JMIR Publications
The Leading eHealth Publisher

Periodic COVID-19 Testing in Emergency Department Staff

Yuemei Zhang, Sheng-Ru Cheng

Submitted to: JMIR Public Health and Surveillance
on: May 18, 2020

Table of Contents

Periodic COVID-19 Testing in Emergency Department Staff

Yuemei Zhang[1] MD, MBA; Sheng-Ru Cheng[2] BSc

[1]Department of Anesthesiology and Pain Medicine University of Washington Seattle US
[2]University of Illinois at Urbana-Champaign Urbana US

Corresponding Author:
Yuemei Zhang MD, MBA
Department of Anesthesiology and Pain Medicine
University of Washington
1959 NE Pacific Street, Box 356540
Seattle
US

Abstract

Background: As the number of COVID-19 cases in the US continues to rise and hospitals are experiencing personal protective equipment (PPE) shortages, healthcare workers have been disproportionately affected by COVID-19 infection. Since COVID-19 testing is now available, some have raised the question of whether we should be routinely testing asymptomatic healthcare workers.

Objective: To model the impact of periodic COVID-19 testing among healthcare workers in regions moderately impacted by COVID-19

Methods: Using publicly available data on COVID-19 infections and emergency department visits, as well as internal hospital staffing information, we generated a mathematical model to predict the impact of periodic COVID-19 testing in asymptomatic members of the emergency department staff in regions affected by COVID-19 infection. We calculated various transmission constants based on the Diamond Princess cruise ship data, used a logistic model to calculate new infections, and we created a Markov model according to average COVID-19 incubation time.

Results: Our model predicts that after 30 days, with a transmission constant of 1.219e-4 new infections per person2, weekly COVID-19 testing of healthcare workers (HCW) would reduce new HCW and patient infections by 5.1% and bi-weekly testing would reduce both by 2.3%. At a transmission constant of 3.660e-4 new infections per person,2 weekly testing would reduce infections by 21.1% and bi-weekly testing would reduce infections by 9.7-9.8%. For a lower transmission constant of 4.067e-5 new infections per person2, weekly and biweekly HCW testing would result in a 1.54% and 0.7% reduction in infections respectively.

Conclusions: Periodic COVID-19 testing for emergency department staff in regions that are heavily-affected by COVID-19 and/or facing resource constraints may reduce COVID-19 transmission significantly among healthcare workers and previously-uninfected patients.

(JMIR Preprints 18/05/2020:20260)
DOI: https://doi.org/10.2196/preprints.20260

Preprint Settings

1) Would you like to publish your submitted manuscript as preprint?
Please make my preprint PDF available to anyone at any time (recommended).
Please make my preprint PDF available only to logged-in users; I understand that my title and abstract will remain visible to all users.
Only make the preprint title and abstract visible.
✓ **No, I do not wish to publish my submitted manuscript as a preprint.**
2) If accepted for publication in a JMIR journal, would you like the PDF to be visible to the public?
✓ **Yes, please make my accepted manuscript PDF available to anyone at any time (Recommended).**
Yes, but please make my accepted manuscript PDF available only to logged-in users; I understand that the title and abstract will remain v
Yes, but only make the title and abstract visible (see Important note, above). I understand that if I later pay to participate in <a href="http

Original Manuscript

Periodic COVID-19 Testing in Emergency Department Staff

Yuemei Zhang, MD,[1] Sheng-Ru Cheng, BS[2]

[1]Department of Anesthesiology and Pain Medicine, University of Washington, Seattle, WA, USA

[2]Dept. of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA

Corresponding author: Sheng-Ru Cheng

Corresponding author's email address: rsrcheng9@gmail.com

Abstract

Background: As the number of COVID-19 cases in the US continues to rise and hospitals are experiencing personal protective equipment (PPE) shortages, healthcare workers have been disproportionately affected by COVID-19 infection. Since COVID-19 testing is now available, some have raised the question of whether we should be routinely testing asymptomatic healthcare workers.

Objective: To provide a quantitative analysis of the predicted impact that regular COVID-19 testing of healthcare workers may have on COVID-19 infection prevention in emergency department patients and staff.

Methods: Using publicly available data on COVID-19 infections and emergency department visits, as well as internal hospital staffing information, we generated a mathematical model to predict the impact of periodic COVID-19 testing in asymptomatic members of the emergency department staff in regions affected by COVID-19 infection. We calculated various transmission constants based on the Diamond Princess cruise ship data, used a logistic model to calculate new infections, and we created a Markov model according to average COVID-19 incubation time.

Results: Our model predicts that after 180 days, with a transmission constant of 1.219e-4 new infections per person^2, weekly COVID-19 testing of healthcare workers (HCW) would reduce new HCW and patient infections by 3~5.9% and bi-weekly testing would reduce both by 1~2.1%. At a transmission constant of 3.660e-4 new infections per person^2, weekly testing would reduce infections by 11~23% and bi-weekly testing would reduce infections by 5.5~13%. For a lower transmission constant of 4.067e-5 new infections per person^2, weekly and biweekly HCW testing would result in a 1% and 0.5~0.8% reduction in infections respectively.

Conclusion: Periodic COVID-19 testing for emergency department staff in regions that are heavily-affected by COVID-19 and/or facing resource constraints may reduce COVID-19 transmission significantly among healthcare workers and previously-uninfected patients.

Introduction

Although it originated as a small cluster of cases restricted to Wuhan, China in Nov. and Dec. of 2019, severe acute respiratory coronavirus 2 (SARS-CoV-2), the virus responsible for causing the coronavirus disease 2019 (COVID19) disease, rapidly spread across the globe and officially declared a pandemic on March 11, 2020 [1]. In the United States, the number of confirmed cases spiked from just 1 case in Jan. 20, 2020 to 6,244,970 confirmed cases and 188,538 deaths as of September 5, 2020 [2]. Washington state, site of the first American case, has had 77,208 confirmed COVID-19 case as of April 14, 2020 [3]. Given its rapid spread and 3.4% mortality rate [4], countries like Italy and China have been forced to ration limited healthcare resources, and there are concerns that the US may need to do so as well [5]. Person-to-person transmission by asymptomatic individuals and pre-symptomatic individuals during the up-to-14 day incubation period [6] may play a significant role in this pandemic [7-10].

While it is not known the extent of hospital-acquired cases of COVID-19, nosocomial infections have been shown to play a key role in propagating viral transmission in previous coronavirus outbreaks, such as the 2003 severe acute respiratory syndrome (SARS) outbreak [11-12]. Because of the risk of exposure to SARS-CoV-2 infected patients and shortages in personal protective equipment (PPE) both in the US and in other countries [13-15], healthcare workers have been disproportionately affected by COVID-19 [16-18].

The goal of this study is to provide a quantitative analysis and model for predicting the impact of periodic COVID-19 testing for all emergency room staff as a possible alternate strategy to mitigate disease transmission in the healthcare setting, since PPE supplies are limited.

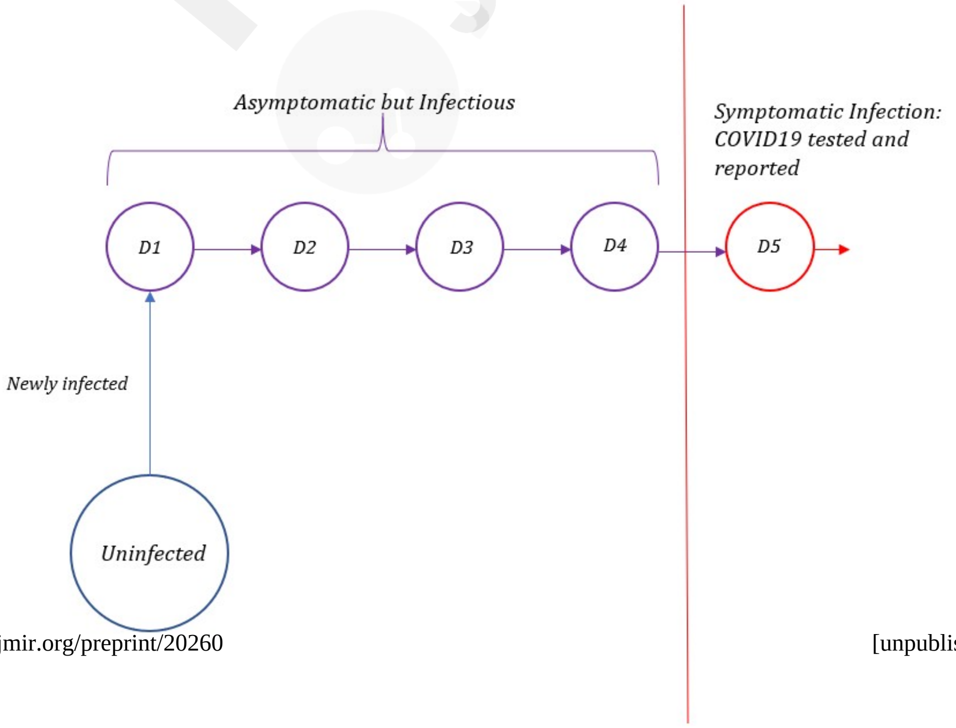
Methods

Data sourcing

In order to model a hospital emergency department and a moderately affected patient population, we chose to base our model on Harborview Medical Center (HMC) and University of Washington Medical Center (UWMC) in King County, WA, since we had access to its emergency department (ED) staffing information. Because HMC and UWMC are two of many hospitals within the region, for the sake of simplicity, we are assuming that both of these hospital's entire patient population essentially lives in King County, WA.

In order to estimate the number of daily ED visits, we used the publicly available UW Medicine Annual Financial Report for the Board of Regents meeting, which reported that during fiscal year 2018 there were 57,516 ED visits to HMC and 28,276 ED visits to UWMC [19]. Next, we divided this number by 365 days / year, since medical emergencies happen daily regardless of holidays, to estimate average daily ED visits. Although it is possible that the rate of ED visits has changed due to COVID-19 symptoms or due to socio-behavioral changes resulting from the COVID-19 pandemic and/or public policies related to it, this number is not currently available to us.

The HMC emergency department currently employs 59 emergency medicine (EM) faculty physicians, 48 EM resident physicians, and 200 full-time equivalent registered nurses (RNs) ... of 307 full-time healt... d 44 EM faculty physi... As, for a total of 176 f...



Initia...

Fig 1. Timeline of Infection for Confirmed COVID-19 Cases. After infection, the individual can transmit the infection to others but does not become symptomatic until day 5.

Since our model is intended to be generalizable to any hospital in the United States, we did not apply hospital-specific policies to our model and instead maintained the same constraints that many other US hospitals have.

Due to the incubation period of the virus, coupled with the current resource limitations in the US, COVID-19 testing is often not performed until symptoms become evident. Furthermore, due to laboratory processing times, COVID-19 test results may not be available until patients have left the emergency department. To estimate the asymptomatic infected population, we looked at the number of newly confirmed COVID-19 cases on each date and retroactively calculated the daily number of individuals that would have been in the pre-symptomatic incubation phase. Based on recently published studies, the average incubation period of COVID-19 is around 5 to 6 days [20-22]. For this model, we used the shorter incubation period of 5 days, meaning that symptoms begin on day 5. This means that, for any time t, the number of asymptomatic but infected individuals can be estimated using the sum of new infections that were confirmed on t + 1 to t + 4 as follows:

$$Asymptomatic(t) = \sum_{i=1}^{4} I'(t+i)$$

In other words, if someone is symptomatic and confirmed to be COVID19+ on any of the days between t+1 to t+4, then s/he can be assumed to be infected but asymptomatic on day t. Using data for King County, WA through April 5, 2020, we calculated 685 asymptomatic cases on April 1, 2020 in King County.

In order to determine the total number of infected individuals in King County on any given date, we then added the number of publicly reported confirmed infections on April 1, 2020 with the asymptomatically infected population that we calculated and subtracted the number of COVID-19 deaths. To determine the total uninfected population, we subtracted the infected population and the number of COVID-19 deaths from King County's estimated 2019 population of 2,252,782 [23]. Subsequently, to determine the proportion of the living population that was infected and uninfected respectively, we divided the total infected population and the total uninfected population by the total living population.

We assume that since the majority of patients and HCWs reside locally, their infection statuses would initially also be representative of that of the general population. Thus to get our initial values of infected and uninfected patients and HCWs per day, we multiplied our proportions with total emergency department (ED) patients per day and total HCW in the ED. For HMC, the initial values are 0.21 infected patients per day, 157.36 uninfected patients per day, 0.41 infected HCW, and 306.57 uninfected HCW. For UWMC, the initial values are 0.12 infected patients per day, 77.34 uninfected patients per day, 0.28 infected HCW, and 175.72 uninfected HCW.

Infected HCW were further subdivided into groups based on how long they had been infected. Because asymptomatic individuals with COVID-19 would remain in the workforce, we included infected HCW in the healthcare workforce for days 1-4 of their infections (during which time they could also infect other HCW and patients), and then removed them from the workforce once they reached day 5 and displayed symptoms. For our initial conditions, we divided infected HCW evenly into 4 groups for HCW on day 1 of infection (D1), day 2 of infection (D2), day 3 of infection (D3) day 4 of infection (D4).

Transmission rate

To investigate the number of preventable infections of healthcare workers from asymptomatic infected patients, we used a logistic model of transmission. Mathematically, logistic model describes a dynamic population growth rate that is limited by a certain constraint such as population. In epidemiology, logistic models have been used to model and predict past outbreaks [24, 25].

In the equation below, k is the transmission constant, M is the total population size, $\frac{dI}{dt}$ is the rate of change of infected population, and I represents total infected population, including the asymptomatic infected population.

$$\frac{dI}{dt} = k \cdot I \cdot (M - I)$$

However, since our data is publicly sourced and only day-by-day case reports are available, we use the discretized form of the logistical model as follows.

$$I'(t) = k \cdot I(t) \cdot (M - I(t))$$

Since I'(t) is the rate of change of the infected population, it can be observed that it is the difference between the infected population at time t + 1 and time t

$$I'(t) = I(t+1) - I(t)$$

To calculate the transmission constant, we rearrange the previous equations to the following

$$k = \frac{I(t+1) - I(t)}{I(t) \cdot [M - I(t)]}$$

Since we are interested in the total infection spread, data for some known infected population, both symptomatic and asymptomatic, is required. For this, we used data extracted from the Diamond Princess cruise ship [6], since the close quarters approximate the clinical setting. Due to the isolated nature of the ship, health officials were able to test everyone onboard the cruise ship, even if there are no symptoms evident. Using the data at hand and the equation above, we can readily determine the transmission constant by dividing the number of new cases at time t + 1 (with time measured in days) by the product of infected population at time t and the uninfected population at time t, which we calculated to be an average of k = 1.219e-4 new infections per person^2.

While we know the transmission rate for healthcare workers is likely different, we do not know whether it is higher or lower, due to both more intimate and close contact with patients than typical interactions on a cruise ship, and due to questions of PPE usage. Furthermore, the transmission rate likely varies by department and institution as well. Since we do not have an accurate transmission rate for the resource-limited clinical environment, we decided to model several different scenarios using 3 times the transmission constant (3.660e-4 new infections per person^2) and one-third the transmission constant (4.067e-5 new infections per person^2) calculated from the Diamond Princess cruise ship scenario.

To calculate the number of patient-to-HCW infections, HCW-to-patient infections, and HCW-to-HCW infections occurring in the ED, we adapted the logistic model to

$$I_m'(t) = k \cdot I_n(t) \cdot U_m(t)$$

where $I_m'(t)$ refers to the new infections of a population *m*, k is the transmission constant, $I_n(t)$ refers to asymptomatically infected individuals of the group *n* transmitting the virus, and $U_m(t)$ refers to uninfected individuals of the group *m* that is being newly infected. For instance, if $I_m'(t)$ represents new HCW-to-patient infections, then $I_n(t)$ would represent asymptomatically infected HCW, and $U_m(t)$ would represent uninfected patients presenting to the emergency department. These calculations would be repeated for every day in our model.

Assuming adequate inpatient beds, patients leave the ED each day, whether that means they were admitted to the hospital or are leaving the institution, and a new batch of patients with characteristics representative of the general population would arrive each day. Therefore, the starting numbers of uninfected patients and infected patients that we used for our calculations stayed constant. In reality, the number of patients presenting to the ED may be disproportionately higher than in the general population, since completely healthy individuals without any acute illness or injury would not visit the ED.

On the other hand, since the two hospitals were unlikely to have significant changes in their employment in the time period we were modeling, we designed a Markov chain to track their infection timelines. New HCW infections comprised the D1 group for the following day, and HCW in D1 would get changed to D2 the following day, HCW in D2 would get changed to D3 the following day, so on and so forth.

Periodic Testing

To simulate periodic COVID-19 testing of all HCW, we used the simplified case of 100% sensitivity for COVID-19 testing. In reality, testing sensitivity is likely to be lower and may vary based on how testing or sample collection is performed, and our model can be adapted for other levels of sensitivity. Currently, there is insufficient data on testing to have information on sensitivity. On any given day that all HCW are tested, we would manually remove (sensitivity)*(number of infected HCW on each day) from each category. With 100% sensitivity, this would mean that all infected HCW on the testing day. For weekly testing, we started this manual elimination process on day 6, and then repeated this process every 7 days. For biweekly testing, we started the manual elimination process on day 13, and then repeated this process every 14 days.

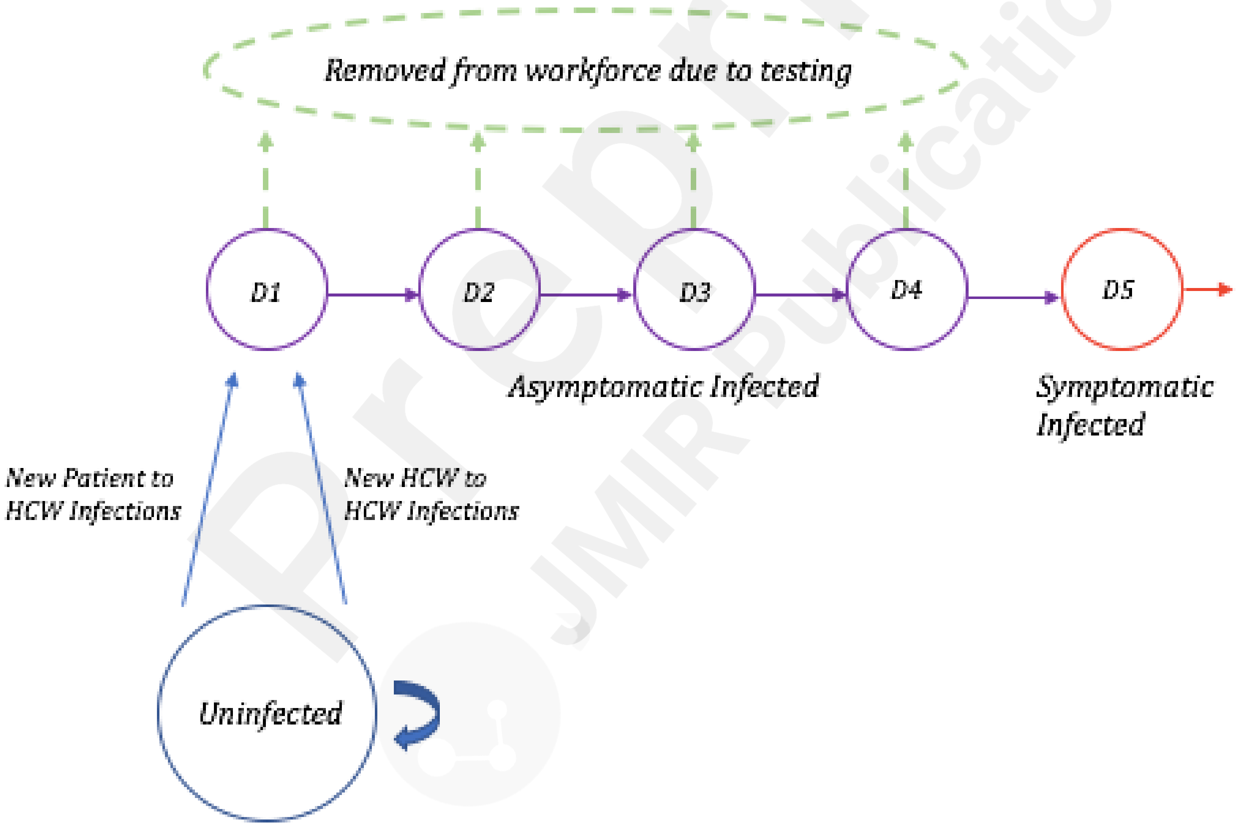


Figure 2. Markov Chain for Healthcare Workers. Healthcare workers (HCW) who are uninfected on any given day can either stay uninfected or become newly infected (blue), at which point they would proceed to day 1 of infection the next day. Individuals who are infected will proceed to the next day of infection with each passing day. Infected HCW are asymptomatic on days 1-4 (purple). On day 5 of infection, infected individuals begin showing symptoms, at which point they are removed from this workforce (red). With COVID-19 testing, On days with COVID-19 testing, asymptomatic infected HCW who test positive may also be removed from the healthcare workforce (green).

Results

Our model predicts that over the course of 180 days, 28364 and 13945 patients visited the emergency department in HMC and UWMC, respectively. At the baseline transmission constant of 1.219e-4 new infections per person^2, without routine COVID-19 testing of HCW, 1.194 HCW infections and 0.985 new patient infections would occur in HMC. For UWMC, 0.506 HCW infections and 0.223 new patient infections would occur. If COVID-19 testing of HCW occurred every 7 days, then 1.802 HCW infections and 0.927 new patient infections would occur in HMC, which is a 5.9% reduction in both HCW and new patient infections. For UWMC, weekly testing would result in 0.489 HCW infections and 0.216 new infections, which yields a 3.1% reduction. If COVID-19 testing of HCW occurred every 14 days, then 0.311 HCW infections and 0.160 new patient infections would occur, which is a 2.3% reduction in both HCW and new patient infections. For UWMC, this would result in 0.499 HCW infections and 0.220 new patient infections, which is a reduction of 1.1%.

Patient Infections with and without Periodic COVID-19 Testing for HCW at HMC

Transmission Rate	No Testing	Weekly Testing	Biweekly Testing
1.219e-4 new infections/person^2	0.985	0.927 (5.92%)	0.964 (2.14%)
3.660e-4 new infections/person^2	4.475	3.409 (23.81%)	3.906 (12.70%)
4.067e-5 new infections/person^2	0.295	0.289 (1.77%)	0.292 (0.85%)

Table 1. Patient Infections with and without Periodic COVID-19 Testing for HCW at HMC. Predicted numbers of new patient infections with various transmission rates and COVID-19 testing frequencies for healthcare workers (HCW) after 180 days within 1 hospital emergency department. Percentages in parentheses represent the decrease in number of infections at each transmission rate with weekly (every 7 days) or biweekly (every 14 days) testing compared to the number of infections if HCW were not routinely tested.

Patient Infections with and without Periodic COVID-19 Testing for HCW at UWMC

Transmission Rate	No Testing	Weekly Testing	Biweekly Testing
1.219e-4 new infections/person^2	0.223	0.215 (3.17%)	0.220 (1.14%)
3.660e-4 new infections/person^2	0.819	0.726 (11.32%)	0.773 (5.56%)
4.067e-5 new infections/person^2	0.0699	0.0693 (1.0%)	0.0696 (0.48%)

Table 2. Patient Infections with and without Periodic COVID-19 Testing for HCW at UWMC. Predicted numbers of new patient infections with various transmission rates and COVID-19 testing frequencies for healthcare workers (HCW) after 180 days within 1 hospital emergency department. Percentages in parentheses represent the decrease in number of infections at each transmission rate with weekly (every 7 days) or biweekly (every 14 days) testing compared to the number of infections if HCW were not routinely tested.

With a transmission constant of 3.660e-4 new infections per person^2, without routine COVID-19 testing of HCW, 8.596 HCW infections and 4.475 new patient infections would occur in HMC. Without routine testing, 1.850 HCW infection and 0.819 new patient will occur in UWMC. If COVID19 testing of HCW occurred every 7 days, then 6.582 HCW infections and 3.409 new patient infections would occur, which is a 23% reduction in both HCW and new patient infections. For UWMC, 1.643 HCW infection and 0.726 new patient infection would occur, which is a reduction of 11.3%. If COVID19 testing of HCW occurred every 14 days, then 1.26 HCW infections and 0.650 new patient infections would occur, which is a 9.7% reduction in HCW infections and 9.8% reduction in new patient infections. In UWMC, a biweekly test would result in 1.748 HCW infection and 0.773 new patient infection, which is a ~5.5% reduction.

HCW Infections with and without Periodic COVID-19 Testing for HCW at HMC

Transmission Rate	No Testing	Weekly Testing	Biweekly Testing
1.219e-4 new infections/person^2	1.914	1.802 (5.86%)	1.873 (2.11%)
3.660e-4 new infections/person^2	8.596	6.582 (23.42%)	7.524 (12.47%)
4.067e-5 new infections/person^2	0.573	0.563 (1.77%)	0.569 (0.84%)

Table 3. HCW Infections with and without Periodic COVID-19 Testing for HCW at HMC. Predicted numbers of new HCW infections with various transmission rates and COVID-19 testing frequencies for healthcare workers after 30 days within 1 hospital emergency department. Percentages in parentheses represent the decrease in number of infections at each transmission rate with weekly (every 7 days) or biweekly (every 14 days) testing compared to the number of infections if HCW were not routinely tested.

For a lower transmission constant of 4.067e-5 new infections per person^2, 0.573 HCW infections and 0.295 new patient infections would occur in HMC without routine COVID-19 testing of HCW. For UWMC, 0.159 HCW infections and 0.0699 new patient infections would occur. If COVID19 testing of HCW occurred every 7 days, then 0.563 HCW infections and 0.289 new patient infections would occur in HMC, which is a 1.77% reduction in both HCW and new patient infections. For UWMC, 0.0484 HCW infections and 0.0693 new patient infections would occur, which is 1~1.5% reduction. If COVID1-9 testing of HCW occurred every 14 days, then 0.569 HCW infections and 0.292 new patient infections would occur, which is a 0.85% reduction in HCW infections and new patient infections. For UWMC, this would result in 0.0488 HCW infections and 0.0696 new patient infections, which is a 0.48~0.7% reduction in potential infections.

HCW Infections with and without Periodic COVID-19 Testing for HCW

Transmission Rate	No Testing	Weekly Testing	Biweekly Testing
1.219e-4 new infections/person^2	0.505	0.489 (3.15%)	0.499 (1.13%o)
3.660e-4 new infections/person^2	1.850	1.643 (11.21%)	1.748 (5.50%)

4.067e-5 new infections/person[2]	0.159	0.157 (0.99%)	0.158 (0.47%)

Table 4. HCW Infections with and without Periodic COVID-19 Testing for HCW at UWMC Predicted numbers of new HCW infections with various transmission rates and COVID-19 testing frequencies for healthcare workers after 30 days within 1 hospital emergency department. Percentages in parentheses represent the decrease in number of infections at each transmission rate with weekly (every 7 days) or biweekly (every 14 days) testing compared to the number of infections if HCW were not routinely tested.

Discussion

This model shows that within a hospital emergency department, periodic COVID-19 testing among healthcare workers would reduce the rate of SARS-CoV-2 infections among emergency department personnel and reduce the rate of new SARS-CoV-2 infections acquired by patients in the ED. As expected, the impact of periodic HCW testing varied with the transmission rate of SARS-CoV-2, showing greater benefit when SARS-CoV-2 transmission rates were higher.

Our model uses the COVID-19 prevalence for King County, WA, an area which is not as heavily affected by COVID-19 as many other places in this country, for the disease prevalence in patients arriving to the ED. A higher COVID-19 prevalence for the patient population may result in higher patient-to-HCW disease transmission rates, in which case, periodic HCW testing would be more beneficial.

A limitation of our model is that we do not know the actual transmission rate in various hospital emergency departments, and transmission rates may vary widely between hospitals based on PPE supply, type of interactions with patients and severity of illness (which also impacts the types of procedures and therapies involved), and other factors. Additionally, the transmission rate may be different for different types of healthcare workers: for instance, those who perform aerosolizing procedures like intubation may experience a higher rate of transmission.

By changing the initial parameters, this model can be adapted for different ED visit rates, different ED staffing numbers, different levels of infection prevalence, different transmission constants, and different levels of testing sensitivity. Lower levels of testing sensitivity will lead to decreased utility in periodic HCW testing. In addition, our analysis was performed with the population characteristics of a county that is moderately affected by COVID-19. Currently, there are many regions of the country with a much higher COVID-19 prevalence, which would lead to a greater potential benefit from periodic HCW testing to prevent HCW infections.

Due to the current state of COVID-19 testing, US statistics on confirmed COVID-19 cases may not be the most reliable, either. Per CDC guidelines that were updated March 24, 2020 at the time of this writing, laboratory testing for COVID-19 is only indicated for individuals who are not healthcare workers nor first responders if they have symptoms that are consistent with COVID-19 [26]. However, many individuals with COVID-19 may be asymptomatic or only have mild symptoms [27]. In addition, COVID-19 testing shortages may make the US statistics on COVID-19 cases less reliable [28]. Therefore, the numbers for COVID-19 incidence and prevalence used in our model, which are based on official reports, may be erroneously low.

Of note, our model only includes emergency department staff in our numbers, but healthcare workers from other specialties and departments also see patients in the ED. For instance, in many hospitals, non-emergency medicine physicians will see inpatient admissions in the ED, specialists may be consulted to see patients in the ED, and surgeons and anesthesiologists participate in trauma resuscitations. Additionally, at some teaching hospitals, resident physicians in specialties outside of emergency medicine will also have emergency medicine rotations.

Given the uncertainty and unavailable data regarding COVID-19, some of the numbers and factual assumptions in this model may be incorrect, which could affect the model's predictions. To simplify calculations, this model assumes that COVID-19 infections are spread homogeneously throughout the state, that healthcare workers freely interact with patients and all other healthcare workers and does not take into account individual variation in incubation times. Ultimately, this model is intended to be a tool and an approximation, and it can be adapted to different healthcare settings or regions by changing the starting conditions.

1. Adhanom T. WHO Director-General's opening remarks at the media briefing on COVID-19 - 11 March 2020. World Health Organization [Internet] 2020 Mar 11 [cited 2020 Mar 15]; Available from: https://www.who.int/dg/speeches/detail/who-director-general-s-opening-remarks-at-the-media-briefing-on-covid-19---11-march-2020
2. Dong E, Du H, Gardner L. An interactive web-based dashboard to track COVID-19 in real time. Lancet Infect Dis 2020 May;20(5):533–534. PMID:32087114
3. 2019 Novel Coronavirus Outbreak (COVID-19) [Internet]. Washington State Department of Health. [cited 2020 Apr 14]. Available from: https://www.doh.wa.gov/Emergencies/COVID19
4. Adhanom T. WHO Director-General's opening remarks at the media briefing on COVID-19-3 March 2020. World Health Organization [Internet] 2020 Mar 3 [cited 2020 Mar 15]; Available from: https://www.who.int/dg/speeches/detail/who-director-general-s-opening-remarks-at-the-media-briefing-on-covid-19---3-march-2020
5. Cha AE. Spiking U.S. coronavirus cases could force rationing decisions similar to those made in Italy, China. The Washington Post [Internet] The Washington Post; 2020 Mar 15 [cited 2020 Mar 31]; Available from: https://www.washingtonpost.com/health/2020/03/15/coronavirus-rationing-us/
6. Rapid risk assessment: Novel coronavirus disease 2019 (COVID-19) pandemic: increased transmission in the EU/EEA and the UK – sixth update [Internet]. ECDC. 2020 [cited 2020 Apr 15]. Available from: https://www.ecdc.europa.eu/en/publications-data/rapid-risk-assessment-novel-coronavirus-disease-2019-covid-19-pandemic-increased
7. Li R, Pei S, Chen B, Song Y, Zhang T, Yang W, Shaman J. Substantial undocumented infection facilitates the rapid dissemination of novel coronavirus (SARS-CoV-2). Science 2020 May 1;368(6490):489–493. PMID:32179701
8. Tindale LC, Stockdale JE, Coombe M, Garlock ES, Lau WYV, Saraswat M, Zhang L, Chen D, Wallinga J, Colijn C. Evidence for transmission of COVID-19 prior to symptom onset. Elife [Internet] 2020 Jun 22;9. PMID:32568070
9. Ganyani T, Kremer C, Chen D, Torneri A, Faes C, Wallinga J, Hens N. Estimating the generation interval for COVID-19 based on symptom onset data. medRxiv Cold Spring Harbor Laboratory Press; 2020 Mar 8;2020.03.05.20031815.
10. Liu Y, Centre for Mathematical Modelling of Infectious Diseases nCoV Working Group, Funk S, Flasche S. The contribution of pre-symptomatic infection to the transmission dynamics of COVID-2019. Wellcome Open Res 2020 Apr 1;5:58. PMID:32685697
11. Lee N, Sung JJY. Nosocomial Transmission of SARS. Curr Infect Dis Rep Springer; 2003 Dec;5(6):473–476. PMID:14642187

12. Nishiyama A, Wakasugi N, Kirikae T, Quy T, Ha LD, Van Ban V, Long HT, Keicho N, Sasazuki T, Kuratsuji T. Risk factors for SARS infection within hospitals in Hanoi, Vietnam. Jpn J Infect Dis nih.go.jp; 2008 Sep;61(5):388–390. PMID:18806349
13. Cranley E. A Chinese official warned of a shortage of protective masks and suits amid the Wuhan coronavirus outbreak. Business Insider [Internet] 2020 Jan 27 [cited 2020 Apr 15]; Available from: https://www.businessinsider.com/chinese-official-protective-mask-and-suit-shortage-wuhan-coronavirus-2020-1
14. Rappleye H, Lehren AW, Strickler L, Fitzpatrick S. “This system is doomed”: Doctors, nurses sound off in NBC News coronavirus survey. NBC News [Internet] 2020 Mar 20 [cited 2020 Apr 15]; Available from: https://www.nbcnews.com/news/us-news/system-doomed-doctors-nurses-sound-nbc-news-coronavirus-survey-n1164841
15. Jacobs A, Richtel M, Baker M. Doctors Say Shortage of Protective Gear Is Dire During Coronavirus Pandemic. The New York Times [Internet] 2020 Mar 19 [cited 2020 Apr 15]; Available from: https://www.nytimes.com/2020/03/19/health/coronavirus-masks-shortage.html
16. Gan N, Thomas N, Culver D. Over 1,700 frontline medics likely infected with coronavirus in China, presenting new crisis for the government. CNN [Internet] CNN; 2020 Feb 14 [cited 2020 Apr 15]; Available from: https://www.cnn.com/2020/02/13/asia/coronavirus-health-care-workers-infected-intl-hnk/index.html
17. Bernstein L, Boburg S, Sacchetti M, Brown E. Covid-19 hits doctors, nurses and EMTs, threatening health system. The Washington Post [Internet] The Washington Post; 2020 Mar 17 [cited 2020 Apr 15]; Available from: https://www.washingtonpost.com/health/covid-19-hits-doctors-nurses-emts-threatening-health-system/2020/03/17/f21147e8-67aa-11ea-b313-df458622c2cc_story.html
18. Woodward A. Several young doctors in China have died of the coronavirus. Medical workers are far more vulnerable to infection than the general population. Business Insider [Internet] 2020 Mar 4 [cited 2020 Apr 16]; Available from: https://www.businessinsider.com/why-coronavirus-killed-young-chinese-doctors-2020-2
19. UW Medicine Annual Financial Report. UW Medicine; 2019 Feb; Available from: https://s3-us-west-2.amazonaws.com/uw-s3-cdn/wp-content/uploads/sites/12/2019/02/06104924/2019-02-B-6.pdf.
20. Lauer SA, Grantz KH, Bi Q, Jones FK, Zheng Q, Meredith HR, Azman AS, Reich NG, Lessler J. The Incubation Period of Coronavirus Disease 2019 (COVID-19) From Publicly Reported Confirmed Cases: Estimation and Application. Ann Intern Med 2020 May 5;172(9):577–582. PMID:32150748
21. Backer JA, Klinkenberg D, Wallinga J. Incubation period of 2019 novel coronavirus (2019-nCoV) infections among travellers from Wuhan, China, 20-28 January 2020. Euro Surveill [Internet] 2020 Feb;25(5). PMID:32046819
22. Linton NM, Kobayashi T, Yang Y, Hayashi K, Akhmetzhanov AR, Jung S-M, Yuan B, Kinoshita R, Nishiura H. Incubation Period and Other Epidemiological Characteristics of 2019 Novel Coronavirus Infections with Right Truncation: A Statistical Analysis of Publicly Available Case Data. J Clin Med Res [Internet] 2020 Feb 17;9(2). PMID:32079150
23. United States Census Bureau. QuickFacts: King County, Washington [Internet]. [cited 2020 Apr 27]. Available from: https://www.census.gov/quickfacts/fact/table/kingcountywashington,WA/PST045219
24. Liang K. Mathematical model of infection kinetics and its analysis for COVID-19, SARS and MERS. Infect Genet Evol 2020 Aug;82:104306. PMID:32278147
25. Hsieh Y-H, Lee J-Y, Chang H-L. SARS epidemiology modeling. Emerg Infect Dis. 2004. p. 1165–7; author reply 1167–8. PMID:15224675
26. Centers for Disease Control and Prevention. *Evaluating and Testing Persons for Coronavirus Disease 2019 (COVID-19)*. 2020 March 14, 2020 [cited 2020 Mar 25]
27. Bendix A. South Korea has tested 140,000 people for the coronavirus. That could explain why its death rate is just 0.6% — far lower than in China or the US. Business Insider [Internet] 2020 Mar 6 [cited 2020 Apr 27]; Available from:

https://www.businessinsider.com/south-korea-coronavirus-testing-death-rate-2020-3
28. Belmonte A. 'Don't believe the numbers you see': Johns Hopkins professor says up to 500,000 Americans have coronavirus [Internet]. Yahoo Finance. 2020 Mar 14 [cited 2020 Apr 27]. Available from: https://finance.yahoo.com/news/marty-makary-on-coronavirus-in-the-us-183558545.html

Supplementary Files