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A passive cold storage device economic model to evaluate selected immunization location scenarios

Bryan A. Norman[a], Sevnaz Nourollahi[a], Sheng-I Chen[d], Shawn T. Brown[b], Erin G. Claypool[a], Diana L. Connor[c], Michelle M. Schmitz[c], Jayant Rajgopal[a], Angela R. Wateska[c], Bruce Y. Lee[c,*]

[a] Department of Industrial Engineering, School of Engineering, University of Pittsburgh, Pittsburgh, PA, United States
[b] Pittsburgh Supercomputing Center (PSC), Pittsburgh, PA, United States
[c] Public Health Computational and Operational Research (PHICOR) Group, Johns Hopkins Bloomberg School of Public Health, 855 North Wolfe Street, Suite 600, Baltimore, MD 21205, United States
[d] Nestlé USA, Walnut Creek, CA, United States

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ABSTRACT

Background: The challenge of keeping vaccines cold at health posts given the unreliability of power sources in many low- and middle-income countries and the expense and maintenance requirements of solar refrigerators has motivated the development of passive cold storage devices (PCDs), containers that keep vaccines cold without using an active energy source. With different PCDs under development, manufacturers, policymakers and funders need guidance on how varying different PCD characteristics may affect the devices' cost and utility.
Methods: We developed an economic spreadsheet model representing the lowest two levels of a typical Expanded Program on Immunization (EPI) vaccine supply chain: a district store, the immunization locations that the district store serves, and the transport vehicles that operate between the district store and the immunization locations. The model compares the use of three vaccine storage device options [(1) portable PCDs, (2) stationary PCDs, or (3) solar refrigerators] and allows the user to vary different device (e.g., size and cost) and scenario characteristics (e.g., catchment area population size and vaccine schedule).
Results: For a sample set of select scenarios and equipment specification, we found the portable PCD to generally be better suited to populations of 5,000 or less. The stationary PCD replenished once per month can be a robust design especially with a 35L capacity and a cost of $2,500 or less. The solar device was generally a reasonable alternative for most of the scenarios explored if the cost was $2,100 or less (including installation). No one device type dominated over all explored circumstances. Therefore, the best device may vary from country-to-country and location-to-location within a country.
Conclusions: This study introduces a quantitative model to help guide PCD development. Although our selected set of explored scenarios and device designs was not exhaustive, future explorations can further alter model input values to represent additional scenarios and device designs.

1. Introduction

Cold storage is critical in vaccine supply chains because most vaccines consist of proteins that may rapidly break down and become ineffective when exposed to higher temperatures, necessitating their storage in either refrigerators or freezers until administration [1,2]. However, power source and maintenance unreliability in many low- and middle-income countries hinders the use of traditional refrigerators and freezers. Solar refrigerators can overcome these limitations but can be quite costly, require more complicated installation and maintenance, and for models with batteries, have varying battery lifetimes [3–10].

This situation has motivated the development of another alternative, passive cold storage devices (PCDs), containers that keep vaccines cold without needing an active energy source [11,12]. PCDs are composed of materials and designs that minimize heat leakage and provide space to carry vaccines and a cooling medium (i.e., a phase-changing material such as ice) keeping temperatures low. Without incorporated machinery, PCDs may require much less maintenance than refrigerators and freezers. Other benefits depend on the PCD design; for example, smaller and lighter PCDs may be

* Corresponding author. Tel.: +1 443 287 6705.
E-mail addresses: bruceleemdmba@gmail.com, brulee@jhsph.edu (B.Y. Lee).

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portable but, unlike standard vaccine carriers or cold boxes, may store vaccines for extended periods of time (i.e., several days up to one month) [13,14].

With different PCDs currently under development, manufacturers, policymakers and funders need guidance on how varying different PCD characteristics may affect the device's cost and use. Therefore, we developed an economic spreadsheet model representing the lowest two levels of a vaccine supply chain: a district store, the immunization locations that the district store serves, and the transport vehicles that operate between the district store and the immunization locations. The model compares the use of three vaccine storage device options to support health post vaccination [(1) portable PCDs, (2) stationary PCDs, or (3) solar refrigerators] and allows the user to vary different device characteristics (e.g., size and cost) and scenario characteristics (e.g., population and vaccine schedule). The model can help delineate a PCD target product profile (TPP) (i.e., a menu of desirable characteristics to guide PCD development), and potential PCD use cases (i.e., the roles, situations, and circumstances under which a PCD would be favorable) [14,15]. Here, we employ our model to evaluate a sample set of selected scenarios and device designs.

2. Methods

2.1. Model structure

Our equation-based spreadsheet model developed in Microsoft Excel (Microsoft Corporation, Redmond, WA) represents a typical district store, the immunization locations that it serves, the catchment areas served by each immunization location, transport vehicles, transport and storage devices, and all associated costs.

The influence diagram in Fig. 1 depicts the model's cost relationships for a portable PCD. The models for the stationary PCD (with only minor changes to the transport section, since the stationary PCD assumes that only vaccines and ice, not PCDs, are transported) and a solar refrigerator (which does not use ice) are similar. All three models assume that district store-based trucks will serve immunization locations in a transport loop, visiting several immunization locations per outing.

2.2. Model inputs and parameters

Table 1 lists all model parameters and their evaluated ranges [16–18]. (The model is available on our website: hermes.psc.edu.) The device hold time (HT) is the duration between ice and vaccine replenishment shipments. The swapping factor is the ratio of extra PCDs needed, in the case of portable PCDs, to swap in fully loaded PCDs (i.e., with vaccines and ice) and swap out depleted PCDs. For example, if 10 PCDs are required across an entire district and the swapping factor is 1.2, then an extra 2 PCDs (for a total of $12 = 10 \times 1.2$) will be needed to exchange full and empty PCDs.

2.3. Logistics calculations

The following steps compute the number of devices needed:

- *Step 1*: Number of doses administered per vaccination day for each vaccine equals the product of births per vaccination day, the vaccine's target coverage, and number of doses needed to complete the vaccine's regimen.
- *Step 2*: Number of vials per device replenishment equals the number of doses administered per day (Step 1) multiplied by days between vaccine and ice replenishment shipments divided by doses per vial. For relevant vaccines (e.g., lyophilized vaccines

Table 1
Inputs for the model.

User inputs	Units	Value for initial experiments
Cold storage device characteristics		
Passive cold device (PCD)		
Portable PCD		
Device capital cost	$US	700, 1000, 1300
Net storage capacity	Liters	4–8
Device hold time	Days	28
Required ice per week of hold time	kg	1
Swapping factor		1.2
Equipment lifetime	Years	10
Stationary PCD		
Device capital cost	$US	1750, 2500, 3250
Net storage capacity	Liters	20–50
Device hold time	Days	28, 84
Required ice per week of hold time	kg	1.8
Equipment lifetime	Years	10
Freezer[b]		
Capital cost	$US	570
Net storage capacity	Liters	72
Equipment life	Years	10
Annual maintenance cost (default 5% capital cost)	$US	29
Energy consumption rate	kWh/hr	0.11
Cost per power unit	$US/kWh	0.1123
Solar refrigerator[a]		
Capital cost	$US	2100, 3000
Net storage capacity	Liters	19.5
Annual maintenance cost	$US	150
Shipping interval	Days	28
Equipment life	Years	10
Demand		
Catchment population per immunization location	Individuals	1000–30,000
Birth rate	Per 1000 persons	35.0
Immunization locations served	Number of locations	24
Immunization sessions per location per month	Number of sessions	28
Transport route		
Average one way distance to IHC	km	30[c]
IHCs per loop	Number of locations	4
Vehicles		
Vehicle capital cost	$US	40,000
Total distance traveled during vehicle lifetime	km	300,000
Maintenance cost (% of vehicle capital cost/km)	%	15%
Fuel		
Fuel efficiency	km/Liter	5
Cost of fuel	$US/Liter	1.3
Total $/km	$US	0.45
Driver		
Driver per diem	$US	15
Vehicle storage capacity		
Number of PCDs	Devices	8
Number of cold boxes	Devices	6
Cold boxes[d]		
Net capacity per cold box	Liters	20
Cost per cold box	$US	700
Economic		
Discount rate	%	3%

[a] The freezer used at the district level is based on the Dometic TFW 800 model [18].
[b] Based on Vestfrost MKS 044 model and solar costs obtained from EPI Logistics Forecasting Tool [17,21].
[c] A representative value based on district to clinic distances.
[d] Cold box costs were based on Dometic RCW-25 costs [16].