**mAHTPred: a sequence-based meta predictor for improving the prediction of anti-hypertensive peptides using effective feature representation**

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**1 Machine learning algorithms**

Four machine learning algorithms are implemented in mATHPred. A brief description of these methods and how they were used in this study as follows:

**1.1 Random forest (RF)**

Breiman (Breiman, 2001) proposed RF algorithm that performs both classification and regression using ensemble of decision trees, and is regarded as one of the powerful ML algorithm which is widely used in bioinformatics and computational biology (Manavalan, et al., 2017; Manavalan, et al., 2014; Manavalan, et al., 2018; Manavalan, et al., 2018; Song, et al., 2017; Wei, et al., 2017). In RF, three key parameters are the number of trees (*ntree*), number of features randomly selected (*mtry*), and the minimum number of samples required to split and internal node (*nsplit*). Grid search was employed to fine-tune these parameters with the following search space:

 $\left\{\begin{array}{c}50 \leq ntree\leq 2000 with step Δntree=25\\1\leq mtry \leq 15 with step ∆mtry=1\\1\leq nsplit \leq 12 with step ∆nsplit=1\end{array}\right.$ (1)

**1.2 Extremely randomized tree (ERT)**

Geurts et al. (Geurts, et al., 2006) proposed the ERT algorithm that perform classification and regression by utilizing hundreds or thousands of independent decision trees, which has been applied in a large number of biological problems (Manavalan, et al., 2018; Manavalan, et al., 2018). ERT aims to further decrease the variance of the prediction model by including stronger randomization techniques. The ERT algorithm is similar to RF, but with the following differences: (*i*) ERT does not apply a bagging procedure for the construction of each tree. Instead, it uses the whole input training set for the construction of each tree. (*ii*) ERT selects a node split very randomly (both a variable index and variable splitting values are chosen randomly), whereas RF finds the best split (optimized by a variable index and a variable splitting value) among a random subset of variables. Furthermore, Grid search was performed to fine-tune the regularization parameters *ntree*, *mtry*, and *nsplit*, whose search space are as follows:

 $\left\{\begin{array}{c}50 \leq ntree\leq 2000 with step Δntree=25\\1\leq mtry \leq 15 with step ∆mtry=1\\1\leq nsplit \leq 12 with step ∆nsplit=1\end{array}\right.$ (2)

**1.3 Support vector machine (SVM)**

The objective of SVM is to find the optimal hyperplane with the largest margin to decrease the misclassification rate (Noble, 2006). Basically, it maps the given input features into a high-dimensional space using kernel functions and finds a hyperplane that maximizes the distance between the hyperplane and two classes. For a given test sample that was mapped into the high-dimensional space (as described above), and SVM can predict the test sample based on which side of the hyperplane they fall in. Notably, SVM is one of the most widely used ML algorithms applied to various classification problems (Cao, et al., 2014; Chen, et al., 2018; Feng, et al., 2018; Manavalan and Lee, 2017; Manavalan, et al., 2018; Wei, et al., 2018; Wei, et al., 2018). In this study, we experimented different kernel functions including, linear, polynomial functions, and Gaussian radial-basis function (RBF). Of these, RBF kernel was the most suitable for addressing our problem. Two critical parameters, *C* (controls the trade-off between the training error and margin) and g (controls how peaked Gaussians are centered on the support vectors) requires optimization in RBF-SVM. Therefore, we optimized these parameters using the following range:

 $\left\{\begin{array}{c}2^{-5}\leq C \leq 2^{15} with step ∆C=2\\2^{-15}\leq γ \leq 2^{15} with step ∆γ=2^{-1}\end{array}\right.$ (3)

**1.4 Gradient boosting (GB)**

Friedman proposed the GB algorithm (Friedman, 2001), which is a forward learning ensemble method that performs both classification and regression problems. GB produces a final strong prediction model based on the ensemble of weak models (decision trees), which has been widely used in bioinformatics and computational biology (Manavalan, et al., 2018; Rawi, et al., 2018). GB consecutively fits new models to provide a more accurate estimate of the response variables, compared to other ensemble methods such as RF, ERT, and AB. In GB, the three most influential parameters are *ntree*, *mtry*, and *nsplit*, we optimized with the following search space:

 $\left\{\begin{array}{c}50 \leq ntree\leq 1000 with step Δntree=25\\1\leq mtry \leq 10 with step ∆mtry=1\\1\leq nsplit \leq 6 with step ∆nsplit=1\end{array}\right.$ (4)

2 10-fold cross-validation

Generally, three CV methods, namely an independent data set test, a sub-sampling (or *k*-fold CV) test, and a leave-one-out CV (LOOCV) test, are often used to evaluate the anticipated success rate of a predictor. Among the three methods, however, the LOOCV test is deemed the least arbitrary and most objective as demonstrated by Eqs.28-32 of (Chou, 2011), and hence it has been widely recognized and increasingly adopted by investigators to examine the quality of various predictors (Cao, et al., 2017; Cao, et al., 2016; Cao, et al., 2017; Cao, et al., 2014; Chen, et al., 2018; Chen, et al., 2013; Chen, et al., 2016; Chen, et al., 2017; Kosylo, et al., 2018; Lai, et al., 2017; Lin, et al., 2012; Lin, et al., 2017; Liu, et al., 2018; Tang, et al., 2017; Yang, et al., 2016; Yang, et al., 2018; Zhao, et al., 2017). However, it seems time- and source-consuming. Thus, we used 10-fold CV to examine the proposed models. In 10-fold CV, the benchmarking dataset was randomly partitioned into 10 subsets. One subset is used as a test set and the remaining nine subsets are used as the training sets. This procedure is repeated for 10 times, where each subset being used once as a test set. The performance of the 10 corresponding results are averaged that implies the performance of the classifier.

3 Performance Evaluation

To evaluate the performance of the constructed models, we used four measurements that were commonly used in binary classification tasks (Feng, et al., 2013; Liu, et al., 2018; Liu, et al., 2018; Liu, et al., 2017; Tang, et al., 2018), including sensitivity, specificity, accuracy, and Matthews correlation coefficient (MCC). They are calculated as follows:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| $$Sensitivity =\frac{TP}{TP+FN}$$$$Specificity =\frac{TN}{TN+FP}$$

|  |  |  |  |
| --- | --- | --- | --- |
|

|  |  |
| --- | --- |
| $$Accuracy =\frac{TP+TN}{TP+TN+FP+FN}$$$$MCC =\frac{TP×TN-FP×FN}{√(TP+FP)(TP+FN)(TN+FP)(TN+FN)}$$ | (5) |

 |  |

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where TP is the number of true positives (i.e., AHTPs classified correctly as AHTPs) and TN is the number of true negatives (i.e., non-AHTPs classified correctly as non-AHTPs). FP is the number of false positives (i.e., AHTPs classified incorrectly as non-AHTPs) and FN is the number of false negatives (i.e., non-AHTPs classified incorrectly as AHTPs). Additionally, the receiver operating characteristic (ROC) curve, which is a plot of the true positive rate against the false positive rate under different classification thresholds, is depicted to visually measure the comprehensive performance of different classifiers.

**4 Implementation of a webserver**

Generally, user-friendly web servers have been helpful for experimentalists, where they can do the prediction without going through mathematical equations, and also it represent the future direction for developing novel and more useful predictors (Chou and Shen, 2009). Indeed, it has been demonstrated by a series of publications (Chen, et al., 2017; Chen, et al., 2016; Han, et al., 2018; McDermaid, et al., 2018). In this view, we established a user-friendly webserver, mAHTPred, for a wider research community, which is freely accessible via http:/thegleelab.org/mAHTPred. To validate our findings, all data sets utilized in this study can be freely downloaded from our web server. Below, we provide researchers a simple two-step guideline on how to use our webserver in order to obtain the predicted outcomes. In the first step, users need to submit the query sequences into the input box. Note that the input sequences should be in FASTA format. Examples of FASTA-formatted sequences can be seen by clicking on the FASTA format button which is located above the input box. As a final step, clicking on the ‘Submit’ button will provide the predicted results as the output.

**5. Motif analysis**

We combined benchmark dataset and independent datasets and applied MERCI program (Vens, et al., 2011) to identify the motifs present in both AHTPs and non-AHTPs. Results showed that 11 exclusive motifs were present in AHTPs (“PFP”, “LHL”, “YPF”, “LHLP”, “IYP”, “YPFP”, “APFP”, “PFPG”, “VAPF”, “VAPFP”, “YPFPG”), whereas none was found in non-AHTPs.

**Figure S1.** ROC curves of mAHTPred and the existing methods on the independent dataset.

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**Table S1.** The details of hybrid features generated with different combination and the final input features dimensions.

|  |  |  |
| --- | --- | --- |
| Hybrid feature | Combinations | Input features dimensions |
| H1 | AAC, OF | 25 |
| H2 | DPC, OF | 405 |
| H3 | AAI, OF | 25 |
| H4 | CTD, OF | 152 |
| H5 | AAC, DPC | 420 |
| H6 | AAC, AAI | 40 |
| H7 | AAC, CTD | 167 |
| H8 | AAI, DPC | 420 |
| H9 | DPC, CTD | 547 |
| H10 | AAI, CTD | 167 |
| H11 | AAC, AAI, DPC | 440 |
| H12 | AAC, AAI, CTD | 187 |
| H13 | AAC, CTD, OF | 172 |
| H14 | AAI, DPC, CTD | 567 |
| H15 | DPC, CTD, OF | 552 |
| H16 | AAI, CTD, OF | 172 |
| H17 | AAC, AAI, DPC, CTD | 587 |
| H18 | AAI, DPC, CTD, OF | 572 |
| H19 | AAC, AAI, CTD, OF | 192 |
| H20 | AAC, DPC, AAI, CTD, OF | 592 |

**Table S2.** The details of standard amino acid residue classification based on ten physicochemical properties used in OVP.

|  |  |
| --- | --- |
| **Physicochemical property** | **Amino acid group** |
| Aromatic | F, Y, W, H |
| Negative | D, E |
| Positive | K, R, H |
| Polar | N, Q, S, D, E, C, T, K, R, H, Y, W |
| Hydrophobic | A, G, C, T, I, V, L, K, H, F, Y, W, M |
| Aliphatic | I, V, L |
| Tiny | A, S, G, C |
| Charged | K, H, R, D, E |
| Small | P, N, D, T, C, A, G, S, V |
| Imino acid | P |

**Table S3.** The details of standard amino acid classification based on seven physicochemical properties used in 21-bit.

|  |  |  |  |
| --- | --- | --- | --- |
| **Physicochemical property** | **Group 1** | **Group 2** | **page30image79448Group 3** |
| Hydrophobicity | A, C, F, G, H, I, L, M, N, P, Q, S, T, V, W, Y | D, E | K, R |
| Normalized Van der Waals volume | C, F, I, L, M, V, W | A, G, H, P, S, T, Y | D, E, K, N, Q, R |
| Polarity | A, C, D, G, P, S, T | E, I, L, N, Q, V | F, H, K, M, R, W, Y |
| Polarizability | C, F, I, L, M, V, W, Y | A, G, P, S, T | D, E, H, K, N, Q, R |
| Charge | A, D, G, S, T | C, E, I, L, N, P, Q, V | F, H, K, M, R, W, Y |
| Secondary structures | D, G, N, P, S | A, E, H, K, L, M, Q, R | C, F, I, T, V, W, Y |
| Solvent Accessibility | A, C, F, G, I, L, V, W | H, M, P, S, T, Y | D, E, K, N, R, Q |

**Table S4.** List of all the 51 feature descriptors

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Feature identifier | Feature descriptor | Dimensions | Feature identifier | Feature descriptor | Dimensions |
| F1 | AAC | 20 | F27 | TOBC4 | 80 |
| F2 | DPC | 400 | F28 | TOBNC4 | 160 |
| F3 | CTD | 147 | F29 | TOBN5 | 100 |
| F4 | AAI | 20 | F30 | TOBC5 | 100 |
| F5 | BPFN3 | 60 | F31 | TOBNC5 | 200 |
| F6 | BPFC3 | 60 | F32 | H1 | 25 |
| F7 | BPFNC3 | 120 | F33 | H2 | 405 |
| F8 | BPFN4 | 80 | F34 | H3 | 25 |
| F9 | BPFC4 | 80 | F35 | H4 | 152 |
| F10 | BPFNC4 | 160 | F36 | H5 | 420 |
| F11 | BPFN5 | 100 | F37 | H6 | 40 |
| F12 | BPFC5 | 100 | F38 | H7 | 167 |
| F13 | BPFNC5 | 200 | F39 | H8 | 420 |
| F14 | OVPN3 | 60 | F40 | H9 | 547 |
| F15 | OVPC3 | 60 | F41 | H10 | 167 |
| F16 | OVPNC3 | 120 | F42 | H11 | 440 |
| F17 | OVPN4 | 80 | F43 | H12 | 187 |
| F18 | OVPC4 | 80 | F44 | H13 | 172 |
| F19 | OVPNC4 | 160 | F45 | H14 | 567 |
| F20 | OVPN5 | 100 | F46 | H15 | 552 |
| F21 | OVPC5 | 100 | F47 | H16 | 172 |
| F22 | OVPNC5 | 200 | F48 | H17 | 587 |
| F23 | TOBN3 | 60 | F49 | H18 | 572 |
| F24 | TOBC3 | 60 | F50 | H19 | 192 |
| F25 | TOBNC3 | 120 | F51 | H20 | 592 |
| F26 | TOBN4 | 80 |  |  |  |

**Table S5.** Performance of the 51 individual feature descriptors with RF classifier on the benchmarking dataset during 10-fold CV, where the descriptors are ranked according to the accuracy.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Descriptor** | **MCC** | **Accuracy** | **Sensitivity** | **Specificity** | **AUC** |
| CTD | 0.643 | 0.820 | 0.777 | 0.863 | 0.884 |
| H8 | 0.627 | 0.813 | 0.788 | 0.839 | 0.878 |
| H11 | 0.625 | 0.812 | 0.785 | 0.839 | 0.875 |
| H5 | 0.624 | 0.812 | 0.783 | 0.840 | 0.879 |
| H20 | 0.624 | 0.811 | 0.774 | 0.848 | 0.870 |
| H17 | 0.623 | 0.811 | 0.767 | 0.854 | 0.875 |
| H18 | 0.616 | 0.807 | 0.763 | 0.850 | 0.870 |
| H9 | 0.612 | 0.805 | 0.766 | 0.845 | 0.870 |
| H14 | 0.612 | 0.805 | 0.768 | 0.842 | 0.873 |
| DPC | 0.605 | 0.802 | 0.777 | 0.828 | 0.871 |
| H2 | 0.603 | 0.801 | 0.785 | 0.817 | 0.874 |
| H15 | 0.602 | 0.800 | 0.762 | 0.838 | 0.865 |
| PBFNC5 | 0.600 | 0.800 | 0.780 | 0.819 | 0.872 |
| H12 | 0.601 | 0.799 | 0.744 | 0.853 | 0.863 |
| H19 | 0.600 | 0.799 | 0.747 | 0.850 | 0.861 |
| H10 | 0.588 | 0.793 | 0.751 | 0.835 | 0.857 |
| H7 | 0.585 | 0.791 | 0.740 | 0.841 | 0.858 |
| H13 | 0.585 | 0.791 | 0.739 | 0.842 | 0.856 |
| H16 | 0.583 | 0.790 | 0.742 | 0.839 | 0.860 |
| H3 | 0.578 | 0.789 | 0.761 | 0.816 | 0.852 |
| H1 | 0.576 | 0.788 | 0.760 | 0.815 | 0.850 |
| BPFNC4 | 0.576 | 0.788 | 0.768 | 0.807 | 0.851 |
| OVPC5 | 0.579 | 0.788 | 0.733 | 0.842 | 0.848 |
| AAC | 0.575 | 0.787 | 0.756 | 0.818 | 0.849 |
| H6 | 0.574 | 0.786 | 0.756 | 0.817 | 0.849 |
| BPFC5 | 0.575 | 0.786 | 0.746 | 0.827 | 0.859 |
| AAI | 0.572 | 0.786 | 0.765 | 0.807 | 0.848 |
| OVPNC5 | 0.565 | 0.781 | 0.731 | 0.831 | 0.847 |
| H4 | 0.564 | 0.780 | 0.727 | 0.834 | 0.848 |
| OVPNC4 | 0.551 | 0.774 | 0.720 | 0.828 | 0.828 |
| BPFC4 | 0.548 | 0.773 | 0.736 | 0.811 | 0.838 |
| BPFNC3 | 0.542 | 0.771 | 0.744 | 0.797 | 0.835 |
| OVPC4 | 0.535 | 0.767 | 0.727 | 0.806 | 0.826 |
| OVPNC3 | 0.530 | 0.764 | 0.723 | 0.805 | 0.823 |
| BPFN5 | 0.520 | 0.759 | 0.716 | 0.802 | 0.823 |
| OVPN5 | 0.519 | 0.759 | 0.724 | 0.794 | 0.812 |
| OVPC3 | 0.459 | 0.728 | 0.679 | 0.778 | 0.774 |
| OVPN4 | 0.456 | 0.727 | 0.687 | 0.768 | 0.774 |
| BPFC3 | 0.450 | 0.725 | 0.692 | 0.757 | 0.787 |
| BPFN4 | 0.447 | 0.723 | 0.685 | 0.761 | 0.781 |
| TOBNC5 | 0.429 | 0.714 | 0.699 | 0.730 | 0.776 |
| TOBN5 | 0.422 | 0.711 | 0.698 | 0.724 | 0.770 |
| TOBNC4 | 0.416 | 0.708 | 0.668 | 0.747 | 0.765 |
| TOBN4 | 0.402 | 0.701 | 0.685 | 0.717 | 0.751 |
| BPFN3 | 0.390 | 0.695 | 0.674 | 0.716 | 0.739 |
| TOBNC3 | 0.385 | 0.692 | 0.699 | 0.686 | 0.745 |
| OVPN3 | 0.362 | 0.681 | 0.650 | 0.712 | 0.731 |
| TOBN3 | 0.337 | 0.668 | 0.646 | 0.690 | 0.710 |
| TOBC5 | 0.318 | 0.659 | 0.648 | 0.669 | 0.709 |
| TOBC3 | 0.293 | 0.646 | 0.642 | 0.651 | 0.691 |
| TOBC4 | 0.290 | 0.645 | 0.657 | 0.633 | 0.694 |

**Table S6.** Performance of the 51 individual feature descriptors with ERT classifier on the benchmarking dataset during 10-fold CV, where the descriptors are ranked according to the accuracy.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Descriptor** | **MCC** | **Accuracy** | **Sensitivity** | **Specificity** | **AUC** |
| H11 | 0.646 | 0.823 | 0.793 | 0.852 | 0.883 |
| H20 | 0.647 | 0.823 | 0.788 | 0.858 | 0.882 |
| H17 | 0.641 | 0.820 | 0.786 | 0.853 | 0.881 |
| H18 | 0.641 | 0.820 | 0.785 | 0.854 | 0.878 |
| H14 | 0.639 | 0.819 | 0.780 | 0.858 | 0.877 |
| H9 | 0.637 | 0.818 | 0.777 | 0.859 | 0.878 |
| H5 | 0.636 | 0.817 | 0.782 | 0.852 | 0.880 |
| H8 | 0.635 | 0.817 | 0.783 | 0.850 | 0.879 |
| H15 | 0.635 | 0.817 | 0.779 | 0.854 | 0.875 |
| BPFNC5 | 0.615 | 0.807 | 0.783 | 0.831 | 0.873 |
| H12 | 0.617 | 0.807 | 0.762 | 0.852 | 0.869 |
| H2 | 0.613 | 0.806 | 0.788 | 0.825 | 0.879 |
| H19 | 0.616 | 0.806 | 0.755 | 0.858 | 0.866 |
| H13 | 0.611 | 0.804 | 0.756 | 0.852 | 0.865 |
| DPC | 0.607 | 0.803 | 0.789 | 0.818 | 0.877 |
| H16 | 0.607 | 0.802 | 0.751 | 0.852 | 0.866 |
| H7 | 0.601 | 0.799 | 0.746 | 0.852 | 0.865 |
| H10 | 0.601 | 0.799 | 0.748 | 0.850 | 0.866 |
| AAC | 0.595 | 0.797 | 0.762 | 0.831 | 0.856 |
| BPFNC4 | 0.592 | 0.796 | 0.773 | 0.818 | 0.857 |
| AAI | 0.591 | 0.795 | 0.757 | 0.832 | 0.853 |
| H6 | 0.590 | 0.795 | 0.772 | 0.817 | 0.855 |
| H1 | 0.588 | 0.794 | 0.765 | 0.823 | 0.856 |
| H3 | 0.588 | 0.794 | 0.776 | 0.812 | 0.858 |
| H4 | 0.578 | 0.788 | 0.736 | 0.839 | 0.855 |
| OVPC5 | 0.576 | 0.786 | 0.735 | 0.838 | 0.848 |
| CTD | 0.574 | 0.785 | 0.728 | 0.842 | 0.851 |
| BPFC5 | 0.570 | 0.784 | 0.743 | 0.826 | 0.855 |
| OVPNC5 | 0.573 | 0.784 | 0.725 | 0.843 | 0.843 |
| BPFNC3 | 0.547 | 0.773 | 0.753 | 0.794 | 0.842 |
| OVPNC4 | 0.547 | 0.772 | 0.717 | 0.826 | 0.834 |
| BPFC4 | 0.542 | 0.769 | 0.721 | 0.818 | 0.836 |
| OVPC4 | 0.536 | 0.767 | 0.716 | 0.817 | 0.825 |
| OVPNC3 | 0.529 | 0.764 | 0.734 | 0.794 | 0.824 |
| OVPN5 | 0.520 | 0.759 | 0.701 | 0.816 | 0.812 |
| BPFN5 | 0.517 | 0.757 | 0.703 | 0.811 | 0.822 |
| BPFC3 | 0.455 | 0.727 | 0.690 | 0.763 | 0.780 |
| OVPN4 | 0.451 | 0.725 | 0.693 | 0.757 | 0.776 |
| BPFN4 | 0.442 | 0.720 | 0.682 | 0.758 | 0.777 |
| OVPC3 | 0.437 | 0.718 | 0.689 | 0.747 | 0.771 |
| TOBN5 | 0.431 | 0.715 | 0.693 | 0.737 | 0.769 |
| TOBNC5 | 0.426 | 0.713 | 0.698 | 0.728 | 0.774 |
| TOBNC4 | 0.418 | 0.709 | 0.680 | 0.737 | 0.760 |
| TOBN4 | 0.384 | 0.692 | 0.677 | 0.707 | 0.747 |
| TOBNC3 | 0.380 | 0.690 | 0.690 | 0.690 | 0.738 |
| BPFN3 | 0.369 | 0.685 | 0.664 | 0.705 | 0.735 |
| OVPN3 | 0.356 | 0.678 | 0.653 | 0.703 | 0.727 |
| TOBC4 | 0.316 | 0.658 | 0.650 | 0.667 | 0.717 |
| TOBN3 | 0.311 | 0.656 | 0.646 | 0.665 | 0.706 |
| TOBC5 | 0.306 | 0.653 | 0.636 | 0.669 | 0.698 |
| TOBC3 | 0.283 | 0.641 | 0.624 | 0.658 | 0.671 |

**Table S7.** Performance of the 51 individual feature descriptors with SVM classifier on the benchmarking dataset during 10-fold CV, where the descriptors are ranked according to the accuracy.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Descriptor** | **MCC** | **Accuracy** | **Sensitivity** | **Specificity** | **AUC** |
| H8 | 0.628 | 0.813 | 0.768 | 0.858 | 0.877 |
| H5 | 0.627 | 0.809 | 0.731 | 0.888 | 0.881 |
| H11 | 0.624 | 0.807 | 0.714 | 0.899 | 0.881 |
| DPC | 0.606 | 0.802 | 0.758 | 0.846 | 0.871 |
| BPFNC5 | 0.599 | 0.797 | 0.735 | 0.860 | 0.870 |
| BPFNC4 | 0.585 | 0.792 | 0.756 | 0.828 | 0.855 |
| H2 | 0.586 | 0.789 | 0.708 | 0.871 | 0.866 |
| BPFC5 | 0.578 | 0.785 | 0.705 | 0.865 | 0.859 |
| H20 | 0.565 | 0.783 | 0.771 | 0.794 | 0.843 |
| H17 | 0.559 | 0.779 | 0.770 | 0.789 | 0.844 |
| H18 | 0.553 | 0.777 | 0.777 | 0.777 | 0.841 |
| H6 | 0.554 | 0.776 | 0.734 | 0.818 | 0.842 |
| H14 | 0.552 | 0.776 | 0.765 | 0.788 | 0.841 |
| H15 | 0.550 | 0.775 | 0.773 | 0.777 | 0.840 |
| H7 | 0.549 | 0.774 | 0.766 | 0.783 | 0.832 |
| H9 | 0.549 | 0.774 | 0.766 | 0.783 | 0.840 |
| H13 | 0.549 | 0.774 | 0.766 | 0.783 | 0.830 |
| H12 | 0.548 | 0.774 | 0.766 | 0.782 | 0.833 |
| BPFNC3 | 0.555 | 0.773 | 0.680 | 0.865 | 0.844 |
| H19 | 0.546 | 0.773 | 0.765 | 0.781 | 0.829 |
| OVPC5 | 0.561 | 0.772 | 0.651 | 0.894 | 0.842 |
| OVPNC5 | 0.556 | 0.772 | 0.671 | 0.873 | 0.839 |
| AAC | 0.544 | 0.771 | 0.730 | 0.813 | 0.838 |
| H1 | 0.536 | 0.767 | 0.725 | 0.809 | 0.833 |
| OVPNC4 | 0.537 | 0.767 | 0.710 | 0.824 | 0.831 |
| H16 | 0.536 | 0.767 | 0.717 | 0.816 | 0.824 |
| BPFC4 | 0.561 | 0.766 | 0.608 | 0.924 | 0.836 |
| H4 | 0.535 | 0.766 | 0.717 | 0.815 | 0.822 |
| AAI | 0.531 | 0.766 | 0.755 | 0.777 | 0.826 |
| H10 | 0.531 | 0.766 | 0.757 | 0.774 | 0.827 |
| CTD | 0.525 | 0.760 | 0.685 | 0.835 | 0.821 |
| H3 | 0.515 | 0.757 | 0.750 | 0.765 | 0.824 |
| OVPNC3 | 0.509 | 0.753 | 0.700 | 0.806 | 0.821 |
| OVPC4 | 0.516 | 0.750 | 0.628 | 0.873 | 0.817 |
| OVPN5 | 0.510 | 0.747 | 0.623 | 0.871 | 0.808 |
| BPFC3 | 0.471 | 0.734 | 0.686 | 0.783 | 0.784 |
| BPFN4 | 0.496 | 0.731 | 0.548 | 0.914 | 0.784 |
| BPFN5 | 0.524 | 0.728 | 0.481 | 0.975 | 0.827 |
| OVPC3 | 0.451 | 0.725 | 0.688 | 0.762 | 0.773 |
| OVPN4 | 0.448 | 0.722 | 0.663 | 0.782 | 0.777 |
| TOBNC5 | 0.429 | 0.713 | 0.659 | 0.767 | 0.765 |
| TOBN5 | 0.425 | 0.711 | 0.646 | 0.776 | 0.760 |
| TOBNC4 | 0.419 | 0.709 | 0.681 | 0.737 | 0.759 |
| BPFN3 | 0.404 | 0.700 | 0.627 | 0.773 | 0.737 |
| TOBNC3 | 0.374 | 0.687 | 0.662 | 0.712 | 0.739 |
| OVPN3 | 0.362 | 0.676 | 0.559 | 0.793 | 0.719 |
| TOBN3 | 0.344 | 0.672 | 0.668 | 0.676 | 0.709 |
| TOBC5 | 0.330 | 0.665 | 0.648 | 0.681 | 0.709 |
| TOBN4 | 0.394 | 0.664 | 0.389 | 0.940 | 0.669 |
| TOBC4 | 0.314 | 0.654 | 0.555 | 0.753 | 0.692 |
| TOBC3 | 0.294 | 0.646 | 0.578 | 0.713 | 0.701 |

**Table S8.** Performance of the 51 individual feature descriptors with GB classifier on the benchmarking dataset during 10-fold CV, where the descriptors are ranked according to the accuracy.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Descriptor** | **MCC** | **Accuracy** | **Sensitivity** | **Specificity** | **AUC** |
| H11 | 0.619 | 0.809 | 0.795 | 0.824 | 0.861 |
| H8 | 0.615 | 0.807 | 0.789 | 0.826 | 0.867 |
| H17 | 0.612 | 0.805 | 0.762 | 0.848 | 0.867 |
| H5 | 0.609 | 0.805 | 0.790 | 0.819 | 0.863 |
| H14 | 0.607 | 0.802 | 0.760 | 0.845 | 0.864 |
| H20 | 0.603 | 0.801 | 0.759 | 0.842 | 0.867 |
| H9 | 0.595 | 0.796 | 0.750 | 0.842 | 0.853 |
| H18 | 0.594 | 0.796 | 0.757 | 0.836 | 0.860 |
| H2 | 0.592 | 0.796 | 0.785 | 0.806 | 0.856 |
| DPC | 0.590 | 0.795 | 0.797 | 0.793 | 0.851 |
| H12 | 0.591 | 0.795 | 0.760 | 0.829 | 0.851 |
| BPFNC5 | 0.588 | 0.794 | 0.780 | 0.808 | 0.852 |
| H15 | 0.590 | 0.794 | 0.754 | 0.835 | 0.862 |
| H19 | 0.589 | 0.793 | 0.743 | 0.843 | 0.852 |
| H7 | 0.583 | 0.790 | 0.748 | 0.832 | 0.846 |
| H10 | 0.581 | 0.790 | 0.754 | 0.826 | 0.855 |
| H16 | 0.579 | 0.789 | 0.751 | 0.826 | 0.847 |
| H13 | 0.576 | 0.786 | 0.738 | 0.835 | 0.850 |
| BPFNC4 | 0.566 | 0.783 | 0.765 | 0.801 | 0.846 |
| H1 | 0.566 | 0.783 | 0.753 | 0.813 | 0.833 |
| AAC | 0.563 | 0.782 | 0.762 | 0.801 | 0.828 |
| AAI | 0.558 | 0.779 | 0.761 | 0.796 | 0.827 |
| OVPC5 | 0.558 | 0.778 | 0.738 | 0.818 | 0.831 |
| H3 | 0.557 | 0.778 | 0.756 | 0.801 | 0.833 |
| BPFC5 | 0.556 | 0.778 | 0.746 | 0.809 | 0.828 |
| OVPNC5 | 0.558 | 0.778 | 0.733 | 0.823 | 0.837 |
| H6 | 0.550 | 0.775 | 0.757 | 0.793 | 0.825 |
| CTD | 0.549 | 0.774 | 0.742 | 0.806 | 0.839 |
| H4 | 0.550 | 0.774 | 0.728 | 0.819 | 0.836 |
| OVPNC4 | 0.538 | 0.768 | 0.737 | 0.800 | 0.825 |
| BPFNC3 | 0.531 | 0.766 | 0.753 | 0.779 | 0.817 |
| BPFC4 | 0.525 | 0.762 | 0.723 | 0.801 | 0.821 |
| OVPC4 | 0.517 | 0.758 | 0.731 | 0.785 | 0.790 |
| OVPNC3 | 0.518 | 0.758 | 0.719 | 0.797 | 0.811 |
| BPFN5 | 0.503 | 0.751 | 0.725 | 0.778 | 0.796 |
| OVPN5 | 0.502 | 0.750 | 0.717 | 0.783 | 0.779 |
| BPFC3 | 0.427 | 0.713 | 0.691 | 0.735 | 0.735 |
| OVPN4 | 0.426 | 0.713 | 0.701 | 0.725 | 0.745 |
| BPFN4 | 0.422 | 0.711 | 0.696 | 0.726 | 0.748 |
| TOBNC5 | 0.415 | 0.708 | 0.690 | 0.725 | 0.754 |
| OVPC3 | 0.413 | 0.707 | 0.682 | 0.731 | 0.717 |
| TOBN5 | 0.408 | 0.704 | 0.707 | 0.701 | 0.730 |
| TOBNC4 | 0.398 | 0.699 | 0.679 | 0.719 | 0.743 |
| TOBN4 | 0.374 | 0.687 | 0.680 | 0.693 | 0.721 |
| TOBNC3 | 0.356 | 0.678 | 0.679 | 0.677 | 0.713 |
| BPFN3 | 0.351 | 0.675 | 0.655 | 0.696 | 0.707 |
| OVPN3 | 0.328 | 0.664 | 0.634 | 0.693 | 0.688 |
| TOBC5 | 0.300 | 0.650 | 0.632 | 0.668 | 0.685 |
| TOBN3 | 0.276 | 0.638 | 0.623 | 0.653 | 0.660 |
| TOBC4 | 0.270 | 0.635 | 0.641 | 0.629 | 0.658 |
| TOBC3 | 0.266 | 0.633 | 0.599 | 0.666 | 0.644 |

**Table S9.** Performance of the 51 individual feature descriptors with AB classifier on the benchmarking dataset during 10-fold CV, where the descriptors are ranked according to the accuracy.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Descriptor** | **MCC** | **Accuracy** | **Sensitivity** | **Specificity** | **AUC** |
| H15 | 0.537 | 0.768 | 0.778 | 0.759 | 0.770 |
| H9 | 0.524 | 0.762 | 0.771 | 0.753 | 0.763 |
| H20 | 0.519 | 0.760 | 0.759 | 0.760 | 0.760 |
| H18 | 0.518 | 0.759 | 0.758 | 0.760 | 0.760 |
| H14 | 0.509 | 0.755 | 0.757 | 0.753 | 0.755 |
| H17 | 0.509 | 0.755 | 0.757 | 0.753 | 0.755 |
| H7 | 0.508 | 0.754 | 0.732 | 0.776 | 0.755 |
| H10 | 0.508 | 0.754 | 0.732 | 0.776 | 0.755 |
| H12 | 0.508 | 0.754 | 0.732 | 0.776 | 0.755 |
| BPFNC5 | 0.495 | 0.748 | 0.733 | 0.762 | 0.748 |
| CTD | 0.490 | 0.745 | 0.742 | 0.748 | 0.745 |
| H13 | 0.490 | 0.745 | 0.745 | 0.745 | 0.745 |
| H16 | 0.490 | 0.745 | 0.745 | 0.745 | 0.745 |
| H19 | 0.490 | 0.745 | 0.745 | 0.745 | 0.745 |
| OVPNC5 | 0.487 | 0.743 | 0.704 | 0.781 | 0.743 |
| H4 | 0.482 | 0.741 | 0.743 | 0.739 | 0.742 |
| H5 | 0.479 | 0.739 | 0.727 | 0.751 | 0.743 |
| H8 | 0.479 | 0.739 | 0.727 | 0.751 | 0.743 |
| H11 | 0.479 | 0.739 | 0.727 | 0.751 | 0.743 |
| H1 | 0.478 | 0.739 | 0.716 | 0.761 | 0.737 |
| H3 | 0.478 | 0.739 | 0.716 | 0.761 | 0.737 |
| DPC | 0.477 | 0.734 | 0.638 | 0.830 | 0.741 |
| BPFC5 | 0.465 | 0.732 | 0.725 | 0.739 | 0.732 |
| H2 | 0.473 | 0.731 | 0.621 | 0.840 | 0.738 |
| AAC | 0.460 | 0.730 | 0.702 | 0.757 | 0.730 |
| AAI | 0.460 | 0.730 | 0.702 | 0.757 | 0.730 |
| H6 | 0.460 | 0.730 | 0.702 | 0.757 | 0.730 |
| BPFNC4 | 0.458 | 0.729 | 0.719 | 0.739 | 0.729 |
| BPFC4 | 0.454 | 0.727 | 0.703 | 0.750 | 0.727 |
| OVPNC4 | 0.451 | 0.725 | 0.681 | 0.768 | 0.725 |
| BPFNC3 | 0.442 | 0.721 | 0.694 | 0.747 | 0.721 |
| OVPC5 | 0.441 | 0.720 | 0.686 | 0.755 | 0.720 |
| OVPNC3 | 0.433 | 0.716 | 0.676 | 0.756 | 0.716 |
| BPFN5 | 0.416 | 0.708 | 0.679 | 0.736 | 0.708 |
| OVPC4 | 0.403 | 0.700 | 0.648 | 0.753 | 0.700 |
| OVPN5 | 0.391 | 0.694 | 0.648 | 0.740 | 0.694 |
| BPFC3 | 0.387 | 0.693 | 0.655 | 0.731 | 0.693 |
| OVPC3 | 0.361 | 0.678 | 0.596 | 0.760 | 0.678 |
| OVPN4 | 0.354 | 0.677 | 0.653 | 0.701 | 0.677 |
| TOBNC4 | 0.324 | 0.662 | 0.622 | 0.701 | 0.662 |
| BPFN4 | 0.323 | 0.661 | 0.627 | 0.696 | 0.661 |
| TOBNC5 | 0.316 | 0.658 | 0.631 | 0.685 | 0.657 |
| OVPN3 | 0.307 | 0.653 | 0.631 | 0.676 | 0.653 |
| TOBNC3 | 0.307 | 0.653 | 0.609 | 0.697 | 0.653 |
| TOBC5 | 0.300 | 0.650 | 0.613 | 0.686 | 0.648 |
| TOBN5 | 0.293 | 0.646 | 0.620 | 0.673 | 0.645 |
| TOBC4 | 0.292 | 0.645 | 0.599 | 0.691 | 0.645 |
| BPFN3 | 0.287 | 0.644 | 0.617 | 0.670 | 0.644 |
| TOBC3 | 0.273 | 0.636 | 0.607 | 0.666 | 0.636 |
| TOBN4 | 0.272 | 0.636 | 0.599 | 0.673 | 0.636 |
| TOBN3 | 0.257 | 0.628 | 0.586 | 0.670 | 0.628 |

**Table S10.** Performance of the 51 individual feature descriptors with *k*-NN classifier on the benchmarking dataset during 10-fold CV, where the descriptors are ranked according to the accuracy.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Descriptor** | **MCC** | **Accuracy** | **Sensitivity** | **Specificity** | **AUC** |
| H6 | 0.517 | 0.757 | 0.698 | 0.816 | 0.817 |
| AAC | 0.498 | 0.749 | 0.715 | 0.782 | 0.819 |
| H5 | 0.503 | 0.744 | 0.627 | 0.862 | 0.815 |
| H1 | 0.486 | 0.742 | 0.682 | 0.801 | 0.807 |
| H11 | 0.486 | 0.740 | 0.671 | 0.809 | 0.813 |
| OVPNC5 | 0.474 | 0.736 | 0.693 | 0.779 | 0.808 |
| H8 | 0.486 | 0.734 | 0.602 | 0.866 | 0.808 |
| DPC | 0.482 | 0.727 | 0.562 | 0.893 | 0.808 |
| OVPC5 | 0.454 | 0.726 | 0.690 | 0.762 | 0.791 |
| OVPNC3 | 0.446 | 0.721 | 0.658 | 0.784 | 0.783 |
| OVPNC4 | 0.445 | 0.721 | 0.670 | 0.772 | 0.794 |
| H2 | 0.446 | 0.721 | 0.664 | 0.779 | 0.780 |
| BPFNC5 | 0.446 | 0.717 | 0.830 | 0.605 | 0.824 |
| H7 | 0.427 | 0.713 | 0.747 | 0.679 | 0.781 |
| H12 | 0.427 | 0.713 | 0.748 | 0.678 | 0.782 |
| H9 | 0.426 | 0.713 | 0.680 | 0.745 | 0.778 |
| H14 | 0.426 | 0.713 | 0.678 | 0.747 | 0.778 |
| CTD | 0.425 | 0.712 | 0.676 | 0.748 | 0.778 |
| H17 | 0.425 | 0.712 | 0.676 | 0.748 | 0.781 |
| BPFNC4 | 0.432 | 0.711 | 0.816 | 0.607 | 0.807 |
| H10 | 0.423 | 0.711 | 0.675 | 0.747 | 0.779 |
| BPFC5 | 0.420 | 0.708 | 0.780 | 0.635 | 0.790 |
| BPFNC3 | 0.420 | 0.708 | 0.780 | 0.635 | 0.789 |
| AAI | 0.414 | 0.707 | 0.720 | 0.694 | 0.788 |
| H20 | 0.414 | 0.706 | 0.755 | 0.657 | 0.779 |
| BPFC4 | 0.409 | 0.704 | 0.736 | 0.673 | 0.778 |
| OVPC4 | 0.411 | 0.703 | 0.619 | 0.786 | 0.774 |
| H19 | 0.407 | 0.703 | 0.753 | 0.653 | 0.778 |
| H4 | 0.405 | 0.702 | 0.748 | 0.655 | 0.778 |
| H16 | 0.405 | 0.702 | 0.753 | 0.651 | 0.779 |
| H18 | 0.402 | 0.700 | 0.750 | 0.650 | 0.777 |
| H15 | 0.401 | 0.699 | 0.749 | 0.650 | 0.777 |
| H13 | 0.397 | 0.697 | 0.749 | 0.645 | 0.777 |
| OVPN5 | 0.372 | 0.686 | 0.671 | 0.700 | 0.758 |
| OVPC3 | 0.359 | 0.680 | 0.665 | 0.694 | 0.743 |
| H3 | 0.359 | 0.679 | 0.711 | 0.647 | 0.744 |
| TOBNC5 | 0.352 | 0.675 | 0.634 | 0.716 | 0.725 |
| BPFC3 | 0.349 | 0.675 | 0.667 | 0.682 | 0.744 |
| OVPN4 | 0.347 | 0.674 | 0.688 | 0.659 | 0.722 |
| BPFN4 | 0.340 | 0.669 | 0.715 | 0.623 | 0.723 |
| TOBNC4 | 0.337 | 0.668 | 0.633 | 0.703 | 0.719 |
| BPFN5 | 0.337 | 0.667 | 0.737 | 0.597 | 0.757 |
| TOBN5 | 0.326 | 0.662 | 0.711 | 0.613 | 0.710 |
| OVPN3 | 0.308 | 0.654 | 0.661 | 0.647 | 0.707 |
| TOBC5 | 0.300 | 0.650 | 0.646 | 0.654 | 0.701 |
| TOBN4 | 0.290 | 0.645 | 0.678 | 0.611 | 0.690 |
| TOBNC3 | 0.288 | 0.644 | 0.658 | 0.630 | 0.699 |
| TOBN3 | 0.285 | 0.642 | 0.671 | 0.613 | 0.675 |
| TOBC4 | 0.276 | 0.638 | 0.664 | 0.612 | 0.686 |
| TOBC3 | 0.270 | 0.635 | 0.616 | 0.654 | 0.695 |
| BPFN3 | 0.255 | 0.625 | 0.730 | 0.520 | 0.691 |

**Table S11.** List of feature importance score (FIS) by RF method

|  |  |  |
| --- | --- | --- |
| **Rank** | **Feature identifier** | **FIS** |
| 1 | F28 | 0.763 |
| 2 | F47 | 0.757 |
| 3 | F39 | 0.577 |
| 4 | F18 | 0.525 |
| 5 | F15 | 0.487 |
| 6 | F41 | 0.380 |
| 7 | F3 | 0.317 |
| 8 | F14 | 0.280 |
| 9 | F10 | 0.269 |
| 10 | F7 | 0.263 |
| 11 | F4 | 0.248 |
| 12 | F49 | 0.240 |
| 13 | F6 | 0.227 |
| 14 | F13 | 0.185 |
| 15 | F0 | 0.157 |
| 16 | F36 | 0.155 |
| 17 | F31 | 0.155 |
| 18 | F44 | 0.155 |
| 19 | F9 | 0.152 |
| 20 | F38 | 0.152 |
| 21 | F25 | 0.149 |
| 22 | F23 | 0.146 |
| 23 | F11 | 0.144 |
| 24 | F34 | 0.141 |
| 25 | F40 | 0.132 |
| 26 | F43 | 0.129 |
| 27 | F45 | 0.126 |
| 28 | F26 | 0.125 |
| 29 | F50 | 0.122 |
| 30 | F30 | 0.121 |
| 31 | F27 | 0.118 |
| 32 | F5 | 0.116 |
| 33 | F24 | 0.116 |
| 34 | F19 | 0.115 |
| 35 | F46 | 0.114 |
| 36 | F33 | 0.114 |
| 37 | F48 | 0.113 |
| 38 | F42 | 0.113 |
| 39 | F1 | 0.111 |
| 40 | F20 | 0.108 |
| 41 | F2 | 0.107 |
| 42 | F21 | 0.107 |
| 43 | F16 | 0.105 |
| 44 | F37 | 0.105 |
| 45 | F22 | 0.103 |
| 46 | F8 | 0.098 |
| 47 | F17 | 0.094 |
| 48 | F35 | 0.092 |
| 49 | F12 | 0.092 |
| 50 | F32 | 0.092 |
| 51 | F29 | 0.090 |

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