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Pandemic burden in low-income settings and impact of limited and delayed interventions: A granular modelling analysis of COVID-19 in Kabwe, Zambia

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ABSTRACT

Objectives: Pandemic response in low-income countries (LICs) or settings often suffers from scarce epidemic surveillance and constrained mitigation capacity. The drivers of pandemic burden in such settings, and the impact of limited and delayed interventions remain poorly understood.
Methods: We analysed COVID-19 seroprevalence and all-cause excess deaths data from the peri-urban district of Kabwe, Zambia between March 2020 and September 2021 with a novel mathematical model. Data encompassed three consecutive waves caused by the wild-type, Beta and Delta variants.
Results: Across all three waves, we estimated a high cumulative attack rate, with 78% (95% credible interval [CrI] 71-85) of the population infected, and a high all-cause excess mortality, at 402 (95% CrI 277-473) deaths per 100,000 people. Ambitiously improving health care to a capacity similar to that in high-income settings could have averted up to 46% (95% CrI 41-53) of accrued excess deaths, if implemented from June 2020 onward. An early and accelerated vaccination rollout could have achieved the highest reductions in deaths. Had vaccination started as in some high-income settings in December 2020 and with the same daily capacity (doses per 100 population), up to 68% (95% CrI 64-71) of accrued excess deaths could have been averted. Slower rollouts would have still averted 62% (95% CrI 58-68), 54% (95% CrI 49-61) or 26% (95% CrI 20-38) of excess deaths if matching the average vaccination capacity of upper-middle-, lower-middle- or LICs, respectively.
Conclusions: Robust quantitative analyses of pandemic data are of pressing need to inform future global pandemic preparedness commitments.

Introduction

The World Health Organization's (WHO) Preparedness and Resilience for Emerging Threats (PRET) initiative calls for the formulation of preparedness plans and priority actions underpinned by learnings from the COVID-19 pandemic [1]. However, 4 years after the emergence of SARS-CoV-2, the true burden of the pandemic and the impact of constraints in scaling up mitigation strategies in

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resource-limited settings remain poorly understood. Systematic issues with epidemiological surveillance data have been highlighted as a key challenge in undertaking such retrospective assessments robustly [2]. To inform the PRET agenda, however, methods are needed across all regions and income settings to reliably leverage limited surveillance data and better understand the true burden of pandemic emergencies.

A knowledge gap exists, particularly for low-income countries (LICs). Most available studies from LICs in Africa have assessed the burden of the pandemic on the basis of official test-positive cases, hospitalisations and/or deaths counts [3–7]. When surveillance capacity is limited, however, such an approach has been demonstrated to yield vast underestimates of pandemic burden given underascertainment issues common to passive surveillance systems [8]. For instance, in a recent analysis of global seroprevalence studies it was estimated that official case counts captured only 1.2% of likely true infections between July and September 2020, and 0.6% between April and June 2021 in African low- and middle-income countries, compared to 12% and 63%, respectively, in high-income European countries [9]. Similarly, excess mortality studies have found that official death counts between 2020 and 2021 likely only account for 7% of true COVID-19 deaths in sub-Saharan Africa, as opposed to 67% in Western Europe [10]. This evidence indicates that official count data greatly underestimate the impact of COVID-19 in LICs. In turn, studies relying solely on these data have misrepresented the true epidemic dynamics of SARS-CoV-2 and its impact on population health [8].

Therefore, we aimed to robustly estimate the burden of the COVID-19 pandemic and the impact of limited and delayed interventions to mitigate it in an LIC setting, by relying on sparse data typically available from such settings, which often have severe constraints in scaling up mitigation strategies. We thus performed a novel mathematical modelling analysis in Kabwe, Zambia. We fitted our model to seroprevalence and all-cause mortality epidemiological data from Kabwe between March 2020 and September 2021, inclusive, capturing the first three local epidemic waves. We compared factual outcomes (as inferred by our model's fit) with a range of counterfactual scenarios of earlier and enhanced local COVID-19 vaccination and improved health care for severe cases.

Materials and methods

Model overview

We developed a flexible compartmental SARS-CoV-2 transmission model to infer transmissibility and severity dynamics of the COVID-19 pandemic with limited surveillance data. Briefly, this was a stochastic, compartmental, SEIR-type state-space model of SARS-CoV-2 transmission, fitted using a particle Markov-chain Monte Carlo (pMCMC) Bayesian inference framework. The population was disaggregated into 16 age groups (0-4, 5-9, …, 70-74, and ≥75 years), and five vaccination strata (unvaccinated, 1st dose–no effect, 1st dose–full effect, 2nd dose–full effect, 2nd dose–waned). We accounted for partially protective and waning immunity and fitted parameters of time-varying contact rates and probability of death given infection. The Supplementary materials include details on full model structure, parameters, and fitting.

Study setting

Kabwe is a district of the Central Province in Zambia, north of the capital, Lusaka, with 299,206 inhabitants [11]. This district has been previously characterised as demographically and economically representative of medium- to high-density, peri-urban, low-income settings in the Southern Africa region [12]. The age distribution, urban-to-rural ratio and active economic participation of the local population resemble the national picture of Zambia [13], which has a median age, fertility rate and population growth rate similar to those of other LICs in the Southern Africa region [14].

Local reports suggest a pandemic impact higher than that of Lusaka, the nation's capital, amidst limited testing capacity [12], severe constraints in health care capabilities to treat severe COVID-19 cases [15], and limited and overburdened frontline health care personnel [16]. The study period encompasses three epidemic waves known to have been related to the transmission of the wild-type, Beta and Delta variants [17]. This period was also characterised by a transient adherence to non-pharmaceutical interventions (NPIs) [18], and constraints in health care for severe COVID-19 cases [19]. The first COVID-19 vaccines arrived in Zambia on 20 April 2021, but these were administered to health workers only, and the national vaccination for the general population was not launched until December 2021 [20].

Data sources

We fitted the model to seroprevalence and all-cause mortality data from Kabwe between March 2020 and September 2021. The former came from two sources. We had a single data point of immunoglobulin G aggregated data from Kabwe from a random representative sample of individuals of all ages (5 years and older) of the general population, collected on 17 July 2020 as part of a previously published multi-district COVID-19 prevalence study in Zambia [21]. We also accessed age-disaggregated seroprevalence data from an original semi-random household cluster weekly seroprevalence survey conducted between November 2020 and February 2021 [12] and between June and July of 2021 (unpublished).

Regarding mortality data, we accessed monthly aggregate death counts between January 2017 and December 2020, and all-cause mortality daily time series between January 2020 and September 2021. The former were routinely reported to the Zambia National Public Health Institute (ZNPHI), and the latter were purposely collected from mortuary records in Kabwe by the ZNPHI as part of a multi-district excess mortality study (unpublished) and thus accounted for deaths occurring in the community and in health facilities. Following a previously proposed approach [8], we leveraged historical monthly counts from January 2017 to December 2019 to project expected deaths over the study period, considering these as the all-cause deaths that would have occurred in Kabwe in the absence of the pandemic. We thus fitted the model to all-cause excess mortality data from March 2020 to September 2021 and the aforedescribed seroprevalence data. The Supplementary material section 3 includes the full details.

Transmissibility and severity dynamics inference

We estimated the time-varying reproduction number R_t and the infection–fatality ratio IFR_t. The R_t represents the average number of secondary infections that each primary infection generates at time t, given the intrinsic transmissibility of a pathogen, and contact rates (potentially affected by NPIs, for example) and immunity in the population at time t (from prior infection, vaccination or both) [22,23]. As there are no contact surveys specific to Kabwe or Zambia, we assumed a contact matrix based on the nearest location with a known survey, Manicaland, Zimbabwe, as done in a recently published modelling analysis of the COVID-19 pandemic in Lusaka, Zambia [24]. To account for time-varying contact rates (e.g., in relation to NPIs), we fitted $\beta(t)$, a scaling parameter for the contact rates, as a piecewise linear function with change points at regular fortnightly intervals. It should be noted that this parameter did not affect the distribution of contacts by age, but rather acted uniformly across all age-specific contacts.

We defined IFR_t as the overall probability of death given infection at time t, accounting for immunity and the age distribution of new infections at time t. We relied on a recently proposed parametric approach to modelling time-varying disease severity in transmission models [25], accounting for variations across distinct epidemic waves. Given that we fitted our model to all-cause mortality data (i.e., as opposed to confirmed COVID-19 deaths), our estimates of IFR_t reflected the overall effect of the pandemic on driving excess mortality, an approach that has been demonstrated to better estimate pandemic impact in the absence of reliable cause-specific mortality data [8]. To compare our estimates of IFR_t in Kabwe with other settings, we further derived a naïve calculation by taking published global COVID-19 age-specific IFR estimates for the first wave [26], and aggregated them by weighting with the age distribution of the population in Kabwe.

Counterfactual vaccination rollout scenarios

To simulate counterfactual scenarios of COVID-19 vaccination, we assumed a two-course primary programme with vaccine effectiveness similar to that quantified against the wild-type and Alpha variants from the literature [25]. We implemented an old-to-young prioritised range of vaccination schedules, with daily vaccines delivered matching the officially reported number of doses per 100 population (henceforth termed average vaccination capacity) in high-income, upper-middle-income, lower-middle-income, and low-income settings [27].

For each vaccination capacity scenario, we considered three different rollout dates. These included late April 2020, on the 100th day from the first full SARS-CoV-2 genome sequencing, as per the Coalition for Epidemic Preparedness Innovations (CEPI) 100 Days Mission [28]; mid-December 2020, when some high-income countries began their vaccination campaigns [27]; and late April 2021, when the initial rounds of vaccination started in Zambia, targeting only key workers [20].

We assumed a minimum age eligibility of 12 years and a 70% uptake of a primary course of vaccination amongst the eligible population (Supplementary material sections 4.1 and 6 include sensitivity analysis with lower and higher uptake). We further assumed a mean delay from the application of a dose to full protection effect of 21 days for first and 7 days for second doses, and a mean time to waning of second-dose protection of 24 weeks.

Counterfactual health care improvement scenarios

To simulate health care improvement counterfactual scenarios, we reduced the overall IFR_t by scaling-down the fitted multiplicative piecewise linear function, assuming no change in the age-specific conditional probabilities, which we derived from the literature [26]. Thus, the simulated scenarios scaled pandemic severity solely in response to an assumed reduction in the probability of death conditional on infection whilst retaining the inferred variability (given other independent factors implicit in the input data, such as infection with the Beta and Delta variants) and uncertainty in IFR_t.

We thus modelled a reduction in the IFR_t by 15%, 30% and 45%, as informed by early-pandemic estimates of the relation between health care capacity and expected pandemic severity in resource-constrained settings [29], and by robust evidence that population-wide changes in pandemic severity were driven by adaptation of health care capacity to care for severe COVID-19 in other settings [25]. We simulated such reductions in IFR_t starting from either June 2020, when dexamethasone was found to decrease the risk of death in severe COVID-19 cases [30], or from September 2020 and March 2021, before the onset of the second and third local waves, respectively. For each of these scenarios, we implemented a gradual decrease in IFR_t from its inferred to the reduced (improved health care) value over a period of 3 weeks, assuming a gradual rather than abrupt improvement in health care capabilities. Supplementary material section 4 includes the full details of the counterfactual scenario modelling mechanisms and parameters.

Results

Pandemic burden in Kabwe, Zambia

The model reproduced the seroprevalence and all-cause deaths data well (Figure 1a and b), allowing us to robustly infer the pandemic's R_t and IFR_t (Figure 1c & d). We found that the COVID-19 attack rates in Kabwe were high. After each wave (i.e., in early October 2020, early April 2021, and end of September 2021), a cumulative 14% (95% credible interval [CrI] 11-18), 46% (95% CrI 40-52) and 78% (95% CrI 71-85) of the population, respectively, had been infected with the virus at least once (Figure 1a), with reinfections estimated to account for up to 0% (95% CrI 0-0), 1.1% (95% CrI 0.8-1.2) and 14.9% (95% CrI 14.1-15.5) of daily incidence, respectively (Figure 1e). This translated into an estimated total of 1124 (95% CrI 774-1323) all-cause excess deaths in Kabwe between March 2020 and September 2021, for a cumulative rate of 402 (95% CrI 277-473) per 100,000 people, a result that was robust to assumptions of underascertainment in our input data (Supplementary materials section 6).

Local factors driving pandemic transmissibility and severity varied across each epidemic wave. Early on in the first wave, Zambia implemented national-level NPIs [18]. We infer that these led to a gradual decrease in R_t locally between March and July 2020 (Figure 1c), enough to interrupt transmission during the first wave, with R_t dipping below 1 (its critical threshold for controlled transmission) between July and September 2020. Although daily infection rates peaked at a relatively low (compared with subsequent waves) 2.6 (95% CrI 1.4-4.3) per 1000 people in early July 2020 (Figure 1e), the estimated IFR_t was 0.34% (95% CrI 0.19-0.51) at this point, on average 2.8 times higher than the expected 0.12% given the age profile of the population and in the absence of constraints to health care provision for severe COVID-19 cases (Figure 1d).

Levels of R_t increased again to approximately 1 in August and September, and above 1 from early October 2020 (Figure 1c), well before the Beta variant was first detected in the country in December 2020 [17,31]. We thus find that the second wave, which ensued in Kabwe between October 2020 and April 2021, was driven, at least initially, by increases in contact rates (Figure 1e). Daily incidence peaked at 5.7 (95% CrI 4.0-8.2) infections per 1000 people (Figure 1e), more than double the first wave peak, and the IFR_t at this peak marginally increased to 0.39% (95% CrI 0.23-0.63).

Finally, likely as the combined result of persistently high contact rates (Supplementary materials Figure 9) and the subsequent local detection of the Delta variant in June 2021 [17,31], R_t rose above 1 again from late April to mid-June 2021 (Figure 1c). Although infection-induced immunity levels after the second wave had increased to 38% (95% CrI 32-43) (Figure 1a), this did not lead to sufficient herd immunity, and the third epidemic wave followed. Daily incidence and IFR_t were highest during this wave, peaking at 7.2 (95% CrI 4.5-10.5) infections per 1000 people and 0.61% (0.37-0.87) (Figure 1e and d), respectively. Hence, mortality was also at its highest during this wave, with daily excess deaths peaking at 1.75 times higher than baseline deaths (Figure 1f).

Impact of limited and delayed interventions

Overall, we find that a vaccination rollout in December 2020, as observed in some high-income settings [27], or earlier, as per CEPI's 100 Days Mission [28], at a higher average capacity than

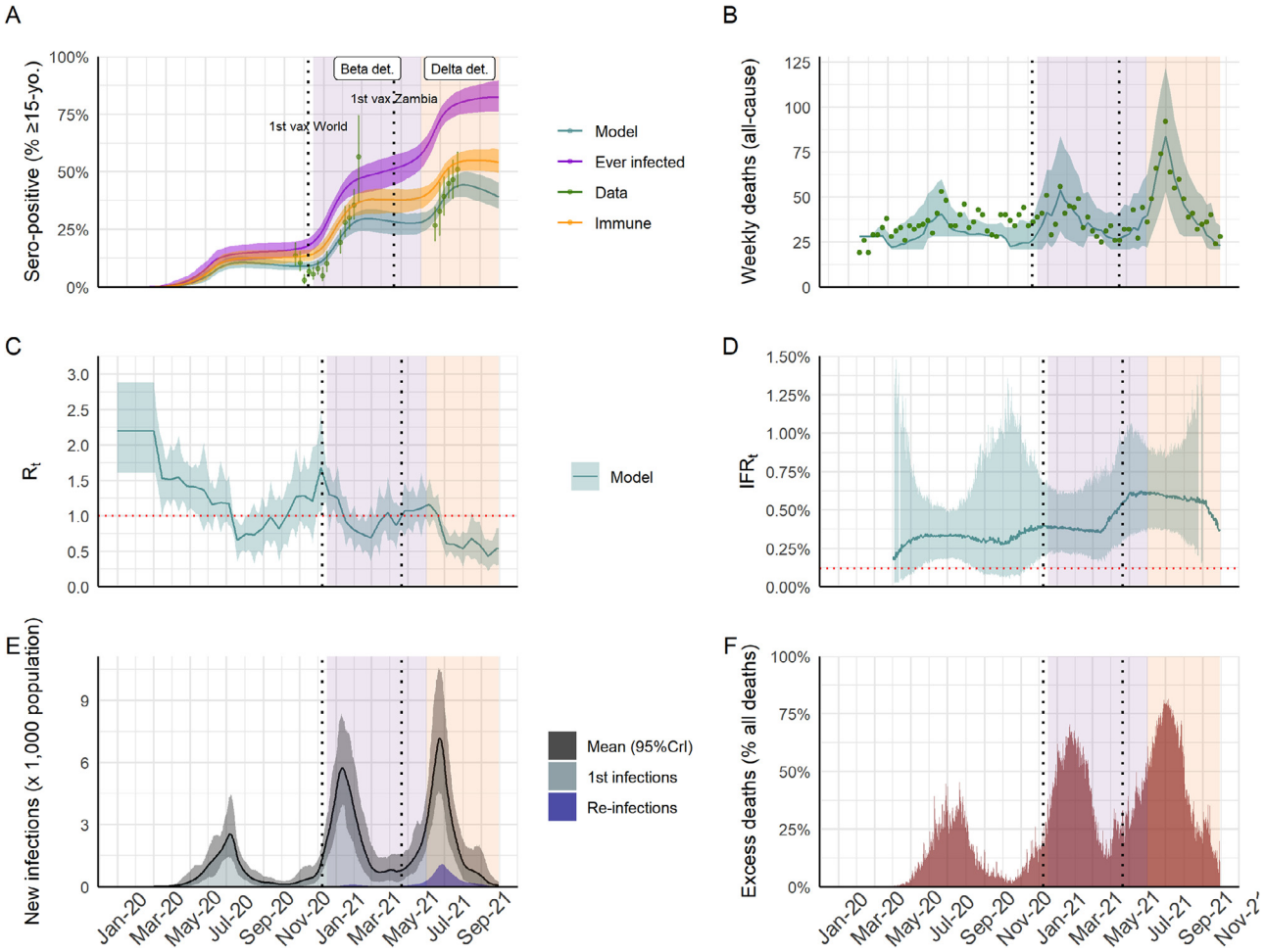

Figure 1. SARS-CoV-2 pandemic transmissibility and severity in Kabwe, Zambia from March 2020 to September 2021. Across all panels, shared rectangle areas illustrate the periods of time where the Beta (light purple) and Delta (light orange) variants were detected and known to dominate transmission in Zambia [17,31], and black dashed vertical lines the date when the first COVID-19 vaccine was delivered in the world (2020-12-08) and in Zambia (2021-04-19) [27]. (a and b) Model fit (blue line mean and shaded area 95% CrI) to data (green dots; in [a], the dot represents the mean, and error bars the 95% binomial confidence interval) to seroprevalence and all-cause excess deaths, respectively. In (a), the purple line and shaded area show the inferred mean and 95% CrI for the cumulative proportion of the population ever infected, and the orange line and shaded area the mean and 95% CrI of population immune against infection (as a result of prior infection). (c) Inferred time-varying reproduction number, R_t (line mean and 95% CrI shaded area). The red horizontal dotted line at a y-axis value of 1.0 shows the critical threshold for pathogen transmission. (d) Inferred time-varying infection fatality ratio, IFR_t (line mean and 95% CrI shaded area). The red horizontal dotted line at a y-axis value of 0.12% shows the naïve estimate drawn by adjusting age-specific IFR estimates from Brazeau et al. [26], which came from a range of countries with known reliable hospital reporting systems, by the age distribution of the population in Kabwe. (e) Inferred new daily infection rate per 1000 population (black line mean and 95% CrI shaded area), with breakdown of area under the curve into incident first infections (blue area) or reinfections (orange). (f) Inferred likely proportion of daily deaths that correspond to the excess mortality driven by the local COVID-19 pandemic. CrI, credible interval; det., detected; vax., vaccine; yo, year-old.

what was achieved by LICs would have averted more excess deaths in Kabwe than even the most optimistic scenarios of improved health care (Figure 2). For instance, a rollout of COVID-19 vaccination in December 2020 with a daily capacity matching that of lower-middle-income countries would have averted 54% (95% CrI 49-61) of excess deaths accrued between March 2020 and September 2021, as opposed to 46% (95% CrI 41-53) excess deaths averted with a decrease in IFR_t by 45% from June 2020 onward as a result of improvements in health care to levels achieved by high-income settings (Figure 2).

Across rollout dates, a higher proportion of excess deaths would have been averted with higher income-level average vaccination capacity (Figure 2a, Supplementary Table 11). For instance, with a December 2020 rollout, 26% (95% CrI 20-38), 54% (95% CrI 49-61), 62% (95% CrI 58-68) and 68% (95% CrI 64-71) of excess deaths would have been averted given the capacity of low-, lower-middle-, upper-middle- or high-income countries, respectively (Figure 2a). Such differences are explained by the population-level immunity profile attained by each scenario (Figure 3). In the above scenarios, it would have taken 82, 122, 206 and 194 days, respectively, for 45% of the population to acquire immunity against infection. More importantly, by the time of this immunity milestone, vaccination (either alone or hybrid) would have accounted for 4%, 36%, 42% and 49% of the population-level protection, respectively (Figure 3).

We estimate that a reduction in IFR_t (relative to the inferred levels) by 30% from June 2020 onward would have been necessary to drive the mean IFR_t of the first wave down to 0.12%, consistent with our naïve estimation of what would have been expected in the absence of health care constraints (Supplementary materials Figure 21). Such reduction in IFR_t would have averted 32% (95% CrI 20-48), 29% (95% CrI 19-45), or 17% (95% CrI 15-21) of accrued excess deaths, if implemented from June 2020, September 2020 or March 2021 onward, respectively (Figure 2b). Given that excess mortality during the pandemic increased after the first wave in Kabwe (Figure 1e), even a modest improvement in health care leading to a 15% decrease in the IFR_t would have averted a non-negligible 18% (95% CrI 8-27), 15% (95% CrI 7-27) or 10% (95% CrI 6-16) of accrued excess deaths, respectively (Figure 2b).

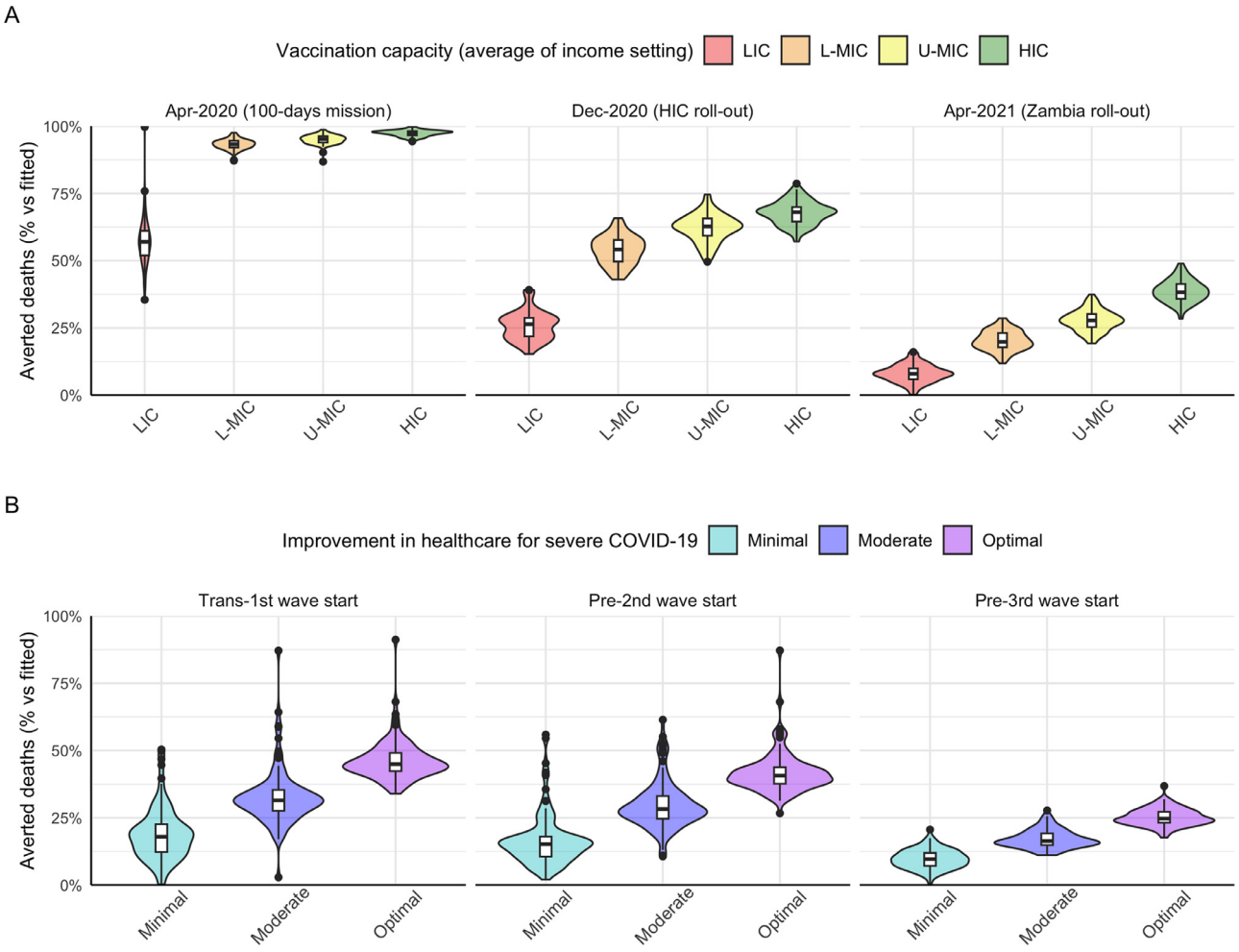

Figure 2. Estimated excess deaths averted in counterfactual simulated scenarios, compared with the model fit to data. (a) The results of simulated vaccination scenarios and (b) health care improvement scenarios. Vaccination capacity in (a) was defined as daily total doses delivered per 100 population, as per official reports, averaged for LIC (red), L-MIC (orange), U-MIC (yellow) and HIC (green) (Supplementary Figure 3) [27]. Simulated rollout dates were the 100th day from the first full genome sequencing of SARS-CoV-2 (20 April 2020), as per CEPI's 100 Day Mission [28], the time of rollout in some HIC (14 December 2020) [27], and the official date when the first vaccine was delivered in Zambia (19 April 2021) [27]. Health care improvement in (b) was defined as a reduction in the inferred IFR_t by 15% (minimal, light blue), 30% (moderate, dark blue) and 45% (optimal, purple), as informed by estimates from the literature in the absence of constraints to deliver general and intensive care unit hospital-based care for severe COVID-19 cases [29]. We defined IFR_t as the overall probability of death given infection at time t, accounting for immunity and the age distribution of new infections at time t (see Methods and Supplementary materials section 1.6). Assumed dates of implementation of health care improvement were during the first wave (15 June 2020), when dexamethasone was identified as the first effective treatment to reduce the risk of death in severe COVID-19 [30] and before the onset of the local second (5 October 2020) and third (5 April 2021) waves. We assumed a 21-day time frame for implementing improvement, during which IFR_t decreased linearly between the inferred baseline and the reduced value. HIC, high-income countries; IFR, infection fatality ratio; LIC, low-income countries; L-MIC, lower-middle-income countries; U-MIC, upper-middle-income countries.

Discussion

To our knowledge, we present the first in-depth analysis of the burden imposed by the COVID-19 pandemic and of the dire impact of real-world constraints to implement pandemic mitigation strategies in LICs. We find not only that the burden of the pandemic in Kabwe was high, but also that mitigation constraints drove a disproportionately higher burden than expected if resources had been available for Kabwe to reach the health care and vaccination provisions of higher-income settings.

Previous studies have demonstrated that an early and rapid implementation of such pandemic mitigation strategies was critical to limit the burden of the pandemic as more severe variants of concern emerged and NPIs were phased out [25,32,33]. Such pandemic response strategies limited excess mortality in settings where they were available, as evidenced when comparing the 140.0 (95% CI 133.5-146.3) excess deaths per 100,000 population in Western Europe between 2020 and 2021 with the estimate for the Southern Africa region, at 308.6 (95% CI 287.3-331.6) [10], despite the much older age profile of the population in the former setting. In Kabwe, we estimate a much higher excess mortality, at 402 (95% CrI 277-473) between March 2020 and September 2021 alone.

Our findings hold key lessons to inform future global commitments [1] by taking into account evidence from all income sectors regardless of surveillance data limitations. Whilst we found evidence that local adherence to national NPI policies in Kabwe likely achieved the interruption of SARS-CoV-2 transmission in the first wave, their effect was short-lived. Indeed, the model shows that the subsequent steady rise in contact rates after the first wave synergised with a low level of infection-derived immunity at the time, leading to the very high incidence rates in subsequent waves and, thus, high excess mortality. Our work, therefore, provides substantive evidence that in settings where prolonged and/or dynamic adoption/release of NPIs may not be a sustainable pillar of a pandemic response (e.g., markedly higher economic impact and job loss in LICs compared with high-income countries) [34], there is

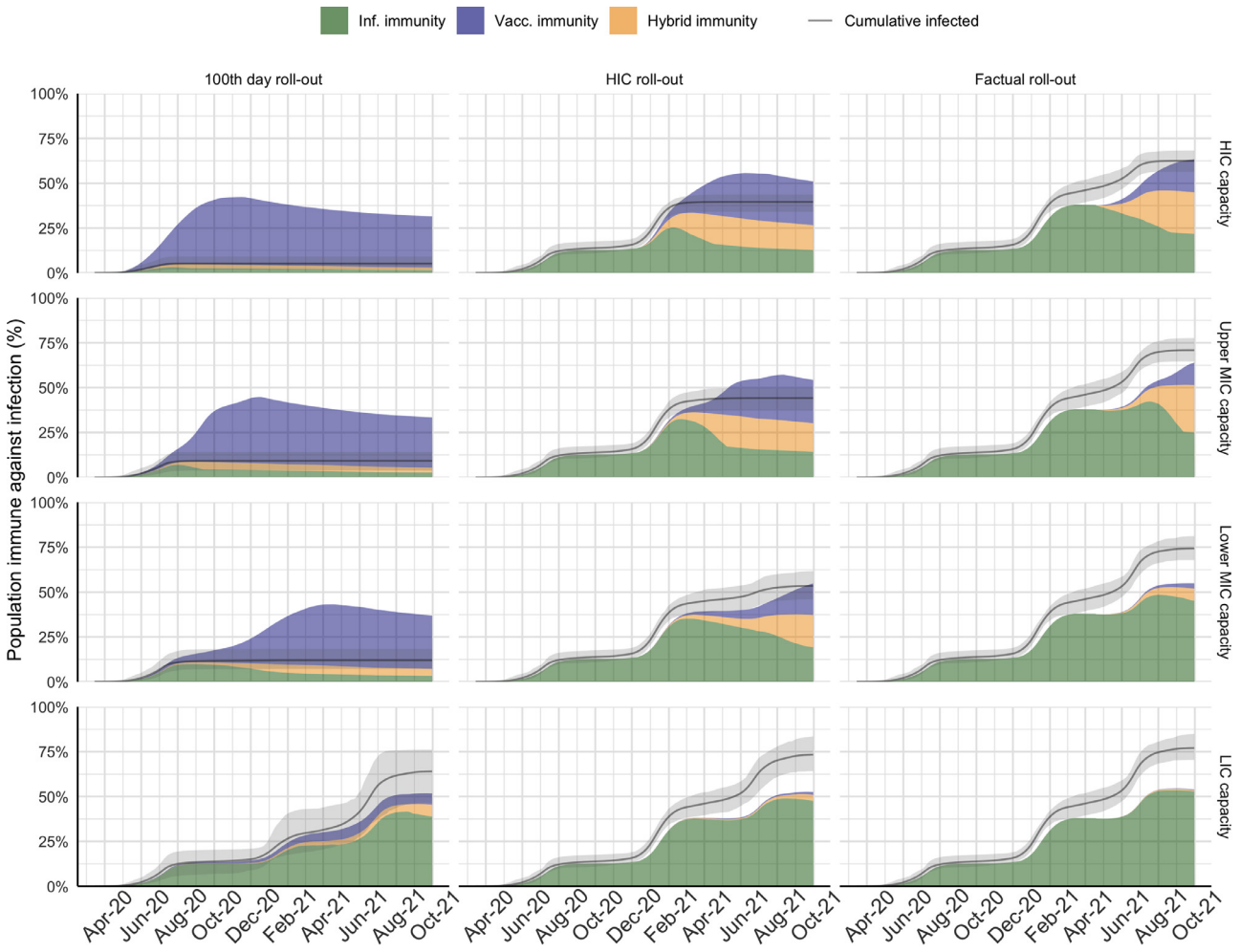

Figure 3. Time-varying profile of immunity against SARS-CoV-2 in the population over the modelled period in Kabwe. Details of vaccination capacity and timing as per Figure 2. The black line and the shaded area represent the cumulative proportion of the population ever infected, and the shaded areas show the breakdown of population-level immunity against infection from prior infection alone (green), vaccination alone (purple) or hybrid* (yellow).
*Within-host mechanisms of hybrid immunity were not explicitly modelled; rather, we assume a multiplying effect between parameters of protection against infection from vaccination and prior infection. See Supplementary materials sections 1.5 and 4.1.

an imperative need to ensure rapid and sustained access and logistical support to strengthen baseline critical health care capacity and deliver emerging therapies, such as vaccines.

Given the size and age distribution of the population in Kabwe, we find that vaccination rollout in December 2020 with an average capacity matching that of lower-middle-income countries would have sufficed to achieve key global immunisations milestones (Supplementary Figure 12). Even in the absence of changes in inferred contact rates (i.e., no change in the stringency of NPIs), such a vaccination programme could have averted over half of the accrued excess mortality in Kabwe between March 2020 and September 2021. For future pandemic preparedness, CEPI's 100 Day Mission holds great promise as an almost full mitigation strategy for pathogens similar to SARS-CoV-2 in Kabwe or settings with comparable demographics, provided such hypothetical vaccines are made available early and distributed equitably.

Furthermore, it has been previously demonstrated that differences in the IFR of COVID-19 across countries with comparable health care capacity were explained by their population age distribution [26]. Notably, a recent study in Lusaka, Zambia estimated that adjusting global age-specific IFR estimates using the local age distribution yielded an overall IFR of 0.11%, which explained the local excess mortality of the first COVID-19 wave [24]. In contrast, we estimate that the first-wave IFR_t was almost threefold higher than what would have been expected by a similar simple adjustment of global age-specific IFR estimates, suggesting that pandemic-driven mortality was much higher in Kabwe than in the settings from which the latter estimates were derived. Furthermore, we inferred a sequential increase in severity during the second and third waves in Kabwe, related to the Beta and Delta variants. Whilst we were unable to ascertain the specific effects of these variants on IFR_t increases, given the absence of variant frequency data, we show that implementation of improved health care to decrease the risk of death from severe COVID-19 would have averted a significant proportion of excess deaths, regardless of the timing of implementation. Our findings are consistent with early-pandemic estimates that the protective effect of a young population profile against SARS-CoV-2 could be nullified in the presence of severe health care constraints in treating those with severe COVID-19 [29].

Our analysis had several limitations. Firstly, we did not have access to cause- and age-specific mortality data or COVID-19 health care data (e.g., admissions, occupancy). These data would have decreased our model's uncertainty in IFR_t, allowing us to better characterise the specific effects of health care constraints on pandemic outcomes. Such data limitations, however, were not unique to Kabwe but were prevalent across resource-constrained settings [8]. Emphasis should be placed on strengthening pandemic surveillance across all income settings as part of global pandemic pre-

paredness strategies. Secondly, the all-cause mortality data suffered from an unknown level of underreporting. In sensitivity analyses, we found that the model's performance in recovering the data decreased when varying the level of underreporting between historical and pandemic deaths (Supplementary material section 6). Our analysis thus demonstrates that, even with very sparse surveillance data, judicious use of advanced mathematical modelling techniques can derive robust inference of pandemic dynamics. Lastly, across all counterfactual scenarios, we assumed no changes in the inferred parameters of time-varying contact rates, as a proxy of no change in local NPIs, and we did not model combinations of vaccination and health care improvement. Further analyses of the non-linear effects of combined interventions and their cost-effectiveness are crucially needed to inform global pandemic preparedness, but these were outside of the scope of our study.

Robust COVID-19 analytics proved critical to inform NPI policies, vaccination strategies, and the adaptation of health care capacity in settings where they were available in real time [35]. This, however, was not the case in Kabwe or many LICs. Our work provides a foundation for further exploration of advanced modelling techniques for using sparse epidemiological surveillance data. The WHO's PRET initiative and CEPI's 100 Day Mission indeed call for preparedness and response strategies to be underpinned by lessons learnt from the COVID-19 pandemic [1,28]. However, to avoid a devastatingly disproportionate burden of future pandemics in LICs, a global and equitable approach to pandemic preparedness requires anchoring in robust epidemiological analytics from all settings.

Conclusion

Equitable global pandemic preparedness requires robust analytics from all income settings and regions of the world. However, constraints in epidemiological surveillance capacity have forestalled the production of robust pandemic analyses in most low-income settings. We present the most detailed analysis to date of COVID-19 burden in an African low-income setting, the Kabwe District of Zambia. Local infection and all-cause excess deaths between March 2020 and September 2021 were among the highest recorded in the African continent. Such high pandemic burden was largely driven by constraints in timely access to vaccines and health care. Our novel methods provide a foundation for utilising sparse data, typical of low-income settings, to produce robust pandemic analytics.

Declarations of competing interest

The authors have no competing interests to declare.

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Data sharing and ethical approval

This study made secondary use of seroprevalence data collected by Zambart as part of their TREATS COVID study, and all-cause mortality data from the Zambia National Public Health Institute's (ZNPHI) Excess Mortality in 12 Districts study. All code and data needed to reproduce the present analysis are publicly available at github.com/mrc-ide/ZamCovid_kabwe. The TREATS COVID study was approved by the Zambia Biomedical Research and Ethics Committee, the Zambia National Health Research Authority and the London School of Hygiene & Tropical Medicine Ethics Committee. ZNPHI's excess mortality study received administrative approval from the Permanent Secretary Ministry of Health, ethical approval from the ERES (Excellence in Research Ethics and Science) Converge independent review board and authority to conduct the study from the Zambia National Health Research Authority. No additional review was needed for the conduct of this study on the basis of the above pre-existing ethical approval and use of open-source data.

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Author contributions

PNPG, SLC, AS, STN, RV, KH and AC conceptualised the study; PNPG, KH, ESK and AC wrote the initial manuscript draft; SLC, AS and KS acquired the data for the study; PNPG developed and SLC, MB, ESK and AC contributed to the development of analytical methods used; PNPG, SLC and AC analysed and interpreted the results; all authors reviewed and approved the final version of the manuscript.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijid.2024.107182.

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