Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
COVID-19: using chest CT of major trauma patients to monitor and evaluate the effect of lockdown and the importance of household size

R. Blanks a,⁎, E.J. Adam b, T.M. Jacob b, J.H. Patel b, S. Grubnic b

a Cancer Epidemiology Unit, Nuffield Department of Population Health, University of Oxford, Richard Doll Building, Roosevelt Drive, Oxford OX3 7LF, UK
b Department of Radiology, St George’s University Hospitals NHS Trust, Blackshaw Road, Tooting, London, SW17 0QT, UK

AIM: To use theory and practice to show how disease progression and regression can be described pre- and post-lockdown using an attack–sustain–decline–respite (ASDR) model and investigate how pre-lockdown disease prevalence and household size impacts on the effectiveness of lockdown.

MATERIALS AND METHODS: Computed tomography (CT) scans from major trauma patients (considered as a random population sample) from the radiology department of St George’s University Hospitals NHS Trust, London, have been used to explore COVID-19 disease at the population level.

RESULTS: At lockdown on 23 March 2020 in the catchment area of St George's University Hospitals NHS Trust, an earlier paper showed that there was a high prevalence of disease of >20%. With further follow-up and at the end of lockdown, it have been now estimated that around 57% of the population had been affected, which was similar to that predicted from a simple model based on average household size and prevalence at lockdown. With an average household size of around three persons, there was a 2-week sustain period and a 5-week decline period before the prevalence of the disease returned to background levels.

CONCLUSIONS: The present results suggest that the effect of lockdown is dependent on the disease prevalence at the start of lockdown and the average household size. It may therefore be important to lockdown early in an area with a high average household size. This paper is the second in a series of papers to show how radiology measurements of major trauma patients can be used to help monitor the spread of the COVID-19 pandemic.

© 2021 The Royal College of Radiologists. Published by Elsevier Ltd. All rights reserved.

DOI of original article: https://doi.org/10.1016/j.crad.2020.10.008.

⁎ Guarantor and correspondent: R. Blanks, Cancer Epidemiology Unit, Nuffield Department of Population Health, University of Oxford, Richard Doll Building, Roosevelt Drive, Oxford OX3 7LF, UK. Tel.: +01865 289663.

E-mail address: roger.blanks@ndph.ox.ac.uk (R. Blanks).

https://doi.org/10.1016/j.crad.2021.01.014

0009-9260/© 2021 The Royal College of Radiologists. Published by Elsevier Ltd. All rights reserved.
Introduction

This paper uses updated data from St George’s University Hospitals NHS Trust in London from January 2020 to June 2020 and control information from 2019 to describe the disease prevalence both before and during lockdown. Lockdown is described in terms of simple models and the effect of lockdown is shown to be related to pre-lockdown prevalence and influenced by average household size. The data from January to April 2020 is described in an earlier paper. Briefly, the data examined computed tomography (CT) examinations of major trauma patients in 2020 and used a control group from 2019 prior to the spread of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). Signs of COVID-19 were used to estimate the prevalence of the disease in the whole population of the catchment area of St George’s Hospital trauma centre by assuming that major trauma patients represented a random sample of the local population. The catchment area of St George’s Hospital trauma centre is a population of around 2.6 million. Full lockdown began on 23 March 2020 and lasted for about 7 weeks before being partially relaxed on 10 May.

The earlier results suggested that CT examinations are able to detect changes in the lungs in people without suspected COVID-19 infection. CT reveals pathological changes, which either cause no symptoms or symptoms so mild as to be clinically unsuspected. It is likely that the majority of people, estimated as 80% by one study, with SARS-CoV-2 have no symptoms and the spread of the virus may mostly be by "silent" transmission. Antibody responses are not detectable in all people with COVID-19, especially those with less severe forms, so asymptomatic individuals or those with sufficiently mild disease that it is found incidentally, would therefore be more likely to have antibody-negative disease, possibly just mounting a T-cell response. A control group pre-COVID-19 was used to avoid confounding by non-COVID-19 conditions that may produce similar CT signs. Finally, there was double reading in consensus, and the radiologists were blinded to the time period, so unable to determine whether the scan was from the pre-COVID-19 or epidemic time period, eliminating bias. Therefore, a method was produced that is useful primarily at the population level rather than the individual level. Chest CT will never be the method of choice for detecting the virus at the individual level, but radiologists may be in a unique position to monitor the spread of the virus and the impact of lockdown at the local population level. The advantage of the method is all major trauma centres will have data available to produce the necessary information. The disadvantage is that the method can be time consuming for radiologists.

These methods can be used both retrospectively and prospectively where such data are available. The present study explains how to monitor the growth of the pandemic before lockdown, the effect of lockdown, and how lockdown can be affected by average household size. With lockdown, the probability of catching the infection outside of the home greatly reduces; however, if there is high disease prevalence prior to lockdown, with a highly contagious disease in-house spread becomes the most important route of disease transmission in larger households with more time at home.

Materials and methods

Ethical approval for the study was given by the National NHS Research Ethics Committee (REC) and the combined Health Research Authority (HRA) and Health and Care Research Wales (HCRW) (reference 20/YH/0202).

The attack—sustain—decline—respite model of lockdown

The lockdown can be described in terms of an attack—sustain—decline—respite (ASDR) model. The first period of time is the “attack” phase where the virus increases exponentially with a “fast” attack if there is a high growth rate and a “slow” attack if there is slow growth rate. Lockdown then occurs and the period of time over which the virus still increases or does not drop back is the “sustain”. There is then a “decline” period where the virus level decreases back down to background and a “respite” period post-lockdown, after which the virus levels start increasing again for a further “second wave”. These second and subsequent waves can be described by the same model.

The effect of household size on lockdown

At the point of lockdown, a proportion P0 of the population will have had the disease, recovered, and no longer be contagious. A further proportion P1 will have the disease at the time of lockdown and be contagious. After lockdown, a final proportion of the population will have had the disease P2 and some of these will have been infected during lockdown, particularly in larger households.

If it is assumed that the disease is distributed randomly within the population and transmission within a household during lockdown is 100% then the relationship is derived as:

\[ P_2 = P_0 + [1 - (1-P_1)^n] \]  \( \text{(1)} \)

where \( n \) is the average household size. If we assume a rapid exponential rise (“fast attack”) and that \( P_0 \) is close to zero, then \( P_0 + P_1 \) will be similar to \( P_0 \). After lockdown, the proportion of the population who have been exposed can be estimated as

\[ P_2 = [1-(1-P_1)^n] \]  \( \text{(2)} \)

Table 1 shows examples of the calculation of equation 2 for varying proportions with the disease at the start of lockdown and average household size. Table 1 shows that in an area where the vast majority live in single-person households, lockdown has an immediate effect, and the proportion who have had the disease at the end of lockdown is the same as that at the beginning. There is no disease transmission within lockdown and the progress of the disease is therefore halted at the same level as at the start of lockdown; however, consider an area with an
Results

Keeping the post-lockdown proportion (P2) below a defined level

We may wish to define a level below which we want to keep the proportion of the population exposed after lockdown. Let us assume this chosen level is 10%. In an area with an average household size of two persons, the P1 value must be <5.1%, for an average household of three or four persons, the P1 value must be <3.5% and <2.6%, respectively.

Example from St George’s Hospital catchment area

COVID-19 affected people in London in increasing numbers, making an impact at the population level from as early as the beginning of February, although it would have been present in small numbers as early as January. In the catchment area of St George’s Hospital, southwest London, CT data from major trauma patients (which is considered to approximate a random sample of the population) indicated that during the attack phase and at the time of lockdown >20% of the population had already been exposed (520,000 people from a population of 2.6 million). Fig 1 shows a graph of the prevalence of disease for the first 6 months of 2020 from January to the end of June and Fig 2 shows the percentage of the population who had had COVID-19. Lockdown occurred on 23 March, and the data prior to that has been modelled previously using an exponential model where the percentage who have had the disease = constant × e^x where the present data give 0.60 e^{0.30T} where T is weeks from 1 January 2020 and the growth rate is 0.30 per week or roughly 0.04 (4%) per day.

Using the ASDR terminology, there was a fast attack over a period of about 2 months, which is the period from the disease first being visible at the population level to lockdown. After lockdown there was a sustain period of about 10 days during which the prevalence did not fall and then a decline period of about 5 weeks during which the prevalence reduced back to background levels, and then an unspecified “respite” period probably of about 3 months (June/July/August) before the virus levels started rising again around September.

From Fig 2 it can be seen that at the beginning of lockdown >20% of the population had been exposed and at the end of lockdown >50% had been exposed suggesting that over half the exposure may have occurred during the lockdown period. The present model of the percentage who have had the disease in weeks = 0.60 e^{0.30T} suggests that the best estimate of those exposed prior to lockdown (at week 12.8) is 27.9%. If we assume that people who are infectious are those who had the disease within 1 month of lockdown then P1 is estimated as 0.60 e^{0.30×12.8} = 0.60 e^{3.0} = 0.60 e^{0.30×8.8} = 19.5% or 0.195. The final percentage of the population exposed after lockdown (P2) is 57.2% or 0.572 (shown in Fig 2). To explore further, equations 2 and 1 can be re-parameterised to estimate the average household occupancy n = ln(P2) / ln(1−P1) or n = ln(P2−P0) / ln(1−P1) if P0 is not negligible. Therefore n = ln(0.572)/ln(0.805) = 2.6 persons per household or ln(0.488)/ln(0.805) = 3.3, respectively. The actual household occupancy in Tooting (the area within which the hospital is situated) is 2.7 persons per household. The example from St George’s Hospital confirms that the equation gives reasonable answers based on actual observed data and helps validate the model.

Fig 1 also shows that it took about 6 or 7 weeks after lockdown for the disease prevalence to return to the extremely high average population density of eight per household. If we assume that at lockdown only 1%(1 in 100) of the population have the disease and they are able to transmit that disease, at the end of lockdown 7.7% of the population will have been exposed. If at lockdown 10% have the disease, after lockdown 57% will have been exposed in this high-density population. Therefore, the effectiveness of lockdown greatly depends on the prevalence of the disease at lockdown and the housing occupancy in an area.

### Table 1

| Household size | 1% | 5% | 10% | 15% | 20% | 25% |
|---------------|----|----|-----|-----|-----|-----|
| 1             | 1% | 5% | 10% | 15% | 20% | 25% |
| 2             | 2% | 9.8% | 19% | 27.8% | 36% | 43.8% |
| 3             | 3% | 14.3% | 27.1% | 38.6% | 48.8% | 57.8% |
| 4             | 4.9% | 22.6% | 41% | 55.6% | 67.2% | 76.3% |
| 5             | 7.7% | 33.7% | 57% | 72.8% | 83.2% | 90% |

*The proportion of people who had had COVID-19 and are no longer contagious (P0) can be added to the estimated P2 where the attack (growth) rate is less rapid and P0 is significant.*

by week 17 (just before the end of April) and just 5 weeks after the date of lockdown had it not taken place (Fig 2). A similar model is given by the epidemic growth rate formula where the percentage who have had the disease = constant × e^x and the present data give 0.60 e^{0.30T} where T is weeks from 1 January 2020 and the growth rate is 0.30 per week or roughly 0.04 (4%) per day.

Figure 1 Graph of prevalence COVID-19 signs by weeks since 1 January 2020 showing 3-week moving average in green.
baseline, which is the total sustain and decline time periods. These data would therefore suggest a short lockdown of only say 2 weeks in an area with a household density of around three persons and a high pre-lockdown prevalence would not control the virus as it would still be circulating within the households and rapidly re-emerge after only a short lockdown.

Discussion

The present results have explored the COVID-19 disease progression within the southwest London area and the effect of lockdown. These results confirm the importance of the timing of lockdown, and how the average household size should be considered in any discussions of that timing if the lockdown occurs in a local area rather than across the whole population. If the average household size is close to one person (which can occur in some countries such as Sweden), then disease progression is terminated at lockdown; however, if the average household size is very high, e.g., eight persons per household and the disease has progressed to a high level, e.g., 25%, lockdown has almost no effect at all as the model suggests that at the end of lockdown 90% of the population will have been affected.

The response to an “attack” could be a full lockdown, an area-specific lockdown, or an age-dependent lockdown. It would be possible to analyse the effects of all these types of intervention using major trauma patients by looking at data from different hospitals and by looking at data by age within each hospital.

The present study is also able to suggest that in an area such as southwest London with a high prevalence of disease (circa 20%) and an average household size of around three persons the lockdown period requires to be about 6 or 7 weeks for the disease prevalence to return to baseline. This was therefore almost the same as the period of full lockdown, suggesting that in London, the lockdown could not have been lifted any earlier. A further interesting finding from the St George’s data is that around 57% of the population was estimated to have been infected by the end of lockdown. It is interesting to consider whether this has resulted in any level of herd immunity and whether this has affected the rate of disease during September and October when the second wave started. This will be investigated in a further study where the St George’s data will be followed up to include more recent information on the second wave. The idea of herd immunity is complicated by the different responses to the virus where a strong antibody response could occur or just a T-cell and a weak or no antibody response. CT of the lungs has a much greater sensitivity for the detection of low levels of infection than other methods and earlier studies have shown that this may be the case. The present data suggest that far more people may have been exposed to the disease than suggested by other tests conducted in London, including the 17% suggested by antibodies alone. Antibody test result interpretation is complicated by the decline in the response for some people over just a few months and the fact that the period of time over which people showed COVID-19 signs were between early February and early May. SARS-CoV-2-specific memory T-cells may prove important for long-term immune protection, and this could affect the magnitude of the second wave in London compared with other areas of the country, which had much lower levels of the disease prior to lockdown on 23 March. A study of the second wave is planned as a third paper in a trilogy of papers using CT of major trauma patients, which was started with the first wave.

Figure 2 Percentage of the population who have had COVID-19 (dotted line) and pre-lockdown fitted curves showing 100% of population potentially affected by week 17 without lockdown.
The present data could also be used to determine the length of periods of normal activity followed by lockdown. For example, the virus would be kept to <5% population level by having a 6-week normal activity period followed by a 6-week lockdown. With restrictions in place, this period of normal activity could be increased. Further studies are required from different trauma centres to explore this further.

The present observed data was limited to only one hospital (St George’s Hospital) and the number of cases is not large (42 cases in the study population and six in the control population) on which the analysis is based. The variability in the estimated prevalence from week to week can be seen in Fig 1. Further, the exact effect of lockdown will be specific to the experience of a particular area in terms of growth rate of the disease, household size, and other factors relevant to London (e.g., underground train travel with packed carriages). The aim is to investigate the St George’s study replicated by a number of centres throughout the country as the data will be already available, and then to determine the full usefulness of the method. If it then proves to be useful, it could be used retrospectively as well as prospectively anywhere where there is a major trauma centre with CT facilities. The progress of the pandemic and effect of lockdown can be tracked since the beginning of the year throughout the whole country and the variation in pre-lockdown attack rate as well as the length of the sustain and decline periods and the final proportion with the disease after lockdown has finished. Any limitations with major trauma patients representing a random population (e.g., a slightly higher proportion of men) could be adjusted for statistically. Any limitations in numbers of events can be overcome by including more hospitals. In contrast, other methods, such as antibody tests, suffered from small numbers of tests in the early months of the pandemic. For example, in the North East of England the percentage of the population testing positive for antibodies in June 2020 was estimated as 2.4% (95% confidence interval [CI] 0.2–9.5), the very wide confidence limits indicating that the number of samples were too small to get a good estimate even of just antibodies.8

In summary, the present study describes one hospital’s experience of the first wave of the COVID-19 pandemic and considers how the data from major trauma patients in that hospital can be analysed in the wider context of all hospitals in the country and what the data can tell us about the population levels of disease in the local area of that hospital. Further studies of data from hospitals over the country, which for the most part would be available both retrospectively and prospectively, could be used to evaluate the usefulness and improve these methods. Radiology may therefore be able to play a unique role in studying the epidemiology of this disease.

Conflict of interest

The authors declare no conflict of interest.

References

1. Adam EJ, Grubnic S, Jacob T, et al. Using incidental COVID-19 findings on chest CT scans of major trauma patients to measure population prevalence: study methodology and results from London, England. Clin Radiol 2021;76(1):74.e15–21. https://doi.org/10.1016/j.crad.2020.10.008.
2. Petersen I, Phillips A. Three quarters of people with SARS-CoV-2 infection are asymptomatic: analysis of English household survey data. Clin Epidemiol 2020;12:1039–43. https://doi.org/10.2147/CLEP.S276823.
3. Sekine T, Perez-Potti A, Rivera-Ballesteros O, et al. Robust T cell immunity in convalescent individuals with asymptomatic or mild COVID-19. Cell 2020;183:158–68.
4. Tao A, Yang Z, Hou H, et al. Correlation of chest CT and RT-PCR testing in coronavirus disease 2019 (COVID-19) in China: a report of 1014 cases. Radiology 2020 Feb 26:200642.
5. Office of National Statistics UK Coronavirus. COVID-19) Infection Survey pilot: 28. May 2020. Available at: https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/conditionsanddiseases/bulletins/coronaviruscovid19infectionsurveypilot/28may2020 (accessed 12 October 2020).
6. Testing for SARS-CoV-2 antibodies. BMJ 2020;370:m3325. https://doi.org/10.1136/bmj.m3325.
7. Le Bert N, Tan AT, Kunasegaran K, et al. SARS-CoV-2-specific T cell immu-

...nity in cases of COVID-19 and SARS, and uninfected controls. Nature 2020;584:457–62. https://doi.org/10.1038/s41586-020-2550-z.
8. Office of National Statistics. Coronavirus (COVID-19) Infection Survey pilot: England, Wales and Northern Ireland. 9 October 2020. Available at: https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/conditionsanddiseases/bulletins/coronaviruscovid19infectionsurvey pilot/englandwalesandnorthernireland9october2020 (accessed 12 October 2020).