Efficacy of Localized Lockdowns in the SARS-CoV-2 Pandemic

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Abstract

Six months into the pandemic, non-pharmaceutical interventions (e.g., social distancing) are the only available measure to control severe acute respiratory syndrome-coronavirus 2 (SARS-CoV-2) transmission. Around the world, policymakers have implemented localized lockdowns in small geographic areas to prevent spread of the disease. Using an integrated dataset from Chile, we estimated the direct and indirect (spillover) causal effects of localized lockdowns on SARS-CoV-2 transmission. Our results show that the effectiveness of localized lockdowns is strongly modulated by duration and is affected by spillover effects from neighboring geographic areas. Our projections suggest that extending localized lockdowns will slow down the epidemic but by themselves will be unable to control epidemic growth due to spillovers from neighboring areas with high interdependencies, unless those contiguous areas also implement lockdowns.
Behavioral non-pharmaceutical interventions (NPIs) are the only readily available measures to prevent and control transmission of the severe acute respiratory syndrome-coronavirus 2 (SARS-CoV-2). NPIs range from simple individual-level recommended behaviors, such as wearing face masks, frequent hand-washing, or maintaining physical distance; to society-level regulatory actions, such as school closures, quarantines, or lockdowns (1). The effects of those interventions have been typically described using mathematical models (2-5) and have informed health policy since the beginning of the pandemic (6, 7). However, there is a lack of empirical evidence of the causal effects of NPIs (8, 9), as most research focuses on associations (10, 11). Understanding the impact of NPIs in SARS-CoV-2 transmission is crucial, because those interventions will probably continue until an effective vaccine or treatment becomes available (1, 2).

Several countries have managed to control the SARS-CoV-2 epidemic using NPIs (5, 12-14). As governments have begun easing restrictions, localized lockdowns are becoming an increasingly relevant policy option in cases of resurgence (15-17). Localized lockdowns are typically implemented in transmission hotspots and can be implemented for populations/areas large and small to suppress an outbreak. In principle, localized lockdowns can reduce social and economic costs compared to larger-scale SARS-CoV-2 suppression strategies and can provide a gradual exit from nationwide lockdowns. Early in the pandemic, the Chinese government imposed a localized lockdown and other strict NPIs in the city of Wuhan (5), effectively suppressing the SARS-CoV-2 transmission (10). Subsequently, similar targeted lockdowns have been implemented in neighborhoods (e.g., Beijing, China), suburbs (e.g., Melbourne, Australia), towns (e.g., Vo, Italy), districts (e.g., North Rhine-Westphalia, Germany), and, most recently, at the city level in Leicester, England (12, 16). Despite the increasing prevalence of localized lockdowns, there is limited evidence of their effectiveness.
On May 22, 2020, the World Health Organization declared South America the new epicenter of COVID-19, the disease caused by SARS-CoV-2. The first COVID-19 case in Chile was reported in March 3, 2020, and by the end of March, national borders, schools, and non-essential businesses were closed and night-time curfews were enforced (18) (Fig. 1A). Most importantly, policymakers in Chile implemented localized lockdowns at the municipality (comuna) level, the smallest administrative subdivision in the country, at various points in time. The criteria used by the government to impose lockdowns were loosely defined as a function of the number and density (per km²) of infectious COVID-19 cases, increases in case incidence, and health system capacity (18). Across the country, there was substantial variation in the duration of these municipality-level localized lockdowns and, for each municipality under lockdown, in the lockdown status of neighboring municipalities. We used this policy as a natural experiment to evaluate the efficacy of localized lockdowns on SARS-CoV-2 transmission.

Allowing for interference between municipalities (19, 20), we estimated the individual direct effects of extending the duration of these local lockdowns and the individual total (sum of direct and spillover) effects of maintaining lockdowns in neighboring municipalities. We characterized transmission by the instantaneous reproduction number ($R_t$); that is, the average number of secondary cases per primary infected case (21). We did this using causal time-series analysis at the municipality level based on the daily series of COVID-19 cases reported by the Ministry of Health (22), adjusted for the time-lag between onset of symptoms and case report (Fig. 1A) (10, 21). Based on the potential outcomes framework for causal inference (23, 24), we used the augmented synthetic control method to analyze the progression of the epidemic in comparable municipalities that underwent different lockdown interventions (25, 26), varying the duration of the intervention ($\Delta D$) and the proportion of the population under lockdown in the neighboring
municipalities at each time point \( t \) (Fig. 1E). We estimated the counterfactual progression that the disease would have exhibited had an alternative lockdown policy taken place (Fig. 1E).

We adjusted for or balanced several municipality-level characteristics that may affect virus transmission (table S2) including: the proportion of the population that is rural, female, older than 65 years of age, living in poverty, living in overcrowded households (\( \geq 2.5 \) people per room), or lacks adequate sanitation infrastructure (access to potable water and sewage); average monthly income, and municipality area. We analyzed all the municipalities in Greater Santiago that started their first lockdown after March 15, 2020 and finished by May 15, 2020 (Fig. 1B); that is, the first period of confinement that arguably shaped the evolution of the epidemic (Fig. 1A, 1C). Our data set combined information from administrative COVID-19 surveillance records (22), a nationally representative household survey (27), and census data (28) (Supplementary Materials). We provide open-source code with step-by-step explanations to implement the analyses in related settings.

Overall, our results suggest that the effectiveness of localized lockdowns is strongly modulated by the duration of the intervention and the amount of spillover from neighboring geographic areas. The larger the proportion of neighbors under lockdown, the higher the efficacy to control transmission. We illustrate these findings with three representative municipalities in Greater Santiago that were put under lockdown on March 26: Lo Barnechea, Providencia, and Santiago (Fig. 2; see the Supplementary Materials for additional results). There is a high degree of economic and social interdependency among municipalities within the city, particularly for the municipality of Santiago, which hosts much of the country’s financial, commercial, and political activity, as well as all major government infrastructure. Fig. 2 shows a large reduction in \( R_t \) (Fig. 2B) and COVID-19 cases (Fig. 2C) with an extended lockdown. Had the lockdown been...
extended for three additional weeks, maintaining $P_t$ constant, we estimate that the reduction in $R_t$ would have been larger. The average $R_t$ would have decreased from 1.83 to 1.27 (difference: -0.56, 95% confidence interval [CI]: [-0.63,-0.50]) in Lo Barnechea, from 1.82 to 1.34 (difference: -0.47, 95%CI: [-0.59,-0.36]) in Providencia, and from 1.95 to 1.23 (difference: -0.72, 95%CI: [-0.85,-0.58]) in Santiago. These reductions in $R_t$ are equivalent to 177 (95%CI: [167,188]; or 143 per 100,000 population) averted COVID-19 cases over three weeks in Lo Barnechea, 94 (95%CI: [76,111]; or 59 per 100,000 population) averted cases in Providencia, and 1343 (95%CI: [1245,1441]; 267 per 100,000 population) averted cases in Santiago, which would represent 33-62% reductions in reported cases in that timeframe.

The reductions in transmission would have been even larger if it was possible to control lockdowns in neighboring municipalities to reduce spillover effects. Assuming neighboring municipalities of Lo Barnechea, Providencia, and Santiago maintained their lockdown status ($P_t=53.0\%$, $P_t=80.3\%$, and $P_t=35.8\%$) for three additional weeks, we estimate that the average $R_t$ would have decreased to 1.19 (95%CI: 1.13, 1.25), 1.25 (95%CI: 1.14, 1.37), and 1.21 (95%CI: 1.08, 1.34), respectively (Fig. 2B). Figs. 3A and 3B show the relationship between daily COVID-19 incidence and days of extended lockdown as a function of changes in $P_t$, after adjusting for observed covariates. The larger $P_t$, the greater the number of averted cases. Overall, results in Greater Santiago suggest that the decision to reopen these municipalities was premature, especially when lockdowns were brief, because the effectiveness of lockdowns strongly depends on the duration of the intervention and the amount of spillovers (findings for other municipalities with lockdowns are consistent with these results; Figs. S3-S6).

Fig. S5 reaffirms the results from a different angle. As happened with Lo Barnechea, Providencia, and Santiago, the municipality of Punta Arenas was placed under lockdown early
on in the pandemic, from April 1 to May 7. It initiated lockdown with one of the highest case incidence per 100,000 population in the country. Notably, Punta Arenas is geographically isolated and has few local interdependencies that could result in active transmission networks during a localized lockdown. Our estimates show negligible spillover effects: increasing $P_t$ from 0 to 1 would only result in a reduction of $R_t = 0.02$ (Fig. S5 and Table S13), probably due its geographical isolation and minor interdependencies with neighboring municipalities.

Having assessed the role of duration and spillovers, we evaluate the impact of lockdowns in geographic areas of increasing size. We considered three target lockdown areas (Fig. 4A): the municipality of Ñuñoa (red), a cluster of six municipalities (orange), and Greater Santiago (green). We extended the study period to encompass the mandatory lockdown for Greater Santiago that began on May 15, and varied the population under lockdown in the targeted area and the proportion of the population under lockdown in neighboring municipalities ($P_t$). Fig. 4B shows the estimated $R_t$ from March 15 to June 15. In general, an epidemic will continue to grow as long as $R_t$ is greater than one. Fig. 4 shows that the epidemic kept expanding in all three target areas until a city-wide lockdown was implemented on May 15. These results highlight the challenges of suppressing virus transmission in areas with a high degree of economic and social interdependencies, such as Chile’s capital, when there is a substantial proportion of neighbors that are not under lockdown.

Epidemiologists have long known that the only way to stop an epidemic is to break the chain of transmission. Today, strategies to suppress SARS-CoV-2 transmission are limited to NPIs. In principle, localized lockdowns can break transmission chains by limiting contact between infectious and susceptible individuals, and this goal could be achieved at household, neighborhood, municipality, county, or state levels. The social distancing imposed by a
lockdown, however, must be maintained and enforced until an adequate control of transmission is achieved. Localized lockdowns may also provide a gradual exit to larger-scale strategies at lower cost, if effectively implemented. In this paper, we have shown that effective implementation of localized lockdowns is challenging and is affected by spillovers from neighboring areas where transmission networks exist, such as in a city.

We used recent methods from the causal inference literature to provide empirical estimates for the effects of localized lockdowns and, crucially, of the effects of interventions on neighboring areas. We found that localized lockdowns can help contain transmission, but their efficacy is dependent on the duration of the intervention and potential spillovers from neighboring areas. For instance, the efficacy of localized lockdowns within Greater Santiago, where there is high economic and social interdependency between municipalities, was strongly affected by suppression measures in place in neighboring municipalities. In contrast, localized lockdowns showed good results in municipalities such as Punta Arenas, which are geographically isolated and thus have transmission networks that are relatively unaffected by neighboring areas.

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Author contributions

YL, EU, JZ: conceptualization, resources, data curation, results interpretation, writing and revising the manuscript. YL: data analysis. YL, JZ: modeling methods.

Competing interests

Authors declare no competing interests.

Data and materials availability

The datasets used and/or analyzed during the current study are available from Base de Datos CoVID-19 repository at http://www.minciencia.gob.cl/covid19. The R code used for analysis is available at http://jrzubizarreta.com/.
Fig. 1. Background and study overview. (A) Incidence of COVID-19 cases in Chile, March 1 to July 15. The majority (66%) of cases have been reported in Greater Santiago (solid line). (B) Municipality-level lockdowns in Greater Santiago on March 31, April 15, April 30, and May 15, 2020. (C) Variation of the instantaneous reproduction number ($R_t$) and the proportion of the population under lockdown in Greater Santiago over time. (D) Histogram of daily $R_t$ for all municipalities from March 15 to June 15, 2020, before lockdown, during the first lockdown, after reopening, and during the second lockdown. Municipalities with fewer than 10 COVID-19 cases were excluded. (E) Illustration of alternative lockdown interventions of varying durations (blue area) and proportion of neighbors under lockdown (grey line).
Fig. 2. **Duration and spillover effects of localized lockdowns.** (A) Cumulative COVID-19 cases in Chile and Greater Santiago before May 15, 2020. (B) municipalities of Lo Barnechea, Providencia, and Santiago (red diamonds), and their corresponding neighbors (blue for the immediate neighbors under lockdown and white otherwise) on the last date under lockdown, April 13. (C, D) Estimated instantaneous reproduction number $R_t$ and incidence $I_t$ under different lockdown interventions for each municipality (further results in the Supplementary Materials). In (C), the grey and blue lines show the proportion of the population in the observed municipality...
and surrounding municipalities under lockdown, respectively. In (C, D), the lighter shade of blue extends the duration of the lockdown that actually took place. The solid black lines show the reproduction number $R_t$ (C) and daily incidence (D), and the dashed lines show the predicted $R_t$ and case incidence for the extended lockdown. The direct and total effects of the extended lockdown are the difference between the solid black line and dashed line with grey and blue bands, respectively. The bands around the curves indicate 95% confidence intervals.
Fig. 3. Duration and spillovers strongly modulate the efficacy of lockdowns. Prediction of the instantaneous reproduction number $R_t$ as a function of time (A) with 50% of neighboring population under lockdown since intervention (lockdown extended for 0-14 days). (B) Average daily COVID-19 incidence over three weeks with a varying duration of extended lockdown ($\Delta_D$ =0-14 days) and a varying proportion of the neighboring population under lockdown ($P_t$ =0-1).
**Fig. 4. Efficacy of lockdowns for different target areas.** (A) In blue, municipalities of Greater Santiago under lockdown at different points in time; outlined in red (Ñuñoa), orange (cluster of six municipalities), and green (Greater Santiago), lockdown target areas of increasing size. (B-D) Estimated instantaneous reproduction number $R_t$ with changing proportions of the population under lockdown in each geographic area and its immediate neighboring areas. (B-C) also show the predicted $R_t$ (dashed line) had the lockdowns in the geographic area and for its immediate neighbors been extended. (B-C) if the lockdowns in the area and the neighbors are extended. We estimate that the epidemic would have continued to grow ($R_t \geq 1$) even with the extended localized lockdowns. The epidemic kept growing until Greater Santiago was put under lockdown.