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A Comparison of Computational Methods for Identifying Virulence Factors

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Abstract

Bacterial pathogens continue to threaten public health worldwide today. Identification of bacterial virulence factors can help to find novel drug/vaccine targets against pathogenicity. It can also help to reveal the mechanisms of the related diseases at the molecular level. With the explosive growth in protein sequences generated in the postgenomic age, it is highly desired to develop computational methods for rapidly and effectively identifying virulence factors according to their sequence information alone. In this study, based on the protein-protein interaction networks from the STRING database, a novel network-based method was proposed for identifying the virulence factors in the proteomes of UPEC 536, UPEC CFT073, P. aeruginosa PA01, L. pneumophila Philadelphia 1, C. jejuni NCTC 11168 and M. tuberculosis H37Rv. Evaluated on the same benchmark datasets derived from the aforementioned species, the identification accuracies achieved by the network-based method were around 0.9, significantly higher than those by the sequence-based methods such as BLAST, feature selection and VirulentPred. Further analysis showed that the functional associations such as the gene neighborhood and co-occurrence were the primary associations between these virulence factors in the STRING database. The high success rates indicate that the network-based method is quite promising. The novel approach holds high potential for identifying virulence factors in many other various organisms as well because it can be easily extended to identify the virulence factors in many other bacterial species, as long as the relevant significant statistical data are available for them.


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Introduction

The Escherichia coli O104:H4 bacteria outbreak since May-02-2011 in Germany has brought into focus the need to use reagents to rapidly identify pathogenic organisms and genes involved in the mechanisms of pathogenicity. Although the majority of E. Coli strains are beneficial to human bodies, the genome of this new strain of O104 was modified by mutations or the genetic materials secreted from other bacteria, rendering it able to produce Shiga toxin and resist to many kinds of antibiotics and also to the mineral tellurium dioxide, causing foodborne illness [1]. In the course of pathogens infection and pathogenesis, virulence factors (VF) play a key role. VF are the molecules produced by pathogens that increase the ability of pathogens to cause disease. According to their mechanisms and functions, VF can be generally classified into the following seven groups: (1) adhesins that attach microbes to their hosts, (2) colonization factors that enable certain bacteria to colonize within host cells, (3) effectors that suppress hosts’ defenses, (4) invasions that disrupt the host membranes and stimulate endocytosis, (5) toxins that poison the host cells and cause tissue damage, (6) capsular polysaccharides that protect pathogens from host defenses, and (7) siderophores that take up iron [2–4]. House-keeping proteins that are required for maintaining the basic cellular functions and are not related to pathogenesis are not virulence factors [2]. Therefore, virulence factors can be the potential targets of drugs to treat infectious diseases specifically, without killing or inhibiting other bacterial growth, avoiding the higher evolutionary pressure to develop drug resistance [4].

At present, complete genome sequences of almost all major bacterial pathogens have been determined [http://cmr.jcvi.org/tigr-scripts/CMR/CmrHomePage.cgi], providing significant insights into microbial pathogenesis and drug resistance. Meanwhile, several repositories aiming at collecting the virulence factors with their structures, functions and mechanisms have also emerged, facilitating the study of virulence factors of bacterial pathogens. The Virulence Factor Database [VFDB, http://www.mgc.ac.cn/VFs/], constructed by the virulence-guided classification system, currently contains 409 virulence factors and 2,353 VF-related genes [accessed June...
Materials and Methods

1. Benchmark Dataset

Datasets of virulence factors were downloaded from VFDB [5], a well-established database based on experimentally validated virulence factors extracted from literatures and supplemented with comprehensive genomics information from bacterial pathogens. A total of 2,293 proteins of virulence factors were obtained, involving 24 pathogens from 

According to the total amount of virulence factors in each of these species, we selected five of them that contained the largest amounts of virulence factors. These five species were: (i) *Escherichia coli* CFT073 (UPEC 536), (ii) *Pseudomonas aeruginosa* PAO1 (*P. aeruginosa* PAO1), (iii) *Salmonella enterica* (serovar *typhimurium*) LT2, (iv) *Escherichia coli* CFT073 (UPEC CFT073), and (v) *Legionella pneumophila* Philadelphia 1 (*L. pneumophila* Philadelphia 1). The numbers of virulence factors in the above five species were 290, 190, 165, 117, and 117, respectively. Since these five species are closely related, we also selected another two species that were distinct in phylogeny. The two species were *Campylobacter jejuni* NCTC 11168 (*C. jejuni* NCTC 11168) and *Mycobacterium tuberculosis* H37Rv (*M. tuberculosis* H37Rv), and they contained 98 and 86 virulence factors, respectively. All the aforementioned species, except *Salmonella enterica* (serovar *typhimurium*) LT2, were included in the STRING database [15]. Consequently, the virulence factors in the remaining six species would form our first-hand dataset.

The protein-protein interaction (PPI) network used here was retrieved from the STRING database [15] (http://string-db.org/). For each of the six species, a PPI network was constructed by integrating different sources of information derived from experimental, computational, and text-mining methods. Furthermore, all interactions in STRING are provided with a probabilistic confidence score, representing a rough estimate of how likely a given interaction describes a functional linkage between two proteins might occur. In order to predict virulence factors based on the STRING database, we extracted all the proteins and interactions between them for the 6 species mentioned above. Mapping these known virulence factors from VFDB to STRING proteins, we found 207, 110, 189, 116, 98 and 83 proteins for UPEC 536, UPEC CFT073, *P. aeruginosa* PAO1, *L. pneumophila* Philadelphia 1, *C. jejuni* NCTC 11168, and *M. tuberculosis* H37Rv, respectively, by BLASTP with the cutoff of HSP score being 90. These proteins comprised our positive dataset. Proteins, not known as virulence factors, were randomly selected from the remaining proteins of each species in STRING to compose the negative dataset, with the ratio between the size of negative dataset and positive dataset equalling 5:1. Then, all the virulent and non-virulent sequences of the six species were randomly divided into a training dataset with a proportion of 80% and a testing dataset with 20%. The training dataset was used by the jackknife cross-validation method to assess the identification performance of each virulence factor classifier developed by us, while the testing dataset was used to compare our methods with other existing tools (such as VirulentPred) in identifying the virulence factors.

2. STRING Network-Based Method

It has been demonstrated that the STRING network-based method could be used to predict protein phenotypes [16]. The prediction accuracy thus obtained was 65.4% for budding yeast, much higher than the success rate (15.4%) by a random guess. In this study, we are to apply this novel method to predict virulence factors. In the PPI network, when predicting whether a protein was a virulence factor or not, we considered two kinds of information: the number of its neighbor nodes (proteins) and the strengths of its interactions (confidence scores) with them. The detailed process of the prediction based on STRING network is described as follows.

Firstly, suppose a PPI network consisting of n nodes \(\{p_1, p_2, ..., p_n\}\), in which each node is divided into 2 classes \(\{T_1, T_2\}\), where \(T_1\) stands for “virulence factor”, \(T_2\) the “non-virulence factor”. Then we denoted the class of the i-th
Identifying Virulence Factors

Amino Acid and Pseudo Amino Acid Composition

In this method, virulence factors were coded by amino acid composition (AAC) and pseudo-amino acid composition (PseAAC) [17], from which some important features are selected by the feature selection method. Generally, the frequency of occurrence of each amino acid in a protein sequence can be used to code the sequence. That is, a protein can be represented by a 20-D (dimensional) numerical vector. However, this traditional amino acid composition nearly loses the sequence-order information completely. To improve it, the pseudo amino acid composition (PseAAC) was proposed [17,18] to complement the simple amino acid composition (AAC) for representing the sample of a protein. Since the concept of PseAAC was introduced, it has been widely used to study various problems in proteins and protein-related systems, such as predicting subcellular location of proteins [19], structural classes of proteins [20] and DNA-binding proteins [21], etc. In this study, we only employed the sequence-order information reflected by a series of PseAAC components [17] to code proteins. These kinds of sequence-order information were derived according to the following five physicochemical and biochemical properties of amino acids: (i) codon diversity, (ii) electrostatic charge, (iii) molecular volume, (iv) polarity, and (v) secondary structure propensity. The values of such five properties were retrieved from [22–24]. To get the optimal results, we set $r = 50$ and $\alpha = 0.15$ for the PseAAC, as done in [24]. Since each of the aforementioned five features can generate $e\cdot50$ discrete numbers, each protein sample will be coded by a $(20\times5\times5 = 270)$-D vector in the feature space.

Feature Selection and NNA Classifier

In machine learning, feature selection is a technique that selects an optimal subset of features to build a more robust learning model. Here, we used Maximum Relevance Minimum Redundancy (mRMR) method [25] to rank the 270 features based on their relevance to the classification variable (maximum relevance) and the redundancy among them (minimum redundancy). More important features will be selected earlier and ranked in higher position. Meanwhile, in spite of the features being ranked according to mRMR criteria, it is a bit of a challenge to get the optimal number of features used for the prediction. To solve the problem, we adopted Incremental Feature Selection (IFS) [26] to find the optimal number of features. For the 270 features ranking from higher to lower, we added features one by one to code the protein. Thus, we obtained a series of feature subsets

$$S_i = \{f_1,f_2,\ldots,f_i\} \quad (1 \leq i \leq 270)$$

where $f_i$ is the $i$-th feature in the ranked feature list. Subsequently, a Nearest Neighbor Algorithm (NNA) [27] classifier was constructed for each feature subset to predict whether a protein was a virulence factor or not. NNA is one of the simplest and most effective machine learning algorithms, which assigns the unknown sample to the class of its nearest neighbor. The core of this algorithm is the distance function:

$$D(v_i,v_j) = 1 - \frac{v_i \cdot v_j}{||v_i|| \cdot ||v_j||}$$

where $v_i \cdot v_j$ is the inner product of the two coding vectors $v_i$ and $v_j$, and $||v||$ represents the module of vector $v$. Since each protein is coded by an i-D $(1 \leq i \leq 270)$ vector and the training set contains
proteins \(\{p_1, p_2, \ldots, p_k, \ldots, p_n\}\), we can determine the class of a queried protein \(p\) as follows

\[
    r = \min \left\{ \frac{D(p, p_k \Rightarrow 1)}{D(p, p_k \Rightarrow 2)} \right\} \quad (k = 1, 2, \ldots, n) \quad (9)
\]

where \(\min \left\{ D(p, p_j \Rightarrow j) \right\} (j = 1, 2)\) is the nearest distance of the queried protein \(p\) and the \(j\)-th class protein \(p_j \Rightarrow j\), in which \(j = 1\) means protein \(p_j\) belongs to positive samples and \(j = 2\) negative samples. According to the theory of NNA, if \(r < 1\), the queried protein is assigned to the virulence factors; otherwise not. Since the NNA classifier can be applied for every feature subset to perform a prediction, we draw an IFS (Incremental Feature Selection) curve to reflect the relationship between the performance of the NNA classifier and the feature subset. In the curve, \(x\)-axis is the number of features of the subset \(S_j\) and \(y\)-axis is the prediction accuracy of the NNA classifier. The optimal prediction result is the highest point in the curve, which corresponds to the feature subset in the \(x\)-axis that achieves the highest overall accuracy in the curve.

6. Jackknife Cross-Validation and Evaluation

In statistical prediction, the jackknife cross-validation, also known as the leave-one-out cross-validation (LOOCV), is regarded as an objective and effective method to evaluate a classifier for its effectiveness in practical application. Accordingly, we adopted this method here to examine the quality of the present classifiers. During the jackknifing process, each of the proteins in the dataset was in turn singled out for testing by the classifier trained with the remaining proteins. To evaluate the performance quality, we calculated the following six indexes: sensitivity (\(S_n\)), specificity (\(S_p\)), precision (\(P\)), recall (\(R\)), accuracy (\(AC\)) and Matthews Correlation Coefficient (\(MCC\)), as formulated below:

\[
    S_n = \frac{TP}{TP + FN} \\
    S_p = \frac{TN}{TN + FP} \\
    P = \frac{TP}{TP + FP} \\
    R = \frac{TP}{TP + FN} \\
    AC = \frac{TP + TN}{TP + FP + TN + FN} \\
    MCC = \frac{(TP \times TN) - (FN \times FP)}{\sqrt{(TP + FN) \times (TN + FP) \times (TP + FP) \times (TN + FN)}}
\]

where \(TP\) represents the true positive, \(TN\) the true negative, \(FP\) the false positive, and \(FN\) the false negative. \(S_n\), \(S_p\) and \(AC\) are the percentages of virulent proteins, non-virulent proteins and any proteins that are correctly predicted, respectively. Precision (\(P\)) is the proportion of the true positives against all the positive results (both true positives and false positives), while recall (\(R\)) in our classification context is referred to as the true positive rate (\(S_n\)) in fact but is used in precision/recall curves. \(MCC\) equaling to 1 indicates a perfect prediction, whereas 0 means a completely random prediction. Then, we further calculated ROC score defined as the areas under the ROC curves, the plot of true positive rate (\(S_n\)) as a function of the number of false positive rate (\(1-S_p\)) by R package ROCR [28]. We also used ROCR to draw precision/recall curves for the comparison of the aforementioned three methods.

Results and Discussion

1. Virulence Factors and Databases

By the use of the molecular version of Robert Koch’s postulates, which built a causal relationship between pathogens and disease, Stanley Falkow attempted to provide a definition of the term ‘virulence factor’: (1) the potential virulence factor gene should be found in all pathogenic strains of the genus or species but be absent from non-pathogenic strains; (2) virulence of the microbe with the inactivated gene should be less than that of the unaltered microbe in an appropriate animal model; (3) reintroduction of the relevant gene into the microbe should restore virulence in the animal model [29,30]. His work has provided an experimentally rigorous approach to the study of virulence in certain bacterial pathogens. However, it should be noted that the definition of the virulence factor is also problematic and controversial [31,32]. For example, some “classic” virulence factors, such as invasion genes (e.g., yip), iheB and ompA), were also found in the genomes of commensal bacteria [32]. In spite of this imprecise definition, the virulence factor concept has still been used as a powerful engine in driving research in the fields of microbial pathogenesis and infectious diseases, and thus has greatly furthered our understanding of microbial pathogenesis [33–36].

Except VFDB and MvirDB mentioned above, several other databases have been developed specially for virulence factors, such as PHI-base (Pathogen Host Interactions database) [37], ARDB (Antibiotic Resistance Genes Database) [30] and ATDB (Animal Toxin Database) [39] and so on. Among these databases, VFDB was found to be the broadest and most comprehensive and had the highest quality with its curated dataset and virulence-guided classification system [5,33]. Via exhaustive literature screening and expert review, VFDB has provided up-to-date information regarding experimentally validated bacterial virulence factors from genera of medically important bacterial pathogens. And
therefore, we used the virulence factors from VFDB as our primary dataset.

2. Results by BLAST
At first, we conducted the homology search for each species by BLASTP with the cutoff of HSP score being 90. However, most of the proteins (more than 80 percent) in the training dataset will be discarded for the poor homology among them. Thence, in the following study, to make use of the most of the data, no cutoff was set for the BLAST method. If the ratio of the smallest e-values of positive and negative samples was less than one, then the query protein was assigned to the virulence factor class regardless of how poor the alignment was; if not, non-virulence factor class. In some cases, it was also possible that no hit whatsoever existed for a query protein, and then the query protein would be excluded from the training dataset. For example, in UPEC 536, among 993 (207 × 6 × 0.8) proteins, 960 were predicted by the BLAST and 33 proteins were discarded. The prediction results are given in Table 1. As can be seen, the $S_n$, $S_p$, $AC$, and $MCC$ for UPEC 536 were 0.460, 0.869, 0.900.
and 0.315, respectively. The results of the other 5 species are also shown in Table 1. We can find that the overall prediction accuracies are around or less than 0.8.

3. Results by the Feature Selection Method

We also applied feature selection method to predict whether a protein is a virulence factor or not. The model was constructed as follows. First of all, each of the proteins in the training dataset was coded as a 270-D feature vector in the feature space (see Section 4 of Materials and Methods). Then, the mRMR program was run to rank the 270 features according to the criteria of Maximum Relevance and Minimum Redundancy. The mRMR-ranked features can be found in Table S1 and will be participated in IFS procedure for feature selection and analysis. For each feature subset, a NNA classifier was built and its prediction accuracy was calculated by the jackknife cross-validation. Based on the number

![Figure 2. The distribution of the number of features of the optimal feature subset for each of the six species. In the feature space, all the features can be classified into six classes: amino acid composition, codon diversity, electrostatic charge, molecular volume, polarity and secondary structure. doi:10.1371/journal.pone.0042517.g002](image-url)
Figure 3. Histogram illustration to show the difference of the amino acid occurrence frequency between virulence and non-virulence factors. The histograms were plotted for Ala, Ser, Arg, and Val in UPEC 536, respectively. X-axis is the amino acid composition, while y-axis is the frequency of sequences that own the corresponding amino acid composition in the dataset. P-values are given by the Wilcoxon rank sum test and measure how much evidence we have against the null hypothesis that the amino acid composition distribution is the same for virulence and non-virulence factors. Traditionally, when p-value $<0.05$, we say the null hypothesis is rejected, that is, the amino acid composition distribution is significantly different for virulence and non-virulence factors. The feature distribution histograms and p-values show the difference of the amino acid composition frequencies between virulence and non-virulence factors is significant, and thus it is reasonable to pick out virulence factors from proteomes based on amino acid composition features.

doi:10.1371/journal.pone.0042517.g003

Table 2. Prediction based on feature selection method.

<table>
<thead>
<tr>
<th>Species</th>
<th>TP</th>
<th>FP</th>
<th>TN</th>
<th>FN</th>
<th>Sn</th>
<th>Sp</th>
<th>AC</th>
<th>MCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPEC 536</td>
<td>87</td>
<td>96</td>
<td>732</td>
<td>78</td>
<td>0.52727</td>
<td>0.88406</td>
<td>0.82477</td>
<td>0.39489</td>
</tr>
<tr>
<td>UPEC CFT073</td>
<td>47</td>
<td>66</td>
<td>374</td>
<td>41</td>
<td>0.53409</td>
<td>0.85000</td>
<td>0.79735</td>
<td>0.34901</td>
</tr>
<tr>
<td>L. pneumophila Philadelphia 1</td>
<td>40</td>
<td>55</td>
<td>409</td>
<td>52</td>
<td>0.43478</td>
<td>0.88147</td>
<td>0.80755</td>
<td>0.31223</td>
</tr>
<tr>
<td>P. aeruginosa PAO1</td>
<td>49</td>
<td>100</td>
<td>656</td>
<td>102</td>
<td>0.32450</td>
<td>0.86772</td>
<td>0.77729</td>
<td>0.19326</td>
</tr>
<tr>
<td>C. jejuni NCTC 11168</td>
<td>36</td>
<td>36</td>
<td>356</td>
<td>42</td>
<td>0.46154</td>
<td>0.90816</td>
<td>0.83404</td>
<td>0.38189</td>
</tr>
<tr>
<td>M. tuberculosis H37Rv</td>
<td>26</td>
<td>41</td>
<td>291</td>
<td>40</td>
<td>0.39394</td>
<td>0.87651</td>
<td>0.79648</td>
<td>0.26882</td>
</tr>
</tbody>
</table>

doi:10.1371/journal.pone.0042517.t002
of the features in a feature subset and the corresponding prediction accuracy, we plotted the IFS curve (Figure 1). Again take UPEC 536 for example: it was observed that when the feature subset contained the first 47 features, the prediction accuracy got the highest value of 0.824773. Hence, the optimal prediction model should be constructed by the first 47 features in the mRMR feature list. For the other five species, the optimal number of features and the corresponding accuracy were (148; 0.797348), (112; 0.807554), (20; 0.777288), (204; 0.834043) and (26; 0.796482), respectively.

Table 3. Prediction based on protein-protein interaction network.

<table>
<thead>
<tr>
<th>Species</th>
<th>TP</th>
<th>FP</th>
<th>TN</th>
<th>FN</th>
<th>Sn</th>
<th>Sp</th>
<th>AC</th>
<th>MCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPEC 536</td>
<td>109</td>
<td>18</td>
<td>783</td>
<td>49</td>
<td>0.68987</td>
<td>0.97753</td>
<td>0.93014</td>
<td>0.73041</td>
</tr>
<tr>
<td>UPEC CFT073</td>
<td>80</td>
<td>19</td>
<td>359</td>
<td>3</td>
<td>0.96386</td>
<td>0.94974</td>
<td>0.95228</td>
<td>0.85480</td>
</tr>
<tr>
<td>L. pneumophila Philadelphia 1</td>
<td>59</td>
<td>20</td>
<td>397</td>
<td>30</td>
<td>0.66292</td>
<td>0.95204</td>
<td>0.90119</td>
<td>0.64503</td>
</tr>
<tr>
<td>P. aeruginosa PAO1</td>
<td>126</td>
<td>11</td>
<td>719</td>
<td>24</td>
<td>0.84000</td>
<td>0.98493</td>
<td>0.96023</td>
<td>0.85560</td>
</tr>
<tr>
<td>C. jejuni NCTC 11168</td>
<td>63</td>
<td>11</td>
<td>378</td>
<td>15</td>
<td>0.80769</td>
<td>0.97172</td>
<td>0.94433</td>
<td>0.79612</td>
</tr>
<tr>
<td>M. tuberculosis H37Rv</td>
<td>22</td>
<td>15</td>
<td>291</td>
<td>44</td>
<td>0.33333</td>
<td>0.95098</td>
<td>0.84140</td>
<td>0.36292</td>
</tr>
</tbody>
</table>

Table 3. Prediction based on protein-protein interaction network.

The poor prediction performance for M. tuberculosis H37Rv was higher than those by either the BLAST method or the feature selection method, indicating that the current network-based method is quite promising that may hold very high potential for identifying virulence factors in various organisms. However, it was noted that although the AC value achieved by the network-based method for M. tuberculosis H37Rv was higher than those by the BLAST and feature selection methods, the value was only 0.84140, much less than those for the other five species. The poor prediction performance for M. tuberculosis H37Rv

4. Performance of the Network-Based Method

From STRING, the probabilistic confidence scores of interactions between proteins can usually be acquired, which can then be used to investigate biological problems [16,42,43]. However, some proteins may not interact with any of other proteins in the same training dataset. Take UPEC 536 as an example, only 959 proteins in its training dataset have interactions with other proteins, while the remaining 993–959 = 34 proteins have no interactions at all with the other proteins although they may interact with proteins outside training dataset. Considering the negative dataset was generated randomly, it is always possible that some proteins do not interact with any others in the training dataset. One feasible solution is to put all the non-virulence factors in STRING into the negative dataset. Unfortunately, this would make the size of the negative samples so large that $S_{n}$ would be very low, though $AC$ could be high. In order to balance the positive and negative samples, we tested the performance by setting the ratio between positive samples and negative samples to be 1:2, 1:5 and 1:10. And we found that when the ratio was 1:5, we obtained the desirable performance. For the other five species (i.e., UPEC CFT073, L. pneumophila Philadelphia 1, P. aeruginosa PAO1, C. jejuni NCTC 11168 and M. tuberculosis H37Rv), the corresponding numbers of proteins without any interaction with the others are 528–461 = 67, 556–506 = 50, 907–880 = 27, 470–467 = 3 and 398–372 = 26, respectively. All these proteins were discarded.

Listed in Table 3 are the results obtained by the current network-based method on the six species via the jackknife tests.
might be due to that the quality of protein-protein interaction data for this organism in the STRING database is much poorer [44].

5. Comparison between Network-based and Other Methods

In this study, we developed three different methods to identify virulence factors. As shown from Tables 1, 2, and 3, the network-based method significantly outperformed the BLAST method and the feature selection method in blue and green respectively. It can be seen that of the three methods, the network-based method had the best performance for all the following six cases: (A) UPEC 536; (B) UPEC CFT073; (C) L. pneumophila Philadelphia 1; (D) P. aeruginosa PAO1; (E) C. jejuni NCTC 11168; (F) M. tuberculosis H37Rv.

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Figure 4. The ROC curves of true positive vs. false positive for the three different prediction methods. The curves for the network-based method are colored in red, while those for the BLAST method and the feature selected method in blue and green respectively. It can be seen that of the three methods, the network-based method had the best performance for all the following six cases: (A) UPEC 536; (B) UPEC CFT073; (C) L. pneumophila Philadelphia 1; (D) P. aeruginosa PAO1; (E) C. jejuni NCTC 11168; (F) M. tuberculosis H37Rv.
\[ f(x) = e^{-x} \]  \hspace{1cm} (11)

where \( x \) is either the e-value or distance. By means of Eq. 11, all the e-values and distances could be mapped into the region of (0,1]. After such a transformation, we redrew the ROC and precision/recall curves (Figures 4 and 5). As expected, the two kinds of curves have showed once again that the network-based method achieved the best performance among the three methods for all the six species.

Moreover, based on the independent testing dataset for the six species, we did plan to compare the prediction performance of our three methods with other existing methods, including VirulentPred [12] and Virulent-GO [13]. Unfortunately, no downloadable or online tool whatsoever was available for Virulent-GO. Thus, only the comparison with VirulentPred was made here as a compromise. The concrete comparison procedures are as follows. The positive and negative testing dataset was submitted onto the VirulentPred online service (http://203.92.44.117/virulent/submit.html) directly with default parameters. For our three methods, it should be noticed that the feature set used to code the testing dataset in the feature selection method was the optimal subset, which was obtained from the training dataset. The results of \( S_n \), \( S_p \), \( AC \) and \( MCC \) were also calculated for each method, respectively. As can be seen from Table 4, the network-based method achieved much better...
prediction performance than the BLAST and feature selection methods. Therefore, many new computational methods have been developed to infer the protein function using the principle of guilt-by-association of other functional properties to complement the sequence-based methods [45]. Our method based on the STRING protein-protein interaction network reflects one of the efforts in this regard. As the cornerstone in the current network-based method, the STRING database quantitatively integrates the interaction data from many information sources such as phylogenetic, experimental and existing knowledge information, extending the direct (physical) associations to the indirect (functional) associations. We have analyzed the detailed sub-score information of our STRING network data for the virulence factors in the six species. It was found that most of the interactions among virulence factors in the STRING database were functional associations, mainly with the neighborhood and co-occurrence associations (Figure 6). In view of this, we further studied the locations of the virulence factors in the genomes and biological processes they were involved in.

It has been noted by previous investigators [32,46] that many virulence factors are presented in the pathogenicity islands involved in horizontal gene transfer. In 2009, with the number and diversity of bacterial genomes sequenced, a systematic large-scale analysis across diverse genera has indicated that virulence factors are disproportionately associated with genomic islands (GI) [33]. Subsequently, we mapped our virulence factors of the six species to the SEED subsystems by the SEED Viewer version 2.0 (http://pubseed.theseed.org/seedviewer.cgi) [47]. In the microbial genome annotation, the SEED is the first annotation environment that curates genomic data via the curation of subsystems by an expert annotator across many genomes, not on a gene-by-gene basis. These subsystems group genes by the pathways or structures in which they participate. For instance, type 4 secretion and conjugative transfer are composed of a set of functional roles that some proteins perform (type IV secretion system protein VirD4, inner membrane protein forms channel for type IV secretion and conjugative transfer are composed of a set of functional roles for T-DNA complex VirB5, etc.).

Our method based on the STRING network is really better in identifying the bacterial virulence factors.

### Table 4. Comparison of several methods, including BLAST, Feature Selection, Network-based and VirulentPred, based on the testing dataset.

<table>
<thead>
<tr>
<th>Method</th>
<th>Sn</th>
<th>Sp</th>
<th>AC</th>
<th>MCC</th>
</tr>
</thead>
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<tr>
<td><strong>UPEC S36</strong></td>
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<tr>
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<td>0.52381</td>
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<td>0.37051</td>
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<td>0.93388</td>
<td>0.76544</td>
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<td>VirulentPred</td>
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<td>0.69082</td>
<td>0.71084</td>
<td>0.38351</td>
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<tr>
<td>BLAST</td>
<td>0.66667</td>
<td>0.90476</td>
<td>0.86508</td>
<td>0.54233</td>
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<td>0.42836</td>
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<tr>
<td>Network-based</td>
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<td>0.94898</td>
<td>0.94167</td>
<td>0.81755</td>
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<td>VirulentPred</td>
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<td>0.62727</td>
<td>0.67424</td>
<td>0.40093</td>
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<td>0.91603</td>
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<tr>
<td>VirulentPred</td>
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<td><strong>M. tuberculosis H37Rv</strong></td>
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<td>0.75904</td>
<td>0.76000</td>
<td>0.41840</td>
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</table>

doi:10.1371/journal.pone.0042517.t004
is many folds more likely to interact with each other than a random pair of proteins [48]. In fact, during the course of infecting susceptible hosts, it is necessary for multiple virulence factors in bacterial pathogens to cooperate with each other [13, 34, 49]. For example, it has been shown that the prototypical type 1 secreted toxin, α-hemolysin (HlyA) is encoded by UPEC 536 and CFT073 and its expression is associated with increased clinical severity in the urinary tract infections patients [50]. However, the HlyA protein requires a post-translational modification for activity. The inactive protoxin pro-HlyA is activated by another virulence factor protein HlyC, which is an acyl carrier protein that acts as the fatty acid donor and is responsible for acylation of HylA, resulting in toxin activation [49]. Another example is that the secreted virulence factors by Pseudomonas aeruginosa, including α-lactamase, alkaline phosphatase, hemolytic phospholipase C, and Cif, are not released individually as naked proteins into the surrounding milieu. Instead, it is the bacterial-derived outer membrane vesicles (OMV) that deliver these virulence factors simultaneously and directly into the host airway epithelial cells in a coordinated manner [34]. In addition, Lilburn et al. [42] also proposed an approach by assembling a list of known virulent proteins and using these proteins as bait proteins in STRING functional association network to detect candidate virulent proteins involving in virulence in Vibrio cholerae, including proteins that are overlooked because of the incomplete annotation or the requirement of a follow-up investigation to confirm their roles in virulence. All these facts are consistent with the notion that virulent functions depend on the interaction of a large number of proteins. That is the essence of why the STRING network-based method is able to perform better than the sequence-based methods such as BLASTP and feature selection method (Tables 1, 2, 3, 4 and Figures 4 and 5).

7. Application and Improvement

Although the network-based method was merely tested for the proteins in six species, the high success rates obtained indicated the promising potential to be applied to other species as well. At present, we only considered virulence factors annotated in VFDB and protein-protein interactions in STRING database. Many other databases, such as MvirDB and SwissProt [51], also contain a large number of virulence factors, some of which are not collected in VFDB. Accordingly, for any other given bacterial species, we can also use the current network-based method to identify the virulence factors concerned once significant statistical data are available for the species. In other words, the current method can be easily extended to identify the virulence factors in many other bacterial species.

Despite quite high prediction accuracy by the network-based method, the following limitations should be pointed out. Firstly, some of the hypothetical non-virulent proteins in the training set could turn out to be virulence factors after more of their functions...
are determined in future. It will be less of a problem when more proteins are accurately annotated by experiments. Secondly, some protein-protein interactions from STRING database might not be reliable, such as the case in *M. tuberculosis* H37Rv. Also, some of the methods that generate protein interaction data – e.g., two-hybrids or gene neighbor – are susceptible to noise and might have a high false-positive rate [52–54]. Nevertheless, the STRING by combining the protein-protein interactions from multiple sources could improve their expected accuracy with at least 80% for more than half of the genes, clearly demonstrating the reliability of the data [55] in many cases. With enhanced quality of this small fraction of PPI networks in STRING, the performance of our network-based method can be further improved. Thirdly, the above network-based method has only taken into account of the neighbors that directly interact with the query protein, without considering the full topology of the network, during the prediction process. Yet it has been observed that, up to 69% of yeast proteins share functions with their indirect interaction partners, while only 48% share functions with their immediate interaction neighbors, as indicated in BioGrid [56]. Lastly, since the pathogenicity mechanism involves the interactions between the host and pathogen proteins [57,58], more information about these kinds of interactions would be very useful in improving the methodology and even providing some clues or insights for revealing the mechanism.

Supporting Information

**Figure S1** Enrichment of virulence factors in SEED subsystems by *UPEC 536*. VF: virulence factor. (TIFF)

**Figure S2** Enrichment of virulence factors in SEED subsystems by *UPEC CFT073*. VF: virulence factor. (TIFF)

**Figure S3** Enrichment of virulence factors in SEED subsystems by *L. pneumophila Philadelphia 1*. VF: virulence factor. (TIFF)

**Figure S4** Enrichment of virulence factors in SEED subsystems by *P. aeruginosa PAO1*. VF: virulence factor. (TIFF)

**Figure S5** Enrichment of virulence factors in SEED subsystems by *M. tuberculosis* H37Rv. VF: virulence factor. (TIFF)

**Table S1** The feature list for all the six species by mRMR. The first part is the features ranked according to the criteria of maximum relevance to target. And the second part is the features ranked according to maximum relevance and minimum redundancy. The mRMR method could assign a score to each feature and then rank the features based on their scores.
For a detailed description, see [25]. In the list of each part, the first column is the order of features ranked by mRMR; the second column is the original order of features input into mRMR; the third column is the names of features classified as amino acid composition, codon diversity, electrostatic charge, molecular volume, polarity and secondary structure; and the last column is the mRMR score.

(XLS)

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Author Contributions

Conceived and designed the experiments: XKG PH YXL YDC. Performed the experiments: LLZ LHL. Analyzed the data: LLZ PH. Contributed reagents/materials/analysis tools: LLZ YJW. Wrote the paper: LLZ KYF JD KCC.

References


