Methods

We identified waves in Rt estimates by finding local minima and maxima of median Rt estimates for each data source over a rolling window of 7 days. The centre of each wave was taken as the mean of the Rt estimates at the peak and the preceding trough, the amplitude as the estimate at the peak minus that at the centre, and the period as the time in days between peaks. To avoid the first epidemic wave dominating plots and obscuring differences, all plots were limited to the earliest date that any Rt estimate for England crossed below 1 after the peak.

We sourced weekly data on regional and national test positivity from Public Health England ([#ref](https://www.gov.uk/government/publications/national-covid-19-surveillance-reports)), and used a binary threshold of 5% test positivity (#ref-WHO) to plot over time. We interpreted results in light of known outbreaks and policy changes ([#ref](https://www.health.org.uk/news-and-comment/charts-and-infographics/covid-19-policy-tracker)).

Results

England

*Case counts and Rt estimates*

Across England, positive Covid-19 tests peaked at # cases, # admissions, and # deaths per day in March. From this level, counts among admissions and deaths declined more gradually than from all positive tests through April and May (time to a -50% decline from peak of 40, 45, and 30 days respectively; figure 1A). This mean that counts among all positive tests matched counts of admissions on 20th May, at 900 cases. Admissions and test-positive cases then gave approximately the same counts through June (+- 10%), with all three counts declining by 10% from 20th May to Jun 27th. This trend continued for counts of admissions and deaths from Covid-19 until August 20th. However, from late June, case counts from all reported test-positive cases increased rapidly (+10% over 7 days) and then gradually (+10% until 30 days until August 20th).

*Relationship between Rt estimates*

Rt estimates from all sources of cases moved in sine waves throughout the time series (figure 1B), but the frequency, amplitude, and trend of waves varied both by data source and within each Rt estimate over time. The net effect of the differences in wave frequency and amplitude is seen in the ratios between each Rt estimate (Figure 1C-E). Over April through to mid-June, Rt estimates from cases, admissions, and deaths had minor waves with no clear linear trend, with waves on average centred around 0.85 (95%CI for mean 0.75-0.93), 0.88 (95%CI 0.86-0.9), and 0.84 (95%CI 0.81-0.88) respectively. Rt estimates from admissions saw lower amplitude and higher frequency waves than that from deaths (respective mean wave amplitude from centre 0.05 (95%CI 0.01-0.08), with average period 25 days (95%CI 16-35); amplitude 0.09 (95%CI 0.07-0.1), with mean period 42 days (95%CI 21-63)). Among all estimates, Rt from deaths saw the lowest trough at 0.74 (90% credible interval (CrI) of estimate 0.61-0.87) in late May, before rising to match the Rt from admissions at 0.8 (90%CrI 0.65-0.94) on 26 June.

Through July and August, Rt from deaths and admissions then remained in synchrony (on average, admissions 3% higher, 95%CI 2-5%). Over this period, Rt from both deaths and admissions increased linearly, to reach 0.9 (95%CI 0.68-1.09) and 0.95 (95%CI 0.89-1.01) respectively by 3 August. In contrast, Rt from test-positive cases peaked on the 29th June at 1.36 in a high amplitude wave (amplitude 0.26, centre 1.1), followed by a lower second wave (amplitude 0.1, centre 1.05, peak at 1.15 on 30 July). Therefore, by 10 August the median Rt from admissions only 3% lower than the median Rt from test-positive cases.

Regions

*Case counts and Rt estimates over time*

From the first epidemic wave in March, regions experienced differing levels of case counts and similarity among counts by source of data (figure #). For example, London saw a similar raw case count in cases and admissions (mean difference 69, 95%CI 56-82), while the difference between cases and admissions compared to deaths was far wider (128 and 195)

Regions varied in the timing of the first epidemic wave. The date when Rt crossed below 1, indicating a declining epidemic, was spatially variable when estimated from cases (earliest median estimate below 1 on 28 March in London, latest 23 April in South West), but more consistent when estimated from admissions or deaths (range among regions 4 days and 8 days respectively, with an identical average of 1 April).

On average across all regions, cases saw a higher Rt estimate than admissions or deaths (mean of respective median estimates 1.1 (95%CI 1.09-1.13), 0.89 (95%CI 0.89-0.9), 0.94 (0.92-0.96). However, all regions experienced estimated Rt as waves over the time-series. When averaging across regions and time, cases had a lower frequency (mean periodicity among all regions of 39 days (95%CI 32-46)), and lower amplitude (0.11, 95%CI 0.06-0.15), compared to admissions (periodicity 29 days (95%CI 24-34), amplitude 0.06 (95%CI 0.04-0.07)) or deaths (periodicity 36 (95%CI 30-43)), amplitude 0.12 (95%CI 0.07-0.17)).

Rt estimates’ level, trend, frequency, and amplitude varied by region and over time.

South West had lowest periodicity of admissions and deaths (respective means 42, 95%CI 17-67; 69, 95%CI 0-266)

For example, among Rt estimates from cases, London saw a very long periodicity (mean 67 days, 95%CI 0-239) with a near-linear increase in trend between a trough on 8 May and the following peak on 8 July. In contrast, the North East and Yorkshire had just under monthly periodicity (28 days, 95%CI 22-34) of waves in Rt from cases. A potential driver of this could be changes in case detection, with increase testing around localised outbreaks in some regions. For example, this might be indicated where the North East and Yorkshire saw high test positivity rates among community (Pillar 2) tests (mean 6%, 95%CI 4.5-7.4, from 10 May when testing data became available to 30 August).

When Rt was estimated from deaths, the North East and Yorkshire showed markedly different trends from other regions, falling (in the opposite direction from Rt from admissions) over May to a stable trough over June, before a consistent rise through August. In contrast, cases and admissions experienced at least four and three peaks respectively over April through August.

North East and Yorkshire, and South West, saw the highest amplitude waves in cases

*Relationship between Rt estimates*

Synchrony among estimates therefore also varied regionally and temporally.

* Admissions and deaths:
  + Admissions or deaths similar through the time-series in London, North West, South West
  + in Midlands and South East, similar until July, then diverge
  + In North East & Yorkshire, diverge over mid-May to early July
  + In East of England, similar centre, but dissimilar characteristics over time (out of phase, different frequency + amplitude, no trend in deaths some decline in admissions)
* Cases to admissions and deaths
  + London: similar increasing trend over series, stronger trend and less variation
  + London, South East, Midlands, North West – similar over April through June/July