An End-of-Day Dose Utilization Strategy for COVID-19 Vaccination Clinics

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CHALLENGE: Ensure That Every Vaccine Dose From Opened Vials Is Used By the End of the Day

Efficient and equitable vaccine distribution is a critical step towards stemming the global COVID-19 pandemic. Since December of 2020, U.S. healthcare facilities have been administering the Pfizer and Moderna vaccines, which are delivered in multi-dose vials. Once a vial has been opened, all doses within that vial must be used by the end of the day to avoid being wasted.

There are two reasons why doses may be left over at the end of the day, even with the vaccination team carefully watching the schedule of remaining patients and pooling vials across multiple vaccinators as the end-of-day nears. First, scheduled patients may no-show for their appointments. Second, there is variability in the number of doses within a vial. For example, Pfizer vials are planned to contain five doses, but often contain six and sometimes even seven. Thus, it is not uncommon for a vaccination clinic to have between one and six unused doses left at the end of the day.

The challenge therefore is to identify an efficient and equitable way to use these remaining doses. This must be done without excessive clerical burden, without overly extending the length of the clinic day, and without violating the existing prioritization of patient eligibility.

SOLUTION: A Short Ordered Queue of Eligible Vaccine Recipients

One way that some vaccination clinics are meeting this challenge is by maintaining a list of patients who are eligible for vaccination per current prioritization policies and randomly selecting from this list near the end of the day if extra doses remain available. These patients need to be both easily reachable near the end of the day, when the number of available remaining doses becomes known, and able to reach the vaccination clinic location quickly.

How long should this list of patients be? If too short, it may not be possible to find enough patients available on a given day to use all remaining doses. If too long, however, patients may become progressively less likely to respond as their time on the list grows and they become discouraged while waiting. This can lead to excessive clerical effort to contact patients until enough available patients are found.

A modification to this approach is to *keep a very short ordered queue of patients who are strongly committed to being available, and in return guarantee vaccination to these patients in a near-term time frame, thereby strengthening this commitment.*

For example, consider a clinic offering Pfizer vaccines, with at most seven doses per vial. Given that a new vial will not be opened unless there are remaining scheduled patients awaiting vaccination, at most there will be six extra doses and therefore there need to be six patients in the end-of-day queue, numbered first through sixth. If there are three doses left over at the end of the day, the first three patients in the queue will be brought in and vaccinated, the next three patients will move up in order (now first through third instead of fourth through sixth), and by the end of the next day, three new patients will be identified and added at the end of the queue in locations four through six.

IMPLICATIONS

A critical component of the proposed approach is the likelihood of the patients in the queue getting vaccinated in a timely manner. This is essential to ensuring a high probability that the patients in the queue will be fully committed to being accessible.

As further discussed below, we note that (with certain basic underlying assumptions) **it is very likely that every patient in the queue will be vaccinated within a week** – that is, *in the worst-case scenario*, they would have to be available for roughly five nights before getting vaccinated.

For example, as shown in the more detailed calculations provided below, if we assume at most seven doses in a vial and therefore have six patients "on-call" each day, **the probability of the sixth patient (i.e. last) being vaccinated on the first day is .14, the probability that they are vaccinated by the end of the second day is .57, and *by the end of the sixth day the probability is virtually 1***.

An added benefit to this approach is that, assuming the high probability of being vaccinated is sufficient incentive, it is likely that everyone in the queue will be easy to contact and able to reach the vaccine clinic in time, thus limiting the end-of-day delays and clerical burden.

In addition to reducing the pressure at the end of the day, it should also be easy to replace those patients who have been vaccinated at the end of the day with new patients to add to the end of the queue; these patients do not need to be identified until the end of the following day's clinic operations.

ASSUMPTIONS and TABLE OF RESULTS

For the following results and probability calculations, we assume that for a vial that contains at most v doses, there can be either 0, 1, 2, ... or $v-1$ doses leftover at the end of the day, with equal probability (i.e. $1/v$).

We also assume that the queue always contains $v-1$ patients, that they are all available every night until they get vaccinated, and that whenever a patient is vaccinated, a new patient enters the end of the queue the following day.

Under these conditions, the following table provides the probability of the person starting the queue in the last position being called for vaccination within a given number of days (between 1 and 6) after entering the queue. The probability of vaccination varies (slightly) by the maximum doses per vial, and the table shows results for maximum doses per vial ranging from 5 to 10 doses. These results reveal that there is a near 100% chance that any given patient in the queue will be called to receive a vaccine within five to six days of joining the queue if the maximum doses per vial is between 5 and 10.

	Days in Queue (d)					
Maximum Doses per Vial (v)	**1**	**2**	**3**	**4**	**5**	**6**
5	0.20	0.60	0.84	0.94	0.98	0.99
6	0.17	0.58	0.84	0.95	0.98	0.99
7	0.14	0.57	0.84	0.95	0.99	0.99
8	0.13	0.56	0.84	0.95	0.99	0.99
9	0.11	0.56	0.84	0.95	0.99	0.99
10	0.1	0.55	0.84	0.95	0.99	0.99

PROBABILITY CALCULATIONS

To calculate the probabilities shown in the table above, we first compute the probability that the last individual in line is **not** vaccinated and subtract this number from one to get the probability that the patient **is** vaccinated, with $P(v,d)$ representing the probability that a person entering the end of the queue for a vaccine that comes in v-dose vials (and thus there are $v-1$ people in the queue) is vaccinated by the end of their dth day in queue.

We start by comparing the number of possible outcomes to the number of outcomes in which the last patient in the queue is **not** vaccinated by the end of day d. On any given single day, there are v total possible outcomes: there can be either 0, 1, ... or $v-1$ doses leftover. Of these possible outcomes, all but one (where there are $v-1$ doses left over) result in the last patient in the queue not being vaccinated. Assuming that each of these outcomes is equally likely to occur (with probability $1/v$), the probability of a person entering the queue in the $(v-1)$th position *not* being vaccinated in their first day is $(v-1)/v$ and the probability that they *are* vaccinated on the their first day is $1/v$.

Now let's consider day 2. Recall that as someone in the queue is vaccinated, the remaining people each move up a spot. Thus, the person entering the queue in position $(v-1)$ will be vaccinated by the end of day d so long as there are at least $(v-1)$ leftover doses within d days. The following table shows the possible outcomes for $v=5$ and $d=2$, where the first number given is the number of vaccine doses left over on day 1 and the second number is the number of vaccine doses left over on day 2:

(0,0)	**(0,1)**	**(0,2)**	**(0,3)**	(0,4)
(1,0)	**(1,1)**	**(1,2)**	(1,3)	(1,4)
(2,0)	**(2,1)**	(2,2)	(2,3)	(2,4)
(3,0)	(3,1)	(3,2)	(3,3)	(3,4)
(4,0)	(4,1)	(4,2)	(4,3)	(4,4)

The bolded outcomes (**(0,0), (0,1)**, etc.) are those in which the last person in the queue does *not* get vaccinated within two days of entering the queue. In this example, the last person in the queue is 4th in line ($v=5$ and we assume that there are always $v-1$ people in the queue), so if there are fewer than 4 total vaccines leftover across day 1 and day 2, then this patient does not get called for a vaccination. In this example, there are 10 outcomes in which the patient is not vaccinated and 25 total possible outcomes (five for the first day times five for the second day), meaning that there is a 10/25 chance (40%) that the last person in the queue is not vaccinated within two days of entering the queue, and a 60% chance that they are.

This becomes a bit more complicated to depict when we move on to calculate day 3. Note, however, that having a total of at most n doses left over across d days can occur in the following ways: no doses left over on day 1 and at most n left over on the remaining $d-1$ days, 1 dose left on day 1 and at most $n-1$ doses left over on the remaining $d-1$ days, 2 doses left over on day 1 and at most $n-2$ doses leftover on the remaining $d-1$ days, etc.

Thus, our approach can be generalized to any v and any d by utilizing a recursive function. Let $f(v,d)$ be the function to compute the total number of possible ways in which the last person in line in the queue does not get vaccinated by the end of day d if there are v maximum doses that can be drawn per vaccine vial. We assume $v>1$ because there must be more than one vaccine dose per vial in order for there to be any doses left over. There will be $v-1$ people in line, so in order for the last person in line to **not** get vaccinated by the end of day d, there must be fewer than or equal to $v-2$ doses leftover in total over days 1 through d. The function is expressed as follows:

$$f(v,d) = \begin{cases} v-1, & \text{for } v>1, d=1 \\ \sum_{i=0}^{v-2} f(v-i, d-1) & \text{otherwise} \end{cases}$$

Once we determine $f(v,d)$, i.e. the number of possible outcomes, we must divide this by the number of total possible outcomes to obtain the probability of not getting vaccinated. The number of outcomes per day is v and thus the total number of possible outcomes is v^d. Therefore, the probability of the last person in line **not** getting vaccinated by day d is $f(v,d)$ divided by v^d and the probability that the last person entering the queue does get vaccinated by the end of their dth day in queue is

$$P(v,d) = 1 - \frac{f(v,d)}{v^d}$$