COVID-19: Local/regional inequalities and impacts over critical healthcare infrastructure in Brazil

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Abstract: This article addresses regional inequalities about critical healthcare infrastructure for coping with the COVID-19, based on geo-spatial analysis and compartmental modeling (SEIR). The study sites were the São Paulo Macro Metropolis (MMP) and the Metropolitan Region of Vale do Paraíba/Litoral Norte (RMVPLN). The results indicated the absence of ICU beds in more than 2/3 of the municipalities, in addition to the concentration in regional hubs, for which the migration of COVID-19 cases from neighboring municipalities should be considered. The analysis with the SEIR model, performed for scenarios with and without social isolation, showed that the isolation adopted in the regions was able to postpone the collapse of the health infrastructure, reducing the reproduction rate of the disease. The simulations indicated a reproduction rate of 0.95 in order to avoid collapse in the health infrastructure for RMVPLN in the analyzed period. In addition, for future resilience, it is essential to address inequalities in terms of health infrastructure available for public and private access.

Keywords: COVID-19, regional aspects, Brazil, health infrastructure

Introduction

As already identified, and thoroughly discussed, one of the main problems in coping with COVID-19 has been the strangulation caused on health systems in the vicinity of hospitalization peaks. This is associated with the uncontrolled spread of the disease, generating impacts for infected people and also over all other regular hospital procedures. In this context, a good part of the countries adopted containment measures, which, although at relatively different times, somehow influenced the impacts of the disease. The worst scenarios came from places where the peak was far beyond the possibilities of absorption by health systems, as seen in China, Iran, Italy, Spain and, more recently, in the United States.

Rhodes et al. (2012) had already identified a wide variation in the supply of ICU beds among European countries. At that time, the authors indicated Germany as the country with the best infrastructure for critical healthcare (29.2 ICU beds/100,000 inhabitants) and Portugal as the country with the lowest capacity (4.2 ICU beds/100,000 inhabitants). At that time, Spain and the United Kingdom had relative capacity less than the European average (11.5 ICU beds/100,000 inhabitants), with 9.7 and 6.6 ICU beds/100,000 inhabitants, respectively, and Italy and France had capacity slightly above the European average, with 12.5 and 11.6 ICU beds/100,000 inhabitants, respectively. Brazil, according to DATASUS/CNES (2020), has 13.6 ICU beds/100,000 inhabitants for public sector and 62.6 ICU beds/100,000 inhabitants for the private network.

These numbers, although reinforcing the thesis that a greater relative capacity - in terms of ICU beds - is a relevant factor for the response to the COVID-19 crisis, as in the German case, are less relevant to understand local and regional contexts, since there is also a disparity in the relative supply of hospital beds between regions in the same country. Considering that COVID-19, in the largest countries, affected specific regions, it is important to understand these local/regional contexts for the response to the crisis.

Salluh and Lisboa (2016) point to regional disparities in the supply of ICU beds in Brazil, with a concentration in the South-Southeast and deficiencies in the Northern region, in addition to highlighting the need for certified health apparatus (equipment and teams) to make the treatments effective. In a recent document, Costa and Junqueira (2020) brought these numbers to light and suggested the urgent adoption of measures by local and state governments, in their respective contexts. The document, whose content has an optimistic perspective in relation to the current ICU occupation in Brazil (adopting 50% of current occupation, another relevant aspect in the analysis), indicates the number of 10 ICU beds/100,000 inhabitants as the criticality threshold for the purpose of confronting COVID-19, in the Brazilian case.

In Figure 1, it is possible to view the data presented by Costa and Junqueira (2020), with adaptations, to better identify the criticality in each case.

Figure 1. Criticality data on the availability of ICUs in Brazilian states
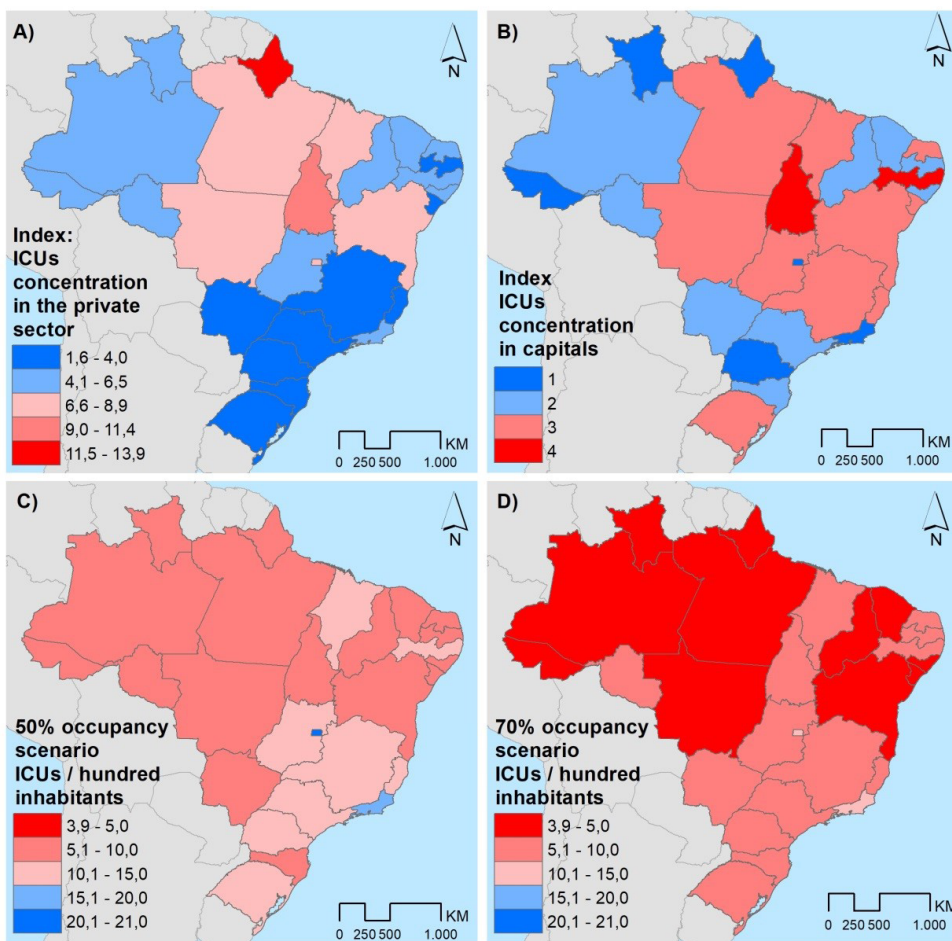
SOURCE: Costa e Junqueira (2020) and data:
ANS: http://www.ans.gov.br/anstabnet/cgi-bin/dh?dados/tabnet_02.def
IBGE: https://www.ibge.gov.br/cidades-e-estados
DATASUS/CNES: http://cnes2.datasus.gov.br/Mod_Ind_Tipo_Leito.asp?VEstado=50

Production: NINFA / LabGEO / ITA

Source: Organized by the authors based on data from Costa and Junqueira (2020).

The map in Figure 1A shows the concentration of ICUs in the private sector: the higher the indicator, the greater the private concentration of ICU beds. Such concentration can lead to a conflict of attendance, if the greatest demand is coming from SUS (Sistema Único de Saúde, the Brazilian public health system) users. Another aspect is the disproportionately high concentration of ICU beds in the capitals (main cities), as illustrated in Figure 1B, in which the ideal situation is a number close to 1: the more concentrated the supply of ICUs in the capitals, disproportionately to the population, the higher the indicator. In the case of São Paulo, the capital, although representing 27% of the state's population, it concentrates 41% of the ICU beds.

The data presented by Costa and Junqueira (2020), while also highlighting re-

gional disparities, point to the state of São Paulo as having "non-critical" infrastructure (available ICU beds). According to the authors, with the availability of 29 ICU beds for every 100,000 inhabitants (14.5 assuming 50% current occupation), the state of São Paulo would be ahead, together with the Federal District, Rio de Janeiro, Maranhão and Espírito Santo (all with availability above 30 ICU beds/100,000 inhabitants), from other states, in a situation of better critical healthcare infrastructure to deal with COVID-19 (Figure 1C). However, considering a current occupation factor of 70%, which is more realistic, as indicated by a document from the National Supplementary Health Agency (ANS, 2013), almost all Brazilian states would be in a critical situation.

MMP and RMVPLN: Intraregional disparities and local contexts

For the purpose of the local/regional context analysis, we discuss in this article the case of the São Paulo Macro Metropolis (MMP) and the Metropolitan Region of Vale do Paraíba and Litoral Norte of São Paulo (RMVPLN) (Figure 2).

The São Paulo Macro Metropolis (MMP) comprises five metropolitan regions (São Paulo, Campinas, Sorocaba, Baixada Santista and Vale do Paraíba/Litoral Norte), in addition to two other urban agglomerations (Piracicaba and Jundiaí) and the Bragantina micro region, in an area of 49,927.83 km². Its 174 municipalities represent 27% of the state's municipalities, and its population of 30.27 million inhabitants represents 74% of the state population in 2010. The macro region is responsible for more than 82% of the State GDP and even 28% of the Brazilian GDP (PASTERNAK; BOGUS, 2019).

**Figure 2. São Paulo Macro Metropolis - MMP**
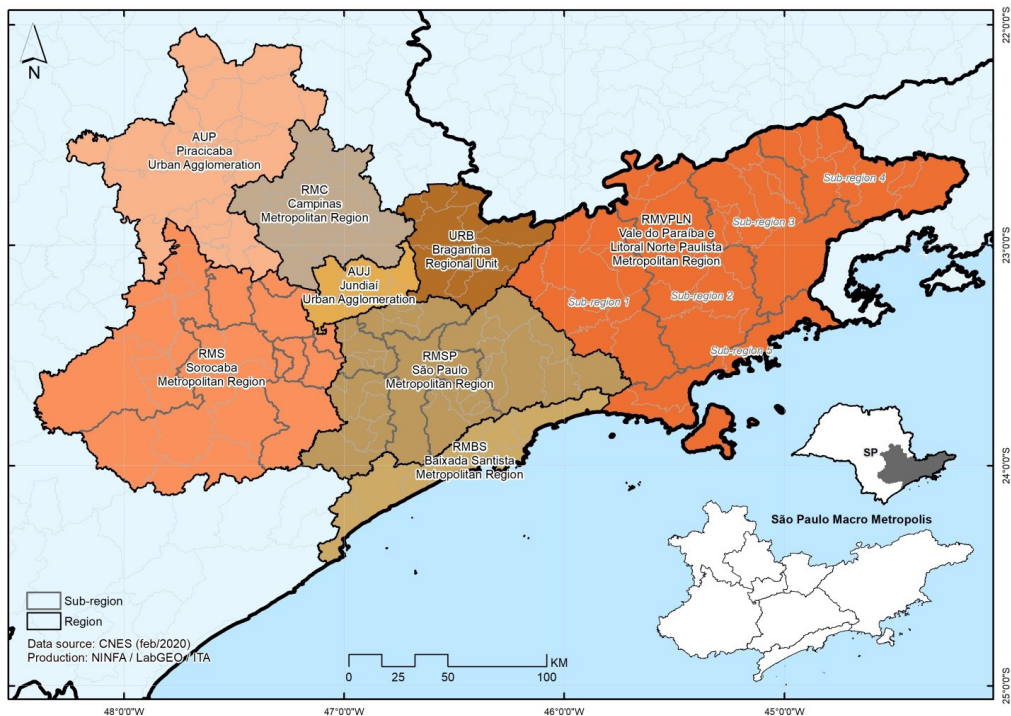
Source: Organized by the authors based on EMPLASA (2019) data.

The Metropolitan Region of Vale do Paraíba and Litoral Norte is part of the MMP, having been created in 2012. It embraces 5 sub-regions, comprising 39 municipalities and more than 2.5 million inhabitants, responsible for 4.8% of state's GDP in 2016. RMVPLN is located between two of the most important Metropolitan Regions of the country: São Paulo and Rio de Janeiro, and stands out for its intense and diversified economic activity. Industrial production is highly developed in the municipalities located on the Presidente Dutra Highway axis. Also noteworthy are port and oil activities in the Litoral Norte and tourism in Serra da Mantiqueira, Litoral Norte and historic cities (EMPLASA, 2019).

Data from DATASUS/CNES (2020) on critical healthcare infrastructure in the MMP municipalities were mapped (Figure 3).

Figure 3. Criticality of the availability of ICU beds in the municipalities of MMP
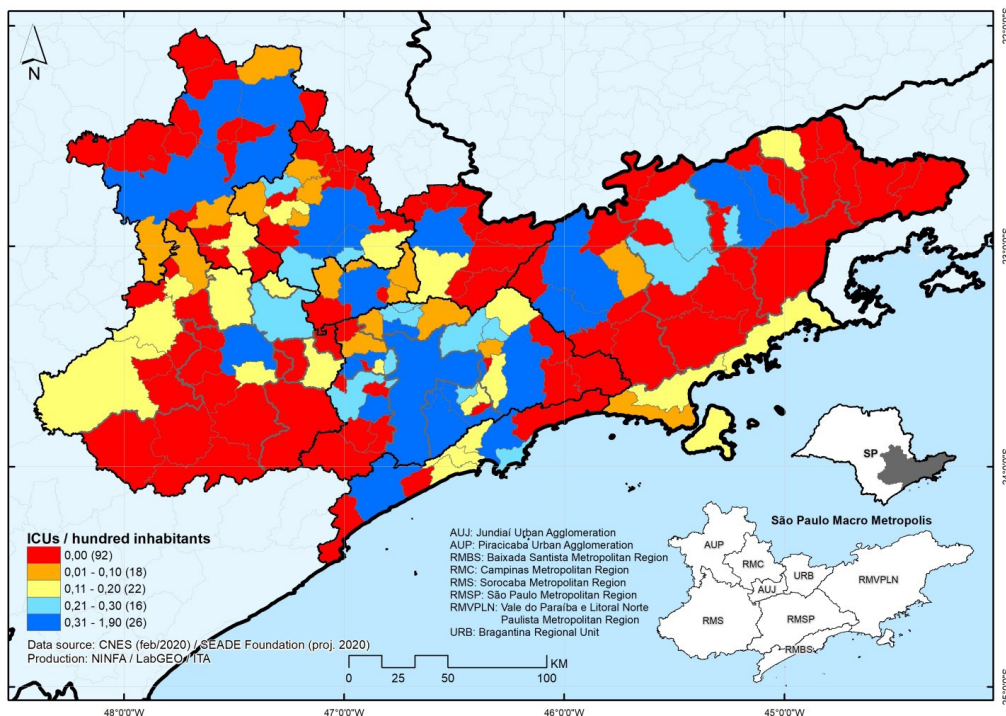
Source: Organized by the authors based on DATASUS / CNES data (2020).

Note the concentration of ICU beds in the capital and also the absence of ICU beds in more than 2/3 of the municipalities of MMP. It is also possible to identify municipalities that, given the best critical healthcare infrastructure, establish themselves as sub-regional hubs and should be demanded by populations in neighboring municipalities. In the case of RMVPLN, the most notorious example is that of the municipality of São José dos Campos, which should attract demands from neighboring municipalities and also from the North Coast of São Paulo. On the other hand, other sub-regions would be more unguarded in terms of local logistics for emergency care.

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In addition to these sub-regional characteristics, there are others, which may aggravate the situation for some hub municipalities, such as the transport corridors as axes for the dissemination of COVID-19.

This fact imposes an additional demand to be addressed by local/regional managers, especially those at the head of the sub-regional hubs.

SEIR modelling: Containment measures and local/regional impacts

The prediction and simulation models allow assessing the progress of the pandemic through the elaboration of some scenarios. Considering the situation already presented for MMP and RMVPLN, a SEIR compartmental model (Susceptibility, Exposure, Infection and Recovery) was developed for a regional approach. The SEIR model is a type of epidemiological compartmental model, that is, it divides the population into compartments - susceptible, exposed, infected and recovered - and through mathematical modeling, works the transmission of the virus between these compartments. It has been used in recent studies, aiming to estimate the number of COVID-19 infections in different scenarios (ROCKLÖV; SJÖDIN; WILDER-SMITH, 2020; RADULESCU; CAVANAGH, 2020; THOMPSON, 2019).

One of the variables for the model used in this work is the reproduction number (R0). The reproduction number represents the average number of secondary cases generated from a primary infection case. For this study case, the instantaneous reproduction number defined by Fraser (2007) was used, in which the initial conditions do not vary, as it is intended to evaluate scenarios from the initial data of the pandemic. The R0 was calculated based on the methodology defined by Thompson et al. (2019), from population data, number of infected daily and number of daily deaths, using the Bayesian statistical inference.

The transition scheme between these compartments is set by the respective variables: β represents the rate of contact between people per unit of time, σ is the parameter of the probability distribution of the incubation time, assumed to be exponential, and γ is the recovery rate. These variables result in the incubation time ($1/\sigma$), the period between the infection of an individual and its ability to infect new individuals; and the infectious time ($1/\gamma$), the period in which the infected person transmits the disease to susceptible individuals, until their recovery. The limits of the incubation time were 4.1 to 7.0 days (WHO, 2020; LI et al., 2020) and the infectious time, from 7.0 to 14.0 days (CHEN et al., 2020).

Regarding the initial conditions, the group of susceptible people is defined as the population of the locality, the group of exposed people as double the number of infected, the group of infected as the total number of cases registered in the locality until the date of the simulation, and the group of recovered equals zero.

Most of the municipalities in the RVPMLN are in critical health infrastructure conditions. Therefore, it is reasonable to assume that there will be patient mobility between municipalities as municipal health systems go into exhaustion. Considering this

mobility, situations were analyzed for the 5 sub-regions of the RMVPLN, with a focus on estimating possible breakdowns of critical health infrastructure and the number of infected people over time.

The analysis also considered a hypothesis in which: i) no measures to contain the pandemic would have been adopted; and ii) such measures would be adopted in sufficient scope to avoid the collapse of the critical health infrastructure in the sub-regions. For such analysis, the initial R0 (disease reproduction rate) considered and the reporting rate (and, consequently, underreporting) were those reported for the state of São Paulo. The containment measures were social isolation, social distancing and adoption of personal hygiene standards (mainly alcohol 70% for hands sanitizing).

All codes and databases used in this work were made available by Covid-19-BR (2020), with adaptation and changes to generate results for our set of municipalities.

The projections of the SEIR model and the queue simulation were carried out with data series collected up to 04/13/2020 and 04/19/2020 for the RMVPLN sub-regions, to allow the projection and comparison of the hypotheses. The simulated period comprises 180 days from those dates. The reporting rate for the state of São Paulo was set in 7.55% for the first simulation and 10.4% for the second, and the initial reproduction number (R0) adopted for the region ranged from 1.95 to 2.16 for the first assessment and between 1.13 and 1.19, for the second assessment, as indicated by the Covid-19-BR (2020).

Hypothesis 1: data collected until 4/13/2020 and scenario WITHOUT adoption of containment measures

The simulation results can be seen in Figure 4, with the evolution of the infected curve, as well as the health system collapse dates for RMVPLN sub-regions 1, 2, 3 and 5. Sub-region 4 was not presented, as it had not notified any cases of COVID-19 until the date of the simulation. The result shown in Figure 4 is an estimate, as it does not consider any action to contain the pandemic.

Figure 4 - COVID19 cases - RMVPLN sub-regions
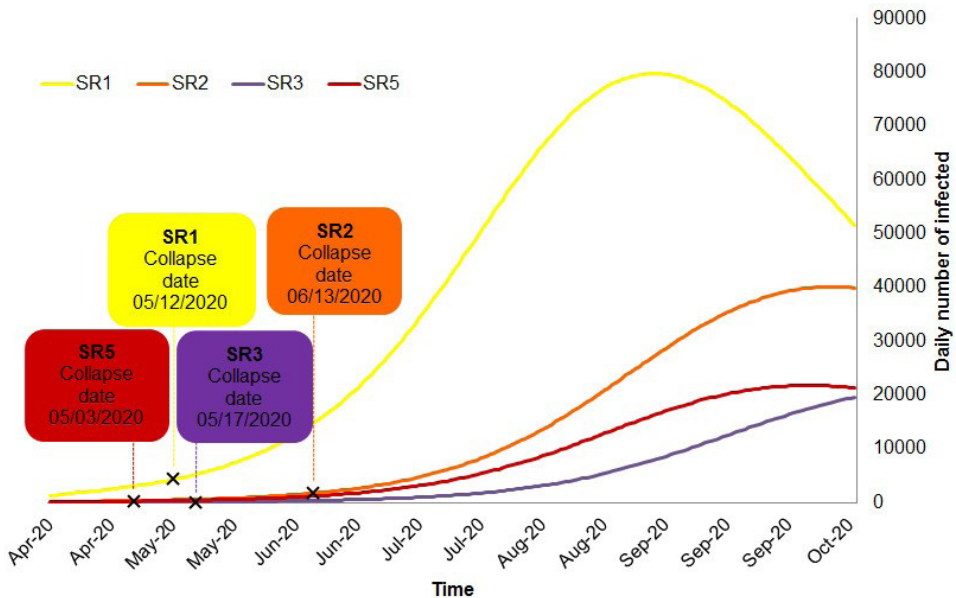
Source: Organized by the authors. Note: Hypothesis 1 - Without containment measure (R0 = 1.95-2.16).

As can be observed in the Figure 4, the collapse of the health systems would have been imminent at the sub-regional level, reaching the limit of the capacity of ICU beds in approximately one month in the sub-regions 1, 3 and 5. It is possible to infer that the collapse in the sub-region 5 (municipalities on the North Coast of SP) would have been due to its limited health infrastructure, as well as its relationship as one of the main tourist destinations for the population of São Paulo city, one of the epicenters of the pandemic in Brazil.

Similarly, sub-region 1 would collapse on 05/12/2020, four weeks after the start of the simulation, despite having a hub municipality (São José dos Campos) with good health infrastructure at the regional level. However, this is the most populous sub-region and showed a more accelerated evolution of cases at the beginning of the pandemic. It is also noted, in this case, that the collapse would last long until reaching the peak of infected (predicted, in the simulation, to occur between the months of August and September/2020). This would imply in the worsening of the crisis, with the health system strangled for more than 3 months.

Therefore, in a hypothetical scenario, without containment measures, and assuming that conditions remain constant, it can be concluded that the RMVPLN health system would not be able to meet the demand of patients.

These results indicate a very serious picture for regional health, if containment measures had not been adopted for COVID-19 in the region.

Hypothesis 2: data until 04/19/2020 and scenario WITH adoption of contain-

ment measures

In this simulation we considered the implementation of containment measures, so that there is no collapse (objective limit), resulted in a R0 in the range of 0.9 to 1.0 for the RMVPLN. The results is shown in Figure 5. The maximum number of infected individuals is significantly reduced to 3,341 (sub-region 1), 183 (sub-region 2), 123 (sub-region 3), 66 (sub-region 4) and 487 (sub-region 5).

The decline in the number of infected people would occur on 05/06/2020 (sub-regions 1 and 5) and 05/11/2020 (sub-regions 2 and 3), as predicted by the simulation. Sub-region 4 has a practically constant number of cases in this simulation, with an average of 63.46 cases and a standard deviation of 2.5 during the simulated period.

Figure 5 - COVID19 cases - RMVPLN sub-regions
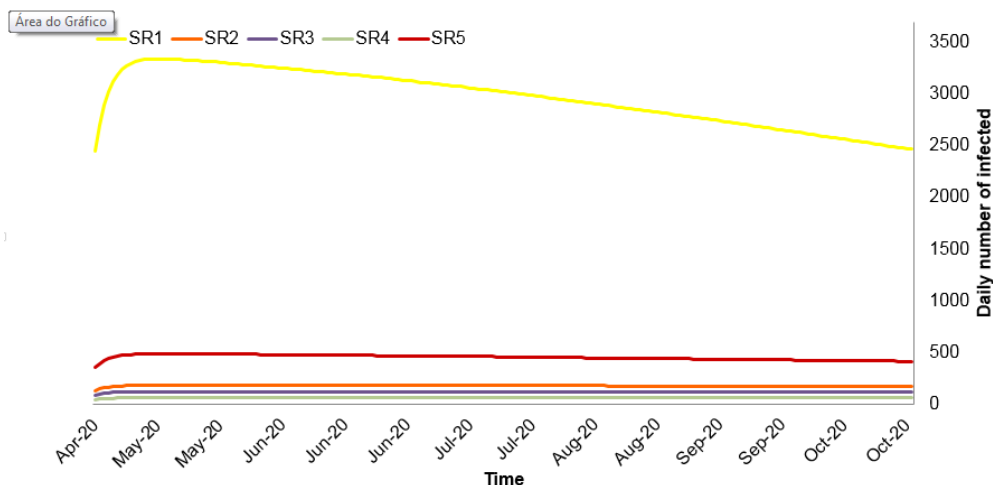
Source: Organized by the authors. Note: Hypothesis 2 - With containment measure (R0 = 0.9-1.0).

In this scenario, the spread of the disease is maintained on a regular basis throughout the analysis time horizon (6 months), and possibly beyond this, with the disease having reached a peak with a relatively small number of infected (slightly less than 3,500). This implies that the containment measures, for the "non-collapse" situation, should be maintained throughout the period, in a way to keep low R0 rates.

This simulation reflects a reduction in the reproduction rate of COVID-19 in the region. The average R0 estimated at that time was 1.16. The simulation, whose objective was to identify the disease reproduction rate to identify the "non-collapse" threshold of critical health infrastructure, indicated an average R0 of 0.95.

Assuming that the rate of adherence to the containment measures adopted by the State of SP ranged from 48% to 59%, in the period of the simulation, as reported by Agência Brasil (2020), and considering a linear relationship between the isolation adherence rate and the disease reproduction rate, in the adopted range, it is reasonable

to assume that a 60% adherence rate would be the minimum level necessary to avoid the collapse of the critical health infrastructure at RMVPLN.

Final remarks

The dissemination of COVID-19 and its impacts are more or less intense according to government policies associated with containment measures, as well as the previous existing apparatus for dealing with the disease. Regional and intraregional asymmetries, in terms of vulnerabilities to pandemics, are important elements of analysis and decision.

The disparity between public and private provision of critical healthcare infrastructure is clear. The concentration of ICU beds to assist private health plans is inversely proportional to the percentage of the population in this segment. This indicates clear demands for negotiations by public managers in states and municipalities in relation to the provision of facilities that today are exclusively geared towards serving private health plans across the country. Regarding the availability of ICU beds with the adoption of a more realistic current occupancy rate (70% on average for total ICU beds), most regions and municipalities would be in a critical situation.

It is important to note that the data and information by countries, or states, although they may help to visualize the macro scenario of the expansion of the disease and indicate times of action at more comprehensive levels, do not denote the local and regional characteristics and specificities. The results presented in this article indicate the absence of ICU beds in more than 2/3 of the municipalities of MMP and RMVPLN, in addition to the concentration in regional hubs, for which the migration of critical cases of COVID-19 hospitalization should be considered. For these, it is necessary to analyze the need for rapid expansion of healthcare infrastructure to attend the critical situations and the maintenance of containment measures, which have helped the slower spread of the disease. Additionally, for future resilience, it's essential to address the inequalities in terms of the healthcare infrastructure available for public and private access.

Based on the simulations, RMVPLN's health systems would not be able to meet the demand of patients in a scenario without containment measures. It should be noted that this scenario has already been overcome, in large measure by the relative effectiveness of the horizontal isolation adopted at the state level, which has ensured that the disease reproduction rate (R0) remains at a level close to 1.16 (in this case, considering the existing underreporting rate).

It was also possible to conclude that, in order to avoid the health systems collapse, the containment measures should be able to reduce the reproduction rate (R0) to the range of 0.9 to 1.0 in the RMVPLN. To achieve this, it is essential to reinforce, or improve, the containment measures and the control of the remaining cases.

This control can be carried out through the large-scale use of tests for COVID-19, as well as the monitoring and isolation of infected people. To ensure the effectiveness of this monitoring so that the health system is not depleted, measures of social distance must be maintained and or improved, in addition to periodically evaluated according to

the number of real cases tested. Still, it is recommended to maintain hygiene practices for biosafety, acquired during the isolation period, until the pandemic is completely contained.

This article addressed some local and regional aspects associated with the critical health infrastructure for coping with COVID-19. Without detriment to other issues, elements associated with social vulnerabilities, effectiveness of measures and containment actions, availability and technical quality of human resources in the health area, availability of personal protective equipment for health agents, among others, are also important for more assertive decision-making at the local/regional level.

Acknowledgments

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COVID-19: desigualdades locais/regionais e impactos sobre a infraestrutura crítica de saúde no Brasil

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Resumo: Este artigo aborda questões de desigualdades locais/regionais sobre infraestrutura crítica de saúde para lidar com o COVID-19, com base em análise geoespacial e modelagem compartimental (SEIR). Os locais de estudo foram a Macrometrópole Paulista (MMP) e a Região Metropolitana do Vale do Paraíba/Litoral Norte de SP (RMVPLN). Os resultados indicaram a ausência de leitos de UTI em mais de 2/3 dos municípios, além da concentração em polos regionais, para os quais deve ser considerada a migração de casos COVID-19 de municípios vizinhos. A análise com o modelo SEIR, realizada para cenários com e sem isolamento social, mostrou que o isolamento adotado nas regiões foi capaz de adiar o colapso da infraestrutura de saúde, reduzindo a taxa de reprodução da doença. As simulações indicaram uma taxa de reprodução de 0,95 para evitar o colapso da infraestrutura de saúde por RMVPLN no período analisado. Além disso, para resiliência futura, é essencial abordar as desigualdades em termos de infraestrutura de saúde disponível para acesso público e privado.

Palavras-chave: COVID-19, aspectos locais/regionais, Brasil, infraestrutura de saúde

COVID-19: desigualdades locales/ regionales e impactos sobre la infraestrutura crítica de salud en Brasil

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Resumen: Este artículo aborda desigualdades locales/regionales sobre infraestructura crítica de salud para hacer frente al COVID-19, basado en análisis geoespacial y modelagem compartimental (SEIR). Los sitios de estudio fueron la Macro Metrópolis de São Paulo (MMP) y la Región Metropolitana de Vale do Paraíba/Litoral Norte (RMVPLN). Los resultados indicaron la ausencia de camas de UCI en más de 2/3 de los municipios, además de la concentración en los centros regionales, para lo cual se debe considerar la migración de los casos de COVID-19 de los municipios vecinos. El análisis con el modelo SEIR, realizado para escenarios con y sin aislamiento social, mostró que el aislamiento adoptado en las regiones fue capaz de posponer el colapso de la infraestructura de salud, reduciendo la tasa de reproducción de la enfermedad. Las simulaciones indicaron una tasa de reproducción de 0,95 para evitar el colapso de la infraestructura de salud para RMVPLN en el período analizado. Además, para la resiliencia futura, es esencial abordar las desigualdades en términos de infraestructura de salud disponible para el acceso público y privado.

Palabras clave: COVID-19, aspectos regionales, Brasil, infraestructura de salud.