Report 41: The 2020 SARS-CoV-2 epidemic in England: key epidemiological drivers and impact of interventions

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Summary

We fitted a model of SARS-CoV-2 transmission in care homes and the community to regional surveillance data for England. Among control measures implemented, only national lockdown brought the reproduction number below 1 consistently; introduced one week earlier it could have reduced first wave deaths from 36,700 to 15,700 (95%CrI: 8,900–26,800). Improved clinical care reduced the infection fatality ratio from 1.25% (95%CrI: 1.18%–1.33%) to 0.77% (95%CrI: 0.71%–0.84%). The infection fatality ratio was higher in the elderly residing in care homes (35.9%, 95%CrI: 29.1%–43.4%) than those residing in the community (10.4%, 95%CrI: 9.1%–11.5%). England is still far from herd immunity, with regional cumulative infection incidence to 1st December 2020 between 4.8% (95%CrI: 4.4%–5.1%) and 15.4% (95%CrI: 14.9%–15.9%) of the population.

1. Introduction

England is among the countries worst-affected by the global pandemic of COVID-19, caused by the novel *Betacoronavirus* SARS-CoV-2. As of 2nd December 2020, over 51,000 deaths have been reported nationally, or 91 deaths per 100,000 people (*1*). The impact of the epidemic has varied across the country, with regional epidemics differing in their severity and timing. A key feature in all regions is the burden suffered by older adults living in care homes, where mortality has been high.

We use a mathematical model of SARS-CoV-2 transmission to reproduce the first two waves of the epidemic across England's seven NHS regions and assess the impact of interventions implemented by the UK government. We analyse the epidemic from importation of SARS-CoV-2 into each region to the 2nd December 2020: encompassing the first national lockdown from March – May, the interventions implemented as COVID-19 deaths increased again in the autumn, eventually leading to the second national lockdown in November.

We built an age-structured stochastic transmission model of SARS-CoV-2, representing care homes, hospital clinical pathways and the wider community (Materials and Methods). We developed a Bayesian evidence-synthesis approach to estimate model parameters and to reconstruct regional epidemics using data from daily recorded deaths, PCR testing, hospital admissions, hospital bed occupancy, individual patient outcomes, contact surveys, and serological surveys. We evaluated temporal changes in transmission as new control measures were implemented and then relaxed, and population immunity accrued. Inclusion of serological data allowed us to robustly estimate region- and age-specific disease severity, to compare severity in care home residents to elderly individuals in the community, and estimate the total epidemic size, by calculating the proportion of individuals infected over time in each region. Finally, we examined counterfactual epidemic scenarios, varying the date and duration of the first national lockdown and the effectiveness of restricting care home visits, to quantify the resulting impact on mortality.

Our analysis, which synthesises multiple data sources and parametrically accounts for their biases, provides a comprehensive overview of transmission, hospitalisation, and mortality patterns of SARS-CoV-2 in the first and second waves (up to 2nd December) in all regions of England. Our results provide crucial insights for controlling the epidemic in the future, emphasising the importance of acting fast to save lives.

2. Results

2.1 Epidemic trajectory

We used our evidence-synthesis approach, to infer the COVID-19 epidemic start date in each NHS England region (Figure 1A), then reconstructed epidemic trajectories for hospitalisations (Figure S7) and deaths in care homes and hospitals (Figure 1B-H). We estimated the basic reproduction number, R_0, defined as the expected number of onward infections from an infectious individual in a fully susceptible population to be 2.9 (95% CrI: 2.8-3.1) nationally. Figure 1I shows how the effective reproduction number R_t^{eff} (the expected number of onward infections from an individual infected at time t) changed in each region over time, in relation to government control measures and accrual of population immunity.

The first COVID-19 death in England occurred on 5th March 2020 (*2*). Seven days later, in response to the growing epidemic, the government began to introduce control measures, initially requiring individuals with a dry persistent cough and/or fever to self-isolate (*3*). On 23rd March this escalated to a full national lockdown (*4*, *5*). Irrespective of initial differences, the level of transmission during lockdown was similar across all regions (Figure 1I), consistent with mobility data showing movement during lockdown reduced to a consistent level nationally (*6*).
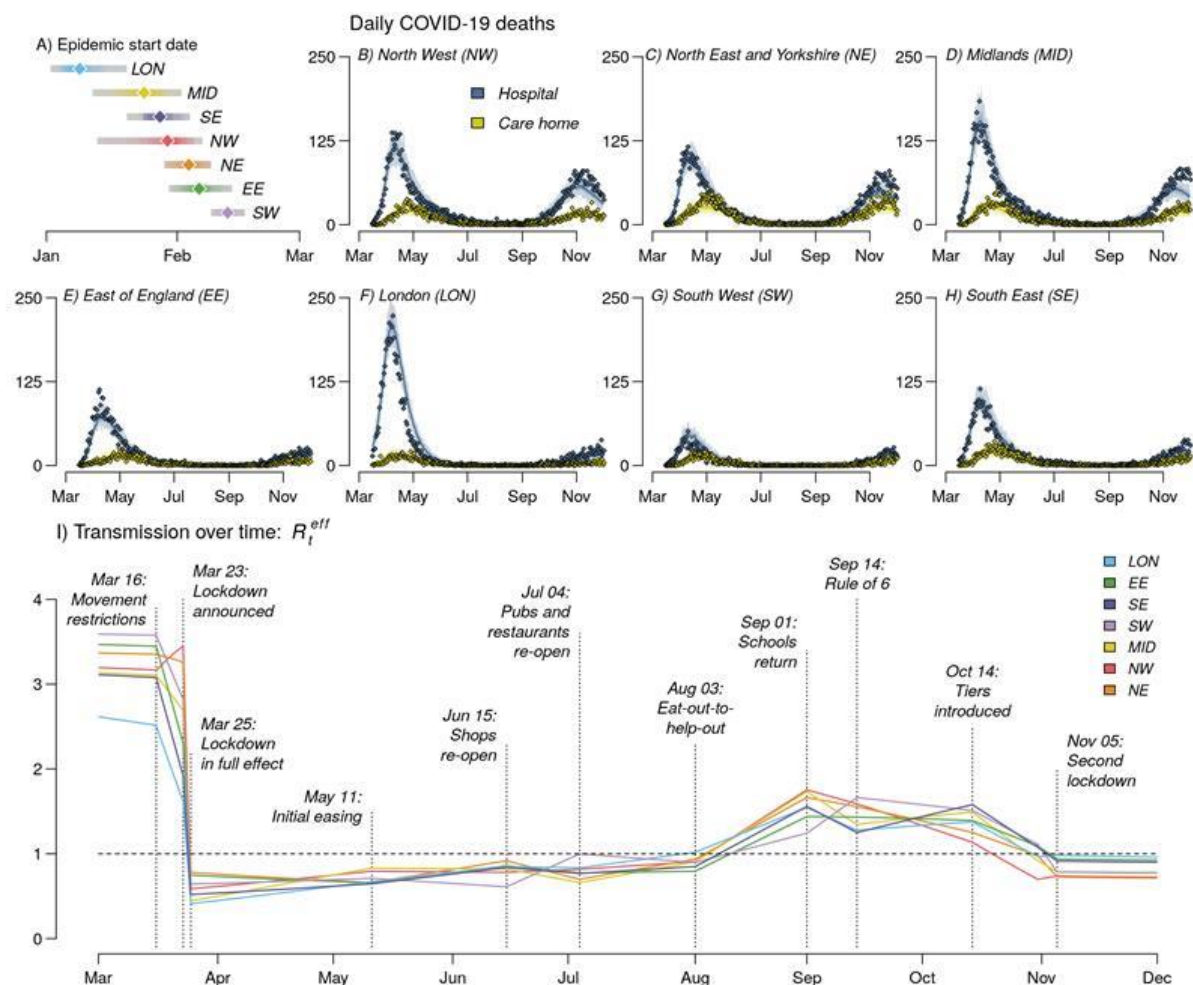
Figure 1: Trajectory of the England COVID-19 epidemic. **A,** The inferred epidemic start date in each NHS England region. **B-H,** The model fit to reported daily deaths from COVID-19 in care homes and hospitals for each NHS England region. The points show the daily data, solid lines the median posterior and the shaded area shows the 95% CrI. **I,** The mean effective reproduction number within the general community (i.e. excluding care homes) in each region from March to December. Vertical lines and labels represent dates of key policy changes, defining the breaking points of the underlying piecewise linear transmission rate. Dashed horizontal line depicts reproduction number of 1.

The epidemic in London began 15 days before (95% CrI: 28 days before, 3 days after) the rest of the country (Figure 1A), meaning the lockdown occurred at a later stage of its epidemic. London experienced a mortality of 88.5 (95% CrI: 79.9–95.3) per 100,000 during the first wave, compared to the national average of 70.7 (95% CrI: 64.6–77.1), despite having a younger population and a smaller care home population than other regions (296 vs 603 per 100,000 nationally).

A key feature of the first epidemic wave in England, in common with other European countries, was the high death toll within care homes, which accounted for 22.6% laboratory-confirmed COVID-19 deaths in England as of 1st August 2020. Although community transmission rates fell during lockdown, transmission within care homes continued to rise, with infection risk peaking in care home residents, between 26th March in London and 12th April in North East and Yorkshire (Figure 2A). Deaths in care homes peaked on average 13 days later than hospital deaths (Figure 1B-H).
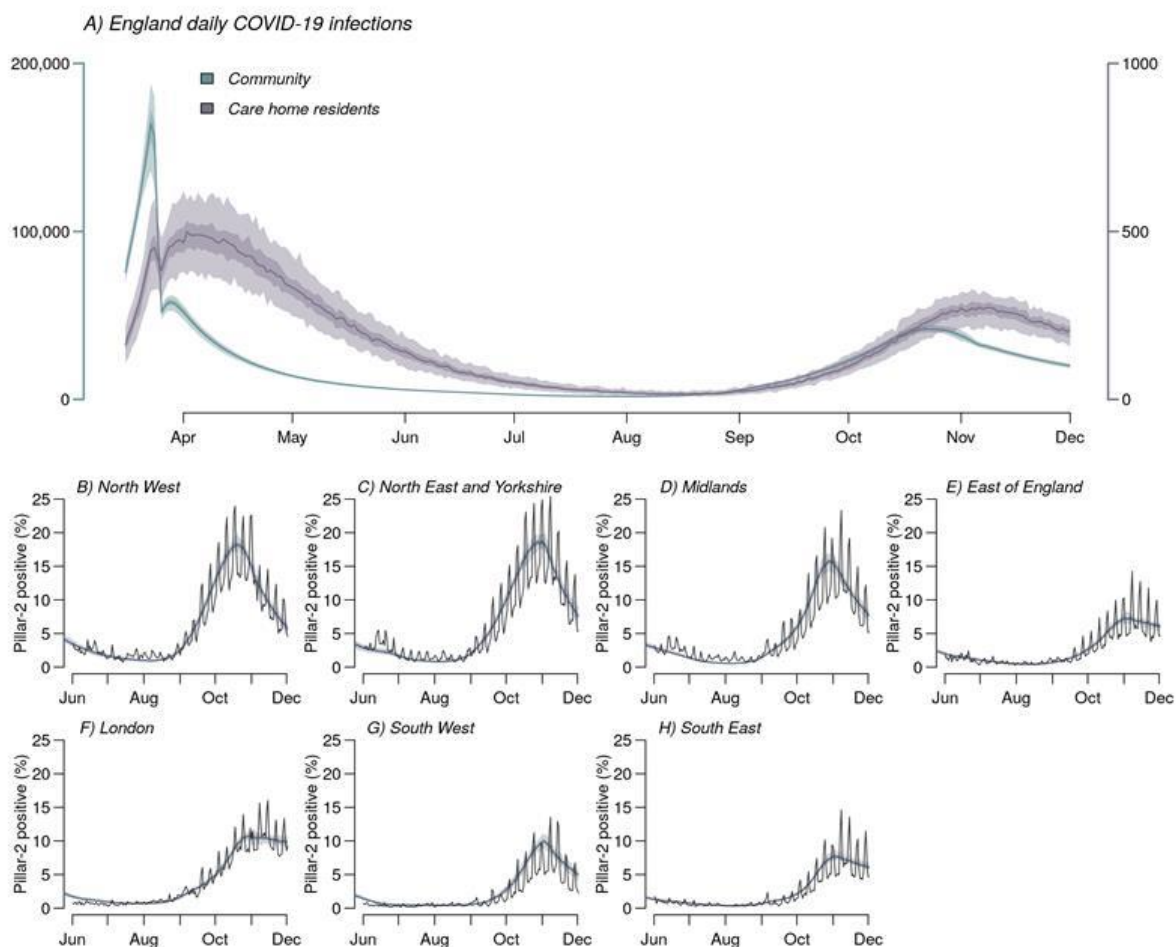
Figure 2: A, Inferred daily SARS-CoV-2 infections in England care home residents (right axis) and the wider community (left axis). **B-H**, Comparison of modelled (shaded bands) and observed (solid line) proportion of PCR tests that are positive, under pillar-2 testing (community swab testing for symptomatic individuals) in >25 year olds. Shaded bands depict 95% CrI, 50% CrI and median model outputs.

The first lockdown in England continued until 11th May, when people unable to work remotely were permitted to resume their jobs. Over the summer restrictions were successively eased, with non-essential shops, pubs and restaurants opening, followed by the government's 'Eat Out to Help Out' restaurant subsidy scheme in August (*7*). This led to a steady increase in transmission, with R_t^{eff} rising above 1 in all regions by mid-August (Figure 1I).

Increasing PCR test positivity marked the beginning of a second epidemic wave (Figure 2B-H, S6). The accompanying introduction of non-pharmaceutical interventions (NPIs) began with the "Rule of Six" (limiting social gatherings to 6 persons maximum) on 14th September (*8*), followed by the localised tiered restrictions on 14th October (*9*). These measures limited transmission in most regions but were not sufficient to reduce R_t^{eff} below 1 (Figure 1I). Consequently, on 31st October, the government announced a second national lockdown, which lasted from 5th November to 1st December (*10*).

Restrictions during the second lockdown were less stringent than the first, with schools and some workplaces remaining open. This was reflected in R_t^{eff} estimates of 0.83 (95% CrI: 0.81–0.85) at the start of the second lockdown, compared to R_t^{eff} = 0.54 (95% CrI: 0.50–0.59) at the start of the first. We estimate that without the population immunity accrued during the first wave, contact rates during the second lockdown would have resulted in a reproduction number of R_t = 0.95 (95% CrI: 0.93–0.98). Hence, population immunity helped to reduce transmission further below the critical threshold of R_t^{eff} = 1.

2.2 Severity and hospitalisation

COVID-19 manifests a broad spectrum of severity, from asymptomatic infection to life-threatening illness requiring intensive care. We estimated age-patterns of clinical progression in people admitted to hospital using individual-level data from 17,702 patients admitted between 18th March and 31st May 2020 (inclusive) in the COVID-19 Hospitalisation in England Surveillance System (CHESS, (*11*)) (Materials and Methods). We derived estimates of the time spent in each stage of the hospital pathway (including general wards, ICU and post-ICU stepdown care), as well as age-stratified probabilities of progression through that pathway (Figure 3 and Figure S8). We accounted for differing length of stays given different outcomes; there were marked differences in average length of ICU stay for those who died in ICU, those who later died in stepdown care and those who were discharged following stepdown care (Figure 3F). Among patients over 65, we found the probability of admission to ICU decreased with increasing age. Severity of COVID-19 increases with age, but for older patients and those with most severe illness, the benefit of ICU admission, ventilation and the corresponding prognosis may not be better than with oxygen therapy in a general ward (*12*). Thus, older and more severely infected patients may be directed to care on a general ward rather than admitted to ICU.

We used estimates of clinical progression to parametrise the transmission model, enabling us to infer temporal and regional differences in disease severity, informed by local demography, observed daily hospital admissions, bed occupancy and deaths. We measured severity of disease by the infection fatality ratio (IFR) and the infection hospitalisation ratio (IHR).
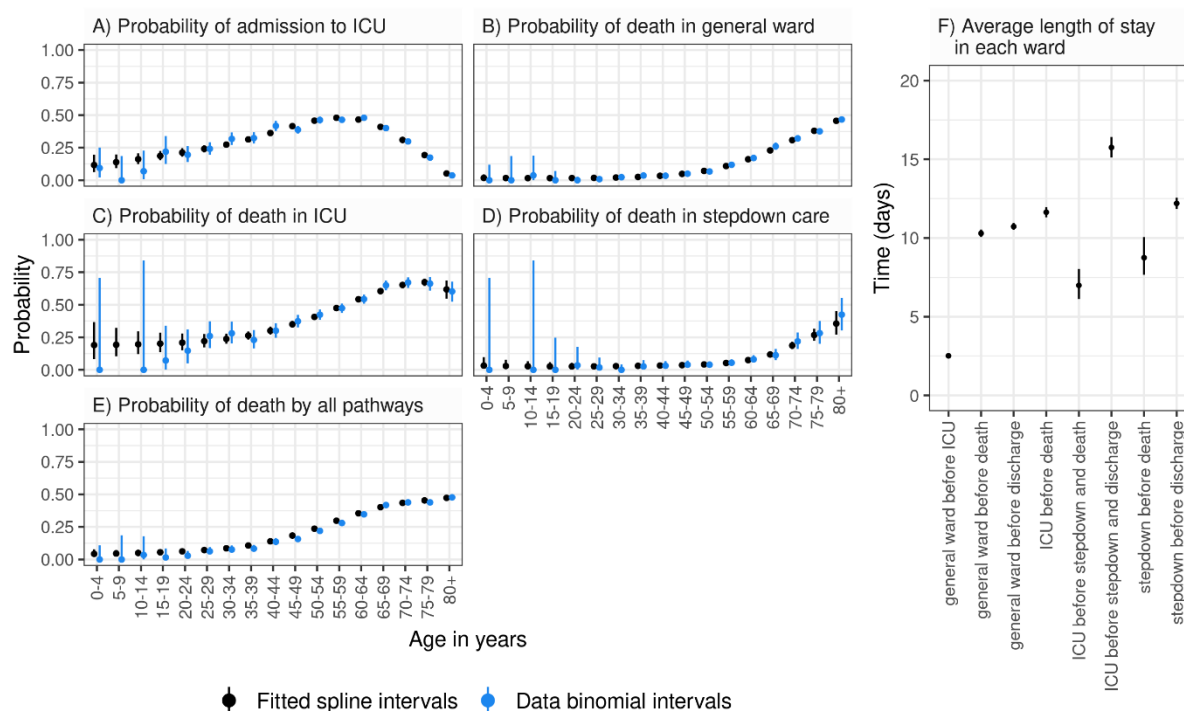
Patient progression in hospital

Figure 3: Age-dependent probabilities of progression through hospital pathways. **A,** Probability of admission to ICU. **B,** Probability of death in a general ward. **C,** Probability of death in ICU. **D,** Probability of death in stepdown care. **E,** Probability of death through all hospital pathways. Black circles and vertical segments show posterior mean and 95% credible intervals of splines fitted to data, blue circles and vertical segments show raw mean values and 95% confidence intervals (exact binomial) for each 5-year age group. **F,** Average length of stay in each ward (posterior mean and 95% credible intervals).

The severity of disease increased with age in all regions with the steepest increase above 65 years (Figure 4A-C), in line with observations worldwide (5). Regional estimates of age-aggregated disease severity depend on the population age distribution, which is similar in most regions of the country, except London, where the median age is 34.6 years (vs 39.5 years nationally). At the start of the first wave, London experienced an IFR (respectively IHR) of 0.91% (95% CrI: 0.82%–1.00%) (resp. 3.02%; 95% CrI: 2.82%–3.19%) compared to the national average of 1.25% (95% CrI: 1.18%–1.33%) (resp. 3.52%; 95% CrI: 3.29%–3.72%) (Figure 4D-E).
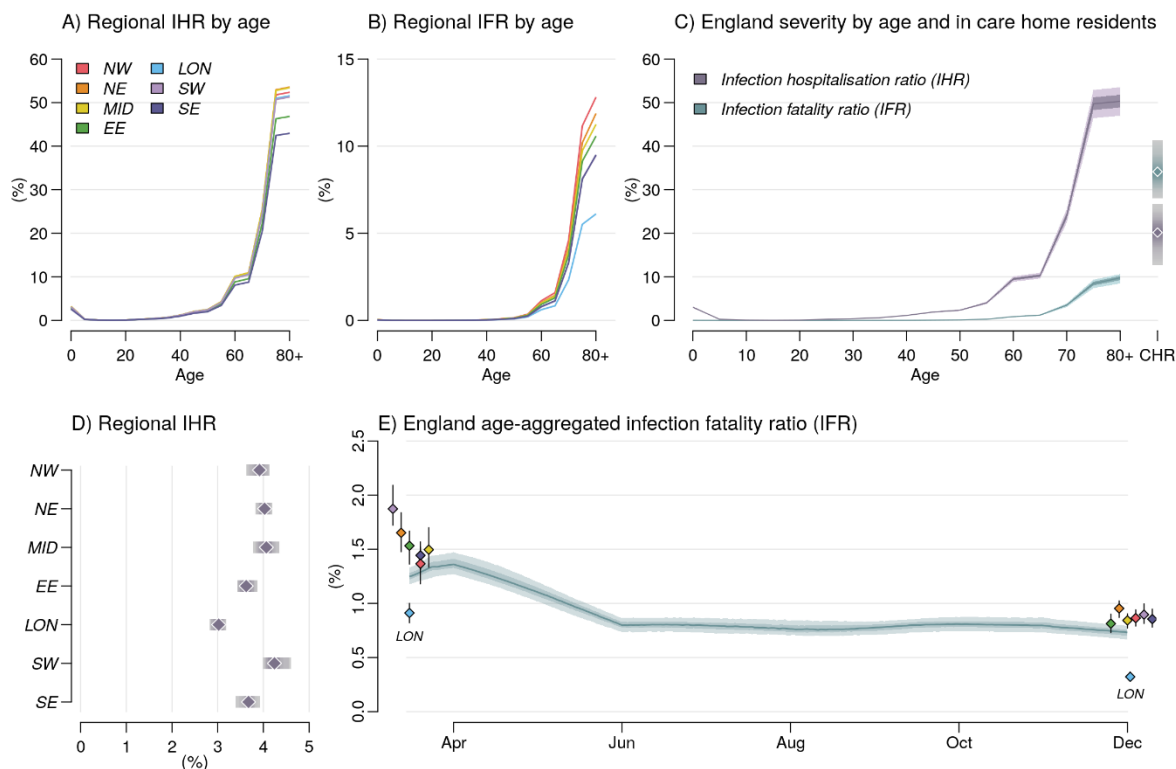
Figure 4: Relative severity of disease by age group and region. **A**, and **B**, Variation in the Infection fatality ratio (IFR) and Infection Hospitalisation Ratio (IHR) by age group in each region. Ages 80+ were modelled as a single risk group, care home residents are not included. **C**, The England IFR and IHR by age group and in care home residents (estimates denoted CHR at the right-hand side of the panel). National severity estimates are produced by aggregating regional estimates based on infection incidence. **D**, The regional IHR, aggregated over age and risk group by infection incidence. Plots a-d use parameter estimates, and incidence weightings calculated as of 1st December 2020. **E,** The England IFR over time, coloured dots show regional estimates of IFR at the start of the epidemic and on 1st December 2020 (clusters each correspond to one time-point, LON: London). In plots **C-E** Shaded bands depict 95% CrI and interquartile ranges, points depict medians.

Regional variation in the population age distribution did not fully account for differences in severity, with London still experiencing lower mortality when stratified by age (Figure 4A-B). The oldest age group (80+) in London had an IFR of 6.1% (95% CrI: 5.2%–6.8%) compared to 12.7% (95% CrI: 10.8%–14.3%) in the North West.

We estimated temporal trends in the IFR for England, by weighting regional estimates by incidence and population demographics. At the start of the first wave, the national IFR was 1.25% (95% CrI: 1.18%–1.33%) (Figure 4E), consistent with earlier reports from serology data alone (*13*). The national IFR initially appeared to increase, as transmission widened from London to regions with older populations and greater disease severity. Over the first wave, the proportion of hospital admissions resulting in death decreased, due to improvements in clinical management and alleviation of capacity constraints (*14*), leading to a national IFR of 0.77% (95% CrI: 0.71%–0.84%) by the end of the first wave. The magnitude of the relative reduction in IFR over time varied between regions, from 36.5% (95% CrI: 26.5%–47.5%) in the North West to 64.6% (95% CrI: 58.6%–68.8%) in London.

The IFR was greater among care home residents (35.9%, 95% CrI: 29.1%–43.4%) than in the 80+ in the community (10.4%, 95% CrI: 9.1%–11.5%, Figure 4C). Many care home residents did not transfer into hospital, and instead died in the facilities where they lived, so conversely the IHR was lower in care home residents (19.1%, 95% CrI: 11.5%–26.8%) than in those aged 80+ in the community (51.1%, 95% CrI: 47.6%–54.3%). We present national estimates of severity at the end of the second wave, stratified by age and care home residency in Table S9.

2.3 Epidemic size

Data from repeated serological surveys of blood donors aged 15-65 informed our estimation of the total regional epidemic size (Figure 5A-G), accounting for imperfect sensitivity and specificity of serological tests (Materials and Methods) (*15*). The cumulative proportion of the population ever infected with SARS-CoV-2 ranged from 4.8% (95% CrI: 4.4%–5.1%) in the South West to 15.4% (95% CrI: 14.9%–15.9%) in London (Figure 5H). Predicted seropositivity was initially greater than cumulative incidence, due to imperfect test specificity. The increase in seropositivity lagged cumulative infections by two weeks, reflecting the time from infection to seroconversion.
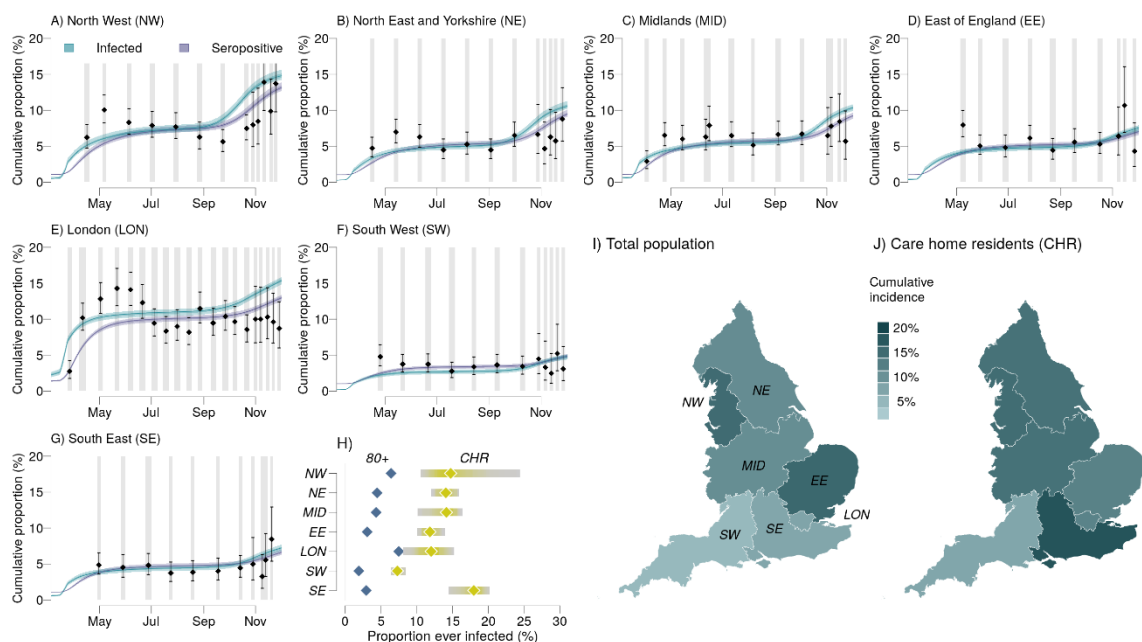

Figure 5: Cumulative incidence and seropositivity by region. **A-G**, Comparison of the estimated proportion of the population testing seropositive with observations from serological surveys. Vertical grey shaded bands show serological survey timings, black points the observed seroprevalence (bars: 95% exact confidence intervals), blue and purple lines show estimated proportion of the population infected and seropositive respectively (shaded bands the 95% CrI, 50% CrI and median). **H,** Comparison by region of the estimated cumulative attack rate in care home residents vs in the 80+ age group in the community (median, 95% CrI). The final epidemic size in each England NHS region **I**) in total and **J**) in care home residents.

Seropositivity notably declined following the first wave in some regions (Figure 5A-G). This may reflect antibody waning (*16*), or temporal trends in the composition of the surveyed population. Lockdown restrictions made attending blood donation centres difficult for all except key workers, who were more likely to have been infected (*17*), and may therefore be overrepresented in the sample of blood donors during the two lockdowns.

The proportion of care home residents ever infected with SARS-CoV-2 was 13.7% (95% CrI: 10.7%–16.7%), much higher than the 4.2% (95% CrI: 4.0%–4.4%) estimated in >80-year olds living in the community. This difference was consistently observed across all regions (Figure 5H). Regional differences in care home attack rates mirrored the patterns seen in the general community, with regions with larger community epidemics also experiencing larger care home epidemics (Figure 5I,J).

2.4 Impact of non-pharmaceutical interventions (NPIs)
We explored counterfactual intervention scenarios and examined the potential impact on mortality of initiating the first national lockdown one week earlier or later; ending that lockdown two weeks earlier or later; and 50% more or less restricted care home visits throughout the epidemic (Figure 6).
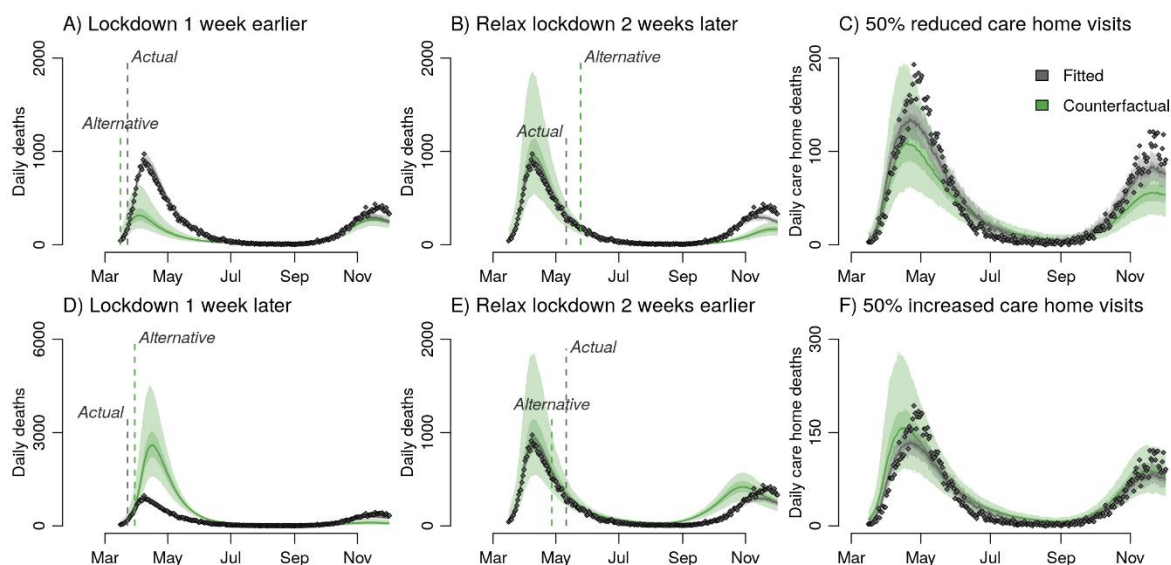

Figure 6: Counterfactual analysis of the impact on mortality aggregated across NHS England regions of **A, D**, initiating lockdown one week earlier / later, **B, E** Relaxing lockdown two weeks earlier / later, and **C, F** 50% more / less restricted care home visits. Panels **A**, **B**, **D** and **E** all present counterfactual outcomes for daily deaths in England but have different y-axis scales to better highlight differences between the observed data and each alternative lockdown scenario.

The timing of the initial national lockdown was crucial in determining the eventual epidemic size in England. Locking down a week earlier could have reduced the first wave death toll (up to 1st July 2020) from 36,700 to 15,700 (95% CrI: 8,900–26,800) while delaying lockdown by a week would have increased the deaths to 102,600 (95% CrI: 66,400–154,800) (Figure 6A, D). The impact varied by region, with regions with less established epidemics at the time of the first lockdown more sensitive to the timing of the intervention (Figure S10). Locking down a week later may have increased deaths, with large variability by region, from 105% in London to 274% in the Midlands but with very large uncertainty (Figure S9). Initiating a lockdown to interrupt the exponential growth phase of an epidemic has a much greater impact on reducing total mortality than extending an existing lockdown. Due to this asymmetry, relaxing the lockdown measures two weeks earlier (respectively later), could have increased deaths by 9,300 (95% CrI: 700–17,000) (respectively prevented 9,800 (95% CrI: 7,400–12,100) deaths) prior to 2nd December (Figure 6B, D).

We also explored counterfactual scenarios varying the level of visit restriction in care homes and estimated that reducing contact between the general population and care home residents by 50% could have reduced care home deaths by 44% (95% CrI: 17%–64%) (Figure 6C).

3. Discussion

We present a comprehensive overview of SARS-CoV-2 transmission, hospitalisation, mortality and intervention impact in the first two epidemic waves across all regions of England between March and December 2020. We successfully reproduce the transmission dynamics of the two epidemic waves, in terms of cases, PCR prevalence, seroprevalence, hospitalised cases (general wards and ICU), and deaths in hospitals and in care homes.

We estimate intense transmission in care homes even during the first national lockdown when R_t^{eff} in the community was well below one in all regions (Figure 2) (*18–20*). Combined with our counterfactual analysis of restricting visits (Figure 6) this suggests that reducing infection levels in care home residents is challenging. This highlights the difficulty of protecting care home residents from COVID-19: due to the necessarily close contact between staff and residents within a care home, once a care home outbreak has begun it is very difficult to reduce transmission, which overrides any impact of reducing the number of introductions (*21*, *22*).

We find that, consistent with existing literature (*23*), disease severity increases with age. Assessment of severity is complicated by the broad clinical spectrum of COVID-19 (*24–26*) hence, recent published estimates are still based on data from early in the pandemic (*27*). Here we provide updated severity estimates based on multiple contemporary data streams. We estimate considerable regional heterogeneity in severity, broadly consistent in the general population and in care homes for IFR and IHR. London experienced the lowest severity even after adjusting for its younger population. The estimated two-fold reduction over time in IFR (Figure 4) cannot be explained solely by the introduction of dexamethasone which reduces mortality amongst ICU patients (*28*), but rather a combination of factors including improvements in clinical management, greater experience in treating patients in ICU, and alleviation of capacity constraints (*14*, *29*).

Our analysis shows large regional variation in burden, especially in the first wave. This is likely due to the pattern of seeding and the timing of lockdown relative to how advanced each region's epidemic was (Figure 1A). Our counterfactual scenarios of initiating the first national lockdown one week earlier or later highlight the importance of early interventions to reduce overall mortality (Figure 6).

The extent and duration of infection-induced immunity to SARS-CoV-2 and its relationship to seropositivity remains unclear. Related seasonal coronaviruses induce immunity that wanes in one or two years (*30*), though antibody titres following SARS-CoV-1 infection appear to decay more slowly (*31*). Our estimated cumulative incidence over time (Figure 5), strongly supports the hypothesis that the epidemic decline after the first national lockdown was due to NPIs, with immunity playing a minimal role (*32*). Population-level immunity was insufficient to prevent a second wave of infection in any region (Figure 1), illustrated by the increase in reported cases and deaths which prompted the second national lockdown (*33*).

With the authorisation of the first SARS-CoV-2 vaccines in December 2020, we are now entering a new phase in the control of the COVID-19 pandemic. However, our estimates of current population immunity are low, with regional cumulative attack rates ranging from 4.8% to 15.4%, therefore any vaccination campaign will need to achieve high coverage and high levels of protection in vaccinated individuals to allow NPIs to be lifted without a resurgence of transmission. While vaccinating the most vulnerable age and risk groups will considerably reduce the burden of COVID-19, a large proportion of younger age groups may also need to be vaccinated to reach the immunity threshold for control. Our high estimates of transmission in care homes imply that vaccine uptake there will need to be especially high, particularly if vaccine efficacy is lower amongst older age groups.

We make a number of simplifying assumptions in our analysis. First, due to the compartmental nature of our model, we do not explicitly model individual care homes, rather the regional care home sector as a whole. However, as care home workers may work across multiple facilities leading to within and between care home transmission, we do not expect the simplification to substantially affect our conclusions. Similarly, we do not model individual households or transmission within and between them. When assessing the impact of NPIs on transmission we therefore capture population averages, rather than the contribution of household and non-household contacts. Second, hospital-acquired infections may have contributed to overall transmission, especially around the peak of the epidemic, and to persistence of infection in England over the summer months (*34*, *35*). Our model does not explicitly represent nosocomial transmission; therefore such effects will be encompassed within our regional R_t^{eff} estimates. Third, each data stream was subject to competing biases, which we statistically accounted for as far as possible (supplement section 1.1.2). A key strength of our evidence-synthesis approach is that we do not rely on any single data source, combining multiple perspectives to provide a robust overall picture of the epidemic. Finally, we model the epidemics in each NHS region in England independently without accounting for spatial effects across regional boundaries, or spatial heterogeneity within regions. This spatial scale was determined by the data and reflects limited movement between regions due to travel restrictions but does allow for movement within regions.

Our analysis provides a comprehensive overview of transmission, hospitalisation, and mortality patterns of COVID-19 in the first and second waves of the epidemic in all regions of England, one of the countries worst-affected by the pandemic. Integration of multiple data streams into a single cohesive modelling framework, enables us to disentangle transmission and severity from features of the surveillance system and provide robust estimates of the epidemiological characteristics of the COVID-19 epidemic in England. As nationwide vaccination programmes are rolled out, our results will help to inform how NPIs are applied in the future.

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5. Acknowledgements

5.1 Disclaimer

The views expressed are those of the authors and not necessarily those of the United Kingdom (UK) Department of Health and Social Care, the National Health Service, the National Institute for Health Research (NIHR), Public Health England (PHE), UK MRC, UKRI or European Union.

6. List of Supplementary Materials

Supplementary materials (Materials and Methods, Supplementary Results)

Supplementary data files: data_rtm.csv, data_serology.csv, support_progression.csv, support_severity.csv

7. Data availability statement

All code and de-identified regionally aggregated data (see supplementary materials for full details) required to reproduce this analysis are available at https://github.com/mrc-ide/sarscov2-transmission-england, (https://zenodo.org/record/4384864).