APPENDIX: Characterizing poliovirus transmission and evolution: Insights from modeling experiences with wild and vaccine-related polioviruses

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This appendix provides the equations (A1), details about multi-stage processes used (A2), calculation of effective mortality rates in the model (A3), documentation of model inputs that change over time (A4), and supplemental results (A5). We use the same acronyms and we refer to Tables and Figures as in the main paper, but we provide additional Tables and Figures in the appendix preceded by an “A” to distinguish them from those from main text. The appendix uses its own list of references provided at the end and different from the main paper.

A1. Equations

We define the following indices and symbols for the full generic model equations. The symbols correspond to those used in the main paper, although in some instances the indices for a symbol differ because the main paper omitted non-essential indices for the main methods description (e.g., the main methods description shows a single index for the pair (immunity state, waning stage) and shows the excretion mode as a superscript (e.g., \( \pi_{i,w,o} \) is the same as \( \pi_{i,fec} \) in the main paper)).

Indices:

\( a \) = situation-specific age group \((a = 0, \ldots, na-1, \) where \( na \) depends on the situation and age group 0 is always from 0-2 months, inclusive; note that maternally immunes only exist in age group 0\)

\( a_m \) = mixing age group \((a_m = 0, \ldots, na_m-1, \) where typically \( na_m = 3 \) with \( a_m = 0 \) (0-4 years), 1 (5-14 years), 2 (15 or more years)\)

\( A(a) \) = mixing matrix age group that situation-specific age group \( a \) belongs to (i.e., \( A(a) = a_m \) if situation-specific age group \( a \) belongs to mixing age group \( a_m \))

\( c(a_m) \) = cut-off for mixing age group \( a_m \) = first situation-specific age group included in mixing age group \( a_m \), where we define \( c(na_m) = na_m \)

\( e \) = excretion and transmission mode \((e = 0 \) (fecal) or 1 (oropharyngeal))

\( fa \) = first situation-specific age group for which we assume immunes can give birth to children with maternal immunity

\( i \) = immunity state \((i = 0 \) (fully susceptible), 1 (maternally immune), 2 (1 successful IPV), 3 (2 successful IPV, 4 (≥ 3 successful IPV), 5 (1 LPV infection), 6 (≥ 2 LPV infections), 7 (IPV and LPV))

\( j \) = virus strain \((j = 0 \) (OPV), 1,\ldots, h-2 \) (OPV-related), h-1 \) (FRPV), h \) (WPV), where \( h = 20 \)

\( k \) = infection stage \((k = 0 \) (first latent stage), \( r-1 \) (last latent stage), \( r \) (first infectious stage), \ldots, \( r+s-1 \) (last infectious stage), where \( r = 2 \) and \( s = 4 \))

\( la \) = last situation-specific age group for which we assume immunes can give birth to children with maternal immunity

\( w \) = waning stage \((w = 0 \) (recent),\ldots, \( nw-1, \) where \( nw = 5 \); note that fully susceptibles and maternally immunes only exists in waning stage 0\)
Symbols for state variables:

\( IPVE_{a,i,w} = \) successfully IPV-vaccinated individuals from immunity state \( i \), age group \( a \), and waning stage \( w \) that have not yet acquired the properties of the next IPV state (i.e., IPV-exposed individuals)

\( LI_{a,i,w,j,k,e} = \) individuals from immunity state \( i \), age group \( a \), and waning stage \( w \) infected with live virus strain \( j \) and residing in infection stage \( k \) of excretion mode \( e \) (i.e., live-virus-infected individuals)

\( PI_{a,i,w} = \) partially infectible individuals in immunity state \( i \), age group \( a \), and waning stage \( w \)

Other symbols:

\( \alpha = \) seasonal amplitude of \( R_0 \) (for any strain) (i.e., difference from the average \( R_0 \) at peak or through, relative to the average \( R_0 \))

\( b = \) birth rate \([1/(\text{people} \times \text{days})]\)

\( \gamma_{i,w,e} = \) total duration of infectious period (in all infectious stages) for immunity state \( i \), waning stage \( w \), and excretion mode \( e \) \([\text{days}]\)

\( EPI_{a,j} = \) effective proportion infectious to situation-specific age group \( a \) with virus strain \( j \)

\( EPIM_{am,j,e} = \) effective proportion infectious to mixing age group \( ma \) with virus strain \( j \) with respect to excretion mode \( e \)

\( EPI^* = \) effective proportion infectious below which we assume 0 force-of-infection (i.e., the transmission threshold)

\( evc_{a}^{IPV} (evc_{a}^{OPV}) = \) effective vaccination coverage with IPV (OPV) = fraction of the population receiving an effective IPV (OPV) dose upon entering situation-specific age group \( a \) (i.e., a dose that takes if given to a fully susceptible individual)

\( evr_{a}^{IPV} (evr_{a}^{OPV}) = \) effective IPV (OPV) vaccination rate = fraction of the population in situation-specific age group \( a \) receiving an effective IPV (OPV) dose per day (i.e., a dose that takes if given to a fully susceptible) \([1/\text{day}]\)

\( \epsilon = \) average time to reach last reversion stage \([\text{days}]\)

\( \phi = \) IPV immunity delay \([\text{days}]\)

\( \theta_k = \) relative infectiousness weight of infection stage \( k \)

\( \kappa(a_m) = \) proportion of potentially infectious contacts of individuals in mixing age group \( a_m \) reserved for individuals within the same mixing age group

\( \lambda_{a,j} = \) force-of-infection to situation-specific age group \( a \) due to virus strain \( j \) \([1/\text{days}]\)

\( mf = \) fraction of newborns born with maternal immunity

\( \mu_a = \) fraction of people in situation-specific age group \( a \) that die (or emigrate) per day \([1/\text{days}]\)
\( \mu^{\text{ave}} \) = fraction of all people that die (or emigrate) per day [1/days]

\( M(a_m, b_m) \) = mixing matrix containing normalized mixing coefficients for potentially infectious contacts of individuals in mixing age group \( a_m \) with individuals in mixing age group \( b_m \)

\( MNI_{a,i} \) = inflow for partially infectibles in situation-specific age group \( a \) and immunity state \( i \) due to individuals moving to the next IPV state after leaving the IPVE state [people/days]

\( MNL_{a,i} \) = inflow for partially infectibles in situation-specific age group \( a \) and immunity state \( i \) due to individuals moving to the next LPV state after recovering from infection [people/days]

\( N \) = total population size [people]

\( N_a \) = total population size in age group \( a \) [people]

\( NM_{a_m} \) = total population size in mixing age group \( a_m \) [people]

\( PIR_j \) = paralysis-to-infection ratio (PIR) for fully susceptible individuals infected with virus strain \( j \) based on functional form for PIR by reversion stage (see methods)

\( RPIR^{\text{MI}} \) = relative PIR for maternally immunes compared to fully susceptibles

\( RPIR^a_{\text{age}} \) = relative PIR for fully susceptible individuals in situation-specific age group \( a \) compared to the first age group

\( \pi_{i,w,e} \) = relative infectiousness for immunity state \( i \), waning stage \( w \), and excretion mode \( e \)

\( R0_j \) = \( R_0 \) for virus strain \( j \) (as a function of time)

\( R0^{\text{ave}}_j \) = average \( R_0 \) for virus strain \( j \) based on functional form for relative \( R_0 \) by reversion stage (see methods)

\( p_e \) = proportion of transmissions via excretion mode \( e \) \((p_0 = 1-p^{\text{oro}} \) and \( p_1 = p^{\text{oro}} \))

\( pd \) = seasonal peak day for \( R_0 \) [day number in each year]

\( \rho \) = average time to reach the last waning stage [days]

\( \sigma_{i,w} \) = relative susceptibility for immunity state \( i \) in waning stage \( w \)

\( \tau \) = relative \( R_0 \) of OPV vs. homotypic FRPV and WPV

\( w_a \) = width of age group \( a \) (with \( w_0 = \rho w_t = 0.25 \times 365 \) days (Table 1)) [days]

\( \tilde{\xi}_{i,w,e} \) = duration of latent period for immunity state \( i \), waning stage \( w \), and excretion mode \( e \) [days]

\( z_p \) = shape parameter for the relationship between PIR and reversion stage

\( z_r \) = shape parameter for the relationship between \( R_0 \) and reversion stage

\( z_w \) = shape parameter of the waning functions
The equation structure does not vary by serotype and we omit serotype-dependence for ease of presentation, although we use serotype-specific model inputs as appropriate (see Tables I-XII). To shorten the equations, we use the indicator function $1_{\{c_1,c_2,\ldots\}}$ that equals 1 if all conditions $c_1,c_2,\ldots$ are true and 0 otherwise. The first 3 equations below represent the full set of differential equations represented in Figure 1b. The last 2 equations reflect the flows between immunity states shown in Figure 1a. The intermediate equations provide the equations of intermediate quantities that we introduce to simplify the notation for the differential equations. We solve the differential equations using Euler integration with a step size of 0.125 days. This approximates $1/10$th of the smallest time constant in the model (i.e., the two latent stages of ~ 1.5 days each).

$$\frac{dPL_{a,i,w}(t)}{dt} = b(t)N(t) \left( (1 - mf(t)) \left( 1 - evc_{0,IPV}(t) - evc_{0,OPV}(t) \right) \right) 1_{\{i=0\}}$$
$$+ \left( 1 - evc_{a-1,IPV}(t) - \sigma_{i,w} evc_{a-1,OPV}(t) \right) (PL_{a-1,i,w}(t) + PI_{0,1,0}(t) 1_{\{a=1,i=0\}}) \frac{1_{\{a>0\}}}{w_{a-1}}$$
$$+ \left( MNL_{a,i}(t) + MNI_{a,i}(t) \right) 1_{\{w=0\}} + PI_{a,i,w-1}(t) \frac{nw - 1}{\rho} 1_{\{w>0,i>1\}}$$
$$- \left\{ \mu(t) + \frac{1_{\{a<na-1\}}}{wa} + \sum_{j=0}^{h} \sigma_{i,w} \lambda_{a,j}(t) + \sigma_{i,w} evr_{a,OPV}(t) + evr_{a,IPV}(t) \right\}$$
$$\frac{dPVE_{a,i,w}(t)}{dt} = b(t)N(t) evc_{0,IPV}(t) \left( (1 - mf(t)) 1_{\{i=0\}} + mf(t) 1_{\{i=1\}} \right) 1_{\{a=0\}}$$
$$+ (PVE_{a-1,i,w}(t) + PVE_{0,1,0}(t) 1_{\{a=1,i=0\}} + evc_{a-1,IPV}(t) PI_{a-1,i,w}(t)$$
$$+ evc_{a-1,OPV}(t) PI_{0,1,0}(t) 1_{\{a=1,i=0\}}) \frac{1_{\{a>0\}}}{w_{a-1}} + PVE_{a,i,w-1}(t) \frac{nw - 1}{\rho} 1_{\{w>0,i>1\}}$$
$$+ evr_{a,IPV}(t) PI_{a,i,w}(t)$$
$$- \left\{ \mu(t) + \frac{1_{\{a<na-1\}}}{wa} + \sum_{j=0}^{h} \sigma_{i,w} \lambda_{a,j}(t) + \sigma_{i,w} evr_{a,OPV}(t) \right\}$$
$$+ \frac{nw - 1}{\rho} 1_{\{w<nw-1,i>1\}} + 1/\varphi \right\} PVE_{a,i,w}(t)$$
\[
\frac{dL|_{\alpha,\text{w},j,k,e}(t)}{dt} = b(t)N(t)e\nu_{0}^{\text{OPV}}(t) \left( (1 - mf(t))1_{\{i=0\}} + \sigma_{1,0}mf(t)1_{\{i=1\}} \right) 1_{\{a=0, j=0, k=0\}} \\
+ (L_{\alpha-1,\text{w},j,k,e}(t) + L|_{\alpha,0,0,j,k,e}(t)1_{\{a=1,i=0\}} \\
+ \sigma_{i,w}e\nu_{\alpha-1}^{\text{OPV}}(t)P_{\alpha-1,\text{w},t}(t)1_{\{j=0,k=0\}} \\
+ e\nu_{0}^{\text{OPV}}(t)P_{0,1,0}(t)1_{\{a=1,i=0,j=0,k=0\}} \frac{1_{\{a>0\}}}{w_{a-1}} \\
\right) \\
+ (e\nu_{\alpha}(t)1_{\{j=0\}} + \lambda_{\alpha,j}(t))\sigma_{i,w}P_{\alpha,i,w}(t)1_{\{k=0\}} + \frac{L_{\alpha,i,w,j,k-1,e}(t)}{\xi_{j,w,e}} \frac{1_{\{0<k\leq r\}}}{w_{a-1}} \\
+ \frac{L_{\alpha,i,w,j,k,e}(t)}{\gamma_{j,w,e}} \frac{1_{\{k=r\}}}{r_{i,w,e}} \\
- \left\{ \mu_{\alpha}(t) + \frac{1_{\{a<na-1\}}}{w_{a}} + \frac{1_{\{r<k\}}}{s_{j,w,e}} + \frac{1_{\{k=r\}}}{s_{j,w,e}} \right\} L_{\alpha,i,w,j,k}(t)
\]

\[
N_{\alpha}(t) = \left( P_{0,1,0}(t) + IPVE_{0,1,0}(t) + \sum_{j=0}^{h} \sum_{k=0}^{r+s-1} L|_{0,1,0,j,k,0}(t) \right) 1_{\{a=0\}} + P_{\alpha,0,0}(t) \\
+ IPVE_{\alpha,0,0}(t) + \sum_{j=0}^{h} \sum_{k=0}^{r+s-1} L|_{\alpha,0,0,j,k,0}(t) \\
+ \sum_{i=2}^{n-1} \sum_{w=0}^{n-1} \left( P_{\alpha,i,w}(t) + IPVE_{\alpha,i,w}(t) + \sum_{j=0}^{h} \sum_{k=0}^{r+s-1} L_{\alpha,i,w,j,k,0}(t) \right)
\]

\[
N(t) = \sum_{a=0}^{na-1} N_{\alpha}(t)
\]

\[
NM_{\alpha}(t) = \sum_{b=c(a+1)}^{c(a+1)} N_{\beta}(t)
\]

\[
mf(t) = \frac{\sum_{a=fa}^{la} \sum_{i=3}^{n-1} \sum_{w=0}^{n-1} P_{\alpha,i,w}(t)}{\sum_{a=fa}^{la} N_{\alpha}(t)}
\]
\[
EPIM_{a_m,j,e}(t) = \sum_{k=r}^{r+s-1} \sum_{b=c(a_m)}^{c(a_m+1)} \left( LI_{0,1,w,j,k,e}(t) \pi_{1,0,e} M(a_m, 0)(t) 1_{b=0} \right)
\]
\[
+ \left( LI_{a,0,w,j,k,e}(t) \pi_{0,0,e} \right)
\]
\[
+ \sum_{i=2}^{7} \sum_{w=0}^{nw-1} LI_{a,i,w,j,k,e}(t) \pi_{i,w,e} \left( M(a_m, A(b))(t) \right) \theta_k \frac{NM_{a_m}(t)}{N}
\]

\[
EPI_{a,j}(t) = \sum_{e=0}^{1} EPIM_{A(a),j,e}(t) p_e
\]

\[
\lambda_{a,j}(t) = 1_{EPI_{a,j}(t) \neq 0} \sum_{e=0}^{1} EPIM_{A(a),j,e}(t) p_e (1 + \mu^{ave}) R0_j(t)
\]

\[
\mu^{ave}(t) = \sum_{a=0}^{na-1} \mu_a(t) N_a(t) / N(t)
\]

\[
R0_j(t) = R0_j^{ave} \left( 1 + R0^{ampl} \times \sin \left( \left( t - \frac{pd}{365} \right) 2\pi + \frac{\pi}{2} \right) \right)
\]

\[
R0_j^{ave} = R0_{h-1}^{ave} - (R0_{h-1}^{ave} - R0_{0}^{ave}) \times ((h - 1 - j)/(h - 1))^2 r, \quad j = 1, \ldots, h-1
\]

\[
R0_{h-1}^{ave} = R0_{h}^{ave}
\]

\[
R0_{0}^{ave} = r R0_{h}^{ave}
\]

\[
M(a_m, b_m)(t) = \kappa(a_m) 1_{a_m=b_m} + \frac{(1 - \kappa(a_m))(1 - \kappa(b_m)) NM_{b_m}(t)}{\sum_{b=0}^{na_m-1} NM_{b}(t)(1 - \kappa(b))}
\]
\[ \sigma_{i,w} = \sigma_{i,nw-1} - (\sigma_{i,nw-1} - \sigma_{i,0}) \times ((w - 1 - j)/(w - 1))^{z_w} \]

\[ \gamma_{i,w,e} = \gamma_{i,nw-1,e} - (\gamma_{i,nw-1,e} - \gamma_{i,0,e}) \times ((w - 1 - j)/(w - 1))^{z_w} \]

\[ \pi_{i,w,e} = \pi_{i,nw-1,e} - (\pi_{i,nw-1,e} - \pi_{i,0,e}) \times ((w - 1 - j)/(w - 1))^{z_w} \]

\[ \xi_{i,w,e} = \xi_{i,0,e} \]

\[ MNI_{a,i}(t) = (IPVE_{a,0,0}(t) + IPVE_{0,1,0}(t)1_{i=0})1_{i=2}/\varphi \]
\[ + \sum_{w=0}^{nw-1} (IPVE_{a,2,w}(t)1_{i=3} + (IPVE_{a,3,w}(t) + IPVE_{a,4,w}(t))1_{i=4}) \]
\[ + (IPVE_{a,5,w}(t) + IPVE_{a,6,w}(t) + IPVE_{a,7,w}(t))1_{i=7})/\varphi \]

\[ MNL_{a,i}(t) = \sum_{j=0}^{h} \sum_{w=0}^{nw-1} (LI_{a,0,0,j,r+s-1,0}(t)/\gamma_{0,0,0} + LI_{0,1,0,j,r+s-1,0}(t)1_{i=0})1_{i=2}/\gamma_{1,0,0})s1_{i=5} \]
\[ + \sum_{w=0}^{nw-1} (LI_{a,5,w,0,j,r+s-1,0}(t)/\gamma_{5,0,0} + LI_{a,6,w,0,j,r+s-1,0}(t)/\gamma_{6,0,0})1_{i=6} \]
\[ + (LI_{a,2,w,0,j,r+s-1,0}(t)/\gamma_{2,0,0} + LI_{a,3,w,0,j,r+s-1,0}(t)/\gamma_{3,0,0} \]
\[ + LI_{a,4,w,0,j,r+s-1,0}(t)/\gamma_{4,0,0} + LI_{a,7,w,0,j,r+s-1,0}(t)/\gamma_{7,0,0})1_{i=7})s \]

The equations derive from and depend on several important assumptions. First, we assume that the IPV take rates already account for any effect of maternal antibodies on the per-dose take rate, which \( evc_{IPV} \) incorporates. However, for maternally immune infants who receive OPV at birth we multiply the effective vaccination coverage by their relative susceptibility, and thus the \( evc_{OPV} \) calculation can use the same per-dose take rate regardless of timing of the first dose. This structural difference between how we handle IPV and OPV given to maternally immune infants preserves consistency in our assumption that IPV boosts already primed or immune individuals in other immunity states at the same rate as fully susceptible, while remaining more convenient by allowing us to use the same average per-dose OPV take rates in the context of birth doses or SIA doses reaching infants before their maternal immunity wanes. Second, we assume that maternally immune infants that receive a routine dose at 3 months flow into the IPV-exposed state (if given IPV) or LPV-infected state (if given OPV) for previously fully susceptible individuals (i.e., see equations for \( IPVE_{1,0,0} \) and \( LI_{1,0,0,0,e} \)). We assume no effect of residual maternal immunity on take at 3 months of age (i.e., we do not multiply by relative susceptibility). Third, as mentioned in the main paper, oropharyngeal infection stages exist as a co-flow and
therefore individuals do not recover into the next LPV state (equation for $M_{\alpha,i}$) or get counted towards the population size (equation for $N_{\alpha}$) (i.e., oropharyngeal infection occurs coincident to fecal-oral infection). Fourth, the expression for the normalized preferential mixing matrix $M(a_m,b_m)$ corresponds to that proposed by Jacquez et al. (1988).

Fifth, to simplify the calculations, the formula for the force-of-infection takes the average net duration of the infectious period taking into account mortality as $1/(\text{recovery rate} + \text{death rate})$ rather than the more cumbersome expression of a multi-stage infection process. Given that the mortality rate remains much lower than the recovery rate in any or all stages, the approximation of the death rate based on a single-stage infection process leads to negligible error.

In situations with two interacting subpopulations (i.e., The Netherlands, northern Nigeria, and western Uttar Pradesh (WUP)), we follow our prior approach to characterize mixing between subpopulations. Specifically, if the under-vaccinated subpopulation represents one of $m$ hypothetical subpopulations, and using superscript 0 and 1 to denote the under-vaccinated and the general subpopulations, respectively, the force-of-infection in the under-vaccinated subpopulation equals:

$$
\lambda^0_{a,j}(t) = 1_{EPIa,j(t)\geq EPI} \sum_{e=0}^{1} \left( EPIM^{0}_{A(a),j,e}(t) p_{\text{within}} + EPIM^{1}_{A(a),j,e}(t)(1 - p_{\text{within}}) \right) p_e (1/y_{0,0,e} + \mu^{\text{ave}}) R_0(t)
$$

The force-of-infection for the general population equals:

$$
\lambda^1_{a,j}(t) = 1_{EPIa,j(t)\geq EPI} \sum_{e=0}^{1} \left( \frac{EPIM^{0}_{A(a),j,e}(t)(1 - p_{\text{within}})}{m - 1} + EPIM^{1}_{A(a),j,e}(t) \left( \frac{(1 - p_{\text{within}})(m - 2)}{m - 1} + p_{\text{within}} \right) \right) p_e (1/y_{0,0,e} + \mu^{\text{ave}}) R_0(t)
$$

We compute the incidence of paralytic cases ($PP_{a,j}$) in situation-specific age group $a$ due to virus strain $j$ from the force-of-infection as follows:

$$
PP_{a,j}(t) = \lambda_{a,j}(t - \delta) PIR_j(\sigma_{1,0} P I_{0,1,0}(t - \delta) RPIR_{M1}^{M1(a=0)} + P I_{a,0,0}(t - \delta) RPIR_{a}^{age})
$$

$$
PIR_j = PIR_{h-1} - (PIR_{h-1} - PIR_0) \times ((h - 1 - j)/(h - 1))^z, \quad j = 1,\ldots,h-1
$$

$$
PIR_{h-1} = PIR_h
$$

We compute non-recipient VAPP incidence as the sum of the incidence for virus strains 0 to $h-2$ (i.e., all VAPP due to contact infections except those from FRPVs) and VDPV incidence as the incidence from virus strain $h-1$ (i.e., only FRPVs). We compute recipient VAPP incidence from the sum of all OPV infections in fully susceptibles and maternally immunes due to $evc_{a,OPV}$ and $evr_{a,OPV}$ and using $PIR_0$. For vaccine given at time of aging from maternally immune to fully susceptible (i.e., at 3 months of age), we assume the relative PIR for maternally immunes still applies.
A2. Details about multi-stage processes for infection, waning, and reversion

This section provides details about processes modeled over multiple stages, including infectiousness, waning, and reversion. To generate the figures in this section, we introduce a pulse of individuals into the first stage of a process and follow how the average properties for this population change as a result of progression through the multiple stages and their assumed properties. We include these figures to show the implied distributions in the model as a result of our assumptions by discrete stages in the process, although we do not include the effect of mortality or any other flows on the flows between stages here, which in the actual model depend on the specific population modeled and influence the distributions as well. The figures for infection in this section reflect the model inputs for type 1, with similar values for types 2 and 3 that lead to slight differences in the results that did not warrant inclusion as additional figures. For the waning curves, we also show the values for types 1 which remain almost identical to type 2 (i.e., only the starting points differ slightly (Table I)). For type 3, the same patterns occur (not shown), but the increase occurs more rapidly due to the assumed shorter time to reach the last waning stage for type 3 compared to types 1 and 2 (Table I). Given relatively large differences in OPV reversion by serotype, we include separate figures for all 3 types to show the differences.

Figure A1 shows the distributions for the duration of fecal and oropharyngeal infectiousness implied by the 2 latent and 4 infectious stages in the model compared with the mean assessment obtained from the experts. Figure A2 shows the average level of infectiousness for a population infected at time 0 assuming either constant infectiousness or the empirically fitted relative infectiousness by infectious stage according to the ratio 3:10:3:1 and compares these with the expert assessments based on the proportion excreting and relative infectiousness for the average titers excreted over time. In these figures, we rescaled the curves so that the areas under the curves remain fixed to better compare the 3 curves within each plot. The unscaled infectious curves differ much more between immunity states due to the relative infectiousness compared to fully susceptible individuals \( \pi_{l,w,e} \) and differences in duration of infectiousness \( \gamma_{l,w,e} \). Figure A2 motivated the assumptions related to different levels of infectiousness by infectious stage to better match the expert assessments about infectiousness over time.
Figure A1: Distribution of the duration of fecal and oropharyngeal infectiousness in the model (solid blue line) and according to the means of expert assessments (black dashed line),\(^{(4)}\) by immunity state

- Fully susceptible, fecal
- Fully susceptible, oropharyngeal
- Maternally immune, fecal
- Maternally immune, oropharyngeal
- 1 successful IPV dose, fecal
- 1 successful IPV dose, oropharyngeal
- 2 successful IPV doses, fecal
- 2 successful IPV doses, oropharyngeal
Figure A1 (cont’d): Distribution of the duration of fecal and oropharyngeal infectiousness in the model (solid blue line) and according to the means of expert assessments (dashed black line),\(^4\) by immunity state.
Figure A2: Average relative infectiousness for a population infected at time 0 according to expert assessments (dashed black line), the model with constant infectiousness (dash-dotted red line), and the model with variable infectiousness by stage (solid blue line), by immunity state.
Figure A2 (cont’d): Average relative infectiousness for a population infected at time 0 according to expert assessments (dashed black line), the model with constant infectiousness (dash-dotted red line), and the model with variable infectiousness by stage (solid blue line), by immunity state.
Figure A3 shows the average relative contribution to transmission compared to fully susceptible individuals, defined as the product of relative susceptibility, relative duration infectiousness, and relative infectiousness, for each active immunity state as a function of the time after entering an immunity state (in the absence of further infections or vaccinations), based on the model inputs for waning in Table I. The experts expressed significant uncertainty about waning, which led us to consider a very wide range for the input values. Figure A3 shows that in the model we assumed less waning than the mean of the uncertain expert assessments as a result of fitting the model. Figure A3 includes both the inputs at each stage and the effective average values that resulted from the multi-stage waning process that we modeled, which produces slightly slower waning due to the steady-state error, but converges to the model input values.

Figure A3: Waning curves for active immunity states, for type 1.
Figure A3 (cont’d): Waning curves for active immunity states for type 1.

### 2 successful IPV doses
- **Fecal-oral, mean expert assessments**
- **Oropharyngeal, mean expert assessments**
- **Fecal-oral, model inputs by stage**
- **Oropharyngeal, model inputs by stage**
- **Fecal-oral, effective contribution**
- **Oropharyngeal, effective contribution**

### 3 or more successful IPV doses
- **Fecal-oral, mean expert assessments**
- **Oropharyngeal, mean expert assessments**
- **Fecal-oral, model inputs by stage**
- **Oropharyngeal, model inputs by stage**
- **Fecal-oral, effective contribution**
- **Oropharyngeal, effective contribution**
Figure A3 (cont’d): Waning curves for active immunity states for type 1.

1 LPV infection

- Fecal-oral, mean expert assessments
- Oropharyngeal, mean expert assessments
- Fecal-oral, model inputs by stage
- Oropharyngeal, model inputs by stage
- Fecal-oral, effective contribution
- Oropharyngeal, effective contribution

2 or more LPV infections and/or successful IPV doses

- Fecal-oral, mean expert assessments
- Oropharyngeal, mean expert assessments
- Fecal-oral, model inputs by stage
- Oropharyngeal, model inputs by stage
- Fecal-oral, effective contribution
- Oropharyngeal, effective contribution
Figure A4 shows both the results of the multistate process for $\tau$ (i.e., relative $R_0$ of OPV compared to homotypic FRPV and WPV) and PIR as a function of the age of the virus and the inputs by discrete reversion stage that lead to these curves (dots indicate the values of the 20 reversion stages). With respect to $\tau$, for which we assumed a linear increase in input values by reversion stage, we see that the multi-stage process leads to a more gradual approach to the maximum input, which occurs due to the dispersion of values as viruses progress through the stages. The true relationship for $\tau$ remains uncertain, and the model calibration focused on determining the correct effective average input values (i.e., by changing the assumptions about the shape and time to last stage) that produce behavior consistent with the known behavior of VDPVs. With respect to the PIR, curves similarly show differences between the results and input values, which again reflect dispersion that occurs due to the multistage process. In this case, the curves look different due to the assumed S-shaped function for PIR and the application of the log transformation after averaging the natural-scale PIR for each model stage. The effective input values represent the PIR of a virus ingested at the given viral age since OPV dose administration (i.e., the evolution time). Importantly, although we assume the lowest PIR for type 1 OPV, PIR becomes greater for type 1 than type 3 by approximately 85 days and greater than the type 2 PIR by approximately 32 days due to the greater PIR for FRPV type 1 than types 2 and 3 (Table I).
Figure A4: Assumed effect of reversion on basic reproductive number ($R_0$, top panel), and paralysis-to-infection ratio (PIR; bottom panel) of oral poliovirus vaccine-related viruses.
A3. Calculation of effective mortality rates

In all situations, we calculate the effective mortality rates \( \mu_a \) based on the UN-estimated age distributions, following the same approach as previously described.\(^6\) Briefly, we first linearly interpolate 5-year estimates from the UN\(^7\) to obtain annual numbers by the situation-specific model age groups. For smaller situation-specific age groups than the five-year-wide age groups provided in the data,\(^7\) we estimate numbers proportional to the width of those situation-specific age groups. We then determine the \( \mu_a \) that exactly reproduce the annual numbers by situation-specific age group using the expressions in Duintjer Tebbens et al. (2011).\(^6\)

In the event of situation-specific age groups of less than five years in width, we calculate a constant single \( \mu \) for all situation-specific age groups within a five-year bracket. For example, we calculate one \( \mu \) for all under-fives based on the changes in the under-five population in the UN data, and then apply this same \( \mu \) for all situation-specific age groups under age five years (e.g., 0-2, 3-11 months, 1, 2, 3, and 4 years all receive the same under-five \( \mu \)). Although this simplification leads to a small error in population size, we do not believe that the data (by five-year age groups) support estimates of \( \mu \) values by smaller age groups. Given the small sample sizes, estimating \( \mu \) for narrower age groups (e.g., 0-2 months) leads to very noisy and erratic results that reflect an artifact of attributing population size proportional to the width of these age groups rather than any realistic changes in \( \mu \) values. We use effective birth rates based on surviving infants to account to some extent for the real difference in death rates between young infants and children aged 1 to 5 years.

Due to emigration or immigration, changing population registries and borders in some places, and/or inaccuracies in population estimates, in some instances we use negative \( \mu_a \) values to reproduce the population estimates. In those instances, the model implicitly adds people to each stock in proportion to the number of people in that stock at the given time, thus providing a somewhat unbiased method to introduce people to the model to match the estimated population sizes by age group over time.
A4. Time series inputs

This section provides values of model inputs regarding vaccination that change over time in graphical form. Demographic data also represent time series inputs from publicly available data. For The Netherlands, Table V already includes all information on vaccination coverage assumptions over time, and for Cuba, we assume the same coverage for each round and directly adopt the target age groups as listed in Más Lago (1999)(8) (as noted in Table VIII).

USA

Figure A5 shows the assumed annual cumulative coverage with IPV administered in campaigns to people under 20 years of age. For older individuals, we assume a fraction of 0.55 of this cumulative coverage (Table IV). The right axis shows the corresponding number of doses administered as a result of both IPV campaigns and routine IPV use (assumed to start in 1958, see Figure A6), compared with the reported number of doses distributed according to Morris et al. (1967)(9) and converted to administered doses by assuming 16% wastage.(10) Figure A6 shows the assumed routine coverage with 3 or more polio doses, and the assumed coverage with 1 or 2 doses for those assumed to receive fewer than 3 doses. We linearly interpolate between prior estimates(10) for 1987 and 1990 in the absence of good estimates for those years.

Figure A5: Assumed annual cumulative coverage of IPV campaigns in the USA, and corresponding doses administered (including from routine vaccination from 1958 forward), compared to estimated doses administered based on Morris et al. (1997)(9) with 16% wastage(10)
Figure A6: Assumed routine coverage with 3 or more polio doses in the USA, and with 1 or 2 doses given fewer than 3 doses, based on prior work\(^{(10)}\) and DTP1 vs. DTP3 coverage,\(^{(11)}\) respectively.

Albania

Figure A7 shows the assumed coverage for the isolated, under-vaccinated sub-population in the Albania model. For the years 1960-1977, coverage represents the fraction of 3-18 months olds receiving mOPV1 or a mix of all three monovalent vaccines in a given round.\(^{(12)}\) We assume much lower coverage than the reported administrative coverage\(^{(12, 13)}\) to account for long periods between campaigns due to irregular supply,\(^{(13)}\) below-average coverage in the subpopulation, and/or poor vaccine take due to cold chain failures. For the years 1978-1996, coverage represents the fraction of children receiving all 3 primary doses by age 12 months. We assume 90% of the administrative coverage data to account for over-reporting in general and/or lower coverage levels in the subpopulation. As per Table VI, we assume booster doses occur at 18 months of age and attain 50% of the coverage with 3 doses, and from 1982 on we add another booster dose with the same coverage at 5 years of age.
Figure A7: Routine coverage assumptions for Albania, based on available data\textsuperscript{(11-13)} and model calibration to characterize the under-vaccinated subpopulation.

![Figure A7](image)

_Tajikistan_

Figure A8 shows the routine coverage assumptions for Tajikistan, including the coverage with the birth dose, coverage with 3 or more primary non-birth doses, and partial coverage with 1 or 2 doses, given fewer than 3 doses. Until 1991, we assume 90% coverage with 3 doses, with no partial or birth dose coverage in the absence of data before Tajikistan became an independent nation. For the birth dose coverage, we first divide the BCG coverage in the 3 modeled sub-national regions measured during the 2007 survey (2006 birth cohort)\textsuperscript{(14)} by the WHO-UNICEF-estimated national BCG coverage for 2006.\textsuperscript{(11)} We then multiply the WHO-UNICEF-estimated national BCG coverage for all years 1992-2010 by this ratio to account for differences between national coverage and coverage for the 3 regions. For the non-birth full and partial coverage, we multiply the WHO-UNICEF-estimated national POL3 coverage\textsuperscript{(11)} for the years 1992-2006 by the ratio of estimated coverage from the 2007 survey\textsuperscript{(14)} and the 2006 WHO-UNICEF-estimated national POL3 coverage.\textsuperscript{(11)} We assume that after 2006, all coverage values remain constant at the level estimated from the 2007 survey\textsuperscript{(14)} until 2010. Finally, we multiply all coverage levels by 0.90 to correct for possible over-estimation of coverage in the surveys due to the exclusion of unregistered children (Table VII).

Figure A9 shows the assumed timing and impact of SIAs conducted in Tajikistan prior to 2010, with the dates based on data reported to WHO (Gacic-Dobo, 2009, personal communication). We assume all SIAs targeted the 3 regions affected by the outbreak with tOPV, and that the (S)NIDs in 1995, 1996, and 1999 targeted 0-4 year olds, while all other (S)NIDs targeted 0-3 year olds. The height of the bars in Figure A9 show the assumed effective per-round impact ($\zeta$), which translate to annual cumulative percentages of missed children of 20%, 20%, 15%, 10%, 10%, 15%, 25%, and 30%, during each year from 1995 to 2002, respectively.
Figure A8: Routine coverage assumptions for Tajikistan, based on available data.\(^{(14,15)}\)

Figure A9: SIA assumptions for Tajikistan during the run-up, based on data reported to WHO (see Table VII for 2010 outbreak response assumptions)
Haiti

Figure A10 shows the routine coverage assumptions for Haiti, based on linear interpolation between results from DHS surveys conducted in 1994-1995, 2000, and 2005-2006 (16) (and applied to the birth cohorts of the preceding years). For the years 1980 (i.e., the assumed beginning of routine tOPV use) to 1992 (i.e., the last birth year before the first survey), we multiply the WHO-UNICEF-estimated coverage (11) for that year by the ratio of each of the four coverage values (i.e., birth dose, 3 or more doses, 1 dose given fewer than 3 doses, 2 doses given fewer than 3 doses) from the 1994-1995 survey to the WHO-UNICEF-estimated POL3 coverage for 1993 (11). Figure A11 shows the assumptions about the SIAs conducted in Haiti prior to the outbreak in 2000-2001, based on very limited data (17, 18). We assume that all SIA targeted 0-4 year old children in the entire country with tOPV and involved two rounds on days 50 and 120 of each year (Table IX). The effective per-round impacts in Figure A11 translate to annual cumulative percentages of missed children of 36%, 16%, 4%, 1%, 1%, 4%, 9%, 16%, 16%, and 16%, during each year from 1986 to 1995, respectively.

Figure A10: Routine coverage assumptions for Haiti, based on available data (11, 16)
Figure A11: SIA assumptions for Haiti during the run-up (see Table IX for 2001 outbreak response assumptions)

Madura

Figure A12 shows the routine coverage assumptions for Madura, based on WHO-UNICEF-estimated coverage for Indonesia from 1981 to 2001.\(^{(11)}\) This may provide an overestimate for the modeled rural subpopulation of Madura, but remains of relatively little consequence given that population immunity comes primarily from WPV transmission and SIAs conducted intermittently from 1995 to 2002. From 2002, we assume constant coverage using the values reported from a convenience sample of the children under 5 years of age in communities affected by the outbreak.\(^{(19)}\) The raw data (Estívariz, 2012, personal communication) provide a basis for estimating partial coverage with 0, 1, 2 or 3 doses given fewer than 4 doses, which we apply without changes over time to all years. Consequently, Figure A13 shows only the coverage with all 4 primary doses by age 12 months. Figure A13 shows the assumptions about the SIAs conducted in Madura prior to the outbreak in 2000-2001, based on data reported to the WHO. We assume that not all SNIDs reached the rural subpopulation and that all SIAs targeted 0-4 year old children in the entire rural subpopulation with tOPV and involved two rounds on days 240 and 280 of each year (Table X). The effective per-round impacts in Figure A11 translate to annual cumulative percentages of missed children of 4% from 1995-1998 and 9% in 2000 and 2002.
Figure A12: Routine coverage assumptions for Madura, based on available data.\textsuperscript{(11, 19)}

![Graph showing routine coverage assumptions for Madura](image)

Figure A13: SIA assumptions for Madura during the run-up (see Table X for 2005 outbreak response assumptions)

![Graph showing SIA assumptions for Madura](image)
Northern Nigeria

Figure A14 shows the routine coverage assumptions for northern Nigeria. We linearly interpolate between DHS surveys conducted in 1990, 1999, 2003, and 2008, which include birth dose coverage, coverage with the third non-birth dose (POL3), and partial coverage, and provide results for each geopolitical zone in Nigeria, including the northwest (NW). For the years 1984 (i.e., the assumed beginning of routine polio immunization program) to 1988 (i.e., the last birth year not covered by DHS surveys), we multiply the WHO-UNICEF estimated POL3 coverage by the POL3 estimate from the 1990 DHS (covering the 1989 birth cohort) divided by the 1990 WHO-UNICEF-estimated POL3 coverage. We assume that the birth dose and partial coverage increased proportionally to the POL3 coverage in those years. For 2008 and beyond, we assume the POL3 coverage increased at the same rate as the WHO-UNICEF-estimated POL3 coverage using the 2008 DHS estimate as the starting point, while we assume that the birth dose and partial coverage stayed constant at the level estimated from the 2008 DHS. To maintain the approximate average coverage values for the entire NW zone in Figure A14, we multiply all coverage values by 1.08 for the general population and all coverage values by 0.29 for the under-vaccinated subpopulation.

Figure A15 shows the assumptions about timing, vaccine use, and the effective impact of the SIAs conducted in northern Nigeria, broken down by modeled subpopulation. Given that we know that many rounds, especially in recent years, did not target the entire NW zone, we account for the fraction of the NW zone targeted in each round, based on estimates of covered states. Thus, Figure A15 shows the product of the assumed effective per-round impact (ζ) and the targeted fraction. The assumptions in Figure A15 translate to the annual cumulative percentages of missed children shown in Figure A16. Figure A16a shows the breakdown by modeled subpopulation and the combined percentages (calculated as the sum over each subpopulation of the annual cumulative percentage of missed children multiplied by the relative size of the subpopulation compared to the NW). Figure A16b shows the breakdown by vaccines containing each serotype (e.g., by not including mOPV1 rounds in the missed children calculation for type 3), which clearly illustrates the large fraction of children that did not receive type 2 or type 3 containing vaccine during SIAs in 2008, which led to the subsequent large type 2 and 3 outbreaks.
Figure A14: Routine coverage assumptions for northern Nigeria, based on available data.\textsuperscript{(11, 20)}
Figure A15: SIA assumptions for northern Nigeria, showing the product of the assumed effective per-round impact (ζ) and the assumed fraction of the NW zone targeted.

(a) General population

(b) Under-vaccinated subpopulation
Figure A16: Annual cumulative percent of missed children by SIAs in northern Nigeria, corresponding to the assumptions in Figure A15.

(a) By (sub-)population (showing children missed by any OPV vaccine)

(b) By type-containing vaccines (showing the combined results for the two modeled subpopulations)
Figure A17 shows the routine coverage assumptions for Bihar and WUP in northern India. We linearly interpolate between DHS survey results conducted in 1992-1993, 1998-1999, and 2005-2006(21) which include coverage with the third non-birth dose (POL3) and partial coverage by state. Only the 2005-2006 DHS reports coverage with the birth dose (POL0), and consequently we estimate the coverage with the birth dose by multiplying the POL3 estimate for a given year with the ratio of POL0 to POL3 estimates in the 2005-2006 survey (i.e., 0.37 in Bihar and 0.39 in WUP).(21) The DHS surveys(21) report a large gap between DTP3 and POL3 coverage coinciding with the beginning of SIAs in India, which suggests that POL3 coverage may include doses given during SIAs, but could also relate to DTP3 supply shortages. Given uncertainty about the two estimates, we assume the average coverage for DTP and POL for each dose. For the years 1980 (i.e., the assumed beginning of routine polio immunization program) to 1990 (i.e., the last birth year not covered by DHS surveys), we assume a linear increase from 0 to the levels estimated from the 1992-1993 survey,(21) and we assume constant levels after the most recent survey in 2005-2008.(21) We assume the same routine vaccination coverage levels for the under-vaccinated and the general population in WUP.

Figure A18 shows the assumption about timing and effective impact of the SIAs conducted in northern India, broken down by modeled subpopulation and color-coded by vaccine used in each round. As for northern Nigeria, Figure A18 shows the product of the assumed effective per-round impact ($\zeta$) and the fraction of the region targeted. The assumptions in Figure A18 translate to the annual cumulative percentages of missed children shown in Figure A19. Figure A19a shows the breakdown by modeled subpopulation and the combined percentage for WUP (calculated as the sum over each subpopulation of the annual cumulative percentage of missed children multiplied by the relative size of the subpopulation compared to all of WUP). Figures A19b and A19c show the breakdown by vaccines containing each serotype, which as in northern Nigeria clearly illustrates the gap in use of type 3-containing vaccines from 2006 and led to the resurgence of type 3 cases in 2007-2009. However, unlike in northern Nigeria, despite the reduction in use of type 2-containing vaccine, a large type 2 cVDPV outbreak did not occur, consistent with the much better routine coverage.
Figure A17: Routine coverage assumptions for northern India, based on available data.\textsuperscript{(21)}

(a) Bihar

- 3 or more non-birth doses by age 12 months
- Birth dose
- 1 non-birth dose (given fewer than 3 non-birth doses)
- 2 non-birth doses (given fewer than 3 non-birth doses)

(b) Western Uttar Pradesh

- 3 or more non-birth doses by age 12 months
- Birth dose
- 1 non-birth dose (given fewer than 3 non-birth doses)
- 2 non-birth doses (given fewer than 3 non-birth doses)
Figure A18: SIA assumptions for northern India, showing the product of the assumed effective per-round impact ($\zeta$) and the assumed fraction of the region targeted.
Figure A19: Annual cumulative percent of missed children by SIAs in northern India, corresponding to the assumptions in Figure A18.
(a) By (sub-)population (showing children missed by any OPV vaccine)

(b) By type-containing vaccines, in WUP (showing the combined results for the two modeled subpopulations in WUP)
(c) By type-containing vaccines, in Bihar
A5. Additional results

This section includes results of the models for different situations leading up to the time periods shown in the main paper figures, as well as further selected results of interest for the different situations.

The USA model already includes the model results and data going back out to 1948, before which we suspect significant underreporting. Figures A20-A27 show the run-ups for The Netherlands, Albania, Tajikistan, Cuba, Haiti, Madura, northern Nigeria, and northern India, respectively.

Figure A20: Run-up for The Netherlands (reported cases from van den Hof (1998),\(^{(22)}\) and frequency of type 3 to total cases during 1953-1958 from Verlinde (1959)\(^{(23)}\))
Figure A21: Run-up for Albania (reported cases starting in 1960 from Prevots et al. (1998)(12))
Figure A22: Run-up for Tajikistan (reported cases starting in 1991 from WHO (2012)\textsuperscript{(24)})

* One arrow represents a year with at least one SIA round. Shorter arrows represent SIAs that we assume targeted 0-3 year old children, longer arrows represent SIAs that we assume targeted 0-4 year old children.
Figure A23: Run-up for Cuba (reported cases from Rodriguez-Cruz (1984)(25))
Figure A24: Run-up for Haiti (reported cases starting in 1980 from WHO (2012)\(^{(24)}\))

- **Reported polio cases (all WPV types)**
- **Paralytic poliomyelitis incidence in the model (WPV1)**

Inception of tOPV

- tOPV NIDs 0-4 years
Figure A25: Run-up for Madura

Paralytic poliomyelitis incidence in the model (WPV1)

Incidence (cases/year)

Year

start routine tOPV

90s

tOPV (s)NIDs 0-4 years
Figure A26: Run-up for Northern Nigeria (reported cases based on WHO data\textsuperscript{24, 26})
Figure A27: Run-up for northern India (reported cases based on WHO data\textsuperscript{(24, 26)})
Table A1 shows the incidence of VAPP in the model (excluding The Netherlands, due to its minimal use of OPV, and Madura, where the total from 1997-2004 remains below 1 case due to the small population size), with comparisons to data provided in the notes when available. We typically observe increased non-recipient VAPP cases leading up to outbreaks (e.g., type 1 in Tajikistan in 2008 and 2009, or type 2 northern Nigeria in 2002-2004) given that relatively more susceptibles become infected secondarily versus from direct receipt of OPV, and that lower population immunity allows circulation of more reverted OPV-related viruses.

The results compare well with the reported US numbers due to direct calibration of the PIR for OPV and the shape parameter to these data. If we extrapolate the total of 4 cases during 1980-1995 for Albania to the entire country, then the resulting 8 VAPP cases approach the reported 11 cases during the same time period. For Cuba, the model matches the total reported VAPP cases during 1963-1996. For India, we did not find data for Bihar and WUP specifically, but we found a report of VAPP in the entire country in 1999 that reported elevated numbers of type 1 non-recipient VAPP cases compared to developed countries and a similarly high contribution of type 3 to the total number of recipient VAPP cases similar to our model. For Tajikistan, Haiti, and northern Nigeria, we did not find data on VAPP incidence.

Our model produces relatively high numbers of type 2 non-recipient VAPP cases in settings of very low OPV use (e.g., northern Nigeria and northern India before SIAs). This relates to the emergence of transmission in higher reversion stages for which we assume much higher PIRs (Figure A4), including a limited number (24 cases) due to FRPVs that emerge and die out during 1986-1997 in WUP in addition to the non-recipient VAPP cases shown in Table A1. The total annual incidence of VAPP per million surviving infants ranges from approximately 2.5 in the USA to almost 7 in Albania. Albania represents somewhat of an outlier because it reflects a population with relatively high routine immunization in the context of low pre-existing population immunity, which remains consistent with the observed high VAPP incidence in Albania.

Table A1: Type-specific incidence of recipient and non-recipient VAPP in the model.

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<th>Situation and serotype</th>
<th>VAPP cases</th>
<th>Recipient</th>
<th>Non-recipient</th>
<th>Total VAPP</th>
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**Notes:**

-<sup>a</sup> See Table II for a comparison of these results with reported VAPP cases
-<sup>b</sup> Diamanti et al. (1998)<sup>13</sup> reports 11 VAPP cases for the whole country during the same time period (the model incidence includes only half of the country), including 3 cases with onset of paralysis within 4-40 days of receipt of OPV, and the type distribution ambiguous due to isolation of multiple serotypes or isolation only from healthy contacts in a large fraction of VAPP cases
-<sup>c</sup> Más Lago (1999)<sup>8</sup> reports a total of 18 VAPP cases during the same time period, including 12 with onset 11-28 days after receiving the first OPV dose, with PV2 isolated from 12 of 18 patients, type 3 from 5 patients, and both type 2 and 3 from 1 patient
-<sup>d</sup> Kohler et al. (2002)<sup>27</sup> report 181 laboratory-confirmed VAPP cases for all of India during the year 1999, including 60 classified as recipient VAPP and 121 as non-recipient VAPP; 33%, 22%, and 33% of cases had only type 1, only type 2, and only type 3 isolated, respectively
Table A2 compares the force-of-infection to 0-4 year old fully susceptible individuals from all OPV-related viruses in the USA model to that reported among a small number of unvaccinated children by Chen et al. (1996), (28) as discussed in the main paper. Figure A28 shows the force-of-infection to 0-4 year olds from all OPV-related viruses after the second NID round in 1991, and the resulting cumulative proportion of fully susceptible infants infected as a function of the time born since the 2nd NID round. Table 14 lists the eventual cumulative percent infected at different time points. Given the absence of cases in Cuba and its role primarily as a situation that bounds the behavior of OPV reversion, we also demonstrate in Figure A29 that the force-of-infection in Cuba does not lead to cVDPVs over a range of potential $R_0$ assumptions for Cuba.

Table A2: Comparison of observations by Chen at al. (1996)(28) with model results for the USA

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportion (95% CI) of unvaccinated children seropositive at 12-23 months, 1990-1991</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Detroit (n=41)</td>
<td>0.17 (0.08-0.35)</td>
<td>0.34 (0.20-0.53)</td>
<td>0.10 (0.03-0.23)</td>
</tr>
<tr>
<td>- Houston (n=48)</td>
<td>0.07 (0.02-0.17)</td>
<td>0.24 (0.13-0.38)</td>
<td>0.15 (0.08-0.28)</td>
</tr>
<tr>
<td>Average annual force of infection of OPV-related virus required for observed proportion seropositive$^{c}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Detroit (n=41)</td>
<td>0.12 (0.06-0.29)</td>
<td>0.28 (0.15-0.50)</td>
<td>0.07 (0.02-0.17)</td>
</tr>
<tr>
<td>- Houston (n=48)</td>
<td>0.05 (0.01-0.12)</td>
<td>0.18 (0.09-0.32)</td>
<td>0.11 (0.06-0.22)</td>
</tr>
<tr>
<td>Average annual force of infection of OPV-related virus in the USA model, 1990-1991</td>
<td>0.17</td>
<td>0.24</td>
<td>0.08</td>
</tr>
</tbody>
</table>

**Acronyms:** CI=confidence intervals; OPV=oral poliovirus vaccine; USA=United States

**Notes:**

$^a$ Calculated as $-\ln(1-proportion seropositive at 12-23 months)/1.5$
Figure A28: Secondary infections with all OPV-related viruses in Cuba

(a) Type 1
- Instantaneous FOI from OPV-related viruses (left axis)
- Cumulative proportion secondarily infected, born day 1 (right axis)
- Cumulative proportion secondarily infected, born day 15 (right axis)
- Cumulative proportion secondarily infected, born day 31 (right axis)
- Cumulative proportion secondarily infected, born day 46 (right axis)

(b) Type 2
- Instantaneous FOI from OPV-related viruses (left axis)
- Cumulative proportion secondarily infected, born day 1 (right axis)
- Cumulative proportion secondarily infected, born day 15 (right axis)
- Cumulative proportion secondarily infected, born day 31 (right axis)
- Cumulative proportion secondarily infected, born day 46 (right axis)

(c) Type 3
- Instantaneous FOI from OPV-related viruses (left axis)
- Cumulative proportion secondarily infected, born day 1 (right axis)
- Cumulative proportion secondarily infected, born day 15 (right axis)
- Cumulative proportion secondarily infected, born day 31 (right axis)
- Cumulative proportion secondarily infected, born day 46 (right axis)
Figure A29: Force-of-infection (FOI) from all OPV-related viruses in Cuba, as a function about the assumed basic reproductive number ($R_0$).
Reference:


