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Authors

Stern, Adi

Yeh, Ming Te

Zinger, Tal

et al.

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## The evolutionary pathway to virulence of an RNA virus

Adi Stern<sup>1,6</sup>, Ming Te Yeh<sup>2,6</sup>, Tal Zinger<sup>1</sup>, Matthew Smith<sup>3</sup>, Caroline Wright<sup>2</sup>, Guy Ling<sup>1</sup>, Rasmus Nielsen<sup>4,5</sup>, Andrew Macadam<sup>3</sup>, and Raul Andino<sup>2,7</sup>

<sup>1</sup>Department of Molecular Microbiology and Biotechnology, Tel-Aviv University, Tel-Aviv, Israel

<sup>2</sup>Department of Microbiology and Immunology, University of California, San Francisco, California 94158, United States of America

<sup>3</sup>National Institute for Biological Standards and Control, London, United Kingdom

<sup>4</sup>Department of Integrative Biology, University of California, Berkeley, California 94720, United States of America

<sup>5</sup>Department of Statistics, University of California, Berkeley, California 94720, United States of America

### Summary

Paralytic polio once afflicted almost half a million children each year. The attenuated oral polio vaccine (OPV) has enabled world-wide vaccination efforts, which resulted in nearly complete control of the disease. However, poliovirus eradication is hampered globally by epidemics of vaccine-derived polio. Here, we describe a combined theoretical and experimental strategy that describes the molecular events leading from OPV to virulent strains. We discover that similar evolutionary events occur in most epidemics. The mutations and the evolutionary trajectories driving these epidemics are replicated using a simple cell-based experimental setup where the rate of evolution is intentionally accelerated. Furthermore, mutations accumulating during epidemics increase the replication fitness of the virus in cell culture and increase virulence in an animal model. Our study uncovers the evolutionary strategies by which vaccine strains become pathogenic, and provides a powerful framework for rational design of safer vaccine strains and for forecasting virulence of viruses.

### Graphical abstract

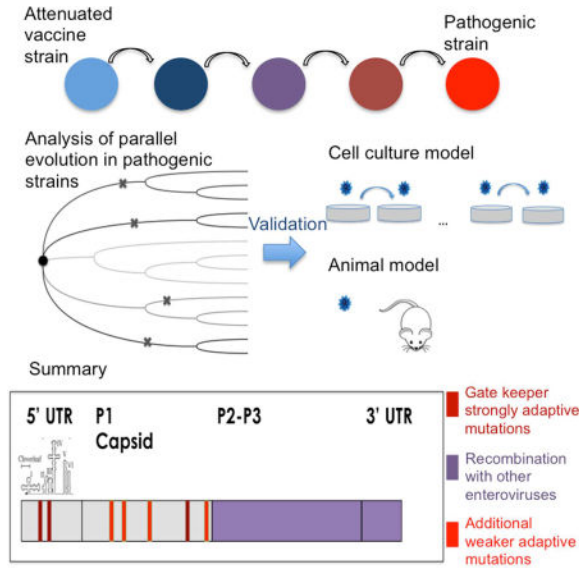
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Correspondence: Adi Stern sternadi@post.tau.ac.il, Raul Andino raul.andino@ucsf.edu.

<sup>6</sup>Co-first author

<sup>7</sup>Lead contact

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## Introduction

Predicting the course of evolution is one of the most challenging and important areas in biology. One key strategy of this endeavor involves assessing how often evolutionary trajectories occur repeatedly, and if they do, using this to predict future evolutionary trajectories. Many laboratory experiments with various microbial systems have shown a remarkable degree of parallelism (e.g., Cuevas et al., 2002; Meyer et al., 2012). Similarly, the parallel (or convergent) emergence of traits such as echolocation, toxin resistance, and pigmentation is being increasingly inferred in natural life settings (Arendt and Reznick, 2008; Feldman et al., 2012; Teeling et al., 2002). However, it is often difficult to identify parallel gain-of-function from a set of ancestors that are shrouded in a distant past. At the molecular level, detecting convergence is even more challenging in the absence of the ancestral sequence. Here we present evidence of extensive parallel substitution and recombination events occurring in repeated epidemics of vaccine-derived polioviruses, where the ancestral sequence is a known entity with the defined sequence of the vaccine strain.

Global eradication of poliovirus is based on immunization with the oral poliovirus vaccine (OPV), composed of three strains (1, 2 and 3), each of which provides protection from the corresponding wild-type (WT) viral serotypes. These highly attenuated strains replicate in the recipient's gut, mimicking natural infection. Vaccination with OPV elicits both humoral and mucosal immunity, thus providing robust and long-lasting protection from infection with WT polioviruses. Using this effective vaccine, WT poliovirus has been brought to the brink of global eradication. However, despite the remarkable success of the polio eradication campaign, in regions with low vaccine coverage, dozens of poliomyelitis outbreaks associated with circulating vaccine-derived polioviruses (cVDPVs) have been observed (Kew et al., 2005). The largest number of these incidents is due to OPV type 2 (OPV2). Following an extensive period of circulation, an evolved form of OPV2 gains both elevated virulence and the ability to effectively circulate in human populations.

To date, limited analyses of localized cVDPVs (Burns et al., 2013; Endegue-Zanga et al., 2015; Famulare et al., 2015; Hovi et al., 2013; Tao et al., 2013) have been undertaken, and many aspects of the evolutionary and epidemiological dynamics of cVDPVs remain unclear (Duintjer Tebbens et al., 2013). Understanding the evolutionary path(s) that leads from the attenuated and non-hazardous form of the virus into a circulating and pathogenic virus is central to the global poliovirus eradication efforts, for prediction of future epidemics, to understand the risks of current strategies and for designing new and safer vaccines.

Notably, the study of cVDPVs allows a unique scrutiny of evolution as it occurs in real-life settings. From an evolutionary perspective, several key features of cVDPV epidemics are exceptional: first, as opposed to natural life setting, the precise ancestor of all type 2 cVDPVs is known - the original OPV2 strain. Second, global nationwide surveillance has led to hundreds of available cVDPV sequences, allowing the reconstruction of a fine-resolution phylogeny of cVDPVs (fig. S1A). Finally, the extremely high rate of evolution of poliovirus (Jorba et al., 2008) drives rapid divergence of cVDPVs from their ancestral founder. Thus, analysis of cVDPV sequences allows a unique study of repeated independent evolutionary processes that often begin and end similarly at the phenotypic level: vaccination with a highly attenuated viral strain ends tragically in cases of paralytic poliomyelitis, indistinguishable from those associated with wild type poliovirus.

To examine cVDPV evolution in detail, we developed a novel evolutionary framework that allowed us to determine the key substitutions that drive loss of attenuation and regain of virulence in OPV2, and offer a coherent model of evolution for cVDPV. We then used a simple *in vitro* experimental evolution paradigm to identify OPV2 adaptive mutations during controlled infection of OPV2 in cell culture (Fig. 1). Notably, the key substitutions inferred to be adaptive in the epidemics were also observed in the *in vitro* system. We then validated the contribution to viral virulence of these key mutations in competition assays and in an animal model. Thus, we propose that our experimental evolution paradigm, which is based on highly accurate sequencing and computational inference, can be a powerful tool to understand and predict adaptation of viruses to their host in real-life setting.

## Results

### Abundant parallel substitutions are detected throughout cVDPV2 evolution

An extensive dataset of 424 full-genome consensus sequences of verified type 2 cVDPVs (defined as more than 0.5% divergence in the VP1 gene that forms part of the capsid) was compiled, with sequences from Belarus, China, Egypt, Madagascar, and Nigeria (Fig. 2A; fig. S1A). Our aim was to use these genomic sequences to uncover the evolutionary pathways that lead from the non-virulent OPV2 strain into a highly virulent cVDPV2 strain, capable of causing acute flaccid paralysis. We used the unique phylogenetic nature of these cVDPV2 sequences, whereby the tree topology is described by one known ancestral sequence that subsequently branches out into several independent epidemics (illustrated in Fig. 1; Fig. 2A). Thus, the tree topology has a known ancestral sequence at the root, and is characterized by multifurcation at the root (i.e., multiple branches diverge from the root), both of which do not typically occur in natural evolutionary settings.

Sequence comparison demonstrated a high level of identity (typically 95–99% identity; fig. S1B) between all cVDPV2 sequences and the OPV2 sequence along the region encoding the capsid (P1) portion of the genome. In all but three of the 424 genomic sequences recombination was identified, either in the P2 or P3 region of the genome. Furthermore in 397 of 424 sequences an additional recombination event was observed leading to replacement of the OPV2 5' untranslated region (UTR). The recombinant sequences were derived from co-circulating HEV-C strains, most often a coxsackievirus strain, but in some cases a circulating PV strain (table S1) (Burns et al., 2013).

We hypothesized that evolution from OPV2 to virulent poliovirus strains involves a limited number of genetic events that are similar in the different parallel epidemics. OPV2 is an avirulent strain, with reduced replicative fitness at body temperature in human cells. This potentially leads to smaller viral population sizes, which in turn reduces neurovirulence and probability of transmission. Accordingly positive selection in human hosts could lead to fitter viruses over time, i.e., viruses that replicate better in human tissues. These viruses will eventually lead to neurovirulence (as exhibited by all cVDPV sequences analyzed here) and potentially increased probability of virus transmission. An analysis of phylogeny of the largest epidemic occurring in Nigeria supported the fact that peaks in transmission correspond to gain of function events described below and to gaps in vaccination (fig. S1C).

To identify the evolutionary changes contributing to cVDPV regain of virulence, we searched for substitutions that occurred repeatedly and independently along the phylogeny of the cVDPV sequences (i.e., with no shared ancestry). To this end we focused on non-recombinant regions of the genomes, and used a phylogenetic mapping approach to reconstruct the history of substitutions of each of the cVDPV sequences (Methods). Two key substitutions have been previously implicated in the loss of attenuation of OPV2: A481G within the 5' UTR of the genome, and a Thr to Ile (or Asn) substitution at amino acid 143 of the capsid protein VP1 corresponding to genomic loci 2908–2909 (Macadam et al., 1991; Ren et al., 1991). Indeed, in each of the independent outbreaks lineages analyzed, these substitutions occurred early on the outbreaks, i.e. are observed in the nearest branch from the OPV2 root. Surprisingly, we also deduced 841 loci in the capsid where additional parallel substitutions occurred. These events occurred repeatedly in two or more different lineages of the phylogeny, with greater than six parallel substitutions on average per locus.

While past studies have assumed that parallel substitutions typically represent the fixation of positively selected mutations (see Zou and Zhang, 2015), the huge number of substitutions observed in parallel lineages seems improbable and challenges this assumption. Instead we propose that several factors characteristic of RNA virus evolution lead to an unusual large number of parallel substitutions, which are not necessarily under positive selection. First, polioviruses possess an exceptionally high substitution rate of ~0.01 substitutions/site/year (Jorba et al., 2008). Given that several of the epidemics examined here spanned five or more years (Burns et al., 2013; Yang et al., 2003), it is quite possible that two independent substitutions at the same locus occurred by chance (a simple calculation yields a probability of ~0.85 for two independent substitutions; Methods). Second, the transition/transversion ratio in polioviruses exceeds ten (Acevedo et al., 2014; Crotty et al., 2001; Freistadt et al., 2007), implying that parallel substitutions involving transitions have an even higher

probability. Indeed, most of the parallel substitutions inferred from our analysis correspond to transition events (Fig. 2B). Third, certain mutations are expected to be under relaxed selection, such as synonymous mutations. Thus for example, codons with two-fold degeneracy may lead to multiple parallel substitution events. Finally, it has been demonstrated that viruses undergo relaxed purifying selection near the tips of the phylogeny (also termed incomplete purifying selection), leading to accumulation of slightly deleterious substitutions (Park et al., 2015; Pybus et al., 2007). A hallmark of this effect is an increase in the ratio of non-synonymous ( $d_n$ ) to synonymous ( $d_s$ ) substitutions towards the tips of the phylogeny, as indeed we observe in this study as well (Fig. 2C). All these effects could thus lead to parallel substitutions not driven by selection, but rather occurring by chance.

### A probabilistic evolutionary model detects a small number of parallel substitutions under selection

To identify among the parallel substitutions those that are under positive selection, we designed a phylogenetic probabilistic Markov model named ParaSel, which infers sites where parallel substitutions are driven by positive selection rather than by random genetic drift (Methods; Fig. 1). Essentially, this model is similar to phylogenetic codon models that search for an increase in the  $d_n/d_s$  ratio (Muse and Gaut, 1994; Nielsen and Yang, 1998). Here, we search for an increase in the substitution rate as compared to a baseline rate that can be loosely defined as the average rate of substitution observed across all sequences. This strategy allows the method to detect selection at non-coding regions and at synonymous sites, which  $d_n/d_s$  signals are inherently incapable of examining. In order to model parallel selection, the ParaSel model assumes that a specific allele will experience positive directional selection across all branches of the phylogeny. This is modeled as an increase in

the background substitution rate by a factor of  $\frac{S}{1 - e^{-S}}$ , the rate of fixation of a non-neutral mutation (Kimura, 1962; Nielsen and Yang, 2003), where  $S = Ns$  is the population-size ( $N$ ) scaled selection coefficient. Similar to most phylogenetic Markov models, ParaSel takes into account ancestry via the topology of the phylogeny, a high rate of evolution is accounted by the branch lengths of the phylogeny, the transition/transversion rate is a parameter of the model, and amongsite rate variation (ASRV) allows a higher rate of evolution for some sites (such as synonymous sites). We also uniquely model incomplete purifying selection by changing the ASRV distribution towards the tips of the tree (Methods). If the ParaSel model provides significantly better fit to the data than a null model that assumes no selection, the posterior probability for parallel selection is calculated at each site (Methods). Testing ParaSel on simulated data demonstrated high levels of sensitivity and specificity of the method (table S2).

Applying ParaSel to the sequences of cVDPVs, we obtained strong statistical support for parallel positive selection acting on a small group of substitutions (table S3). We inferred seven sites with a high posterior probability of selection for parallel substitutions (Fig. 3). Using a similar rationale to the ParaSel model we further extrapolated that the recombination events replacing the 5' UTR and 3' regions of OPV2 with a HEV-C sequence were themselves under positive selection (Methods, fig. S2), with the latter potentially endowing the virus with more fit non-structural proteins. Our inference results overlapped

the results reported by the site-specific  $d_N/d_S$  signal for positive selection only at VP1.143 (Fig. 3C). Thus, ParaSel is a method complementary to  $d_N/d_S$  based methods, since  $d_N/d_S$  only captures diversifying positive selection at amino-acid sites.

By scrutinizing the pattern of substitutions using phylogenetic mapping, we were able to reconstruct the order of emergence of the different parallel selection events during viral adaptation. These substitutions could be assigned into three “waves” of events (Fig. 3A). First, three substitution events occurred almost invariantly in all lineages deriving from OPV2. These substitutions include the known A481G and U2909C attenuation reversions, as well as an additional reversion at U398C in the 5' UTR (Famulare et al., 2015; Macadam et al., 1991; Muzychenko et al., 1991). In all lineages with enough resolution (i.e. enough branching), these mutations preceded all other events observed in the second two “waves”. We thus propose these three mutations serve as “gate-keeper” mutations, which are akin to “driver” mutations in cancer evolution (Krogan et al., 2015).

The second wave of events included one to two recombination events with a HEV-C partner. Interestingly, in the twenty-seven sequences where there was no recombination in the 5' UTR, the gate-keeper and additional mutations led to a sequence similar to a HEV-C sequence, presumably endowing the virus with the same beneficial alterations obtained by the recombination. During the third wave of events, the virus continued to slowly revert to sequences that are conserved across WT poliovirus. We estimate that fine-tuning adaptation of the virus continues even 30 months after vaccine administration.

### **Next generation sequencing of vaccinees confirms rapid emergence of gate-keeper mutations**

We next sought to confirm how fast mutations accumulate post vaccination. Next generation sequencing analysis of OPV2 viruses excreted by eleven individuals, fourteen days after vaccination with trivalent OPV (Table 1), supports a model in which increase in fitness follows a defined evolutionary pathway as all three “gate-keeper” mutations were observed at high frequencies in viruses from all vaccinees studied. The mutant frequencies at day 14 further suggest that the order of emergence is usually A481G followed by VP1-143X, then U398C. At day 14 five samples contained type 2 viruses that were recombinants with OPV1 in the P2 or P3 regions. While not proving definitively that subsequent evolutionary events could not occur without the gatekeeper mutations these findings suggest that alternative evolutionary trajectories are less common.

### **An in vitro model of experimental evolution in cell culture recapitulates several of the phylogenetic findings**

We hypothesized that the increase in virus virulence and circulation in human populations results from a general replicative fitness gain that could be monitored in a simpler system such as cell culture. To examine the possibility of establishing a link between real-life evolution of viral sequences and this simple experimental paradigm, we serially passaged OPV2 strain in HeLa S3 cells for fourteen replication cycles, at either 33°C or 39.5°C (Fig. 1B). High temperature was used in order to create strong selection pressure that could accelerate gain of fitness (Manor et al., 1999), whereas 33°C, the vaccine manufacturing



temperature, was designed as a control. Importantly, we used large viral population sizes for our experiments: during each passage we ensured an input of  $10^6$  particle forming units (PFUs) with a burst size of  $\sim 10^8$  particles. Based on population genetics theory, these large population sizes are expected to accelerate adaptation (Rouzine et al., 2001), especially as compared to real-life setting, where transmission bottlenecks severely slow down the rate at which a population can adapt due to the effects of genetic drift.

Our results showed that the OPV2 consensus sequence replicating in cell culture remained essentially identical during serial passage at high temperature (fig. S3A). However, using a highly accurate sequencing approach (CirSeq (Acevedo and Andino, 2014; Acevedo et al., 2014)), we uncovered a large number of minor alleles accumulating over the passages (fig. S3B). We detected on average more than 18,400 variant alleles per passage with an average coverage of more than 240,000 reads per position (table S5). The vast majority of variants were homogeneously distributed at low frequencies between  $10^{-5}$  and  $10^{-3}$ , with only a few allele frequencies higher than  $10^{-3}$ . Using this powerful sequencing strategy, we were able to (a) estimate mutation rates, and (b) track the frequency of each minor allele across time in order to estimate its relative fitness (Fig 1B). Changes in allele frequency along time are driven by the fitness of each mutation, and by stochastic effects, especially when allele counts are low. We hence used an approximate Bayesian computation (ABC) method (Foll et al., 2014; Foll et al., 2015) (Methods), which compares simulations based on the Wright-Fisher model to the empirical allele frequency data. Then, the simulations yielding the best fit to the empirical data form the posterior probability distribution for the fitness of each allele. This posterior distribution allows inferring whether an allele is under significant positive or purifying selection, and allows estimating the magnitude of the fitness effect. Validation of our approach is shown in fig. S4, which shows a high accuracy of inferring mutations rate and a very high specificity in inferring positive selection from simulated data.

We considered that most of the parallel selection mutations inferred in the epidemic sequences would not arise in the tissue culture experiments, since (a) tissue culture lacks critical features present in a natural infection (acquired immunity, elements of innate immunity, and the complex environment inside the human host), (b) our experimental paradigm lacked the effects of recombination with other viruses, and (c) the length of our experiment was dramatically shorter than the time cVPDVs have been adapting in nature. Nevertheless, four of the seven mutations inferred under parallel selection in the outbreak sequences were identified as positively selected in cell culture at  $39.5^{\circ}\text{C}$  (Fig. 4A). Of the remaining mutations, two were inferred as neutral and one as deleterious at  $39.5^{\circ}\text{C}$  (fig. S5). Conversely, all seven mutations were inferred to be deleterious at  $33^{\circ}\text{C}$ . In general the genome-wide distribution of fitness effects was shifted to the right at  $39.5^{\circ}\text{C}$  as compared to  $33^{\circ}\text{C}$  (Fig. 4B) ( $P < 2.2e-16$ , two-sample K-S test). This reflects the fact that more mutations are neutral or adaptive at high temperature whereas at the lower temperature more mutations are deleterious, confirming the increase in selection pressure at high temperature. We note that both distributions are relatively devoid of lethal alleles, since low confidence (most often low frequency) mutations were filtered out (Methods). The four adaptive mutations at high temperature included all three gate-keeper mutations, and an additional non-synonymous mutation (Fig. 4A; fig. S5).



## Experimental measurements of virus fitness confirm the role of “gate-keeper” mutations in increasing OPV2 virulence

We next sought to directly verify the effect of the gate-keeper mutations on viral fitness and virulence. To this end we performed two sets of complementary experiments: (a) competition assay of OPV2 versus mutants in tissue culture and (b) estimation of OPV2 mouse model of infection, where replicative fitness as well as adaptive immunity and intercellular interactions are all critical for OPV2 replication. We began by cloning the gate-keeper mutations onto the backbone of OPV2, either as single mutations or in combinations.

We performed direct competition assays between the mutant clones and OPV2, by initially combining the two at equal proportions, and infecting HeLa cells at high temperature (Fig. 1C). At the end of each round of infection virus was collected (representing an unknown mix of OPV2 and the mutant) and used to reinfect cells, and thus serially passaged in a similar manner five times. We used next generation sequencing to measure the frequencies of OPV2 versus the mutant over time, and used our ABC approach to measure the fitness of the cloned mutant/s compared to OPV2. Our results confirmed our first analysis: all gate-keeper mutations were found to be adaptive (Fig. 5A). Interestingly, we discovered that the combinations of mutants were fitter than the sum of each mutant's effect on its own, suggesting a synergistic epistatic interaction between all three mutations.

Next, we examined how gate-keeper mutations affect virulence in susceptible mice (Methods; Fig. 1). To this end, we first established a type I interferon receptor knock-out (IFNR-ko) mouse model (Iida-Hosonuma et al., 2005). This IFNR-ko mouse model is susceptible to OPV2 infection (as opposed to wild-type mice) and thus supports determination of viral dissemination and virulence (fig. S6). Using this model, we determined virulence of OPV2 carrying gate-keeper mutations by measuring survival rates following intraperitoneal infection. Similar to the competition assay results, the strongest effect was obtained when combining the three gate-keepers together, leading to increased and accelerated mortality compared to OPV2 and to A481G on its own (log-rank test ;  $P < 0.0005$ ). Only A481G on its own showed a significant increase in virulence as compared to OPV2 (75% survival versus 28.5% nine days post infection; log-rank test ;  $P < 0.05$ ); both U398C and U2909C showed a non-significant delay in mortality (Fig. 5B). Conversely the combination of A481G and U398C led to a slight reduction on virulence as compared to A481G on its own (log-rank test ;  $P < 0.05$ ), suggesting an antagonistic epistatic effect. Thus, these results suggest epistatic effects between the three gate-keeper mutations, which may determine the “order-of-addition” of the OPV2 evolutionary trajectory to increased virulence.

## OPV2 fitness increase appears to rely on synonymous substitutions that disrupt CpG or UpA dinucleotides

Intriguingly, one of the mutations contributing to OPV2 evolution to virulence in the phylogenetic analysis was a synonymous substitution (Fig. 3C). In fact, when lowering the posterior probability threshold of the ParaSel analysis, many more synonymous substitutions were identified (table S3), and these extra substitutions were enriched for substitutions disrupting a CpG or UpA dinucleotide (Fisher exact test,  $P = 0.006$ ). Similarly, the cell

culture experimental evolution analysis identified a number of positively selected synonymous mutations. While there was no overlap between the ParaSel and cell culture results for these mutations, the cell culture analysis at high temperature revealed a higher fitness for mutations disrupting a CpG or a UpA dinucleotide (t-test;  $P < 2e-16$ ,  $P < 1e-15$ , respectively). Furthermore, we observed depletion in the relative ratio of CpG or UpA dinucleotides in cVDPV genomes, and an abundance of CpA and UpGs, both of which represent one transition away from CpG or UpA (fig. S7A). We also observed an overall decrease in the expected dinucleotide frequencies over the first few years of cVDPV evolution (fig. S7B-E), and a more complex pattern for UpA observed over the entire six years. Several recent studies have indeed indicated that an increase in CpG or UpA dinucleotides lead to attenuation of various RNA viruses (Atkinson et al., 2014; Burns et al., 2009; Cheng et al., 2013; Tulloch et al., 2014), and an as-yet unidentified cellular pathway may recognize and target viral genomes containing CpG or UpA sites. Accordingly, our data supports the hypothesis that cVPDVs are under selection to reduce the frequency of CpGs and to some extent also of UpAs in their genomes.

## Conclusions

Our analysis provides a model describing the evolutionary steps sufficient for the OPV2 strain to lose its attenuation and become virulent. These include a series of initial substitutions, most of which are transitions, notably a relatively “easy” event for polioviruses. In particular, the gate-keeper transition mutations appear to endow the highest initial fitness, which drives them to rapid fixation from absent or extremely low levels present in the vaccine stock (Neverov and Chumakov, 2010). This is supported by the fact that all three mutations are already present in viruses excreted by vaccinees 14 days after vaccination, and have been observed previously in viruses from primary vaccinees or in sewage surveillance (Dedepside et al., 2006; Macadam et al., 1991; Nakamura et al., 2015). Following this, we propose that replication becomes more efficient, allowing a larger viral population size, which increases the probability of transmission, co-infection and recombination with prevalent HEV-C strains (Jegouic et al., 2009). The common denominator of all these different recombination events is that they almost always supply the OPV2 strains with the region encoding the viral protease (3C gene) and the RNA-dependent RNA polymerase (3D gene), as well as the 3' UTR. This region is frequently replaced with that of OPV1 within weeks of trivalent OPV vaccination, underlining the selection against the OPV2-derived genes in the human gut. The predominance of HEV-C P3 sequences in cVDPV isolates then suggests OPV1-derived genes are also sub-optimal compared to those obtained from circulating HEV-C viruses. We noted several nucleotide and amino-acid variants at 3C and 3D that almost invariably “arrived” with the HEV-C recombination (table S4). However, we cannot tease apart whether these are positions conserved in HEV-C sequences or rather that selection favored these variants in the context of an OPV2 capsid. Finally, the last so-called “wave” likely contributes a smaller adaptive value to the virus. It is likely that only a critical mass of CpG/UpA disruptions has a significant effect on fitness. The additional nonsynonymous mutations detected are not detected in antigenic sites (Minor, 1986); these mutations, as well as the Cpg/UpA disruptions, merit further investigation.

Previous research has shown that epistatic interactions may dictate the order in which mutations are fixed (Meyer et al., 2012; Weinreich et al., 2006), since the fitness advantage of one mutation is dependent on the presence of previous ones. To test whether such epistatic interactions limited the evolution of Sabin in the capsid region, we calculated the time shared across the phylogeny by all pairs of mutations (fig. S1D). Accordingly, we tested whether pairs of mutations fixed consecutively, and were maintained together along the phylogeny. Our phylogenetic analysis found no support for such epistatic mutations in the capsid region on its own. On the other hand, our experimental results supported an epistatic interaction between locus 398 and 481 in the 5' UTR. Interestingly, the epistatic effect was opposed between the human cell culture model and the mouse model, which suggests that these loci interact with other cellular components that differ between mice and human. Indeed, on passage of OPV2 in mouse L cells expressing the human poliovirus receptor the A481G mutation is selected rapidly whereas the U398C mutation has never been observed (Macadam, unpublished). Based on the cell culture results, this epistatic interaction may explain why most sequences are recombinant in the 5' UTR, since the HEV-C recombination supplies these mutations together with others at once. Together, these lines of evidence lead us to propose a potentially rugged fitness landscape leading from OPV2 to cVDPV (Fig. 6). Additional support for this rugged model is that (a) multiple RNA structures exist in the 5' UTR region and in the P2/P3/3'UTR regions (Burrill et al., 2013b), where recombination is observed.

Such structures may impose epistatic interactions, (b) chimeric sequences reconstructed from OPV2 and a HEV-C sequence displayed elevated fitness at higher temperatures (Jegouic et al., 2009). Thus, we suggest that a relatively small number of events, composed mainly of transition mutations and recombination, can lead OPV2 to a fitness peak similar in altitude to WT.

Our approach combines phylogenetic analysis of sequences from ongoing epidemics based on parallel selection events, and an experimental evolution approach of virus replication in tissue culture. The differences between the two systems is enormous: the evolutionary dynamics of viruses during an epidemic include establishment of an initial infection, immune evasion, navigation among different tissues, and transmission dynamics, all of which are lacking in a tissue culture setup. Nevertheless, our results indicate that some of the key evolutionary features of viral replication can be inferred in the relatively simple experimental evolution setup in tissue culture, which spanned a very short time-frame. We note that our setup was based on HeLa cells; while these cells do not necessarily best mimic gut epithelial cells or neuronal cells where PV strains replicate, we emphasize their key utility: by supporting large virus population sizes, we were able to capture small differences in mutation frequencies as they arose. Other cell lines that we tested (e.g., Vero cells; data not shown) did not allow the experimental design used here, mainly in terms of population size and sequencing. Importantly, using CirSeq and our ABC approach allow us to infer increase in fitness at a much higher resolution and accuracy than previous approaches used to predict loss of attenuation in tissue culture (Taffs et al., 1995). To summarize, we propose that vaccine design can in the future be guided by a similar approach, which will allow predicting in a short time whether or not live attenuated vaccine candidates can revert to

pathogenic forms. The combined approaches like that described here, may also facilitate evolutionary forecasting towards the prediction of future viral epidemics.

## STAR Method text

### CONTACT FOR REAGENT AND RESOURCE SHARING

Further information and requests for reagents should be directed to and will be fulfilled by the Lead Contact, Raul Andino (raul.andino@ucsf.edu).

### EXPERIMENTAL MODEL AND SUBJECT DETAILS

**Mice**—PVRTg21-IFNR-ko mice were obtained from Dr. Satoshi Koike, then bred and maintained in the AAALAC-certified animal facility at UCSF. Mice were specific pathogen free and maintained under a 12-hour light/dark cycle with standard chow diet provided. Both male and female mice were used for all experiments. All animal experiments were conducted in accordance with the guidelines of Laboratory Animal Center of National Institutes of Health. The Institutional Animal Care and Use Committee of University of California of San Francisco approved all animal protocols. (Approved protocol No. AN128674-01A).

**Cells and Virus**—HeLa S3 and Hep2C cells were maintained in Dulbecco's modified Eagle's medium: Nutrient mixture F12 (DMEM/F12, UCSF Cell Culture Facility) supplemented with 10% fetal bovine serum (FBS) and 1X Penicillin/Streptomycin (Invitrogen) at 37 with 5% CO<sub>2</sub>. Oral poliovirus vaccine type 2 (OPV2) SO+2 was obtained from National Institute for Biological Standards and Control (NIBSC, UK). OPV2 was propagated and tittered in HeLa S3 cells at 33 with 5% CO<sub>2</sub> by standard plaque forming assay.

### METHOD DETAILS

#### Phylogenetic analysis

**cVDPV dataset:** Genomic consensus sequences were obtained by mining the literature for circulating vaccine derived polioviruses, and by searching the Genbank repository for sequences labeled as such. All sequences were manually validated, and laboratory manipulated sequences and sequences from immune-compromised individuals and atypical cVDPVs (less than 0.5% divergence compared to the OPV2 sequence, or annotation as such) were removed. This yielded a total of 424 full-length genomic sequences. All sequence alignments were performed using MAFFT version 6.684b and are available at [www.sternadi.com/cell2017](http://www.sternadi.com/cell2017).

**Phylogeny reconstruction:** Initial reconstruction was performed based on the amino-acid sequence of 424 amino-acid sequences of the non-recombinant capsid region. However, the resulting phylogeny supported only one emergence of type 2 cVDPV, followed by subsequent spread from country to country across highly distinct and distant locations across the globe. This scenario was highly incompatible with the epidemiological data that supported multiple emergences of the virus (Burns et al., 2013). Previous research has shown that phylogenetic reconstruction will fail to recover the true history when parallel

advantageous substitutions occur on the background of limited genetic diversity (Bull et al., 1997). We thus used the synonymous sites of the nonrecombinant portion of the capsid, spanning genomic coordinates 1222 till 3384 (the coordinates were chosen to ensure non-recombinant regions, see below).

Our analysis relied on the fact that on average, selection at synonymous sites would be weaker than selection at non-synonymous sites. The tree topology and branch lengths were estimated using the maximum-likelihood methodology implemented in PhyML version 3.0 (Guindon and Gascuel, 2003), with 100 bootstrap replicates generated to assess confidence of splits (branches). The tree was rooted at the OPV2 sequence (accession AY184220). The resulting tree was bifurcating, as imposed by the reconstruction algorithm of PhyML. Epidemiological evidence strongly supports several independent emergence events across disparate locations (e.g. Egypt and China), and it is thus unlikely that this bifurcation at the root is real. Indeed, the ancestral branches surrounding the OPV2 sequence were all near zero and bootstrap support was extremely low. Hence when cumulative branch length from the root to a node was less than  $\epsilon = 6 \times 10^{-5}$  the intermediate branches were collapsed. This value was chosen as it reflects an expectation of one substitution only, suggesting that values lower than it are indicative of zero shared substitutions. The resulting tree is available as supplemental data in fig. S1A.

**Recombination analysis:** Since the recombination donor sequence (OPV2) was well established, identity versus OPV2 allowed detecting recombination breakpoints. Simplot software version 3.5.1 (Lole et al., 1999) was run on all full-length cVDPVs with OPV2 as a reference sequence. A window size of 200 bp and a step size of 20 were used (fig. S1B). Recombination breakpoints were inferred where a sharp drop in % identity occurred, i.e. when sequence identity dropped below more than 2.5 standard deviations of the median identity over the capsid region. This allowed constructing several datasets of non-recombinant regions. The largest such dataset was of the P1 capsid region, where all of the 424 sequences were of OPV2 origin from position 1222 (middle of VP2) through 3384 (the end of VP1). To explore parallel selection outside the capsid region, we further constructed six additional datasets with nonrecombinant sequences: (a) 27 sequences from positions 1–1222, (b) 44 sequences from positions 748 – 1222, (c) 25 sequences from positions 3385–4383, (d) 8 sequences from positions 3385–5382, (e) 4 sequences from 3385–6381, and (f) 3 sequences from 3385–7439. The smaller number of sequences in datasets (c) through (f) precluded statistical significance. We report results in Table S3 from the P1 dataset and from dataset (a) (which incorporates part of (b)). The phylogeny for dataset (a) is available at [www.sternadi.com/cell2017](http://www.sternadi.com/cell2017).

To study the process of recombination, we next projected the recombination breakpoint on to the cVDPV phylogeny. Notably, this assumes that sequences with similar recombination breakpoints are all derived from one shared ancestor where recombination occurred. Different recombination breakpoints indicate dissimilar ancestry with regards to the recombination. We first classified each cVDPV sequence based on the inferred breakpoint, and labeled breakpoints in windows of 100 bps (e.g., a breakpoint inferred at base 4736 and a breakpoint inferred at base 4760 would both be labeled as a breakpoint at position 4700). Fig. S2 displays the pattern of recombination in the (A) 5' UTR region, and (B) 3' P2-P3

region. Interestingly, this shows that some clades may have undergone at least two recombination events during evolution, such as the clade marked by an arrow in fig. S2.

**Substitution mapping:** In order to infer the mutational history of a site we mapped substitution events to specific branches of the phylogeny. At each site we calculated the joint posterior probability of two characters  $a, b$  (where  $a, b \in \{A, C, G, T\}$ ) populating the nodes along each branch of the tree:  $P(a, b / X) = P(a, b) / P(X)$ , using the HKY model (Hasegawa et al., 1985). Full details of this calculation were described previously (Stern et al., 2010). Only sites and branches where  $P(a, b / X) > 0.6$  were reported.

**Co-evolution of pairs of sites:** In order to test for correlated evolution between pairs of sites in the non-recombinant region, we measured the fraction of shared time  $O(i, j)$  when site 1 is in state  $i$  and site 2 is in state  $j$  (Huelsenbeck et al., 2003). This fraction was then compared to the expected fraction of time these two states should share together  $E(i, j)$ , based on the marginal probabilities of finding each character on its own. The metric for assessing correlated evolution is then the difference:

$$d_{ij}(\tau, v, h_1, h_2) = O(i, j) - E(i, j) \quad (1)$$

where  $\tau$  is the tree topology,  $v$  is a set of branch lengths representing the time, and  $h_1$  and  $h_2$  are character mappings for characters 1 and 2 based on the mapping described above using joint posterior probabilities. A key difference in our approach here as compared to (Huelsenbeck et al., 2003) is that we do not integrate over different trees and branch lengths but rather use only one such realization. We compared values of  $d_{ij}$  to a set of values obtained by simulating over the same set of tree topology and branch lengths, with a null model of evolution where directional selection is absent and sites are simulated independently. Our results (fig. S1D) show no difference between the simulated and real data; thus we could not detect pairs of sites displaying a significant pattern of co-evolution.

**Calculating the *ad-hoc* probability of parallel substitutions in two or more lineages of the phylogeny:** Let  $p$  denote the probability of a given substitution during one year of viral evolution. Based on the molecular clock calibration of PVs whereby the expected number of substitutions per site per year is 0.011 (Jorba et al., 2008), let us set  $p=0.011$ . The sum of branch lengths in our phylogeny is 3.40761, which can be translated to an accumulated 310 years of viral evolution (which occurred during overlapping timeframes in independent infections). We can now use the binomial distribution to estimate the probability of two or more substitutions at the same locus throughout the phylogeny as:

$$P(X \geq 2) = 1 - P(X=1) - P(X=0) = 1 - \binom{310}{1} p \cdot (1-p)^{309} - \binom{310}{0} (1-p)^{310} \approx 0.85 \quad (2)$$



Notably, this is a highly simplistic estimate that ignores rate variation, transition/transversion rates, and other biological properties of viral replication. However it still captures the fact that the probability of parallel substitutions is extremely high in polioviruses in the scenario described herein.

**An evolutionary Markov model for detecting parallel directional selection:** Under strong parallel (directional) selection, we expect one allele to be highly preferred over all other alleles (Kosakovsky Pond et al., 2008; Seoighe et al., 2007). Hence the rate of a substitution leading to this allele along the phylogeny will be higher, in proportion to the selective advantage it confers, and correspondingly substitutions that change this allele to an allele of lower fitness will have a reduced rate. This is captured by assuming a continuous time Markov process, defined by an instantaneous rate matrix  $Q$  with elements  $Q(i,j)$ , for  $i \neq j$ , given by:

$$Q(i, j) = \begin{cases} H(i, j) & i, j \text{ are not the preferred allele } k \\ H(i, j) \cdot \frac{S}{1 - e^{-S}} & j = k, \text{ directional selection for allele } k \\ H(i, j) \cdot \frac{S}{e^S - 1} & i = k, \text{ negative selection against losing allele } k \end{cases} \quad (3)$$

where  $H$  is any standard rate matrix over any alphabet (e.g., nucleotides or amino-acids).  $S =$

$4Ns$  is the genomic population size ( $N$ ) scaled selection coefficient, and  $\frac{S}{1 - e^{-S}}$  is the rate of fixation of a non-neutral mutation (Kimura, 1962; Nielsen and Yang, 2003). The diagonal elements of  $Q$  are defined so that the sum of entries in each row is zero.

Since we do not know *a priori* which allele is preferred, the likelihood function was calculated using a mixture model in which all possible assignments of preferred allele was given equal prior weight. We denote the model in which allele  $k$ ,  $k \in \{1, 2, \dots, K\}$ , is preferred as  $M_k$  and the standard baseline model without selection by  $M_{base}$ . Further, we assume a proportion  $P_{DS}$  of sites (to be estimated) are under directional selection. Thus the total likelihood function, given an alignment of sequences and a phylogeny, is

$$P(X) = \sum_{k=1}^K \frac{P_{DS}}{K} P(X|M_k) + (1 - P_{DS}) \cdot P(X|M_{base}) \quad (4)$$

We further assume among-site rate variation (ASRV), where rates followed a discrete approximation of the gamma distribution with a mean of one (Yang, 1994).

Finally, to model incomplete selection near the tips of the tree, we introduced the parameter  $\beta$ , which effectively increases the branch lengths at the tips of the tree by rescaling the among-site rate variation distribution. Site-specific evolutionary rates are directly linked to branch lengths, and a site evolving with rate  $r$  can be modeled by multiplying all branch lengths in a tree by  $r$ . We model incomplete purifying selection by modifying  $r$  only at the tips of the tree as follows:  $r_{relax} = r + (r_{max} - r) \cdot \beta$ , where  $r_{max}$  is the maximal rate category of the discretized gamma distribution. This modification was applied to the edges leading to



leaves of the tree at all sites of the alignment, and shifts the ASRV distribution towards values representing less purifying selection without affecting the maximal rate. Importantly this captures incomplete purifying selection that may occur during shorter timescales in viral evolution, due to smaller effective population sizes (Pybus et al., 2007).

Thus, parameters in the model are:  $S$ ,  $P_{DS}$ ,  $\alpha$  (shape parameter of the gamma distribution), parameters of the baseline model (here the transition/transversion rate  $K$  in the HKY model (Hasegawa et al., 1985)), relaxation parameter  $\beta$ , and a scaling factor for the branch lengths of the phylogeny ( $\tau$ ). All parameters were optimized under maximum likelihood using the Brent optimization scheme (Brent, 1971) and the BFGS optimization scheme (Byrd et al., 1995), with the likelihood function initialized at multiple starting points to reduce the chance of the algorithm being trapped in a local, but not global, maximum. Similar results were obtained with both optimization methods (data not shown).

To test whether the data exhibited significant support for directional selection, we used model selection based on the corrected Akaike Information Criterion (AIC). This approach was necessary since none of the asymptotic methods are applicable for using the  $X^2$  approximation for a likelihood ratio test, typically used when comparing two phylogenetic models. This pathology occurs since  $S$  is only estimated in the alternative model and not in the null model.

**Testing for site-specific directional selection:** Given significant support for the selection model, as specified by the AIC comparison, we calculated the posterior probability that a site  $i$  with site pattern  $X_i$  experienced directional selection by calculating the posterior probability of a site evolving under each of the  $K$  directional selection models. This is given by

$$P(M_k|X_i) = \frac{P_{DS} P(X_i|M_k)}{P(X_i)}.$$

We note that our model, similar to most evolutionary models, assumes that sites in the alignment are independent. This assumption hence means our method fails to take into account different forms of linkage among sites. However, polioviruses possess extremely high rates of recombination (Kirkegaard and Baltimore, 1986; Runckel et al., 2013), suggesting that linkage among sites may be frequently broken up in these viruses.

**Testing ParaSel on simulated data:** We began by simulating 100 datasets of nucleotide sequences under a neutral model of evolution (HKY). Sequences were simulated using the OPV2 root sequence along the phylogeny of the cVDPVs as obtained above. All parameters were inspired by those inferred above for the cVDPV data. For computational reasons, the sequence length was truncated to 200.

We next sought to test the effect of an epistatic interaction on ParaSel inference. To this end, 100 datasets were simulated similar to above with an HKY model; however, only sequences which maintained a paired base composition at a given pair of sites that allows RNA base-

pairing (G:C, G:U or A:U) were retained, thus creating simulated data with purifying selection against non-base pairs.

Finally, we simulated 100 datasets with 10% of sites under directional selection for “A”, and 90% of sites under a neutral HKY model. Furthermore, we tested the specificity and sensitivity of the method to detect the specific sites under selection, and used a receiver-operator-characteristic curve to explore different thresholds of the posterior probability.

We then ran ParaSel on the simulated dataset and tested in how many datasets the method showed significantly lower AIC scores under the ParaSel model as compared to the null model. All results are summarized in table S2.

**Recombination as an adaptive event:** We wished to infer whether the recombination events with HEV-C sequences are under positive parallel selection as well. Sequences were classified for presence or absence of a recombination breakpoint. Notably all but three of the cVDPVs were recombinant at the 3' region, whereas in the 5' UTR region all but twenty-seven of the cVDPVs underwent recombination. This allowed us to map the recombination events onto the phylogeny. Indeed, this showed that almost all of the lineages coming out of the ancestral OPV2 sequence were recombinant (fig. S2). We could not utilize ParaSel for inferring selection of these recombination events since we wanted to avoid inference based on one character only. However, the rate of substitutions is likely much higher than the combined rate of co-infection and the rate of strand displacement (that leads to recombinant genomes for polioviruses). Thus, given our inferences of positive selection for many of the point mutations, the exceptional parallelism of the recombination events strongly suggests that they are under positive selection as well. This is line with experimental data confirming this conjecture (Jegouic et al., 2009).

**Inferring site-specific diversifying selection using dn/ds:** The “selecton” web-server (Stern et al., 2007) was used to run the M8 and M8a models (Yang et al., 2000) in order to test for the existence of diversifying positive selection. A likelihood ratio test between the two models yielded strong significant support for positive selection ( $P < 10^{-8}$ ). Next, site-specific values of  $d_n/d_s$  were inferred based on the M8 model using the posterior probability distribution of  $d_n/d_s$  values at each site. Sites were considered to be under positive diversifying selection when the lower bound of the 95% credible interval of this distribution was higher than one.

**Calculating odds ratios of dinucleotides in cVDPV genomes:** Odds ratios for

dinucleotides were calculated as  $R(X_P Y) = \frac{f_{XY}}{f_X \cdot f_Y}$  where  $X$  and  $Y$  stand for single nucleotides,  $f_{XY}$  stands for the joint frequency of a dinucleotide and  $f_X \cdot f_Y$  is the expected frequency based on the product of the two bases' frequencies. As proposed by Burge et al. (Burge et al., 1992), values below or above the range of 0.81–1.19 were considered low or high abundance, respectively. Indeed overall levels of both CpG and UpA dinucleotides were consistently lower than 0.81 (fig. S7A). The CpG levels in cVDPV strains were found to decrease constantly over time, with a linear regression model explaining 15% of the variance

(fig. S7B,D). A 2<sup>nd</sup> degree polynomial model led to a non-significant fit, suggesting that selection operates in a linear fashion against the accumulation of CpG sites.

On the other hand, UpA levels showed a more complex pattern. In the first 2–3 years, levels of UpA decrease over time (fig. S7C), particularly in the capsid region. Surprisingly, after that levels of UpA increase till reaching what appear to be a steady state at 0.76 O/E (fig. S7E), which still reflects lower than expected dinucleotide frequencies. Quadratic models with increasingly high order polynomials indeed yielded a significant fit ( $P < 0.000142$ ,  $P < 0.001370$ ,  $P < 0.004$  for 2<sup>nd</sup>, 3<sup>rd</sup>, and 4<sup>th</sup> degree polynomials, respectively), suggesting a more complex model of evolution with potential interaction with other as yet unknown factors. All in all, it appears that the dinucleotide levels in the OPV2 genome have an optimal steady state level that the genomes converge upon.

### Experimental validation

**Next generation sequencing of excreted viruses:** Stool samples were collected from primary vaccinees 14 days after vaccination with trivalent OPV (Dunn et al., 1990) and processed by adding 1g to 10 ml PBS containing 1g of glass beads and 1 ml chloroform in a 50mL Falcon tube. Tubes were shaken vigorously at 4°C for 20 minutes using a mechanical shaker then centrifuged for 20 minutes at 1500 × g in a refrigerated centrifuge. RNA was purified from stool extracts using Roche High Pure viral RNA kits. Water only controls were extracted, amplified and sequenced in parallel with each set of samples. Almost full-length poliovirus genomes were amplified in duplicate by one-step RT-PCR using a SuperScript® III One-Step RT-PCR System with Platinum® Taq High Fidelity DNA Polymerase (Invitrogen) and primers PCR F (5'-AGA GGC CCA CGT GGC GGC TAG -3') and PVR 3' (5'-CCG AAT TAA AGA AAA ATT TAC CCC TAC A -3'). Products were purified using AMPure XP magnetic beads (Beckman Coulter), quantified using Qubit High Sensitivity dsDNA assay (Life Technologies) and diluted to 0.2 ng/μl in molecular grade 10 mM Tris-EDTA, pH8.0.

Sequencing libraries were prepared using Nextera XT reagents (Illumina) and the manufacturer's protocol, and sequenced on a MiSeq using a 2 × 251 paired-end v2 Flow Cell (Illumina). Quality trimming and assembly were carried out as in Mee et al. (2015). Reads were then mapped to an OPV2 reference sequence using Geneious R7 (Biomatters) software and SNPs present at 1.0% identified. Only those SNPs present in both replica amplicons were retained.

Recombinant type 2 virus genomes were identified by deep sequencing type 2 viruses and mapping reads to OPV1, 2 & 3 reference sequences as above. Type 2 viruses were obtained by incubation of stool extracts with high titre polyclonal antisera against type 1 and type 3 poliovirus followed by infection of HEp2c cells and incubation at 35°C until full cytopathic effect. Capsid sequences of these viruses mapped to OPV2 alone.

**Viral serial passaging in tissue culture:** To test adaptation of OPV2 to high temperature, we passaged oral polio vaccine (OPV) type 2 in cell culture. Originally we performed serial passaging in Vero cells at 37°C. Notably this led to very poor growth of the virus, and due to

the low virus yield we lacked the right population size for accurate next generation sequencing.

We next passaged OPV2 at HeLa S3 (ATCC, CCL2.2) cells, which are more supportive of viral replication, at both 33°C (control condition) and 39.5°C. For both conditions,  $10^7$  HeLa S3 cells were seeded the day before the experiment and infected with OPV2 at MOI of 0.1 for one hour to allow virus adsorption, and then replaced with virus culture medium. The infected cells were maintained for 24 hours, allowing two replication cycles per passage, leading to total of seven passages and fourteen replication cycles. Cells were then harvested by freezing at  $-80^{\circ}\text{C}$ . After three freeze-thaw cycles, virus suspension was clarified by centrifugation at  $3,500 \times g$  for 10 minutes at  $4^{\circ}\text{C}$ , and stored at  $-80^{\circ}\text{C}$  for future passages. Plaque assays were performed to determine virus titer of each passage at an MOI of 0.1 for subsequent passages.

**Viral population deep sequencing and inference of mutation frequencies:** Highly accurate sequencing of viral populations was obtained by our newly developed CirSeq approach (Acevedo and Andino, 2014; Acevedo et al., 2014). Briefly, this approach is based on the conversion of short fragments of the viral RNAs to circular molecules. When copied with reverse transcriptase, tandemly repeated cDNAs are produced. Mutations in the original viral RNA are shared by all tandem repeats, while errors produced during reverse transcription, PCR or sequencing will be randomly distributed along the tandem repeats. Subsequent computational mapping can thus reduce sequencing error to a point that is much lower than the estimated mutation rate of an RNA virus.

Viral populations were amplified once in HeLa S3 to increase the percentage of viral RNA for sequencing. Library preparation and sequencing were performed as described in ref. (Acevedo et al., 2014; Stern et al., 2014) on a HiSeq (Illumina). Initially passages 2,4, and 7 were sequenced for both temperatures. Subsequently passages 1,3,5,6,7, were sequenced at  $39.5^{\circ}\text{C}$ , and passages 2 and 4 were discarded for the  $39.5^{\circ}\text{C}$  analysis due to batch effects. Reads were mapped to the OPV2 reference genome (Genbank accession AY184220) using Q23 as a quality threshold, yielding a Cirseq error rate of approximately  $10^{-7}$ . We then estimated allele frequencies as in (Stern et al., 2014), yielding values for minor allele frequencies that typically ranged between  $10^{-6}$  and  $10^{-2}$  (fig. S3). We further assessed the reliability of allele frequencies. Based on the geometric distribution, in order to guarantee that a viral template occurring at frequency  $f$  is detected with probability  $p$  or better, it is necessary to sequence at least  $\log(1-p) / \log(1-f) - 1$  templates (Lorenzo-Redondo et al., 2016). We estimated the number of templates sequences as the coverage at a certain locus, allowing us to calculate  $p$  for each mutation. Only allele frequencies where  $p > 0.95$  were retained for analysis of fitness.

**Generation of gatekeeper mutant viruses:** Gatekeeper mutations were introduced into the OPV2 infectious cDNA clone (pRA-SABIN2) with PCR-directed mutagenesis. PCR was performed using pRA-Sabin2 as template with primers containing gatekeeper mutation (primer sequences are provided in Key Resources Table). The PCR product was digested with Dpn I (NEB) at  $37^{\circ}\text{C}$  for 1 hour, and transformed into One shot Top10 competent cells (Invitrogen). Plasmids were verified with Sanger sequencing for the introduced gatekeeper

mutation. Protocols for virus generation from infectious cDNA clone and quantification have been previously described (Burrill et al., 2013a).

**Competition assays:** HeLa S3 cells were coinfecting with OPV2 and gatekeeper mutant virus at a multiplicity of infection (MOI) of 0.05 for 10 hours. Cells were harvested with 3 freeze-thaw cycles and cleared at 3500 rpm for 10 minutes at 4°C. The viral supernatant was titered by plaque assay and passaged further at low MOI for 10 hours. This process was repeated to get a total of 5 passages. Viral RNA was purified from supernatants of passages 1, 3, and 5 using the ZR Viral RNA Kit (Zymo Research). The proportions of OPV2 and gatekeeper mutant virus in each viral RNA sample were determined by standard next generation sequencing. RNA libraries were prepared with the KAPA Stranded mRNA-Seq Kit (KAPA Biosystems) and NEXTflex RNA-Seq Barcodes (BIOO Scientific), and sequenced on a MiSeq (Illumina).

**Virulence of gatekeeper mutant viruses in mice:** A novel mouse model of infection for OPV2 was established by using poliovirus receptor (PVR) transgenic Tg21 mice deficient in the alpha/beta interferon (IFN) receptor gene (Ida-Hosonuma et al., 2005). To determine viral dissemination, a total of 18 10-day-old IFNR-ko mice were intraperitoneally (i.p.) inoculated with  $10^5$  plaque-forming unit (PFU) of OPV2. Various tissues were harvested from 3 mice everyday till Day 6 post inoculation. The harvested tissues were weighted, homogenized in 1 ml of culture medium and cleared at  $10,000 \times g$  for 10 minutes at 4°C. Virus titer in cleared supernatant was determined by plaque assay, and expressed as log PFU per milligram of tissue.

For virulence testing, mice were infected either OPV2 or gatekeeper mutant virus. I.p. infections were performed using 10-day-old mice with  $1 \times 10^6$  PFU per mouse (7–8 mice per virus strain, 100  $\mu$ l per mouse). An additional group of mice were inoculated the same way with 100  $\mu$ l of viral medium as a control. Mice were monitored daily for signs of paralysis. Mice were euthanized upon appearance of dual hind limb paralysis, a sign of imminent death, and death was recorded for the following day.

## QUANTIFICATION AND STATISTICAL ANALYSIS

**Inferring mutational fitness from time-series allele frequencies—**Mutational fitness values  $w$  of different alleles (mutations) were inferred based on the time-series of allele frequencies. We elaborated on a novel approximate Bayesian computation (ABC) method ((Foll et al., 2014), Zinger and Stern, unpublished) that takes into account stochastic effects of viral replication and library preparation. Importantly, this model accounts for genetic drift that affects alleles present at low counts during early passages.

Our approach uses as a baseline the methodology described previously (Foll et al., 2014), which bypasses the need for computationally intensive likelihood calculations, and instead relies on simulations using parameters sampled from the prior distribution of the model parameters. Based on the distance between a simulated trajectory and the real data, a rejection-based scheme is used to create the posterior distribution of the parameter at each site. Here, we use a Wright-Fisher model with a binomial sampling step that further accounts for novel mutations and back mutations at each generation (Stern et al., 2014) to

simulate trajectories of allele frequencies, and assume a uniform prior distribution over our mutational specific parameter  $w$  (mutational fitness) spanning  $[0,2]$ . At each locus, we retain the top 1% out of 1,000,000 simulations to be used as a posterior distribution for a rejection ABC algorithm. Our approach differs from that described in Foll et al. (2014) on three levels: first, we infer the base-by-base mutation rates directly from the data, rather than assuming a predetermined mutation rate value. This is made feasible due to the high precision of the CirSeq approach (Acevedo and Andino, 2014; Acevedo et al., 2014) (see section on Inferring mutation rates). Second, we do not estimate the effective population size  $N_e$ . Our experimental setup was designed for very high population sizes ( $10^6$  PFUs at each passage), and furthermore we obtain coverage ranging typically from  $10^5$ – $10^6$  reads per locus (fig. S3). We hence assume a large population size in our simulations ( $10^5$ ). Finally, when testing the distance between simulations ( $sim$ ) to the data ( $d$ ), we calculate the  $l_1$  distance between the curves defined by  $y = w^p$  where  $p \in \{1 \dots 7\}$  are the passage numbers. Notably, we would like to emphasize that since we are looking at rare new mutations, this implies that mutations are approximately independent.

The ABC approach described herein has been tested extensively validated and found to yield very good estimates of fitness (Foll et al., 2015). We further tested our approach on simulated data (fig. S4) using a population size and mutation rate similar to that used in this study. Reassuringly the results show that our method is highly successful in recapitulating the true fitness value used in the simulations.

**Inferring mutation rates**—We infer mutation rates based on the change in frequencies of synonymous mutations across time. Since mutations at neutral sites accumulate freely, we expect the rate of divergence of neutral sites to be precisely equal to the mutation rate (Kimura, 1968). We thus use synonymous mutations, excluding those that disrupt or create CpG or UpA sites, as a proxy for neutral mutations, and divide the mutations into the four types of transitions (fig. S6). We used linear regression to estimate the slope at each independent trajectory at each site. The mean value across sites was used as an estimate of the mutation rate. We tested our approach on 100 simulated datasets using a Wright-Fisher model as described above, assuming a set of one hundred loci all evolving neutrally ( $w=1$ ) and a mutation rate of  $10^{-5}$  mutations/base/generation. Two approaches were tested: once, linear regression was used to fit all passages, and second we used the last five time-points only. The latter was done to test the effects of random genetic drift operating at earlier passages when allele counts are low. We further tested a combination of two different scenarios: population size of  $N=100,000$  as used here and a lower population size ( $N=10,000$ ). Finally, we also tested a noisier scenario where 10% of the hundred simulated loci were deleterious ( $w=0.5$ ). The results of the simulations are presented in fig. S6C. The results showed excellent recovery of the mutation rate, apart for the scenario when  $N=10,000$  and only the last time-points are used. Based on these results we chose to estimate the mutation rates based on all time-points (fig. S6A).

We further compared our mutation rates estimates to those obtained using our previous approach that relies on the frequencies of lethal mutations (Acevedo et al., 2014). The neutral regression approach yielded lower mutation rates for most types of mutations (fig. S6B). We hypothesize that this occurs due to the experimental protocol of expanding the



viral populations before sequencing at high multiplicity of infection (MOI), and since during the second replication cycle at each passage high MOI will occur as well. Under this scenario, genomes with deleterious mutations may be compensated for by other co-infecting functional genomes, leading to a general elevation in frequencies of deleterious mutations (Stern et al., 2014). Furthermore, we noticed a general elevation of C→T mutations, consistent with our previous report on elevation of this type of mutation due to library preparation (Lou et al., 2013). This strengthens the use of an approach relying on changes in neutral mutation frequencies across time, which is expected to overcome this effect since it assumes any bias in library preparation will not increase over serial passages.

**Inference of beneficial mutations**—After inferring the mutation rates, we next set out to infer whether the set of mutations found using ParaSel are under positive selection. To this end, similar to (Foll et al., 2014; Sunnaker et al., 2013), we assumed a uniform prior over  $w$ , spanning the interval  $[0,2]$ . We retained the best 1% of simulation as defined above to create posterior distributions (fig. S5) and median values of these distributions. We report mutations under positive selection based on Bayesian “p-values” ( $P(w > 1|data)$ ) and thus a mutation is considered significant if at least 95% of the posterior distribution exceeds one. We thus considered a mutation to be adaptive at high temperature if it adhered to the following criteria: (a) it was found to be under positive selection in the 39.5°C experiment, and (b) it was not found to be under positive selection in the control 33°C experiment.

## DATA AND SOFTWARE AVAILABILITY

All sequence alignments and phylogenies used in this study, and fitness of viral mutations passaged at 33 and 39.5°C are available at [www.sternadi.com/cell2017](http://www.sternadi.com/cell2017). The ParaSel software is available at [www.sternadi.com/parasel](http://www.sternadi.com/parasel). Read files for all sequencing data were deposited in the NCBI Sequence Read Archive (SRA) as listed in the Key Resources Table.

## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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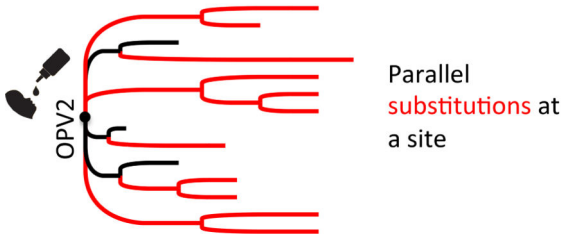
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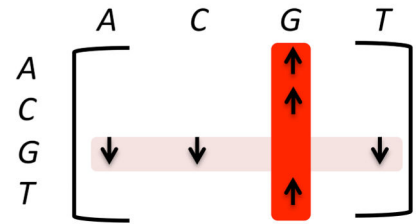
- Mutations contributing to evolution of virulence in an attenuated RNA virus are inferred
- An experimental evolution approach in cell culture recapitulates the key mutations
- Contribution to virulence is validated *in vitro* and in an animal model of infection

Understanding how an attenuated strain of polio evolved to become fully virulent provides a new framework for rational design of safer vaccines.

**(A) Phylogenetic analysis of epidemic sequences**



**ParaSel Markov Model**



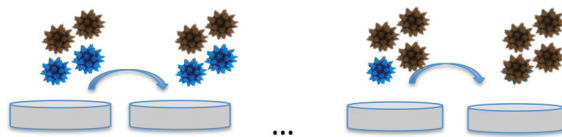
**(B) In vitro experimental evolution system**



CirSeq

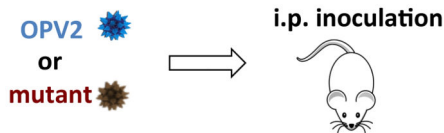
**(C) Direct assessment of virulence of mutations**

i. Competition in cell culture



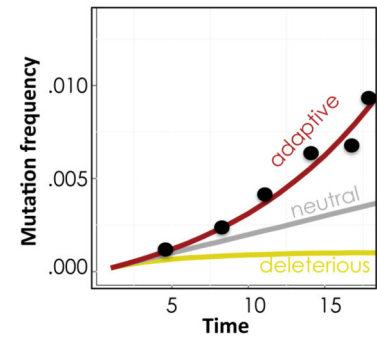
NGS

ii. Mouse model of infection

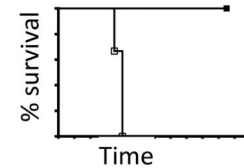


**ABC method for inferring fitness**

Simulations using theoretical model, and fit to observed mutation frequencies (•)



**Survival curve**



**Figure 1. Schematic of analyses and experiments performed in the manuscript**

Experiments and data are illustrated on the left and computational approaches for data analysis on the right. (A) A phylogenetic analysis of cVDPV consensus sequences from epidemics across the globe was undertaken with the aim of detecting parallel substitutions under selection (in red) as compared to the ancestral OPV2 state (in black). A novel Markov model denoted ParaSel was developed, which assumes that selection will lead to an increase in the rate of substitutions into a certain nucleotide, and decrease in the rate of loss of this nucleotide (exemplified as the “G”). The model then allows calculating the likelihood of the data and performing model choice, followed by inference of specific sites where selection led to parallel substitutions. (B) An experimental evolution approach was used to monitor the emergence of mutations in OPV2 conferring an evolutionary fitness advantage during growth in cell culture at elevated body temperature. (C) Direct assessment of the effect of mutations inferred in (A) and (B) on viral virulence was performed using (i) competition assays between selected mutants and OPV2 at elevated body temperature, and (ii) a mouse model of infection that allowed comparing the virulence of selected mutants versus OPV2. An ABC approach (Methods) was used to infer whether an increase in the frequency of a

mutation over time represents significant adaptive evolution. The method compares theoretical simulations of allele frequencies to the empirical data. Accordingly, deleterious alleles are expected to be present at low frequencies throughout the experiment due to purifying selection, whereas adaptive alleles will increase rapidly in frequency. Neutral alleles will accumulate at a rate equal to the mutation rate.

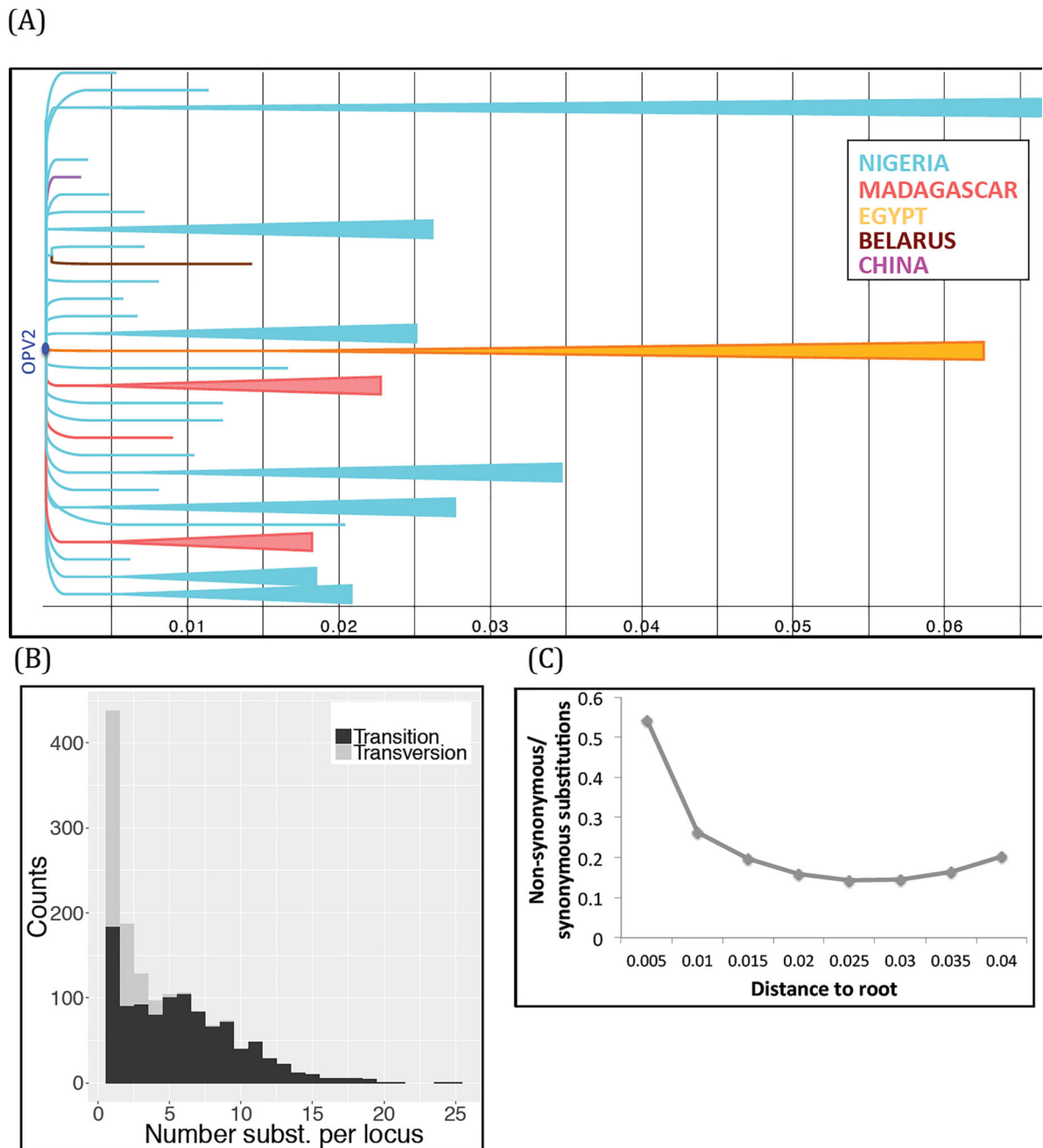
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**Figure 2. Phylogenetic analysis of cVDPV2 sequences. See also Fig. S1 and Table S1**  
 (A) Maximum-likelihood phylogenetic tree for 424 cVDPV sequences, based on synonymous polymorphisms in the non-recombinant capsid region. The x-axis represents substitutions per site, where 0.011 substitutions are equivalent to one year of viral circulation based on the PV molecular clock (Jorba et al., 2008). Clades were collapsed for visualization. (B) The distribution of the number of independently occurring substitutions inferred across the phylogeny. Transitions are colored in black and transversions are in grey. Notably the transition/transversion ratio is much higher in events mapped two or more times. (C) The ratio of the number of non-synonymous to synonymous substitutions across time

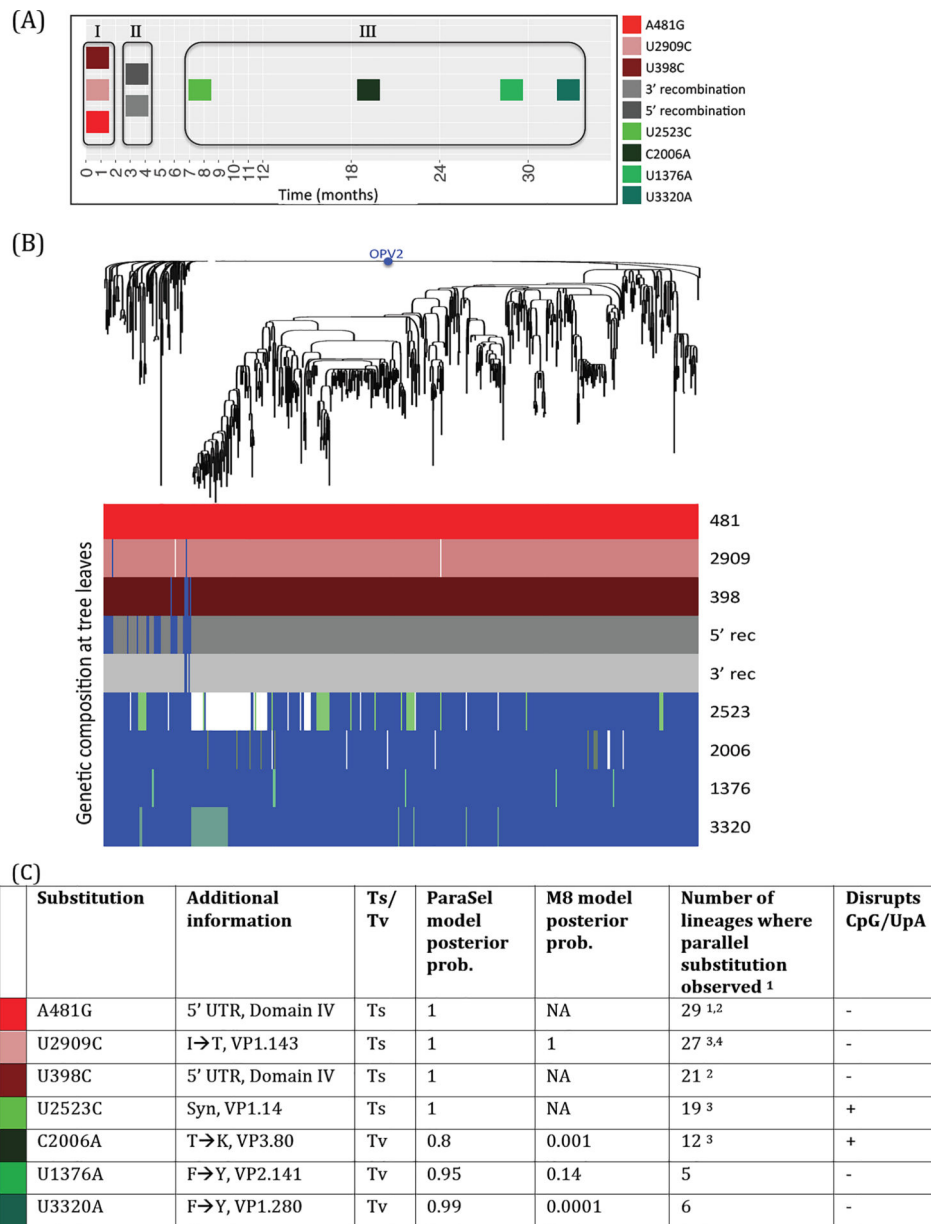
shows that strong adaptation occurs early on in the epidemics, which is relaxed later on, and that incomplete purifying selection likely occurs during recent evolution. (A) through (C) all refer to the non-recombinant capsid region.

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<sup>1</sup> A total of 29 epidemics (lineages coming out of the OPV2 sequence) were analyzed here.

<sup>2</sup> In several lineages, substitution is obtained via recombination rather than via mutation.

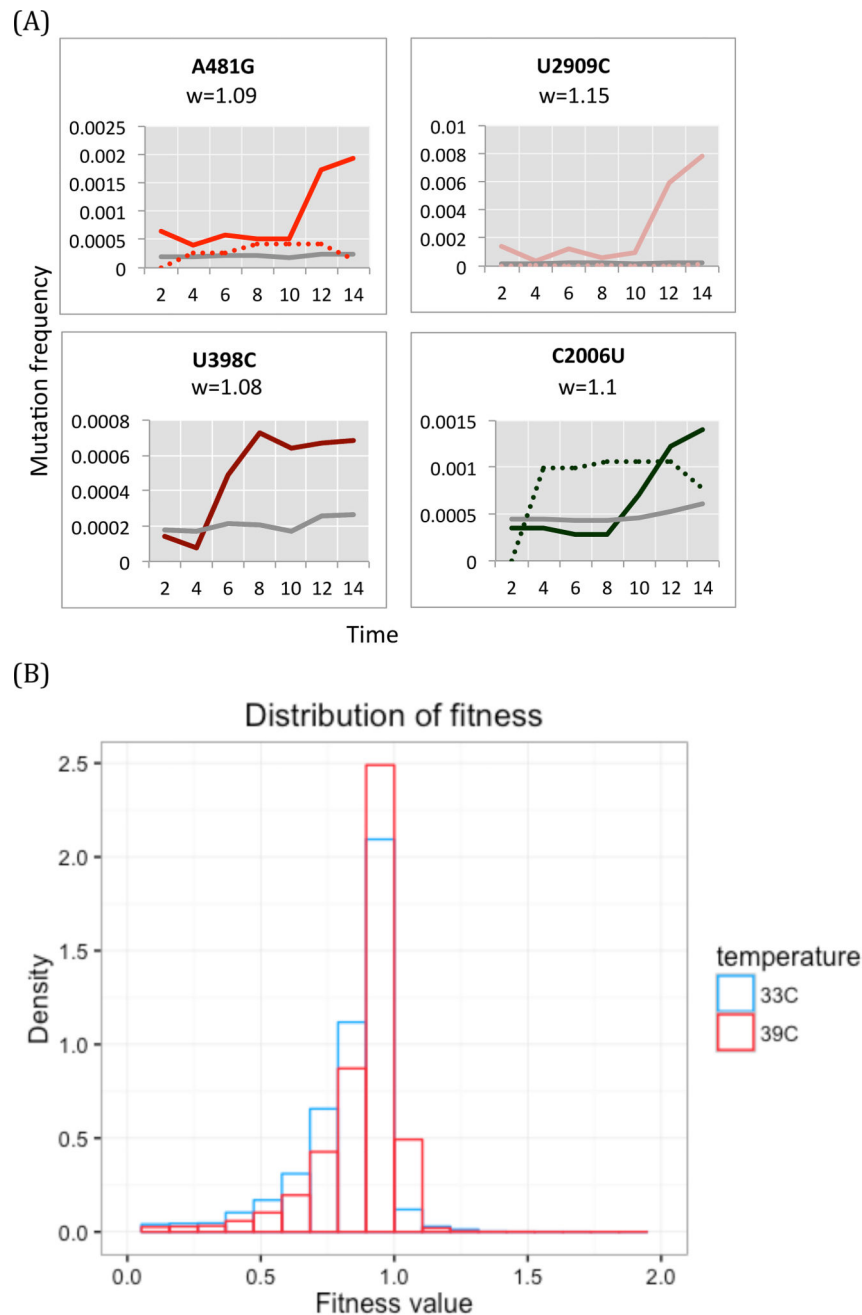
<sup>3</sup> Alternative substitutions found at this locus are counted as well (e.g., U2523A).

<sup>4</sup> In two additional lineages an A2908G substitution led to a replacement of I→V at VP1.143.

**Figure 3. Results of ParaSel phylogenetic model allow reconstructing the regain of virulence of cVDPVs from independent epidemics across the globe. See also Fig. S2 and Table S3**

Seven substitutions and two recombination events are inferred to be under parallel positive selection. (A) The timeline shows the approximate inferred timing of each event, illustrating a sequential process of increase in fitness. Three “waves” of events are observed, inferred based on the estimated fixation time of each event. The relative timing of each event within each wave could not be inferred consistently and is shown based on one of the epidemics (B) A projection of each of the nine events (bottom) onto the phylogenetic tree of the cVDPVs (top). A thin line colored in red/grey/green, corresponding to the colors in panel A, represents a substitution or recombination event under parallel selection present in the

sequence corresponding to the leaf of the tree on the top. Blue represents the ancestral OPV2 state, whereas white represents a third alternative. (C) A table summarizing the properties of the substitutions detected by ParaSel, with colors as in (A). Ts refers to transition, whereas Tv refers to transversion. Additional information specifies the location of the substitution on the accepted RNA structure of the 5' UTR (Andino et al., 1990; Pilipenko et al., 1989), or the amino-acid replacement and its location in the capsid forming genes VP1 through VP4.



**Figure 4. Results of in vitro experimental evolution at 33°C and 39.5°C. See also Figs. S3 and S5 and Table S5-S7**

Viruses were serially passaged in HeLa cells for seven passages (corresponding to 14 generations) at both temperatures. Passages were sequenced using highly accurate CirSeq sequencing (Acevedo et al., 2014). (A) Four mutations predicted with ParaSel were validated using the experimental evolution approach. Time-series trajectories are shown in solid lines (39.5°C) and dashed lines (33°C), with colors corresponding to those in Fig. 3. For U398C, lack of coverage precluded inferring reliable allele frequencies at 33°C. The grey line in each box represents the neutral allele behavior over time, based on the mean behavior of synonymous mutations in the relevant class of mutation, excluding CpG and

UpA sites. (C) Distributions of genome-wide fitness values obtained at 33°C (blue) and 39.5°C (red) show that the 39.5°C distribution is shifted to the right, indicating more adaptation at elevated temperature.

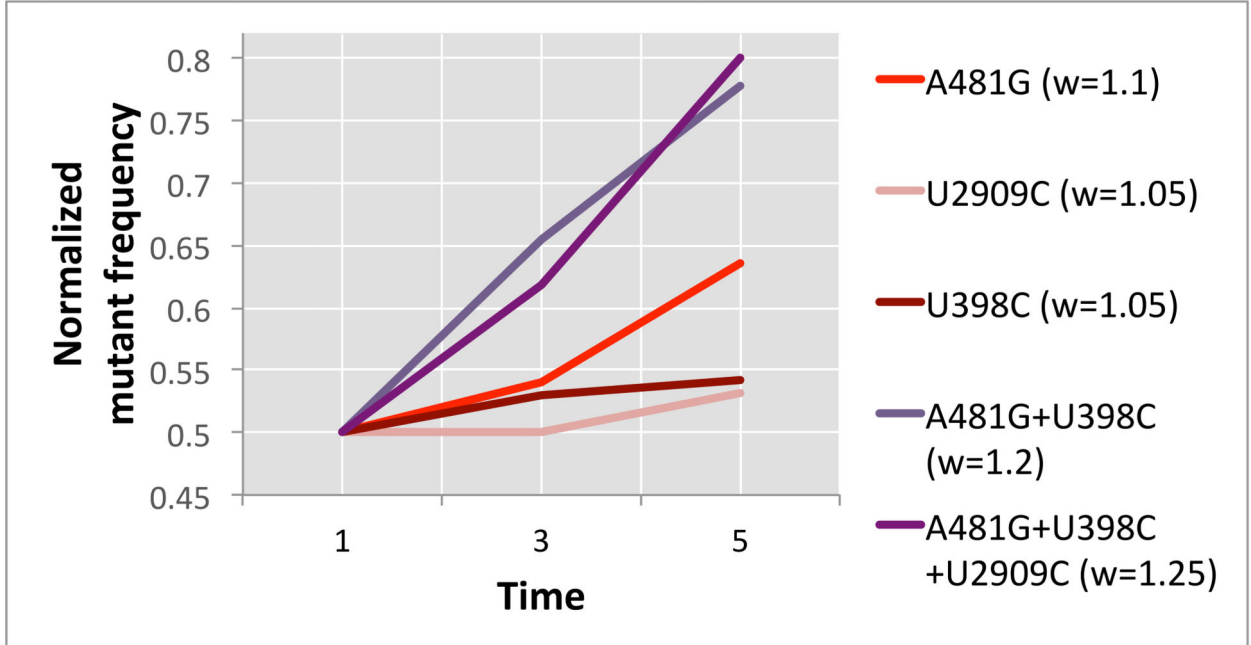
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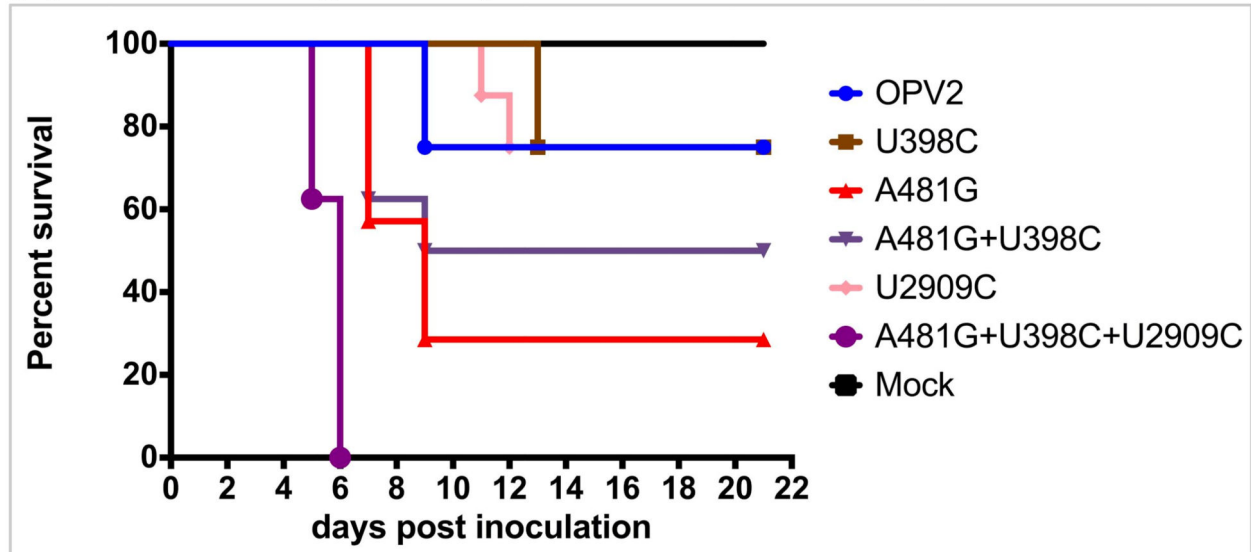
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## (A) Competition in cell culture, “gate-keeper” mutants



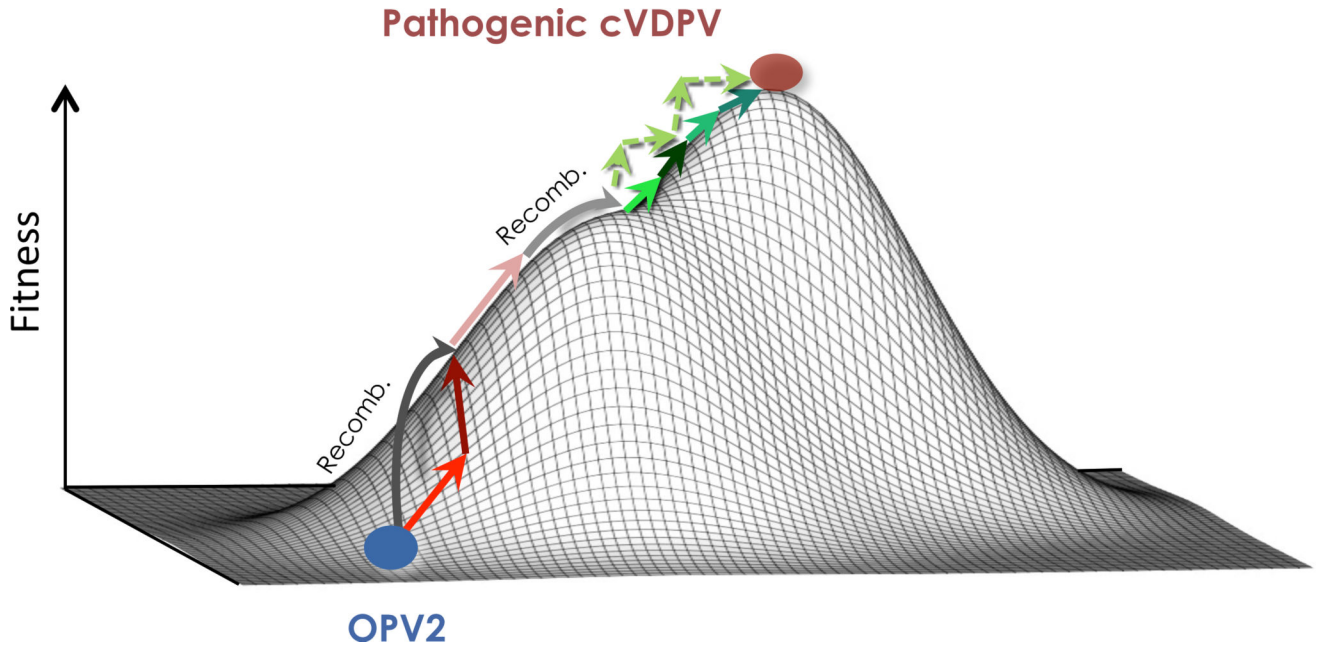
## (B) Virulence of gate-keeper mutations in susceptible mice



**Figure 5. Direct assessment of virulence of mutations. See also Fig. S6**

(A) Results of competition assay of the three gate-keeper mutations reveal that all three mutations outcompete the OPV2 strain, on their own or in combination. Mutant frequencies varied between 0.3 and 0.6 at the first passage and were normalized for purpose of presentation to begin at 0.5. (B) Survival analysis of susceptible mice infected with OPV2 gate-keeper mutants. The analysis reveals that the A481G mutation leads to increased virulence as compared to OPV2, with an even stronger effect observed for the combination of all three mutants. Potential epistatic interactions are observed in (A) and (C) for combinations of mutations (see text).





**Figure 6. A model summarizing the proposed path/s to virulence of OPV2. See also Table S4** Illustrative fitness landscape of OPV2, which starts off as poorly adapted to replication in human cells at high temperature and is thus illustrated at the bottom of the landscape. Colored arrows (corresponding to Fig. 3) represent substitutions that increase the fitness of the virus, while the grey arrows represent recombination with a HEV-C sequence. Substitutions disrupting CpG/UpA are illustrated by dashed arrows, with potentially several different options leading to the same fitness altitude in the landscape.

**Table 1**  
Frequencies of gate-keeper mutants in day 14 stool samples of eleven individuals vaccinated with trivalent OPV.

Nucleotide	Change	Codon	Amino Acid Change	Vaccinee										
				S3	S5	S6	S8	S10	S14	S17	S18	S20	S29	S30
398	U -> C			0.03	0.33	0.06	0.02	0.06	0.04	0.12	0.09	0.22	0.20	0.07
481	A -> G			0.99	1.00	0.94	0.99	0.99	0.95	0.94	0.99	0.98	1.00	0.98
2908-10	AUU -> ACU, AAU, GUU, AGU	VP1-143	I -> T, N, V, S	0.89	0.67	0.54	0.32	0.81	0.31	0.09	0.71	0.44	0.73	0.65
Recombinant *	(R)/non-recombinant (NR)			NR	R	R	NR	R	NR	NR	R	NR	R	NR

\* OPV2/OPV1, in P2 or P3

## KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Antibodies		
Bacterial and Virus Strains		
Oral Poliovaccine Sabin Type 2 reference strain (OPV2)	NIBSC	01/530
OPV2-U398C	This paper	pRA-Sabin2-398
OPV2-A481G	This paper	pRA-Sabin2-481
OPV2-U398C/A481G	This paper	pRA-Sabin2-398/481
OPV2-U2909C	This paper	pRA-Sabin2-2909
OPV2-U398C/A481G/U2909C	This paper	pRA-Sabin2-398/481/2909
Biological Samples		
Chemicals, Peptides, and Recombinant Proteins		
Critical Commercial Assays		
KAPA Stranded mRNA-Seq Kit with KAPA mRNA Capture Beads	KAPA Biosystems	Cat# KK8420
HiSeq Rapid Cluster Kit v2	Illumina	Cat# GD-402-4002
HiSeq Rapid SBS Kit v2	Illumina	Cat# FC-402-4022
MiSeq Reagent Kit v2 (300 cycle)	Illumina	Cat# MS-102-2002
ZR Viral RNA Kit	ZYMO Research	Cat# R1035
SuperScript III One-Step RT-PCR System with Platinum Taq High Fidelity DNA Polymerase	Invitrogen	Cat# 12574030
AMPure XP magnetic beads	Beckman Coulter	Cat# A63880
Qubit High Sensitivity dsDNA assay	Life Technologies	Cat# Q32854
Deposited Data		
CirSeq passages of OPV2	This paper	SRA: PRJNA313030
OPV2 Gate Keeper clones competition assays	This paper	SRA: SRP098858
Poliovirus shed from OPV vaccinees	This paper	SRA: PRJNA369470
Experimental Models: Cell Lines		
Human: HeLa S3 cells	ATCC	CCL2.2
Human: Hep 2C cells	NIBSC	740502

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Experimental Models: Organisms/Strains		
Mouse: PVRTg21-IFNR-ko	Gift from Satoshi Koike, Tokyo Metropolitan Institute of Medical Science	N/A
Oligonucleotides		
NEXTflex RNA-Seq Barcodes	BIOO Scientific	Cat# 512914
Primer 398F (5'-CGCCATAGGACGCTAGATGTGAACAAGGTGTGAAGAGC-3')	This paper	N/A
Primer 398R (5'-CTTGTTACATCTAGCGTCCTATGGCGTTAGCCATAGGTAGG-3')	This paper	N/A
Primer 481F (5'-CCTAACCACGGAGCAGGCGGTCGCGAACCAGTGACTGG-3')	This paper	N/A
Primer 481R (5'-CGCGACCGCCTGCTCCGTGGTTAGGATTAGCCGCATTC-3')	This paper	N/A
Primer 2909F (5'-CCTCAAACACTACTGATGCAAATAACGGACATGCATTG-3')	This paper	N/A
Primer 2909R (5'-GTTATTTGCATCAGTGTAGTTTGGAGGTGACCACAAAAGTG-3')	This paper	N/A
PCR F (5'-AGAGGCCACGTGGCGGCTAG-3')	This paper	N/A
PCR 3' (5'-CCGAATTAAGAAAATTTACCCCTACA-3')	This paper	N/A
Recombinant DNA		
Plasmid: pRA-Sabin2	This paper	pRA-Sabin2
Plasmid: pRA-Sabin2-U398C	This paper	pRA-Sabin2-398
Plasmid: pRA-Sabin2-A481G	This paper	pRA-Sabin2-481
Plasmid: pRA-Sabin2-U398C/A481G	This paper	pRA-Sabin2-398/481
Plasmid: pRA-Sabin2-U2909C	This paper	pRA-Sabin2-2909
Plasmid: pRA-Sabin2-U398C/A481G/U2909C	This paper	pRA-Sabin2-398/481/2909
Software and Algorithms		
Prism	GraphPad Software	Version 5
R statistical package	<a href="https://www.r-project.org">https://www.r-project.org</a>	V3.3.3
MAFFT	<a href="http://mafft.cbrc.jp/alignment/software/">http://mafft.cbrc.jp/alignment/software/</a>	V6.684b
PhyML	Guindon and Gascuel, 2003	V3.0
Simplot	Loleet et al., 1999	V3.5.1
Geneious	Biomatters	R7
Other		
ParaSel software	This paper <a href="http://www.sternadi.com/parasel">www.sternadi.com/parasel</a>	N/A
Sequence alignment and phylogeny	This paper <a href="http://www.sternadi.com/cell2017">www.sternadi.com/cell2017</a>	Alignment/phylogeny
Fitness of viral mutations passaged at 33°C	This paper <a href="http://www.sternadi.com/cell2017">www.sternadi.com/cell2017</a>	33C
Fitness of viral mutations passaged at 39.5°C	This paper <a href="http://www.sternadi.com/cell2017">www.sternadi.com/cell2017</a>	39.5C