Protecting Public Health and Preserving the Financial Viability of North Carolina's Critical Health Care Facilities during Infectious Disease Outbreaks

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Abstract

Hospitals represent a critical line of defense for reducing the impacts of COVID-19, which has killed more than 480,000 Americans as of February 14th, 2020. While hospitals' primary emphasis will always be on ensuring sufficient health-related resource capacity to serve COVID-19 patients (e.g., ICU beds, ventilators), the impacts of the pandemic on the financial viability of hospitals has also become a critical concern. In an effort to ensure adequate hospital capacity to handle a potential surge of COVID-19 patients in April and May 2020, many hospitals reduced or cancelled elective and non-emergency inpatient surgical procedures which account for a significant portion of their revenues. While this was a sensible precautionary measure during a time when much about COVID-19 was unknown, social measures (e.g., social distancing, masks) reduced the severity of the predicted surge such that a significant fraction of the capacity made available by these cancellations went unused, with devastating financial impacts. In April, the North Carolina Hospital Association estimated that hospitals across North Carolina *were losing over $1 Billion per* month due to reduced revenues, largely attributed to the reduction in elective surgeries. A more carefully calibrated determination of when and how much capacity should be made available during COVID-19 (or similar infectious disease) outbreaks is needed. This work involves an analysis of data collected over the period March 2020-Janaury 2021 that reveals connections and tradeoffs across increases in COVID-19 hospital admissions, reductions in elective procedures, hospital capacity and hospital revenues for the Research Triangle hospital system. These suggest that the halt to elective and non-emergency inpatient procedures in March-May 2020, combined with a reduction in emergency room procedures (which were not restricted) led to a reduction in daily hospital system revenues of as much as 40% relative to expectations, and a cumulative loss of 4.7% of annual gross revenues for inpatient procedures, which translates to annual losses on the order of $600 million. Over the entire period March 2020 through January 2021, the total system losses due to reduced inpatient procedures assumed to be related to the pandemic were on the order of 6.5% of gross revenues from inpatient procedures, or about $835 million. Following the analysis of observed data, a simulation model that couples COVID-19 community transmission with patient flow dynamics and billing records within the Research Triangle system was developed. The model links community transmission, COVID-19 and non-COVID-19 hospital admissions, and actions to cancel elective and non-emergency procedures to resource utilization (e.g., ICU beds, ventilators) and revenues within the hospital system, enabling an analysis of the financial and healthcare tradeoffs, as well as how changes in hospital decisions and societal policies intended to reduce community transmission (e.g., mask mandates, social distancing measures) can affect these outcomes. Simulation results suggest that the Research Triangle hospital system alone could lose over $1 billion in gross revenue during the period March 2020 – May 2021. Estimated revenue losses are, however, very sensitive to the effective reproductive rate (R_e) through the February-May 2021 period. If the effective reproductive rate during this period return to the higher levels observed regionally in November – December 2020, the system may again cancel elective and non-

emergency procedures to maintain sufficient ICU capacity for a surge of new COVID-19 patients, which would translate into an estimated $235 million in additional revenue losses during the February – May 2021 period. However, a decision not to cancel these procedures could result in overloaded ICU facilities and critically-ill patients receiving sub-standard care. Societally imposed measures that reduce community transmission in the spring of 2021 to something significantly below that observed in November-December 2020 could reduce COVID-19 hospital admissions sufficiently to enable current ICU capacity in the system to accommodate all of the severely ill patients without cancelling elective and non-emergency procedures and limit revenue losses in the February – May 2021 period to $80 million (a savings of $155 million compared to the high transmission scenario), mostly due to ongoing reductions in emergency department visits. How this savings compares to the regional economic losses associated with the imposition of societal measures to reduce community transmission has not been explored. Overall, this study finds that societal measures to reduce community transmission have a much larger impact on available healthcare capacity and hospital system financial losses than hospital-level decisions (i.e. cancelling procedures). This study illustrates tradeoffs between hospital capacity, quality of care, and financial risk faced by health care facilities throughout the U.S. as a result of COVID-19, providing potential insights for hospitals seeking to navigate these uncertain scenarios.

Introduction

Severe Acute Respiratory Syndrome Coronavirus-2 (SARS-CoV-2) first emerged in China in December 2019. Dozens of documented cases of COVID-19, the disease caused by SARS-CoV-2, occurred in the United States by late February 2020 (Fauci et al., 2020) and quickly spread to all 50 U.S. states as well as 186 countries around the world (Dong et al., 2020). The novel nature of the virus, along with the current state of largely uncontrolled community spread in many parts of the US, suggests that large portions of the population remain susceptible and further outbreaks have the potential to pose significant risks to health systems throughout the country. Hospitals represent a critical line of defense for reducing the impacts of COVID-19, which has killed more than 480,000 Americans as of February 14th, 2020 (Dong et al. 2020). While the primary emphasis has been on ensuring sufficient health-related resource capacity (e.g., ICU beds, ventilators) to manage new cases, the impacts of the pandemic on the financial viability of hospitals and other primary care facilities has also become critical.

As the number of COVID-19 cases surged in the spring of 2020, hospitals had to make operational decisions that sought to ensure enough available capacity to accommodate a potentially rapid influx of COVID-19 patients. One approach to doing this was reducing or eliminating elective and/or non-emergency procedures, including many orthopedic procedures, all plastic surgeries, some vascular surgeries, and others (American College of Surgeons, 2020). The North Carolina Department of Health and Human Services (NCDHHS) decided to undertake the approach and shut down these types of procedures in all North Carolina hospitals from March 20th – May 1st, 2020 (Cohen, 2020). This was a cautious and sensible decision in an environment in which data were scarce and much about the virus and how it spread were unknown. Nonetheless, in states like North Carolina stay-at-home restrictions and other social distancing measures were reducing community spread of SARS-CoV-2 relative to expected levels, leading to much of the hospital capacity freed up by cancelling procedures going unused and creating substantial financial shortfalls. By April 2020, the North Carolina Hospital Association estimated that hospitals in North Carolina *were losing over $1 Billion per* month (NCHA, 2020) due to reduced revenues, and this was largely attributed to the elimination of elective surgeries. Although North Carolina hospitals and hospital systems later received $720 million in one-time payments through the CARES Act (CDC, 2020) many systems struggled to recover financially. Vidant Health, a rural health system serving 1.4 million residents in Eastern North Carolina, was forced to lay off 191 employees and saw its credit rating downgraded by Moody's in May, impacting approximately $300 million in bonds (Moody's, 2020). The financial impacts of the ongoing COVID-19 pandemic have the potential to exacerbate current trends in which falling revenues were already driving higher rates of hospital closures, particularly in rural areas (Balasubramanian and Jones, 2016; Topchik et al., 2020). This problem is not limited to North Carolina, as revenue losses caused by the suspension of elective and non-emergency procedures contributed to the loss of 1.4 million health care service jobs across the U.S. in April 2020 alone (BLS, 2020). The American Hospital Association estimates the aggregate pandemic-related financial losses by hospitals and health systems will be $320 billion in 2020, with 2/3 of those losses coming in the four-month period from March to June 2020 when concerns over hospital resources were most severe (AHA, 2020). While protecting public health will always be the priority, doing so in a manner that makes most efficient use of health care capacity will be critical in maintaining a financially stable health care system capable of managing the ongoing risks of COVID-19, as well as any similar infectious disease outbreaks in the future. This research is intended to assist hospitals by both developing a better understanding of the tradeoffs associated with the decisions made in the spring of 2020, and the potential advantages of formulating more carefully calibrated health care capacity management policies that protect public health while ensuring that the system remains financially sustainable.

Hospitals have a number of options available to help them manage critical hospital resources. Typically, utilization of critical resources like ICU capacity have scheduled and unscheduled flow variability. Admissions to the ICU can come from the emergency department, inpatient nursing units, other regional hospitals, as well as emergency and add-on surgery. These sources are variable and largely beyond the control of the hospital. Elective and non-emergency surgeries that require post-op admission to the ICU can be controlled by the hospital, and cancelling or rescheduling the procedures makes it possible to exercise some amount of control over the patient flow into the ICU (Kolker, 2008). In addition to pre-emptively cancelling elective and non-emergency procedures, other actions include creating additional surge capacity (Einav et al., 2014; Watson et al., 2013), and making stricter standards for admission to the hospital or other critical care triage methods that limit access to resources (e.g., beds, ventilators, medications) (Maves et al., 2020). These options represent decisions that can be made within a hospital to control patient flow (Armony et al., 2015). Following the framework in Villa et al. (2014), patient flows are defined along three interrelated dimensions: (i) the hospital system, (ii) patient pipelines, and (iii) production units. The hospital system itself can be a single hospital or a regional collection of facilities, which maintain a specified capacity of relevant resources such as beds, staff, and equipment. The hospital system is characterized by metrics such as hospital census levels (i.e., overall patient population) that can be managed to a certain extent by reducing elective or non-emergency procedures. Patient pipelines describe the rate at which different types of patients move through the hospital, from admission to discharge. Pipeline flows are characterized by metrics such as admission rates and length-of-stay, and these flows can be altered by tightening admission standards or via other triage methods designed to keep capacity available for the sickest or most at-risk patients. Finally, production units refer to the specific resources, like ICU beds or ventilators, used as patients move through their respective pipelines in the hospital. Each production unit can be measured with a utilization rate and in some cases can be augmented by opening areas not typically used for acute patient care to create surge capacity. A hospital expecting, or experiencing, a large influx of new COVID-19 patients must make decisions that change patient flow to ensure that hospital resources are available to the by patients who need it most.

Any decision related to managing and/or reducing patient flows gives rise to concerns over potential negative impacts, including reduced quality of care (Asplin et al., 2006), but there are often financial impacts as well (AHA, 2020), and informed decision-making requires an understanding of these tradeoffs. This work involves the development of a simulation model that links all hospital admissions (COVID-19 patients, all scheduled procedures (elective and otherwise), and admissions from the emergency department), ICU capacity utilization, and revenues for the Research Triangle regional hospital system in North Carolina. The simulation model enables the exploration of tradeoffs that this system faces as it seeks to meet multiple objectives during a COVID-19 outbreak, including maintaining access to critical health care capacity for the sickest patients (e.g., ICU beds, ventilators), maintaining access to health care for other (non-COVID-19) patients, and ensuring an acceptable level of system-wide financial stability. This involves first analyzing observed data from the period March 2020 – February 2021 to understand the dynamic interplay of the various factors, then using this information to model multiple hypothetical scenarios with different hospital decisions and varying levels of COVID-19 community transmission (i.e., indicative of varying levels of societal commitment to mask wearing and social distancing, etc.). Although these data and modeling results focus on a particular hospital system, the tradeoffs between hospital capacity, quality of care, and financial risk faced by health care facilities throughout the U.S. during the COVID-19 pandemic means that the insights gleaned from this research should be useful to many hospitals seeking to navigate these uncertain scenarios.

Observed Data from March 2020 through February 2021

The Research Triangle hospital system experienced two periods of rising COVID-19 admissions over the past year, the first in June-July of 2020 and another, period beginning in November 2020 and continuing through the end of this study in February 2021 (Figure 1). Both periods seen scheduled (non-COVID-19 related) procedures decline, including elective and non-emergency procedures, with the reduction in March-May 2020 driven by state government mandates while the current reductions seem to be driven by a general reluctance to seek out hospital services for elective and non-emergency procedures when COVID-19 hospitalizations are elevated. The substantial decline in (non-COVID-19) emergency department admissions during both of these periods was unexpected and suggests that many individuals that might have otherwise come to the emergency room for non-COVID-19 related ailments elected not to do so during the pandemic. The overall decline in admissions from March 2020 – January 2021 resulted in hospital revenue losses equivalent to 6.5% of annual inpatient revenue. In 2019, the Research Triangle hospital system (Table 1) generated a combined $25.3 billion in gross revenue (American Hospital Directory, 2020). Gross hospital revenue refers to the charges billed by the hospital, before contractual adjustments. All revenue discussed in this manuscript refers to hospital gross inpatient revenue, as estimated based on the weighted MS-DRG codes of admitted patients used in the Medicaid prospective payment system (see 'Modelling Methods to Generate Synthetic Results' for a more detailed description of MS-DRG codes). Assuming that 51% of hospital revenue is generated by inpatient services (AHA, 2019), this translates to $835 million in lost revenues for the Research Triangle hospital system.

The November 2020- February 2021 surge of COVID-19 patients has been bigger than the wave in spring 2020, yet the financial impact to hospitals has been more limited. From March 20th – May 1st, all hospitals in North Carolina were mandated to cancel all elective and non-emergency surgeries, leading to large amounts of unused capacity throughout the hospital system and reductions in estimated hospital system revenue that peaked with daily losses that were over 30% relative to expected revenue. In North Carolina, the cancellation mandates were lifted before hospitals saw significant numbers of COVID-19 patients, and much of this unused capacity was left unfilled by a spring COVID-19 surge that did not materialize in North Carolina. By the time cases began to rise in June, the scheduled inpatient admissions in the region had returned to normal and emergency department admissions had recovered about half of their spring level. And, while hospital decisions to cancel elective and non-emergency procedures contributed to a significant decline in hospital admissions, the reduction in admissions through the emergency department was as large or larger. Although discerning a reason for the decrease in emergency department visits is beyond the scope of this study, the reduction is consistent with data from other parts of the United States (Jeffery et al., 2020). Interestingly, observations from other regions also reinforced the finding that in the first months of the pandemic, reductions in emergency department visits may have been more of a response to national media reporting than specific changes to local or regional risks. During the second wave in the fall/winter of 2020-21, reductions in emergency department visits were more closely tied to local increases in COVID-19 hospital admissions. As COVID-19 admissions remained high through the late summer and early fall of 2020, revenue from new COVID-19 patients made up for most of the lost revenue from reduced emergency department admissions, and region-wide revenue returned to roughly expected levels.

As COVID-19 cases increased as the fall progressed, non-COVID-19 admissions for both scheduled inpatient procedures and emergency department admissions dropped, leading to a slight reduction in hospital revenues. The reduction in scheduled procedures observed during the fall/winter of 2020-21 does not appear to be the result of hospital policies similar to the cancellation of elective and non-emergency procedures in the spring. Instead, this also appears to be a patient-led effort to avoid using the healthcare system. As a result, the total reduction in admissions during the fall/winter wave was smaller than the reductions in admitted patients during the spring. Additionally, scheduled inpatient procedures made up a smaller share of the reduced admissions in the fall 2020 COVID-19 surge. These procedures, compared to admissions from the emergency department, generate higher revenues for the hospital. When elective and non-emergency surgeries are cancelled to make more hospital capacity available, they have a larger impact on hospital finances. At the same time, the reduction in non-COVID-19 admissions during the fall/winter of 2020/21 happened concurrently with an increase in COVID-19 patients, and the additional revenue from COVID-19 patients partially mitigated the revenue losses from reduced non-COVID-19 admissions.

When COVID-19 patients are admitted to a hospital they consume hospital resources (e.g., beds, oxygen, ICU beds, ventilators) for varying amounts of time. Patient flow data obtained from the University of North Carolina Hospital system and the Mt. Sinai Hospital system describe the timing of resource utilization for individual patients. The University of North Carolina hospital system is a subset of the larger Research Triangle hospital system for which we have patient-level flow data. For a given resource, patient flow data enables us to quantify the probability that a patient will be using that resource as a function of the time after the patient was admitted. Figure 2 shows the probabilities generated in the Mt. Sinai system during the New York City outbreak from March 1st – May 1st. Notably, the probability distributions for some resources shift considerably as the outbreak becomes more severe. As the number of beds occupied by COVID-19 patients increases, fewer COVID-19 patients use room air, more patients require low- and high-flow oxygen, and there are higher probabilities of patients remaining on CPAP/BiPAP machines and ventilators for longer durations, all of which indicates that the admitted COVID-19 patients are becoming increasingly ill as the surge progresses. It is not clear from the data what drives this more severe illnesses observed in patients who are admitted during the peak of the surge in COVID-19 admissions, but it could be attributable to admission triage (i.e., turning healthier patients away before they can be admitted to the hospital) or self-selection (healthier patients being discouraged by overcrowding or longer wait times). By applying the resource utilization probabilities to COVID-19 hospitalization timeseries, estimates of the total population using each resource can be generated at each time step. Estimates of the ICU population made from applying resource utilization probabilities to observed COVID-19 hospitalizations in the Research Triangle hospital system can be compared against reported COVID-19 ICU populations from NCDHHS data. Figure 1 shows agreement between the ICU estimates and observations from June 2020 – January 2021 (NCDHHS data on COVID-19 ICU populations begins in June 2020).

Modelling Methods to Generate Simulated Results

This study develops a pandemic hospital capacity utilization model consisting of three parts, (i) a mathematical epidemiological model used to simulate infection spread of new COVID-19 cases in the community and how these relate to admissions in nine hospitals in the Research Triangle region of North Carolina, (ii) a probabilistic patient-flow model that dynamically links COVID-19 admissions with utilization of scarce hospital resources, including ICU beds, and (iii) a statistical model linking changes in non-COVID-19 patient admissions to changes in hospital revenues and non-COVID-19 ICU populations. The model components address tradeoffs between capacity utilization and revenue losses faced by hospitals during a pandemic. Simulations build upon previous efforts to track hospital ICU capacity over time through process simulation (Alban et al., 2020) by quantifying the concurrent reductions in non-COVID-19 emergency department and scheduled inpatient admissions observed during periods of increased COVID-19 hospitalizations. As COVID-19 transmission grows within a community, hospitals can adjust their admission requirements for non-COVID-19 patients to accommodate an influx of patients, particularly as it relates to maintaining ICU capacity as hospitals often operate near peak ICU capacity under normal conditions (Opgenorth et al., 2018).

Data on ICU capacity utilization and COVID-19 admissions at nine Research Triangle hospitals (Table 1) was obtained from the North Carolina Department of Health and Human Services. Length-of-stay and resource utilization (e.g., ICU beds, ventilators, non-ventilator oxygen augmentation equipment) probability distributions for COVID-19 patients are derived from patient-level data from the University of North Carolina Hospital System and Mt. Sinai (New York) Hospital Systems, enabling the estimation of the progression of positive COVID-19 hospital admission data and the proportion of hospitalizations needing additional resources such as the ICU. Patient-level data on overall admissions trends were obtained from the UNC Hospital System covering the period January 2018 – January 2021.

Quantifying the financial impacts of changing hospital admissions patterns and the number/types of procedures it is performing is not as straightforward as it might seem, largely due to the complexity of hospital billing codes and procedures (Gottlober et al., 2001). For example, changes to the composition of hospital admissions can impact hospital revenues based on the 'complexity' weights (MS-DRG codes) assigned to each patient within the prospective payment system used to determine hospital Medicaid reimbursement rates. Some adjustments are made to the MS-DRG payments to account for other factors affecting the hospital cost of services (e.g., wage index, low income patient share), but these adjustments result in hospital revenues that scale linearly with weighted MS-DRG values. In this work, individual

MS-DRG codes from patient-level admissions obtained from the UNC Hospital system can be used as a proxy for regional hospital gross revenues. Revenue losses associated with the COVID-19 pandemic are estimated by comparing cumulative weighted MS-DRG values from March 2020 – January 2021 from seasonal trends across 2018 and 2019. The pandemic hospital capacity utilization model is used here to simulate financial risk for the regional system of nine Research Triangle hospitals under a number of different COVID-19 community transmission scenarios developed from data reflecting the most recent COVID-19 outbreak in the region. Observed data during the period March 2020 – January 2021 enables patients to be tracked as they are admitted to the hospital, utilize hospital resources (ICU, Ventilators), and are subsequently discharged (Figure 3). However, simulating patient flows in future periods can help to quantify the risks of patient demand for some resources (e.g, ICU) exceeding capacity and/or the financial impact of admissions triage and/or cancelling elective and non-emergency procedures. These simulations can be conducted under alterative transmission scenarios to estimate the sensitivity of hospital operations to infection dynamics within the community.

Transmission Model

Community transmission is estimated using a compartmental model to describe the epidemiological transmission dynamics within the different population groups. The model has four (4) compartments, (i) the susceptible population, those who remain vulnerable to infection, (ii) the exposed population, those who have been exposed to the infection but are not yet infectious, (iii) the infectious population, those who are transmitting the virus, and (iv) the hospitalized population, those who are infected and have been admitted to the hospital. In this work we calibrated the model for the Research Triangle hospital system using observed data on total system hospitalizations from June 2020 – January 2021. The total infectious population is estimated assuming a hospitalization rate of 2.0% of all infections (Angulo et al., 2021) and an average infectious period of 9 days (Byrne et al., 2020; Park et al., 2020), such that:

$$I_t = \frac{p_i}{r_h} * \sum_{d=t}^{t+6} \frac{H_d}{7} \quad (1)$$

where I = infected population (people), H = daily new hospitalizations (people/day) ; r_h = hospitalization rate of infections, p_i = period of infectiousness (days); and t = timestep (days)

Daily change in infections are then used to estimate the exposed population, assuming an average period of latency period (days from exposure to when one can infect others) of 3 days (He et al., 2020), such that:

$$E_t = p_e * \left(\frac{I_t - I_{t-1}}{t-(t-1)} + \frac{I_t}{p_i}\right) \quad (2)$$

where E = exposed population (people), and p_e = period of non-infectious exposure (days)

Daily changes in exposed population are subsequently used to estimate the change in the regional population that remains susceptible to infection, such that:

$$S_t = S_{t-1} - \left(\frac{E_t - E_{t-1}}{t-(t-1)} + \frac{E_t}{p_e}\right) \tag{3}$$

where S = susceptible population (people)

Finally, the effective reproductive rate (R_e), the average number of secondary infections resulting from one person in the infectious population, is a function of the newly exposed population, the total infected population, and the percent of the population remaining susceptible to infection. The effective reproductive rate is calculated assuming a regional population for the Research Triangle of 1.58 million people, such that:

$$Re_t = \frac{\left(E_t - E_{t-1} + \frac{E_t}{p_e}\right)}{I_t/p_i} * \frac{N}{S_t} \tag{4}$$

where Re = effective reproductive rate and N = total regional population

When applied to hospitalization data from March, 2020 – January 2021, aggregated across 11 hospitals in the Research Triangle region of North Carolina, this results in the susceptible population declining 20.1%, from 1.58 million to 1.25 million. For much of November and December, the regional reproductive rate varied between 1.2 and 1.6, resulting in rapid increases in daily hospital admissions of COVID-19 patients (Figure 4). As a point of comparison, estimates of the effective reproductive rate exceeded 3.0 in Wuhan, Milan, and New York City (Arroyo-Marioli et al., 2021) before the implementation of any non-pharmaceutical interventions (e.g., social distancing, mask-wearing) in those cities. By mid-January, the reproductive rate in the Research Triangle dropped below one to 0.8, meaning the prevalence of the disease was declining along with hospital admissions. Simulated community transmission scenarios extend the timeseries of reproductive rate through May 2021 to simulate regional hospitalizations in the near future. Scenarios are developed under two conditions, one in which the reproductive rate remains at an average of 0.8, non-pharmaceutical policies stay in place, and daily COVID-19 hospitalizations continue to decline, and another in which the effective reproductive rate returns to a level of 1.4 through the month of February 2021 before falling back to 0.8 in March. New regional COVID-19 hospitalizations are calculated based on the reproductive rate by rearranging equation (4) and substituting equation (2), such that:

$$I_t = \frac{\frac{N*p_i}{S_t*Ro_t}*(I_{t-1}*(p_e+1)+E_{t-1})}{\left(\left(1+\frac{1}{p_i}\right)*\frac{(p_e+1)}{Ro_t/p_i}*\frac{N}{S_t}-1\right)} \tag{5}$$

and

$$H_d = 7 * \left(I_t * \frac{r_h}{p_i} - \sum_{d=t}^{t+5} \frac{H_d}{7}\right) \quad (6)$$

Probabilistic COVID-19 Patient Flow

A retrospective cohort study of hospitalized adults with COVID-19 in the University of North Carolina and Mt. Sinai hospital systems was used to determine the timing and duration of resource administration for individual patients using logic developed in Wang et al. (2020). COVID-19 patients are divided chronologically into 200-member cohorts and resource utilization probability distributions are developed for resources, including (a) room-air bed, (b) low-flow oxygen, (c) high-flow oxygen, (d) CPAP-BiPAP machines, and (e) mechanical ventilation in each cohort. Among these five types of oxygen augmentations, room air, low-flow oxygen, and high-flow oxygen are assumed to be used in a normal hospital bed, while CPAP, BiPAP, and mechanical ventilation are assumed to occur in ICU beds. Although not all members of every 200-person cohort enters the hospital on the same day, resource utilization probability distribution can be expressed with respect to the number of days since admission. Patients are tracked via the number of days since their admission, and the probability of using an oxygen resource on a given day is equal to the percentage of the cohort using that resource after they have been admitted for the given number of days, such that:

$$O_{r,c,t} = \frac{RU_{r,c,t}}{CS} \quad (7)$$

where O = probability of cohort c using oxygen resource r at time t, RU = number of members of cohort c using resource r at time t, CS = initial cohort size; r = oxygen resource; c = cohort index

To simulate expected resource utilization based on regional hospitalization scenarios, the probability distributions from a single cohort are applied to every COVID-19 patient admitted to the hospital on a given day. Starting from the admission day t_a, the contribution of that day's hospitalizations to the total resource utilization on future day t_f is determined by the resource probability distribution at day $t_f - t_a$. Resource utilization at time t_f continues to accumulate based on the contribution of patients admitted at all days $t_a < t_f$ such that:

$$RU^*_{r,t_f} = \sum_{t=0}^{t_f} TP_{r,c_t,t_f-t} * H_t \quad (8)$$

where RU^* = synthetic resource utilization estimate (people), t_f = day of resource utilization; and c_t = the cohort probability distribution assigned to day t of the synthetic regional *hospitalization* timeseries

Each 200-person cohort contained in the UNC and Mt. Sinai patient-flow data contains its own resource utilization probability distribution. The ensemble of cohorts from the period March 1st to May 1st in the Mt. Sinai system and the period March 1st to November 1st in the UNC Hospital System are sampled (with replacement) and applied to each day of the hospitalization record to simulate the uncertainty in the expected resource utilization implied by COVID-19 hospitalizations.

Non-COVID-19 Patient Response to COVID-19 admissions

The response of non-COVID-19 patients to increasing COVID-19 admissions is developed from patient-level admission data obtained from the University of North Carolina Hospital System. Individual admissions can be classified and grouped by their admission type (scheduled inpatient, emergency department), as shown in Figure 1. Reductions in admissions and total weighted MS-DRG (adjusted for complexity, these values serve as proxies for revenue generated from a procedure) in the observed data occur after the suspension of elective and non-emergency procedures on March 20th, 2020. Both reduced admissions and total MS-DRG values for each patient subgroup can be estimated with a logistic function, such that:

$$MSDRG_{a,t} = MSDRG_a^o - \frac{MSDRG_a^o - MSDRG_a^{**}}{1+e^{-k_a(t-z_a)}} \quad (9)$$

where $MSDRG$ = total weighted MS-DRG of patient group a (-); a = scheduled inpatient, emergency department, $MSDRG^o$ = initial weighted group MS-DRG values before COVID-19-related reductions (-); $MSDRG^{**}$ = final weighted group MS-DRG values after COVID-19-related reductions are complete (-); k = model fit parameter to determine the rate of decline for patient group a (-), z = model fit parameters to determine the timing of decline for patient group a (-)

and:

$$ADMIT_{a,t} = ADMIT_a^o - \frac{ADMIT_a^o - ADMIT_a^{**}}{1+e^{-k_a(t-z_a)}} \quad (10)$$

where $ADMIT$ = total daily admissions of patient group a; a = scheduled inpatient, emergency department, $ADMIT^o$ = initial daily admissions before COVID-19-related reductions; $ADMIT^{**}$ = final daily admissions after COVID-19-related reductions are complete

The logistic function parameters are calibrated individually for each patient group by minimizing the sum of squared errors between logistic estimates and observed values for the period March 17 – May 1, 2020. Once appropriate parameters are estimated for each patient group type, the function can be scaled to estimate any size of reduction by changing the $MSDRG^o$ and $MSDRG^{I**}$ parameters. This calibrated logistic function can then be used to extend the observed record of non-COVID-19 patient admissions and weighted MS-DRG values to simulate a response to resource capacity limitations under different future transmission scenarios.

Simulations also consider the relationship between non-COVID-19 ICU populations and overall hospital admissions. Although ICU data is only available for April 2020 – January 2021, we can compare ICU populations during three different periods: (i) August-September 2020, when both scheduled and emergency department admissions were in line with historical averages, (ii) June – July 2020, when only emergency department admissions were reduced compared to historical averages, and (iii) April – May, when both emergency department and scheduled inpatient admissions were at reduced levels. The difference between period (i), the baseline period, and period (ii), when only emergency department admissions were reduced, can be used to calculate the ratio between reduced emergency department admissions and reduced ICU population, such that:

$$k_{ICU,ED} = \frac{\Sigma_{AUG-SEPT} POP_{ICU} - \Sigma_{JUNE-JULY} POP_{ICU}}{\Sigma_{AUG-SEPT} ADMIT_{ED} - \Sigma_{JUNE-JULY} ADMIT_{ED}} \quad (11)$$

where $k_{ICU,ED}$ = ratio of reduced ICU population-days to reduced admissions via the emergency room; POP_{ICU} = total daily population in the ICU; $ADMIT_{ED}$ = total daily admissions from the emergency department

Assuming this ratio of reduced emergency department admissions to reduced ICU population-days from June-July 2020 held in April-May 2020, we can estimate the reduction in ICU populations that occurs for every reduction in admission for scheduled inpatient procedures based on the additional reduction in ICU population during that period, beyond what would have been estimated from only the reduced emergency department admissions, such that:

$$k_{ICU,IP} = \frac{\Sigma_{APR-MAY} POP_{ICU} - \Sigma_{AUG-SEPT} POP_{ICU} - k_{ICU,ER} * \Sigma_{APR-MAY} ADMIT_{ER} - \Sigma_{AUG-SEPT} ADMIT_{ER}}{\Sigma_{APR-MAY} ADMIT_{IP} - \Sigma_{AUG-SEPT} ADMIT_{IP}} \quad (12)$$

By linking changes in patient flow (i.e., admissions) and appropriate weighted MS-DRG (i.e., revenue) values for these patients to changes in ICU populations, the pandemic hospital capacity utilization model can simulate the financial and physical responses to increasing ICU utilization by COVID-19 patients. As the available ICU capacity declines across the region, hospitals may be forced to cancel elective and non-emergency procedures to ensure there is enough ICU capacity to provide care to an increasing COVID-19 hospitalized population. This decision introduces a tradeoff between available capacity, quality-of-care, and financial losses. The simulations described here quantify those risks under different future community transmission scenarios that determine future COVID-19 admissions and ICU utilization. The observed data described in the 'Observations' section can be simulated forward using equations (1) – (12) to test the relative impact of hospital decisions and community actions to suppress transmission on these health care tradeoffs.

Results

Impact of hospital system decisions to reduce/eliminate elective and non-emergency procedures

Simulated transmission scenarios are used to extend the observed data from the end of the observed data (January 31, 2021) through May 2021 in order to evaluate risks to the Research Triangle hospital system. The first simulation considers a high transmission scenario in which the Research Triangle community relaxes social measures (e.g., social distancing, mask wearing) that contributed to effective reproductive rates falling from an average of 1.4 in early January to an average of 0.8 in late January. In other words, in this scenario the effective reproductive rate is set to 1.4 at the beginning of February, the same rate observed during the surge of new COVID infections and hospitalizations observed in November – December 2020. In this scenario, if hospitals were to take no action in response to increased COVID-19 admissions, patients requiring ICU treatment would exceed capacity by the end of February. In order to avoid this, we simulate the impact of cancelling elective and non-emergency procedures after available system ICU capacity falls below 30 beds (5% of capacity) in early February. This reduction in elective and non-emergency procedures avoids overloading ICU capacity, but has a financial impact, reducing daily revenues by as much as 10% and increasing the cumulative annual revenue losses from 5.5% to 8.3% (as compared to 2019).

According to the American Hospital Association 2019 Hospital Statistics report, inpatient revenues from scheduled and emergency procedures accounted for 51% of total hospital revenue (outpatient procedures account for much of the remaining 49%), and in aggregate, the Research Triangle hospital system generated over $25 billion in gross revenue in 2019 (American Hospital Directory, 2020). Conservatively assuming that no outpatient revenue streams have been affected by COVID-19 admissions, our results suggest that the Research Triangle hospital system will lose $710 million in revenue if no elective and non-emergency procedures are cancelled in February, and $1.07 billion if all such procedures were to be cancelled. If elective procedures are not canceled, ICU capacity would be exceeded in early March, (during which time, some very ill patients would not have access to the ICU), but much of the roughly $360 million in revenue losses ($1.07 billion - $710 million) would not occur. It should be noted that we assume a similar lag in non-COVID-19 admissions returning to their pre-pandemic levels as was observed in the spring/summer wave.

Impacts of reducing community-wide transmission via changes in societal behavior

While the scenario above demonstrates the potential impact of hospital-level decisions to ensure greater access to healthcare resources by cancelling elective and non-emergency procedures, societal-level decisions can perform a similar function. If a lower effective reproductive rate in the community can be achieved and sustained by societally-imposed measures such as social distancing and mask mandates, ICU capacity can be maintained at a sufficient level to treat critically ill patients while the hospital system's financial losses can be reduced or even avoided. In Figure 6, a scenario is described in which the average effective reproductive rate within the community remains at a relatively low level of 0.8 throughout the spring of 2021, similar to that which was observed in February 2021. This lower rate is assumed to have been largely achieved via social measures (e.g. social distancing, mask wearing) and resulted in the effective reproductive rate falling from an average of 1.4 in early January to 0.8 in late January. In this case, COVID-19 hospitalizations continue to fall from their current levels throughout spring 2021 and ICU populations do not reach a point where elective and non-emergency procedures need to be canceled. With no further lost revenues during the period February-May 2021, this low transmission scenario results in cumulative hospital losses over the period March 2020-May 2021 equal to 7.1% of total 2019 inpatient revenues, or $915 million (compared to 8.3% of annual revenue, or $1.07 billion, in the high transmission scenario). This represents a savings of approximately $155 million for Research Triangle system hospitals compared to a high transmission scenario in which social measures are relaxed. If these measures were to be relaxed, the assumption is that the effective reproductive rate would increase from 0.8 to 1.4 and require the cancellation of elective and non-emergency procedures to ensure sufficient ICU capacity for incoming COVID-19 patients, as depicted in Figure 5, as described earlier.

Discussion

The modeled simulations illustrate that the ability to cancel elective and non-emergency inpatient procedures is a potentially useful tool for helping hospitals avoid capacity constraints during a pandemic, but one that carries significant financial risk. The financial impact of cancelling procedures, however, can be somewhat mitigated by employing such action in a more carefully calibrated manner. When elective and non-emergency inpatient procedures were cancelled for all North Carolina hospitals in mid-March, the smaller than expected surge of COVID-19 patients led to unused hospital capacity and financial losses that peaked in April when revenues (as measured by total weighted MS-DRG values) from admitted patients were nearly 40% below the 2018-2019 baseline (Figure 1). If, instead, inpatient elective procedure cancellations were tied to ICU capacity triggers as in the simulations described here, we show (Figure 5) peak daily revenue falling 10% below the 2018-2019 baseline for a hypothetical surge of COVID-19 patients peaking in late February 2021. Overall, cancelling elective and non-emergency procedures in March 2020 resulted in roughly $600 million in losses of gross system revenue over a period of 3 months, while the hypothetical cancellations modeled for spring 2021 which were tied to ICU capacity triggers resulted in only $155 million in additional revenue losses (although these losses were partially mitigated by the influx of new COVID-19 patients admitted to the hospital system as well).

One key uncertainty that emerged from these simulations was the progression and duration of the COVID-19 outbreak within the community. In late January 2021, the reproductive rate as calculated from hospital admissions in equation (4) dropped from 1.4 to 0.8. If we assume that this rate remains below 1 for the remainder of winter/spring 2021, no changes in hospital admission policy are needed to keep from overloading system-wide ICU capacity (Figure 6). However, if the reproductive rate for the month of February were to increase for 0.8 to 1.4 (the level observed in November-December 2020), hospital admission triage procedures would likely be required to avoid an exceedance of system-wide ICU capacity, and this would likely result in some very ill patients being denied access to ICU services. This narrow window of roughly one month in which to make a decision suggests that the threshold used to trigger the cancellation of elective and non-emergency procedures could be very important. In this simulation, we use a simple trigger, in which elective and non-emergency procedures are cancelled when the total (COVID-19 plus non-COVID-19) ICU population reaches 95% of system-wide ICU capacity. This trigger is evaluated against two potential transmission scenarios (where February R_e is equal to 1.4 and 0.8), but more complex thresholds based on infectious disease forecasting models could be used to develop triggers that are robust to a wider range of potential scenarios. In particular, COVID-19 testing results data could be used to determine how the effective reproductive rate is changing. Testing data could provide an earlier indicator of changes to COVID-19 effective reproductive rate relative to the changes in hospital admissions (which is used in these simulations), because individuals typically test positive for COVID-19 before they are admitted to the hospital. Individual-level testing may be suitable for this purpose, but monitoring community wastewater for SARS-CoV-2 may also provide valuable information (Hart and Halden, 2020), and has two important benefits compared to monitoring data from individual tests. First, wastewater testing may show changes in overall community infections earlier than individual testing because it does not require individuals to seek out testing before they can be sampled. Second, wastewater samples are more representative of the entire community, and consistent in the terms of the group being sampled through time, relative to individual-level testing, which may be biased by certain subgroups (e.g., healthcare workers) being tested more frequently or by the availability of testing changing over time.

An attempt was made in this work to use recently collected data on the concentrations of SARS-CoV-2 found in wastewater within communities served by those hospitals and communities modeled in this work. Unfortunately, the timing and frequency of wastewater sampling, usually weekly, was not sufficient to allow for the development of a predictive model that would link wastewater concentrations of SARS-CoV-2 and hospital admissions of COVID-19 patients. Nonetheless, in future work we would like to use wastewater testing data at a number of sites throughout the Research Triangle region to develop a predictive ability with respect to hospital admissions and refine thresholds for hospital decisions involving the cancellation of elective and non-emergency procedures in advance of a surge of COVID-19 related hospital admissions.

Conclusions

During an infectious disease outbreak such as COVID-19 that threatens to overwhelm hospital resources, hospitals are faced with making decisions that ensure sufficient capacity to handle admission of a surge of newly sick patients, decisions that also have substantial financial consequences. There currently appear to be two primary tools available to manage this tradeoff, (i) hospitals can cancel elective and non-emergency procedures, freeing up capacity for COVID-19 patients, while reducing care for non-COVID patients and incurring significant financial losses, or (ii) society, in the form of state and local governments, can institute measures (e.g. mask mandates, social distancing) that lead to reduced transmission of infections, limiting the number of people that need to be admitted to the hospital, ensuring available capacity for both COVID and non-COVID patients and reducing revenue losses for hospitals.

Data collected over the period March 2020 – January 2021 suggests that reduced admissions due to cancelled elective and non-emergency procedures and reduced emergency department visits cost hospitals in the Research Triangle system an estimated 5.5% of their annual revenue from inpatient procedures, or $710 million. Simulations from March 2020 through May 2021 suggest that the impact of hospital-level decisions are largely dependent on disease transmission levels within the community. Changing community transmission is mostly beyond the control of the healthcare system, and is dependent on societal-level choices. In a high transmission scenario (effective reproductive rate of 1.4), the losses to Research Triangle hospitals could exceed $1 billion, as the cancellation of elective and non-emergency procedures would need to be enforced to avoid overloading the ICU capacity in the system. If, instead, the effective reproductive rate were lowered to a level of 0.8 in a low-transmission scenario (e.g. by tight enforcement of mask mandates and social distancing), the revenue losses could be limited to $915 million, a savings of nearly $155 million compared to the high transmission case. It should be noted, however, that this analysis did not estimate the broader societal losses stemming from the reduced economic activity associated with many societal measures to reduce disease transmission.

The simulations described here illustrate the connections between community transmission and the decisions facing hospitals during a pandemic. Although these results focus on a particular hospital system, the tradeoffs between hospital capacity, quality of care, and financial risk faced by health care facilities throughout the U.S. as a result of COVID-19 means that they may provide insights for many hospitals seeking to navigate these uncertain scenarios through adaptive decision-making.

Figures and Tables

Table 1*: Hospitals in the Research Triangle regional hospital system*

Hospital Name	Bed Capacity	ICU Capacity	Ventilator Capacity	2019 Total Revenue ($MM)
UNC Rex Hospital	491	181	134	3,096
UNC Medical Center	818	135	295	5,359
UNC Chatham Hospital	25	4	6	N/A
Duke Raleigh Hospital	182	15	25	1,947
Duke Regional Hospital	256	22	36	1,310
Duke University Hospital	850	109	130	8,245
Wake Medical Center	588	76	123	3,836
Wake Medical Center - Cary	178	12	17	1,119
Central Carolina Hospital	53	8	6	443

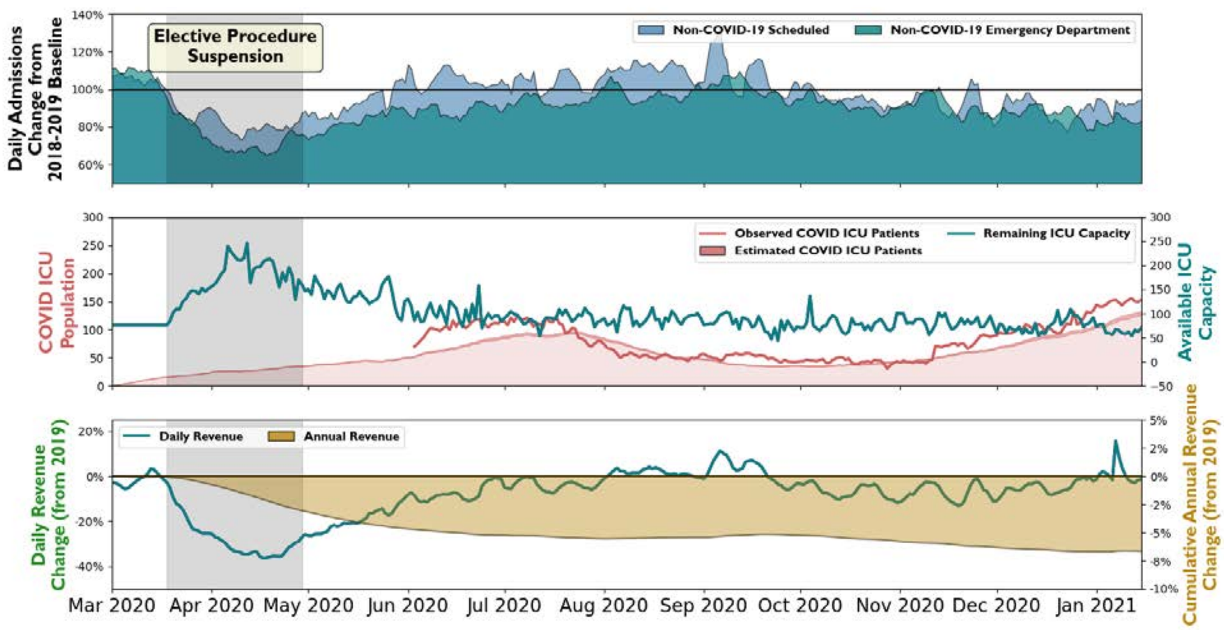

Figure 1: Observed data including new hospital admissions, ICU capacity and COVID-19 population, and lost revenues for nine hospitals in the Research Triangle during the period March 2020 – January 2021.

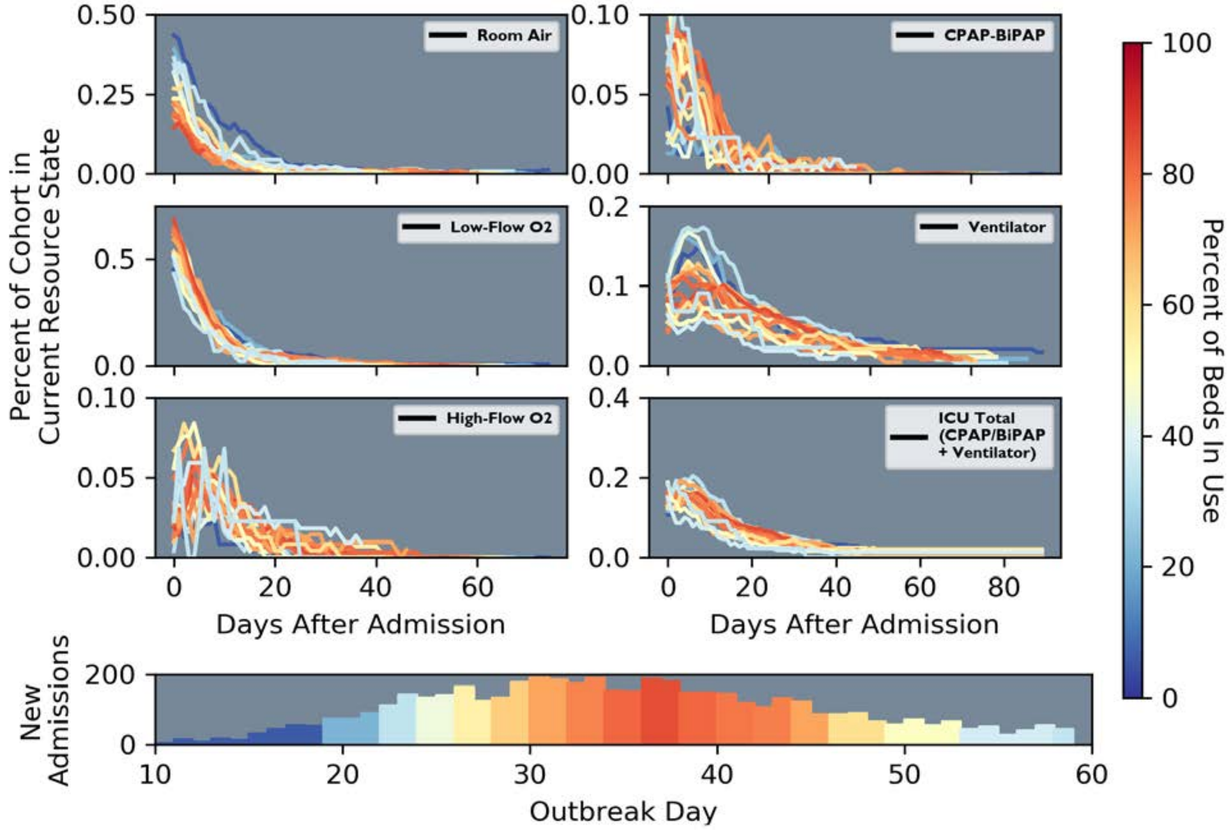

Figure 2: Cohort level probability distributions for resource use through time, Mt. Sinai hospital system (March – May, 2020). Line color shows the percentage of all regional hospital beds occupied by COVID-19 patients at the time of cohort admission.

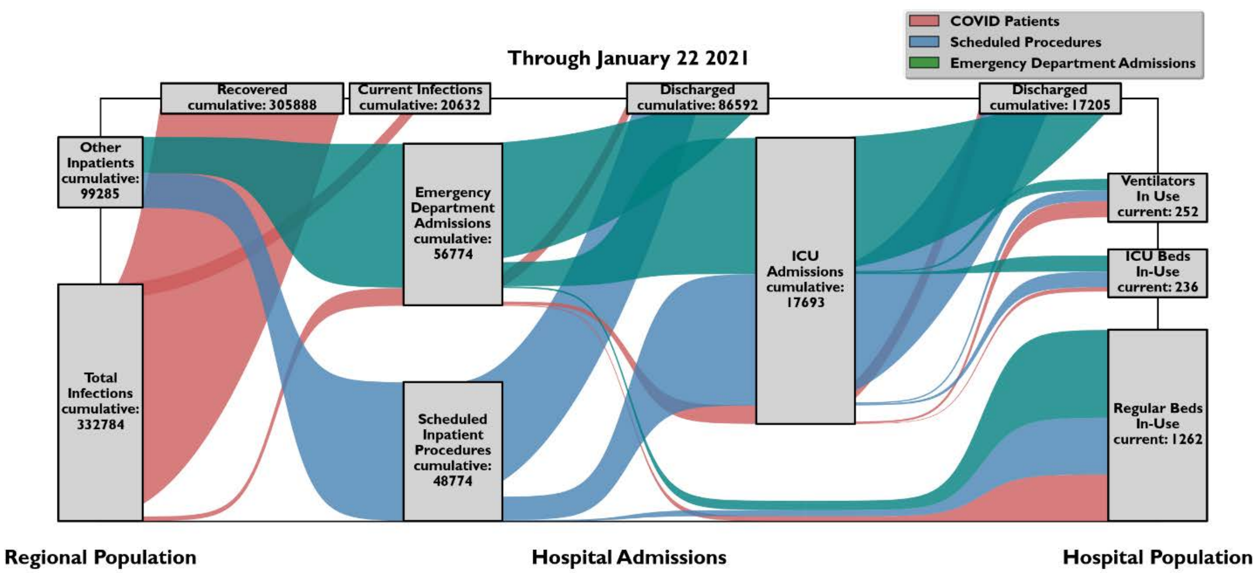

Figure 3: Patient flows between the community and the Research Triangle hospital system, including ICU and ventilator resources.

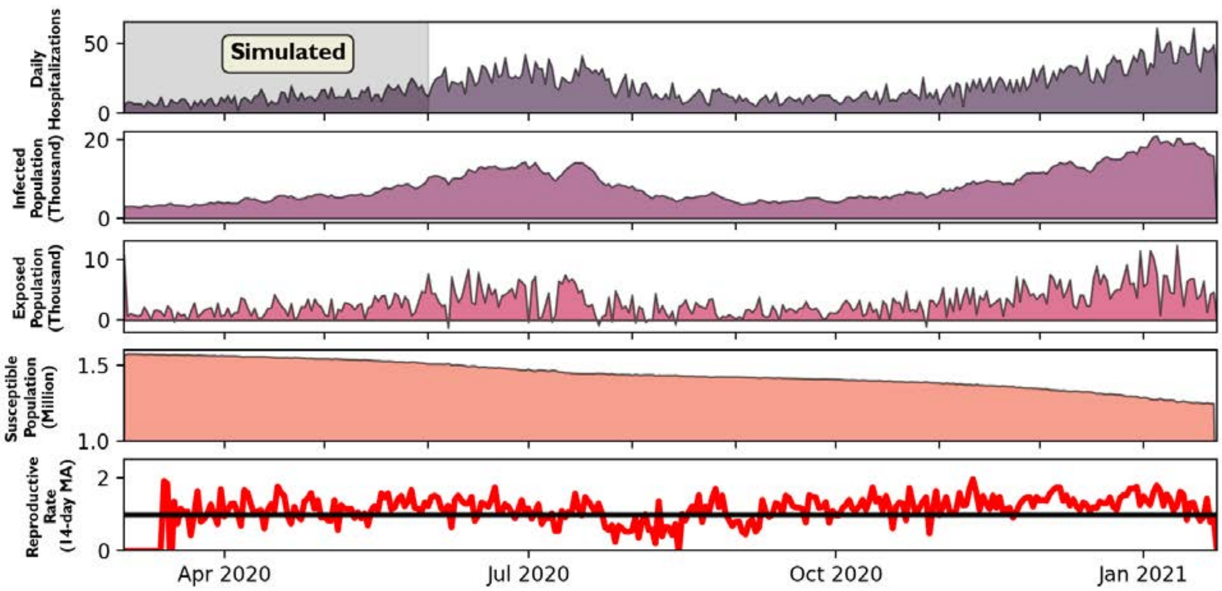

Figure 4: Daily hospitalization data (From NC DHHS) is used to model susceptible, exposed, and infected populations calculated within the SEIRH model, as well as the reproductive rate for COVID-19 transmission in the population served by the Research Triangle hospital system. Note: daily hospitalizations from March-May 2020 are estimated from DHHS data from June 2020 – January 2021

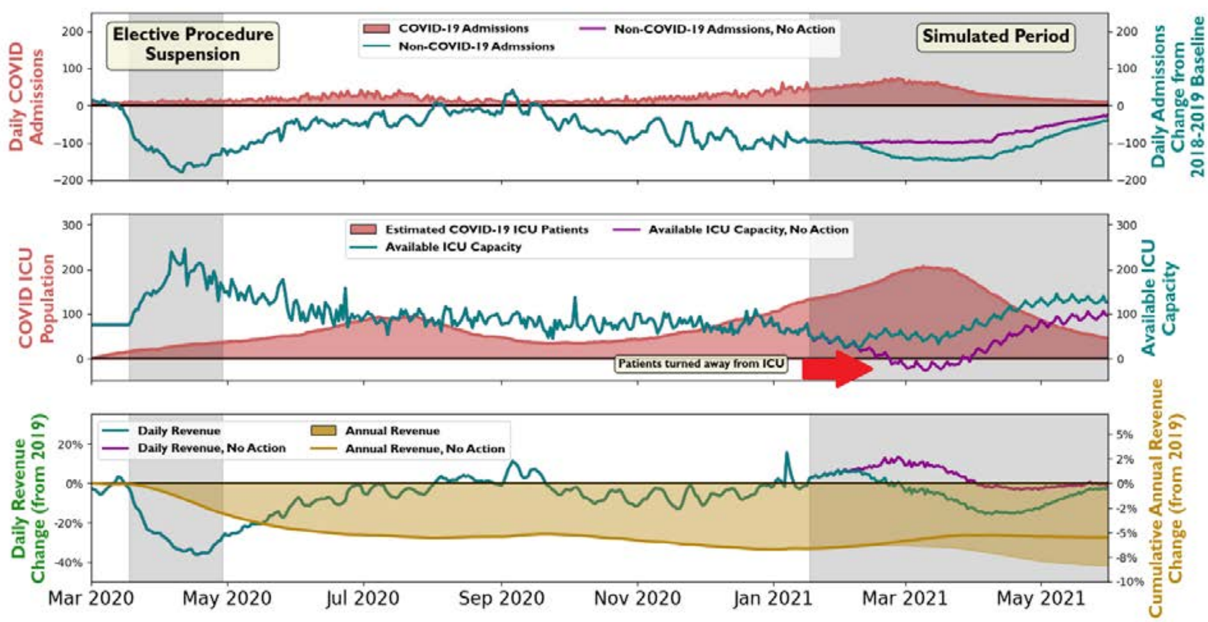

Figure 5: Simulated admissions, ICU capacity, and revenue losses for the Research Triangle hospital system under a scenario of continued higher community transmission. Results assuming hospital action to cancel elective and non-emergency procedures in early February are compared to a scenario of no action.

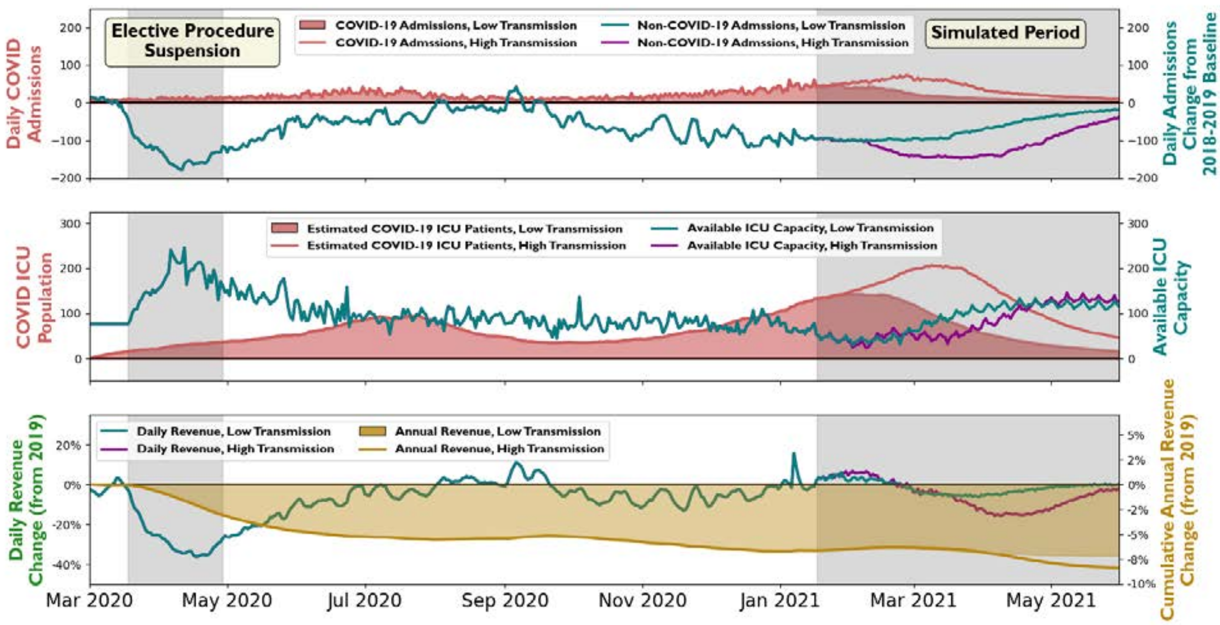

Figure 6: Simulated admissions, ICU capacity, and revenue losses for the Research Triangle hospital system under simulated scenarios involving high/low community transmission rates.

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