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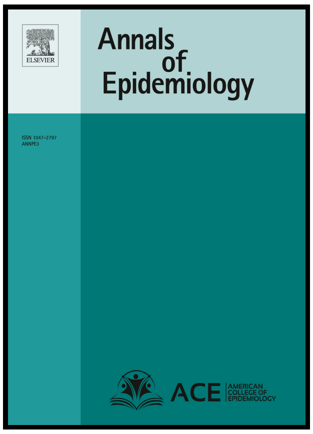

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Super-spreaders of novel coronaviruses that cause SARS, MERS and COVID-19: A systematic review

Super-spreaders of novel coronaviruses that cause SARS, MERS and COVID-19: A systematic review

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Running title: Characteristics of novel coronavirus super-spreaders

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DECLARATIONS

Conflict of interest
The authors declare that we have no conflict of interest.

Approval to use the data to undertake the research
This was a secondary analysis of data in the public domain and therefore ethics approval was not required for the study.

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Author contributions:
JB and IL conceived of the research. JB designed and ran the searches of bibliographic databases. All authors screened scientific studies and resolved differences using discussion or by consulting another author. IL and NJ designed the quality assessment which was undertaken by JB, NJ and FH. JB designed the database, JB and IL coordinated the project. All authors extracted data. JB summarised the dataset with descriptive statistics. JB and FH wrote the first draft and all authors revised for content.

ABSTRACT

OBJECTIVE Most index cases with novel coronavirus infections transmit disease to just one or two other individuals, but some individuals 'super-spread' – they infect many secondary cases. Understanding common factors that super-spreaders may share could inform outbreak models, and be used to guide contact tracing during outbreaks.

METHODS We conducted a comprehensive search in MEDLINE, Scopus and preprint servers to identify studies about people documented as transmitting pathogens that cause SARS, MERS or COVID-19 to at least nine other people. We extracted data from and applied quality assessment to eligible published scientific studies about super-spreaders to describe them by age, sex, location, occupation, activities, symptom severity, any underlying conditions and disease outcome. We included scientific studies published by mid June 2021.

RESULTS The completeness of data reporting was often limited, which meant we could not identify traits such as patient age, sex or occupation. Where demographic information was available, the most typical super-spreader was a male age 40+. Most SARS or MERS super-spreaders were very symptomatic, the super-spreading occurred in hospital settings and frequently the individual died. In contrast, COVID-19 super-spreaders often had very mild disease and most COVID-19 super-spreading happened in community settings.

CONCLUSION SARS and MERS super-spreaders were often symptomatic, middle- or older-age adults who had a high mortality rate. In contrast, COVID-19 super-spreaders tended to have mild disease and were documented to be any adult age. More outbreak reports should be published with anonymised but useful demographic information to improve understanding of super-spreading, super-spreaders, and the settings that super-spreading happens in.

Keywords

Coronavirus; super-spreading; heterogeneity of transmission; index cases

Introduction

During the COVID-19 pandemic the role of super-spreaders in the transmission of the disease became a widely discussed topic within the scientific community and in the media. Throughout 2020, the media reported COVID-19 super-spreading in fitness classes, religious worship, skiing trips and public transport. It has long been noted that for a variety of diseases 20% of the host population has the potential to cause 80% of transmission (20/80 rule) (Woolhouse et al. 1997). Fully understanding the role of super-spreaders could enable more effective containment of disease outbreaks, and more accurate modelling of epidemics. Studies have described super-spreading events for SARS e.g., (Zeng et al. 2009; Shen et al. 2004), MERS e.g. (Kang et al. 2017; Alanazi et al. 2019) and COVID-19 e.g. (Kim and Jiang 2020; Safer et al. 2021). However, to date, there is little focus on the characteristics of the individual super-spreader and what factors might make an individual into a super-spreader (Stein 2020; Chen et al. 2021; Lloyd-Smith et al. 2005). By compiling details from super-spreading events across three novel coronavirus outbreaks, we aimed to assess whether there are any common factors between super-spreaders. This information may be used to guide contact tracing during outbreaks, or aid early identification of super-spreaders, and prevent super-spreading, therefore helping to reduce total transmission and reduce harms from future pandemics (Stein 2020; Kain et al. 2021; Lloyd-Smith et al. 2005).

Reasons offered to explain why only some cases become super-spreaders can be grouped into four categories: transmission pathways suited to that pathogen (e.g., droplet, fecal oral, contact with bodily fluids, etc.), biological/individual factors (e.g. age, sex, ethnicity, viral load, duration of shedding), behavioural factors (e.g. type of work, number of contacts), and environmental factors (e.g. air circulation in work place) (Frieden and Lee 2020). We undertook this review to research attributes of individuals believed to be index patients in super-spreading events of novel coronaviruses that cause any of MERS, SARS or COVID-19, using evidence published by June 2021. We were interested in specific individual, behavioural and environmental factors which were likely to be most available in outbreak reports: transmission setting, sex, age, ethnicity, occupation, how many cases were in the cluster, severity of symptoms, disease course outcomes and comorbidities.

Methods

We defined a "super-spreader" as an index case who was described in the scientific literature as linked to at least nine secondary infections with eligible viruses. We chose nine as the threshold to be indisputably much higher than the commonly cited effective reproductive numbers (between 2 and 5) for the novel coronavirus diseases: SARS, MERS, and COVID-19 (World Health Organization 2003; Choi et al. 2018; Viceconte and Petrosillo 2020). There is no formal consensus on how to define super-spreaders relative to the typical reproductive number for a stated pathogen (Al-Tawfiq and Rodriguez-Morales 2020). Super-spreading was defined as "above the average number of secondary cases" for SARS (World Health Organization 2003). Others suggested that super-spreaders should be defined as the 1% of index cases that generated the most secondary infections (Xu et al. 2020; Lloyd-Smith et al. 2005). We acknowledge that other definitions of 'super-spreader' have merits.

We were only interested in transmission between humans outside of deliberate experiments. We refer to 'super-spreading events' as events where super-spreading is believed to have happened. Events ranged from a small birthday party to the annual Hajj pilgrimage in size and scope.

There was ambiguity in primary studies about how many secondary infections were directly linked to each index case. Different studies identified different numbers of secondary cases for the same index case, sometimes fewer than nine. We tried to be inclusive about this eligibility criteria: if at least one peer-reviewed assessment identified a minimum of nine secondary infections, we included the individual as a super-spreader. However, some sources that describe the same specific index case, may have suggested fewer secondary cases. Therefore, the range of secondary cases reported sometimes includes values under nine. We report the full range of possible counts of secondary cases from each specific index case as identified in relevant literature even if some of these were less than nine.

We undertook a structured search of scientific bibliographic databases using the search terms in Box 1. Note that how phrases in this search were interpreted by the search engine is that partial matches are returned; eg., searching for SARS would match to any of SARS (the disease), SARS-CoV (original name of virus that causes SARS), SARS-CoV-1 (new name of virus that causes SARS) or SARS-CoV-2 (virus that causes COVID-19). Searches were completed in June 2021. The search results were combined into a single database and de-duplicated. We chose not to use data from public-access inventories of apparent nCoV super- spreader events because we wanted to confine our efforts to the most validated evidence available to date, using evidence that had been collected by applying criteria that we understood, was designed to have minimal bias, and we could describe transparently. This review has PROSPERO registration CRD42020190596.

Screening

Eligible publications were published in 2002 or later. Our latest search date was 18 June 2021. We considered publications in all languages if we could translate them to English or Spanish. Two independent screeners applied eligibility criteria, with a third person deciding if no consensus could be reached. Studies had to be chosen by at least two reviewers to go to full text review. Full-text review confirmed eligibility criteria. The study had to describe infection(s) confirmed by rt-PCR, cell-culture or clinical presentation and known exposure history. Eligibility criteria were:

- Study must describe one of these 3 novel coronavirus (nCoV) diseases: MERS, SARS, COVID-19

- Study design: almost any, but case or case-cluster studies were preferred. Preprints or grey literature from credible sources could be used and could be supported by sources such as public statements by individuals themselves, interviews and press releases.
- Any unplanned non-laboratory setting (e.g., clinical, schools, homes, places of worship, etc.).

SCOPUS SEARCH
(TITLE-ABS-KEY (coronavirus OR covid* OR wuhan OR mers* OR "Middle East Respiratory" OR sars OR "sudden acute respiratory") AND ALL (super*)) AND PUBYEAR > 1999 AND (LIMIT-TO (SUBJAREA , "MEDI"))

medrxiv/bioRxiv/Preprint.org servers
(coronavirus or COVID* or MERS* or “Middle East Respiratory” or SARS* or “sudden acute respiratory syndrome”)
And
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((coronavirus or COVID* or MERS* or “Middle East Respiratory” or SARS* or “sudden acute respiratory syndrome”).ab.)
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Box 1. Phrases used for scientific bibliographic database searches

Extraction and Synthesis

One investigator undertook initial extractions which were checked by another researcher, with differences resolved by discussion or a third opinion. We tabulated and descriptively summarised this information separately for each disease. The extracted information was grouped by virus / linked disease (MERS, SARS, COVID-19). Pooled summaries were only undertaken if there were at least 20 super-spreaders found for any disease. No pooling of data beyond descriptive statistics (such as median age or percentage female) was attempted for smaller groups. We expected that much information would be heterogeneous and need to be reported as stated by authors. Throughout the results, we often report raw numbers (such as numbers of persons found in a specific age group) but note that that because COVID-19 pandemic was much bigger than SARS or MERS outbreaks, the results should be considered relative to all cases (proportionately) for each specific disease.

Activities when super-spreading: We reported the activities that super-spreaders seem to have been doing when spreading infection (such as being an inpatient, working in a call centre, attending a fitness class, etc.).

Setting: We determined where super-spreader had their impact, in settings such as households, hospitals, places of worship etc. Additionally, country was reported, as was city or other regional information when available. For reporting purposes setting was grouped with activities when super-spreading.

Age and sex of the super-spreader: Age (in years) and gender was reported.

Ethnicity and Occupation: We knew from preliminary searches that this information is largely unavailable, but report the information we found narratively.

Secondary cases: We recorded the direct count of first generation cases and took this to equal the number of people that each super-spreader was believed to transmit to. This was expressed as individual case counts. This estimate was sometimes described as a range, as counts for index cases occasionally varied across different sources. We report all available information.

Symptoms and disease outcomes: Outcomes (especially mortality rates) for the super-spreaders were summarised in simple narrative format.

Underlying conditions: We recorded narratively which underlying conditions the super-spreader individuals were reported to have (such as diabetes or heart disease). There is a hypothesis that super-spreaders are more likely (than the general population) to be people with compromised immune systems (Lakdawala and Menachery 2021). Conversely, there was also widespread public perception early in the COVID-19 pandemic (Grey 2020) that super-spreaders might often be nearly or completely asymptomatic. We collected data that might address either hypothesis.

Deviations from protocol

We intended to report on tertiary and onward transmission counts, broken into percentiles or median estimates. We extracted this information but found that it was reported with such variability and inconsistency that it was not possible to summarise, and is not elaborated upon further. A post-hoc sensitivity analysis was undertaken.

Quality Assessment

We designed a customised quality assessment of the primary studies (Table 1). This checklist was designed to assess the credibility of sources and the rigour of their contact tracing methods and transmission chain reconstructions. We defined studies with six “Yes” answers as “Most credible”, studies with four or five “Yes” answers as “Fairly credible” and those with three or fewer “Yes” answers as “Less credible”.

Additional Analyses and Interpretations

We examined the information collected to attempt to establish whether people identified as super-spreaders of novel coronaviruses ‘could be anyone’ or tend to fit a profile, such as being late middle age males or especially socially connected individuals. We were interested in whether super-spreading depended on certain types of people or the situations they were in. This information was only interpreted narratively but with respect to relevant literature or statistics such as the age distribution of people in the country where the super-spreader lived.

We did not collect information on viral load carried by identified super-spreaders because this information is not systematically reported. However, we collected information to address the hypotheses that super-spreaders tend to be especially asymptomatic or especially severely ill. Severity of disease was indicated by mortality outcomes. Survival rates for super-spreaders were calculated for each disease. The survival rates of patients who are super-spreaders were compared to publicly available survival rates of known MERS/SARS/COVID-19 cases.

A sensitivity analysis was undertaken. We considered if broad findings about age profile, sex balance, settings or symptomatic status were especially different (segregated by disease) for individuals linked to a higher number of secondary cases (specified as at least 12 in all reports) and where the evidence base was at least fairly credible, i.e., quality scores ≥ 4. We compare these subgroup findings narratively to results from the main analysis.

Results

The search procedure is illustrated in Figure 1. Counts of super-spreaders identified for each disease were: COVID-19, 76; SARS, 29; MERS, 14. There were many more COVID-19 super-spreading individuals documented, partly due to the much wider spread of COVID-19, and long pandemic duration, starting in 2020, as well as better ascertainment methods available in 2020 compared to earlier years and greater numbers of papers published around this disease compared to MERS and SARS. The data summaries are discussed narratively and also presented in condensed format in Table 2 (with sensitivity analysis).

Quality Assessment

Figure 2 shows information about the distribution of quality scores for the individuals identified. The quality score data are shown as percentages with each score, to make it possible to compare the quality of evidence associated with each disease, in spite of the different case counts (many more for COVID-19). Altogether, 30% (36/119) of super-spreader individuals had epidemiologic descriptions that scored 6 in the quality assessment exercise (most credible rating). Proportionately, MERS super-spreaders had the highest number of “most credible” ratings (7/14, 50%). 28% (8/29) of SARS super-spreaders had epidemiologic evidence that was most credible (scores ≥ 6); this proportion was similar for COVID-19 super-spreaders (26% (21/76)). Proportionately, more COVID-19 outbreak reports were good or better quality than those for SARS or MERS, which is reassuring in light of much commentary about poor quality research published during the COVID-19 pandemic (Bramstedt 2020).

Table 1 Quality Assessment Checklist for included studies

	Category	Answers (from cluster of sources about each event)
1.Primary	Is the document a primary source of information, i.e. have they conducted the study themselves or are they reporting on the work of others?	YES: collected majority of info themselves, but may mention some secondary data to inform their summary. Primary needs to be original interviews or review of original medical records. NO: Obviously mostly or entirely citing others UNCLEAR: other answers, including unclear sources or not clear that majority of the info being reported was primary data collection
2.Document	Has main source of information been subject to peer review?	YES: Publication title = in Scimago or Pubmed NO: other source
3.Case definition	Is there a formal case definition (ideally chain based upon a PCR/antigen/lab test among at least one of the index/secondaries) as opposed to only symptoms etc. *If not explicitly stated this could be surmised if the study was from a health agency.*	YES: There is a statement what case definition is, and this involves either A) Contact history/chain with lab-confirmed cases and fever+cough symptoms B) PCR- or antigen-confirmation of most cases NO: No case definition provided UNCLEAR: Other case definition
4.Rigour	Do sources state that a formal contact tracing procedure was in place? *If not explicitly stated this could be surmised if the study is from a health agency.*	YES: Describes interview(s) with most/all original index case(s) NO: clearly No Interviews with index cases or valid proxies UNCLEAR: Few/minority interviews with index/contacts, or can't tell, or not easy to answer YES or NO
5.Exposure	Is there evidence that there has been close (enough) contact between the super-spreader and infected individuals (e.g. same hospital ward, apartment) **This may be difficult to define**	YES: Is plausible from contact history that had opportunity to spend at least 10 minutes within 2m of each other; or another mechanism for super-spreading has been suitably described and defended (eg., Amoy Gardens aerosolised) NO: Contact history not describing plausible high risk contact opportunities UNCLEAR: If contact history not sufficiently described
6.Timeliness	Do the dates of contacts and illness match likely incubation periods (i.e. MERS median 5 range 2-14 days, SARS variable 2-7 days, COVID median 5 range 2-14 days)	YES: see windows <- NO: outside those windows UNCLEAR: not stated, can't be sure

Scoring: number of YES answers: Most credible: 6 YES answers, Fairly credible: 4-5 YES answers, Less credible: 0-3 YES answers

Figure 1 Study Selection Procedure

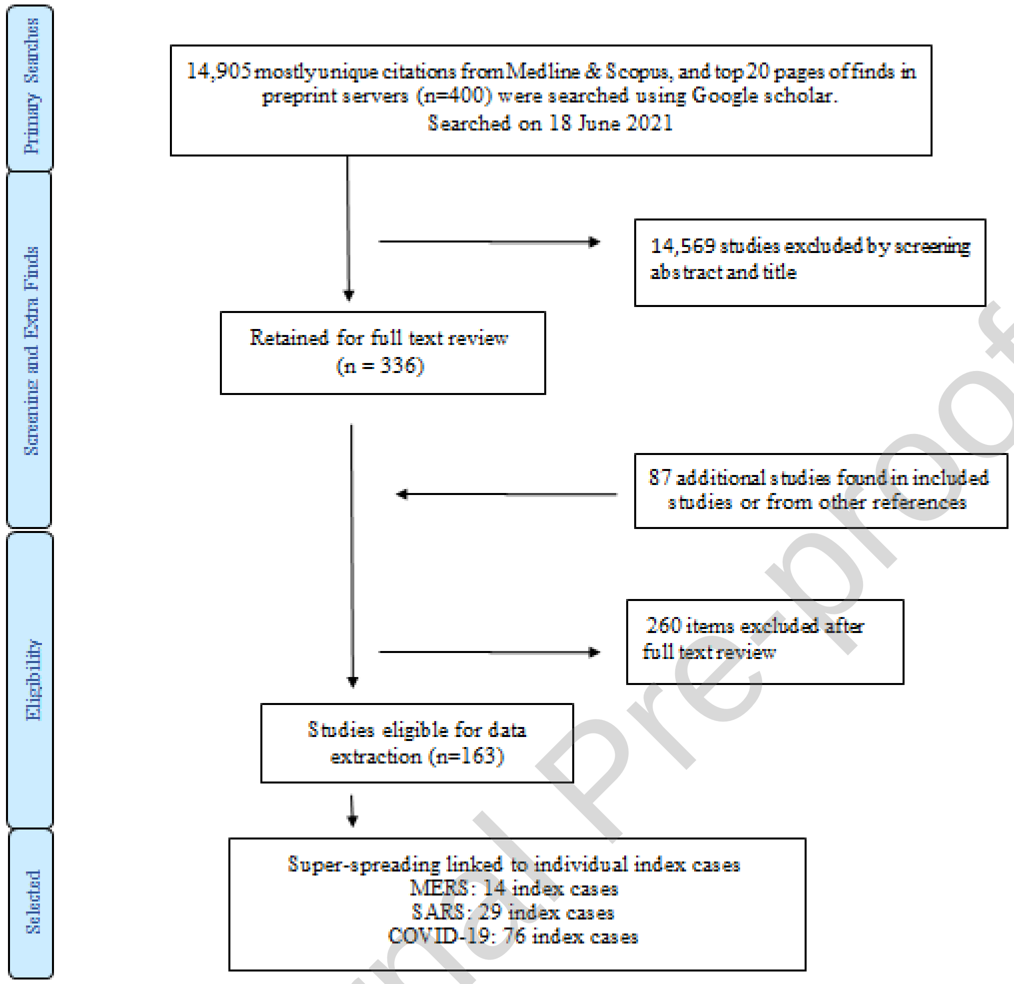
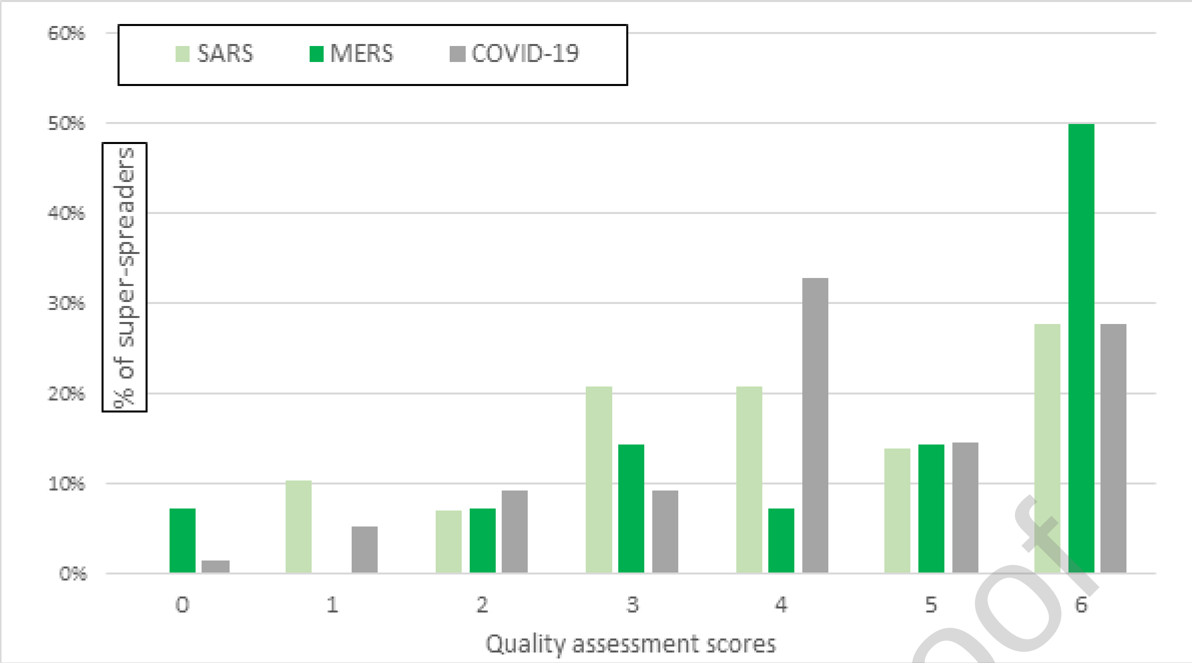


Figure 2. Quality assessment scores for epidemiologic information on nCoV super-spreaders.



Note: Questions in Table 1 were used to determine the quality assessment scores shown in Figure 2.

MERS

We provide a narrative summary because only 14 eligible MERS super-spreader individuals were identified. See Table S1 in Supplemental Material for MERS super-spreader details. Eight index cases were in Saudi Arabia, five in South Korea and one in the UAE. These transmissions happened in 2014-2017. The five South Korean super-spreaders were linked to the May-July 2015 MERS outbreak.

Activities when super-spreading and settings

All MERS super-spreading was linked to clinical settings, usually from hospital inpatients admitted for their recognised respiratory illness, although day patients who attended clinic for other reasons (e.g., receiving dialysis) were also identified. Most secondary cases were other hospital patients and health care workers.

Age and sex

Index case age and sex was available for 12 individuals, who had median age 48 years (range 23-75 years, IQ range 38-60.5). There were two females and 10 males.

Ethnicity and occupation

Traits such as ethnicity and occupation were mostly not reported. Two super-spreaders were stated to be Korean, one was Yemeni, and the patient in UAE was described as 'ex-patriate'. Occupation was described for three MERS super-spreaders in the Middle East: police storage room staff, camel butcher and factory worker. Most secondary cases were health care workers.

Secondary case counts

Estimated counts of secondary cases caused by these 14 index patients ranged in published studies (sometimes quite preliminary) from two to 89. The largest counts of identified secondary cases and total people in epidemiological clusters were in South Korea.

Symptom severity and outcomes

No MERS super-spreaders were described as asymptomatic; specific symptoms of severe illness were documented for nine super-spreaders among whom pneumonia was the single most common diagnosis (n=5). No information was given on survival or otherwise of two MERS super-spreaders. Of the remaining 12 super-spreaders, four survived to discharge and eight were recorded as deceased from MERS (mortality rate 67%). The crude case fatality rate for MERS has been reported as 34.8% (World Health Organization 2017) (World Health Organization 2017).

Underlying conditions

Two of the MERS super-spreaders were investigated for comorbidities but reported to have no underlying health conditions; information was not provided for two others. Among the 10 super-spreaders with documented underlying conditions, a range of conditions were mentioned, including hypertension and kidney disease. Diabetes mellitus was the most commonly mentioned comorbidity (four of the 14 super-spreaders).

SARS

Altogether, 29 eligible SARS super-spreader individuals were identified. Of these, 16 were in China, five in Singapore, three each in Canada and Hong Kong, and one each in Vietnam and Taiwan. All transmissions occurred in the period December 2002 to April 2003 (most were in March 2003). See Table S2 in Supplemental Material for summary extracted SARS super-spreader details.

Activities when super-spreading and settings

Almost all transmissions occurred while patients were in clinical settings (usually when they were admitted to hospital for treatment related to their SARS, but also when being treated as outpatients, visiting other inpatients or transiting between hospitals). Some transmission in the community was deemed likely for five super-spreaders. Air travel was identified as the transmission location for one patient.

Age and sex

Index case sex was available for 27 individuals. There were seven females and 20 males. Index case age was available for 23 individuals who had median age 54 years (range 22-91 years, IQ range 42-70).

Ethnicity and occupation

Ethnicity or national origin was only reported for nine SARS super-spreaders: five were described as Chinese, one Malay, one Filipino, one Asian American and one of 'non-Asian' descent. There was no evidence that ethnic representation was different from ethnic distribution in the origin areas. Occupation was mostly not reported. Five individuals had occupational links to clinical settings: an ambulance driver, clinical professor, nurse, hospital laundry worker and family physician. There were two businesspeople, one seafood merchant, one vegetable seller. A patient aged 73-74 was described as retired. Similar to large MERS outbreaks, where occupational data were available for secondary cases, the secondary cases tended to be health professionals. Other occupations listed among the secondary cases were taxi drivers and market stall traders.

Secondary case counts

Estimated counts of secondary cases generated by these 29 index patients ranged from four to 51. Most cases were in the Far East (China, Hong Kong and Taiwan) plus Canada.

Symptom severity and outcomes

No SARS super-spreaders were described as asymptomatic. Information was available on symptom severity for 22 SARS super-spreaders. Altogether, 18 were described as having fever; symptoms of respiratory illness were reported for 17. No information was given on mortality for 13 SARS super-spreaders. Of the remaining 16 patients, three survived to discharge and 13 were recorded as deceased from SARS (mortality rate 81.3%). SARS mortality rates are sex- and age-dependent, and have been estimated at 26% for Chinese patients age ≥ 80 years (World Health Organization 2003).

Underlying conditions

There was no information about possible underlying health conditions in 16 of the 29 SARS super-spreaders. Two were described as having unremarkable or 'previously healthy' histories. Underlying health conditions were reported for 11 patients. Eight of the 11 had cardiovascular conditions, six had forms of diabetes.

COVID-19

In total, 76 eligible super-spreaders of COVID-19 were found. Of these, 38 were in east or southeast Asia, 15 were in Europe, 14 in North American and nine elsewhere in the world. The USA contributed 12 super-spreaders to the database, the largest count from a single territory. The majority of super-spreader events (n = 61) reported on in this study occurred before end of May 2020. See Table S3 in Supplemental Material for summary of extracted COVID-19 super-spreader details.

Activities when super-spreading and settings

Information on activities that were happening when super-spreading events happened was available for 56 individuals. In contrast to the MERS and SARS outbreaks, most super-spreading COVID-19 index patients were active in the community at the time that they were index patients, not receiving medical care. Just 12 of the super-spreaders were linked to clinical settings, either as patients or health care workers interacting with patients and colleagues. Other activities or settings linked to super-spreading were social/business in nature (n=22), religious worship (n=7), fitness or sport (n=5), education (n=4), public transport (n=3) and residential settings (one each of prison, summer camp and long-term care facility).

Age and sex

Index case age was mostly unavailable; where age data were available this was predominately in Asian countries. Approximate or specific age information was provided for 28 individuals who had median age 56 years (range 18-85 years, IQ range 43-67). From the 36 cases where sex was reported, there were 23 males and 13 females. All 13 super-spreaders whose sex was reported as female were from countries in east and southeast Asia (where males were equally represented, n=12). This sex imbalance for COVID-19 super-spreaders is likely an artefact of widespread lack of reporting index patient sex rather than evidence of underlying sex disparity in representation.

Ethnicity and occupation

Ethnicity was rarely reported (only for six individuals). Where ethnicity was reported it was typically described by nationality: “American” (n=3), “British” (n=2), and Korean (n=1). Occupation was mostly not reported but was described for 26 individuals (34%). There were six health care workers, four fitness instructors, four school staff, three religious leaders, two retired individuals, two businesspeople, and one person each described as office worker, summer camp staff, sales representative, pilot and meat processing plant worker. One person may be plausibly inferred as a working as a church organist or piano player (Katelaris et al. 2021).

Secondary case counts

Estimated counts of secondary cases ranged from eight to 78. The index cases with the largest counts of secondary infections were in Jordan, South Korea, Myanmar, Hong Kong and the USA.

Symptom severity and outcomes

Symptom status was recorded for 50 individuals. Seven were described as asymptomatic at the time of super-spreading. Three were described as entirely asymptomatic, while four subsequently developed symptoms (in Yu et al. 2020; Mahale et al. 2020; Leung et al. 2020; Lam et al. 2020; Groves et al. 2021; Cheng et al. 2021). Additionally, 13 super-spreaders were described as pre-symptomatic and three as mildly symptomatic. Other individuals had symptoms at the time of their super-spreading. No information on survival was available for 41 index cases. Three super-spreaders were reported to have died, while 32 were reported to have survived. This suggests a case fatality rate for super-spreaders of about 8.8%, which is 3.27 times higher than all-age COVID-19 case fatality rate of 2.7% suggested by pooled analysis of data available in the first 9 months of the COVID-19 pandemic (Ahammed et al. 2021).

Underlying conditions

Individual underlying health status was rarely reported for COVID-19 super-spreader individuals. It is likely that in some cases this lack of information means absence of underlying conditions, but we cannot be sure without explicit statements. Just four super-spreaders were reported to have underlying conditions, while one was reported to have had a previous “record of good health”.

The lack of specific age data on most super-spreader individuals resulted in small country-level datasets, making robust comparison with age distribution in each country untenable. The country that contributed the most specific age data was China. We therefore undertook a China-only comparison with the with age-distribution estimates within the Chinese population of 2003 (SARS) or 2020 (COVID-19) (see Supplemental Figure S4). This limited comparison suggests that older individuals (age 40+) were over-represented for both SARS and COVID-19 compared with age-distribution estimates within the Chinese population of 2003 (SARS) or 2020 (COVID-19). These data suggest that in China individuals more prone to super-spreading are relatively older, at least age 40+.

Sensitivity analysis

In our sensitivity analysis, we considered the age distribution, sex balance, transmission settings and symptomatic status of super-spreader individuals for each disease, where the subgroups were defined by those individuals linked to at least 12 secondary cases in all reports, or where the evidence base had quality score ≥ 4. Results are in Table 2. There was divergence from the main analysis findings, in that females slightly dominated the COVID-19 super-spreaders linked to ≥ 12 secondary cases; but this result was not confirmed for the most credibly documented COVID-19 super-spreaders (where males strongly dominated, as they did for all SARS and MERS subgroups). The median age was about 55 in these subgroups (compared to 48, 54 or 56 in all-data findings). Almost all settings for subsets of SARS or MERS super-spreaders were clinical; but community settings were the large majority for COVID-19 super-spreading. All subset SARS or MERS index cases were symptomatic, but about 30% of COVID-19 index cases in these subgroups were pre-symptomatic or never developed symptoms. Overall, this sensitivity analysis has results that agree with and reinforce conclusions that may be drawn from the results gained by analysing the larger dataset.

Table 2. Age, sex, symptomatic status and transmission settings for subgroups

	n	Age Median: IQR	Sex %M	% symptomatic at time of transmission	% in community or mixed settings
All studies, when at least some reports say ≥ 9 secondary infections					
SARS	29	54: 42-70	71.4%	100%	12.0%
MERS	14	48: 38:60	83.3%	100%	0%
COVID-19	76	56:43:67	63.9%	73.7%	84.2%
When all reports say ≥ 12 secondary infections					

SARS	18	57: 42-64	76.5%	100%	11.8%
MERS	5	47: 41-53	100%	100%	0%
COVID-19	32	55: 43-59	44.0%	72.0%	87.5%
Only studies with Quality score ≥ 4					
SARS	18	54: 43-71	72.2%	100%	12.5%
MERS	10	50: 42-63	90.0%	100%	10%
COVID-19	32	55: 44-58	94.4%	70.4%	75.0%

Note: n = number of studies that contributed *any* useable data to any of age, sex etc., but often did not provide useable data for *all* of these fields. All non-clinical settings (including care homes or prisons, for instance) were treated as community settings; persons who were linked to transmission in both community and clinical settings were treated as 'mixed' settings.

Discussion

We produced a dataset that would provide empirical parameters for anyone attempting to model the role of super-spreading individuals related to novel coronaviruses. The data we provide help to indicate which persons (by age or sex category, at least) in a population seem to be mostly likely to become super-spreaders. This information could help indicate which persons in a specific population (with known age/sex distribution and contact patterns) might contribute to epidemic growth. However, this is an appropriate opportunity to state that no one chooses to be highly infectious and hence in no way do we mean to imply stigma on any persons with such demographic traits; no one chooses to be highly infectious.

Observable mortality rates for super-spreaders of all the nCoV we examined were much higher than mortality statistics for the same diseases. However, we note that mortality outcomes for COVID-19 index cases were particularly incompletely reported. The count of COVID-19 super-spreaders who died was only three – so we may have an inaccurate picture of how often COVID-19 super-spreaders tend to die from the illness.

For MERS and SARS, super-spreaders tended to be quite ill. No asymptomatic super-spreaders were described for MERS and SARS, in spite of the prevalence of asymptomatic or mild infection among MERS cases being 26.9% (World Health Organization 2017) . This may be because for MERS and SARS only symptomatic people were tested. This contrasts to COVID-19, where super-spreaders who were completely asymptomatic throughout their disease course, or who were pre-symptomatic at the time that they transmitted disease to others, were commonly reported. A recent meta-analysis found at least one third of all COVID-19 cases were estimated to be truly asymptomatic (Sah et al. 2021). This high prevalence of undetected infection severely challenged COVID-19 control. However, we acknowledge that biases in ascertainment may have affected epidemiologic reporting of symptom severity, especially for COVID-19. Individuals may have been motivated to incorrectly describe their symptoms as asymptomatic if they had social contact, due to legal proscription against social contact for people with COVID-19 symptoms in their jurisdictions at the time of their super-spreading.

Only two individuals aged under 20 years old were identified as super-spreaders for any of these novel coronaviruses (both had COVID-19). One of these was age 18, another was described as a teenage staff member (so can be inferred to be close to or already reached adult age). In addition, not many super-spreaders were age 19-39. Because younger people tend to have much higher social contact rates than older individuals (Mossong et al. 2008), more youthful super-spreaders might have been expected. As asymptomatic infection of MERS (Khan et al. 2020; Al-Tawfiq and Gautret 2019) is more common in younger people, and droplet spread of infectious respiratory disease tends to closely correlate with symptom severity (Bischoff et al. 2013), this might explain why that we found relatively few super-spreaders under the age of 40 for MERS. However given that COVID-19 asymptomatic infection is also most common in younger people (McDonald et al. 2021) and that many COVID-19 super-spreaders were asymptomatic, it is surprising there were not more younger COVID-19 super-spreaders. For SARS, it is unclear why there are fewer younger super-spreaders. There is little information on how asymptomatic SARS infection varies with age, although a study in Singapore indicates almost no difference in age between symptomatic and asymptomatic cases (Wilder-Smith et al. 2005). There is no clear explanation as to why most nCoV super-spreaders were aged over 40.

We tried to identify super-spreaders who generated at least nine secondary infections. However, the counts of secondary infections from individual index cases varied in the epidemiological studies. We did not aspire to evaluate which studies were most accurate (in absence of all primary epidemiological data). Identifying 'super-spreaders' is challenging when there is much uncertainty about the true count of secondary cases.

There was insufficient information about occupation to link specific lines of work to super-spreading. There was also very limited information about patient ethnicity. There were some large differences in settings or traits for MERS or SARS super-spreaders compared to COVID-19 index patients. MERS and SARS super-spreaders were much more likely to have been spreading in clinical settings, whilst COVID-19 spreading appeared to occur more commonly in the community. Alongside this, MERS and SARS super-spreaders were more likely to experience severe symptoms, while non-symptomatic super-spreading from COVID-19 index patients was common. These findings reiterate the value of high awareness of asymptomatic COVID-19 infection.

Limitations

Ascertainment bias affected our efforts. Universal screening of all MERS and SARS contacts rarely happened, in contrast to much broader testing of all COVID-19 contacts. Therefore, it is unsurprising that we collected data about more COVID-19 super-spreaders. Even when a super-spreading individual is detected within a surveillance system, a decision is made whether or not to publish as a case study (or academic publication) and it is unknown what biases this introduces. Case studies may be more likely for diseases perceived to be rare, which might explain why relatively more studies on MERS and SARS were produced. It is also possible that super-spreaders who are considered unusual or have already generated publicity are preferentially published. We have reported attributes, such as symptom severity, as described in the original studies. It may be that some attributes have not been reported faithfully. When extracting data from individual publications the details presented varied greatly between studies. More complete reporting would be desirable.

To systematically collect data about super-spreading individuals we had to create consistent criteria to define them. Slightly different criteria would have identified a different group of people. We did not collect data that would allow a sensitivity analysis using lower eligibility thresholds (such as only 3 or 5 secondary cases). After our searches and analysis was completed, a useful database of infection trees was published that could be used to support confirmatory and replicated analyses of nCoV super spreading events using different definitions of what is a "super spreading individual", at outbreaktrees.ecology.uga.edu (Taube, Miller, and Drake 2022).

COVID-19 is fast moving and our findings are only relevant to the time period investigated. Our latest searches were in June 2021 and all our super-spreaders were active in 2020; data about super-spreading linked to the Delta and Omicron variants of COVID-19 would not have been included.

Conclusion

A key question is what makes individuals into super-spreaders (Chen et al. 2021; Stein 2020; Lloyd-Smith et al. 2005). We demonstrate that this question is challenging to answer due to the limited number of published studies on super-spreader individuals and inconsistencies in the available details about index cases in available studies. One solution would be to encourage publication of more outbreak reports with suitably anonymised, consistent descriptions of index and secondary patients. Since early 2020, detailed contact tracing databases have been assembled in many jurisdictions to facilitate COVID-19 control: these may form a rich resource for identifying super-spreaders. Should stronger data emerge, they could be incorporated into disease modelling or be used to guide intensive contact tracing in outbreak situations.

For all three diseases we found that males and people age 40+ were traits most typical of super-spreaders, while people under age 18 years were unlikely to be identified as super-spreaders. However, characteristics varied between the coronaviruses. Most super-spreading from MERS or SARS was observed in clinical environments, while COVID-19 super-spreading happened predominantly in community settings. Generally, MERS and SARS super-spreaders were highly symptomatic, had poor disease outcomes and underlying health conditions. In contrast, many individuals who super-spread COVID-19 were observed to have mild or no symptoms at the time of their high transmission rate, and where survival status was documented, the majority survived the infectious period.

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Declaration of interests

☐The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Super-spreaders of novel coronaviruses that cause SARS, MERS and COVID-19 : A systematic review

Supplemental Material, Tables S1-S3 and Figure S4.

NOTES for all tables: Quality scores are based on count of 'Yes' answers to quality checklist shown as Table 1. #secondaries means the number of direct secondary cases caused by the specified index case, according to the group of related articles that describe this index case, hence the answer can be a range if multiple sources have different estimates for the number of secondary cases linked to the index patient.

Table S1. Traits of MERS super-spreader individuals

Name, age, sex	Dates/country	Activities/setting	Estimated #secondaries	symptoms & outcome	Underlying condition	Quality score	Key Source(s)
Pt III-A 45, M	2014, UAE	patient in ED then ICU	11	Breathing difficulties. Died	No information	5	(Hunter et al. 2016)
Pt1, 53, M	2014, Saudi Arabia	While receiving kidney dialysis, clinic	14	Symptoms not reported. Died	In receipt of regular dialysis	5	(Assiri et al. 2016)
Index, no info	2015, Saudi Arabia	patient in ED	10	No information	No information	3	(Saad et al. 2014)
Case 02, 56, M	2015, Saudi Arabia	Hospital ED and inpatient	8-9	Symptoms not reported. Died	Diabetes, hypertension, hypothyroidism, coronary artery disease	4	(Alenazi et al. 2017; Barry et al. 2020; El Bushra et al. 2017)
Pt 1664 ~48, F	2016, Saudi Arabia	Hospital inpatient	17-23	Symptoms not reported. Died	Unspecified comorbidities	2	(Adegboye and Elfaki 2018)
Pt1, 68, M	2015, S.Korea	Seeking treatment in ED, later as hospital inpatient	19-38	pneumonia, severe cough, hospitalised	hypertension	6	(K. M. Kim et al. 2015; Korea Centers for

Name, age, sex	Dates/country	Activities/setting	Estimated #secondaries	symptoms & outcome	Underlying condition	Quality score	Key Source(s)
				for months. Survived			Disease and Prevention 2015; G. E. Park et al. 2016; Cowling et al. 2015)
Pt14, 35, M	2015, S.Korea	Seeking treatment in ED, later as hospital inpatient	73-93	pneumonia, severe cough, respiratory failure, diarrhea. Survived	Ascertained but none known	6	(K. M. Kim et al. 2015; Korea Centers for Disease and Prevention 2015; G. E. Park et al. 2016; Cowling et al. 2015)
Pt15, 35, M	2015, S.Korea	As hospital inpatient	4-9	pneumonia without severe cough. Survived.	Liver failure	3	(Nishiura et al. 2016; S. W. Kim et al. 2017)
Pt16, 41, M	2015, S.Korea	As hospital inpatient	21-25	pneumonia, severe cough. Survived	pancreatitis	6	(Choe et al. 2020; Korea Centers for Disease and Prevention 2015)
Pt76, 75, F	2015, S.Korea	As hospital inpatient	10-12	pneumonia, slight cough. Died.	multiple myeloma; diabetes mellitus	6	(Choe et al. 2020; Korea Centers for Disease and Prevention 2015)
Case 5, 65, M	2017, Saudi Arabia	Seeking treatment in ED, later as hospital inpatient	9-11	Symptoms not reported. Died	Diabetes Mellitus, Hypertension	6	(Alanazi et al. 2019)
Index A, ~47, M	2017, Saudi Arabia	Seeking treatment in ED, later as hospital inpatient	16-19	Cough, Shortness of breath, chest pain. No fever. History of Diarrhea prior to admission. Died	Diabetes Mellitus, Hypertension, Chronic Kidney Disease	6	(Alanazi et al. 2019)

Name, age, sex	Dates/country	Activities/setting	Estimated #secondaries	symptoms & outcome	Underlying condition	Quality score	Key Source(s)
Index B, 23, M	2017, Saudi Arabia	Seeking treatment in ED, later as hospital inpatient	9	Fever, cough, rhinorrhea. Died	Ascertained but none known	6	(Alanazi et al. 2019)
Index, no info	2017, Saudi Arabia	While receiving dialysis and within household	Up to 10	No information	Was receiving dialysis	0	(WHO 2017)

Table S2. Traits of SA7RS super-spreader individuals

Name, age, sex	Dates/country	Activities/setting	Estimated #secondaries	symptoms & outcome	Underlying condition(s)	Quality score	Key Source(s)
Heyuan index, adult, M	17 Dec 2002, China	As inpatient	10+	high fever, mild respiratory symptoms. Outcome not stated	None known	4	(Zhong et al. 2003)
Case A, 46, M	Late Jan 2003, China	As inpatient, multiple hospitals	74	fever, cough, sputum, cherst abnormalities, shortness of breath, respiratory difficulties. Outcome not stated	No information	5	(Jiang et al. 2003; Zhong et al. 2003)
Pt ZH, no info	Unstated, China	As inpatient	≥ 9	No information	No information	1	(WHO 2003)
Pt Y, no info	Unstated, China	As inpatient	11	No information	No information	1	(WHO 2003)
Case C, 42, F	Early Feb, China	As inpatient	11	cough and shortness of breath, hypoxemia. Died	acute myocardial infarction and 3rd degree atrioventricular block, acute renal failure	4	(Jiang et al. 2003)
HK index, 64, M	Early Feb, Hong Kong	Hotel guest, shopping, As inpatient	10-12	Prolonged period of mild symptoms, followed by respiratory failure, cough, dyspnea, pleurisy, malaise, myalgia, rigor, fever, headache, ventilated in ICU. Died	"Unremarkable medical history"	2	(K. W. Tsang et al. 2003a)
Case B, 55, M	Early Feb, China	As inpatient	9	Fever, chills, myalgia, malaise, rhinorrhea, cough, congested	No information	4	(Jiang et al. 2003)

Name, age, sex	Dates/country	Activities/setting	Estimated #secondaries	symptoms & outcome	Underlying condition(s)	Quality score	Key Source(s)
				pharynx, swollen tonsils, ventilated in ICU. Died			
Case 1, 27, F	Late Feb, China	While seeking treatment, social contacts, as inpatient	12-18	No information	No information	5	(Liang et al. 2004; Cooper et al. 2009)
Pt B, 47, M	Late Feb, Viet Nam	In community & As inpatient	9-12	Lower respiratory symptoms , medical ventilation. Died	No information	1	(T. Tsang et al. 2003b)
Index A, ~22, M	Late Feb, Singapore	In community & As inpatient	21	Fever, dry cough, cough, dyspnoea, vomiting, required oxygen, ICU care, headache. Survived	No information	3	(Goh et al. 2006; Chen et al. 2006)
Case A, ~73, M	Early March, China	As inpatient	4-9	No information	No information	5	(Zeng et al. 2009; Cooper et al. 2009)
Case A wife, adult, F	March, China	No information, likely in community	19	No information	No information	6	(Zeng et al. 2009)
Pt, 26, M	Early March, Hong Kong	As inpatient	43	Fever, chills, rigor, cough, vomiting, diarrhea. Unstated outcome	“previously healthy”	6	(Wong and Hui 2004; Lee et al. 2003)
Case C, adult, M	Early March, Canada	In community, as inpatient, while in transit between hospitals	18	Myocardial infarction symptoms, also treated with renal dialysis. Died	shortness of breath secondary to a pleural effusion	4	(Varia et al. 2003)
Index B, 27, F	Mid March 2003, Singapore	As inpatient	11-23	Fever, sore throat, vomiting, diarrhoea, not ventilated. Survived	None known, young HCP	3	(Goh et al. 2006; Chen et al. 2006)

Name, age, sex	Dates/country	Activities/setting	Estimated #secondaries	symptoms & outcome	Underlying condition(s)	Quality score	Key Source(s)
Case B, 76, M	Mid March, Canada	In community and as inpatient	23	Fever, diaphoresis, fatigue, intubated. Died	atrial fibrillation, type 2 diabetes , coronary heart disease, hypertension	3	(Varia et al. 2003; Poutanen et al. 2003)
Index C, 53, F	Mid March, Singapore	As inpatient	18-25	Dyspnea, fever, pneumonia gram-negative bacteraemia. heart failure, cough, dyspnoea diarrhoea, ICU, intubated. Died	T2 diabetes and ischemic heart disease	3	(Goh et al. 2006; Chen et al. 2006)
Flight 2 index, 72, M	Mid March, China	Air travel (as passenger) and as inpatient	10-24	Fever, cough. Died	No information	6	(Olsen et al. 2003; Liang et al. 2004)
Tai Po index, age?, M	Late March, Hong Kong	As inpatient	24	Diarrhea and abdominal pain, fever. Outcome not stated	No information	5	(Ho et al. 2003)
Index 1, 91, M	Late March, China	As inpatient	12-13	Stroke, fever. Died	No information	6	(Zeng et al. 2009)
Case Z, 88, M	Late March, China	As inpatient	13	cerebral infarction. Outcome not stated	No information	6	Zeng *et al.* 2009)
Index D, 60, M	Late March and Early April, Singapore	As inpatient	37-51	Fever, pneumonia. Survived	Ischaemic heart disease, diabetes mellitus, renal impairment, steroid-induced gastrointestinal bleeding	3	(Goh et al. 2006; Chen et al. 2006)
Hospital C Index Pt, 54, M	Early April, Canada	As inpatient	9	Fever, myalgia, headache, mild diarrhoea, cough. Outcome not	hyperlipidemia, hypertension, noninsulin-dependent diabetes	4	(Ofner-Agostini et al. 2006; Ofner et al. 2003)

Name, age, sex	Dates/country	Activities/setting	Estimated #secondaries	symptoms & outcome	Underlying condition(s)	Quality score	Key Source(s)
				stated			
Pt A, 62, F	Early April, China	As inpatient	33	Fever, headache. Died	Diabetes mellitus	6	(Z. Shen et al. 2004)
Index E, ~64, M	Early April, Singapore	As inpatient	7-15	myalgia, cough, fever, dyspnoea. Died	Ischemic heart disease hypertension, atrial fibrillation	3	(Goh et al. 2006; Chen et al. 2006)
Pt D, 70, F	Mid April, China	Visitor to hospital inpatient	10	No information	No information	6	(Z. Shen et al. 2004)
Pt M, 54, M	Mid April, China	As inpatient	33	Myalgia, sore throat, mild productive cough, fever. Died	Coronary disease, type II diabetes, chronic renal failure	4	(Cooper et al. 2009)
Hospital A Index Pt, 42, M	Mid April, Taiwan	Lived and worked at hospital	Up to 49	Fever, diarrhea, shortness of breath. Died	T2DM, peripheral vascular disease, treated for presumed salmonella infection	2	(Simmerman et al. 2003; Prevention 2003)
23, M	Late April, China	Mostly in community	12	No information	None reported	6	(Z. Shen et al. 2004)

Note: Year is 2003 in all SARS cases except if noted otherwise.

Table S3. Traits of COVID-19 super-spreader individuals

Name, age, sex	Dates/country	Activities/setting	Estimated direct # secondaries	symptoms & outcome	Underlying condition	Quality score	Key Source(s)
Pt 1, Adult, M	Early Jan 2020, China	As inpatient	11-13	Unclear if had symptoms. Died within 28 days of diagnosis	Yes but not specified	3	(Li et al. 2020)
Pt A, 24, M	Jan 2020, China	Socialising	13	Occasional chest discomfort and dyspnea (only for 2 days). Survived	hepatitis B, dyslipidemia, hypoglycemia, and slight liver dysfunction	6	(Yu et al. 2020)
Dr. B, Adult, ?sex	Likely January 2020, China	Being at work at hospital, mostly transmitted to colleagues	16	*Onset after SSing.* Mild symptoms. Survived	No information	4	(Wei et al. 2020)
C-1, 50s, M	Early Jan 2020, China	Visiting hospital to support inpatient	11-21	Fever, headache, chest pain and myalgias. Died	No information	4	(Hu et al. 2021)
C-29, 50s, M	Mid Jan 2020, China	Working as HCP	12	Had symptoms. Survived	No information	4	(Hu et al. 2021)
Mrs. S, 64, F	Mid Jan 2020, China	Pilgrimage, public transport, communal meal	28-32	*Onset after SSing.* Fever, cough, chills, myalgia. Survived	No information	6	(Lin et al. 2020; Y. Shen et al. 2020; Yin and Jin 2020)
Index, No info	~20 Jan 20, China	Meals together	9-10	No information	No information	1	(Liu et al. 2020)
Pt A, Age?, M	Late Jan 2020, China	Riding public bus	9-11	*Onset after SSing:* yes symptoms but not specified. Outcome not stated	No information	6	(Luo et al. 2020)
Pt A1, no info	Late Jan 2020, China	Restaurant meal	9	*Onset after SSing started:* fever, cough. Outcome not stated	No information	3	(Lu et al. 2020)
Case 4, Likely adult, M	Late Jan 2020, China	Working as supermarket staff; socialising	12	*Onset after SSing started:* fever. Outcome not stated	No information	2	(Tian et al. 2021; Zhang et al. 2020)

Name, age, sex	Dates/country	Activities/setting	Estimated direct # secondaries	symptoms & outcome	Underlying condition	Quality score	Key Source(s)
Pt 1, 24, M	Late Jan 2020, Hong Kong	Meals with family, socialising	11	*Onset after SSing started*: fever & cough. Survived	"record of good health"	5	(Lam et al. 2020)
UK-A, 53, M	Jan-Feb 2020, France & UK	Skiing, socialising	9	Unspecified mild-moderate severity. Survived	No information	6	(Danis et al. 2020)
Z-21, 61, F	Jan-Feb 2020, China	Mostly within household socialising	10	No information	No information	1	(Xu et al. 2020)
Pt 12-31, ~60, F	Jan-Feb 2020, S. Korea	Church services, church community socialising, church singing, group meal	8-40	Headache, fever, pneumonia (later). Survived	No information	1	(Y. Kim and Jiang 2020; Kang 2020; J. Y. Park 2020)
Case 102, 43, M	Early Feb 2020, Hong Kong	Leading religious worship, socialising	9-18	*No symptoms ever*. Survived	No information	4	(Adam et al. 2020; Leung et al. 2020)
Carnival index, Likely adult, Sex?	Mid Feb 2020, Germany	Carnival, social & work contacts	26-37	Symptomatic. Outcome not stated	No information	4	(Müller et al. 2021)
Index, (no info)	Feb 2020, S. Korea	Link to psychiatric inpatient ward	11+	No information	No information	1	(Y. Kim and Jiang 2020; Shim et al. 2020)
Instructor A, mid 40s, F	Feb 2020, S. Korea	Teaching dance fitness classes	24	Mild, just a cough. Survived	No information	6	(Jang et al. 2020; Y. Kim and Jiang 2020)
Instructor B, mid 40s, F	Feb 2020, S. Korea	Teaching dance fitness classes	25-26	Mild, just a cough. Survived	No information	6	(Jang et al. 2020; Y. Kim and Jiang 2020)
Pt 1-125, 56-57,F	Feb 2020, S. Korea	Working within call-centre	18	No information on symptoms. Survived	No information	0	(Y. Kim and Jiang 2020; S. Y. Park et al. 2020)
Pt1, 57, M	Late Feb 2020, Germany	Scientific conferences and while attending hospital	15	*Onset after SSing started*: fever, cough, sneezing, loss of smell and	No information	6	(Hijnen et al. 2020)

Name, age, sex	Dates/country	Activities/setting	Estimated direct # secondaries	symptoms & outcome	Underlying condition	Quality score	Key Source(s)
				taste. Survived			
S3, Adult, sex?	Late Feb 2020, Italy	Possibly agricultural work	17	Unclear symptoms and outcome	No information	5	(Valent et al. 2020)
Flight-index, 27, F	Feb-Mar 2020, UK->Viet Nam	As aeroplane passenger and in community	19	Unclear when symptomatic. Cough, fever, sore throat, fatigue, and shortness of breath. Outcome not stated	No information	6	(Khanh et al. 2020)
A1.1, Age? M	Feb-Mar 2020, USA	Restaurant meal, funeral, birthday party	10	Mild respiratory symptoms. Survived	No information	5	(Ghinai et al. 2020)
Pt A, Adult, sex?	Early 2020, USA	Nosocomial, as patient &/or staff	Up to 14	Fever, bilateral lower lobe interstitial infiltrates. Unclear outcome	Diabetes mellitus type 2, an active cancer	4	(Thompson et al. 2021)
Pt 2-125, 82, M	~7 Mar 20, S. Korea	In community including religious worship	11	No information on symptoms. Survived	No information	2	(Y. Kim and Jiang 2020)
E1, Adult, M	Early March 2020, Switzerland	Social event(s) at workplace (office)	8-10	Fatigue, slight cough at time he was SSring. Survived	No information	6	(Weissberg et al. 2020)
Choir index, no info	10 Mar 2020, USA	Choir practice events	10+	Sore throat. Survived	No information	3	(Hamner 2020)
Bride's father, 58, M	Mid March 2020, Jordan	Large gathering, wedding, dancing, greetings, prewedding activities	Up to 76	Fever, cough. Survived	No information	4	(Yusef et al. 2020)
Pt 2-167, 44, F	Mid March 2020, S. Korea	Unclear, possibly providing health care	24	No information on symptoms. Survived	No information	2	(Y. Kim and Jiang 2020)
Pt 2-205,	Mid March	In community	51	No	No	2	(Y. Kim and

Name, age, sex	Dates/country	Activities/setting	Estimated direct # secondaries	symptoms & outcome	Underlying condition	Quality score	Key Source(s)
74, F	2020, S. Korea	including religious worship		information on symptoms. Survived	information		Jiang 2020)
Pt 2-309, 85, F	Mid March 2020, S. Korea	Unclear	21	Was symptomatic. Survived	No information	2	(Y. Kim and Jiang 2020)
Pt 1, ~42, M	Mid March 2020, Viet Nam	Socialising, travelling	13	*Onset after SSing started:* fever, cough, muscle aches, fatigue, and headache. Survived after long severe illness	No information	6	(Chau et al. 2021)
Pastor, 57, M	Mid March 2020, USA	Religious leader, church and bible study	35	Headache, body aches, lethargy, chills, nausea, mild fever, cough. Survived	No information	6	(Viner et al. 2020)
Pt 2-476, 82, F	Late March 2020, S. Korea	Unclear, possibly providing health care	9	Was symptomatic. Survived	No information	2	(Y. Kim and Jiang 2020)
Missionary-index, 68, M	Late March/ early April 2020, Thailand	Acting as religious and community leader	11-26	*Onset after SSing started*: unspecified symptoms. Survived	No information	5	(Phiriyasart et al. 2020)
Case 590, No info	Jan-May 2020 Tunisia	No information	9	No information	No information	4	(Safer et al. 2021)
Case 399, No info	Jan-May 2020 Tunisia	No information	12	No information	No information	4	(Safer et al. 2021)
Case 75, No info	Jan-May 2020 Tunisia	Family gathering, wedding, meal	10	No information	No information	4	(Safer et al. 2021)
Case 106, No info	Jan-May 2020 Tunisia	Family gathering, wedding, meal	14	No information	No information	4	(Safer et al. 2021)
Case 704, No info	Jan-May 2020 Tunisia	No information	9	No information	No information	4	(Safer et al. 2021)
Case 342, No info	Jan-May 2020 Tunisia	No information	9	No information	No information	4	(Safer et al. 2021)
Case 453, No info	Jan-May 2020 Tunisia	Family gathering	21	No info on symptoms. Died	No information	4	(Safer et al. 2021)
Pt 2-508,	~1 Apr 20,	Unclear	15	No	No	2	(Y. Kim and

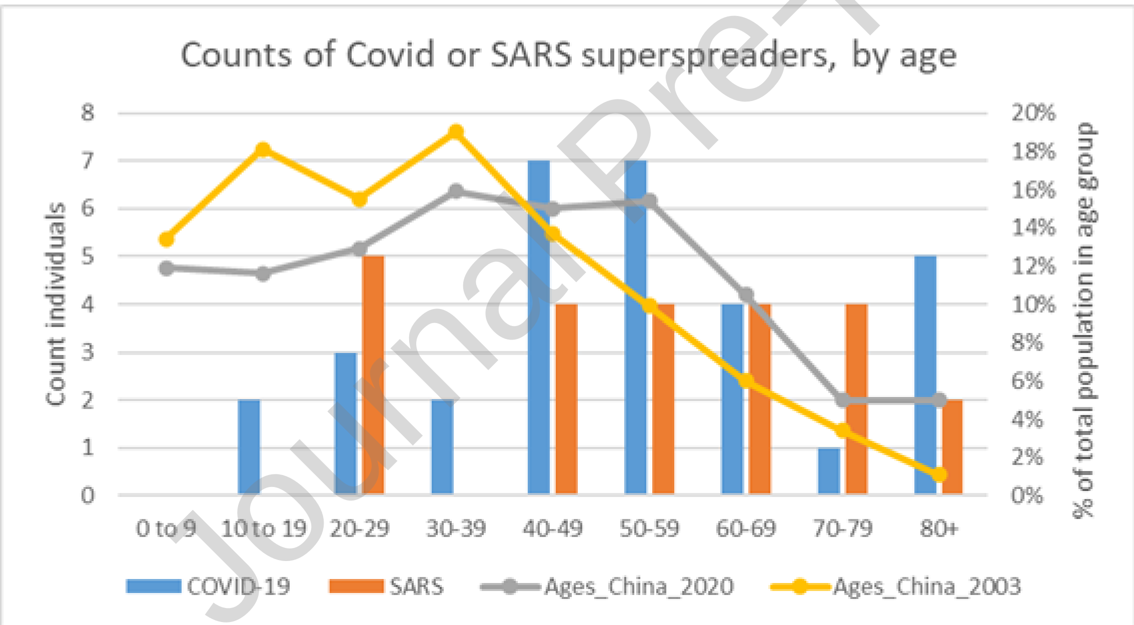
Name, age, sex	Dates/country	Activities/setting	Estimated direct # secondaries	symptoms & outcome	Underlying condition	Quality score	Key Source(s)
47-F	S. Korea			information on symptoms or outcome	information		Jiang 2020)
Imported primary, no info	Mar-Apr 2020, Faroes	Unclear	14-15	No information	No information	4	(Kristiansen et al. 2021)
Domestic primary, No info	Mar-Apr 2020, Faroes	Unclear	15	No information	No information	4	Kristiansen *et al.* 2021)
School-linked, No info	Mar-Apr 2020, Faroes	Unclear	10	No information	No information	4	Kristiansen *et al.* 2021)
Resident, Adult?, sex?	Mid April 2020, USA	Recipient of dialysis in nursing home	14-16	Elevated temperature and malaise. Outcome unclear	In receipt of dialysis	6	(Bigelow et al. 2020)
B1, Adult	May 2020, Germany	meat processing plant worker and community contacts	18-29	*Always asymptomatic.* Survived	No information	6	(Günther et al. 2020)
CS010, No info	May-Jul 2020, Mexico	Unclear	17	No information	No information	5	(Martinez-Fierro et al. 2021)
CS120, No info	May-Jul 2020, Mexico	Unclear	9	No information	No information	5	(Martinez-Fierro et al. 2021)
Index, No info	Summer 2020, Ireland	Social events	25	No information	No information	3	(Murphy et al. 2020)
Team A player, adult, M	16 Jun 2020, USA	Indoor team sport (ice hockey player)	14	*Onset after main SSring*: fever, cough, sore throat, and a headache. Survived	No information	6	(Atrubin et al. 2020)
Staff index, Teens, sex?	Late June 2020, USA	Residential camp staff	26+	Chills. Survived	No information	6	(Szablewski et al. 2020)
Inst A, Adult, M	29 Jun 2020, USA	Fitness class instruction	10	*Onset after main SSring*: fatigue,chills, body aches, cough, congestion, sore throat, and headache. Outcome	No information	6	(Groves et al. 2021)

Name, age, sex	Dates/country	Activities/setting	Estimated direct # secondaries	symptoms & outcome	Underlying condition	Quality score	Key Source(s)
				unclear			
Inst B, Adult, M	1-2 Jul 2020, USA	Fitness class instruction	11	*Onset after main SSring*: body aches sore throat, fever, chills, cough, shortness of breath, fatigue, admitted to ICU. Outcome unclear	No information	6	(Groves et al. 2021)
School staff 1, adult	Jun-Jul 2020, UK	Working in a school	9	No information	No information	4	(Ismail et al. 2021)
Sch. staff 2, adult	Jun-Jul 2020, UK	Working in a school	13	No information	No information	4	Ismail *et al.* 2021)
Sch. staff 4, adult	Jun-Jul 2020, UK	Working in a school	11-12	No information	No information	4	Ismail *et al.* 2021)
Sch. staff 4, adult	Jun-Jul 2020, UK	Working in a school	10	No information	No information	4	Ismail *et al.* 2021)
Pianist, 18, M	16-17 Jul 2020, Australia	Playing instrument and singing in churches	12	Cough, fever. Survived	No information	5	(Katelaris et al. 2021)
Index, 85, M	Before August 2020, Japan	As inpatient	12	Fever, cough, and dyspnea. Chest computed tomography revealed unilateral pleural effusion and no findings of pneumonia. Outcome not stated	No information	4	(Sugimoto and Kohama 2020)
Case-1, No info	Between 23 March & 13 July 2020, Myanmar	No information	Up to 11	No information	No information	3	(Thway et al. 2020)
Case-24, No info	Between 23 March & 13 July 2020, Myanmar	No information	Up to 78	No information	No information	3	(Thway et al. 2020)
Case-24, No info	Between 23 March & 13	No information	17	No information	No information	3	(Thway et al. 2020)

Name, age, sex	Dates/country	Activities/setting	Estimated direct # secondaries	symptoms & outcome	Underlying condition	Quality score	Key Source(s)
	July 2020, Myanmar						
HCW1, Adult, sex?	Before 27 Apr 2020, Germany	At work in pediatric dialysis unit	11	Fever, body aches, cough, headache, fatigue, blocked nose, loss of taste/smell. Outcome not stated	No information	5	(Schwierzeck et al. 2021)
Imported index, no info	Before August 2020, Hong Kong	Socialising; attended a wedding	10	No information	No information	4	(Adam et al. 2020)
Bar and Band index, no info	Before August 2020, Hong Kong	No information	Up to 60	No information	No information	4	(Adam et al. 2020)
Group D index, no info	Before August 2020, Hong Kong	No information	11	No information	No information	4	(Adam et al. 2020)
Wedding guest, no info	7 Aug 2020, USA	Wedding preparations and wedding party	30	*Onset after main SSring*: On 8 Aug had onset of fever, runny nose, cough, and fatigue. Survived	No information	6	(Mahale et al. 2020)
Pt B1, Adult, sex?	11-12 Aug 2020, USA	Health care worker at long term care facility	38-39	Fever, chills, cough, myalgia, runny nose and headache. Survived	No information	6	(Mahale et al. 2020)
Pt A3, Adult, sex?	15-19 Aug 2020, USA	Working as prison staff	At least 64	Cough, myalgia, runny nose, sore throat, and a new onset loss of taste sensation. Survived	No information	6	(Mahale et al. 2020)
Case-123, No info	Before 24 Aug 2020, Thailand	No information	17	No information	No information	5	(Phucharoen et al. 2020)
Case-169, No info	Before 24 Aug 2020,	No information	17	No information	No information	5	(Phucharoen et al.

Name, age, sex	Dates/country	Activities/setting	Estimated direct # secondaries	symptoms & outcome	Underlying condition	Quality score	Key Source(s)
	Thailand						2020)
Index, 33, M	Before 9 Nov 2020, India	At home, community socialising, at work as HCP in hospital	16	Fever, cough, and sore throat at presentation, but unclear at point of exposures. Outcome not stated	No health information; he lived in a poor area	6	(Mohindra et al. 2021)
P2, 84, F	Dec 2020, Hong Kong	As inpatient	21	*Never had symptoms*. Survived	Diabetic ketoacidosis	5	(Cheng et al. 2021)

Figure S4. Age distribution of super-spreader cases compared to concurrent proportion of population in each age group in China.



Note: All super-spreader individuals are counted here but the population proportions in each age group are only for China in 2003 and 2020 because China contributed most of the age-specific data for either SARS or COVID super-spreaders Detailed breakdown or comparison for each contributing country is not informative when ages were generally unavailable outside of China. *Chinese Population distribution source*: https://www.populationpyramid.net/china.

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