Strategic Optimization of Patient Flow and Staffing Schemes during the COVID-19 Pandemic through Operations Management in a Neonatal Intensive Care Unit

Paul Sherwin O. Tarnate, MD and Anna Lisa T. Ong-Lim, MD

Division of Infectious and Tropical Diseases in Pediatrics, Department of Pediatrics, Philippine General Hospital, University of the Philippines Manila

ABSTRACT

Background. The COVID-19 pandemic posed challenges in making time-bound hospital management decisions. The University of the Philippines -Philippine General Hospital (UP-PGH) is a tertiary COVID-19 referral center located in Manila, Philippines. The mismatch of increasing suspected or confirmed COVID-19 infected mothers with few documented cases of infected infants has caused significant patient overflow and manpower shortage in its NICU.

Objective. We present an evaluated scheme for NICU bed reallocation to maximize capacity performance, staff rostering, and resource conservation, while preserving COVID-19 infection prevention and control measures.

Methods. Existing process workflows translated into operational models helped create a solution that modified cohorting and testing schemes. Staffing models were transitioned to meet patient flow. Outcome measurements were obtained, and feedback was monitored during the implementation phase.

Results. The scheme evaluation demonstrated benefits in (a) achieving shorter COVID-19 subunit length of stay; (b) better occupancy rates with minimal overflows; (c) workforce shortage mitigation with increased non-COVID workforce pool; (d) reduced personal protective equipment requirements; and (e) zero true SARS-CoV-2 infections.

Conclusion. Designed for hospital operations leaders and stakeholders, this operations process can aid in hospital policy formulation in modifying cohorting schemes to maintain quality NICU care and service during the COVID-19 pandemic.

Keywords: COVID-19, operations research, NICU, patient flow

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Corresponding author: Paul Sherwin O. Tarnate, MD
Division of Infectious and Tropical Diseases in Pediatrics
Department of Pediatrics
Philippine General Hospital
University of the Philippines Manila
Taft Avenue, Ermita, Manila 1000, Philippines
Email: psotarnate@gmail.com
ORCiD: https://orcid.org/0009-0008-1006-3669

INTRODUCTION

The COVID-19 pandemic is a challenging infectious disease outbreak that required disaster management guidelines and protocols to maintain smooth operations and prevent an overwhelmed health care system. It tested hospital operations managers to make time-critical decisions to ensure quality service delivery while maintaining a safe environment for their health care workers.[1,2] Historically, disaster management mainly involved *increasing physical space and medical support*, but many other literature explored valid and effective alternative responses. Previous infectious disease outbreaks prompted the development of guidelines and models to assist hospital planning, including those of the H1N1, influenza, and SARS-CoV epidemics.

Underutilization of operations research for decision-making

Operations research (OR) is a mathematical science subfield that deals with advanced analytical methods to help in better decision-making. It is involved in improvement of program outcomes, assessment of feasibility of new strategies and ultimately advocating policy change. Problem formulation with the corresponding model construction is the first step, followed by derivation of solutions from the model. The final goal is testing the solution and implementation of the results. Methodologies in healthcare operations research involves healthcare operations improvement, workforce scheduling, and resource allocation.[3,4] Operations research in health care was historically not part of the mainstream decision-making by clinicians due to multiple factors, such as: (1) insufficient mathematical/engineering background in the health care sector; (2) lack of access to OR papers, which typically do not target heath care professionals; (3) lack of data for modelling; (4) poor in-house OR expertise; and (5) expense involved in engaging external OR consultants. However, even if OR requires a background in mathematics, it may simply be about using intuition to execute.[5]

Institutional problem

The University of the Philippines-Philippine General Hospital (UP-PGH) was initially assigned as the country's COVID-19 referral center, activating hospital-wide disaster planning as the number of COVID-19 cases continued to increase. The Infectious and Tropical Diseases in Pediatrics (INTROP) and Newborn Medicine services, in coordination with the hospital's COVID-19 Crisis Management Team, implemented a cohorting system last March 2020 for infants born to mothers with suspected or confirmed COVID-19 infection. Even as the numbers of suspected and proven SARS-CoV-2 infected mothers admitted in the institution continued to rise, infants largely tested negative, using the standard protocol where RT-PCR would be performed on the 24th hour of life. This mismatch became a unique challenge in the cohorting process in the Neonatal Intensive Care Unit (NICU) causing some significant problems: (a) patient overflows in the COVID-19 subunit led to mixing of cohorts, which posed concerns in the maintenance of safe isolation and possible undue exposure to other neonates and healthcare workers from SARS-CoV-2; (b) admission processes were delayed due to establishing SARS-CoV-2 RT-PCR testing at the 24th hour of life, with due emphasis on scheduled hospital-wide PCR running times; (c) the healthcare staff rostering largely focused on decking manpower for COVID-19 areas, decreasing the number of the available pool to man non-COVID areas; and (d) the required personal protective equipment was compounded by the number of staff making rounds in the COVID-19 subunit.

Creation and evaluation of new cohorting scheme

As in all operational analysis, valuable feedback was forwarded to provide improvement points in cohorting schemes, staff rostering, and resource allocation. This paper evaluated the newly developed cohorting scheme (pertained in this paper as *New Scheme*) against the old cohorting scheme (*Old Scheme*) in the triaging of infants admitted to the UP-PGH NICU, in terms of patient flow, unit capacity performance, staff rostering and personal protective equipment (PPE) conservation, and the preservation of infection and control measures for SARS-CoV-2 infection.

METHODS

Study design and setting

The University of the Philippines – Philippine General Hospital (UP-PGH) is a tertiary government medical center located in Manila, Philippines. It has been designated a COVID-19 referral center, with its NICU catering to infants of mothers diagnosed to have COVID-19. This presented a distinctive setup in which neonates were cohorted based on maternal COVID-19 status.

Physical space

The Unit is divided into two (2) subunits: the non-COVID-19 subunit and the COVID-19 subunit. During the evaluation period, the original physical space for the NICU was under renovation. The non-COVID-19 subunit (denoted here as "non-COVID NICU") was assigned a single room accommodating ten (10) patients, together with an adjacent transitional room having a capacity of four (4) patients, completing a fourteen (14)-patient capacity. With the advent of the COVID-19 pandemic, the hospital administration provided three (3) rooms for the NICU COVID-19 subunit, allocated for infants born to mothers with suspected or confirmed SARS-CoV-2 infection. The room names are simplified in this study to avoid confusion:

- COVID Room A – cohort room for infants of neonates with asymptomatic unscreened mothers with no significant COVID-19 exposure
- COVID Room B – cohort room for infants of mothers with symptomatic unscreened mothers or if with significant COVID-19 exposure
- COVID Room C – cohort room for infants of COVID-19 positive mothers

Each room has a capacity of eight (8) patients each, totaling twenty-four (24) patients for this subunit. Should overflows be encountered, each room's capacity was increased to ten (10) as needed.

Patient flow algorithms based on old and new cohorting schemes

Based on the admission algorithm for infants delivered at the UP-PGH, all pregnant mothers were screened for significant exposure and COVID-19 symptoms, with their SARS-CoV-2 RT-PCR results verified to be able to cohort infants into COVID and non-COVID subunits of the Neonatal Intensive Care Unit. The old cohorting system is simplified into an algorithm as shown in Figure 1.

After determination of critical paths, the new operational scheme was instituted with the aim of resolving the problems that arose with the use of the old scheme. The new cohorting scheme algorithm (21 October 2020) is shown in Figure 2.

Identification of critical paths

The critical path is the longest sequence of activities or tasks that must be completed to successfully finish a defined process. To aid in the determination of critical path, the algorithms were translated into process flow models for analysis as shown in Figure 3. Each node (circle) is denoted by *X*, where *X* represents a specific activity of the whole process:

A: Identification of mother's status / Classification
B: Birth and assessment of clinical status
C: Initial cohorting (old) / RT-PCR testing at birth (new)
D: RT-PCR testing at 24th hour of life
E: Determination of need for continued NICU care
F: Disposition (*e.g.,* recohorting)
G: Course and discharge

In essence, the admission process of a newborn was laid out into a series of discrete activities, and the activities that must be done on time were determined.

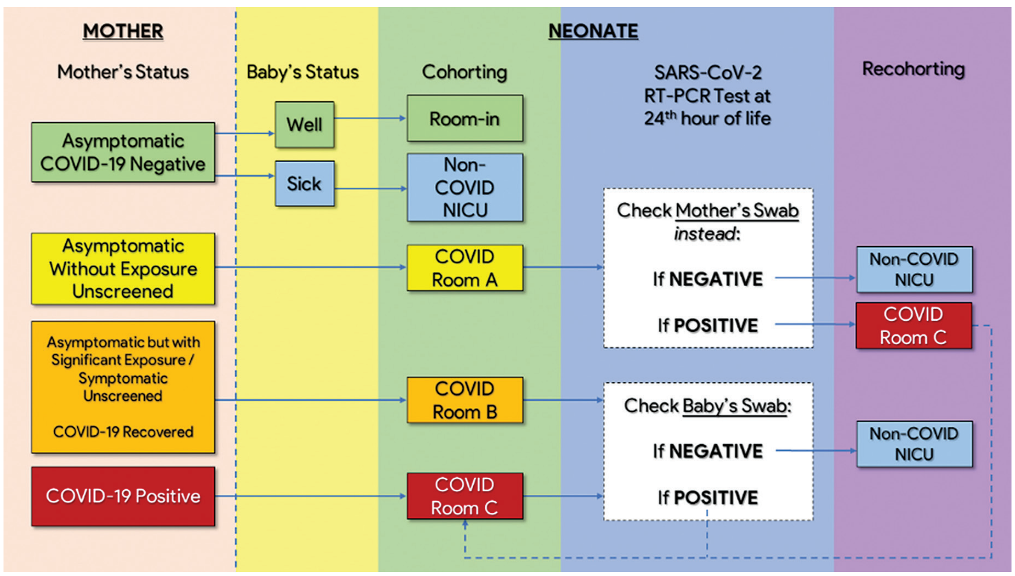

Figure 1. Decision algorithm of the Old Scheme implemented in the NICU.

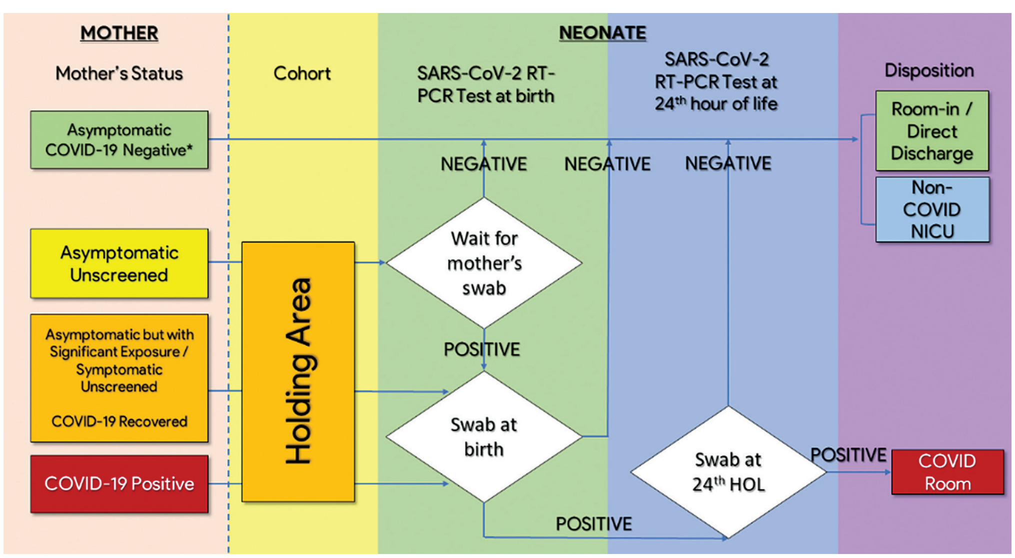

Figure 2. Decision algorithm of the New Scheme implemented in the NICU.

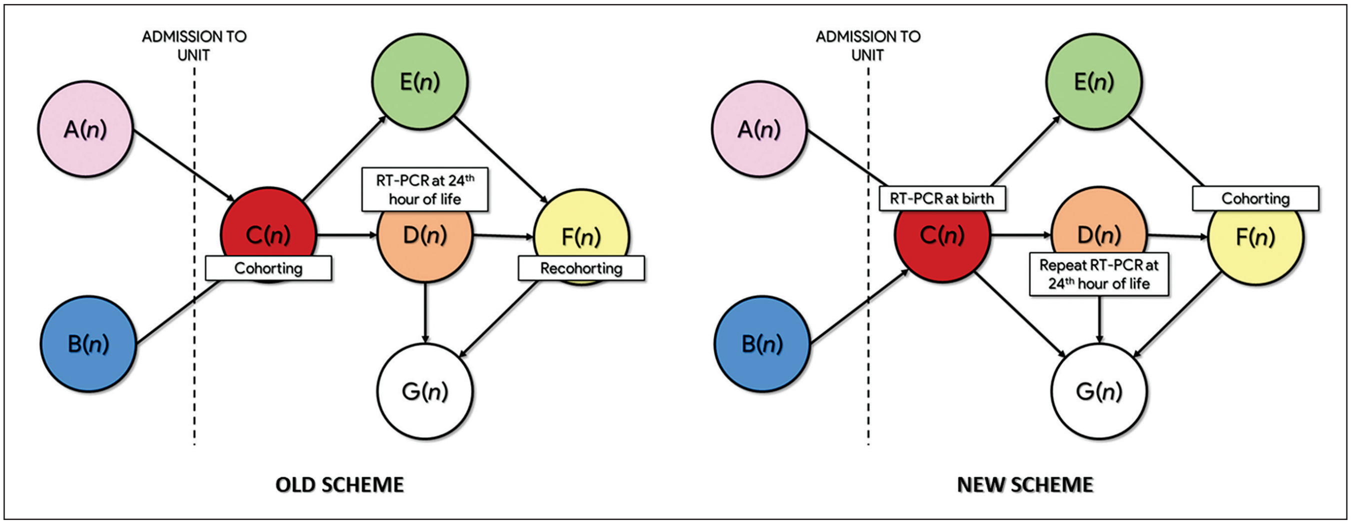

Figure 3. Process flow / operations model comparisons between schemes.

Each activity also has immediate predecessors, which require completion prior to starting the next activity. The completion time required for each activity is *n* number of *days* denoted as *X(n)*. If the activity was *not applicable* to the patient, the time required to finish the activity was *zero (0)*. The length of stay of the patient in days, denoted by t(*ij*), where *i* is the admission time and *j* is the discharge (or trans-out) time, was recorded per patient as part of census monitoring of the NICU. By estimating activity time *n* based on workforce feedback and derived from the t(*ij*), critical path analysis was performed. Activities C, D, F, and G were identified as critical path tasks.

Data collection and procedure

The list of admitted neonates in the NICU was obtained through the UP-PGH's electronic medical record system, the Computerized Registry of Admissions and Discharges (RADISH). The *Old Scheme* evaluation period will be from August 21 to October 20, 2020 (sixty days before implementation of the new scheme), while the *New Scheme* evaluation period will be from October 21 to December 20, 2020 (sixty days after implementation of the new scheme). The following data were recorded in an electronic data collection form: (a) *Admission time,* defined as the recorded date and time the neonate was placed under care within the Unit; (b) *Unit transfer time* as the recorded date and time the neonate was transferred out of the Unit for rooming-in or other reasons; and (c) *Discharge time* as the recorded date and time the neonate was discharged from the Unit. NICU length of stay (LOS) was considered the time spent by each neonate being admitted *within* the unit (*i.e.*, this may correspond to *admission-to-unit-transfer time* or *admission-to-discharge time*, whichever temporally comes first). Time was calculated in days with one decimal place (fraction of a day).

Reports of SARS-CoV-2 RT-PCR tests of neonates admitted in the NICU were duly recorded. Phenomenological data regarding pediatric resident and nursing staffing schemes were documented. PPE estimation was done using a modified adaptation of the Perelman School of Medicine Personal Protective Equipment Calculator for COVID-19 - CHIME (last updated 30 April 2020).[6]

Data processing and statistical analysis

Descriptive statistics were used to summarize the population sizes of admitted neonates, as well as illustrating differences in SARS-CoV-2 detection rates and PPE consumption, under the old scheme and new scheme. Frequency and proportion were used for categorical variables, median and interquartile ranges for non-normally distributed continuous variables, and mean and standard deviation for normally distributed continuous variables. The theoretical least time to complete the course of an admitted patient in the old scheme versus the new scheme was made using the Program Evaluation Review Technique (PERT). Since the distribution parameters of the lengths of stay (LOS) of neonates were unspecified or non-normative, non-parametric methods of analysis was done for statistical robustness. Mann-Whitney-Wilcoxon test was used in validating differences between recorded length of stay (LOS) of neonates under old and new operational schemes. An electronic programmable spreadsheet (Microsoft® Excel® for Microsoft 365 MSO) will be used in recording and computing data, as well as for graphing tools.

Ethical considerations

Approval from the Research Ethics Board (REB) was obtained before the conduct of this study. Review of medical records and its anonymity were maintained in accordance with the National Ethical Guidelines of Health and Health-Related Research (NEGHHR) 2017. The principal investigator accomplished the data collection forms to ensure that only the data needed by the study were collected and that no data were used for any purpose other than what was intended for this study. All patient information and data collected in the study were kept confidential.

RESULTS

Troubleshooting patient flow

Table 1 shows the baseline comparisons of the admission data in NICU during the schemes' evaluation period. Notice that most neonates were eventually discharged (86%, 68.5%), but there was an increase in transfers to outside of the unit (from 5.4% to 22.8%) with the *New Scheme.* Overall hospital days were grossly longer during the *New Scheme* (1527.5 patient-days vs. 1298.8 patient-days). The overall average and median length of stay (LOS) for the *Old Scheme* was 4.7 days and 5.5 days, respectively. The average LOS for the *New Scheme* relatively increased to 5.8 days, but median LOS was much lower at 2.5 days.

To further elucidate the comparisons, Table 2 illustrates the admission data into the NICU COVID subunit during each evaluation period. There was a decrease in the proportion of NICU COVID subunit admissions (from 90.6% down to 77.6%), but the trend towards the increase in unit transfers remain the same (from 18.7% to 80.9%), with patient discharge being carried out once the neonates are transferred to the non-COVID subunit or roomed-in with their respective mothers. Distinguishable is the decrease in hospital patient-days during the *New Scheme*, with only an average LOS of 1.1 days and a median of 0.8 day.

Although no simulation models were used in the setting of our NICU, valuable feedback on where bottlenecks occurred helped determine which activities caused considerable delay. Since critical paths were identified, tweaking the activities within the path contributed to the potential shortening of the length of stay. This was theoretically determined by considering best- and worst- case scenario using the Program Evaluation and Review Technique (PERT). PERT analyzes and represents the critical path tasks to identify the least time for completing a whole project or, in this case, a whole admission. This helps in aiming for a reduced time (and cost) of the admission, considering variation in the completion times of each task or activity (optimistic, likely, pessimistic). The PERT data are approximation of the time required for each task to be completed based on phenomenological information. For instance, in the *Old Scheme* PERT, the critical path task "D: RT-PCR testing at 24th hour of life," is assigned theoretical PERT data in days depending on specific scenarios in mind:

1. *Optimistic* – If a neonate for admission has a COVID-19 negative mother, the time it would take for the task to be finished is at 0 day (since protocols no longer require RT-PCR process in this subset of neonates).
2. *Likely* – If a neonate for admission has an asymptomatic unscreened mother, the time it would take for the decision point of doing an RT-PCR swab depends on the maternal RT-PCR results, which will be expected to come out within 0.9 day (less than 24 hours).
3. *Pessimistic* – If a neonate for admission has a COVID-19 positive mother, the time it would take to accomplish the RT-PCR swab task will be at most a shift after the 24th hour of life (to be included in the batch RT-PCR testing of neonates).

Tables 3 and 4 show the Program Evaluation and Review Technique (PERT) results for the *Old Scheme* and *New Scheme*. With due considerations for each scenario, the estimated length of stay will be approximately 7+ days for the *Old Scheme* and 6+ days (shorter) for the *New Scheme.* Real-time admission data are discussed in detail in the next section (see *"Discussion"*).

Table 1. Baseline Comparisons of Admission Data in NICU between Schemes

Admissions & Lengths of Stay	Old Scheme	New Scheme
Evaluation Period	Aug 21 to Oct 20	Oct 21 to Dec 20
Number of admissions into the unit (%)	**278**	**263**
Unit transfers	15 (5.4)	60 (22.8)
Discharges	239 (86.0)	180 (68.5)
Still admitted	24 (8.6)	23 (8.7%)
Hospital patient-days (%)	**1298.8**	**1527.5**
Unit transfer-days	20.5 (1.6)	126.1 (8.3)
Discharge-days	1056.6 (81.4)	1108.1 (72.5)
Days until end of evaluation period*	221.7 (17.0)	293.3 (19.2)
Length of stay	-	-
Mean (± standard deviation)	4.7 (5.5)	5.8 (8.3)
Median (interquartile range)	5.5 (3.8)	2.5 (5.3)

** for patients who are still admitted during the evaluation period*

Table 2. Baseline Comparisons of Admission Data in NICU COVID Subunits between Schemes

Admissions & Lengths Of Stay	Old Scheme	New Scheme
Evaluation Period	Aug 21 to Oct 20	Oct 21 to Dec 20
Number of admissions – COVID subunit (%)	**252 / 278 (90.6)**	**204 / 263 (77.6)**
Unit transfers	47 (18.7)	165 (80.9)
Discharges	190 (75.4)	39 (19.1)
Still admitted	15 (5.9)	0
Hospital days (%)	**906.2**	**223.9**
Unit transfer-days	207.6 (22.9)	145.7 (65.1)
Discharge-days	561.7 (62.0)	78.2 (34.9)
Days until end of evaluation period*	136.9 (15.1)	0
Length of stay	-	-
Mean (± standard deviation)	4.3 (7.7)	1.1 (1.3)
Median (interquartile range)	2.2 (2.3)	0.8 (0.8)

** for patients who are still admitted during the evaluation period*

Table 3. Program Evaluation and Review Technique (PERT) for the Old Scheme

Critical Path Tasks*	PERT Data (days)			PERT Expected Time (te)	Standard Deviation	Variance
	Optimistic	Likely	Pessimistic			
C	0.1	0.1	0.1	0.10	0.000	0.000
D	0	0.9	1.4	0.83	0.233	0.054
F	0	0.35	0.7	0.35	0.117	0.014
G	0	2.35	4.8	2.37	0.800	0.640
				Σ_{te} = 3.650		Σ_V = 0.708
Completion Time (days): 6.93			***Probability of Completion:*** 100.00%			Z = 3.8980

** Critical path tasks: C: Initial cohorting; D: RT-PCR testing at 24th hour of life; F: Recohorting; G: Course and discharge*

Table 4. Program Evaluation and Review Technique (PERT) for the New Scheme

Critical Path Tasks*	PERT Data (days)			PERT Expected Time (te)	Standard Deviation	Variance
	Optimistic	Likely	Pessimistic			
C	0	0.1	0.67	0.18	0.112	0.012
D	0	0	0.33	0.06	0.055	0.003
F	0	0.35	0.7	0.35	0.117	0.014
G	0	1.45	5.3	1.85	0.883	0.780
				Σ_{te} = 2.43		Σ_V = 0.809
Completion Time (days): 5.94			***Probability of Completion:*** 100.00%			Z = 3.8978

** Critical path tasks: C: RT-PCR testing at birth; D: RT-PCR testing at 24th hour of life; F: Recohorting; G: Course and discharge*

Figure 4A-C shows the daily occupancy data of each COVID Room during the evaluation period of the *Old Scheme*. COVID Room A served as the cohort room for infants of neonates with asymptomatic unscreened mothers with no significant COVID-19 exposure. During the evaluation period, this room was beyond half capacity for 85.0% of the time (51/60 days) and has been on full capacity for a 33.3% of the period (20/60 days). COVID Room B served as the cohort room for infants of mothers with symptomatic unscreened mothers or if with significant COVID-19 exposure. It was usually used for its designated purpose, but it also served as an overflow room of Room A and Room C. This room was beyond half capacity for 58.3% of the time (35/60 days) and has been on full capacity for 8.3% of the period (5/60 days), which may suggest underutilization of this room. COVID Room C served as the cohort room for infants of COVID-19 positive mothers. This room was beyond half capacity for 68.3% of the time (41/60 days) and has been on full capacity for 25.0% of the period (15/60 days). Figure 4D likewise shows the daily occupancy data for the Holding Area during the evaluation period of the *New Scheme*. The Holding Area served as the starting point for all admissions to the COVID subunit in the *New Scheme*. This room was beyond half capacity for 43.3% of the time (26/60 days) and has been on full capacity for only 6.7% of the period (4/60 days), the least occupancy rate among all evaluated rooms.

Performance management

Using the Mann-Whitney Wilcoxon Test, the sum of ranks in the *Old Scheme* was 74993 (R_1) while the sum of ranks in the *New Scheme* was 71618 (R_2). Hence, the test statistic $W = R_1$ = 74993. An upper tail test was performed, where H_0: median (difference) ≤ 0 (*i.e.*, length of stay is *greater* in the *New Scheme*) and H_a: median (difference) >0 (*i.e.*, length of stay is lesser in the *New Scheme*). Both sample sizes were greater than 10, which meant normal approximation and Z-statistic were used. The significance level was α = 0.05, and the critical value for an upper tail test was z_c = 1.64. The rejection region for this upper tail test was $R = \{z : z > 1.6449\}$.

The Z-statistic was computed using the formula

$$z = \frac{W - \mu_W}{\sigma_W}$$

where:

$$\mu_W = \frac{n_1 (n_1 + n_2 + 1)}{2} \qquad \sigma_W = \sqrt{\frac{n_1 n_2 (n_1 + n_2 + 1)}{12}}$$

Since it was observed that $z = -0.1898 \leq z_c = 1.6449$, it can be concluded that the hypothesis that the lengths of stay using the *New Scheme* is greater than that of the *Old Scheme* was not rejected. Using the P-value approach, the p-value is p = 0.392 which was greater than the α = 0.05. Therefore, there was *not enough evidence* to claim that the difference between the median lengths of stay of the *Old Scheme* and *New Scheme* was statistically significant at α = 0.05. Figure 5 illustrates the boxplots compaing the LOS using Wilcoxon rank scores of the *Old Scheme* vs *New Scheme* for the whole NICU. The

Figure 4. Occupancy per day in the Old Scheme: **(A)** COVID Room A; **(B)** COVID Room B; **(C)** COVID Room C; and New Scheme: **(D)** Holding Area.

bottom side of the box represents the first, quartile, and the top side, the third quartile. The width of the central box represents the inter-quartile deviation. The horizontal line inside the box represents the median. The vertical lines protruding from the box extends to the minimum and maximum values.

To facilitate uncertainty reduction in the sense that the measured lengths of stay were greatly contributed by activity *G(n) = Course and discharge*, sensitivity analysis was performed involving neonates admitted within the COVID subunit (in which activities include the critical paths) between the two *Schemes*.

Running through the Mann-Whitney Wilcoxon Test, the sum of ranks in the *Old Scheme* (COVID subunit) was 75884 (R_1) while the sum of ranks in the *New Scheme* (COVID subunit) was 28312 (R_2). Hence, the test statistic $W = R_1 = 75884$. An upper tail test was similarly performed, with H_0 and H_a as previously stated. The significance level was $\alpha = 0.05$, and the critical value for an upper tail test remained at $z_c = 1.64$. The rejection region for this upper tail test was $R = \{z : z > 1.6449\}$.

Since it was observed that $z = 13.080 > z_c = 1.6449$, it can be concluded that the hypothesis that the lengths of stay using the *New Scheme* is greater than that of the *Old Scheme* was rejected. Using the P-value approach, the p-value is $p < 0.001$ which was less than the $\alpha = 0.05$. Therefore, there was *enough evidence* to claim that the difference between the median lengths of stay of the *Old Scheme* (COVID subunit) was statistically greater than that of the *New Scheme* (COVID subunit) at $\alpha = 0.05$ significance level. Figure 6 shows the boxplots comparing the LOS using Wilcoxon rank scores of the *Old Scheme* vs *New Scheme* for their respective COVID subunits.

Staff rostering

In the NICU, a total of forty (40) nurses comprised its nursing pool. Nurse rostering during the *Old Scheme* assigned three (3) nurses for the COVID-19 subunit to cater to each Room, (1) bedside nurse for the non-COVID-19 subunit, and (1) charge nurse for the whole unit, with a total of five (5) nurses per shift. There are three (3) shifts in a day with eight (8) hours per shift. Thus, there were a total of fifteen (15) nurses assigned for duty per day. Coverage constraints remain at 8:1 patient-to-nurse ratio, with no COVID subunit nurse to work in the non-COVID subunit to prevent cross-contamination. Each week, time-related constraints dictated the COVID-19 subunit nurses to undergo quarantine for the following seven (7) days for observation. The totality of this setup and these constraints made the available proportion

Data Summary								
Groups	N	Min	Q_1	Median	Q_3	Max	Mean	SD
Group 1	278	2	144.25	270	398.75	536	269.759	149.2431
Group 2	263	1	126	271	412.5	541	272.3118	163.7391

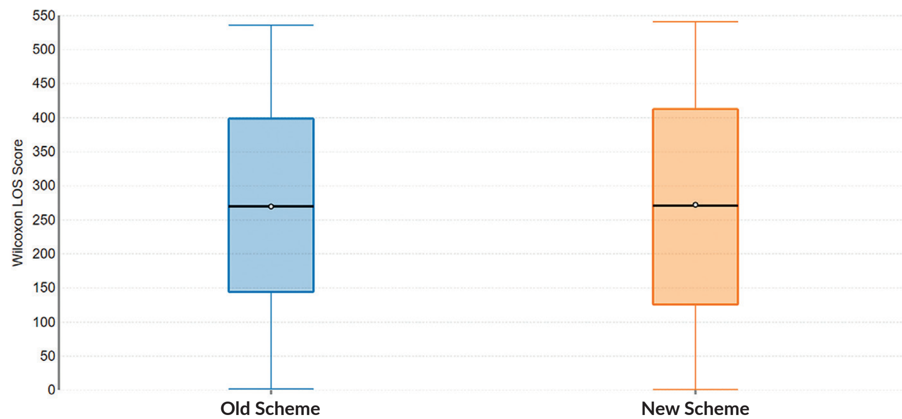

Figure 5. Boxplots comparing the lengths of stay (LOS) in the NICU between the two schemes using the Mann-Whitney-Wilcoxon Test.

Boxplot created: Good Calculators. 2021. Box-and-Whisker Plot Maker. [online] Available at: <https://goodcalculators.com/box-plot-maker/>

Data Summary								
Groups	N	Min	Q_1	Median	Q_3	Max	Mean	SD
Group 1	252	7	226.75	314.5	389.25	456	301.127	104.2745
Group 2	204	1	56.75	114.5	203.5	449	138.7843	104.1307

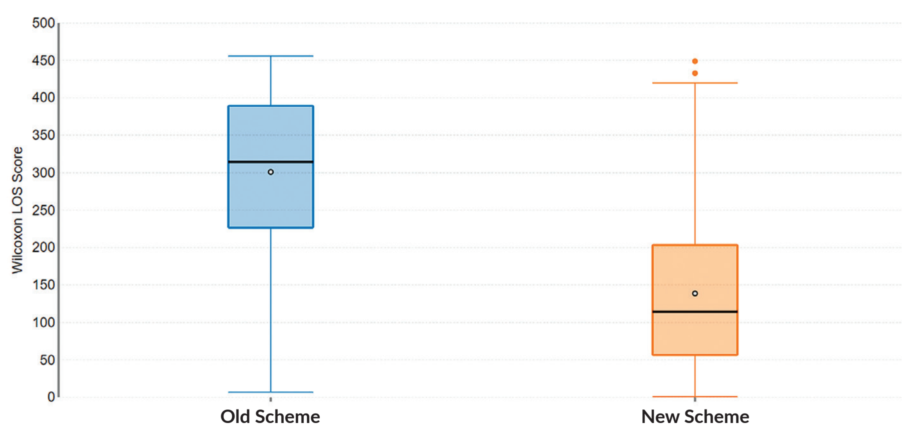

Figure 6. Boxplots comparing the lengths of stay (LOS) in the COVID subunits between the two schemes using the Mann-Whitney-Wilcoxon Test.

Boxplot created: Good Calculators. 2021. Box-and-Whisker Plot Maker. [online] Available at: <https://goodcalculators.com/box-plot-maker/>

of the nursing pool for the non-COVID subunit relatively smaller. Similarly, one (1) senior pediatric resident and two (2) junior pediatric residents per day were assigned to the COVID subunit, translating to nine (9) pediatric residents going on duty in rotations. The non-COVID subunit is manned by one (1) senior pediatric resident and three (3) junior pediatric residents. In total, required physician manpower for the setup was nine (9) for the planning period of four (4) weeks.

With the implementation of the *New Scheme*, the COVID subunit was now limited to a single room, while all other pre-existing rooms redesignated to become part of the non-COVID subunit expansion. Only one (1) bedside nurse was required to man the Holding Area each shift while all other nursing staff were reassigned to the non-COVID subunit, minimizing the affected workforce by the previously mentioned coverage and time-related constraints. From the original six (6) pediatric senior residents and ten (10) pediatric junior residents, the rostering was cut to three (3) seniors and six (6) juniors. This gave the opportunity to reassign physicians to man other areas (including the non-NICU pediatric floors).

Resource Allocation

A Personal Protective Equipment (PPE) Forecasting Calculator was recently developed collaboratively by the University of Pennsylvania and Penn Medicine. Projected hospitalized/ICU/ventilated censuses and admissions may be inputted with modifiable scenarios (standard vs contingency) to estimate daily and cumulative PPE forecasts.[1,6] Using this calculator, PPE cumulative requirement estimates using the *Old Scheme* versus the *New Scheme* were calculated using staffing-based and contact-based calculation assumptions. For both schemes, length of shifts for healthcare workers remained at eight (8) hours per shift. Patient-to-staff ratios for residents, fellows, and consultants were assigned at 24:1 and 8:1 for the *Old Scheme* and *New Scheme*, respectively. Patient-to-nurse ratios remained at 8:1 for both schemes. PPE use calculations were staff-based, except for clean gloves which are replaced per contact with neonates with presumed SARS-CoV-2 infection. It was assumed one (1) set of N95, gown, and eye protection, and at most two (2) changes of surgical masks were used by each healthcare worker per shift. One (1) pair of gloves was used per patient contact which ranged up to a maximum of one (1) change per hour. Number of real-time admissions were inputted per day throughout the evaluation period (*i.e.*, sixty days each). Table 5 summarizes the cumulative requirement (60 days) for each evaluation period. Overall, there is a general reduction in the estimated PPE cumulative requirement (58.2-72.7% reduction).

Neonatal SARS-CoV-2 infection prevention and control

Table 6 shows the SARS-CoV-2 RT-PCR results of infants born to mothers with suspected or proven COVID-19 infection during both evaluation periods. A total of 120/278 (43.2%) and 166/263 (63.1%) RT-PCR swabs of infants (during the *Old Scheme* and *New Scheme,* respectively) were no longer performed due to the COVID-19 negative statuses of their mothers. Infants of mothers who are unscreened for COVID-19 continued to represent the major proportion of the admissions on both evaluation periods (43.2% to 67.7%).

During the *Old Scheme*, there was a total of 158/278 (56.8%) infants born to COVID-19 positive mothers, of which 154 specimens were successfully processed. Infant SARS-CoV-2 RT-PCR results returned negative at 153/154 (99.4%), with one infant recorded as RT-PCR positive (0.6%). This neonate whose RT-PCR result returned positive was discharged asymptomatic prior to knowing the result.

Likewise, during the *New Scheme,* a total of 97/263 (36.9%) infants of COVID-19 positive mothers were recorded, of which 94 specimens were successfully processed. Results returned negative for 90/94 (95.7%) RT-PCR specimens. Repeat RT-PCR tests at the 24th hour of life were no longer done since the neonates remained asymptomatic and were cleared for discharge. A total of 4/94 (4.3%) RT-PCR tests done upon the infant's birth returned positive, in which subsequently no established primary SARS-CoV-2 positive infections were recorded upon repeat testing at 24th hour of life. No healthcare-associated SARS-CoV-2 infections were recorded on using either *Scheme* (Table 7).

In estimating SARS-CoV-2 RT-PCR cost-per-neonate (*P*), this can be calculated by multiplying the RT-PCR cost (*s*) by the ratio of RT-PCR tests done over the number of tested neonates. That is,

$$P = \text{RT PCR cost (s)} \times \frac{\text{RT PCR tests done}}{\text{number of tested neonates}}$$

Table 5. Estimated Personal Protective Equipment (PPE) Cumulative Requirement between Schemes

Personal Protective Equipment (PPE)	Old Scheme Aug 21 to Oct 20	New Scheme Oct 21 to Dec20	% Reduction Scheme: Old vs. New
N95	779	326	58.2
Surgical mask	1,527	653	57.2
Gloves (pairs)	34,895	9,520	72.7
Gown	779	326	58.2
Booties	779	326	58.2
Bouffant Cap	779	326	58.2
Disposable eye protection	779	326	58.2

Table 6. SARS-CoV-2 RT-PCR Results of Infants Born to Mothers with Suspected or Proven COVID-19 Infection during both Schemes

SARS-CoV-2 Monitoring			Old Scheme		New Scheme	
Evaluation Period			Aug 21 to Oct 20		Oct 21 to Dec 20	
Maternal Status	Maternal RT-PCR	Infant RT-PCR	Frequency (%)			
COVID-19 Negative	Negative	*Not done*	17	(100.0)	25	(100.0)
	Subtotal		**17**	**(6.1)**	**25**	**(9.5)**
COVID-19 Suspect	Negative	*Not done*	92	(76.7)	137	(77.0)
	Positive	*Positive*	0		3	(1.7)
		Negative	28	(23.3)	38	(21.3)
	Subtotal		**120**	**(43.2)**	**178**	**(67.7)**
COVID-19 Probable	Negative	*Not done*	2	(22.2)	1	(50.0)
	Positive	*Positive*	0		0	
		Negative	7	(77.8)	1	(50.0)
	Subtotal		**9**	**(3.2)**	**2**	**(0.8)**
COVID-19 Confirmed	Positive	*Positive*	1	(0.9)	1	(1.8)
		Negative	105	(95.5)	50	(92.6)
		*Error**	4	(3.6)	3	(5.6)
	Subtotal		**110**	**(39.6)**	**54**	**(20.5)**
COVID-19 Recovered	Negative	*Not done*	**9**	**(40.9)**	**3**	**(75.0)**
	Positive	*Positive*	0		0	
		Negative	13	(59.1)	1	(25.0)
	Subtotal		**22**	**(7.9)**	**4**	**(1.5)**
Grand Total			**278**		**263**	

** specimen not processed by the laboratory for logistic reasons*

During the *Old Scheme*, *P* was equivalent to 154/154(*s*) = 1*s*, which implied that there was a 1:1 ratio for RT-PCR cost-per-neonate. On the other hand, during the *New Scheme*, since four tests returned positive, these will be repeated at the 24th hour of life as per protocol. *P* then was equivalent to (94+4)/94*s* = 98/94*s* = 1.04*s*, which meant a 4% increase in the RT-PCR test cost per neonate.

DISCUSSION

Much has been written about maximizing patient flows, in which they refer to ways in boosting the ability of health care systems to effectively care for patients with minimal delays in their movement through different stages of care. Patient flow involves the medical care, hospital resources, and internal systems to efficiently move patients from admission to discharge. Bed shortages or patient overflow is the most cited constraint on patient flow and is treated as a symptom of an underlying root cause—more likely from the way of utilization of beds rather than their gross number.[7] Streamlining patient flow for appropriate isolation, management, and infection prevention can contribute to the prevention of nosocomial infection for both patient and healthcare worker. One must also consider the substantial increases in critical care bed capacity in managing patient flow.[8] Hospital patient bed demand changes over time, which can influence a growing mismatch resulting in unnecessary patient overflow. Establishing bed demand for each requirement can address patient overflow.[5] Appointing clinical bed managers may also contribute to solving encountered challenges in efficient bed management in view of ICU surge capacities.[7,9]

Table 7. SARS-CoV-2 Primary and Secondary Infection Monitoring between Schemes

SARS-CoV-2 Monitoring	Old Scheme	New Scheme
Evaluation Period	Aug 21 to Oct 20	Oct 21 to Dec 20
Positive SARS-CoV-2 initial swabs	**1***	**4**
Positive on repeat	-	0
Undetermined**	-	1 (25.0)
Negative on repeat***	-	3 (75.0)
Secondary SARS-CoV-2 infections	**0**	**0**
Total (frequency)	**1/154 (0.6)**	**0/94 (0)**

* *considered COVID-19 positive, since RT-PCR test was done at 24th hour of life*
** *clinician unable to repeat RT-PCR*
*** *initial positive result attributed to maternal fluids*

Reviewing the data presented in Tables 1 and 2, the increase in transfers to outside of the unit with the *New Scheme* may be due to allowances for rooming-in with their respective mothers after initial stabilization. Longer overall hospital days during the *New Scheme* may be due to the need for prolonged admission for the cases during this evaluation period. Interestingly, the median LOS for the *New Scheme* was much lower, raising the possibility that the distribution of LOS in the *New Scheme* was lower than that of the *Old Scheme*. The decrease in hospital patient-days during the *New Scheme* supports the notion that the overall increased LOS in the *New Scheme* may be due to the contribution of the patient course *after* transfer outside of the COVID subunit.

Approaches that allow rapid identification and isolation of suspected/known COVID-19 cases and initiation of planning for surge ICU bed capacities may be good strategies to maintain quality ICU care and services.[10] Alban et al. established a stochastic patient flow simulation model to support intensive care unit capacity management issues. They provided a way to estimate patient ICU capacity requirements given the COVID-19 patient arrival rates and unplanned non-COVID-19 patient capacities. Their simple web-based tool can also be used to support similar capacity decisions for hospitals to estimate throughput rates and degree of need to transfer patients to alternative facilities. This is accomplished by inputting parameters such as patient length of stay, arrival rates, and reserved bed capacities per category.[11] A Monte Carlo simulation instantiation of a susceptible, infected, removed (SIR) model with a 1-day cycle has been used by Weissman et al. to estimate the timing of surges in clinical demand before exceeding existing hospital capacity in best- and worst-case scenarios in surges of patients with COVID-19.[1] Reviewing the PERT results in Tables 3 and 4 show that the faster turnover of admitted neonates (either direct discharge or unit transfer) may have contributed to the good occupancy rate.

Hospital operations have long been gauged by various critical performance metrics to help hospital managers improve the efficiency of health care of their respective hospital units. The length of stay (LOS) has been identified as one such metric, with prior research pointing to its association to cost, efficiency, quality of health care, and speed of service delivery. Lower LOS generally are viewed as a valid and comprehensive reflection of better operational performance.[12]

Statistical analyses involving LOS have been frequently done incorrectly in various literature in that parametric statistical tests were applied to non-normally distributed LOS datasets, leading to reduction of power and increased type II error probability. Non-parametric statistical methods instead were advocated to be a core component in LOS analyses.[13] For two balanced inpatient samples, comparison of LOS datasets should be through methods with high power and acceptable type I error, such as the Student t test with logarithmic or rank transformation, the Mann-Whitney-Wilcoxon test, or the Kruskal-Wallis test.[14] Reviewing the Mann-Whitney-Wilcoxon test results between the two schemes, there was enough evidence to claim that lengths of stay of neonates admitted within its COVID subunit were found to be significantly shorter using the *New Scheme*.

Rostering is defined as "the placing, subject to constraints, of resources into slots in a pattern. One may seek to minimize some objective, or simply to obtain a feasible allocation. Often the resources will rotate through a roster."[15] Rostering of the healthcare workforce has historically been a complex scheduling problem, with the goal of evenly balancing workload to achieve a more contented and more effective workforce. Burke et al. provided an illustrative example to highlight rostering terminology use. In a certain *planning period* of typically four (4) weeks, staff members with their particular *skill category* (*e.g.*, the head nurse, bedside nurses, nursing aides) are distributed to *shift types* (AM, PM, Night). *Coverage constraints*, which pertains to personnel requirements, are determined by nurse-patient ratios imposed by the management. *Time-related constraints* refer to restrictions on personal schedules, which includes personal requests and preferences.[16]

Inasmuch as there are decades of research on nurse staffing methods, evidence remains uninformative and there is still no concrete evidence to support the choice of any single tool to address healthcare worker rostering problems.[17] Making plans for manpower augmentation, segregation of teams that handle COVID-19, and work structure modifications (*e.g.*, extra shifts, restricting leave) may be recommended in ICU staffing issues. Acceptable shift hours and provision of rest and mental health support are also included in intensive care management recommendations.[8,10] Creating models with ideal healthcare worker-to-patient ratios may also aid in staffing challenges.[9] The implementation of the *New Scheme* decreased the need for manpower augmentation while maintaining acceptable shift hours and standard patient-to-healthcare worker ratios. By modifying the process, most of the healthcare workforce were freed from COVID-19 assignments, allowing an increase in the working pool for the non-COVID subunit (and even non-NICU floors).

Shortage of masks and other PPE may threaten efforts to prevent transmission especially in resource-limited settings. Thus, appropriate rationing of scarce ICU resources might be needed.[8,10] Ethical values and guiding principles that aim to save the most lives and more years of life are a consensus in the rationing of scarce healthcare resources in the COVID-19 pandemic.[18] During the implementation of the *New Scheme*, cumulative estimates for PPE showed substantial reduction.

While there are insufficient data to create recommendations on routine Essential Intrapartum and Newborn Care (EINC) for the purpose of preventing SARS-CoV-2 transmission to the neonate, infection prevention and control protocols should be in place until adequate data are available. Current recommendations regarding SARS-CoV-2 testing in neonates are to test all those born to mothers with suspected or confirmed COVID-19, regardless of the clinical status of the neonate. The Centers for Disease Prevention and Control (CDC) recommends timing of the test at approximately 24 hours of age. However, the optimal testing after birth is still largely unknown. Early testing may lead to false positives as the infant's nasopharynx may be contaminated with maternal fluids. All neonates born to mothers with suspected or confirmed COVID-19 infection must be considered infected unless proven otherwise by test results. If a neonate does not remain in the mother's room, due care must be exercised in placing the neonate with other high-risk neonates by considering resource availability and capabilities for isolation and cohorting. In some hospitals where the NICU is the only suitable environment for appropriate care for sick neonates, determination of placement guidelines should be made at the facility level.[19]

Evidence from recent systematic reviews and meta-analyses of reported neonatal SARS-CoV-2 infections have demonstrated that vertical transmission of SARS-CoV-2 is yet to be established and that neonatal infection is uncommon. Ongoing research is needed to establish epidemiology of COVID-19 in neonates, though.[20,21] However, horizontal transmission is likely possible since a lack of mother-neonate separation from birth is associated with late infection.[22] Similar findings have been likewise observed in our institution: a recent retrospective study using data from April to June 2020 involving infants born to mothers with SARS-CoV-2 infection showed no documented positive RT-PCR results among these neonates.[23]

Insofar as the management team valued achieving the goal of improving patient flow, maintenance of infection prevention and control remained a priority. In the background of proper cohorting schemes to prevent horizontal SARS-CoV-2 transmission and infection, recent evidence showing little to no vertically transmitted SARS-CoV-2 infection in neonates contributed to the decision of integrating the three rooms into a single Holding Area, freeing the other rooms for non-COVID subunit use. In any case, each neonate was placed in an isolette for added protection for possible SARS-CoV-2 transmission.

Instituting early RT-PCR testing time in the *New Scheme* (upon birth instead of 24th hour of life) contributed to the faster disposition of admitted patients in the Holding Area. Although it carried a risk of producing results not representative of infant COVID-19 status as the infant's nasopharynx may be contaminated with maternal fluids, the overall benefits of the scheme nevertheless outweighed this risk. This study's findings may also support existing data in that SARS-CoV-2 vertical transmission cannot be fully established yet.

In estimation of costs, it is fortunate that the cost increase using the *New Scheme* was offset by considering operational costs (O) per day. The average LOS of a neonate in the COVID subunit during the *Old Scheme* and *New Scheme* were 4.3 days and 1.1 days, respectively. Hence, since $4.3(O) > 1.1(O)$, the lesser theoretical operational costs for the *New Scheme* offset the slight increase in costs for RT-PCR testing.

Summary of Findings

As part of the feedback cycle of operations management, this study established five (5) key findings in using the *New Scheme* over the *Old Scheme*:

1. ***Troubleshooting patient flow.*** Identifying and modifying activities within the critical path, (*i.e.*, by performing the initial swab upon birth), resulted to theoretical shorter length of stay, as identified using the Program Evaluation and Review Technique (PERT), and better COVID subunit occupancy rates.
2. ***Performance management.*** Although the overall median lengths of stay within the whole NICU did not significantly differ, the LOS of neonates admitted within its COVID subunit using the *New Scheme* were found to be significantly shorter compared to when using the *Old Scheme*.
3. ***Staff rostering.*** By modifying the process, most of the healthcare workforce were freed from COVID-19 assignments, allowing increase in the staff pool for decking to non-COVID areas.
4. ***Resource allocation.*** Cumulative estimates for PPE show substantial reduction in using the *New Scheme*.
5. ***Neonatal SARS-CoV-2 infection prevention and control.*** Although early RT-PCR testing time carried a risk in producing results not representative of infant COVID-19 status, there was still no true primary nor healthcare-associated SARS-CoV-2 positive infections recorded on using the *New Scheme*.

CONCLUSIONS AND IMPLICATIONS

This paper aimed to present an evaluated scheme for the reallocation of neonatal intensive care unit beds to maximize capacity performance, as well as staff rostering and resource conservation, while preserving COVID-19 infection prevention and control measures. Decision to continue pursuing this scheme was made through operations research in the assessment of its feasibility and derivation of solutions from the model.

Our modified scheme took a multi-faceted approach: considerations for alleviating patient overflow, healthcare workforce redistribution, and maintenance of close infection monitoring and preventive measures. The dynamics of all these factors contributed to the eventual recorded favorable outcomes. The results of the evaluation demonstrated benefits in (a) achieving shorter median lengths of stay for the COVID-19 subunit; (b) better occupancy rates with minimal overflows; (c) mitigation of workforce shortages; (d) saving PPE resources; and (e) maintenance of SARS-CoV-2 infection identification and prevention protocols.

Other institutions should be encouraged to utilize operations research to optimize their capacity and increase hospital efficiency. Planning for workflow optimization may help in addressing issues should potentially overwhelming surge of admissions recur in the future. Substantial preparations for rapid diagnosis, isolation, and infection prevention must also be instituted to prevent nosocomial transmission of SARS-CoV-2. Collaborations among hospital administrators, governments, and policy makers must focus on addressing key issues arising from a fairly understood disease.

Designed for hospital operations leaders and stakeholders alike, this operations blueprint can aid in the planning and formulation of hospital policies in the safe and effective triaging of infants born to mothers with suspected or confirmed COVID-19 infection. Operations models can be designed based on published medical data for infection prevention and control and adapted to institutional needs and local data on epidemic-related surges in need for hospital capacity. Modification of patient cohorting schemes to maximize bed capacity with concomitant effective staff rostering and prudent hospital resource allocation, with maintenance of infection and prevention control measures, enabled the maintenance of quality NICU care and service during the COVID-19 pandemic in our institution.

Recommendations

Further work is needed to program the electronic medical record system of the institution to facilitate handy access of data needed for planning in case of emergency situations, especially in a pandemic setup. Data technology may open more modelling opportunities for operations researchers. The implications of this analysis on both theory and practice include an emphasis on further research on the evaluation of current process setups, framework development for patient flow management on a national level, new policy initiatives for improved recognition and swift triaging of patients in a coordinated network of institutions, and publicizing operations research methods in dealing with hospital admission surges.

Statement of Authorship

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