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Staffing with disease-based epidemiologic indices may reduce shortage of intensive care unit staff during the COVID-19 pandemic

Short title: ICU staffing during the COVID-19 pandemic

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Abstract

Purpose: Healthcare worker (HCW) safety is of pivotal importance during a pandemic such as Coronavirus Disease 2019 (COVID-19), and employee health and well-being ensures functionality of healthcare institutions. This is particularly true for an intensive care unit (ICU) where highly specialized staff cannot be readily replaced. In the light of lacking evidence for optimal staffing models in a pandemic, we hypothesized that staff shortage can be reduced when staff scheduling takes the epidemiology of a disease epidemic into account.

Methods: Various staffing models were constructed and comprehensive statistical modeling performed. A typical, routine staffing model was defined that assumed full-time employment (40 hours/week) in a 40 bed ICU with a 2:1 ratio of patients to staff. The pandemic model assumed staff worked 12-hour shifts for 7 days every other week. Potential in-hospital staff infections were constructed for a total period of 120 days with a probability of 10%, 25%, and 40% being infected per week when at work. Simulations included the probability of infection at work for a given week, of fatality once infected, and the quarantine time, if infected.

Results: Pandemic-adjusted staffing significantly reduced workforce shortage and the effect progressively increased as the probability of infection increased. Maximum effects were observed at week 4 for each infection probability with a 17%, 32%, and 38% staffing reduction for an infection probability of 0.10, 0.25, and 0.40, respectively.

Conclusions: Staffing along epidemiologic considerations may reduce HCW shortage by leveling the nadir from affected workforce. Although this requires considerable efforts and commitment of staff, it may be essential in an effort to best maintain staff health and operational functionality of healthcare facilities and systems.

Key words: COVID-19, intensive care unit, work shift, SARS-CoV-2, staffing, incubation time, quarantine

Glossary of Terms:

COVID-19: Coronavirus Disease 2019

HCW: Health care worker

ICU: Intensive care unit

SARS-CoV-2: Severe acute respiratory syndrome coronavirus 2

WHO: World Health Organization

Key points:

Question: Is COVID-19 incubation-time based staffing of benefit with regard to reducing the number of infected healthcare workers (HCW)?

Findings: Comprehensive statistical modelling reveals significant reduction of ICU staff shortage due to infection when both incubation and quarantine times of COVID-19 are considered.

Meaning: Scheduling ICU staff according to a pandemic's epidemiological characteristics reduces the number of infected staff and increases the chances of operational functionality of healthcare facilities and systems.

INTRODUCTION

Healthcare worker (HCW) safety is pivotal during a pandemic such as Coronavirus Disease 2019 (COVID-19) to maintain operational functionality of healthcare systems. In late December 2019 an outbreak of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) was reported in the Hubei Province of China. With a median incubation time of 3 days (range 0-24 days) and mean incubation time of 5 days,^{1,2} the predominantly respiratory droplet transmitted disease spread at a high rate to a global level. On March 12 2020, the World Health Organization (WHO) formally declared the COVID-19 outbreak a pandemic.

Despite its primary transmission route, namely, human-human transmission via respiratory droplets and/or aerosols, the virus remains active and infectious for hours in aerosols and for few several days on surfaces.³ Importantly, both public and HCW health is affected, causing a global shortage of HCWs as quarantine for infected individuals is recommended for a period of 14 days.⁴ This is a particular threat to patient outcomes in the intensive care unit (ICU) setting, as ICU staff (physicians, nurses, respiratory therapists) are highly specialized and cannot readily be replaced.

Evidence providing guidance for HCW staffing in ICUs and other acute care services under regular (non-pandemic) conditions is abundant and mainly focuses on economics and outcome quality.^{5,6} Data in pandemic situations, such as currently with COVID-19, is far more sparse, and only a few authors have suggested that institutions should “allow isolation teams to have a 2-week off-duty observation period (“wash-out” period), after every period of ward cover if manpower allows”.⁷

However, an additional qualified workforce to implement respective policies is typically not available, and optimal HCW staffing strategies remain unclear. We therefore aimed to study the dynamics of staff shortages over time under usual scheduling compared to a schedule adapted to disease epidemiology, specifically that of COVID-19. This is done to optimize schedules and to allow for optimal allocation of staff resources, which is crucial for maintaining a maximum of work power during a pandemic crisis, to ensure ICU capacity, and to save the lives of those most severely affected by the COVID-19 pandemic.

We hypothesized that HCW shortage could be reduced when shift models adjusted to specific disease epidemiology like COVID-19 are implemented by adapting working hours and periods of “off time,” in which staff are quarantined at home such that they cannot readily be infected during this dedicated off time.

METHODS

This study uses publicly available epidemiologic data about COVID-19 and does not involve any clinical or patient derived data. Therefore, and due to the urgency of the current COVID-19 pandemic, no waiver from an institutional review board or research ethical committee was sought.

To study the dynamics of staff-dropouts over time for different scheduling strategies, we defined two theoretical scenarios (Table 1), of which one is a typical routine staffing according to a theoretical labor law (Scenario A) as applicable in this or similar form in most Western healthcare systems, and the other following the characteristics of a pandemic virus including both its incubation period and different quarantine times (Scenario B). While the recommended quarantine time of 14 days would require extensive additional qualified workforce, which is likely not readily available in most hospitals, an abbreviated quarantine of 7 days covers the median incubation time of 3 days (range 0-24 days) and mean of 5 days, allowing for testing before starting into a new cycle of shifts.

Workforce

We assumed an exemplary workforce of 84 HCWs per scenario, all of whom are employed on a full-time basis (40 hours per week). Assuming a 40 bed ICU and a 2:1 ratio of patients to staff, we require 20 staff members to be present at all times (7 x 24 hours/week). With this starting position, we define 2 potential scenarios of in-hospital infection, including a COVID-19 infection probability of either 10%, 25%, or 40% per week, over a period of 120 days. The reported duration of COVID-19 infection ranges from 15 to 21 days.⁸ Based on reported mortality rates of a range of 1% to 15% for infected individuals,⁹ we assume that 99% of affected HCWs will be able to return to work 14 to 21 days after diagnosis, whereas 3% to 10% will not return.

Scenarios

Scenario A: The regular 40-hour per week schedule, requires $168 \text{ total hours} \div 40 \text{ hours per staff} = 4.2$ full time staff member per week, in order for a single staff member to be present at all times. Based on our 2:1 patient to staff member ratio assumption, this requires $4.2 \times 20 = 84$ staff members for each week. For a second week, we assume the same 84 staff members would be scheduled, assuming no infections.

Scenario B: Each staff member works $7 \text{ days} \times 12 \text{ hours/day} = 84 \text{ hours}$ for 1st week and then are quarantined for the 2nd week, then repeat (3rd week on, 4th week off, etc.). This scenario thus requires $168 \text{ total hours of coverage} \div 84 \text{ hours of coverage per staff member} = 2.0$ full time employees for every 20 patients during week 1 of a 2-week period. We would thus need $2.0 \times 20 = 40$ total staff members for week 1 and another, a completely separate 40 staff members for week 2 (when week 1 staff is on quarantined), for a total of 80 staff members. This is 5% less staffing than required for Scenario A. We report results as the percent of the starting work force (not the actual numbers) that is present for each week, so that a perceived benefit for Scenario B will have been achieved with slightly less staff than Scenario A. When a staff member in Scenario B is off work (every other week, quarantined at home), we assume they are not at risk for COVID-19.

Simulations

We conducted simulations varying the probability of becoming COVID-19 infected when at work for a given week (10%, 25% and 40 %), the probability of dying once infected with COVID-19 (10%, 3% and 1%), and the quarantine time if infected with COVID-19 (3 weeks and 2 weeks). A staff member was assumed to be immune for the duration of the 120 days after recuperating from an infection.

For both scenarios, each staff was assigned a single probability of being infected each week at work as a random draw from a binomial distribution with the given underlying probability (10%, 25% or 40%).

Whether a staff became infected in a given week was then determined by a random draw from the Bernoulli distribution using the staff member's randomly drawn probability of being infected.

Likewise, whether or not a staff member died after infection was determined by a random draw from

the Bernoulli distribution at either 10% or 3% or 1%, depending on the simulation. After becoming infected, a staff member was considered to be away from work and quarantined for 2 or 3 weeks, depending on the simulation, unless they died. 500 simulations were run for each variation of the parameters of interest.

The primary outcome was the percentage of initial staff members who were at work for each of the 17 weeks (120 days). Scenarios A and B were compared on the percent of HCWs at work during each week. Note that while we are assuming a 40-bed ICU with a 2:1 ratio of patients to staff for illustrative purposes, the estimated percentage of initial staff that is at work would apply to any ICU in which the staffing scheme is applied.

RESULTS

Our main simulations in **Figures 1-3**, using a three-week quarantine period after infection, show workforce savings due to rotating staff each week (Scenario B) for each infection probability, and most noticeably in the first 6-10 weeks. The effect progressively increases as the probability of infection increases from 0.10 to 0.25 to 0.40. **Table 2** details the absolute savings in the workforce by comparing the scenarios on the percentage working at each week. For example, the maximum effect for Scenario B occurred at week 4 for each infection probability: 17% savings for infection probability of 0.10, 32% for probability of 0.25 and 38% for probability 0.40. In each case, the scenarios equalized towards the end of the 17-week period as most staff had been infected, recovered, and returned back to the work force.

Second, we conducted simulations analogous to the main simulations above but assuming a 3% mortality probability after infection instead of 10%. Results were very similar to the primary findings (**Supplemental Digital Content, Figures 1-3, Table 1, <http://links.lww.com/AA/D81>**). Additionally, assuming a 1% mortality probability after infection was assessed. Results were also very similar to the primary findings (**Supplemental Digital Content, Figures 4-6, Table 2, <http://links.lww.com/AA/D81>**).

Third, simulation results assuming a 2 week (instead of 3 week) quarantine period are shown in **Figures 4-6**. We still observe effects due to the staff rotations in Scenario B, and in a similar pattern as for the primary aim, but to a lesser extent. With a 2 week quarantine period, the maximum savings occur earlier, in the first few months (**Table 3**).

DISCUSSION

In the current analysis, we demonstrate that HCW staffing shortages may be reduced when epidemiology-based staffing models are used in a pandemic setting. This may be of particular importance with regard to both reducing infections of HCW and to maintain operational functionality of healthcare facilities and systems.

Specifically, our data provide implications in terms of health and safety for personnel, operational functionality and the potential outcome benefit for patients treated in ICUs.

While our data provide evidence for adjusted staffing in a pandemic such as currently with COVID-19, basic recommendations such as appropriate training and equipment to avoid cross-contamination remain of key importance.⁷ Furthermore, surveillance of employee health status must be enhanced⁷ and infected individuals must be removed from the workplace immediately. If possible, it may appear advisable to define a pool of standby professionals to replace dropouts during the “on-duty” periods. Yet, to avoid any cross contamination with healthy clusters, such replacements might preferably be scheduled in parallel with the cluster, even if this means a shorter on-duty time.

Staff must be trained on appropriate physical and psychological self-care¹⁰, and rigorous isolation precautions to protect personnel and non-affected patients are pivotal.¹¹ Supportive coping mechanisms to avoid burnout since resource deprivation and higher workload due to shortages in manpower are major drivers of burnout and concomitant potential additional drop-outs.¹²

While this manuscript focuses on ICU workforce, an adapted form of staffing throughout all departments of a hospital in a comparable cadence appears to be beneficial to avoid cross-contaminations whenever possible. Further respective staffing logic may be advisable for companies outside the healthcare sector.

A number of limitations of our analysis must be recognized. First, the theoretical nature of the models, as opposed to having implemented a research study to compare these staffing scenarios, is certainly a limitation. Additionally, as ICU care is a 24/7/365 business, our standard scenario is a simplified version and exact working schemes likely differ between hospitals. Nevertheless, it may provide guidance given the diversity of labor laws and “best common practice” for routine staffing in health care settings globally. Second, epidemiologic data and recommendations (e.g., regarding quarantine times) may be diverse and may differ among regions and affected healthcare systems. Nevertheless, our simulations reveal a consistent dip in HCW availability that is expected after 4 weeks of a COVID-19 outbreak independent of specific sickness periods and quarantine times.

Our simulations reveal significant benefits of a staffing model beyond routine staffing practices. While an epidemiology-based model may reduce staff shortages, we recommend to adjust staff scheduling in an effort to prevent a significant dip in available healthy HCWs whenever possible. Apparently, the networking time over the two-week period is slightly higher in the pandemic scenario ($84 \text{ hours} \div 2 \text{ staff members} = 42 \text{ hours each}$ versus 40 hours per week in our standard scenario). Yet, the high burden for staff members working 84 hours per week must be balanced by a week off to recover. In conclusion, staffing with disease-based epidemiologic indices may reduce HCW shortage by mitigating the shortage of affected workforce. Although this requires considerable efforts by and commitment of staff members, it may be essential in an effort to best maintain staff health and operational functionality of healthcare facilities and systems.

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Figure Legends

Figure 1. Comparing Scenario B (rotating staff each week in a pandemic schedule with 84 h / week followed by 1 week off, displayed in red) to Scenario A (regular schedule with 40 h / week, displayed in blue) on percent of starting work force available to work each week. The average probability of being infected at work was 0.10 (each staff's probability was a random draw from the underlying probability), and probability of mortality given infection was 10%. **Infected staff were quarantined for 3 weeks before returning to work.**

Figure 2. Comparing Scenario B (rotating staff each week in a pandemic schedule with 84 h / week followed by 1 week off, displayed in red) to Scenario A (regular schedule with 40 h / week, displayed in blue) on percent of starting work force available to work each week. The average probability of being infected at work was 0.25 (each staff's probability was a random draw from the underlying probability), and probability of mortality given infection was 10%. **Infected staff were quarantined for 3 weeks before returning to work.**

Figure 3. Comparing Scenario B (rotating staff each week in a pandemic schedule with 84 h / week followed by 1 week off, displayed in red) to Scenario A (regular schedule with 40 h / week, displayed in blue) on percent of starting work force available to work each week. The average probability of being infected at work was 0.40 (each staff's probability was a random draw from the underlying probability), and probability of mortality given infection was 10%. **Infected staff were quarantined for 3 weeks before returning to work.**

Figure 4. Comparing Scenario B (rotating staff each week in a pandemic schedule with 84 h / week followed by 1 week off , displayed in red) to Scenario A (regular schedule with 40 h / week, displayed in blue) on percent of starting work force available to work each week. The average probability of being infected at work was 0.10 and probability of mortality given infection was 10%. **Infected staff were quarantined for 2 weeks before returning to work.**

Figure 5. Comparing Scenario B (rotating staff each week in a pandemic schedule with 84 h / week followed by 1 week off, displayed in red) to Scenario A (regular schedule with 40 h / week, displayed in blue) on percent of starting work force available to work each week. The average probability of being infected at work was 0.25 and probability of mortality given infection was 10%. **Infected staff were quarantined for 2 weeks before returning to work.**

Figure 6. Comparing Scenario B (rotating staff each week in a pandemic schedule with 84 h / week followed by 1 week off, displayed in red) to Scenario A (regular schedule with 40 h / week, displayed in blue) on percent of starting work force available to work each week. The average probability of being infected at work was 0.40 and probability of mortality given infection was 10%. **Infected staff were quarantined for 2 weeks before returning to work.**

Table Legends

Table 1. Staffing scenarios in routine and pandemic times.

Table 2. Labor Sparing Using Rotating Weeks (B) and Standard (A): *Three* Week Quarantine After Infection.

Scenarios Rotating Weeks (B) and Standard (A) are compared on the absolute difference for each week in the percent of the starting labor force. We assume infection probabilities of 0.10, 0.25 and 0.40, a two-week sick leave for infected staff who survive, and a mortality probability of 0.10. Table shows numerical results from

Figures 1-3.

Table 3. Labor Sparing Using Rotating Weeks (B) and Standard (A): *Two* Week Quarantine After Infection.

Scenarios Rotating Weeks (B) and Standard (A) are compared on the absolute difference for each week in the percent of the starting labor force. We assume infection probabilities of 0.10, 0.25 and 0.40, a two-week sick leave for infected staff who survive, and a mortality probability of 0.10. Table shows numerical results from Figures 4-6.

Tables

Table 1: Staffing scenarios in routine and pandemic times			
<i>Scenario</i>	<i>On-duty per 7 days</i>	<i>Off-duty</i>	<i>Quarantine if infected</i>
A (routine)	5 x 8h shifts (3 shifts per 24h)	2 shifts during week	2 or 3 weeks
B (pandemic)*	7 x 12h shifts (2 shifts per 24h)	One week off	2 or 3 weeks
*Numbers based on mean COVID-19 incubation time ² and the recommended COVID-19 quarantine period of 14 (optionally 7 or 21) days ⁴			

Table 2: Labor Sparing Using Rotating Weeks (B) and Standard (A): Three Week Quarantine After Infection

Infection	<i>0.10</i>			<i>0.25</i>			<i>0.40</i>		
Mortality	<i>0.10</i>			<i>0.10</i>			<i>0.10</i>		
	% Working		<i>Savings</i>	% Working			% Working		<i>Savings</i>
<i>Week</i>	<i>A</i>	<i>B</i>		<i>A</i>	<i>B</i>		<i>A</i>	<i>B</i>	
1	100.0	100.0	0.0	100.0	100.0	0.0	100.0	100.0	0.0
2	90.0	100.0	10.0	74.7	100.0	25.3	60.3	100.0	39.7
3	81.1	90.0	8.9	56.6	74.3	17.7	36.4	60.1	23.7
4	73.1	90.0	16.9	42.7	75.2	32.5	22.1	60.1	38.0
5	75.1	90.2	15.1	55.0	79.0	24.0	49.3	72.4	23.1
6	76.8	90.2	13.4	63.7	79.0	15.3	65.7	72.7	7.1
7	78.4	90.3	12.0	70.5	82.1	11.6	75.3	79.1	3.8
8	79.5	90.5	11.0	75.5	81.8	6.3	81.1	79.1	-2.0
9	80.8	90.6	9.8	78.9	84.4	5.5	84.5	83.7	-0.7
10	81.8	90.6	8.8	81.6	84.2	2.6	86.6	83.9	-2.7
11	82.6	90.4	7.8	83.6	85.7	2.1	87.8	86.2	-1.6
12	83.3	90.4	7.1	85.0	85.5	0.5	88.6	86.8	-1.7
13	84.0	90.4	6.4	86.1	86.8	0.7	89.1	87.9	-1.2
14	84.6	90.6	5.9	86.9	86.9	0.0	89.4	88.4	-1.0
15	85.2	90.6	5.4	87.6	87.4	-0.2	89.6	88.7	-1.0
16	85.6	90.6	5.0	88.1	87.3	-0.8	89.7	89.1	-0.6
17	86.1	90.4	4.2	88.6	88.3	-0.2	89.8	89.2	-0.6
Mean	8.7 (4.2)			8.4 (10.7)			7.2 (14.4)		
(SD)									
Reference	Figure 1			Figure 2			Figure 3		

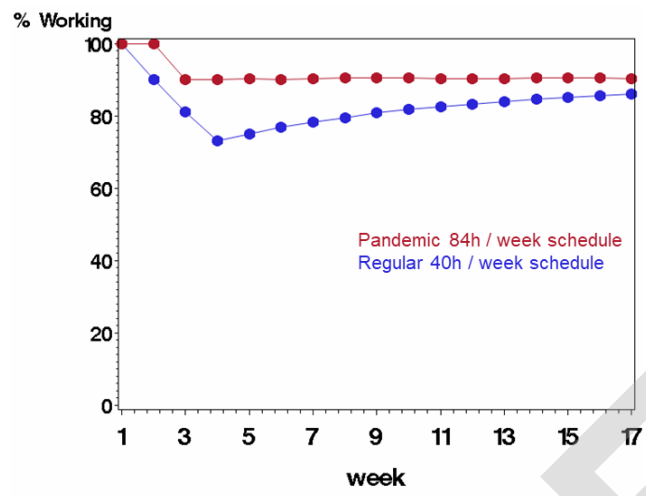
Quarantine: number of weeks a staff member stays off of work after being infected
Infection: probability of an uninfected staff becoming infected in a given week at work
Mortality: probability of an infected staff succumbing to the coronavirus
% working: Percent of starting staff working for the given week
Savings: Absolute difference between **Scenario B** (rotating weeks, 7-12 hour shifts) and **Scenario A** (Standard 8-hr shifts each week)

Table 3: Labor Sparing Using Rotating Weeks (B) and Standard (A): Two Week Quarantine After Infection

<i>Infection</i>	<i>0.10</i>			<i>0.25</i>			<i>0.40</i>		
<i>Mortality</i>	<i>0.10</i>			<i>0.10</i>			<i>0.10</i>		
	% Working		Savings <i>s</i>	% Working		Savings	% Working		Savings
<i>Week</i>	<i>A</i>	<i>B</i>		<i>A</i>	<i>B</i>		<i>A</i>	<i>B</i>	
1	100.0	100.0	0.0	100.0	100.0	0.0	100.0	100.0	0.0
2	89.9	100.0	10.1	75.1	100.0	24.9	60.0	100.0	40.0
3	80.8	90.2	9.4	56.6	74.9	18.3	36.3	60.1	23.8
4	82.1	89.9	7.8	65.1	74.8	9.7	58.1	59.9	1.9
5	83.2	90.4	7.3	71.5	78.8	7.4	71.2	72.4	1.2
6	84.1	90.0	5.9	76.3	78.8	2.5	78.9	72.6	-6.4
7	85.0	90.4	5.4	79.8	81.8	1.9	83.1	79.5	-3.6
8	85.5	90.4	4.9	82.3	82.1	-0.2	85.8	79.4	-6.3
9	86.0	90.2	4.2	84.1	83.9	-0.1	87.4	83.4	-4.0
10	86.4	90.0	3.5	85.3	83.8	-1.5	88.5	83.5	-5.0
11	86.8	90.1	3.3	86.4	85.6	-0.8	89.2	86.1	-3.0
12	87.2	90.4	3.1	87.4	85.4	-2.0	89.5	86.2	-3.3
13	87.6	90.2	2.6	88.0	87.0	-0.9	89.7	87.6	-2.1
14	87.9	90.1	2.1	88.5	86.5	-2.0	89.9	87.4	-2.6
15	87.9	90.3	2.5	88.8	87.6	-1.2	90.0	88.7	-1.3
16	88.0	90.5	2.4	89.1	87.3	-1.7	90.1	88.3	-1.7
17	88.3	90.1	1.8	89.2	88.4	-0.9	90.1	89.1	-1.0
Mean	4.5 (2.8)			3.1 (7.8)			1.6 (12.0)		
(SD)									
Reference	Figure 4			Figure 5			Figure 6		

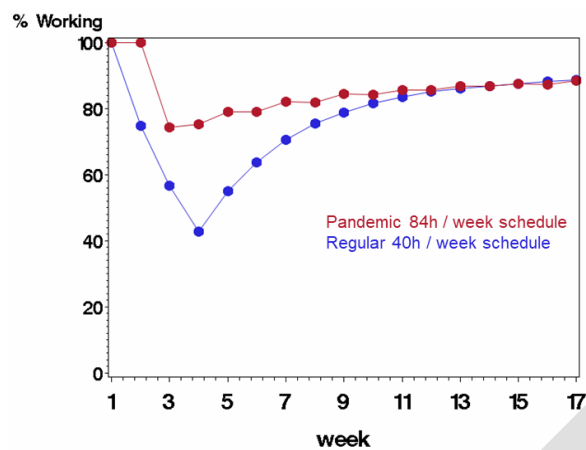
Quarantine: number of weeks a staff member stays off of work after being infected
Infection: probability of an uninfected staff becoming infected in a given week at work
Mortality: probability of an infected staff succumbing to the coronavirus
% working: Percent of starting staff working for the given week
Savings: Absolute difference between **Scenario B** (rotating weeks, 7-12 hour shifts) and **Scenario A** (Standard 8-hr shifts each week)

Figure 1



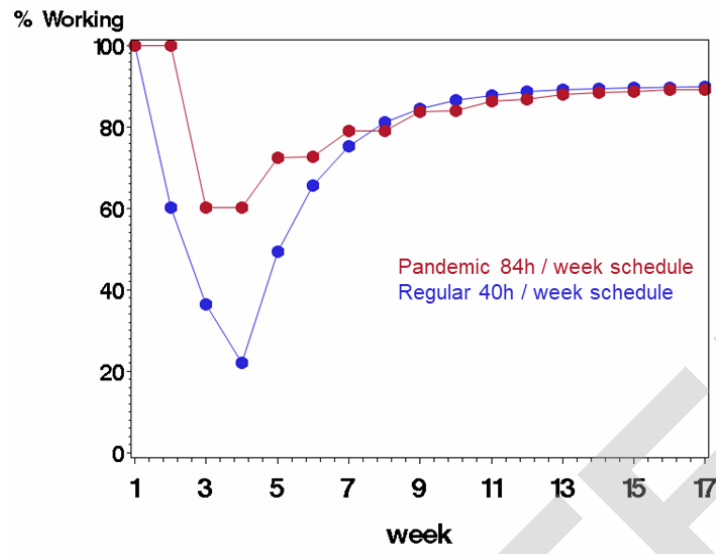
ACCEPTED

Figure 2



ACCEPTED

Figure 3



ACCEPTED

Figure 4

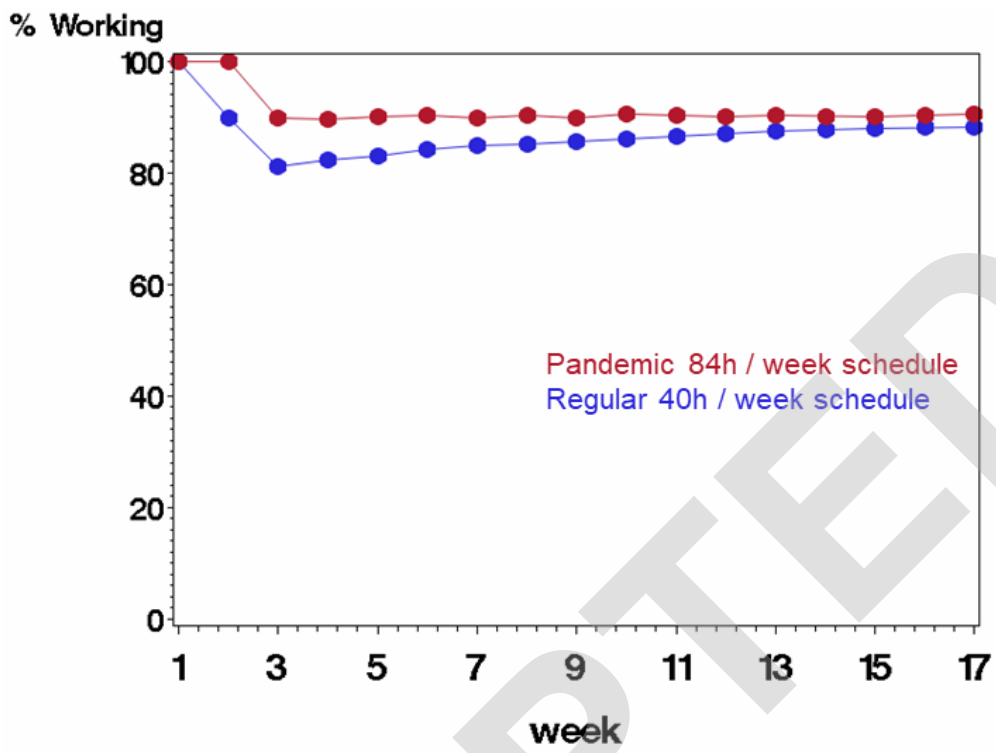
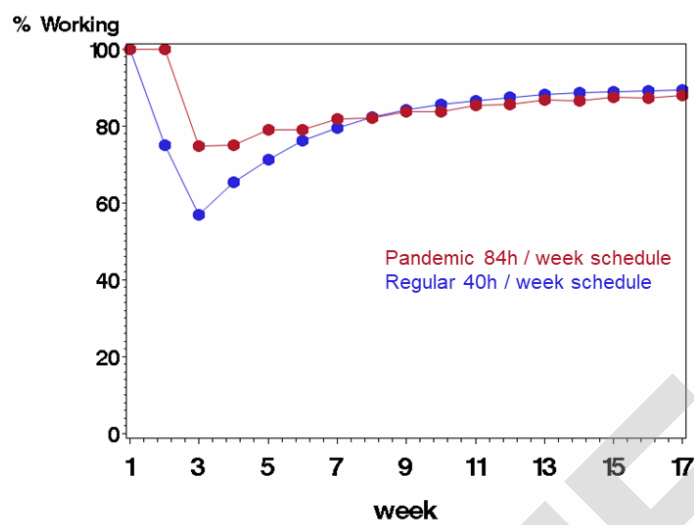
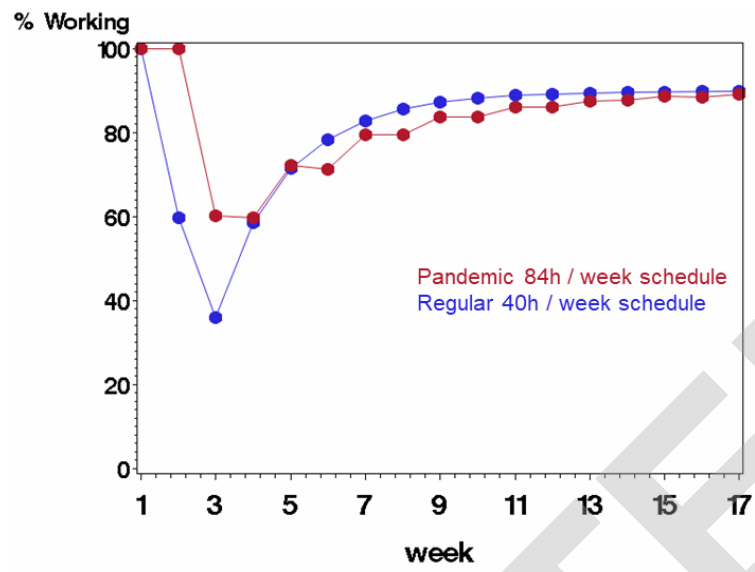


Figure 5



ACCEPTED

Figure 6



ACCEPTED