases (95 percent) were included. There were no significant differences in age and gender between the excluded and the included cases.

Categories of the contact pattern

The contact pattern is a synthetic variable comprising the place of exposure, the relation between close contacts and sources of infection, and the mode of contact such as dining together with SARS patients, exposure to respiratory secretions, and visiting SARS patients. Different places of exposure had different risks of SARS-associated coronavirus transmission (14). Health-care facilities were severely affected, and transmission in hospitals was a major factor in the amplification of the outbreaks. In addition to health-care workers, other patients in the same ward or on the same floor with SARS patients and visitors to the hospital were affected. Aerosol-generating medical procedures (e.g., endotracheal intubation, bronchoscopy) may be associated with an increased risk of transmission in health-care settings (14). After health-care facilities, households of SARS patients were the second most common setting of SARS-associated coronavirus transmission. An increased risk among household members of SARS patients had been shown in those with close prolonged contact with the index patient, especially in those who shared a bed, were close in proximity (within 1 m) to the patient, and dined together (15). Thus, a spouse had a higher risk of acquiring SARS. Transmission to casual and social contacts appeared to be uncommon (14).

The incubation period typically is interpreted as the time required for the infecting pathogen to multiply in the host until it leads to disease (16). A higher risk of transmission may correspond to a shorter incubation period. Furthermore, the length of the incubation period of an infectious disease is likely to be affected by several factors, including the dose of the invading organism (8). Therefore, according to the place of exposure, the relation between close contacts and sources of infection, and the mode of contact, we classified the contact pattern into eight categories as follows.

1. Household close contact between husband and wife. Household close contact was defined as a person living in the same household with the household index, who was the person with probable SARS and the first person introducing SARS into the household.
2. Household close contact among other family members.
3. Hospital close contact in routine diagnosis, treatment, and nursing care. Hospital close contact meant that hospitals were the setting of SARS-associated coronavirus transmission. In this category, health-care workers were affected through close contact. Routine diagnosis, treatment, and nursing care didn’t include aerosol-generating medical procedures and other medical procedures of exposure to respiratory secretions.
4. Hospital close contact in aerosol-generating medical procedures and other medical procedures of exposure to respiratory secretions, such as endotracheal intubation, bronchoscopy, suction before performing intubation, manipulating oxygen masks, or presenting during noninvasive ventilation of a SARS patient for more than 30 minutes. In this category, health-care workers were affected primarily through droplets and small-particle aerosols.
5. Hospital close contact in the company and attendance of SARS patients. In this category, a person involved in

Am J Epidemiol 2006;163:211–216
direct patient care was affected through close contact with and exposure to respiratory secretions and excreta.

Hospital close contact from visiting SARS patients. In this category, visitors were affected through close contact.

Hospital close contact with SARS patients in the same ward or on the same floor. In this category, other patients in the same ward or on the same floor with SARS patients were affected.

Other close contacts, including casual and social contacts.

Statistical analysis

We used a nonparametric method to obtain estimates of important parameters characterizing the incubation period of SARS, which is defined as the time from infection to onset of clinical symptoms of SARS. Of 209 probable SARS cases, 48 cases had determinate incubation periods (“complete” observations) from a single contact date, and 161 cases had multiple possible incubation periods (“incomplete” observations) from multiple contact dates. Our analyses depended on the following assumptions: the incubation period was uniformly distributed (“unif”) between the times of first and last contact; and the time of infection and incubation time are statistically independent. Let \( \eta \) denote incubation time, \( t \) denote onset time, and \( s \) denote infection time, and let \( a \) and \( b \) be the earliest and latest times that infection could have occurred. As we assumed \( s = u(\eta, a, b) \), \( s = (a + b)/2 \). If \( s \) is observed (“complete” observations), then \( \eta = a = s = b \), and \( s = s \). Given \( a \) and \( b \), \( E[\eta|a, b] = E[t - \eta|a, b] + E[\eta|a, b] = \mu + 1/2(a + b) = \mu + \delta \). Thus, \( \mu \) is the mean incubation period. \( \delta \) is the time of infection after the earliest possible infection. \( \delta \) is uniformly distributed between the times of first and last contact.

Similarly, the variance of the incubation distribution can be estimated by use of a mixture of “complete” and “incomplete” observations. For an “incomplete” observation, note that \( E[(t - \delta)^2] = E[(t - s + s - \delta)^2] = E[(t - s)^2] + 2\sigma(s - \delta) \). By our assumptions, \( E[s - \delta] = E[\delta] = 0 \); and by standard calculations for the uniform distribution, \( E[(s - \delta)^2] = (b - a)^2/12 \). Hence, for the \( i \)th “incomplete” observation, \( (t_i - \delta_i)^2 = \mu^2 + \sigma^2 + \hat{\sigma}^2 \). Thus, we may estimate \( \sigma^2 \) by use of \( \hat{\sigma}^2 = 1/N \sum_{i=1}^{N} (t_i - \delta_i)^2 - \mu^2 \). As before, for “complete” observations, \( a_i = b_i = s_i = s \), so that the contribution of “complete” observations to this expression is the usual formula for a sample variance.

Under our assumptions, the cumulative distribution function of the incubation period can be estimated by \( \hat{F}(y) = \frac{1}{N} \sum_{i=1}^{N} \Phi(y, t_i) \), where \( \Phi(y, t_i) = \begin{cases} 1, & y \geq u_i \\ 0, & y < l_i \\ \frac{y - l_i}{u_i - l_i}, & l_i \leq y < u_i \end{cases} \). Given a probability \( \alpha \), the quantile \( \hat{y}_\alpha = F^{-1}(\alpha) \) can be estimated by \( \hat{y}_\alpha = \hat{F}^{-1}(\alpha) \), where the estimates of 95 percent, 99 percent, and other quantiles of the incubation period can be obtained for any given \( \alpha \), the standard deviation of \( \hat{F}(y) \) can be estimated by \( \sigma(y) = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\Phi(y, t_i) - \hat{F}_i(y))^2} / N \). As before, the sample quantile \( \hat{y}_\alpha = \hat{F}^{-1}(\alpha) \). Then, the asymptotic 100(1 - \( \alpha \)) percent confidence interval \( (\hat{y}_\alpha, \hat{y}_{\alpha}^{\alpha}) \) for \( y_\alpha \) can be obtained by inverting the confidence interval for \( F(y_\alpha) \), namely \( \hat{F}^{-1}(\alpha) = \hat{F}^{-1}(\alpha + z_{1-\alpha/2} \sigma(y_\alpha)) \), where \( z_{1-\alpha/2} \) is the 1 - \( \alpha/2 \) quantile of standard normal distribution. One-sided confidence limits can be calculated in the analogous way. Thus, \( y_{\alpha}^+ \) and \( y_{\alpha}^- \) can be viewed as the 100(1 - \( \alpha/2 \)) percent one-sided upper limit and lower limit, respectively.

We performed several simple analyses, including group summary statistical analysis, one-way analysis of variance, linear regression analysis, and analysis of covariance, to explore the influence of contact pattern, affected area, gender, age, and occupation on the mean incubation period. In addition, to see whether there was an unexpected significant difference between “complete” observations and “incomplete” observations, an indicator variable \( X_{\eta} \), which takes 0 for a “complete” observation and 1 for an “incomplete” one, was included in our analyses. A \( p \) value of less than 0.05 was considered significant. All analyses were performed by using Minitab, version 12, software (Minitab, Inc., State College, Pennsylvania).

RESULTS

Estimate of the incubation period

The estimates of the mean and variance of the SARS incubation period were 5.29 days and 12.33 days, respectively. The 90 percent, 95 percent, and 99 percent quantiles were 10.70 days (60 percent confidence interval (CI): 10.00, 11.58; 80 percent CI: 9.78, 11.99; 90 percent CI: 9.46, 12.26), 13.91 days (60 percent CI: 12.93, 14.99; 80 percent CI: 12.43, 15.64; 90 percent CI: 12.01, 16.00), and 20.08 days (60 percent CI: 18.92, 21.33; 80 percent CI: 18.46, 22.22; 90 percent CI: 18.08, 24.80), respectively. Hence, with a probability of 0.8, 90 percent of patients would experience the onset of symptoms within 11.58 days of infection; and with a probability of 0.9, 99 percent of patients would experience the onset of symptoms within 22.22 days of infection. The shape of the estimated cumulative distribution function is presented in figure 1.

Univariate analysis

Table 1 showed the SARS incubation periods grouped by indicator variable \( X_{\eta} \), contact pattern, affected area, gender, and occupation, respectively. The mean incubation period was 5.30 days for “complete” observations and 5.28 days for “incomplete” observations, and it was 5.50 days for males and 5.11 days for females. The ascending order of the mean incubation periods grouped by contact pattern was categories 4, 1, 7, 3, 2, 8, 6, and 5. The fourth contact pattern, that is, hospital close contact in aerosol-generating medical procedures and other medical procedures of exposure to respiratory secretions, had the shortest mean incubation period (3.60 days). The means of category 6 (hospital
close contact from visiting SARS patients) and category 8 (other close contacts) were very close to that of category 5 (hospital close contact in the company and attendance of SARS patients). The mean incubation period of medical personnel (4.81 days) was shorter than that of nonmedical personnel (5.63 days).

One-way analysis of variance showed that there was no significant difference in the incubation period between “complete” observations and “incomplete” observations ($p = 0.982$), and that the contact pattern, gender, and occupation also had no significant effect on the incubation period ($p = 0.103, 0.463$, and $0.129$, respectively).

The effect of the affected area on the SARS incubation period was also investigated by one-way analysis of variance. A $p$ value of less than 0.001 indicated that the effect was highly significant. Among the affected areas, Tianjin had the shortest mean incubation period (2.93 days), and Beijing had the second shortest (3.62 days), while Inner Mongolia had the longest (7.17 days) (table 1).

The effect of age on the incubation period was examined by fitting a linear regression model. The result showed that age had no significant linear effect on the incubation period ($p = 0.238$).

Analysis of covariance

Taking the indicator variable $X_0$, contact pattern, affected area, gender, and occupation as category factors and age as covariate, we performed an analysis of covariance to identify the factors influencing the incubation period. The result indicated that these six factors together had a significant synthetic effect on the SARS incubation period ($p < 0.001$). However, the tests of effect of each factor showed that only the affected area was significant ($p < 0.001$); $p$ values for the indicator variable $X_0$, contact pattern, gender, occupation, and age were $0.104, 0.655, 0.950, 0.385$, and $0.100$, respectively. The results indicated again that only the affected area had a significant effect on the SARS incubation period, and that the contact pattern, gender, age, and occupation did not.

DISCUSSION

The incubation period is a key factor in the epidemiology of an infectious disease. Analyses of the SARS incubation period data have been published for various populations of patients (2–7, 17–19). However, the sample sizes of these

![FIGURE 1. Estimated cumulative distribution function, People's Republic of China, 2003. The two solid step curves indicate two empirical distribution functions generated from the lower and upper bounds of the interval-censored incubation period data together with complete data, and the dotted curve indicates the estimated cumulative distribution function of the incubation period for severe acute respiratory syndrome.](https://academic.oup.com/aje/article-abstract/163/3/211/59735)

| Grouped factor                      | No. of observations | Incubation period, days (mean (SD*)) |
|------------------------------------|---------------------|-------------------------------------|
| Indicator variable $X_0$†          |                     |                                     |
| Complete observations              | 48                  | 5.30 (3.72)                         |
| Incomplete observations            | 161                 | 5.28 (3.89)                         |
| Contact pattern                    |                     |                                     |
| Category 1                         | 14                  | 4.61 (2.11)                         |
| Category 2                         | 27                  | 5.80 (4.68)                         |
| Category 3                         | 46                  | 5.14 (4.15)                         |
| Category 4                         | 36                  | 3.60 (2.23)                         |
| Category 5                         | 42                  | 6.20 (3.72)                         |
| Category 6                         | 10                  | 6.15 (3.99)                         |
| Category 7                         | 13                  | 5.11 (4.27)                         |
| Category 8                         | 21                  | 6.14 (4.41)                         |
| Affected area (China)              |                     |                                     |
| Beijing                            | 41                  | 3.62 (2.82)                         |
| Tianjin                            | 32                  | 2.93 (1.23)                         |
| Hebei                              | 60                  | 6.47 (4.78)                         |
| Shanxi                             | 9                   | 4.94 (2.54)                         |
| Inner Mongolia                     | 51                  | 7.17 (3.64)                         |
| Jilin                              | 13                  | 4.08 (2.18)                         |
| Fujian                             | 1                   | 4                                   |
| Hubei                              | 2                   | 3.75 (1.77)                         |
| Gender                             |                     |                                     |
| Male                               | 95                  | 5.50 (3.89)                         |
| Female                             | 114                 | 5.11 (3.81)                         |
| Occupation                         |                     |                                     |
| Medical personnel                  | 87                  | 4.81 (3.51)                         |
| Nonmedical personnel               | 122                 | 5.63 (4.05)                         |

* SD, standard deviation.
† Indicator variable $X_0$, which takes 0 for a “complete” observation and 1 for an “incomplete” one, was used to determine whether there was an unexpected significant difference between “complete” observations and “incomplete” observations.
studies were not large enough (usually fewer than 60 cases). In addition, in many cases, the difficulties posed by “incomplete” data due to multiple contact dates led to researchers’ presenting descriptive summary statistics without further analysis. In the present study, a nonparametric method was used to enable the inclusion of probable SARS cases with multiple contact dates, and the sample size was over 200, which agreed with the recommendation of the World Health Organization (7). Therefore, we believe that our estimates of the incubation period of SARS should be of sufficient reliability.

Our estimate of the mean SARS incubation period (5.29 days) was approximately consistent with the results based on the studies of cases having a single documented exposure to a known case (with means ranging from 4 to 7 days) (2–6), while the estimate of variance (12.33 days²) was much smaller than what were reported by Donnelly et al. (17) (16.69 days²) and by Leung et al. (20) (15.9 days²). The mean incubation period influences the timescale of the development of the epidemic, as it partly determines the time interval between a case and the infections that the case subsequently generates (13). Thus, a more reliable estimate of the mean incubation period would help public health officials to understand the course of the epidemic more accurately and to make better public health decisions.

The maximum incubation period is particularly important as it forms the basis for many recommended control measures, including contact tracing and the duration of quarantine. Knowledge about the maximum incubation period can also help physicians to make diagnostic decisions about whether the presenting symptoms and clinical history of a patient point to SARS or to some other disease (18). However, the maximum incubation period of SARS was less clear (13), with a number of reports of incubation periods exceeding the World Health Organization’s maximum incubation period of 10 days (7, 21). Our results showed that, with a probability of 0.8, 90 percent of patients would experience the onset of symptoms within 11.58 days of infection and that, with a probability of 0.9, 99 percent of patients would experience the onset of symptoms within 22.22 days of infection. These findings suggested that the duration of quarantine might need to be reconsidered to better the practice of public health. At the beginning and the end of a SARS epidemic, to control the epidemic completely, we recommend a period of 22 days for quarantine, which would capture 99 percent of all probable SARS cases with a probability of 0.9. To some extent, such a modification of quarantine policy would increase the resources expended for quarantine.

To some degree, the contact pattern, which is a synthetic variable comprising the place of exposure, the relation between close contacts and sources of infection, and the mode of contact, may reflect the route of infection and the dose of the invading organism. Thus, the contact pattern’s having no significant effect on the SARS incubation period suggested that the route of infection and the dose of the invading organism might not be relevant to the SARS incubation period. Clinically, SARS patients tend to go downhill after a period of apparent initial recovery. Once their immune system kicks in, they begin to recover, but then they deteriorate rapidly (23). Therefore, SARS may be more like an immunomodulated disease than the traditional infectious disease discussed in the introduction. Such diseases as hepatitis A, measles, or typhoid often have their incubation periods depend on “dose,” because these diseases result from the direct pathologic effects of the microbes (8, 9, 12); however, diseases such as dengue, hantavirus pulmonary syndrome, and maybe SARS depend more on the immune system’s response to the virus than on the direct pathologic effect of those viral infections.

Since the incubation period of SARS may depend more on the immune system’s response to the virus than on “dose,” the significant effect of an affected area on the SARS incubation period suggested that the host resistances of cases in various affected areas might be significantly different. However, the different demographic characteristics, lifestyle, natural environment, and epidemic features in the different affected areas may also confound the effect of the affected area. Further studies need to be conducted.

That there was no significant influence of gender on the SARS incubation period indicated that factors associated with gender, such as sex hormones, had no significant impact on the disease progression rate after the infection was established. Generally, infection acquired at a young age was associated with an appreciably longer incubation period (16). However, our study showed that age had no significant effect on the SARS incubation period. Since an analysis of all 1,755 SARS patients in Hong Kong showed that there were a clear excess of young adults and a relative deficit of children and adolescents (20) and that health-care workers, who were mostly young, accounted for 21 percent of all SARS cases globally (14), our result might be partly explained by the age distribution of SARS patients.

To study the influence of occupation on the incubation period, we dichotomized the patients into medical personnel and nonmedical personnel. If the dose of the invading organism were relevant to the SARS incubation period, it was obvious that medical personnel would have a significantly
shorter incubation period than nonmedical personnel would. That there was no significant effect of occupation on the SARS incubation period in our study suggested that SARS may have its incubation period depend more on the immune system’s response to the virus than on “dose.”

Although we believe that our estimates of the incubation period of SARS are reasonably accurate, there may unavoidably be some limitations. First, as the study was retrospective, it was very difficult to avoid recall bias. During the investigation of death cases with SARS, the close-contact information was obtained indirectly, which might affect the validity of results to some extent. Second, although efforts were made to sample SARS cases from all the provinces of mainland China, the availability was different in different affected areas and among the different populations affected. Therefore, selective bias was unavoidable. Finally, the SARS diagnosis at present is based mainly on symptoms and physical signs, and no specific diagnostic tests are available. Thus, although most of the probable SARS cases in this study were selected from clear transmission chains of SARS, and although some of the cases were further confirmed by the SARS-associated coronavirus antibody test, there might still be case misclassification bias. Despite these possible limitations, we believe that our results are, so far, the most reliable and available. They are useful for the development of intervention strategies and epidemic control.

ACKNOWLEDGMENTS

This study was supported by the special programs of oppugning SARS from the Shanghai Science and Technology Commission (grant NK2003-002), the key programs of oppugning SARS from the Ministry of Education of China (grant 10), and the National Natural Science Foundation of China (grant 10271078).

The authors thank Dr. Glen Satten for his detailed guidance and assistance with statistical analysis.

Conflict of interest: none declared.

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