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Scaffold hopping of potential anti-tumor agents by WEGA: a shape-based approach

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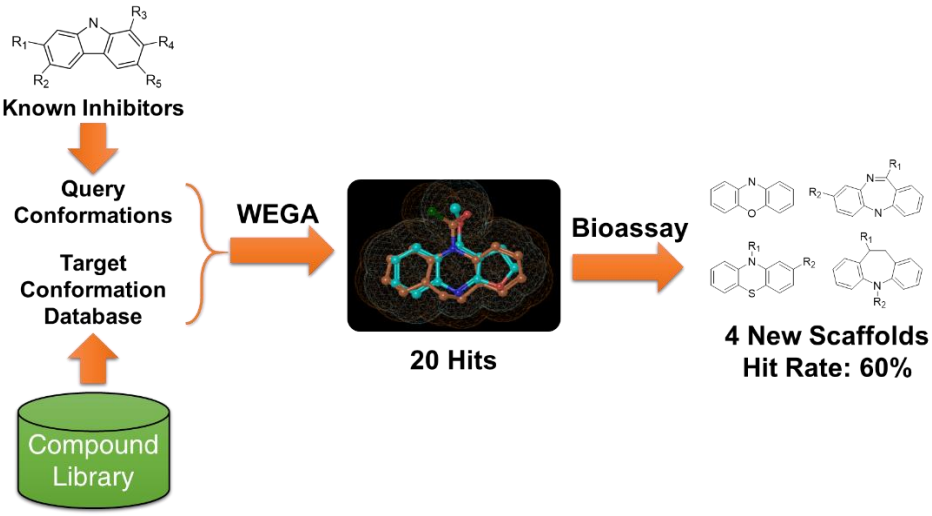

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Scaffold hopping of potential anti-tumor agents by WEGA: a shape-based approach

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In this paper, we describe the first prospective application of the shape-comparison program, WEGA (weighted Gaussian algorithm), to find new scaffolds for anti-tumor agents. A series of sixteen carbazole alkaloids extracted from Clausena vestita D. D. Tao, which have anti-tumor activities at the cellular level, were used as query molecules. A compound library was screened by ranking molecules based upon their 3D shape and pharmacophore similarities to known inhibitors. The relationship between the structures and activities were also studied through comparative molecular field analysis (CoMFA). Twelve hits show comparable growth inhibition activity against HepG2 cells (a hit rate of 60%); eight of the hits have new scaffolds (in comparison with known inhibitors). These results indicate that a shape-based screening approach, such as WEGA, can be efficiently used for scaffold hopping in a lead identification process.

Introduction

In lead optimization, systematic decoration of a common scaffold and bioisosteric replacement are the main techniques of structural variation. Scaffold hopping is an approach to generating novel chemical entities from known chemical frames. Since finding new, druggable scaffolds is a bottle-neck in the pharmaceutical development process, new scaffold hopping technology is demanded[1]. In this paper, we propose a new scaffold hopping technique that utilizes WEGA (weighted Gaussian algorithm)[2], a shape comparison program.

WEGA aligns chemical structures based upon three-dimensional shape and pharmacophore features. It is suitable for large-scale virtual screening with single or multiple bioactive compounds as the query "templates," regardless of whether corresponding experimentally determined conformations are available.

In our previous study, sixteen anti-cancer compounds were isolated from *Clausena vestita*, and their anti-tumor activities were evaluated via cell growth inhibition assays in our labs.[3] Those carbazole alkaloids share almost the same scaffolds. In this study, to identify potential anti-tumor agents based on the known inhibitors, and to discover new scaffolds, we employed WEGA for ligand-based scaffold hopping by screening the Guangdong small molecule tangible library (GSMTL)[4]. The results were confirmed through exactly the same *in vitro* experiments. A high hit rate and various new scaffolds demonstrate the applicability of scaffold hopping via WEGA. Furthermore, to understand the three-dimensional quantitative structure-activity relationship (3D-QSAR)[5], a comparative molecular field analysis (CoMFA) study was performed based on our results; CoMFA analysis is widely used for lead optimization when ligand-based information is available[6-13]. We hope that this study provides another alternative approach for scaffold hopping and will inspire the development of new anti-tumor agents.

We reported a data set of sixteen carbazole alkaloids[3] that are derived from *Clausena vestita D. D. Tao*. Their *in vitro* biological activity data were reported as IC_{50} values; this data was used in the current study (Table 1). The alkaloids' chemical structures are depicted in Figure 1. Their growth inhibition of HepG2 cells were converted to the corresponding pIC_{50} values using the formula (pIC_{50} = - log IC_{50}). Their activity was significantly affected by structural modifications within the carbazole skeleton (as revealed by the IC_{50} values of carbazole alkaloids).

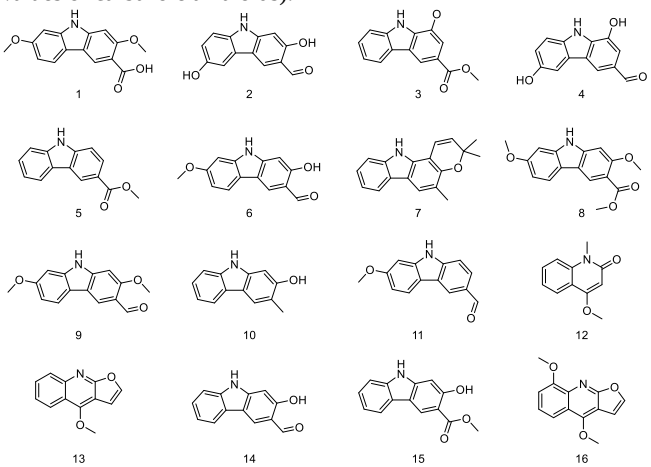

Figure 1. Chemical structures of the sixteen alkaloids isolated from *Clausena vestita D. D. Tao*.

Results and discussion

The virtual screening protocol by WEGA is depicted in Figure 2. First, 3D conformations were generated for both the query template (known inhibitors) and the target compound database. Following shape-based alignment, the similarities between the query and target molecules were calculated by WEGA. Highly scored compounds exhibiting similar shape/pharmacophore features with the known inhibitors were identified. The hits were further confirmed through *in vitro* bioassays detecting anti-tumor activity.

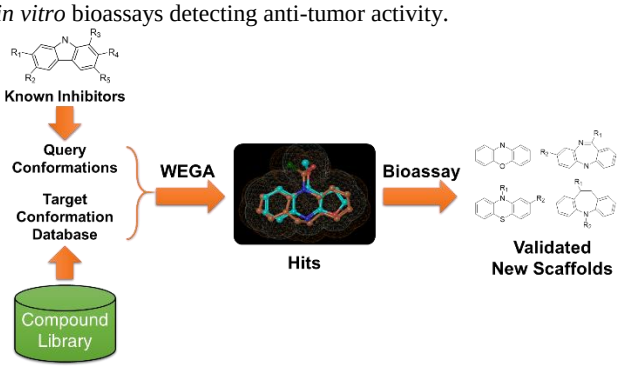

Figure 2. Schematic representation of WEGA's workflow for database virtual screening.

The eleven anti-tumor compounds (No. 1-6, 9-11, 13, 14) with exact IC_{50} values were used as query molecules in this study. Their chemical structures were drawn in ChemBioDraw Ultra 13.0, and converted into 3D conformations by using the ligand preparation protocol in Discovery Studio 3.5. Twenty 3D conformations were generated by means of the CAESAR[14] algorithm in Discovery Studio 3.5 for each query molecule.

The target database used in this study is GSMTL, which contains more than 7,200 annotated chemical compounds with purities > 95%. Most of the compounds are natural products; the rest are synthesized. The 2D chemical structures of all compounds in the library were drawn with ISIS/Draw and stored in an ISIS/Base database. Conformational ensembles (maximum size of 250) were also generated for each compound in the database through the CAESAR algorithm.

GSMTL was virtually screened with WEGA based upon the 3D conformations of the query molecules. To achieve the best shape alignment for each pair of molecules, four initial alignments were considered for the superposition optimization, and the best one was selected. Both heavy atoms and hydrogens were considered for representing the molecular shape. For each compound in the target database, all its conformations were calculated for similarity with all query molecules. The highest similarity score was kept as the final score for each compound in the target library. The top 20 compounds were then selected for further bioactivity validation.

To validate whether the WEGA approach could distinguish actives from random compounds, the self-similarity between actives (known inhibitors) were also calculated (the scores between the same molecules were excluded). The distribution of the relative frequencies of the WEGA scores of both actives and random compounds (GSMTL in this case) are depicted in Figure 3. The random compounds' scores have a normal distributions; most scores range from 0.2 to 0.6, while the actives' scores distribute mainly from 0.7 to 0.9. This indicates that the WEGA similarity calculation can discriminate actives from random compounds and that the WEGA score is suitable for selecting probable inhibitors.

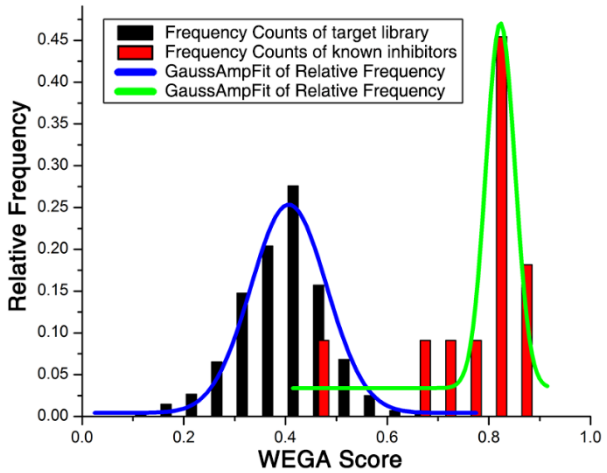

Figure 3. The distribution of the relative frequency for the WEGA scores between known inhibitors themselves as well as scores between random compounds and known inhibitors. An amplitude version of the Gaussian peak function was used for curve fitting.

With WEGA, the top 20 compounds from the target library with the most similar shapes and pharmacophore features (relative to the query molecules) were retrieved (Figure 4). Among these compounds, 4 hits have a carbazole scaffold (highlighted in Figure 4 at the top). This scaffold was already known from the training set. Sixteen hits have new scaffolds belonging to four compound classes, which were not reported. Figure 5 demonstrates two representative WEGA hits and their superimposed conformations.

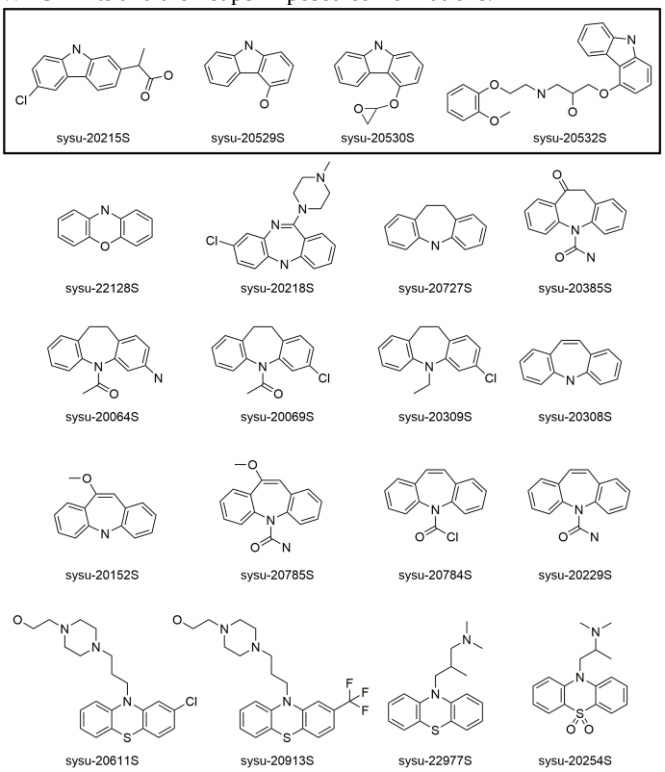

Figure 4. Chemical structures of the compounds identified by WEGA. Compounds with known carbazole scaffolds are highlighted.

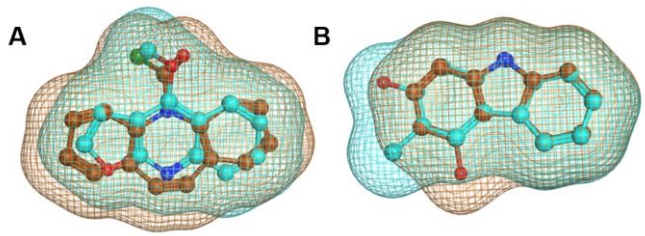

Figure 5. Two compounds retrieved by WEGA screening and their superposed conformations. (A) SYSU-20784 and 13 (B) SYSU-20530 and 10. The retrieved compounds are depicted in brown and the template molecules in cyan. The mesh surfaces indicate the molecular volumes.

Cell viability was determined using the Cell Counting Kit-8 (CCK-8) assay based on water-soluble tetrazolium salt (WST)-8. The top 20 compounds with new scaffolds were screened for potential anti-tumor activities on HepG2; 12 of them were confirmed through CCK8 experiments, with IC_{50} values ranging from 4 μM to 200 μM. Therefore, the confirmed hit rate was 60% (12/20). The experimental pIC_{50} values are also listed in Table 1. Besides the carbazole scaffold, a phenothiazine-like compound, SYSU-20913S, exhibits comparably high potency (4.4 μM). The other scaffolds were also confirmed for their anti-proliferative activities. Details of the names and scaffolds of the 12 active hits were supplied in Table S1.

Table 1. Anti-proliferative activity of the known compounds and the WEGA hits.

Known Compounds		**Screened Hits**	
ID	pIC_{50}[b]	**ID**	pIC_{50}
1	4.61	sysu-20064S	<3.80[a]
2	4.48	sysu-20069S	<3.80[a]
3	4.80	sysu-20152S	4.15
4	3.87	sysu-20215S	3.78
5	4.43	sysu-20218S	4.32
6	4.54	sysu-20229S	<3.80[a]
7	<3.80[a]	sysu-20254S	<3.80[a]
8	<3.80[a]	sysu-20308S	<3.80[a]
9	3.99	sysu-20309S	<3.80[a]
10	4.84	sysu-20385S	4.71
11	5.37	sysu-20529S	3.91
12	<3.80[a]	sysu-20530S	4.77
13	4.26	sysu-20532S	4.76
14	4.18	sysu-20611S	4.79
15	<3.80[a]	sysu-20727S	<3.80[a]
16	<3.80[a]	sysu-20784S	4.47
		sysu-20785S	<3.80[a]
		sysu-20913S	5.36
		sysu-22128S	3.69
		sysu-22977S	4.21

[a] The mean IC_{50} value could not be determined as one or more of the corresponding data points was higher than the threshold value (160 μM). [b] $pIC_{50}=\log_{10}(1/IC_{50})$

The structural and activity information of all 36 (16+20) compounds were used to build a 3D-QSAR model via CoMFA. Their structures were generated and optimized through the energy minimization module in the Molecular Operating Environment (MOE) v2012.10 (Chemical Computing Group) with the MMFF94 force field. The energy minimized conformation of the most active compound 11 was chosen as the putative bioactive conformation. After, all the other compounds were aligned, through WEGA, based on template compound 11. The aligned poses were further refined through the flexible alignment module in MOE and Schrodinger 2013.1. The aligned conformations were shown in Figure 6.

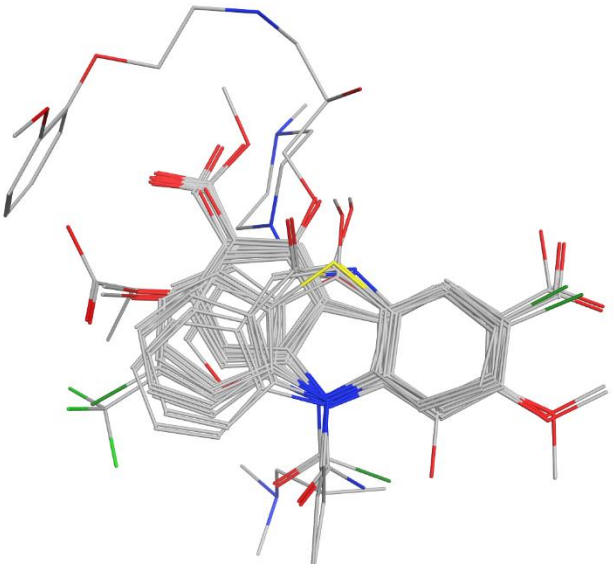

Figure 6. The superposition of the 36 compounds for CoMFA.

The CoMFA model was built as described in the references[15, 16] with minor modifications. The steric (Lennard-Jones potential) and electrostatic (Columbic potential) field energies were calculated from a standard Tripos force field. An atom having the van der Waals radius of a sp^3-hybridized carbon with one formal positive charge was used as a probe. A lattice with 0.5 Å grid spacing, and which extended at least 1 Å in each direction beyond the aligned molecules, was generated. The truncation for both steric and electrostatic energies was set at 30.00 kcal/mol and the electrostatic contributions were ignored at the lattice intersections with maximum steric interactions.

Partial least squares (PLS)[17] regression analysis was used to explore a quantitative relationship between molecular descriptors and biological activities. All regression analyses were done in SYBYL-X 2.0. The leave-one-out (LOO) cross-validation, with a column filtering of a certain value, was performed to determine the optimum number of principal components. The cross-validated regression coefficient R^2_{cv} suggests the robustness and predictive ability of the derived models[18]. According to a commonly recognized statistical standard, a reliable QSAR model should have an $R^2_{cv} \geq 0.5$[19]. Then, non-cross-validation was carried out to derive the final PLS regression models with the conventional correlation coefficient r^2 and the standard error of estimate. The region focusing method[20] was performed to enhance the resolution and predictive ability of the derived model; this refined the model by increasing the weight for those lattice points pertinent to the model.

The final CoMFA model achieved a cross-validated correlation coefficient (q^2) of 0.609 with 7 principal components. The non-cross-validated PLS analysis generated a high conventional correlation coefficient (r^2) of 0.978, with a standard estimated error of 0.239. The Fischer's F value for test of significance is 178.746.

The relative contributions to this CoMFA model were 48% for the steric field and 52% for the electrostatic field. Detailed activity data are described in Table S2.

The effects of all field descriptors contributing to bioactivity can be partitioned and viewed as CoMFA 3D coefficient contour plots as shown in Figure 7 with compound 11 (7-methoxy-9*H*-carbazole-3-carbaldehyde) as an example. In Figure 7A, plots in blue and red represent the positions can be substituted with electropositive and negative groups to improve the activity. In Figure 7B, plots in green and yellow represent the positions can be substituted with bulky and slim groups to improve the activity.

In case of compound 11, if site 1-, 2-, or 8- was substituted with an electropositive group, the activity would increase; if site 3-, 4-, or 9- was substituted with electronegative group, the activity would increase as well. Bulkier groups are favorable on position 1-, 3-, and 9-, slimmer groups are good for positions 2- and 4- (Figure 7).

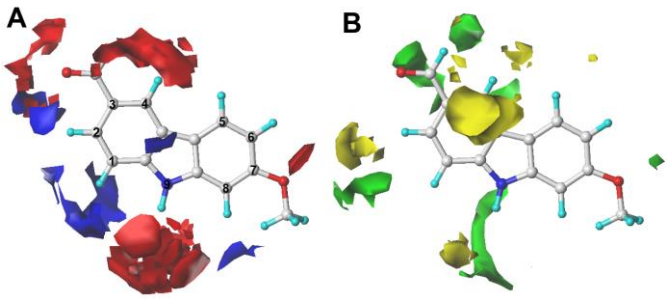

Figure 7. The CoMFA contour maps, with compound 11 as the reference. Green and yellow refer to the sterically favored and disfavored areas, respectively, whereas blue and red contours refer to regions where electropositive substituents are favorable and unfavorable, respectively.

To evaluate the selectivity of these agents, we estimated the cytotoxic effect of five active hits, on the normal liver cell line LO2 (Table S3). Their IC50 values on LO2 cells were either undetectable or much higher than those on HepG2 tumor cells, indicating a much lower cytotoxic effect on the normal cell line.

To determine whether this computational approach can truly enrich the yield of actives, we have conducted a control experiment. We randomly selected 20 compounds from the negative hits concluded by WEGA. Then, we tested the 20 compounds with anti-proliferative assay. Only 2 compounds showed detectable activities. The data are listed in Table S4 (Supplemental material).

Conclusion

In summary, this letter reported the first application of WEGA for identifying potential anti-tumor agents based on the known inhibitors; the results led to the discovery of even new scaffolds. A ligand-based scaffold hopping protocol was proved successful by the virtual screening of the GSMTL and by *in vitro* anti-tumor experiments. The high hit rate and various new scaffolds demonstrate the applicability of scaffold hopping by WEGA. Furthermore, the CoMFA study we performed provide additional information for future lead-optimization possibilities with respect to this series of anti-tumor compounds, and may inspire the development of new anti-tumor agents.

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Abbreviations

WEGA, weighted Gaussian algorithm; 3D-QSAR, three-dimensional quantitative structure-activity relationship; CoMFA, comparative molecular field analysis; GSMTL, Guangdong small molecule tangible library; CCK-8, Cell Counting Kit-8; MOE, Molecular Operating Environment; PLS, partial least squares; LOO, leave-one-out;

Notes and references

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