Molecular evolution of dengue 2 virus in Puerto Rico: positive selection in the viral envelope accompanies clade reintroduction

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INTRODUCTION

Denguevirus (DENV) is a mosquito-borne flavivirus that infects 50–100 million people each year and is expanding in both range and prevalence. Of the four co-circulating viral serotypes (DENV-1 to DENV-4) that cause mild to severe febrile disease, DENV-2 has been implicated in the onset of dengue haemorrhagic fever (DHF) in the Americas in the early 1980s. To identify patterns of genetic change since DENV-2’s reintroduction into the region, molecular evolution in DENV-2 from Puerto Rico (PR) and surrounding countries was examined over a 20 year period of fluctuating disease incidence. Structural genes (over 20% of the viral genome), which affect viral packaging, host-cell entry and immune response, were sequenced for 91 DENV-2 isolates derived from both low- and high-prevalence years. Phylogenetic analyses indicated that DENV-2 outbreaks in PR have been caused by viruses assigned to subtype IIIb, originally from Asia. Variation amongst DENV-2 viruses in PR has since largely arisen in situ, except for a lineage-replacement event in 1994 that appears to have non-PR New World origins. Although most structural genes have remained relatively conserved since the 1980s, strong evidence was found for positive selection acting on a number of amino acid sites in the envelope gene, which have also been important in defining phylogenetic structure. Some of these changes are exhibited by the multiple lineages present in 1994, during the largest Puerto Rican outbreak of dengue, suggesting that they may have altered disease dynamics, although their functional significance will require further investigation.

Denguevirus is a circumtropical, mosquito-borne flavivirus that infects 50–100 million people each year and is expanding in both range and prevalence. Of the four co-circulating viral serotypes (DENV-1 to DENV-4) that cause mild to severe febrile disease, DENV-2 has been implicated in the onset of dengue haemorrhagic fever (DHF) in the Americas in the early 1980s. To identify patterns of genetic change since DENV-2’s reintroduction into the region, molecular evolution in DENV-2 from Puerto Rico (PR) and surrounding countries was examined over a 20 year period of fluctuating disease incidence. Structural genes (over 20% of the viral genome), which affect viral packaging, host-cell entry and immune response, were sequenced for 91 DENV-2 isolates derived from both low- and high-prevalence years. Phylogenetic analyses indicated that DENV-2 outbreaks in PR have been caused by viruses assigned to subtype IIIb, originally from Asia. Variation amongst DENV-2 viruses in PR has since largely arisen in situ, except for a lineage-replacement event in 1994 that appears to have non-PR New World origins. Although most structural genes have remained relatively conserved since the 1980s, strong evidence was found for positive selection acting on a number of amino acid sites in the envelope gene, which have also been important in defining phylogenetic structure. Some of these changes are exhibited by the multiple lineages present in 1994, during the largest Puerto Rican outbreak of dengue, suggesting that they may have altered disease dynamics, although their functional significance will require further investigation.
DENV consists of four closely related serotypes (DENV-1 to DENV-4) that were first described based on unique host-antibody responses, but are supported by considerable genetic divergence since their Asian/African origins in sylvatic primates (Gubler, 1997; Wang et al., 2000). These can be further subdivided into subtypes (also known as ‘subtypes’ or ‘genotypes’) based on levels of genetic variation (Trent et al., 1989; Rico-Hesse, 1990; Lewis et al., 1993) and, although all four serotypes can produce severe disease, certain subtypes such as Asian DENV-2 have been associated more often with DHF/DSS (Rico-Hesse et al., 1997; Gubler, 1998a; Leitmeyer et al., 1999). However, it has been difficult to associate patterns of viral genetic variation with phenotypic changes in disease for several reasons: (i) DENV does not cause similar disease in animal or in vitro models; (ii) phenotypic changes in transmission or virulence are confounded with changing epidemiology due to host factors [e.g. increasing numbers of severe cases have been partly attributed to enhancement of infection in hosts with immunity to other serotypes (Halstead, 1988; Kliks et al., 1989; Thein et al., 1997)]; and (iii) few studies are restricted to a single host population with sufficient temporal sampling and supporting epidemiological data to associate molecular evolution with phenotypic change.

Dengue expansion in the Americas has been particularly evident in Puerto Rico (PR), which provides an opportunity for detailed phylogenetic study of dengue evolution over the last two decades. A densely populated island in the Caribbean, PR first experienced a major dengue outbreak in 1915 and DENV-2 was first identified in 1969 (Dietz et al., 1996). However, PR has only experienced continuous dengue transmission of multiple serotypes since 1985 (Gubler, 1993), along with steadily larger and more frequent epidemics marked by increased numbers of DHF/DSS cases (Dietz et al., 1996; Gubler, 1998b; WHO, 1999). The first major DHF/DSS epidemic in PR occurred in 1986, the year following hyperendemic transmission, where three serotypes were present (DENV-1, -2 and -4), each associated with DHF/DSS (Dietz et al., 1996). Hyperendemic transmission in the Americas began somewhat earlier (Gubler, 1993), but the first DHF/DSS epidemic in the region was in Cuba in 1981 (Kouri et al., 1989) and was associated specifically with a DENV-2 subtype new to the Americas (Rico-Hesse, 1990; Lewis et al., 1993; Guzman et al., 1995; Rico-Hesse et al., 1997). DENV-2 in the Americas prior to 1981 had only been associated with classic dengue fever, despite co-circulation with other serotypes (Gubler, 1997; Watts et al., 1999; Halstead et al., 2001), whereas severe dengue had been endemic to South-East Asia since the 1950s (Gubler, 1998a). Since the early 1980s, Asian DENV-2 has largely replaced the American subtype throughout the Caribbean (Lewis et al., 1993; Vorndam et al., 1994; Foster et al., 2003). In light of this dynamic epidemiological history and evidence associating genotype with virulence (Gubler et al., 1978; Rico-Hesse, 1990; Leitmeyer et al., 1999; Cologna & Rico-Hesse, 2003) and/or number of infections (Bennett et al., 2003), a detailed analysis of molecular evolution in PR following the DENV-2 subtype replacement is essential to investigate the possible link between viral evolution and disease incidence.

In this study, we apply a longitudinal phylogenetic approach to a 20 year sequence dataset to examine patterns of molecular evolution and compare them with epidemiological observations. We focus on three genes that are critical to virus structure and host-cell entry (capsid, membrane and envelope) and that together represent over 20% of the approximately 11 kbp DENV-2 genome. Our results document evolutionary patterns in an emergent virus and contrast the relative roles of natural selection and genetic drift on a dengue serotype since it became re-established in densely populated PR.

**METHODS**

We sequenced the three structural genes – capsid, membrane and envelope – for 91 DENV-2 isolates obtained from PR and other parts of the Americas since the early 1980s. Isolates were sampled from the US Centers for Disease Control and Prevention (CDC) serum bank; those from PR were selected from years with differing epidemic profiles (Fig. 1). Sample years with relatively high incidences of DENV-2 include 1988 (n=13 isolates) and 1994 (n=19). Sample years with relatively low incidences of DENV-2 include 1986 (n=2), 1991 (n=16), 1997 (n=1), 1998 (n=14) and 2001 (n=9). In addition to these 74 PR isolates, we sequenced a virus isolated from Jamaica in 1983, the earliest available representative of the
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replacement subtype in the region (Deubel et al., 1986, 1988). To provide a regional context for the PR data, we sequenced 16 additional isolates from various dates and locations throughout the Caribbean basin and Central and South America. Isolate label, GenBank accession number (Benson et al., 2004), location and year of isolation, as well as the dataset in which they are included for analysis, can be found in Supplementary Table S1 (available in JGV Online). Isolates were selected randomly without regard to symptoms. All samples sequenced in this study had low-passage histories (maximum of two), reducing the risk of in vitro artificial selection. RNA extractions were made from the first C6/36 Aedes albopictus cell-culture passage or from the first Toxorhynchites amboinensis mosquito passage. To further eliminate potential biases due to artificial selection, samples were not processed in temporal (year) order.

We extracted sample RNA by using QIAamp Viral RNA Mini kits (Qiagen), purified the extraction with QIAquick PCR purification kits (Qiagen) and amplified each isolate for capsid, membrane and envelope (2322 bp of the 11 kb viral genome or 21%) by using one-step RT-PCR according to manufacturer’s protocols (RT-PCR conditions and primer sequences can be obtained from the corresponding author). We sequenced both strands of the amplified products by using forward and reverse primers in standard dye-labelling reactions. Sequence data were collected on an ABI 377 slab-gel automated sequencer (Applied Biosystems) and MegaBACE 1000 96-capillary sequencer, edited, compiled and eventually aligned in SEQUENCHER 4.2 (Gene Codes Biosystems). We imported aligned sequences into PAUP* (Swofford, 2002) for phylogenetic analysis.

In addition to the 91 DENV-2 sequences obtained, several previously published sequences were incorporated into the alignments for phylogenetic analyses. We generated three phylogenetic trees to address (i) the evolutionary relationships of DENV-2 strains circulating in PR relative to known DENV-2 subtypes, (ii) the pattern of genetic change within PR and related regions and (iii) the influence of positive selection on this change, referred to as ‘DENV-2 Global,’ ‘DENV-2 SubtypeIIIb’ and ‘DENV-2 SubtypeIIIb Selection’ datasets, respectively. The DENV-2 Global dataset combines a subset (n = 31) of the PR and other American isolates that we obtained, with 29 envelope and full structural-gene sequences (when available) for all DENV-2 subtypes, as well as a sequence from sylvatic DENV-2 (MAL PB.1407070 from Malaysia, 1970; GenBank no. AF231717; Wang et al., 2000) as an outgroup (Fig. 2a; Supplementary Table S1 (available in JGV Online)). The DENV-2 SubtypeIIIb dataset includes 82 PR and American isolates in addition to 19 published sequences of the same subtype, including the earliest representative in the region, Jamaica 1983 (GenBank no. M20558; Deubel et al., 1986, 1988) and the closest global representative, China 1985 (GenBank no. AF119661) as outgroup (Fig. 2b; Supplementary Table S1, available in JGV Online). The DENV-2 SubtypeIIIb Selection dataset includes only our PR and American isolates of the subtype with their complete capsid-, membrane- and envelope-gene sequences (83 isolates, including the outgroup: phylogeny not shown; see Supplementary Table S1, available in JGV Online). Maximum-likelihood (ML) phylogenetic trees were estimated by using the GTR + Ψ + I model of nucleotide substitution, with the GTR substitution matrix, base composition, gamma distribution of among-site rate variation (I) and proportion of invariant sites (I) all estimated from the data. The only exception was capsid for the DENV-2 SubtypeIIIb Selection dataset, whose best-fit model of evolution included two rather than six substitution rates (HKY85 + I + Ψ; Hasegawa et al., 1985). Parameter values are available from the corresponding author upon request. To assess support for the ML tree topologies, we used Bayesian MCMC (Metropolis–Hastings Markov chain Monte Carlo) tree-sampling methods to generate posterior probabilities for each node, allowing substitution rate to vary by codon position, sampling four chains of 1 × 10^6–2 × 10^6 generations every 100 generations with a burn-in of 2000–4000. Chain length was determined based on convergence of likelihood values, giving effective sample sizes of over 400 (implemented in MrBayes v. 3; Huelsenbeck et al., 2001; Ronquist & Huelsenbeck, 2003). Because this latter method is based on ML, it is consistent with our analytical approach and is the preferred method. However, standard bootstrap-support values, based on 1000 replicate neighbour-joining (NJ) trees under the ML substitution model described above, were also included for comparison.

To test for recombination among the DENV-2 isolates sequenced, we used the SplitsTree 3.2 package (Rambaut, 2000), which employs split decomposition to identify conflicts in phylogenetic signal (such as those caused by recombination), and other previously described methods (Bennett et al., 2003). We also assessed the overall degree of recombination in the datasets by using a parsimony-informative sites ML test (PIST; Worobey, 2001).

Rates of nucleotide substitution were estimated by using an ML method available in the TipDate program (Rambaut, 2000), which compares the branch lengths of viral sequences sampled at different times. We compared the following models of substitution rate by using likelihood-ratio tests: different rates for every branch, DR; a single rate with dated tips, SRDT; and a single rate that varied linearly through time, VRDT (Rambaut, 2000).

To assess the extent of adaptive evolution in DENV-2 in PR, we compared rates of non-synonymous (dN) versus synonymous (dS) substitutions per site for each of the three genes sequenced in this study. Sites with disproportionately high relative rates of dN across phylogenetic history provide strong evidence for positive selection (Yang et al., 2000). We used a maximum-likelihood approach to compare models of evolution that allow dN/dS to vary across sites based on an ML tree for the DENV-2 SubtypeIIIb Selection dataset (Yang et al., 2000). One model specifies a distribution of dN/dS classes across sites that are constrained to be ≤1:0 (model M7), thereby specifying neutral evolution, whereas the more complex M8 model incorporates an additional class of codons where dN/dS can be >1, thus allowing for positive selection. These models were compared by using standard likelihood-ratio tests. To identify individual codons probably subject to positive selection, we applied a Bayesian approach to generate posterior probabilities of a given dN/dS class for each amino acid site, such that sites with high probabilities (>0.99) of falling into dN/dS category >1 are most likely to have been under positive selection. We also tested for selection on individual viral lineages by comparing the M0 model, in which each branch is assumed to have the same dN/dS ratio, with the FR (‘free-ratio’) model in which each branch is allowed to have a different dN/dS ratio (Yang et al., 2000). All of these analyses were performed by using CODEML from the PAML package (Yang, 1997).

**RESULTS**

DENV-2 in PR has exhibited a dynamic epidemiological history, with continuous transmission beginning in 1986 (Fig. 1). Since then, there have been seasonal and annual fluctuations in the number of viruses isolated by the CDC dengue-monitoring programme. Annual fluctuations ranged between low and high years, differing by over ninefold and peaking in 1994 (Fig. 1). This was the largest dengue outbreak in PR’s history, with record numbers of hospitalizations (n = 2004), DHF cases (n = 139) and deaths (n = 40) (data not shown; Rigau-Pérez et al., 2001).

Ninety of the 91 DENV-2 viruses collected between 1983 and 2001 from the Americas fell into two distinct subtypes: V, the American subtype, and IIIb, the Asian/American subtype (Fig. 2a). The single remaining isolate (El Salvador
2000) was most similar to isolates collected from Thailand between 1980 and 1993 [denoted subtype IIIa by Lewis et al. (1993) or Asian genotype I by Twiddy et al. (2002a)] (Fig. 2a). Caribbean isolates collected after 1981 were all of subtype IIIb. Throughout the study area, subtype V was not found after 1995. Subtypes IIIb and V differ at approximately 7.0% of their nucleotide sequence (Fig. 2a). ML estimates for the number of non-synonymous and synonymous substitutions along the branch leading to subtype V were 8.1 and 15.3, respectively (\(d_N/d_S = 0.0222\)). The equivalent estimates for the branch leading to subtype IIIb were 1.9 and 4.6, respectively (\(d_N/d_S = 0.0177\)) (Fig. 2a). Although the
bootstrap support for the subtype IIIb clade based on the genes that we have examined is not compelling (71%), this group has been historically well recognized (Lewis et al., 1999; Twiddy et al., 2002a) and its cohesiveness is supported by a high ML-based Bayesian posterior node probability (0.99).

Within the American subtype IIIb, Asian and American variants fell into two groups, the first supported by 0-99 Bayesian posterior probability or in 74% of bootstrap replicates and the second by 1-00 Bayesian posterior probability or in 52% of bootstrap replicates (Fig. 2a). ML estimates for the number of non-synonymous versus synonymous substitutions along their branches were 3-8 and 9-4, respectively (dN/dS = 0.1704), leading to the American lineage and 1-4 and 13-1, respectively (dN/dS = 0.0458), leading to the Asian lineage. Most of the amino acid substitutions distinguishing these two lineages were conservative, but did include replacement of glutamine with leucine (L) at envelope site (E) 131, replacing a hydrophilic with a hydrophobic residue. The closest Asian subtype IIIb virus related to the lineage appearing in Jamaica in 1983 was isolated in China in 1985 and was used as a root to the American subtype IIIb phylogeny in Fig. 2(b).

Sequence differences within the American subtype IIIb accumulated throughout our sampling period. We found no evidence that recombination had been important during this evolution based on either graphical split-tree decomposition or tests against expected levels of homoplasy under clonal evolution (PIST, P < 0.6). Analysis of the pattern of nucleotide substitutions suggested that evolutionary rates varied branch by branch in our best-supported phylogenetic tree (Fig. 2b). Specifically, the DR model was a better fit than the simpler SRDT model (P < 0.01), thereby rejecting the molecular clock. However, most of the rate variation could be attributed to substitutions within one lineage containing both temporally and geographically diverse DENV-2 isolates collected from the Americas. This lineage included isolates from Martinique (1992, 1998), PR (1994, 1998), Costa Rica (1999, 2000) and Venezuela (1999, 2000). Removing these isolates from rate estimates provided a much better fit to an SRDT model (P = 0-2), giving us a substitution-rate estimate of 8.34 × 10⁻⁴ [5.97 × 10⁻⁴, 10.15 × 10⁻⁴ (mean ± 95% ML confidence interval)] substitutions per site year⁻¹. The age of the most recent common ancestor (MRCA) for this PR subset is 20-42 years [19-72, 22-26 (mean ± 95% ML confidence interval)].

Within PR, there is evidence for in situ time-ordered evolution punctuated by significant evolutionary shifts in the predominant circulating lineage (Fig. 2b). For example, DENV isolates collected from 1988 to 1991 fall within a distinct clade, with individuals grouped clearly according to time of isolation (Fig. 2b). However, the large 1994 outbreak is marked by the presence of three distinctive lineages that are more or less equally divergent from each other. Although one group is nested within the lineage present in 1991, the two remaining groups fall into separate clades (Fig. 2b), both of which contain isolates collected from regions outside PR. One of these lineages apparently persisted at low levels in PR from 1994 until 1998, whereas the other became the dominant lineage and showed a similarly time-ordered phylogenetic pattern. This lineage may have arisen from a Dominican Republic isolate from 1984 (Fig. 2b). In addition, several other non-PR isolates from the Caribbean and South America between 1990 and 2000 are also associated with this lineage, further supporting its foreign origin.

Most significantly, the fixation of variation in DENV-2 subtype IIIb from PR appears to have been shaped, in part, by adaptive evolution. Positive selection was detected by measuring rates of non-synonymous (dN) and synonymous (dS) nucleotide substitutions per site across the subtype IIIb
PR phylogeny (DENV-2 Subtype IIIb Selection dataset). Although our analysis of the capsid and membrane genes suggested that their evolution is shaped by negative selection \((d_{\kappa}/d_s \ll 1)\), we found statistically significant evidence \((P=0.02)\) for positive selection \((d_{\kappa}/d_s = 3.2)\) acting at a small number of sites in the envelope gene. By using a Bayesian approach, this selection was assigned to four amino acid sites within the DENV-2 envelope gene – positions 91, 129, 131 and 491 (all \(P>0.98\)), all of which change frequently within the phylogeny and often define major clades (Fig. 2b). It should also be noted that these selection analyses are based on codon variation and are therefore unable to detect a single selection event that results in fixation of a mutation, in which all descendents become monomorphic.

**DISCUSSION**

We have performed a comprehensive analysis of DENV-2 evolution in PR during the period following the introduction of epidemic DHF into the region (Kouri et al., 1989; Guzman et al., 1984). Our results show that subtype IIIb has been the dominant lineage in PR and parts of the Americas for the past 10–20 years. Subtype IIIb has been distributed extensively throughout the Caribbean (PR, Martinique, Trinidad, Jamaica) and South and Central America (Columbia, Costa Rica, El Salvador) and, in those localities from which we have isolates of both subtypes (i.e. Costa Rica, PR and Venezuela), subtype IIIb has been isolated most recently. Subtype V was last isolated in the Caribbean in 1981 and overall in 1995 (Rico-Hesse, 1990; Guzman et al., 1995; Leitmeyer et al., 1999; Sariol et al., 1999; Foster et al., 2004). This and our extensive temporal sampling in PR since that time, which has yielded only subtype IIb (Fig. 2a), supports the observation that subtype IIIb is replacing the original American subtype V in the Caribbean and much of South and Central America (Foster et al., 2004).

Since DENV-2 subtype IIIb was established in 1986, much of the variation in PR has arisen in situ, as suggested by our phylogenetic analysis, particularly the observation that two major lineages, from 1988 to 1994 and from 1994 to 2001, are restricted to PR. As such, a Colombian isolate from 1993 that fell within the other PR 1994 clade is likely to represent an exportation of a PR virus to that locality (Fig. 2b). However, 1994, the year of PR’s largest and most severe dengue epidemic (Rigau-Pérez et al., 2001), was unique in that two novel lineages appeared in this country. Both lineages were divergent from the predominant lineage present in PR prior to 1994 and probably have foreign origins. The lineage that became dominant in PR after 1994 persisted until 2001 and was related to several foreign isolates from as early as 1984 from the Dominican Republic (GenBank no. AY484625; Foster et al., 2004), further supporting a foreign source for this lineage. The third lineage present in 1994, consisting mainly of South and Central American isolates from 1992 to 2000, includes only four divergent PR isolates from 1994 and 1998, suggesting that it never became established in PR. Overall, the complex relationships between DENV-2 strains from PR and other localities underline the importance of spatial heterogeneity and migration on dengue disease dynamics in island localities.

The spread of subtype IIIb throughout the Caribbean basin has been relatively fast, although the exact date of its introduction into the Americas remains problematic. An isolate from the 1981 Cuban epidemic that marked the onset of epidemic DHF in the region was not subtype IIIb, but similar to the New Guinea C 1944 reference strain (GenBank no. M29095; Guzman et al., 1995; Sariol et al., 1999). This is clearly an issue that needs to be investigated further. However, our rate estimations suggest that subtype IIIb in PR originated only 20 years before the most recent sample analysed, i.e. in 1981, and the subtype was definitely in Jamaica by 1983 (Foster et al., 2004). The swift establishment and spread of subtype IIIb since 1983 into at least 12 American countries, where it has seemingly displaced subtype V in the Caribbean basin, has also been accompanied by relatively few amino acid changes that may nevertheless have had dramatic effect on epidemic potential.

A key question in dengue research is, therefore, why DENV-2 subtype IIIb has spread, and in some places replaced subtype V, in the Americas? This replacement event may simply reflect stochastic processes, such as changes in vector density (Kuno, 1997). Alternatively, its rapidity and association with increases in DHF and DSS cases may reflect intrinsic differences in viral transmissibility between the two subtypes, as suggested by recent experimental analyses (Cologna & Rico-Hesse, 2003). Moreover, amino acid differences between subtypes V and IIIb have been correlated with changes in virulence, with those in the envelope gene probably affecting host cell-binding efficiency (Sanchez & Ruiz, 1996; Kinney et al., 1997; Leitmeyer et al., 1999). More importantly, although most amino acid sites in subtype IIIb are conserved, indicating that they are subject to purifying selection, we found strong evidence for positive selection at four amino acid positions within the envelope gene – positions 91, 129, 131 and 431. The fact that these sites change multiple times across our phylogeny and often distinguish major monophyletic groups supports the idea that they are of great functional relevance.

The envelope gene encodes proteins on the viral surface that enable host-cell binding and entry via membrane fusion and also provide the primary target for host immune responses (Roehrig, 1997). Experiments verify that viral gene regions that interact specifically with host cells are evolutionarily constrained, particularly in viruses that infect multiple different hosts (Weaver et al., 1999). Although accounting for a very small proportion of sites, the four amino acid sites under positive selection fall into immunogenic regions (reviewed by Roehrig, 1997). E-91, E-129 and E-131 are in the protein domain (II) responsible for host-cell membrane fusion, where E-91 is just seven residues downstream of the highly conserved (in flaviviruses) fusion loop (transmembrane...
region) and E-129 and E-131 are in the ‘elongated, finger-like’ section of domain II, which becomes folded into domain III during membrane fusion (Modis et al., 2004). Although substitutions at E-91 and E-129 were all conservative (aliphatic, hydrophobic residues before and after), E-131 has undergone non-conservative substitutions, from an aliphatic, hydrophobic residue to a moderately hydrophilic polar amide. Selected site E-491 occurs in the 53 residue ‘stem’ portion (connecting domain III to the viral transmembrane anchor) of the envelope protein, the section that becomes folded with domain II during membrane fusion (Modis et al., 2004). Substitutions at E-491 were also relatively conservative (again amongst aliphatic, hydrophobic residues). Another site, E-359, distinguishes the 1994 clade originating in PR 1988 (Fig. 2b). Although this latter site underwent a mutation only once in subtype IIIb’s evolutionary history in PR, it was a non-conservative amino acid substitution (from threonine, T, to alanine, A) resulting in the substitution of an amino acid potentially involved in phosphorylation/glycosylation (T) with one that is not (A). The overall pattern of amino acid substitution suggests that they may be changing in concert: changes in E domain I (E-91, E-129 and E-131) were often accompanied by changes in E domain III (E-491 or E-359) (Fig. 2b), although never in positions known to interact directly (Modis et al., 2004). Although we lack the power (in terms of number of replicates of amino acid-defined clades) to test the significance of this pattern, it is not unlikely given the physical interlacing of domains I and III during membrane fusion (Modis et al., 2004). Previous studies also report sporadic positive selection in envelope amongst some DENV-2 subtypes (Twiddy et al., 2002a, b), although purifying selection is clearly the dominant evolutionary pressure acting on DENV. Together, these results suggest that positive selection may be acting on host-cell infection rates or immune evasion, which could ultimately affect viral reproduction. Substitutions at some of the selected sites also define phylogenetic structure, indicating their proliferation in descendant DENV populations: synapomorphies at E-91 and/or E-491 distinguish the 1988–1994 and 1994–2001 PR clades, both high years of DENV-2 prevalence in PR.

In DENV, associations between genotypic and epidemiological change are particularly important for inferring changes in virus phenotype, as experimental systems are lacking. The peak years of DENV-2 subtype IIIb transmission in PR were 1988 and 1994 (Fig. 1). The predominant viruses in 1988 are distinguished by a conservative amino acid substitution in envelope and, albeit a positively selected site in an important region, the phenotypic implications are difficult to infer. Alternatively, the outbreak of 1988 may be due to the elevated numbers of immunologically naïve hosts, as this was the first major year of DENV-2 transmission (Fig. 2b). In contrast, 1994 consists of two distinct but equally prevalent clades, one derived from the 1988 group that became extinct after 1994, but was distinguished by a highly non-conservative amino acid substitution, and the other distinguished by a conservative substitution at a positively selected site, which was the lineage that persisted until 2001 and had geographically widespread origins (Fig. 2b).

Although the foreign (1994) clade appears to have the greater epidemic potential based on its spatial and temporal distribution, it is currently difficult to associate specific phenotypic changes, including those at the positively selected sites, with both outbreak severity and clade dynamics. In particular, mutational changes defining these key outbreak clades were either relatively conservative (i.e. the foreign 1994 lineage) or counter to clade persistence (i.e. the native 1994 lineage). It is possible that the native 1994 clade underwent phenotypically relevant mutations to severe outbreak conditions, but that these variants did not persist in PR beyond 1994. This clade’s extinction may be associated with these changes or a largely random event. Alternatively, and similar to the 1988 outbreak, the antigenic novelty of the foreign 1994 lineage relative to the native 1994 clade may account for its long-term success and a concomitant increase in numbers and severity of cases. Future studies should therefore endeavour to characterize the fitness values of individual amino acid changes and be coupled with molecular-epidemiological studies that aim to identify potentially important mutations or genomic regions that may drive disease dynamics.

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