Preprint uploaded to medRxiv MEDRXIV/2020/039057 (awaiting checks and update, v1.1.0) Forecasting Ultra-early Intensive Care Strain from COVID-19 in England

Jacob Deasy[1], Emma Rocheteau[1], Katharina Kohler[2], Daniel J. Stubbs[2], Pietro Barbiero[1], Pietro Liò[1], and Ari Ercole[2,*]

[1]Department of Computer Science and Technology, University of Cambridge, Cambridge, CB3 0FD, UK.
[2]Division of Anaesthesia, Department of Medicine, University of Cambridge, Addenbrooke's Hospital, Cambridge, CB2 0QQ, UK.
[*]Corresponding author: ae105@cam.ac.uk

Abstract

The COVID-19 pandemic has led to unprecedented strain on intensive care unit (ICU) admission in parts of the world. Strategies to create surge ICU capacity require complex local and national service reconfiguration and reduction or cancellation of elective activity. These measures have an inevitable lag-time before additional capacity comes on-line. An accurate short-range forecast would be helpful in guiding such difficult, costly, and ethically challenging decisions.

At the time this work began, cases in England were starting to increase. If this represents a true spread in disease then ICU demand could increase rapidly. Here we present a short-range forecast based on published real-time COVID-19 case data from the seven National Health Service (NHS) commissioning regions in England (East of England, London, Midlands, North East and Yorkshire, North West, South East and South West). We use a Monte Carlo approach to model the likely impact of current diagnoses on regional ICU capacity over a 14-day horizon under the assumption that the increase in cases represents the start of an exponential growth in infections. Our model is designed to be parsimonious and based on available epidemiological data from the literature at the moment.

On the basis of the modelling assumptions made, ICU occupancy is likely to increase dramatically in the days following the time of modelling. If the current exponential growth continues, 5 out of 7 commissioning regions will have more critically ill COVID-19 patients than there are ICU beds within two weeks. Despite variable growth in absolute patients, all commissioning regions are forecast to be heavily burdened under the assumptions used.

Whilst, like any forecast model, there remain uncertainties both in terms of model specification and robust epidemiological data in this early prospective phase, it would seem that surge capacity will be required in the very near future. Our findings should be interpreted with caution, but we hope that our model will help policy decision makers with their preparations. The uncertainties in the data highlight the urgent need for ongoing real-time surveillance to allow forecasts to be constantly updated using high quality local patient-facing data as it emerges.

Introduction

The emergence of a novel COVID-19 coronavirus pandemic has rapidly caused an enormous worldwide medical and socioeconomic impact since the first case emerged on November 16th 2019 [1]. The relatively large numbers of covid-19 patients with hypoxaemic respiratory failure requiring ICU admission for mechanical ventilation and their high mortality [1] (compared to seasonal influenza) is of particular concern in the current circumstances. In Northern Italy, an exponential increase in COVID-19 admissions rapidly overwhelmed normal ICU capacity [2] and surge capacity had to be created quickly. The exact reason for the sudden need for ICU surge capacity in Italy and whether this will generalise to other countries is unclear, but both demographic factors and healthcare system structure are likely to be important. Notably, UK availability of ICU beds per capita compares poorly with other high-income countries—including Italy [3].

Whilst standard medical wards may be repurposed easily, creating ICU capacity is constrained by the need for complex equipment and the delivery of highly specialised care. Nevertheless, there are mechanisms by which ICU capacity can be increased in an emergency, including decreasing patient flow through reducing elective work or changing referral networks, and providing additional emergency physical capacity for mechanical ventilation (e.g. operating theatre ventilators). All of these require significant changes to infrastructure, processes, or staffing and are therefore expensive and possibly time-consuming. Furthermore, the consequences for resources and staff redeployment are significant. Forecasting was therefore essential in guiding such difficult policy decisions in Italy [2]. The explosion of cases seen in Italy means that an early warning of need for surge capacity is likely to be required in England.

Epidemiological simulation has previously been successful in predicting the need for surge H1N1 ICU capacity in 2009 [4, 5]. In recent days, a similar simulation model for COVID-19 has been circulating [6], which suggests an overwhelming demand for critical care, with a peak occurring between May and early June 2020 and lasting 2–3 months depending on non-pharmacological intervention (NPI) assumptions. Crucially, however, such simulation models do not incorporate up-to-date data and are therefore unsuitable for real time short-range forecasting and early warning.

In this paper we use published COVID-19 diagnosis data for England to generate the earliest possible estimates of additional ICU demand due to infections in the coming days, based on cautious epidemiological data from the literature and *under the assumption that the current increase in cases represents the exponential phase of an outbreak* rather than a change in ascertainment. Our emphasis is on making an updatable model from the little time-series data that are available in this ultra-early period, with the understanding that assumptions are necessary where data are unavailable. Our model predictions use the latest results from the rapidly developing COVID-19 literature, account for English demographics, and are stratified by the National Health Service (NHS) commissioning regions across the country.

Methods

We use COVID-19 diagnoses from England as reported by Public Health England (PHE) and matched to NHS commissioning regions [8] as our source data to obtain information on daily cases. We started to extract this data feed on 13/03/20 to give daily case data. We assume that the daily incidence of COVID-19 can be modelled as an exponential growth (in line with what was observed in Italy [2]). Therefore, we forecast the likely distributions of new COVID-19 diagnoses over the next 14 days by using an ordinary least squares fit to linearly extrapolate from the logarithm of the daily incidence.

Using early data from Verity *et al.* 2020 [9] (reproduced in Table 1), we estimate the ICU mortality and ICU admission rate per case by standardising to the local population in each NHS

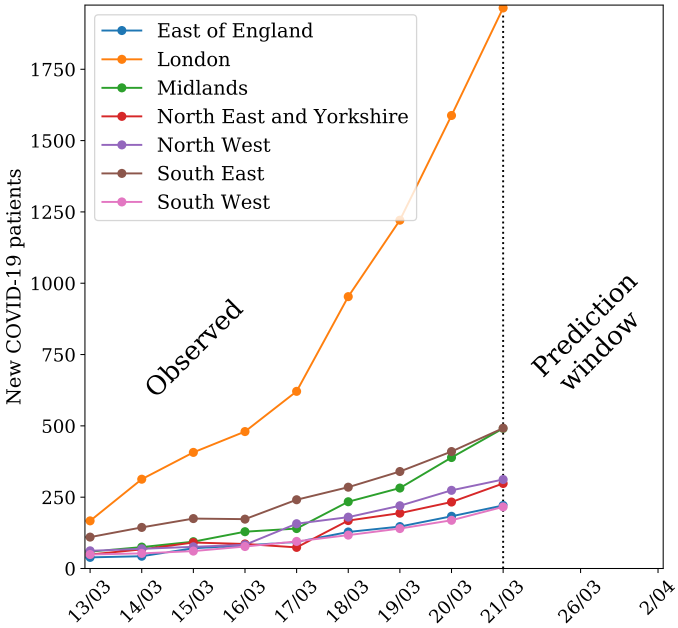

Figure 1: Model timeline. Our model relies on a n-day window for regression, beginning 13/03 with recent observed data. The model predicts two weeks into the future from the time of writing.

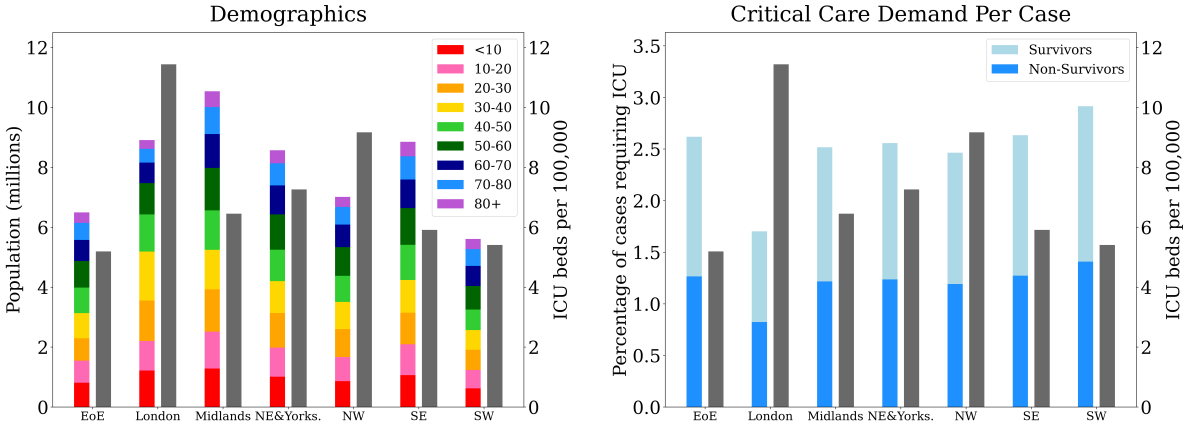

Figure 2: Regional demographics and expected critical care demand per case of COVID-19 stratified by region, each compared to ICU bed capacity per 100,000 people. Population is divided into age categories, and percentage of cases requiring ICU is divided into expected percentage of survivors and non-survivors. The numerical data can be seen in Table 1.

commissioning region in England (see Figure 2, obtained from the Clinical Commissioning Group population estimates for mid-2018 [10]). We adjust by age and sex, which have both been shown to strongly correlate with mortality [9]. There is a higher male:female ratio in China than in England, so we use data from the 2017 Chinese census [11] to adjust for this under the assumption that the added risk of being male holds on a univariate basis. We use the ICU admission rate estimates to obtain ICU admissions from the case predictions in each region.

As new diagnoses have a delay to arrival in the ICU, we model this with a normal distribution ($\mu = 10$, $\sigma = 3.5$). This is in line with multiple early reports from China [12, 13, 14, 15], which indicate a consistent pattern of disease progression, with hospital admission occurring

Region	Mortality (%)	Require ICU (%)	No. Beds
East of England	1.27	2.62	337
London	0.82	1.70	1019
Midlands	1.22	2.52	680
North East and Yorkshire	1.24	2.56	622
North West	1.19	2.46	643
South East	1.27	2.63	523
South West	1.41	2.92	303

Table 1: Mortality and Critical Care Needs due to COVID-19 in England stratified by region along with ICU capacity (Data Sources: [6, 7]).

around day 8, acute respiratory distress syndrome (ARDS) on day 9, and admission to the ICU for mechanical ventilation on day 10. Ten days was also used in the models published in Ferguson *et al.* [6].

Predicting bed occupancy also requires estimates of the length of stay for patients admitted to the ICU. The most up-to-date information indicates a median length of stay of approximately 8 days, with a wide interquartile range and positive skew [13, 14]. We model this with a gamma distribution ($\alpha = 8, \beta = 1$).

We use a Monte Carlo simulation with 100 samples to link the expected daily incidence distribution to the expected excess ICU bed occupancy due to COVID-19. This involves sampling from the daily incidence model, as well as the delay and length of stay distributions to obtain bed occupancy along with uncertainty estimates. We represent bed occupancy as a percentage of the total number of ICU beds in the commissioning region based on data from a snapshot in December 2019 [7].

Results

Figure 3 shows the expected number of new COVID-19 patients per day assuming the current exponential trend in England. We note that all R^2 values are above 0.9, implying that case growth in England is fit well by a linear model in log-space. In London, the R^2 value for the fit is particularly high and the 95% confidence interval is tight, demonstrating this region is likely to already be in a period of exponential growth of new cases. The fit is less reliable in the North East and Yorkshire, a region where we have separately confirmed the trend of observed new cases to have the weakest correlation with the other regions. The log-linear fit produces a strong R^2 value in populous areas outside London (e.g. Midlands), strengthening the argument for exponential growth in areas where the virus has gained a foothold. Irrespective of how many of these cases translate into ICU patients, even the lower confidence bounds indicate more than 1,500 new cases per day in all NHS commissioning regions in England within two weeks of writing.

Figure 4 shows the projected additional ICU occupancy due to COVID-19 from our model over a 14-day horizon for each of the NHS commissioning regions as a percentage of total ICU beds.

All source code has been made available at `https://github.com/ariercole/Cambridge_COVID-19_ICU` [16]. In addition to our analysis and open-source code, an interactive model with current data is available at `http://covid19icu.cl.cam.ac.uk`. As documented cases in the literature evolve, we hope clinical and policy decision makers will be able to experiment based on their region or the statistics demonstrated by their cohort. Given the highly dynamic situation at the time this work was carried out, with model data changing on a daily basis, minimising model development time was crucial. Using agile project management methodologies, we were able to develop a working model, documentation, and web-implementation in less than one week.

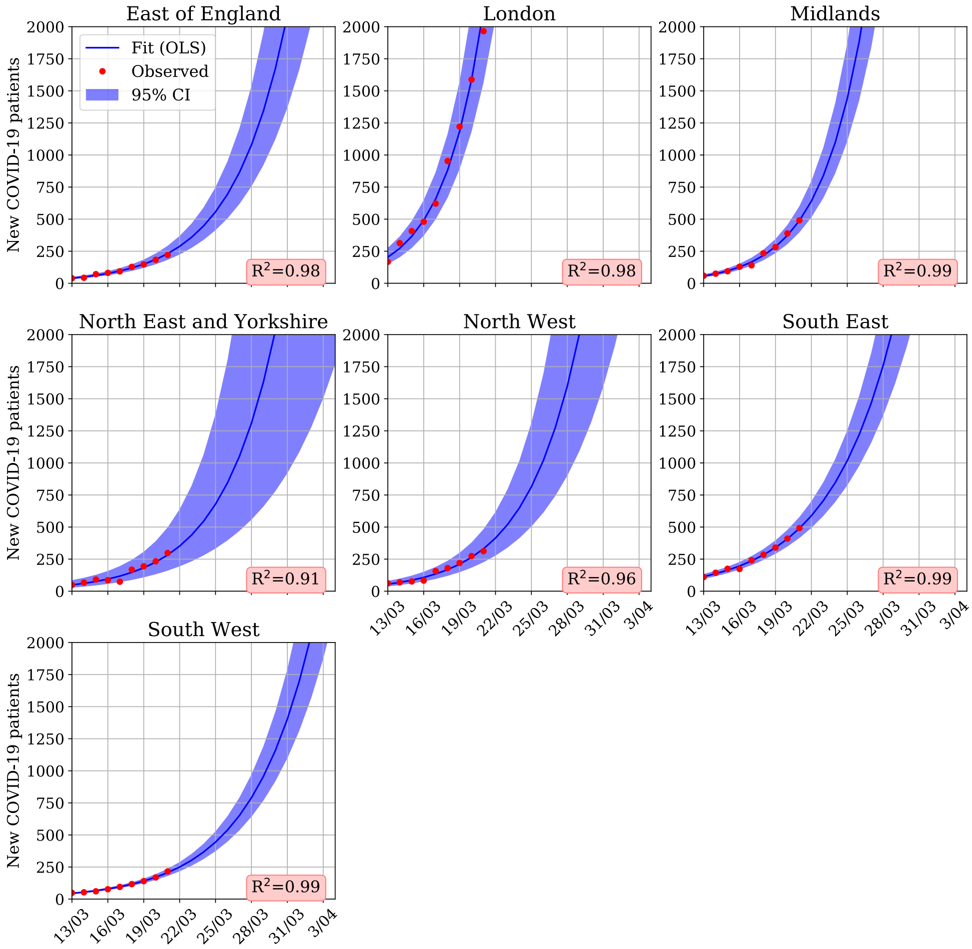

Figure 3: Projected new COVID-19 patients in the seven National Health Service commissioning regions in England. Exponential projections were calculated by an ordinary least squares fit on both estimates of previous values and reported recent values in log-space.

Discussion

It is crucial to appreciate that both model and parameter uncertainties are inevitable, particularly when predicting the behaviour of a novel virus in a new population, and this may radically affect our forecasts. However, we set out to provide the earliest possible data-driven forecast and therefore explicitly accept the limitations of the data available at the time. Our approach has been to keep the model as parsimonious as possible, with parameter estimates from the existing literature, to give a rough guide to early surge needs. With the small amount of available data, there are some specific limitations which need to be discussed.

We have used PHE published data for case ascertainment. We recognise that this data is potentially flawed and does not recognise all cases within the wider population. However, for our needs we specifically focus on the severe cases where, arguably, ascertainment bias is likely minimal due to the roll-out of routine testing for all critical care patients by PHE as part of the "COVID Hospitalisation in England Surveillance System—CHESS" [17]. Moreover, a persist-

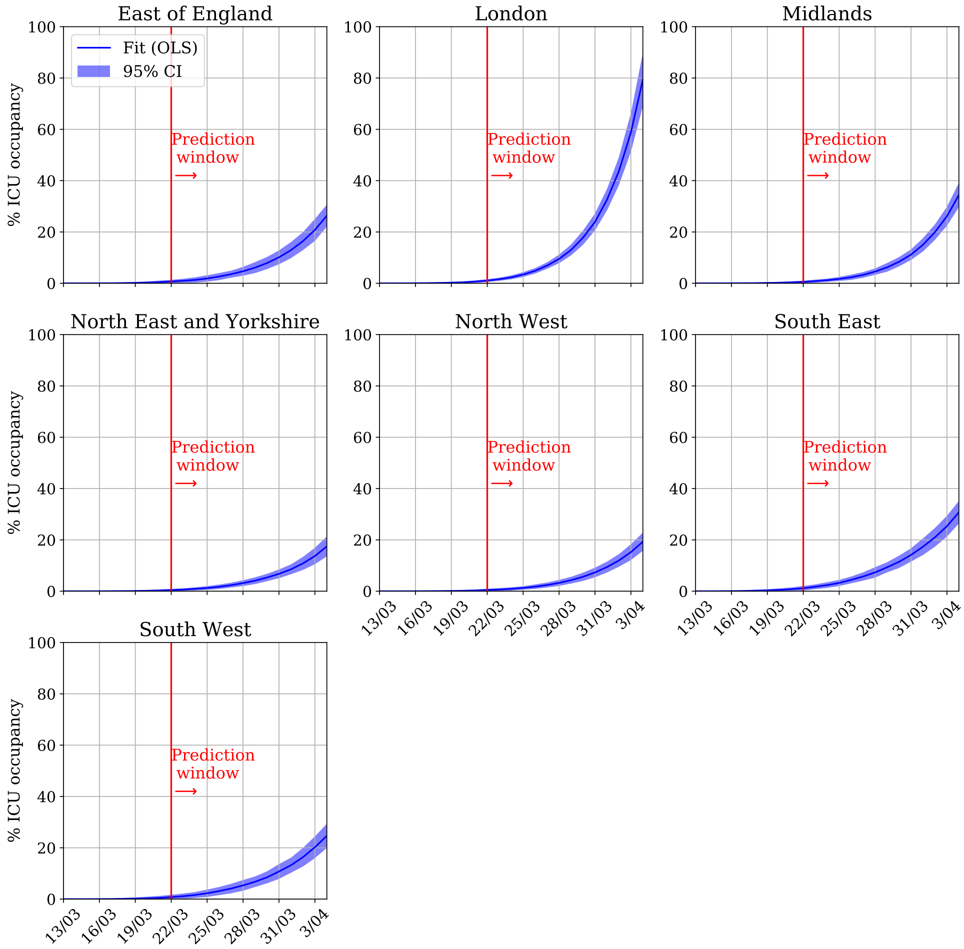

Figure 4: Projected regional COVID-19 ICU occupancy as a percentage of regional capacity the seven National Health Service commissioning regions in England.

ent issue is that case ascertainment and timing after symptom onset is unlikely to be uniform between healthcare settings or over time as the surveyed population varies. Thus, the compatibility between our data and the literature is uncertain. Changes in WHO case-definition and surveillance strategies over time mean that the original epidemiological data may overestimate ICU admission rates as milder cases were not included initially. This would artificially inflate our forecast numbers. Similarly, the UK surveillance has changed over time. If the upturn in COVID-19 cases seen at the time of writing is largely due to an increase in ascertainment, then this would also render our model overly pessimistic. Nevertheless, this will always be a limitation of any early modelling [9].

We assume that each region behaves as an optimally allocated "pool" of ICU beds, which is not necessarily true, since inter-hospital ICU-to-ICU transfers may not be feasible for both operational and clinical reasons, so that patients are unlikely to be uniformly distributed. We do not have more granular data available, but it is worth considering that it is possible for an individual hospital to reach critical capacity before the whole region. In this sense our predictions represent a "best case" scenario.

We forecast the percentage COVID-19 bed requirements in isolation, however the ICU must continue to provide care for other types of patients. Since UK bed occupancy is typically greater than 80% and may frequently exceed 100%, clearly not all beds can simply be reallocated for COVID-19 patients, however some specialist ICUs may not be able to reconfigure. Furthermore, we assumed that all adult critical care beds can be used for mechanically ventilated ICU patients, which operationally may not be possible. Thus, the precise percentage of additional COVID-19 patients that will actually exhaust routine capacity will vary from unit to unit, particularly in ICUs with a substantial post-operative elective surgical workload.

Conclusions

Early warning of an impending need for ICU surge capacity is crucial if there is to be sufficient time to re-configure services. We have shown that ultra-early data can be used to make time-sensitive forecasts of ICU occupancy. We show, subject to our assumptions, that it is credible that ICU requirements may become challenging within weeks. There remains a significant degree of uncertainty in the predictions due both to limitations of the reporting data and modelling assumptions. This emphasises the need for the collection of real-time patient-facing local data by initiatives such as CHESS [17] and a dynamic approach to improving models as new data becomes available.

Declarations of interest statement

None declared.

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