



HAL
open science

Evaluating the strategies to control SARS-CoV-2 Delta variant spread in New Caledonia, a zero-COVID country until September 2021

Noé Ochida, Myrielle Dupont-Rouzeyrol, Pierre-Henri Moury, Thibaut Demaneuf, Ann-Clair Gourinat, Sébastien Mabon, Marc Jouan, Simon Cauchemez, Morgan Mangeas

► To cite this version:

Noé Ochida, Myrielle Dupont-Rouzeyrol, Pierre-Henri Moury, Thibaut Demaneuf, Ann-Clair Gourinat, et al.. Evaluating the strategies to control SARS-CoV-2 Delta variant spread in New Caledonia, a zero-COVID country until September 2021. *IJID Regions*, 2023, 8, pp.64-70. 10.1016/j.ijregi.2023.06.004 . hal-04489303

HAL Id: hal-04489303

<https://hal.science/hal-04489303>

Submitted on 5 Mar 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License



ELSEVIER

Contents lists available at ScienceDirect

IJID Regions

journal homepage: www.elsevier.com/locate/ijregi

Evaluating the strategies to control SARS-CoV-2 Delta variant spread in New Caledonia, a zero-COVID country until September 2021

Noé Ochida^{a,b,*}, Myrielle Dupont-Rouzeyrol^b, Pierre-Henri Moury^{c,d,e}, Thibaut Demaneuf^f, Ann-Clair Gourinat^g, Sébastien Mabon^f, Marc Jouan^{b,d}, Simon Cauchemez^h, Morgan Mangeas^a

^a UMR ENTROPIE, IRD, Université de La Réunion, IFREMER, Université de Nouvelle-Calédonie, CNRS, Noumea, New Caledonia

^b Research and Expertise Unit on Dengue and Arboviruses, Institut Pasteur of New Caledonia, Pasteur Network, Noumea, New Caledonia

^c Department of Anesthesia and Intensive Care Medicine, Grenoble University Hospital, Grenoble, France

^d Research and Expertise Unit of Epidemiology, Institut Pasteur of New Caledonia, Pasteur Network, Noumea, New Caledonia

^e Intensive Care Unit, Gaston-Bourret Territorial Hospital Center, Dumbea-Sur-Mer, New Caledonia

^f Directorate of Health and Social Affairs, Noumea, New Caledonia

^g Microbiology Laboratory, Gaston-Bourret Territorial Hospital Center, Dumbea-Sur-Mer, New Caledonia

^h Mathematical Modelling of Infectious Diseases Unit, Institut Pasteur, Université Paris Cité, UMR2000, CNRS, Paris, France

ARTICLE INFO

Keywords:

COVID-19
SARS-CoV-2
Zero-COVID
Non-pharmaceutical interventions
Vaccine
Modelling

ABSTRACT

Objectives: New Caledonia, a former zero-COVID country, was confronted with a SARS-CoV-2 Delta variant outbreak in September 2021. We evaluate the relative contribution of vaccination, lockdown, and timing of interventions on healthcare burden.

Methods: We developed an age-stratified mathematical model of SARS-CoV-2 transmission and vaccination calibrated for New Caledonia and evaluated three alternative scenarios.

Results: High virus transmission early on was estimated, with R_0 equal to 6.6 (95% confidence interval [6.4–6.7]). Lockdown reduced R_0 by 73% (95% confidence interval [70–76%]). Easing the lockdown increased transmission (39% reduction of the initial R_0); but we did not observe an epidemic rebound. This contrasts with the rebound in hospital admissions (+116% total hospital admissions) that would have been expected in the absence of an intensified vaccination campaign (76,220 people or 34% of the eligible population were first-dose vaccinated during 1 month of lockdown). A 15-day earlier lockdown would have led to a significant reduction in the magnitude of the epidemic (-53% total hospital admissions).

Conclusion: The success of the response against the Delta variant epidemic in New Caledonia was due to an effective lockdown that provided additional time for people to vaccinate. Earlier lockdown would have greatly mitigated the magnitude of the epidemic.

Introduction

Totalling millions of deaths and even more hospitalizations, the COVID-19 pandemic has taken a terrible toll on global health [1]. Worldwide, public health authorities have been faced with the daunting responsibility of stopping or at least slowing down the transmission of the virus to best protect the population. At the start of the pandemic, initial national response strategies have been broadly categorized as elimination (also labeled zero-COVID) strategies i.e., maximum action to exclude disease and eliminate community transmission; or mitigation strategies i.e., “flatten the peak” to avoid overcrowding of health services [2,3]. To implement their response, countries have made extensive use of non-pharmaceutical interventions (NPIs), such as mandatory mask-wearing and physical distancing (including gathering bans),

school, restaurant and non-essential shop closures, quarantine systems, stay-at-home orders, or curfews. Several of these measures were applied together under the term lockdown.

New Caledonia, a French Pacific Island territory, offers an interesting illustration of the zero-COVID approach. Upon the discovery of few imported (original strain) and local cases (Alpha variant), lockdowns were implemented for 1 month in March 2020 and March 2021. In both cases, the approach successfully eliminated the epidemic and the territory was declared COVID-19-free [4,5]. The lockdown consisted of the closure of all places of social life, a stay-at-home order for all persons not carrying out “essential work”, one authorized outing lasting at most 1 hour per day within a 1 km radius from home, and mandatory mask-wearing outside home. Once the lockdown was lifted, border closures for non-residents and mandatory quarantine on entry for residents were

* Corresponding author.

E-mail address: nochida@pasteur.nc (N. Ochida).

<https://doi.org/10.1016/j.ijregi.2023.06.004>

Received 20 February 2023; Received in revised form 21 June 2023; Accepted 26 June 2023

2772-7076/© 2023 The Authors. Published by Elsevier Ltd on behalf of International Society for Infectious Diseases. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>)

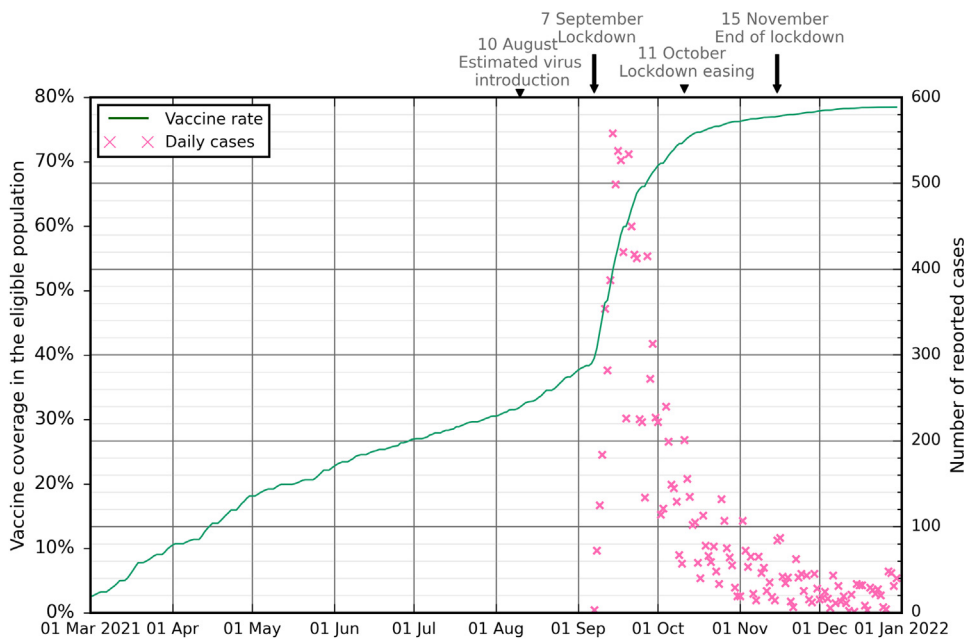


Figure 1. Daily reported COVID-19 cases, vaccine coverage, and interventions timeline in New Caledonia from March 2021 to January 2022. Daily COVID-19 reported cases (pink crosses) and vaccine coverage in the eligible population (i.e., ≥12 years old) (green solid line).

instituted, placing the territory in a so-called sanitary airlock. Apart from that, no particular control measures against COVID-19 were implemented; the whole territory’s strategy was based on maintaining the integrity of the sanitary airlock from April 2020.

On September 06, 2021, a breach in the sanitary airlock was discovered when three unrelated cases admitted the previous days with severe pneumopathy (the first on September 3) tested positive for SARS-CoV-2 infection. A lockdown was announced that evening and implemented the next day, September 7. At that time, 39% of the eligible population had received at least one vaccine dose. In parallel, population screening was intensified, uncovering a large epidemic of locally transmitted cases (Figure 1). During the following week of September 13, hospital admissions escalated despite the lockdown with an average of 47 admissions per day. Thereafter, reported cases and daily hospital admissions steadily declined. During the 1-month lockdown period, from September 7 to October 10, 2021, 76,220 eligible people (34%) received their first vaccine dose over a total population of ~271,000 inhabitants. New Caledonia authorities eased the lockdown on October 11 ending the stay-at-home order and resuming most work activities. This period after October 11 is known as the partial lockdown. During this period, an average of six hospital admissions per day was reported. After the partial lockdown ended no rebound was noted.

In this study, we report the experience of the COVID-19 epidemic due to the Delta variant in New Caledonia, South Pacific. Our objective was to assess the impact of the lockdown and the intensification of the vaccination campaign on the control of the epidemic. We also investigated how the timing of lockdown implementation affected the amplitude of the epidemic wave. This was achieved with a mathematical modeling of the epidemic that specifically described the impact on the health services system in terms of hospital admissions and intensive care unit (ICU) occupancy.

Results

Calibration and parameters estimation

The model satisfyingly described the dynamics of daily hospital admissions (Figure 2b), which was our calibration target. Using daily probability of ICU admission given hospitalization estimates, we were able to statistically reconstruct ICU admissions (Figure 2c) and ICU bed occupancy (Figure 2d). The model simulation shows that the daily cases

peaked at approximately 3000 around September 15th, a week after the lockdown was implemented (Figure 2a). Details regarding infections and hospitalization in each age group can be found in Supplementary Figure 1.

Table 1 summarizes our estimates for the basic reproduction number R_0 and the impact of the successive interventions relative to the pre-lockdown R_0 . Pre-lockdown, R_0 was estimated at 6.6 (95% confidence interval [CI: 6.4-6.7]). We estimated that the implementation of the lockdown dropped the R_0 to 1.8; 73% reduction (95% CI [70-76%]). After the lockdown, during the next period of partial lockdown i.e., when most work activities resumed and the stay-at-home order was kept only during weekends, the R_0 increased to 4.0; a 39% reduction compared to pre-lockdown R_0 . Ending the partial lockdown, i.e., ending the stay-at-home orders on the weekends, had little effect on R_0 , it increased to 4.5. Estimated/calibrated parameters are presented in Supplementary Table 1.

Alternative scenarios

We then examined counterfactual modeling scenarios describing how the trajectory of this epidemic would have changed if different interventions had been implemented. In these scenarios, we used the average probability of ICU admission given hospitalization (estimated over the epidemic) to reconstruct ICU dynamics, rather than using daily probabilities as in Figure 2. The impact on ICU dynamics of using daily versus average probabilities of ICU admission given hospitalization is shown in Supplementary Figure 2. The goal was to circumvent the modeling of context-specific ICU admissions practices, as they are not well generalizable to alternative scenarios (refers to Discussion).

If no lockdown (nor other non-pharmaceutical measures) had been implemented (scenario A), twice as many hospital admissions would have been expected and the peak of ICU bed occupancy would have been three times higher than that observed, a catastrophic scenario (Figure 3, Table 2). Note that in this scenario, we make the assumption that people would have not reduced their contacts (refers to Discussion). If no vaccines had been administered from the beginning of the lockdown to the end of the simulation (scenario B), we would have expected an epidemic rebound at the easing of the lockdown (October 11) and twice as many hospital admissions as in our baseline scenario. The peak in ICU bed occupancy would have been of the same order as in baseline. Lastly, if there had been early detection of the virus achieved through compre-

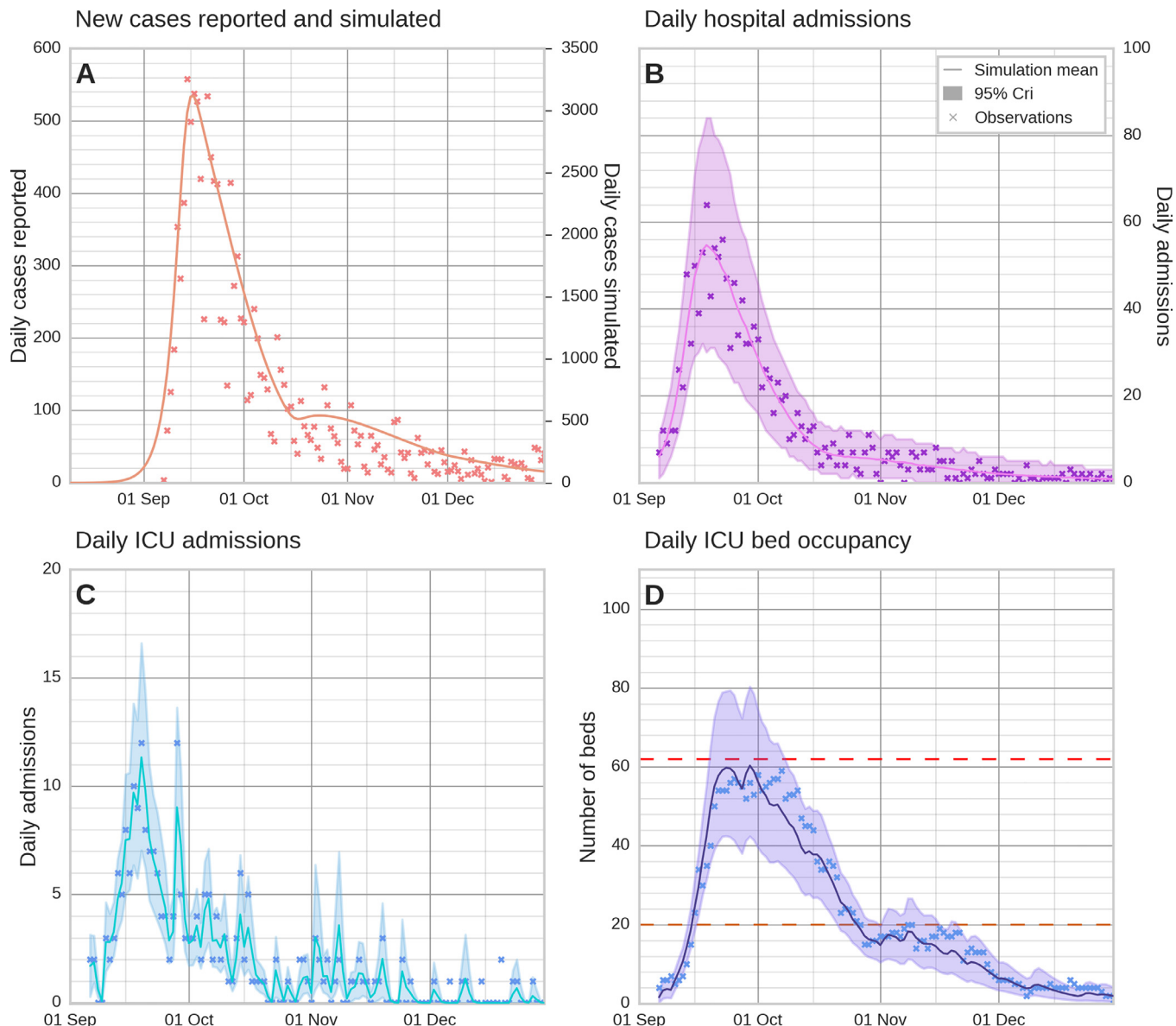


Figure 2. Comparison of the model simulations to observations. Panel A shows simulated daily infections, panel B shows simulated daily hospitalizations, panel C shows daily ICU admissions, and panel D shows the projected ICU bed occupancy; ICU dynamics have been simulated using daily ICU admission probabilities given hospitalization. Observational data points are marked with crosses. Solid lines and shaded areas represent the mean simulation and the 2.5th-97.5th percentile range, respectively, from 1000 simulations using 1000 random samples from the posterior distribution of parameters estimated through Markov Chain Monte Carlo sampling. Dashed lines represent the maximum number of ICU beds under normal (orange) and COVID (red) regimes. ICU: intensive care unit.

Table 1
Estimates of the basic reproduction number R_0 at different periods.

Period	Measures	R_0	95% confidence interval	Reduction
Pre-lockdown	No measure.	6.6	6.4-6.7	Baseline
Lockdown	School closures, closing of stores except for the first necessity stores, obligation to remain at home for “non-essential” workers, 1 hour’s outing per day within a 1 km radius of the domicile with a mandatory mask.	1.8	1.5-2.0	73%
Partial lockdown	Work resumes during the week and stay-at-home order on weekends, re-opening of schools and stores with a gauge, curfew from 10 pm to 5 am, family gatherings of up to 10 people authorized on weekdays, vaccine pass in restaurants.	4.0	3.5-4.6	39%
End of lockdown	Curfew from 10 pm to 5 am, family gatherings of up to 30 people authorized on weekdays, vaccine pass in restaurants.	4.5	3.9-5.1	32%

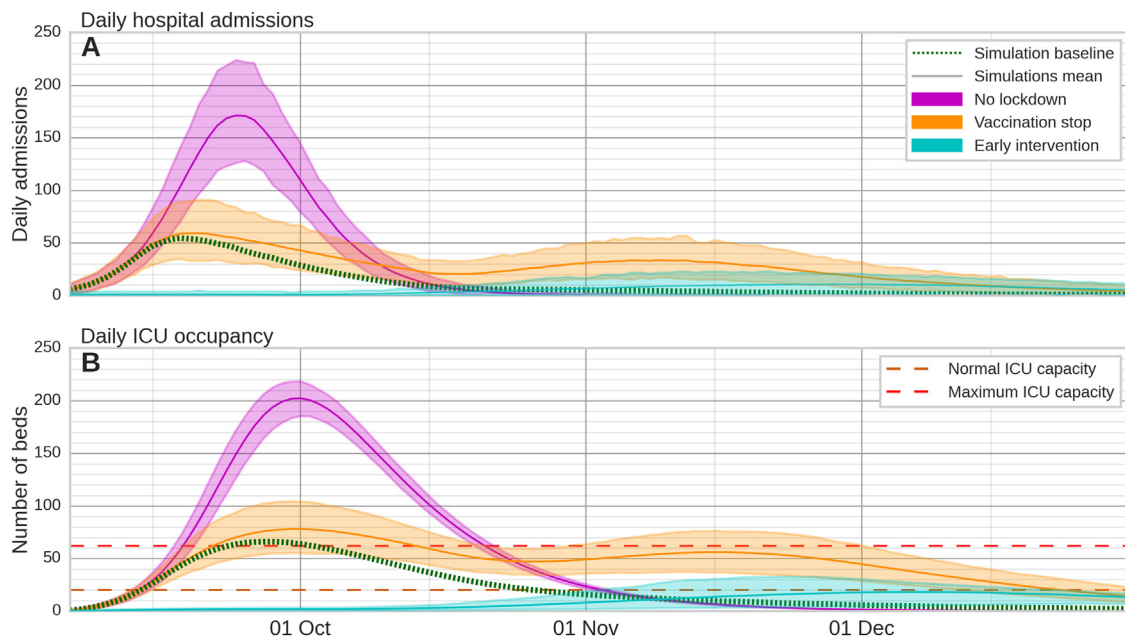


Figure 3. Alternative scenarios compared to observations of hospital admission and ICU bed occupancy. Panel A shows simulated daily hospital admissions and panel B shows daily ICU bed occupancy (simulated using the average probability of ICU admission given hospitalization over the entire epidemic). Scenario A: purple, no lockdown is implemented; Scenario B: orange, no vaccination after lockdown; Scenario C: blue, 2 weeks earlier implementation of the lockdown and associated measures. The mean baseline simulation (no scenario) is represented by a dotted green line. Solid lines and shaded areas represent the mean simulation and the 2.5th-97.5th percentile range, respectively, from 1000 simulations using 1000 random samples from the posterior distribution of parameters estimated via Markov Chain Monte Carlo sampling. Dashed lines represent the maximum number of ICU beds under normal (orange) and COVID (red) regimes. ICU: intensive care unit.

Table 2

Estimates of hospital admissions and ICU occupancy according to three different scenarios.

	Total number of hospital admissions	Peak ICU bed occupancy
Baseline	1415	66
Scenario A	3087 (+118%)	202 (+206%)
Scenario B	3053 (+116%)	78 (+18%)
Scenario C	663 (-53%)	18 (-73%)

hensive surveillance, enabling the timely implementation of measures such as a lockdown initiated 2 weeks earlier (scenario C), it would have significantly curtailed the epidemic and delayed hospital admissions until the easing of the lockdown restrictions. Hospital admissions would have been cut by half and, at the peak, ICU bed occupancy would have remained well below maximum capacity.

Discussion

In this study, we characterized the Delta variant epidemic in New Caledonia. Using mathematical modeling and alternative scenarios, we estimated the relative contribution of the lockdown and vaccination on the control of the epidemic. We also assessed how the timing of the lockdown impacted healthcare burden.

Results showed that before the lockdown, there was high viral transmission with R_0 around 6.6. This value places New Caledonia in the high range of Liu et al.’s review of five estimates of the Delta variant in different provinces of China and UK (mean; 5.08; range 3.2-8) [6]. Contrary to these locations, the epidemic of the Delta variant in New Caledonia was the first active circulation of SARS-CoV-2 in the territory and went initially unnoticed by the surveillance network and therefore by the population. Epidemiological investigations estimated that viral introduction most likely occurred on August 10, 2021. Thus SARS-CoV-2 circulated in New Caledonia for 1 month before its discovery. Then, the implementation of the lockdown resulted in a 73% reduction of R_0 . Our estimates are consistent with those obtained for lockdowns imple-

mented in Europe during the first pandemic wave in spring 2020 [7–9]. NPIs implemented during the lockdown in New Caledonia included school and workplace closures and restrictions on gatherings (private or public); these interventions have already been identified as effective in other countries [6,10–14]. Our results provide further evidence of the effectiveness of NPIs to reduce SARS-CoV-2 spread.

After the lockdown was initiated, hospital admissions declined rapidly, contrary to our alternative scenario A where no lockdown is implemented. This scenario results in twice as many hospital admissions and three times the peak occupancy of ICU beds. A catastrophic scenario where the majority of patients would have suffered from severely degraded quality of care likely resulting in high in hospital mortality. In reality, as hospital admissions declined rapidly, the lockdown was eased into a partial lockdown after 1 month. The easing of the lockdown did not result in an epidemic rebound, in contrast to our model prediction for the alternative scenario B, characterized by no vaccination campaign after the lockdown. Scenario A and B highlight the beneficial interaction between the vaccination campaign and the effective reduction of contacts due to the lockdown in New Caledonia. Finally, scenario C involves implementing the lockdown 2 weeks earlier. In this scenario, the epidemic is mostly under control, highlighting the beneficial effects of early detection and response, as already shown elsewhere [15,16]. Scenario C is a strong argument for strengthening surveillance systems, particularly in the context of Pacific Island Countries and Territories (PICTs) [17].

In the alternative scenarios, the probability of ICU admission given hospitalization (p_{ICU}) was set by using the average probability over the entire epidemic. In reality, the probability of ICU admission varied over time because it depended on physician input. Indeed, we saw a decrease in the estimated probability of ICU admission as the ICU approached its maximum bed occupancy capacity (Supplementary Figure 3). Concurrently, it was also a time of high hospital admissions (Supplementary Figure 4). In the post-peak phase of hospital admissions, a period characterized by reduced hospital admissions, we observe that the daily estimates of the probability of ICU admission given hospitalization, are more irregular, contingent on patient arrival (Supplemen-

tary Figure 4). Epidemiological context was different than the pre-peak period; the pressure on ICU services lessened, enabling a more flexible admission policy in the ICU. Additionally, the demographic profile of the patients may have also evolved, potentially encompassing late arrivals at the hospital. As the variations of daily ICU admission probabilities depend on the magnitude of the epidemic, i.e., number of hospital admissions and the resources of the hospital at a given time, the daily ICU estimates that are context-dependent are not well generalizable for the alternative scenarios. This is why p_{ICU} has been set at the average over the whole period in the alternative scenarios. For reference, Supplementary Figure 5 shows the alternative scenarios using the estimated daily p_{ICU} . In Supplementary Figure 2, we see that when using the average p_{ICU} , the peak in daily ICU bed occupancy estimates exceeds the observations and in particular the total ICU bed capacity. It is a reminder that the capacity ceiling for intensive care beds was reached during this epidemic and that the ICU admission regime was disrupted as a result.

A possible limitation in this study involves scenario A in which no lockdown is implemented. It is very likely that the size of the epidemic is overestimated because this scenario assumes that people would not have reduced their social contacts. Presumably, in the event of a large-scale epidemic with increased hospitalizations and deaths, people would have changed their behavior. However, this scenario is worth considering because it informs us that the drastic decrease in social contacts due to the lockdown gave individuals time to vaccinate themselves and thus be protected against the severe effects caused by SARS-CoV-2 infection. A final possible limitation is that we did not model transmission heterogeneities that emerge from socio-demographic differences between individuals, such as age, employment, or ethnicity. Concerning age, in the absence of data, we assume homogeneous contacts among age groups. We refrain from using a specific age contact matrix, although such matrices have been used in COVID-19 modeling studies [7,11,12,16,18,19]. However, we assume that intergenerational contacts are rather homogeneous in New Caledonia because of the Oceanian lifestyle. Because vaccination and hospitalization risk are explicitly age-dependent in the model, we hope that this may help mitigate this bias. New Caledonia as a PICTs has a multicultural population composed of Melanesian, Polynesian, Asian, and European communities; for future research, it would be interesting to study existing heterogeneities in intra and inter-community contact networks or in access to healthcare. Eventually this social context could be integrated in epidemiological models leading to more tailored public health decisions [20,21]. A population-based prevalence survey of COVID-19 and/or an analysis of hospitalizations could be a first step in studying the burden of COVID-19 in different communities.

In this study, we showed that in New Caledonia, the lockdown greatly reduced SARS-CoV-2 transmission providing an additional delay for a large part of the population to get vaccinated and acquire a level of protection against the virus. The combination of lockdown and intensification of the vaccination complemented each other in a powerful response strategy that slowed and contained the Delta variant epidemic. We also showed that if the measures had been implemented 2 weeks earlier, the epidemic would have been mostly under control. Like other PICTs such as New Zealand, Wallis and Futuna, or Vanuatu, New Caledonia was able to close its borders quickly and thus act on the control of intra-territorial transmission of SARS-CoV-2. This insular context, the lockdown and the intensification of the vaccination campaign made it possible, despite a very strong pressure on the health services, to avoid more severe alternative scenarios.

Material & methods

Model description

Based on Bosetti et al. [18], we developed a deterministic age-structured compartmental model of SARS-CoV-2 transmission and vaccination within the Susceptible-Exposed-Infectious-Recovered (SEIR) framework. The model divides the population into seven epidemiologi-

cal compartments; susceptible (S), pre-infectious (E_1), presymptomatic (E_2), mildly ill (I_{mild}), severely ill requiring hospitalization (I_{hosp}), hospitalized (H). These compartments are further divided into four vaccination status and six age groups 0-11, 12-15, 16-49, 50-64, 65-74, and 75+ years old. New Caledonia's population by age group is based on the 2019 census [22]. Individuals transition between compartments at rates that are inverse of assumed epidemiological durations. We assume a 4-day mean incubation period ($E_1 \rightarrow E_2$) where individuals are infected but not infectious, followed by a 1-day mean presymptomatic infectious period ($E_2 \rightarrow I_{mild}/I_{hosp}$). Additionally, we assume a 3-day symptomatic infection duration, after which individuals either recover or are hospitalized if it is a severe case ($I_{mild} \rightarrow R/I_{hosp} \rightarrow H$). The four vaccination status are based on a two-dose vaccination scheme: unvaccinated (no subscript), first-dose administered (X_{V_0}), first level of vaccine protection (X_{V_1}), and second level of vaccine protection (X_{V_2}). A diagram of the model is presented in Supplementary Figure 6. Daily vaccinations by age group in New Caledonia, as recorded by the Directorate of Health and Social Affairs of New Caledonia, are used to populate the first-dose administered compartment. We assumed that individuals in the first-dose administered compartment (no protection yet) acquire the first level of vaccine protection after a mean period of 14 days (i.e., $X_{V_0} \rightarrow X_{V_1}$) and individuals in 1st level of protection compartments acquire a second level of protection after a mean period of 14 days ($X_{V_1} \rightarrow X_{V_2}$). Almost all vaccination in New Caledonia has been with the Pfizer-BioNTech COVID-19 vaccine BNT162b2, as it was with a few exceptions, the only vaccine distributed in New Caledonia. The vaccine protection effects on susceptibility (i.e., the probability of contracting the virus upon a contact with an infectious individual), infectivity (i.e., the probability of transmitting the virus upon a contact with a susceptible individual) and severity (i.e., the probability of hospitalization if infected) are presented in Supplementary Table 2. We assumed that infection or vaccination conferred lasting immunity during the simulation period.

The probabilities of hospitalization following infection are influenced by age and the number of comorbidities. These probabilities presented in Supplementary Table 3, were derived from data on the prevalence of comorbidities by age, as well as the probabilities of hospitalization given SARS-CoV-2 infection according to age and the number of comorbidities in the French population, as presented by Kiem et al. [23]. We assumed that the prevalence of comorbidities was comparable between New Caledonia and France in the 18-74 years old (Supplementary Table 5). We additionally assume no comorbidities for individuals aged 0-17 and the same prevalence of comorbidities in the 75+ age group as in the 65-74 age group in France. Using probabilities of hospitalization given infection based on age and the number of comorbidities (Supplementary Table 6), the presumed comorbidity prevalence in the population of New Caledonia, and data from the 2019 New Caledonia census [22], we calculated a weighted average of the probabilities of hospitalisation given infection for the age groups considered in our model {0-11, 12-15, 16-49, 50-64, 65-74, 75+}. In calculating the averages, we assumed that the probabilities of hospitalization in age groups 0-11, 12-15, 16-29 in New Caledonia would be equivalent to those if age groups 0-9, 10-17, 18-29 in France respectively. Finally, we adjusted these probabilities to take account of the increased severity of the Delta variant, assuming a 50% increase in all age groups except for the 75+ [18]. Considering studies that indicate a lower susceptibility of children and adolescents to SARS-CoV-2 infection, we assumed that children under 12 years old and adolescents under 16 years old were 50% and 25% less susceptible to contracting the disease respectively [24].

Estimation of epidemiological parameters and modeling the impact of interventions

We modeled the effect of implementing and easing the lockdown on the basic reproduction number R_0 and the effective reproduction

number R_i of each period i sequentially using a logistic function f_i as follow:

$R_i(t) = R_{i-1} \times f_i(t)$ and $f_i(t) = 1 \pm \frac{\eta_i}{1 + e^{-(t-t_i+1-v_i)}}$. The sign of the second term in f_i depends on whether it is a reduction (lockdown) or an increase (lockdown easing). η_i is either the reduction or increase rate parameter depending on the sign of the second term of f_i and v_i is the time when the decrease/increase is 50% effective. Given t_0 as the start of the simulation, t_1 as the date of the virus introduction, t_2 as the date of the lockdown, t_3 as the partial lift date, t_4 as the full lift date and t_5 as the end of simulation date, we first calculate R_1 from t_1 to t_3 as $R_1(t) = R_0 \times f_1(t)$. Then using R_1 , we calculate R_2 from t_1 to t_4 as $R_2(t) = R_1 \times f_2(t)$ and using R_2 , we calculate R_3 from t_1 to t_5 as $R_3(t) = R_2 \times f_3(t)$. R_3 which spans from the start of the virus introduction to the end, accounts for all successive decreases or increases in the reproduction number. Thus, it is the effective reproduction number $R(t)$ for the entire simulation.

Estimates of initial R_0 , η_1 the reduction rate parameter and v_1 the time when lockdown is 50% effective, has been determined in a Bayesian framework. Assuming that hospital admissions followed a Negative Binomial process, posterior distributions of the parameters were estimated by Markov Chain Monte Carlo (MCMC) sampling. To update previous knowledge, we used a likelihood function using observed hospitalization admissions from the Gaston-Bourret Territorial Hospital Center (CHT), the only tertiary hospital in New Caledonia. α_{hosp} was an additional parameter, the overdispersion parameter of the Negative Binomial process. Then, to avoid compounding uncertainties when estimating the subsequent parameters involved in the logistic increase of R_i ; $\{\eta_2, v_2\}, \{\eta_3, v_3\}$, we used a least squares approach. The prior and posterior distributions of parameters for the initial period, as well as subsequent parameters estimated using a least squares approach, are presented in Supplementary Table 1. The 95% CI in our simulations are based on the 2.5th and 97.5th percentiles from 1000 random samples in the posterior distributions of parameters estimated via the Bayesian approach. MCMC sampling was implemented with the PyMC module and least squares with the Scipy module in Python 3.8.

Statistical modeling of ICU admissions

To model ICU admissions and ICU occupancy from simulated hospital admissions, we first estimated the daily probabilities of ICU admission given hospitalization using observed hospital and ICU admissions data and $\tau_{Hosp-ICU}$, the mean delay time from hospital admission to ICU admission.

ws is a vector of length $n + 1$ that holds the probabilities of an individual, who will ultimately be admitted to the ICU, entering ICU on a given day i , from day 0 to day n . Each element of ws is calculated as:

$$ws_i = F(x_2) - F(x_1), \quad x_1 = \begin{cases} 0, & \text{if } i = 0 \\ i - 0.5, & \text{otherwise} \end{cases} \quad x_2 = i + 0.5 \text{ and } i \in \{0, 1, 2, 3, \dots, n - 1, n\}. \quad F \text{ is the cumulative distribution function of the exponential distribution parametrized with } \lambda = 1/\tau_{hosp-ICU}.$$

ds is a vector which holds the daily count of individuals admitted to the ICU under the assumption that every hospital admission results in an ICU admission. Each element of ds is calculated as:

$$ds_i = \sum_{j=0}^i adHosp_{obs,j} \times ws_{i-j}, \quad i \in \{0, 1, 2, 3, \dots, n - 1, n\} \quad \text{and} \quad adHosp_{obs}$$

the time series of hospital admissions.

If $adICU_{obs}$ is the observed time series of ICU admissions, then the probability of ICU admission given hospitalization for a given day i is expressed as $pICU_i = \frac{adICU_{obs,i}}{ds_i}$. The actual observed number of ICU admissions divided by the total ICU admissions possible.

Finally given observed or simulated hospital admissions, daily ICU admissions are given by:

$$adICU_i = \sum_{j=0}^i adHosp_j \times pICU_j \times ws_{i-j}$$

For the alternative scenarios simulations, instead of daily probabilities of ICU admission given hospitalization, we used average probability of ICU admission given hospitalization over the entire epidemic, μ_{pICU} , this was calculated as the total sum of ICU admissions divided by the total sum of hospital admissions (Supplementary Table 4).

Statistical modeling of ICU bed occupancy

n_s is a vector of length $n + 1$ that holds the probabilities that an individual admitted to the ICU will depart day i . Each element of n_s is calculated as:

$$n_{s,i} = 1 - G(x), \quad x = \begin{cases} 0.5, & \text{if } i = 0 \\ i, & \text{otherwise} \end{cases} \quad G \text{ is the cumulative distribution function of the exponential distribution parametrized with } \lambda = 1/\tau_{ICU-R} \text{ and } \tau_{ICU-R} \text{ is the mean duration of ICU occupancy.}$$

ICU occupancy is calculated as follow $occICU_i = \sum_{j=0}^i adICU_j \times n_{s,i-j}$. $\tau_{Hosp-ICU}$ and τ_{ICU-R} were obtained from anonymized data on the course of patients admitted to ICU.

Assessment of three alternative scenarios

To assess the relative contribution of vaccination, lockdown and lockdown implementation time, three alternative scenarios were settled and analyzed.

Scenario A explores the contribution of the lockdown in the reduction of transmission of SARS-CoV-2, i.e., R_0 . In this scenario R_0 remains at its pre-lockdown value from the date of the virus introduction until the end of the simulation.

Scenario B explores the contribution of vaccination to controlling the epidemic. In this scenario, there is no vaccination in population from lockdown until the end of the simulation.

Scenario C investigates how the epidemic trajectory would have been modified due to an earlier intervention. In this this scenario, we maintain the same durations for the lockdown and partial lockdown but shift their starting and ending dates 2 weeks earlier.

Declaration of Competing Interests

The authors have no competing interests to declare.

Funding

We acknowledge the financial support of the South Province of New Caledonia for NO in the form of a doctoral scholarship: Prix d'Encouragement à la Recherche de la Province Sud (PER). The funding source had no role in the study design, data collection, and analysis, decision to publish, or preparation of the manuscript.

Ethical approval

This study did not require ethical approval.

Acknowledgments

We would like to thank the Expert Committee COVID-19 commissioned by the Government of New Caledonia for insights and fruitful discussions. We would like to thank all our colleagues from the Directorate of Health and Social Affairs (DASS) and all our colleagues from the Gaston-Bourret Territorial Hospital Center (CHT), in particular Cécile Cazorla, Head of the Infectious Diseases Department, for all the hard work accomplished during the epidemic.

Author contributions

NO, MM, MJ and MDR conceived and designed the study. PHM, SM, TD and ACG collected the data. NO, MM and PHM checked the data. NO

and MM developed the model and performed the analysis with contribution from SC. NO and MM wrote the original manuscript. PHM, MDR and SC contributed to key revisions of the manuscript. All authors read and approved the final manuscript.

Code availability

Data and source code are available at <https://gitlab.pasteur.fr/noochida/covidnc>.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijregi.2023.06.004.

References

- [1] World Health Organization. WHO Coronavirus (COVID-19) Dashboard, <https://covid19.who.int>; 2023 [accessed 17 April 2023].
- [2] Wu S, Neill R, De Foo C, Chua AQ, Jung AS, Haldane V, et al. Aggressive containment, suppression, and mitigation of Covid-19: lessons learnt from eight countries. *BMJ* 2021;375:e067508. doi:10.1136/bmj-2021-067508.
- [3] Baker MG, Wilson N, Blakely T. Elimination could be the optimal response strategy for Covid-19 and other emerging pandemic diseases. *BMJ* 2020;371:m4907. doi:10.1136/bmj.m4907.
- [4] Kerbaj J, Cazorla C, De Greslan T, Serie M, Gourinat AC, Marot B. COVID-19: the New Caledonia experience. *Clin Infect Dis* 2020;71:2279–81. doi:10.1093/cid/ciaa600.
- [5] Moury PH, Gourinat AC, Riou O, Laumond S, Dupont-Rouzeyrol M, Cazorla C, et al. Successful COVID-19 elimination after an alpha variant outbreak in a “safe travel zone”. *Travel Med Infect Dis* 2021;44:102202. doi:10.1016/j.tmaid.2021.102202.
- [6] Liu Y, Morgenstern C, Kelly J, Lowe R, COVID-19 Working Group CMMID, Jit M. The impact of non-pharmaceutical interventions on SARS-CoV-2 transmission across 130 countries and territories. *BMC Med* 2021;19:40. doi:10.1186/s12916-020-01872-8.
- [7] Salje H, Tran Kiem C, Lefrancq N, Courtejoie N, Bosetti P, Paireau J, et al. Estimating the burden of SARS-CoV-2 in France. *Science* 2020;369:208–11. doi:10.1126/science.abc3517.
- [8] Flaxman S, Mishra S, Gandy A, Unwin HJT, Mellan TA, Coupland H, et al. Estimating the effects of non-pharmaceutical interventions on COVID-19 in Europe. *Nature* 2020;584:257–61. doi:10.1038/s41586-020-2405-7.
- [9] Brauner JM, Mindermann S, Sharma M, Johnston D, Salvatier J, Gavenciak T, et al. Inferring the effectiveness of government interventions against COVID-19. *Science* 2021;371:eabd9338. doi:10.1126/science.abd9338.
- [10] Askitas N, Tatsiramos K, Verheyden B. Estimating worldwide effects of non-pharmaceutical interventions on COVID-19 incidence and population mobility patterns using a multiple-event study. *Sci Rep* 2021 1972;11. doi:10.1038/s41598-021-81442-x.
- [11] Trauer JM, Lydeamore MJ, Dalton GW, Pilcher D, Meehan MT, McBryde ES, et al. Understanding how Victoria, Australia gained control of its second COVID-19 wave. *Nat Commun* 2021;12:6266. doi:10.1038/s41467-021-26558-4.
- [12] Andronico A, Tran Kiem C, Paireau J, Succo T, Bosetti P, Lefrancq N, et al. Evaluating the impact of curfews and other measures on SARS-CoV-2 transmission in French Guiana. *Nat Commun* 2021;12:1634. doi:10.1038/s41467-021-21944-4.
- [13] Sharma M, Mindermann S, Rogers-Smith C, Leech G, Snodin B, Ahuja J, et al. Understanding the effectiveness of government interventions against the resurgence of COVID-19 in Europe. *Nat Commun* 2021;12:5820. doi:10.1038/s41467-021-26013-4.
- [14] Haug N, Geyrhofer L, Londei A, Dervic E, Desvars-Larrive A, Loreto V, et al. Ranking the effectiveness of worldwide COVID-19 government interventions. *Nat Hum Behav* 2020;4:1303–12. doi:10.1038/s41562-020-01009-0.
- [15] Chen S, Guo L, Alghaith T, Dong D, Alluhidan M, Hamza MM, et al. Effective COVID-19 control: a comparative analysis of the stringency and timeliness of government responses in Asia. *Int J Environ Res Public Health* 2021;18:8686. doi:10.3390/ijerph18168686.
- [16] Knock ES, Whittles LK, Lees JA, Perez-Guzman PN, Verity R, FitzJohn RG, et al. Key epidemiological drivers and impact of interventions in the 2020 SARS-CoV-2 epidemic in England. *Sci Transl Med* 2021;13:eabg4262. doi:10.1126/scitranslmed.abg4262.
- [17] Bell L, van Gemert C, Merilles OE, Cash HL, Stoové M, Hellard M. The impact of COVID-19 on public health systems in the Pacific Island Countries and Territories. *Lancet Reg Health West Pac* 2022;25:100498. doi:10.1016/j.lanwpc.2022.100498.
- [18] Bosetti P, Tran Kiem C, Andronico A, Colizza V, Yazdanpanah Y, Fontanet A, et al. Epidemiology and control of SARS-CoV-2 epidemics in partially vaccinated populations: a modeling study applied to France. *BMC Med* 2022;20:33. doi:10.1186/s12916-022-02235-1.
- [19] Sonabend R, Whittles LK, Imai N, Perez-Guzman PN, Knock ES, Rawson T, et al. Non-pharmaceutical interventions, vaccination, and the SARS-CoV-2 delta variant in England: a mathematical modelling study. *Lancet* 2021;398:1825–35. doi:10.1016/S0140-6736(21)02276-5.
- [20] Hou X, Gao S, Li Q, Kang Y, Chen N, Chen K, et al. Intracounty modeling of COVID-19 infection with human mobility: assessing spatial heterogeneity with business traffic, age, and race. *Proc Natl Acad Sci U S A* 2021;118:e2020524118. doi:10.1073/pnas.2020524118.
- [21] James A, Plank MJ, Binny RN, Lustig A, Hannah K, Hendy SC, et al. A structured model for COVID-19 spread: modelling age and healthcare inequities. *Math Med Biol* 2021;38:299–313. doi:10.1093/imammb/dqab006.
- [22] ISEE. Census, <https://www.isee.nc/population/recensement>; 2019 [accessed 17 April 2023].
- [23] Kiem CT, Massonnaud C, Levy-Bruhl D, Poletto C, Colizza V, Bosetti P, et al. Evaluation des stratégies vaccinales COVID-19 avec un modèle mathématique populationnel (in French), <https://hal-pasteur.archives-ouvertes.fr/pasteur-03087143>; 2020 [accessed 27 June 2022].
- [24] Viner RM, Mytton OT, Bonell C, Melendez-Torres GJ, Ward J, Hudson L, et al. Susceptibility to SARS-CoV-2 infection among children and adolescents compared with adults: a systematic review and meta-analysis. *JAMA Pediatr* 2021;175:143–56. doi:10.1001/jamapediatrics.2020.4573.