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FAST TRACK

Incidence, clinical outcomes, and transmission dynamics of severe coronavirus disease 2019 in California and Washington: prospective cohort study

Joseph A Lewnard,^{1,2,3} Vincent X Liu,⁴ Michael L Jackson,⁵ Mark A Schmidt,⁶ Britta L Jewell,^{7,8} Jean P Flores,⁹ Chris Jentz,⁹ Graham R Northrup,³ Ayesha Mahmud,¹⁰ Arthur L Reingold,¹ Maya Petersen,¹ Nicholas P Jewell,^{1,11} Scott Young,^{9,12} Jim Bellows⁹

For numbered affiliations see end of the article.

Correspondence to: J A Lewnard jlewnard@berkeley.edu (or @jLewnard on Twitter ORCID 0000-0002-8505-8839)

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ABSTRACT OBJECTIVE

To understand the epidemiology and burden of severe coronavirus disease 2019 (covid-19) during the first epidemic wave on the west coast of the United States.

DESIGN

Prospective cohort study.

SETTING

Kaiser Permanente integrated healthcare delivery systems serving populations in northern California, southern California, and Washington state.

PARTICIPANTS

1840 people with a first acute hospital admission for confirmed covid-19 by 22 April 2020, among 9 596 321 healthcare plan enrollees. Analyses of hospital length of stay and clinical outcomes included 1328 people admitted by 9 April 2020 (534 in northern California, 711 in southern California, and 83 in Washington).

MAIN OUTCOME MEASURES

Cumulative incidence of first acute hospital admission for confirmed covid-19, and subsequent probabilities of admission to an intensive care unit (ICU) and mortality, as well as duration of hospital stay and ICU stay. The effective reproduction number (R_t) describing transmission dynamics was estimated for each region.

RESULTS

As of 22 April 2020, cumulative incidences of a first acute hospital admission for covid-19 were 15.6 per

100 000 cohort members in northern California, 23.3 per 100 000 in southern California, and 14.7 per 100 000 in Washington. Accounting for censoring of incomplete hospital stays among those admitted by 9 April 2020, the estimated median duration of stay among survivors was 9.3 days (with 95% staying 0.8 to 32.9 days) and among non-survivors was 12.7 days (1.6 to 37.7 days). The censoring adjusted probability of ICU admission for male patients was 48.5% (95% confidence interval 41.8% to 56.3%) and for female patients was 32.0% (26.6% to 38.4%). For patients requiring critical care, the median duration of ICU stay was 10.6 days (with 95% staying 1.3 to 30.8 days). The censoring adjusted case fatality ratio was 23.5% (95% confidence interval 19.6% to 28.2%) among male inpatients and 14.9% (11.8% to 18.6%) among female inpatients; mortality risk increased with age for both male and female patients. Reductions in R_t were identified over the study period within each region.

CONCLUSIONS

Among residents of California and Washington state enrolled in Kaiser Permanente healthcare plans who were admitted to hospital with covid-19, the probabilities of ICU admission, of long hospital stay, and of mortality were identified to be high. Incidence rates of new hospital admissions have stabilized or declined in conjunction with implementation of social distancing interventions.

Introduction

Months after its emergence, the novel severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), responsible for coronavirus disease 2019 (covid-19), has resulted in a pandemic, with cases reported in nearly every country.¹ In total, 1 364 061 cases and 82 246 deaths were reported in the United States as of 14 May 2020, representing the greatest sum of any country.² Surges in covid-19 cases have overwhelmed the capacity of hospital and healthcare systems in regions of the US, mirroring the considerable disruption witnessed in other countries.³⁻⁵ However, the epidemiology of covid-19 in the US remains poorly described, including clinical variables of disease progression, the risk of admission to an intensive care unit (ICU), and death by patient age and sex, and the duration of hospital stay. As such, efforts to forecast trajectories of the epidemic to guide planning and response in the US and other high income settings have relied almost entirely on data from China to inform these variables,⁶ which might not adequately reflect clinical circumstances elsewhere.

WHAT IS ALREADY KNOWN ON THIS TOPIC

Coronavirus disease 2019 (covid-19) has overwhelmed the healthcare systems of certain countries and regions, with major proportions of patients requiring critical care

The west coast of the United States, however, has been spared severe healthcare disruption associated with surges in patients with severe covid-19 seen in other regions

WHAT THIS STUDY ADDS

In enrollees of the Kaiser Permanente healthcare service plan resident in California and Washington state, between 15 and 23 people were admitted to hospital for covid-19 per 100 000 cohort members

About one half of male patients and one third of female patients in this study who were admitted to hospital required critical care, and 23% of male patients and 15% of female patients died following admission

Transmission intensity declined in March 2020 in conjunction with implementation of interventions aiming to mitigate transmission

Metropolitan areas of the western US were among the first to report covid-19 importations and domestically acquired cases. Washington state announced the first known imported case of covid-19 in the US on 21 January 2020. Community transmission of SARS-CoV-2 has occurred at least since February in northern California, leading to covid-19 related deaths as early as 6 February. Most of the cases in California are concentrated in counties surrounding the San Francisco Bay in northern California, and Los Angeles in southern California. These regions were also among the first to implement intensive public health interventions aiming to curtail transmission. Statewide emergency declarations came into effect on 29 February in Washington and 4 March in California. Social distancing recommendations for vulnerable populations were issued in San Francisco on 6 March and large gatherings were banned in Washington on 11 March and in Los Angeles on 12 March. Large scale stay at home orders were implemented on 17 March for the six counties of the San Francisco Bay area, and statewide in California on 19 March and in Washington on 24 March. Understanding the impact of these interventions is of crucial importance to inform their broader use, and could help to account for emerging regional differences in the severity of covid-19 outbreaks across the country.⁷

To inform the epidemiology of covid-19 in these regions, we analyzed healthcare data for all people admitted to hospital with covid-19 within the cohort of 9 596 321 who received comprehensive, integrated care from Kaiser Permanente healthcare systems in northern California, southern California, and Washington state.

Methods

Setting

The Kaiser Permanente healthcare systems for northern California, southern California, and Washington state deliver fully integrated healthcare to diverse membership cohorts. Profiles of enrollees by age, race, and sex are similar to those of the general populations of the states of California and Washington (see supplementary table S1). As most enrollees receive employer sponsored health insurance coverage, however, fewer Kaiser Permanente plan members either have low incomes or reside in low income census tracts compared with national or regional averages.⁸⁻¹¹ Compared with 33% of adults in the US general population, 41% of Kaiser Permanente enrollees in northern California and 31% in southern California aged 25 years or older are estimated to have completed four or more years of college education; similar estimates are not yet available for enrollees in Washington as membership was only established in 2017.^{12 13}

Study design

We analyzed clinical and administrative data captured from all Kaiser Permanente members who had been admitted to hospital within the northern California,

southern California, and Washington healthcare delivery systems with covid-19 laboratory or clinical diagnoses at any recorded healthcare encounter by end of day on 22 April 2020; for analyses of patient outcomes, we included those admitted by 9 April 2020, because data for at least 14 days' follow-up were available at time of analysis. We considered patients to have clinically confirmed covid-19 if no positive test result was available and diagnosis codes included any of the diagnoses listed in supplementary table S2. Clinical diagnoses were overruled by negative laboratory test results.

Recorded encounters included hospital, outpatient, and telehealth visits as well as uses of laboratory diagnostic services. We limited hospital admissions to acute inpatient admissions occurring between 14 days before and 28 days after the first encounter when a patient was flagged for exposure to SARS-CoV-2, was designated as a "person under investigation" for covid-19, or had confirmed covid-19. Because only the most recent designation as exposure to SARS-Cov-2, person under investigation, or confirmed covid-19 was available for the Washington cohort, we considered hospital admissions for covid-19 to include those for which admission or discharge occurred within 30 days of the encounter with this most recent status assigned. Observational admissions were excluded. For both Californian cohorts, we sourced hospital admission events from electronic medical records and outside medical claims. Hospital admissions in the Washington cohort were sourced from a centralized admissions database.

Patients discharged at the end of their most recent hospital stay were considered to be survivors if they had not died by end of day 22 April; while standardized discharge criteria were not in place, considerations included clinical recovery (no hypoxia or mild hypoxia that corrects easily with supplemental oxygen), low perceived risk of clinical deterioration, and access to appropriate post-discharge clinical care at the discharge location, consistent with Centers for Disease Control and Prevention guidance.^{14 15} We used competing risk parametric survival methods to account for censoring of observations from currently admitted patients for all analyses. Available data for patients included dates of covid-19 clinical encounters, age, sex, dates of hospital stay, total duration of hospital stay, duration of ICU stay, survival or non-survival outcome (for completed hospital admissions only), and covid-19 diagnostic tests performed in any setting, along with the results.

Statistical analysis

Incidence estimation

For each of the three cohorts we estimated daily and cumulative incidences of covid-19 related hospital admissions within the full cohort population and within 10 year age strata (ages 0-9, 10-19, 20-29, 30-39, 40-49, 50-59, 60-69, 70-79, and ≥80 years). Hospital admission case data included all patients admitted by end of day 22 April.

Duration of hospital stay

We aimed to infer distributions of the duration of hospital stay among all patients admitted by 9 April 2020, and the distribution of the duration of ICU stay among patients receiving intensive care. We computed length of stay as the number of unique calendar days during which participants were in hospital; durations were summed across all hospital stays for readmitted patients. For these analyses, we used the CFC package¹⁶ in R (version 1.1.463; R Foundation for Statistical Computing, Vienna, Austria) to fit age adjusted Weibull competing risk models. Outcomes included discharge (alive), mortality, or right censoring (for ongoing hospital admission).

Duration of ICU stay was available only among participants with completed hospital admissions. For unbiased inference of the duration of ICU stay, we resampled observations from participants' conditional distribution of ICU lengths of stay, given their duration of hospital admission, age group, and survivor or non-survivor status. We defined sampling weights according to the (unconditional) distribution of total durations for hospital admissions across these patient strata. We fitted Weibull distribution parameters to the resampled data through maximum likelihood to reconstruct unbiased distributions of the total duration of ICU stay.

Probability of ICU admission and mortality

We used a similar approach to correct for censoring of recent hospital admissions when estimating age and sex specific probabilities of ICU admission and death among hospital inpatients admitted by 9 April 2020. Using generalized linear models with a Poisson link function, we estimated the conditional probability of each outcome among those with completed hospital admissions given the duration of hospital stay, age, and sex, accounting for all two way interactions among these covariates needed to minimize values of the bayesian information criterion. We then integrated the estimated conditional probabilities of each outcome over all durations of hospital admissions, weighted by the probability distribution of durations for hospital admissions within each age and sex stratum.

Transmission dynamics

We used hospital admission data to estimate time varying values of the effective reproduction number (R_E), which describes the number of secondary infections resulting from infections acquired on a given day.¹⁷ We compared R_E estimates generated under eight analyses defined by alternative parameterizations of the incubation period, the time from symptoms onset to hospital admission, and the infection to hospital admission ratio, each informed by data from distinct studies.¹⁸⁻²⁸

We sampled the date of SARS-CoV-2 infection for each patient admitted to hospital, assuming time from infection to hospital admission was distributed according to the sum of random draws from fitted distributions of the time from infection to symptoms

onset (incubation period) and the time from symptoms onset to hospital admission. We considered two parameterizations of the incubation period: first, we inferred duration by sampling from previous parameterizations of the incubation period duration on the basis of independent data sources from multiple countries¹⁸⁻²¹ (weighted by the number of participants in each of these studies) and by fitting a Weibull distribution to the resulting pooled sample through maximum likelihood. Second, we considered a log normal parameterization of the incubation period fitted in a previous study.²⁰

We also used estimates from two different studies for the time from symptoms onset to hospital admission. The first study reported variables of a Gamma distribution providing the best fit to patient level observations (compared with Weibull and log normal parameterizations).²² For the second study, we fitted Gamma, Weibull, and log normal distribution parameters against the reported mean and interquartile range of time from symptoms onset to hospital admission, finding that a Gamma distribution minimized summed squared errors compared with reported values.²³ To account for right censoring of infections in those who were not admitted to hospital by the end of the study period, we divided the number of observed infections in those admitted to hospital that were estimated to have been acquired each date by the proportion of those with infections who would be expected to experience hospital admission by 22 April, according to the cumulative distribution function of time from infection to hospital admission.

We weighted the number of infections occurring for each observed patient admitted to hospital by previous estimates of the age specific probability of hospital admission, given infection, from two distinct studies.²⁴⁻²⁵ We propagated uncertainty in this probability by fitting log normal distributions to reported empirical means and 95% uncertainty bounds within each age group (aggregated at ages 0-19 years), for each study, and taking independent draws from these fitted distributions for analyses. Efforts to parameterize the proportion of infections necessitating hospital admission under the assumption of Beta distributed probabilities resulted in greater summed squared errors compared with reported means and 95% uncertainty bounds.

To estimate R_E for new infections acquired each day in each cohort, we applied the method of Wallinga and Teunis¹⁷ to our reconstructed estimates of daily new infections, using the distribution of the serial interval to assign the probability of a transmission link between any two infections on differing days. Similar to the analysis described for incubation periods, we sampled from serial interval estimates from previous studies¹⁸⁻²⁶⁻²⁸ according to the number of participants for whom data were available, and fitted a Weibull distribution to the sampled data by maximum likelihood. To correct for right censoring of transmission pairs, we divided estimates of R_E for infections acquired each day t by the cumulative distribution function of the serial interval

evaluated over the period from day t to the end of the study.

Patient and public involvement

As the study involved secondary analysis of data, patients and members of the public were not directly involved in the study design.

Results

Cumulatively, 1840 members were admitted to hospital with a confirmed diagnosis of covid-19 as of 22 April 2020: 678 in the northern California cohort, 1059 in the southern California cohort, and 103 in the Washington cohort (see supplementary table S3). Median time from admission to covid-19 diagnosis declined from three days to zero days between February and April 2020, and an increasing proportion of admitted patients received a covid-19 diagnosis before admission over this period (see supplementary table S4).

In total, 1328 people were admitted to hospital by 9 April 2020, and thus had 14 days or more of follow-up at time of data analysis for assessment of clinical outcomes (table 1). Among these patients, 534 were from the northern California cohort, 711 from the southern California cohort, and 83 from the Washington cohort. The median age of patients was 61 years (range 18-103 years), with 50% aged 48 to 72 years. Four (0.3%) patients were younger than 20 years, 528 (39.8%) were 65 years or older, and 162 (12.2%) were 80 years or older; 741 (55.8%) were male patients. By end of 22 April 2020, laboratory confirmed diagnosis of covid-19 was available for 1271 (95.7%) patients admitted to hospital by 9 April 2020.

Hospital admissions were complete for 1176 (88.6%) patients who had been admitted to hospital by 9 April 2020; 1095 of whom had complete data on survival or non-survival status (table 1). Among patients with completed hospital stays and outcomes recorded, 202 (18.4%) had died by end of day 22 April 2020. Data on ICU admissions were available for 1101 people (only those in both Californian cohorts), among whom 333 were admitted to ICU.

Incidence of covid-19 related hospital admissions

For the period ending 22 April 2020, the estimated cumulative incidences of covid-19 related hospital admissions were 15.6 per 100 000 cohort members for the northern California cohort, 23.3 per 100 000 for the southern California cohort, and 14.7 per 100 000 for the Washington cohort (fig 1). Incidence increased with age, with hospital admissions by 22 April 2020 in those aged 80 or older reaching 74.0 per 100 000 members in the northern California cohort, 90.4 per 100 000 in the southern California cohort, and 46.7 in the Washington cohort (fig 2). Daily rates of hospital admissions reached their highest levels on 23 March in the northern California cohort, 1 April in the southern California cohort, and 4 April in the Washington cohort, with new daily admissions of 0.6, 1.0, and 1.0 per 100 000 cohort members, respectively.

Duration of hospital stay

Accounting for censoring (see supplementary table S5), the estimated median length of stay for all patients admitted to hospital by 9 April 2020 was 10.1 days, with 50% of hospital stays lasting between 5.3 and 16.8 days and 95% lasting between 0.9 and 34.5 days (fig 3); similarly, the observed median duration of stay for patients admitted by 15 March 2020 was 11 days. Model estimated median durations of stay were 9.3 days for survivors and 12.7 days for non-survivors, with 95% of these patients staying 0.8 to 32.9 days and 1.6 to 37.7 days, respectively. The estimated median duration of ICU stay was 10.5 days among patients receiving intensive care, with 50% of ICU stays lasting between 6.0 and 16.4 days and 95% lasting between 1.3 and 30.7 days. These estimates did not differ in sensitivity analyses restricted to patients with laboratory confirmed covid-19 (see supplementary table S6).

Intensive care requirements and case fatality risk

Across all age groups and sexes (weighted by their representation among new admissions) and accounting for censoring of recent hospital admissions, the estimated probability of ICU admission was 40.7% (95% confidence interval 36.0% to 46.1%) and the probability of death was 18.9% (16.3% to 21.9%) (fig 4). Risk of death increased with age, reaching 37.3% (30.6% to 45.0%) among participants aged 80 years or older admitted to hospital. Additionally, male patients were more likely to be admitted to ICU than female patients (48.5% (41.8% to 56.3%) v 32.0% (26.6% to 38.4%)) and more likely to die (23.5% (19.6% to 28.2%) v 14.9% (11.8% to 18.6%)). These results likewise did not differ in sensitivity analyses restricted to those with laboratory confirmed covid-19 (see supplementary table S7).

Transmission dynamics

Based on all possible combinations of the parameterizations listed in supplementary tables S8 and S9, we estimated that people acquiring infection on 1 March 2020 were expected to be responsible for between 1.39 (95% confidence interval 1.14 to 1.69) and 1.54 (1.18 to 1.98) secondary infections, on average (R_E), in the Kaiser Permanente northern California region; between 2.06 (1.47 to 2.94) and 2.49 (1.88 to 3.33) in the southern California region; and between 1.31 (0.00 to 2.94) and 1.53 (0.00 to 2.59) in the Washington region (see supplementary fig S2). Wider uncertainty intervals are propagated in R_E estimates for Washington owing to the smaller cohort size and lower absolute number of hospital admissions. After implementation of mitigation interventions by state, county, and municipal governments, the estimated R_E among those acquiring infection on 1 April 2020 was between 0.81 (0.62 to 1.03) and 0.90 (0.68 to 1.16) in the Kaiser Permanente northern California region, between 0.78 (0.68 to 0.90) and 0.87 (0.77 to 0.98) in the southern California region, and between 0.78 (0.00 to 1.51) and 0.86 (0.00 to 1.28) in the Washington region.²⁹

Table 1 | Characteristics of patients with confirmed coronavirus disease 2019 (covid-19) admitted to hospital by 9 April 2020. Values are numbers (percentages) unless stated otherwise

Characteristics	Kaiser Permanente region			
	Northern California (n=4 348 020)*	Southern California (n=4 548 811)*	Washington (n=699 490)*	All regions (n=9 596 321)*
No admitted to hospital	534	711	83	1328
Median (range); interquartile range	61 (19-103); 49-73	60 (18-100); 47-71	62 (27-91); 52-72	61 (18-103); 48-72
Age group (years):				
0-9	0 (0)	0 (0)	0 (0)	0 (0)
10-19	1 (0.2)	3 (0.4)	0 (0)	4 (0.3)
20-29	21 (3.9)	26 (3.7)	1 (1.2)	48 (3.6)
30-39	38 (7.1)	77 (10.8)	5 (6.0)	120 (9.0)
40-49	80 (15.0)	100 (14.1)	13 (15.7)	193 (14.5)
50-59	109 (20.5)	144 (20.3)	16 (19.3)	269 (20.3)
60-69	118 (22.1)	163 (22.9)	21 (25.3)	302 (22.8)
70-79	91 (17.1)	119 (16.7)	19 (22.9)	229 (17.3)
≥80	75 (14.1)	79 (11.1)	8 (9.6)	162 (12.2)
Male sex	301 (56.5)	396 (55.7)	44 (53.0)	741 (55.8)
Events before 23 April 2020:				
Laboratory confirmed covid-19	502 (94.0)	686 (96.5)	83 (100)	1271 (95.7)
Hospital admission complete	480 (89.9)	621 (87.3)	75 (90.4)	1176 (88.6)
Discharge alive†	393/472 (83.3)	434/548 (79.2)	66/75 (88.0)	893/1095 (81.6)
Death‡	79/472 (16.7)	114/548 (20.8)	9/75 (12.0)	202/1095 (18.4)
Intensive care unit admission‡				
Among cases with completed hospital admissions	134/480 (27.9)	199/621 (32.0)	–	–
Among survivors	81/393 (20.6)	115/434 (26.5)	–	–
Among non-survivors	53/79 (67.1)	84/114 (73.7)	–	–

*Cohort size.
†Denominators are limited to those with completed hospital admissions. Outcomes were not recorded at time of writing for 81 people with completed hospital admissions.
‡Admission data were not available for Washington state.

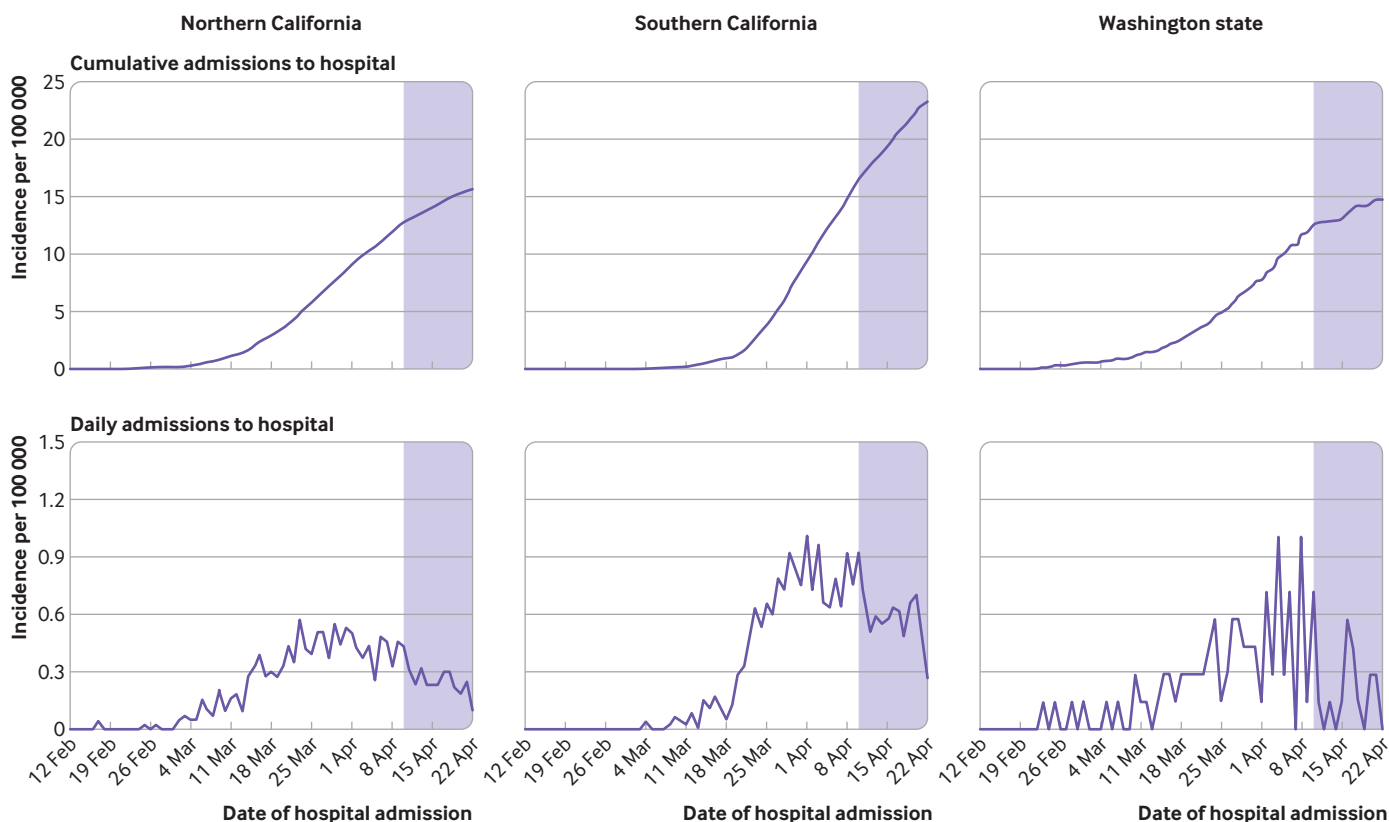


Fig 1 | Cumulative incidence and daily incidence of first acute inpatient admissions in 2020 with confirmed coronavirus disease 2019 among participants with Kaiser Permanente health plans. Shaded regions (10 April onwards) indicate admission dates when participants were excluded from analyses of clinical outcomes (duration of hospital stay, admission to intensive care unit, and case fatality risk) owing to limited follow-up duration

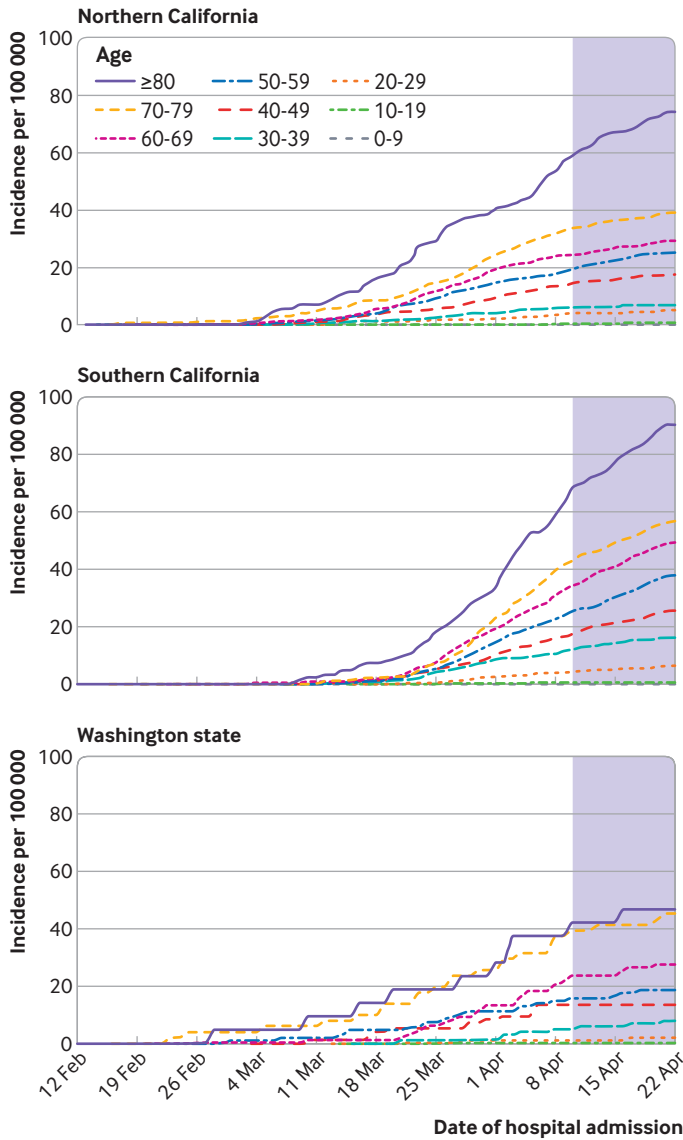


Fig 2 | Age specific cumulative incidence of first inpatient admissions in 2020 with confirmed coronavirus disease 2019 among participants with Kaiser Permanente health plans. Shaded regions (10 April onwards) indicate admission dates when participants were excluded from analyses of clinical outcomes (duration of hospital stay, admission to intensive care unit, and case fatality risk) owing to limited follow-up duration

Discussion

Our study provides an early assessment of the incidence and clinical profile of severe coronavirus disease 2019 (covid-19) among insured residents of California and Washington who receive comprehensive, integrated healthcare from Kaiser Permanente health plans. Incidence rates of hospital admissions for covid-19 increased within these cohorts from late February through mid-March 2020 and have since stabilized or declined amid implementation of social distancing measures. The highest rates of incidence occurred among older adults, with 50% of hospital admissions occurring among those aged 61 years and older and 25% among those aged 72 years and older. Consistent with differences in incidence of hospital admissions, the risk of death was higher in older patients. Long durations of hospital stay, in particular among non-

survivors, indicate the potential for substantial healthcare burden associated with management of patients with severe covid-19. Our estimates also suggest that the effective reproduction number (R_e) declined to a range near 1 after the implementation of social distancing interventions, concurrent with flattening of the incidence rate of new inpatient admissions for covid-19.

Strengths and limitations of this study

Our study has strengths as well as limitations. The Kaiser Permanente cohorts comprise a well monitored population with uniform standards of care and healthcare access, thus reducing the risk of ascertainment bias. Because healthcare capacity was not exceeded in the study regions and within Kaiser Permanente hospitals, hospital and ICU admission are more likely to reflect standard clinical practice during the study period compared with reports from other areas in which a surge in hospital admissions was considerably more pronounced. Although we did not conduct a detailed review of medical records for patients' presenting characteristics and associations with demographic factors, length of hospital stay, or clinical outcome, studies of clinical observations among patients in northern California³⁰ and other parts of the US³¹ are now emerging and will facilitate comparison of infection severity and clinical outcomes across settings. Limited availability of laboratory testing in early phases of the US outbreak might have hindered detection of sporadic cases in January and early February 2020, as evidenced by the recent retrospective identification of a death from covid-19 in northern California in early February.³² Because all people under investigation for covid-19 might not have been tested during early phases of the outbreak, our estimates of disease incidence should be interpreted as lower bounds. Phylogenetic analyses of early SARS-CoV-2 specimens will provide further insight into the extent of undetected transmission in the US, including in these Kaiser Permanente service regions. Last, sensitivity and specificity of SARS-CoV-2 laboratory tests used at facilities across these service regions might have differed.

In interpreting our estimates of R_e , it is important to consider that our analyses include hospital admissions among Kaiser Permanente enrollees only. Although those receiving healthcare from Kaiser Permanente generally resemble commercially insured populations of the same regions,^{8,9} they are likely to have higher socioeconomic status than those without insurance, and thus they do not reflect the general population.¹¹ Our estimates of R_e should therefore be taken to indicate transmission dynamics within communities and social networks within which socioeconomically vulnerable populations might be under-represented; nonetheless, pre-intervention and post-intervention estimates closely resemble state level estimates from other data sources.³⁴ For analyses of transmission dynamics, we relied on data from other settings to infer parameters for the clinical course of covid-19,

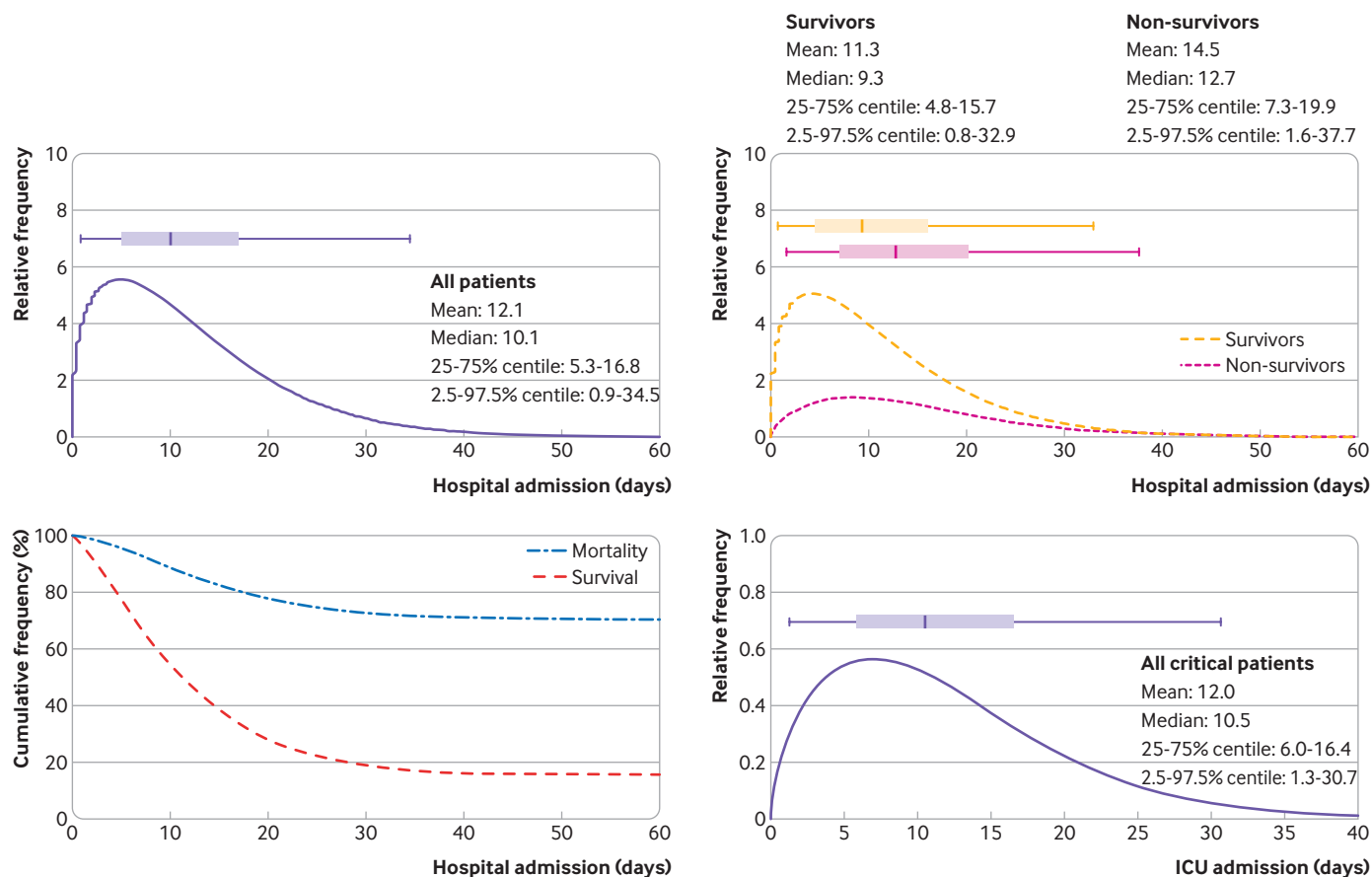


Fig 3 | Fitted durations of hospital admissions for first acute inpatient admissions with confirmed coronavirus disease 2019 by 9 April 2020 among all participants with Kaiser Permanente health plans admitted. Distributions of hospital length of stay for all acute inpatient admissions (top left); acute inpatient admissions, stratified by clinical outcome (top right); time to discharge or death among all acute inpatient admissions; and length of stay in an intensive care unit (ICU) for all inpatients admitted to ICU (bottom left). Box plots overlaid on density estimates indicate estimated medians (center line), interquartile ranges (boxed area), and 2.5% to 97.5% centile values (extended lines). Estimates were obtained by fitting Weibull distributed competing risk models to data on patient survival or non-survival as recorded by end of day 22 April 2020

including the proportion of people with symptoms requiring hospital admission, the serial interval, and the time from infection to hospital admission. Estimates of R_E differed little across analyses using alternative parameterizations of these inputs, indicating our conclusions are robust to the underlying assumptions. Further, our use of data on people who were admitted to hospital in a prospectively followed cohort, receiving care within a unified healthcare delivery system, overcomes inconsistencies affecting studies of reported covid-19 cases or deaths across care providers and jurisdictions.^{35 36}

Comparison with other studies

In many respects, our findings agree with observations in other settings, where older and male patients were more likely than younger or female patients to be admitted to the ICU and to die.^{23 37-39} The 11 day estimated mean duration of hospital stay for patients who are discharged alive is consistent with observations in China.³⁷ However, we estimated a 15 day mean duration of stay among non-survivors, whereas in China non-survivors had a shorter length of hospital stay (7.5 days) than survivors.³⁷ This difference might

reflect, among other factors, alternative approaches to discharge and post-hospital or end-of-life care in diverse settings. These findings have important ramifications for anticipating clinical needs. A widely used model projecting clinical resource needs in the United Kingdom and US assumes a mean duration of hospital stay of eight days for most patients.⁶ Similarly, our finding that 40% of patients admitted to hospital received intensive care is higher than estimates used in numerous influential modeling studies.^{6 40-42}

Our population of hospital patients was older on average than those admitted to hospital in China,^{23 37 43 44} where the median age range was 50-57 years. Notably, the median age of patients in our study matches reports from two case series in New York City.^{31 45} This observation of older ages in US patients admitted to hospital might relate to underlying population demographic structure and differences in health status in US populations compared with those of other settings, or to differences across settings in the clinical threshold for hospital admission. A substantial proportion of the patients admitted to hospital and ICU were, however, younger or middle aged adults, in agreement with past reports that severe disease is not

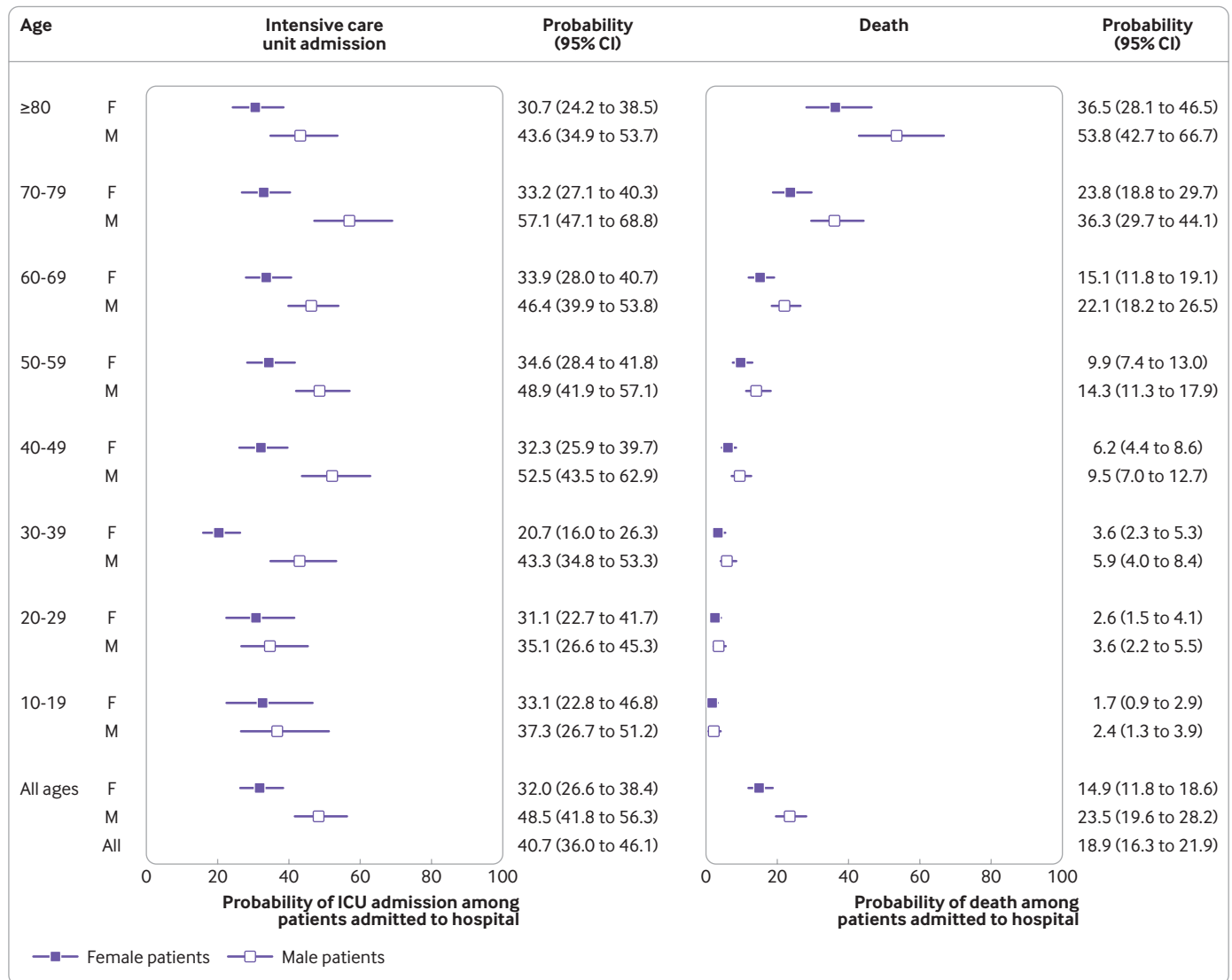


Fig 4 | Estimated probabilities of admission to intensive care unit (ICU) and mortality in enrollees of Kaiser Permanente health plans by age and sex for those with coronavirus disease 2019 (covid-19) admitted by 9 April 2020. Probabilities were stratified by age and sex for ICU admission (left) and mortality (right) for male and female patients within 10 year age strata; children aged 0-9 years are excluded as none were admitted to hospital in this age group. Numerical estimates are indicated alongside plotted values. Sex specific estimates for all ages are plotted at the bottom. Estimates were obtained using parametric (Weibull) survival models to account for censoring of observations among incomplete hospital admissions

strictly limited to older patients.^{38 45-47} Indeed, we did not identify strong evidence of a differential risk of ICU admission among hospital patients of differing ages.

Conclusions and policy implications

The considerable length of stay (2.5-97.5% centile: 0.9-34.5) among patients admitted to hospital with covid-19 in our study indicates that unmitigated transmission of SARS-CoV-2 could threaten US hospital capacity, consistent with observations in Italy and other high resource settings³ as well as recent experience in New York City.² Although current social distancing measures have provided a crucial stopgap in reducing transmission and protecting healthcare systems to date,⁴⁸ hospitals should ensure capacity to manage patients with covid-19 in the coming months in a manner that is responsive to changes in social distancing or other pandemic mitigating measures.

AUTHOR AFFILIATIONS

¹Division of Epidemiology and Biostatistics, School of Public Health, University of California, Berkeley, Berkeley, CA, 94720, USA

²Division of Infectious Diseases and Vaccinology, School of Public Health, University of California, Berkeley, Berkeley, CA, USA

³Center for Computational Biology, College of Engineering, University of California, Berkeley, Berkeley, CA, USA

⁴Division of Research, Kaiser Permanente, Oakland, CA, USA

⁵Health Research Institute, Kaiser Permanente Washington, Seattle, WA, USA

⁶Center for Health Research, Kaiser Permanente Northwest, Portland, OR, USA

⁷MRC Centre for Global Infectious Disease Analysis, Abdul Latif Jameel Institute for Disease and Emergency Analytics, Imperial College London, London, UK

⁸Department of Infectious Disease Epidemiology, Imperial College London, London, UK

⁹The Care Management Institute, Kaiser Permanente, Oakland, California 94612

¹⁰Department of Demography, University of California, Berkeley, Berkeley, CA, USA

¹¹Department of Medical Statistics, London School of Hygiene and Tropical Medicine, London, UK

¹²The Permanente Federation, Kaiser Permanente, Oakland, CA, USA

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Data sharing: The supplementary tables provide aggregate data to reproduce the analyses.

Dissemination to participants and related patient and public communities: Results of this study have been made available to the public through an open access preprint posted to *MedRxiv* (doi:10.1101/2020.04.12.20062943) and have been communicated directly to policy makers. A lay version of the results will be disseminated to Kaiser Permanente healthcare plan members and the public by the Kaiser Permanente press office.

The manuscript's guarantor (JAL) affirms that the manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as originally planned have been explained.

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Supplementary information: additional tables and figures