

Sequencing Needs for Viral Diagnostics

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We built a system to guide decisions regarding the amount of genomic sequencing required to develop diagnostic DNA signatures, which are short sequences that are sufficient to uniquely identify a viral species. We used our existing DNA diagnostic signature prediction pipeline, which selects regions of a target species genome that are conserved among strains of the target (for reliability, to prevent false negatives) and unique relative to other species (for specificity, to avoid false positives). We performed simulations, based on existing sequence data, to assess the number of genome sequences of a target species and of close phylogenetic relatives (near neighbors) that are required to predict diagnostic signature regions that are conserved among strains of the target species and unique relative to other bacterial and viral species. For DNA viruses such as variola (smallpox), three target genomes provide sufficient guidance for selecting species-wide signatures. Three near-neighbor genomes are critical for species specificity. In contrast, most RNA viruses require four target genomes and no near-neighbor genomes, since lack of conservation among strains is more limiting than uniqueness. Severe acute respiratory syndrome and Ebola Zaire are exceptional, as additional target genomes currently do not improve predictions, but near-neighbor sequences are urgently needed. Our results also indicate that double-stranded DNA viruses are more conserved among strains than are RNA viruses, since in most cases there was at least one conserved signature candidate for the DNA viruses and zero conserved signature candidates for the RNA viruses.

Sequencing pathogen genomes is costly, particularly when one considers the scope and number of organisms and strains that could be sequenced. We face challenging decisions as to how limited sequencing resources should be allocated. We have built a system to evaluate sequencing needs using simulations and random sampling of existing sequence data. When some sequence data are already available, the results indicate whether additional target species genome sequences or genome sequences of close phylogenetic relatives (i.e., near neighbors [NNs]) are required to predict high-quality DNA signatures for target detection. In addition, patterns observed in existing sequence data for classes of viruses (single- or double-stranded, RNA or DNA, positive or negative sense) may guide initial investments for unsequenced pathogens. Since we have built a dynamic system, not only a one-time analysis, it is possible to do real-time, automated evaluation concerning whether additional target or NN sequencing may still be warranted or if diminishing returns may have been reached. This is the first such system, to our knowledge, designed to address these issues. The system applies Monte Carlo simulation, which is a general method using stochastic techniques, based on the use of random numbers and probability statistics.

By a DNA diagnostic signature, we mean two primers and a probe, suitable for a TaqMan assay, that are sufficient to identify the given target species, uniquely distinguishing it from other species. Although we limit our discussion here to viral diagnostic signatures, other avenues of our system address similar questions for protein signatures, forensic DNA signa-

tures, single-gene versus whole-genome sequencing, and comparisons of draft versus finished sequence data, for bacteria as well as for viruses. Future papers will discuss these results.

Currently, we have the only fully automated DNA diagnostic signature prediction pipeline, described in detail elsewhere (2–4, 9). This pipeline selects regions of a target genome that are both conserved among strains (to prevent false negatives and low reliability) and unique relative to other species (to preclude false positives and low specificity). We use multiple sequence alignment algorithms to generate a consensus sequence of conserved bases among strains. We have assembled an approximately 1-Gb database of viral and bacterial full-genome sequences for assessing uniqueness. Suffix tree algorithms facilitate the creation of a “consensus plus uniqueness gestalt,” or simply the “gestalt,” of sequence fragments unique in the target consensus relative to everything in the database (5, 9). In this gestalt, all bases that are not conserved and/or not unique are represented by dots, and the remaining sequence fragments may be mined for diagnostic signatures. The DNA signature pipeline then identifies regions suitable for a platform-specific assay; in most cases we predict TaqMan signatures composed of two primers and an internal probe. When these signature candidates are destined for laboratory screening, they undergo rigorous *in silico* screening against the GenBank nonredundant database (a huge sequence database [1]), and, when appropriate, human genomic data, to guard against cross-reaction with nontarget organisms. In addition, signatures to be screened in the laboratory are annotated as to whether they are intergenic or land on genes, particularly genes of interest such as those associated with virulence. Our pipeline is limited by the amount of sequence data available.

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TABLE 1. Number of target and NN sequences required for development of high-quality diagnostic signatures^a

Genome structure	Virus	Target pool size	NN pool size	Minimized target sequences		Minimized NN sequences		No. of TaqMan signatures from full data set
				<i>t</i>	<i>n</i>	<i>t</i>	<i>n</i>	
Double-stranded DNA	Variola	14	15	1	4	7	2	<20
	Vaccinia	6	29	1	4	4	1	0
	Human Papillomavirus virus type 16	5	113	3	4	4	0	6
	Human adenovirus B	6	29	4	1	5	0	3
	JC virus ^b	187	32	5	5	8	0	0
Single-stranded DNA	Maize streak virus	32	155	1	0	1	0	0
Retroid	Hepatitis B	424	39	1	0	1	0	0
	Human immunodeficiency virus 1	333	66	1	8	2	0	0
	Human immunodeficiency virus 2	11	388	2	0	2	0	0
Single-stranded RNA (negative sense)	Vesicular stomatitis virus	4	21	3	0	3	0	2
	Ebola Zaire virus	5	8	1	0	1	0	167
	Marburg virus	6	7	3	1	4	0	0
	Mumps virus	12	53	4	7	5	0	2
Single-stranded RNA (positive sense)	Venezuelan equine encephalitis	18	29	2	1	3	0	0
	Plum pox virus	5	78	2	1	3	0	14
	Human poliovirus 1	22	127	3	1	4	0	0
	Human poliovirus 2	9	140	3	4	4	0	0
	Human poliovirus 3	4	145	2	0	2	0	0
	SARS	50	35	1	0	1	0	85
	Foot-and-mouth disease virus type O	14	120	2	2	3	0	0

^a To objectively select a minimum number of target and NN sequences required for development of high-quality DNA diagnostic signatures, we selected the following: (i) the (*t*, *n*) pair with the minimum number of target sequences for which the 75% quantile of results from random Monte Carlo simulations was less than or equal to *c* + 20, where *c* is the number of signature candidates when the full data set is used; and (ii) the (*t*, *n*) pair with the minimum number of NN sequences for which the 75% quantile was less than or equal to *c* + 20. Thus, if only *t* target strains and *n* NNs had been sequenced, one would have a 75% certainty of predicting no more than 20 poor candidates out of the total candidates generated, which would have been eliminated computationally if all currently existing sequence data had been used in the predictions. TaqMan signature candidates are conserved among all sequenced strains and unique relative to all other bacterial and viral sequences in our 1-Gb database of complete genomes, with no degenerate bases present in the signatures.

^b For JC virus in which *c* was 0, using *c* + 20 required *t* of 10 and *n* of 8 for both minimizations. So in the table above we increased the threshold number of signature candidates to *c* + 30.

Signatures predicted using our DNA signature pipeline are in daily use by BioWatch and BASIS, the U.S. Centers for Disease Control and Prevention (CDC), a multistate task force testing for animal diseases, and other U.S. federal agencies (6–8). We are actively developing signatures for and in collaboration with a number of organizations, including the CDC, U.S. Department of Agriculture, Food and Drug Administration, U.S. Army Medical Research Institute for Infectious Diseases, and others. Our TaqMan-based assays for variola (smallpox) tested best in biosafety level 4 laboratory screening and are in daily use, and our severe acute respiratory syndrome (SARS) assays are performing well in screening at the U.S. Army Medical Research Institute for Infectious Diseases. These accomplishments uniquely qualify us to assess sequencing needs for diagnostic signature development.

For assessing sequencing needs for diagnostic DNA signatures, we ran more than 30,000 Monte Carlo simulations with random samples of target and NN sequences, summarized in Table 1. The goal was to estimate the minimum number of sequences required to approximate the number of TaqMan signature candidates predicted when all sequence data available are used. That is, how much do we overestimate the number of conserved, unique signature candidates when we only have a fraction of the data compared to when we use all of the available data? Which are more valuable, target or near-neighbor sequences, for pruning the list of signature candidates to those most likely to be conserved and unique, and thus likely to succeed in screening?

MATERIALS AND METHODS

We began our analyses with a pool of target strain sequences and a pool of NN sequences, and we randomly selected *s* samples of size *t* target sequences and *n* NN sequences from the target and NN pools, respectively. Each sample of organisms was run through our DNA signature pipeline, with signature prediction based on conservation among the *t* target strains and uniqueness relative to our 1-Gb database minus those NNs in the NN pool that were not chosen in that sample. Thus, for each sample, the number of signature candidates was predicted as though we had only *t* and *n* sequences, as well as the rest of the less-closely related organisms in our database that are not considered NNs. We then assessed how much sequence data was required to approximate the number of signature candidates *c* that were predicted when the full data set (all target and NN sequences) was analyzed. Using the full data set will yield the fewest signatures, because lack of conservation or uniqueness will winnow away all unsuitable candidates.

To complete the process outlined above, we developed a dynamic system, including a database for storing and querying results, a web-based system for displaying results, statistical programs to summarize results and create plots, and a process manager to oversee all of these features. The process manager automatically schedules parallel Monte Carlo runs, manages and maintains a stable load on the computer system, and performs input-output operations from the database. To date, more than 90,000 runs of the DNA signature pipeline have been run, requiring approximately 15 to 20 min each for most viruses, for the examination of 20 viruses. Even with a 24-CPU Sun server, we are limited by processing time to running an *s* of 10 samples for each combination of *t* and *n*, generating hundreds to thousands of DNA signature pipeline runs for each target organism.

We analyzed species for which at least four sequenced complete genomes were available, primarily from the National Center for Biotechnology Information (NCBI) GenBank. In most cases, we performed our analyses at the species level. NN pools for our Monte Carlo analyses were selected based on the relationship between the target set and close taxonomic relatives, or neighbors, elucidated by the NCBI taxonomy structure. NNs were organisms that were in the same family

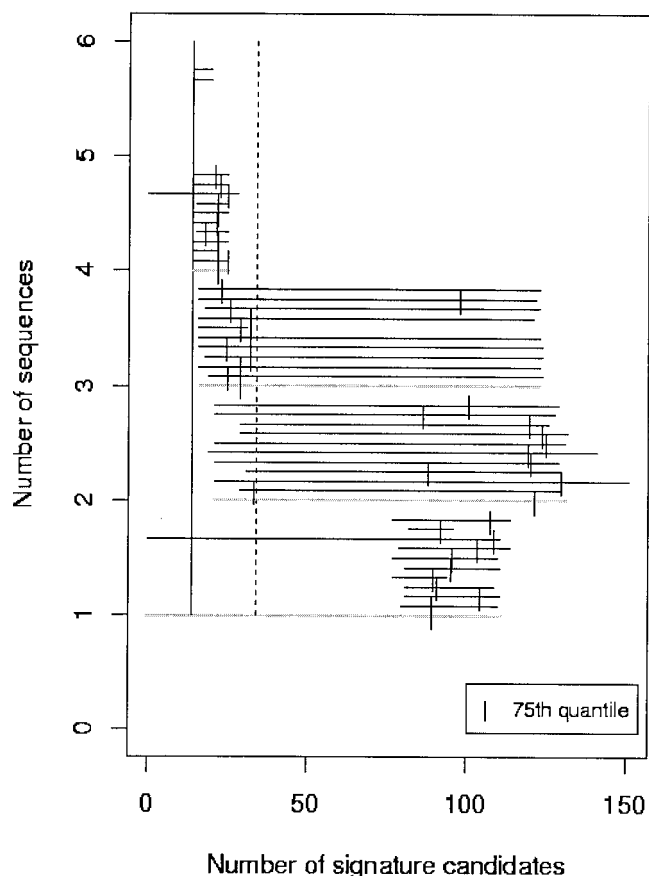


FIG. 1. Range plot for plum pox virus, displaying results typical of many viruses. To discriminate samples in which zero NNs were used, the range is drawn as a horizontal grey line, and when n is >0 , the range is drawn as a black line. The best estimate of the true value is the quality measure determined using the entire target and NN pools and is represented by a vertical black line. This best estimate plus a constant c of 20 is at the location of the vertical dashed line and was selected to indicate a reasonable distance from the true answer. The 75% quantile for each range is shown with a black, vertical tick mark.

as the target species. For analyses at the level of subspecies instead of species, anything in the same genus as the target subspecies was considered a NN. In other words, any organism in the same clade as the target species or subspecies, as given by going up two levels in the NCBI taxonomic structure, was considered a NN.

Range plots illustrate the span of predictions generated by different random samples of genomes (Fig. 1 to 3). Along the y axis, whole numbers represent the number t of target strains and the incremental values between the integers represent the number n of NN genomes. Outcomes indicating the ability to generate signature candidates are plotted along the x axis as a horizontal line spanning the range of predicted values for the s random samples.

The 75% quantiles of the samples are plotted. If a random sample of t target strains and n NN strains were sequenced, there would be a 75% chance that the quality measure for that sample would be less than or equal to the 75% quantile mark. The quality measure shown here is the number of TaqMan signature candidates. The expected outcome is a reduction in the number of signature candidates that are generated as nonunique and nonconserved candidates are eliminated with increases in the number of target and NN sequences used to predict the signatures. One may also plot the fraction of the target genome that is conserved among strains and unique relative to other species as the quality measure (data not shown). This gives a more general estimate of the region that may be available for development of any DNA-sequence-based detection assay, regardless of the technology platform.

These range plots enable us to examine the entire span of outcomes on a relatively simple graph and to rapidly determine the value of target and NN

sequences. Contour or topographic plots, traditionally used for complex data with two independent variables, were uninformative in preliminary analyses, since only one quantile point for each (t, n) pair, and not the entire range, could be displayed at once.

RESULTS

Analyses indicate that lack of conservation, more than lack of uniqueness, limits our ability to find species-specific, species-wide TaqMan signatures for most viruses, and thus more target than NN sequence data are required (Table 1). The range of the number of TaqMan signatures for random subsamples of plum pox virus and NN genomes remains the same for a given target set size, regardless of the number of NNs, illustrated by the rectangular, stair-stepped pattern of horizontal lines in Fig. 1. That is, additional NN genomes do not result in a reduction in the number of signature candidates, as shown by the range of the number of signature candidates that is the same whether there are 0 or 10 NNs; for example, the range of the number of signature candidates indicated by the horizontal range line at y of 2.0, using 0 NNs in the calculations, is the same as the range of the number of signature candidates at y of ~ 2.8 , including 10 NNs in the calculations, in Fig. 1. In contrast, as the number of target sequences increases, the number

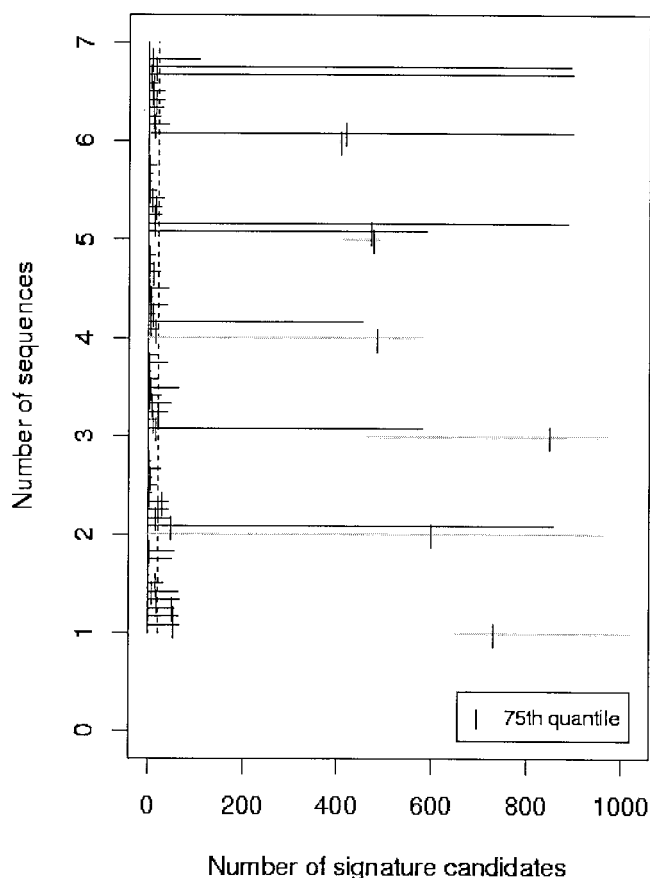


FIG. 2. Range plot for vaccinia, illustrating that NN sequence information is critical to eliminate signature candidates that are not species specific. Three or four each of target and NN sequences appear to be adequate for prediction of a short list of signature candidates that are suitable for laboratory screening.

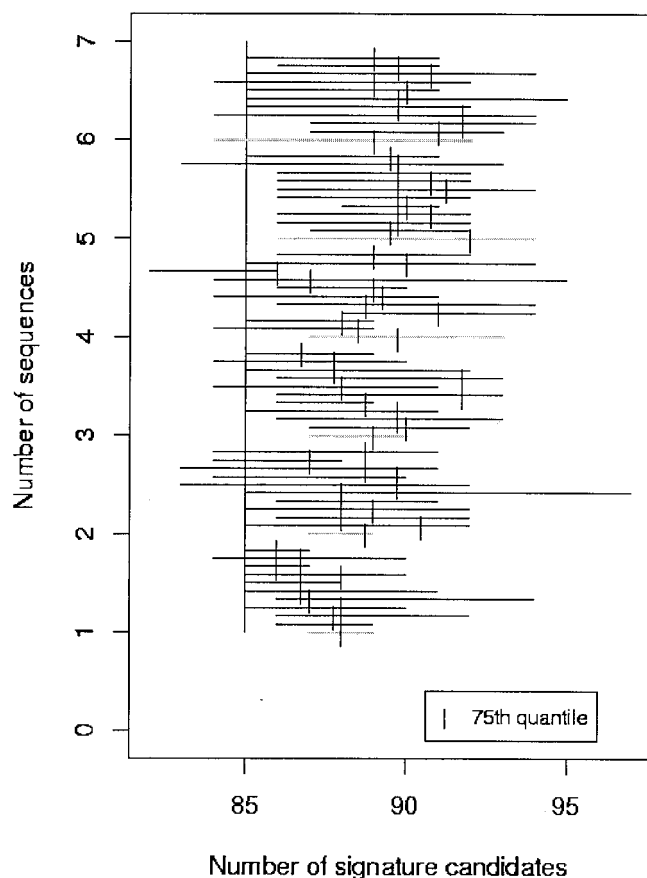


FIG. 3. Range plot for SARS, similar to that for Ebola Zaire (data not shown), illustrates that additional target sequence data do not narrow the list of signature candidates. No NN sequences available at the time of these analyses were similar enough to winnow the list of signature candidates.

of signature candidates decreases; most random samples of two target genomes give over 100 signature candidates (e.g., range line at y of 2.0), while most random samples of four target genomes give fewer than 25 signature candidates (e.g., range line at y of 4.0). This pattern indicates that multiple target sequences, but not NNs, assist in identifying the highest quality signatures. Most of the viruses had results qualitatively similar to those for plum pox virus. There are four notable exceptions discussed below.

The first two exceptions are variola virus and vaccinia virus. For variola and vaccinia, NN sequences are particularly essential to identify unique signatures (Fig. 2). As the size of the NN set grows, regardless of the number of targets, the range of the number of signature candidates shrinks and moves toward fewer signatures. This triangular pattern suggests that NN sequences factor prominently in identifying regions of the genome that are unique to the target species. In fact, conservation among strains of variola and among strains of vaccinia enabled us to generate a reasonable list of signature candidates with only a single target sequence, as long as four NN sequences were available to eliminate nonunique regions (Table 1). NN sequences also facilitated signature generation for other double-stranded DNA viruses but not nearly to the extent as for variola and vaccinia. Human adenovirus B was the

only double-stranded DNA virus for which NNs did not improve signature prediction. Thus, there is a general pattern that NN data aids in signature prediction for double-stranded DNA viruses, but this is not a rule.

The two other exceptional cases are SARS and Ebola Zaire, for which we need close NN sequences but no more target sequences (Fig. 3). For both these species, additional sequences after the first target provide no guidance as to signature prediction. Because sequenced isolates are so closely related, any single target provides virtually the same information for the purpose of generating detection signatures. The second point clearly illustrated in Fig. 3 is that there are no close NNs currently sequenced to reduce the pool of candidates. Currently, we have a severe need for sequence from close NNs of SARS and Ebola Zaire to narrow the pool of signature candidates to those least likely to generate false positives in the field. For Ebola Zaire, neither Ebola Reston nor Marburg virus, currently the most closely related organisms for which we have sequence data, are sufficiently similar to rule out signature candidates that might cross-react in the field.

DISCUSSION

Although analyses presented here illustrate that it may not be possible to find a single, species-wide, species-specific signature for many viruses, other analyses show that it is often possible to find a single TaqMan signature with a limited number of degenerate bases, and it is always possible to find a set of TaqMan signatures that will, in combination, detect all strains (4). These analyses indicate that sequencing three or four strains of most RNA viruses will highlight the regions that are least conserved and thus are inappropriate regions for DNA-based detection signatures. The remaining, more-conserved sequence regions may then be mined for detection signatures, whether a single signature or several signatures are required to detect all strains. In some cases where strains cluster into types, the distinction between types and species may be subjective along a continuum. In these situations, type-specific signatures may be a more appropriate goal than species-specific signatures, particularly if types differ in virulence.

NN sequences aid more in signature prediction if they are closely related to the target. This is the case for variola and vaccinia, due to the low mutation rate for orthopox viruses and the similarity of species in this genus. We are in the process of analyzing sequencing needs to develop diagnostic signatures for bacteria, and preliminary results indicate that variola and vaccinia may be more similar to bacteria, with their much larger genomes, than to other viruses in terms of the requirement for NN sequence data. Indeed, the variola and vaccinia genome sequences are an order of magnitude longer than those of the other viruses with sufficient sequence data for our Monte Carlo methods. Conservation does not depend on sequence length alone, however, as illustrated by JC virus, the shortest of the double-stranded DNA viruses we examined at approximately 5,000 bp, and with a huge number of sequenced genomes (Table 1). Although no single signature was present in all genomes, other analyses (data not shown) indicate that there are 23 TaqMan signature candidates that are shared among at least 75% of the 187 JC genomes. Thus, for this short virus, there is relatively high sequence conservation. In sum-

mary, our results indicate that double-stranded DNA viruses are more conserved among strains than are RNA viruses, since in most cases there was at least one conserved signature candidate for the DNA viruses and zero conserved signature candidates for the RNA viruses.

Sequences for SARS and Ebola Zaire are unusually conserved compared to other RNA viruses because all the sequenced isolates originate from a geographically limited area and have been sampled in a relatively short period of time, thus leaving short opportunity for strain divergence. With time and geographic isolation, strain diversity will become more important, but at this time no further sequencing of SARS and Ebola Zaire isolates are necessary for developing diagnostic signatures for these species. Instead, sequencing of close phylogenetic relatives of these species is urgently needed.

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structure. J.R.S. is responsible for target selection and development of the tools for creating target and NN sequence pools. T.R.S. leads our bioinformatics team and oversees all aspects of the work. We thank Carol Zhou for providing comments on drafts of this paper.

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