1 Modular Vaccine Packaging Increases Packing Efficiency

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Abstract

Background: Within a typical vaccine supply chain, vaccines are packaged into individual cylindrical vials (each containing one or more doses) that are bundled together in rectangular “inner packs” for transport via even larger groupings such as cold boxes and vaccine carriers. The variability of vaccine inner pack and vial size may hinder efficient vaccine distribution because it constrains packing of cold boxes and vaccine carriers to quantities that are often inappropriate or suboptimal in the context of country-specific vaccination guidelines.

Methods: We developed in Microsoft Excel (Microsoft Corp., Redmond, WA) a spreadsheet model that evaluated the impact of different packing schemes for the Benin routine regimen plus the introduction of the Rotarix vaccine. Specifically, we used the model to compare the current packing scheme to that of a proposed modular packing scheme.

Results: Conventional packing of a Dometic RCW25 that aims to maximize fully-immunized children (FICs) results in 123 FICs and a packing efficiency of 81.93% compared to a maximum of 155 FICs and 94.1% efficiency for an alternative modular packaging system.

Conclusions: Our analysis suggests that modular packaging systems could offer significant advantages over conventional vaccine packaging systems with respect to space efficiency and potential FICs, when they are stored in standard vaccine carrying devices. This allows for more vaccines to be stored within the same volume while also simplifying the procedures used by field workers to pack storage devices. Ultimately, modular packaging systems could be a simple way to help increase vaccine coverage worldwide.

1. Introduction

Currently, individual vaccine vials and their component packaging vary significantly in overall length, width, and height. This is because the vaccine packaging size is determined by the dimensions of both individual cylindrical vials (each containing one or more doses of vaccine) and rectangular inner packs that typically contain 10, 20, 50 or 100 vials of a particular vaccine. The variability of inner pack and vial dimensions may hinder efficient vaccine distribution because it constrains packing of cold boxes and vaccine carriers to quantities that are often inappropriate or suboptimal in the context of country-specific vaccination guidelines. In particular, estimating storage space requirements is more difficult with non-standard sizes and in a resource constrained system it may not be possible to take all the vaccines needed in a carrier because of the inefficient packaging. Modularized packaging is one way to address this because the consequent increase in packing efficiency has the potential to reduce storage space requirements and replenishment frequencies. The standardization of packaging also has the benefit of making operations much simpler for personnel since vaccines can be more easily packed and space requirements can be more easily estimated. While vaccine vial size has been a recent topic of academic and policymaker interest, explorations of alternative packing configurations have not yet addressed inner packs. [1-10] The packing analysis in this paper proposes that a solution to inefficient packing caused by inner pack and vial size variability is a modular packing system (where vial and inner pack dimensions are more consistent between different vaccines) that allows for more effective packing into cold boxes and vaccine carriers.

2. Methods

We developed in Microsoft Excel (Microsoft Corp.) a spreadsheet model that evaluated the impact of different packing schemes for the Benin routine regimen plus the introduction of the Rotarix vaccine. The Benin routine vaccine regimen includes Bacillus Calmette-Guerin (BCG), Tetanus, Measles, Oral Polio, Yellow Fever, Diphtheria-Tetanus-Pertussis-Hepatitis B-Haemophilus influenzae type B (DTC-

HepB-Hib), Pneumococcal Conjugate (PCV13), and Rotavirus (Rota) vaccines. Specifically, we used the model to compare the current packing scheme to that of a proposed modular packaging system. The storage device considered is the Dometic RCW25, which is prequalified by the WHO, is used in over 100 countries and was noted as a commonly used storage device in a recent study of in-country vaccine transport devices [11-13].

The RCW25 has a vaccine storage volume with length 40.5 cm, width 26.5 cm and height 19 cm after it is packed with conditioned ice. In Benin, workers at a “Health Post” (the lowest level of the vaccine distribution chain where vaccines are administered) typically travel to a “Commune Store” once per month to pick up vaccines; the amount of vaccines picked up depends on the population characteristics of the catchment area served by the Health Post and is determined by workers at the Health Post based on prior months’ demand. The vaccines are transported back to the Health Post in a vaccine carrier using a motorcycle. In determining packing efficiency, analyses of both current inner pack/vial sizes and the proposed modular system considered the number of fully immunized children (FIC) possible and packing efficiency (% space occupied) per fully packed device. The FIC metric ensures that our evaluations are with vaccine carriers that transport the suite of vaccines required for an FIC (as opposed to simply filling the carrier with just one or two types of vaccines).

2.1 Conventional packaging configuration

The dimensions in Supplementary Table 1 were used for analyses of existing, conventional inner packs and their constituent vials; the volume of the inner pack is simply the product of its length, width, and height as described by the vaccine manufacturer. These dimensions were used to determine the number of conventional inner packs for each vaccine type that could be placed in the RCW25 in order to maximize the FIC per device. To pack the device, we used a combination of algorithms and manual modifications. Note that each inner pack could be positioned in any orientation and that inner packs of the same type could have multiple orientations (see PCV13 in Figure 2). For each inner pack combination we placed the inner packs into the storage device until its dimensions prohibited the addition of any more.

In our simulation of storage device packing, the device is filled with the objective of maximizing the number of children that could be fully immunized as per the Benin routine vaccination schedule. This involved two steps. In step 1 we considered the vaccine schedule required for each FIC – for each vaccine we determined the average number of children that can be fully vaccinated per inner pack, based on the scheduled number of doses, the wastage rate, the number of doses per vial and the number of vials per inner pack, as described in Table 1. For example, for BCG the vaccine schedule is one dose per child and the wastage rate is 50%; therefore, on average, $1/(1-.50) = 2$ doses are needed per FIC (note that in the remainder of the paper when we reference FIC we mean the *expected* FIC given the average wastage rates given in Table 1). BCG has 20 doses per vial and an inner pack of BCG contains 50 vials, therefore the inner pack contains $50 \times 20 = 1,000$ doses total. Because 2 doses on average are needed per FIC, on average $1,000/2 = 500$ children can be immunized per inner pack of BCG.

In step 2, beginning with one inner pack of each vaccine type, we incrementally increased the number of inner packs in order to increase the expected number of FIC that can be served, as illustrated in Table 2. Initially we place one inner pack of each vaccine type into the carrier, resulting in the FIC values given in the first row (“One of each”). The expected number of FIC that the carrier can serve is the minimum FIC in the row, which is 16.5 for PCV13 (bold, highlighted); therefore, we next add an inner pack of PCV13 so that there is enough PCV13 to vaccinate $2 \times 16.5 = 33$ children. This results in the FIC values given in row 2 (“+1 PCV”), with a new limiting FIC value of 24.75 determined by Rotarix; therefore we next add an inner pack of Rotarix. This process is repeated until there is no more room in the storage device. This results in the inner pack values shown in the last row (“FINAL”), with a final FIC value of 123.75.

In determining the exact inner pack configuration within the storage device our approach was slightly different for conventional and modular inner packs. The conventional inner packs are all of different sizes and their packing was therefore done by trial and error filling from the bottom of the storage device. It should be noted that an optimization approach such as 3-dimensional bin packing would be computationally intensive and unrealistic in the field; rather we tried to replicate what a typical field

worker might do in an effort to choose among realistic solutions. While the packing is easy in the early stages, as the number of inner packs increases (at each step in Table 2) it becomes more difficult as we need to abandon the current configuration and start afresh. We were able to pack the number of inner packs shown in the last row of Table 2 using the configuration shown in Figure 2a.

2.2 Proposed modular packaging configuration

In designing modular packaging we assumed that all vaccines have vials with the same diameter but that the vial heights can change to account for differences in dose volumes. This provided uniform vial size in two dimensions and variation in only one dimension. Our data sources provided the rectangular dimensions of existing conventional inner packs but not the cylindrical dimensions of individual vials. We computed these by dividing the length or width of the inner pack by the number of vials in the length or width dimension. When there was inconsistency in the unit length and the unit width, we choose the larger value to be conservative. These values were then used to determine current vaccine vial volume, in order to design similar modular vials.

Specifically, to determine the ideal modular vaccine vial diameter, we analyzed the effects of multiple potential vial diameter sizes on packing efficiency. There are four main considerations for deciding the ideal modular vaccine vial diameter:

- 1) The number of vials in an inner pack: We required the quantities per inner pack to be values that are easy for counting, such as 10, 20, or 50.
- 2) Area efficiency: The modular vaccine vial diameter needed to result in an inner pack configuration that would fit well into the space available in the storage device.
- 3) Vial size as it relates to dose volume: The goal was to create standardized vial sizes but also make them similar in size to conventional vials to preserve existing dose per vial calculations – thus we found candidate vial diameters by calculating the area occupied by the vials when using 10, 20, and 50 vials in an inner pack.

4) Packing array: We considered diameters that could work with both hexagonal and rectangular packing within rectangular inner packs.

The above analysis yielded three potential diameters of 1.6cm, 2.2cm, and 1.9cm. For each diameter and each vaccine type, we calculated the modular vial height based on the volume of the original, conventional vial; the calculated modular vial heights are shown in Supplementary Table 2, and also determine the height of the inner pack in which the vials are subsequently stored. The 1.6cm diameter vials require relatively large heights while the 2.2cm diameter vials require relatively small heights, in order to maintain current volumes/doses per vial. Therefore, we also evaluated a modular system that uses a mixture of 1.6cm diameter vials for some (small-volume) vaccines and 2.2cm diameter vials for other (large-volume) vaccines. We also considered an intermediate vial diameter of 1.9 cm by itself.

We next examined the three different vial sizes in the context of potential inner pack dimensions; optimum inner pack dimensions are shown in Supplementary Table 2, while the vial configuration within each inner pack and the corresponding dimensions are shown in Figure 3a. Note that the inner packs for 1.6cm diameter vials and 2.2cm diameter vials are very similar in length and width; this was done purposely in order to maximize the efficiency of the fourth modular system that uses a combination of the two vial sizes. All three inner pack sizes were chosen such that they can be packed efficiently into the volume of the RCW25. From Supplementary Table 2, for the 1.6 cm and 2.2 cm diameter vials, inner pack dimensions are approximately 8 cm long and 6.5 cm wide. Therefore, they can be stored 5-long along the 40 cm length of the storage device and 4-wide along the 26.5 cm width of the storage device. The result is that there are 20 stacks of inner packs, each occupying the same area, which can each be up to 19cm tall. For the 1.9 cm diameter inner packs, there are 6 stacks of inner packs that can each be up to 19 cm tall. The different packing configurations for each vial size within the two dimensions (length $\times$ width) of the storage device are shown in Figure 3b.

As opposed to the trial-and-error approach with the conventional inner packs as described in Section 2.1, we used a heuristic algorithm for packing the modular inner packs into the storage device. We experimented with two versions of the heuristic based on how workers might fill the storage device. In version 1 the device was packed by starting on one side of the storage device and sequentially stacking inner packs vertically and building up multiple stacks (we refer to this as the *tower method*), while in version 2 we sequentially fill the storage device horizontally filling the storage device from the bottom and building up multiple layers (we refer to this as the *layer method*). For both methods we started by assigning the storage orientations for inner packs as described in the previous paragraph, and then sorted inner packs in decreasing order of height. In the *tower* method we used a first-fit-decreasing heuristic where inner packs were stacked in decreasing order of height in a single tower until no more can be placed in that tower, and we then search for the largest inner pack that fits in the remaining space (Figure 1a). When no inner packs can be fitted into the current tower a new tower is started and this procedure is repeated until all inner packs are exhausted. In the *layer* method, the inner packs are sequentially placed in the same layer in decreasing order of height until there is no more space in the layer to form several different towers. These towers are then built up layer by layer in a sequential fashion until all inner packs are exhausted. It is also possible to optimize the construction of the towers by creating a mathematical programming model rather than using the first-fit-decreasing heuristic but we have chosen not to illustrate those results here because it would not be realistic to apply a mathematical programming approach in practice, and the heuristic tower and layer methods represent much more applicable approaches.

3. Results

3.1 Conventional packing efficiency

The number of children who can be fully vaccinated with each vaccine type for the conventional inner packs is shown in the bottom row of Table 2 and the maximum expected FIC served by a single storage device is 123. The resulting configuration of inner packs within the device is illustrated in Figure 2a.

Currently, the FIC-optimizing configuration of conventional inner packs occupies 16.71 liters, representing 81.93% of the available volume of the RCW25; we refer to this as the volume efficiency of the packing. Although there is not enough empty space to add an inner pack of the vaccine currently determining the maximum FIC value (Rotarix), we can still use this space for other vaccines if we wish to do so. Thus, after filling the device to its FIC capacity, it is possible to add in two inner packs of Yellow Fever or two inner packs of Tetanus or one inner pack of each (the inner packs of these two vaccines are the same size). The occupied volume and volume efficiency now rise to 17.22 liters and 84.4% respectively. Figure 2b illustrates the arrangement with one extra inner pack of yellow fever (on top of the previous three) and one extra inner pack of tetanus (stored vertically in the empty space shown in Figure 2a).

It is important to note that these packing efficiencies were achieved by evaluating many different possibilities and therefore almost certainly reflect a higher packing density than would be achieved in practice, since storage devices are generally not packed and repacked multiple times. Thus, it is not likely that this high a degree of space utilization is regularly achieved in actual practice.

3.2 Conventional versus modular packing efficiency

The maximum FIC that can be served by one RCW25 given the current inner pack sizes is 123 as calculated above; the same methodology can be applied using the modular inner pack data and the results are shown in Table 3 (detailed information about the numbers of doses and inner packs achieved with conventional packing and each modular packaging system can be found in Supplementary Table 3). The results also show that the tower method often outperforms the layer method. In the discussion below we use the term “baseline” or “base” to refer to the 123 FIC obtained with conventional packaging.

Generally speaking, all modular packing systems exceed baseline packing efficiency, both in terms of maximum FIC served and volume efficiency. For example, using modular inner packs with vial diameter 2.2 cm, 155 FIC can be served per storage device, with a 94.1% volume efficiency, when the tower

method is applied. It is also worth noting that (a) this increase in efficiency is mainly because of the new inner pack sizing and is not dependent on the specific approach used to store the inner packs within the device, and (b) potential improvements are likely to be even higher because any optimization of conventional packing in the field is highly unlikely and in reality the actual FIC figure attained is likely to be much lower than our baseline value of 123, which was obtained after significant effort. For catchment areas with higher populations where larger volumes of vaccine are required, this has the potential for reductions in the number of vaccine carriers required and/or reductions in the replenishment frequency, which in turn could yield lower transportation and personnel costs. Estimating such potential savings would be the next step in analysis of this novel modular packaging system.

4. Discussion

The results of our study show that the modular inner packs permit more vaccines to be stored in the storage device. This follows from the fact that we choose to standardize vial diameters and inner pack sizes which in turn leads to easier and more efficient packing in a vaccine carrier. Under the current situation with widely varying inner pack sizes it is not possible to arrive at a consistent, space-efficient, packing arrangement. Additionally, the modular inner packs would actually provide even greater packing efficiency because the height of the inner packs was determined conservatively; adjusting for this will likely increase the packing efficiency difference by approximately an additional 5%. We also recommend the tower approach over the layer approach since the former generally provides slightly better packing efficiency.

It should be noted that if the demand is not high enough to warrant filling the cold box (e.g., at a catchment area with a low population) then packaging is obviously less of an issue. Simply filling the carrier with additional vaccines to maximize FIC might not be appropriate if there is potential for wastage of excess vaccines at such locations. The issue of packaging is of greater importance when we have sufficient demand and the cold boxes we have cannot take everything needed because of the inconsistent

packaging sizes, or when inconsistent sizes make it difficult for health care workers to manage limited space in a simple and efficient fashion.

Overall, there are seven advantages to using the modular packaging; the first two are probably the most important.

1. It achieves higher packing densities for a reasonable packing method such as the tower or the layer approach, as indicated by the data in Table 3. Also, recall that the heights of the modular inner packs were found by using conservative volume estimates and therefore the actual packing density differences between conventional and modular systems will likely be a few percentage points greater. It is also important to note that the conventional packing densities discussed assume that packers optimize space efficiency by packing and re-packing to achieve maximum efficiency. Thus, the packing densities achieved in practice are probably lower, which further increases the advantage of using the modular systems.
2. The modular packing procedure is much simpler and more consistent. Vaccines are simply stacked vertically in the twenty or six vertical stacks (depending on the vial size); there is no need to explore numerous complicated orientations and geometrical configurations. Thus, high packing efficiencies can be obtained consistently with little effort or special expertise required. This is a tremendous advantage from a practical standpoint because the personnel packing the storage devices will not require special training to ensure that carefully planned packing procedures are followed routinely in the field.
3. The simplified modular packing procedure will be faster since the person packing the storage device does not have to spend time exploring different configurations.
4. Counting the number of vials is easier because the inner packs have uniform quantities (this advantage is somewhat reduced if more than one standard size is adopted).
5. It is easier to handle the inner packs because they are all the same size, rather than trying to handle vaccines with different inner pack sizes. For example, transporting a stack of vaccines that

has an inner pack that is 12cm x 15cm on top of an inner pack that is 15cm x 18cm which is on top of an inner pack that is 20cm x 20cm is more difficult to transport without toppling it than a stack of three inner packs that all have the same dimensions.

6. Ideally, the vaccines should be packed with about 1cm of clearance space in between each inner pack to promote good air flow and uniform cooling (especially in refrigerators). If the inner packs have a consistent modular size, this would facilitate inserting spacers in between the stacks of inner packs to insure proper clearance is maintained.
7. If the inner packs are a consistent size, then cold storage devices can be manufactured with storage spaces that have dimensions that most efficiently accommodate the inner packs.

5. Limitations

While our analysis suggests that modular packaging systems offer benefits over conventional vaccine packaging in the form of increased potential FICs, higher packing densities, and simplifying the process of a worker packing a storage device, there are several limitations to our study. First, the only packing device considered was the Dometic RCW25. While this is a very commonly used cold storage transport device (found in over 100 countries), there are several other such devices available, and further analysis of other cold boxes would clarify the increased efficiencies that could be achieved with these other devices. Second, we assumed a single conventional packaging type for each existing vaccine, while it is likely that existing packaging varies for vaccines from different manufacturers or with different dose schedules. Similarly, in designing a potential modular packaging system, we assumed that all vaccines could fit in new, optimized vials based on the volume of current vials. This may not be the case for all existing vaccines. Third, our packing approach is a heuristic algorithm related to inner pack heights and if these heights are widely different it might not provide packings that are as good as the ones in our illustration. Finally, in order to quantify the economic benefits of improved packaging, a potential next step would be to utilize our HERMES vaccine supply chain modeling software to determine the economic

impact of changing packaging sizes.[1, 4-6, 7, 9,10,14-20] The impact could vary significantly depending on the country and circumstances (e.g., vaccine regimen). So such an analysis would require extensive simulation experiments and could be the basis of a future study.

6. Conclusions

Our analysis suggests that modular packaging systems could offer significant advantages over conventional vaccine packaging systems with respect to space efficiency when combined with a reasonable packing method such as the layer or tower method, when they are stored in standard vaccine carrying devices. This allows for more vaccines to be stored within the same volume while also simplifying the procedures used by field workers for packing storage devices. Ultimately, this could be a simple way to help increase vaccine coverage worldwide.

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References

- [1] Assi TM, Brown ST, Djibo A, Norman BA, Rajgopal J, Welling JS, et al. Impact of changing the measles vaccine vial size on Niger's vaccine supply chain: a computational model. *BMC public health*. 2011;11:425.
- [2] Dhamodharan A, Proano RA. Determining the optimal vaccine vial size in developing countries: a Monte Carlo simulation approach. *Health care management science*. 2012;15:188-96.
- [3] Parmar D, Baruwa EM, Zuber P, Kone S. Impact of wastage on single and multi-dose vaccine vials: Implications for introducing pneumococcal vaccines in developing countries. *Human vaccines*. 2010;6.
- [4] Lee BY, Assi TM, Rookkapan K, Wateska AR, Rajgopal J, Sornsrivichai V, et al. Maintaining vaccine delivery following the introduction of the rotavirus and pneumococcal vaccines in Thailand. *PloS one*. 2011;6:e24673.
- [5] Lee BY, Burke DS. Constructing target product profiles (TPPs) to help vaccines overcome post-approval obstacles. *Vaccine*. 2010;28:2806-9.
- [6] Assi TM, Brown ST, Kone S, Norman BA, Djibo A, Connor DL, et al. Removing the regional level from the Niger vaccine supply chain. *Vaccine*. 2013;31:2828-34.
- [7] Brown ST, Schreiber B, Cakouros BE, Wateska AR, Dicko HM, Connor DL, et al. The benefits of redesigning Benin's vaccine supply chain. *Vaccine*. 2014;32:4097-103.
- [8] Drain PK, Nelson CM, Lloyd JS. Single-dose versus multi-dose vaccine vials for immunization programmes in developing countries. *Bulletin of the World Health Organization*. 2003;81:726-31.
- [9] Haidari LA, Connor DL, Wateska AR, Brown ST, Mueller LE, Norman BA, et al. Augmenting transport versus increasing cold storage to improve vaccine supply chains. *PloS one*. 2013;8:e64303.
- [10] Haidari LA, Connor DL, Wateska AR, Brown ST, Mueller LE, Norman BA, et al. Only adding stationary storage to vaccine supply chains may create and worsen transport bottlenecks. *Journal of public health management and practice : JPHMP*. 2013;19 Suppl 2:S65-7.
- [11] PATH, World Health Organization (WHO). *Delivering Vaccines: A Cost Comparison of In-Country Vaccine Transport Container Options*. Seattle: PATH, WHO; 2013
- [12] WHO. Prequalified Devices and Equipment : Dometic RCW25. Geneva: WHO; 2010. Available at: http://www.who.int/immunization_standards/vaccine_quality/pqs_e004_005_dometic_rcw25.pdf. accessed Mar 20, 2015
- [13] Personal communication, Dometic, March 17, 2015.
- [14] Assi TM, Rookkapan K, Rajgopal J, Sornsrivichai V, Brown ST, Welling JS, et al. How influenza vaccination policy may affect vaccine logistics. *Vaccine*. 2012;30:4517-23.
- [15] Lee BY, Assi TM, Rajgopal J, Norman BA, Chen SI, Brown ST, et al. Impact of introducing the pneumococcal and rotavirus vaccines into the routine immunization program in Niger. *American journal of public health*. 2012;102:269-76.
- [16] Lee BY, Assi TM, Rookkapan K, Connor DL, Rajgopal J, Sornsrivichai V, et al. Replacing the measles ten-dose vaccine presentation with the single-dose presentation in Thailand. *Vaccine*. 2011;29:3811-7.
- [17] Lee BY, Cakouros BE, Assi TM, Connor DL, Welling J, Kone S, et al. The impact of making vaccines thermostable in Niger's vaccine supply chain. *Vaccine*. 2012;30:5637-43.
- [18] Lee BY, Norman BA, Assi TM, Chen SI, Bailey RR, Rajgopal J, et al. Single versus multi-dose vaccine vials: an economic computational model. *Vaccine*. 2010;28:5292-300.
- [19] Norman BA, Nourollahi S, Chen SI, Brown ST, Claypool EG, Connor DL, et al. A passive cold storage device economic model to evaluate selected immunization location scenarios. *Vaccine*. 2013;31:5232-8.
- [20] Rajgopal J, Connor DL, Assi TM, Norman BA, Chen SI, Bailey RR, et al. The optimal number of routine vaccines to order at health clinics in low or middle income countries. *Vaccine*. 2011;29:5512-8.

Vaccines used in Benin								
	BCG	Tetanus	Measles	Oral Polio	Yellow Fever	DTC- HepB-Hib liquid	PCV13	Rota
Scheduled doses per child	1	2	1	4	1	3	3	2
Wastage rate	0.5	0.15	0.45	0.17	0.45	0.05	0.01	0.01
Doses per vial	20	10	10	20	10	2	1	1
Vials per inner pack	50	10	50	100	10	100	50	50
FIC per inner pack	500	42.5	275	415	55	63.33	16.5	24.75

Table 1: The number of potentially fully-immunized children from a given inner pack of vaccines used in Benin.

Vaccines used in Benin

		BCG	Tetanus	Measles	Oral Polio	Yellow Fever	DTC-HepB-Hib liquid	PCV13	Rota
One of Each	Number of inner packs	1	1	1	1	1	1	1	1
	FIC	500	42.5	275	415	55	63.33	16.5	24.75
+1 PCV	Number of inner packs	1	1	1	1	1	1	2	1
	FIC	500	42.5	275	415	55	63.33	33	24.75
+1 Rota	Number of inner packs	1	1	1	1	1	1	2	2
	FIC	500	42.5	275	415	55	63.33	33	49.5
FINAL	Number of inner packs	1	3	1	1	3	2	8	5
	FIC	500	127.5	275	415	165	126.67	132	123.75

Table 2: Inner pack sizes and FIC for a complete packing of the storage device utilizing vaccine inner packs currently used in Benin.

Diameter (cm)	Layer Method		Tower Method	
	FIC	Vol. %	FIC	Vol. %
2.2 (10 vials)	152	92.6%	155	94.1%
1.6 (20 vials)	138	81.3%	148	86.6%
1.9 (50 vials)	148	87.9%	148	87.9%
Mix 1.6+2.2	148	87.4%	145	86.1%

Table 3. Maximum FIC and occupied volume for different proposed modular vaccine vial diameters, using two device-filling methods

Figure 1: Tower (a) and Layer (b) packing methods.

Figure 2.a: Packing arrangement in RCW25 for conventional inner packs (Top view)

PCV13	1 layer; 17.9 cm height
Rota	2 layers; 8.5 cm height
Oral Polio	1 layer; 7.5 cm height
Tetanus	1 layer; 10.6 cm height
Yellow Fever	4 layers; 4.7 cm height

Figure 2.b: Packing arrangement in RCW25 for conventional inner packs

1.91cm diameter vials

1.6cm diameter vials

2.2cm diameter vials

1.6cm diameter 4x5 inner packs

2.2cm diameter 4x5 inner packs

1.91cm diameter 3x2 inner packs

Figure 3: Packing configurations within inner packs for each proposed modular vial size (a) and within storage device (b).