

A Pharmacophore-Based Evolutionary Approach for Screening Selective Estrogen Receptor Modulators

Jinn-Moon Yang* and Tsai-Wei Shen

Department of Biological Science and Technology, and Institute of Bioinformatics, National Chiao Tung University, Hsinchu, Taiwan

ABSTRACT We developed a pharmacophore-based evolutionary approach for virtual screening. This tool, termed the Generic Evolutionary Method for molecular DOCKing (GEMDOCK), combines an evolutionary approach with a new pharmacophore-based scoring function. The former integrates discrete and continuous global search strategies with local search strategies to expedite convergence. The latter, integrating an empirical-based energy function and pharmacological preferences (binding-site pharmacological interactions and ligand preferences), simultaneously serves as the scoring function for both molecular docking and postdocking analyses to improve screening accuracy. We apply pharmacological interaction preferences to select the ligands that form pharmacological interactions with target proteins, and use the ligand preferences to eliminate the ligands that violate the electrostatic or hydrophilic constraints. We assessed the accuracy of our approach using human estrogen receptor (ER) and a ligand database from the comparative studies of Bissantz et al. (*J Med Chem* 2000;43:4759–4767). Using GEMDOCK, the average goodness-of-hit (GH) score was 0.83 and the average false-positive rate was 0.13% for ER antagonists, and the average GH score was 0.48 and the average false-positive rate was 0.75% for ER agonists. The performance of GEMDOCK was superior to competing methods such as GOLD and DOCK. We found that our pharmacophore-based scoring function indeed was able to reduce the number of false positives; moreover, the resulting pharmacological interactions at the binding site, as well as ligand preferences, were important to the screening accuracy of our experiments. These results suggest that GEMDOCK constitutes a robust tool for virtual database screening. *Proteins* 2005;59:205–220.

© 2005 Wiley-Liss, Inc.

Key words: estrogen receptor; evolutionary approach; hot spots; pharmacophore-based scoring function; SERMs; virtual screening

INTRODUCTION

Virtual screening (VS) of molecular compound libraries has emerged as a powerful and inexpensive method for the discovery of novel lead compounds for drug develop-

ment.^{1,2} Given the structure of a target protein active site and a potential small ligand database, VS predicts the binding mode and the binding affinity for each ligand and ranks a series of candidate ligands. There are 4 main reasons for the rapid acceptance and success of VS: (1) the availability of the growing number of protein crystal structures; (2) the advent of structural proteomics technologies; (3) the enrichment and speed of VS^{1,3}; and (4) the contribution of VS to the reduction in the cost of drug discovery. VS generally encompasses 4 phases based on both high-throughput molecular docking methods and the crystal structures of the target protein. These include target protein preparation, compound database preparation, molecular docking, and postdocking analysis.¹ The molecular docking method screens the compound library to find lead compounds for the target protein, whereas postdocking analysis enriches the hit rate and optimizes the confirmed lead molecules through structure–activity relationship.⁴

The VS computational method involves 2 basic critical elements: efficient molecular docking and a reliable scoring method. A molecular docking method for VS should be able to screen a large number of potential ligands with reasonable accuracy and speed. The many molecular docking approaches that have been developed can be roughly categorized as rigid docking,⁵ flexible ligand docking,^{6,7} and protein flexible docking. Most current VS methods employ flexible docking tools, such as incremental and fragment-based approaches (DOCK⁸ and FlexX⁷) and evolutionary algorithms (GOLD,⁶ AutoDock,⁹ and GEMDOCK¹⁰).

Scoring methods for VS should effectively discriminate between correct binding states and non-native docked conformations during the molecular docking phase and distinguish a small number of active compounds from hundreds of thousands of nonactive compounds during the postdocking analysis. The scoring functions that calculate

Grant sponsor: National Science Council of Taiwan; Grant numbers: NSC-92-2113-M-009-024 and NSC-93-2113-M-009-010. Grant sponsor: Veterans General Hospitals, University System of Taiwan; Grant number: VGHUST93-G5-05-3.

*Correspondence to: Jinn-Moon Yang, Department of Biological Science and Technology, and Institute of Bioinformatics, National Chiao Tung University, Hsinchu, 30050, Taiwan. E-mail: moon@cc.nctu.edu.tw

Received 9 June 2004; Accepted 18 October 2004

Published online 22 February 2005 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/prot.20387

the binding free energy mainly include knowledge-based,¹¹ physics-based,¹² and empirical-based¹³ scoring functions. The performance of these scoring functions is often inconsistent across different systems from a database search.^{14,15} It has been proposed that combining multiple scoring functions (consensus scoring) improves the enrichment of true positives.^{14,15}

While the field of VS may be maturing,¹⁻³ and many good VS methods have been proposed, the promise of the virtual compound library¹⁶ to rapidly increase the number of candidate ligands demands further improvement in terms of the computational efficiency of flexible docking algorithms.^{6,7,9} In addition, some VS methods are capable of identifying so-called "pharmacological preferences" that are often the important interactions or binding-site hot spots typically evolved from known active ligands and the target protein.^{17,18} These preferences might improve screening accuracy and guide the design and selection of lead compounds for subsequent investigation and refinement during lead discovery and lead optimization processes. Finally, the screening quality of docking methods using energy-based scoring functions alone is often influenced by the molecular weight and the structure of the ligand being screened (e.g., the numbers of charged and polar atoms). These methods are often biased toward both the selection of high molecular weight compounds (due to the contribution of the compound size^{19,20}) and charged polar compounds (due to the pair-atom potentials of the electrostatic energy and hydrogen-bonding energy).

To address the above issues, we developed a new VS method, termed GEMDOCK (Generic Evolutionary Method for molecular DOCKing), modified from our previous studies.^{10,21} GEMDOCK is an evolutionary-based approach that was applied in some fast VS algorithms.^{6,9} Our approach uses multiple operators (e.g., discrete and continuous genetic operators) that cooperate using family competition (similar to a local search procedure) to balance exploration and exploitation. Like some VS methods,^{18,22,23} GEMDOCK evolves the pharmacological preferences from a number of known active ligands to take advantage of the similarity of a putative ligand to those that are known to bind to a protein's active site, thereby guiding the docking of the putative ligand. However, unlike existing pharmacophore-based docking methods, we developed and incorporated a new scoring function that evolves a pharmacological consensus (e.g., hot spots) and ligand preferences using the target protein and known active ligands. This scoring function not only serves as the basis for molecular docking but also ranks the screened ligands prior to postdocking analysis by reducing the deleterious effect of certain structural features within some of the ligands.

While GEMDOCK is generally applicable, in particular, it has been validated by its application to the docking of a number of selective estrogen receptor modulators (SERMs) that are of great interest in cancer chemotherapy, as well as estrogen replacement therapy in postmenopausal women.²⁴⁻²⁶ To evaluate the strengths and limitations of GEMDOCK, and to compare it with several widely used methods (DOCK, GOLD, and FlexX), we evaluated the

screening utility of GEMDOCK by testing human estrogen receptor (ER) with the ligand data set, as proposed by Bissantz et al.¹⁴ We also assessed whether our new scoring function was applicable to both the molecular docking and ligand scoring during VS. The screening performance of GEMDOCK on this ligand data set is superior to that of the best available methods, and the docking accuracy is also comparable. Thus, GEMDOCK constitutes a rapid method that reduces the number of false positives during the screening of large databases when both pharmacological interactions and ligand preferences are mined from known active compounds. When known active ligands are not available, the screening accuracy of GEMDOCK is somewhat influenced and is comparable to that of comparative methods on this ligand data set.

MATERIALS AND METHODS

GEMDOCK was modified and enhanced from our previous tool¹⁰ for VS (Fig. 1). GEMDOCK can be sequentially applied to prepare target proteins and ligand databases, predict docked conformations and binding affinity using flexible ligand docking, and rank a series of candidates for postdocking analysis. Several programs were developed separately for each phase, and Linux shell script was used to integrate these programs and automate the process. In this section, we give details of the ligand database and target protein preparations, outline the scoring function used in this study, describe details of mining binding-site pharmacological interactions (e.g., hot spots) and ligand preferences, and briefly describe the docking method.

Preparations of Ligand Databases and Target Proteins

SERMs exert their physiological effects by binding to the 2 currently known estrogen receptors (ER α or ER β), which are members of the nuclear receptor superfamily of ligand-dependent transcription factors; moreover, SERMs display tissue-selective estrogen agonistic or antagonistic profiles.²⁴⁻²⁶ SERMs often beneficially affect the cardiovascular and central nervous systems, and exert significant estrogenlike effects on some estrogen targets such as bone, lipid, breast, and uterine cells. Despite the benefits of SERMs, long-term treatment with SERMs is often limited by intolerable side effects, such as benign and malignant uterine lesions. Therefore, the design of new SERMs has become a challenging task.

We used the ligand data set and initial ligand conformation from the comparative studies of Bissantz et al.¹⁴ (e.g., DOCK, FlexX, and GOLD) to evaluate the screening accuracy of GEMDOCK using the ER antagonists. The ligand data set included the 10 known active compounds (EST01-EST10) listed in Figure 2 and 990 randomly chosen compounds from the Available Chemical Directory (ACD). The data set is available on the Web at <http://gemdock.life.nctu.edu.tw/dock/download.php>. For screening ER agonists, a set of 10 known ER agonists (Fig. 3, ESA01-ESA10) used in this study was identical to that reported earlier.²⁷ In total, the database used for screening ligands against the ER-antagonist complex [Protein

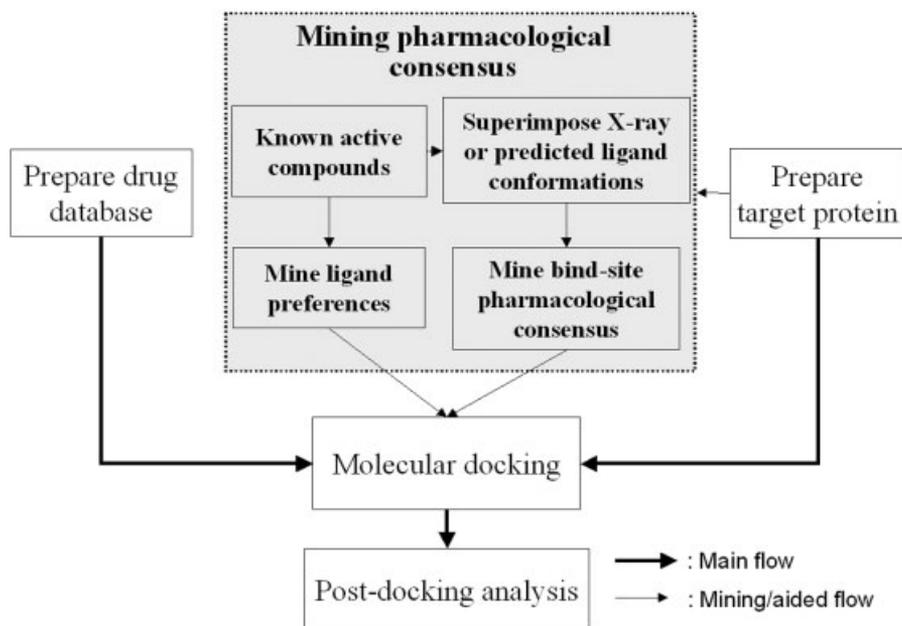


Fig. 1. The main steps of GEMDOCK for virtual database screening, including the target protein and compound database preparation, flexible docking, and postdocking analysis. GEMDOCK mines a pharmacological consensus from the target protein and known active ligands when available.

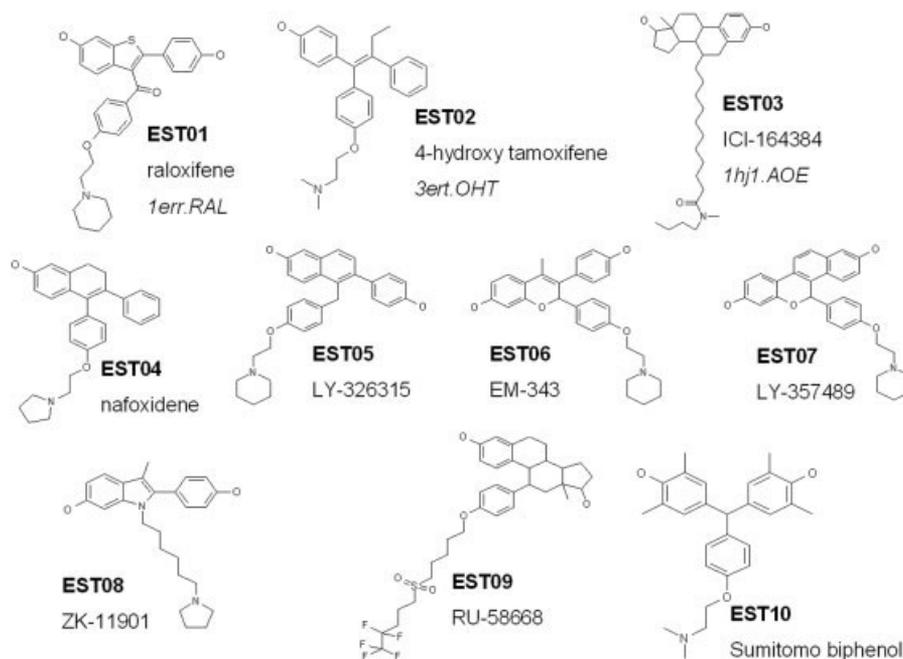


Fig. 2. Ten known ER antagonists are studied with respect to evolving the pharmacological consensus and docking against the ER-antagonist complex. Three ligands, EST01–EST03, are obtained from the PDB and each ligand is denoted by 4 characters followed by 3 characters, as in the PDB (e.g., 3ert.OHT, “3ert” denotes the PDB code and “OHT” is the ligand name in the PDB).

Data Bank (PDB) code: 3ert^{26]} and ER-agonist complex (PDB code: 1gwr^{28]}) contained 1000 molecules; that is, 990 random compounds were the same for the 2 screens. In addition, 3 ER-antagonist complexes (PDB codes: 1err, 3ert, and 1hj1) and 4 ER-agonist complexes (PDB codes: 1gwr, 1l2i, 1qkm, and 3erd) with experimentally deter-

mined X-ray structures from the PDB were selected to evaluate not only the docking accuracy but also the pharmacological consensus evolved from known active ligands (i.e., Figs. 2 and 3) and reference proteins (Fig. 4). Each ligand from the PDB was represented systematically by 4 characters followed by 3 characters. For example, in

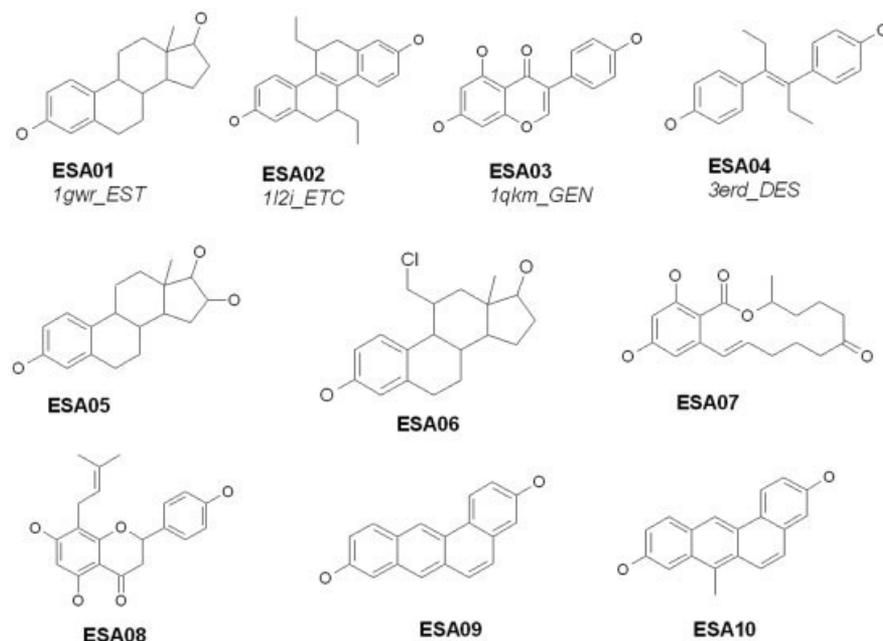


Fig. 3. Ten known ER agonists are docked against the ER-agonist complex (PDB code: 1gwr), and the pharmacological consensus is evolved. Four ligands, ESA01–ESA04, are obtained from the PDB, and each ligand is represented by 4 characters followed by 3 characters in the PDB.

the ligand “3ert.OHT,” “3ert” denotes the PDB code and “OHT” is the ligand code in the PDB. These ligand structures are shown in Figure 2 (e.g., EST01, EST02, and EST03) and Figure 3 (e.g., ESA01, ESA02, ESA03, and ESA04).

The ER-antagonist complex (PDB code: 3ert) and ER-agonist complex (PDB code: 1gwr) were selected as reference proteins for virtual screening. These complexes were reasonable choices, because their ligand-binding cavities are wide enough to accommodate a broad variety of ligands and therefore did not require binding-site modifications. As shown in Figure 4, the structures of these 2 reference proteins complexed with tamoxifen (3ert) or estradiol (1gwr) show that both ligands bind at the same site within the core of the ligand-binding domain and that each ligand induces a different conformation of helix 12 (H12). Comparison of the structures of these 2 complexes reveals that the H12 (blue) sits above the ligand-binding cavity in the ER-agonist complex (1gwr), thereby forming a lid. In contrast, the side-chains of antagonists (e.g., tamoxifen and raloxifene) in the ER-antagonist complexes prevent the agonistlike induced conformational change of H12 (green), projecting out of the ligand-binding pocket. When preparing the size and location of the ligand-binding site, we considered the protein atoms located less than 10 Å from each ligand atom. The metal atoms were retained, and all structured water molecules were removed from the active site. GEMDOCK then assigned a formal charge and atom type for each protein atom based on our previous study.¹⁰

Scoring Function

We developed a new scoring function that simultaneously serves as the scoring function for both molecular

docking and the ranking of screened compounds for post-docking analysis. This function consists of a simple empirical binding score and a pharmacophore-based score to reduce the number of false positives. The energy function can be dissected into the following terms:

$$E_{tot} = E_{bind} + E_{pharma} + E_{ligpre} \quad (1)$$

where E_{bind} is the empirical binding energy, E_{pharma} is the energy of binding site pharmacophores (hot spots), and E_{ligpre} is a penalty value if a ligand does not satisfy the ligand preferences. E_{pharma} and E_{ligpre} (see subsection on mining pharmacological consensuses) are especially useful in selecting active compounds from hundreds of thousands of nonactive compounds by excluding ligands that violate the characteristics of known active ligands, thereby improving the number of true positives. The values of E_{pharma} and E_{ligpre} are determined according to the pharmacological consensus derived from known active compounds and the target protein. In contrast, the values of E_{pharma} and E_{ligpre} are set to zero if active compounds are not available.

The empirical-binding energy (E_{bind}) is given as

$$E_{bind} = E_{inter} + E_{intra} + E_{penal} \quad (2)$$

where E_{inter} and E_{intra} are the intermolecular and intramolecular energies, respectively, and E_{penal} is a large penalty value if the ligand is out of the range of the search box. For our present work, E_{penal} was set to 10,000. The intermolecular energy is defined as

$$E_{inter} = \sum_{i=1}^{lig} \sum_{j=1}^{pro} \left[F(r_{ij}^{Bij}) + 332.0 \frac{q_i q_j}{4r_{ij}^2} \right], \quad (3)$$

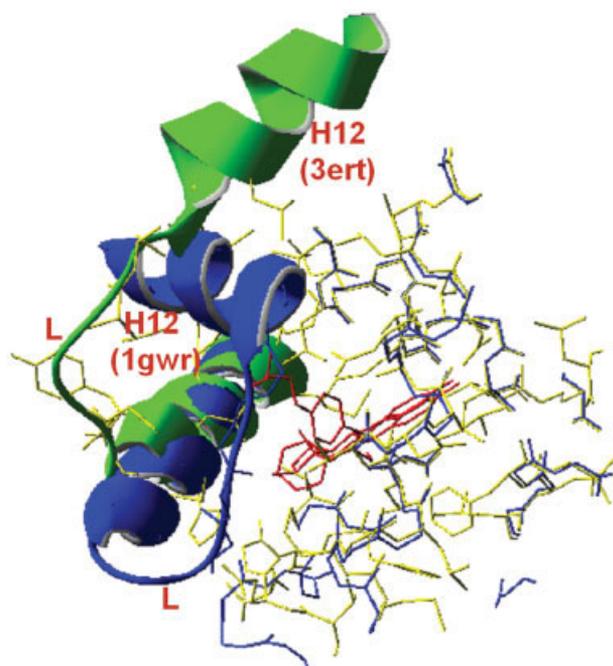


Fig. 4. Comparing the binding sites of the ER reference proteins by superimposing the complexes of the ER agonists (yellow; PDB code: 1gwr) and ER antagonists (blue; PDB code: 3ert). The bound ligands (estradiol and tamoxifen) are shown in red. In the ER-agonist complex, helix 12 (H12) (blue) sits above the ligand-binding cavity, forming a lid. H12 in the ER-antagonist complex protrudes from the pocket.

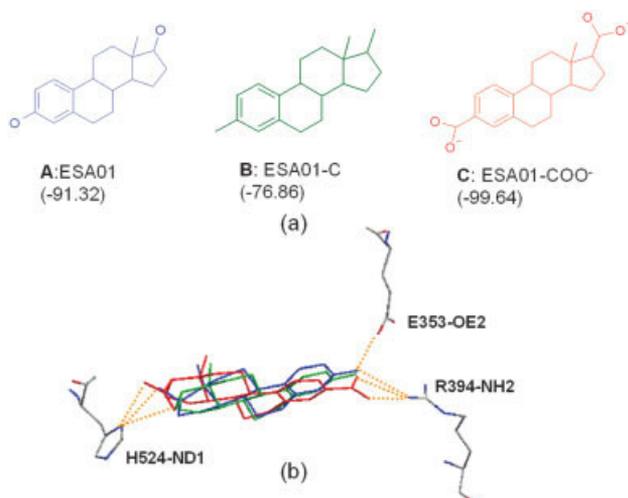


Fig. 8. Docking energy is influenced by ligand structures generated by CORINA. (a) The fraction of polar atoms in ESA01-C is the smallest among these 3 ligands, whereas that of ESA01-COO is the largest. (b) The docked positions are similar, but the docking energies differ: -91.32 for ESA01, -76.86 for ESA01-C, and -99.64 for ESA01-COO.

where r_{ij} is the distance between the atoms i and j , q_i and q_j are the formal charges, and 332.0 is a factor that converts the electrostatic energy into kilocalories per mole. The lig and pro denote the numbers of the heavy atoms in the ligand and receptor, respectively. $F(r_{ij}^{B_{ij}})$ is a simple atomic pairwise potential function (Fig. 5), as defined in our previous study,¹⁰ where $r_{ij}^{B_{ij}}$ is the distance between atoms

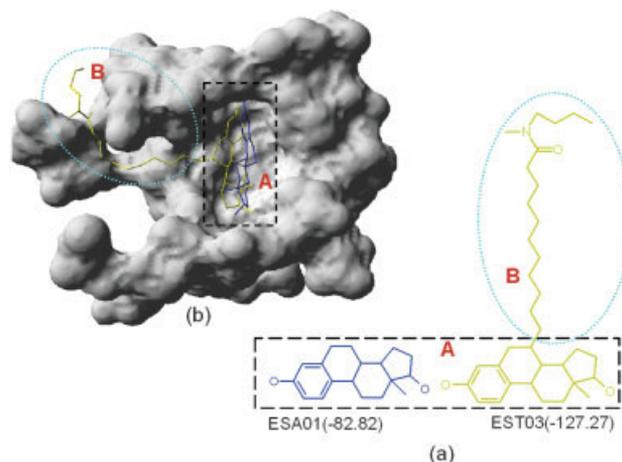


Fig. 9. The influence of molecular weight on docking energy. (a) ESA01 (blue) and EST03 (yellow) have a common group A, and EST03 has an additional substructure group B. (b) The docked conformations (into reference protein 3ert) are similar, and the docking energies are -82.82 for ESA01 and -127.27 for EST03.

i and j with interaction type B_{ij} formed by pairwise heavy atoms between ligands and proteins, and B_{ij} is either a hydrogen bond or a steric state. In this atomic pairwise model, these 2 potentials are calculated by the same function form but different parameters, V_1, \dots, V_6 , given in Figure 5. The energy value of a hydrogen bonding should be larger than that for steric potential. In this model, atoms are divided into 4 different atom types¹⁰: donor, acceptor, both, and nonpolar. A hydrogen bond can be formed by the following pair-atom types: donor-acceptor (or acceptor-donor), donor-both (or both-donor), acceptor-both (or both-acceptor), and both-both. Other pair-atom combinations are used to form the steric state. We used the atom formal charge to calculate the electrostatic energy,¹⁰ which is set to 5 or -5 , respectively, if the electrostatic energy is more than 5 or less than -5 . These parameters, V_1 to V_6 , and the maximum electrostatic energy were refined according to the docking accuracies of our previous work¹⁰ on a highly diverse data set of 100 protein-ligand complexes proposed by Jones et al.⁶

The intramolecular energy of a ligand is

$$E_{intra} = \sum_{i=1}^{lig} \sum_{j=i+2}^{lig} \left[F(r_{ij}^{B_{ij}}) + 332.0 \frac{q_i q_j}{4r_{ij}^2} \right] + \sum_{k=1}^{dihed} A [1 - \cos(m\theta_k - \theta_0)], \quad (4)$$

where $F(r_{ij}^{B_{ij}})$ is defined as for Eq. (3) except the value is set to 1000 when $r_{ij}^{B_{ij}} < 2.0$ Å, and $dihed$ is the number of rotatable bonds in a ligand. We followed the work of Gehlhaar et al.¹³ to set the values of A , m , and θ_0 . For the sp^3-sp^3 bond, $A = 3.0$, $m = 3$, and $\theta_0 = \pi$; for the sp^3-sp^2 bond, $A = 1.5$, $m = 6$, and $\theta_0 = 0$.

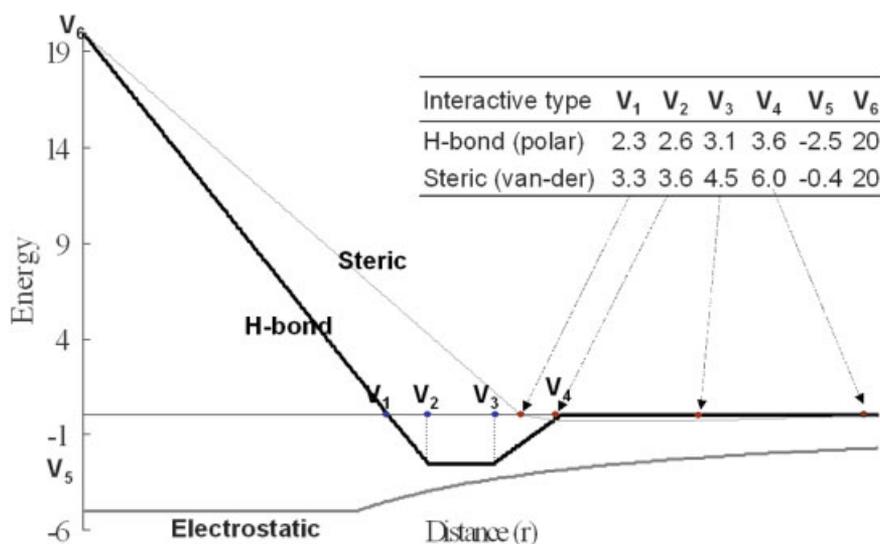


Fig. 5. The linear energy function of pairwise atoms for steric interactions (light line), hydrogen bonds (bold line), and electrostatic potential in GEMDOCK.

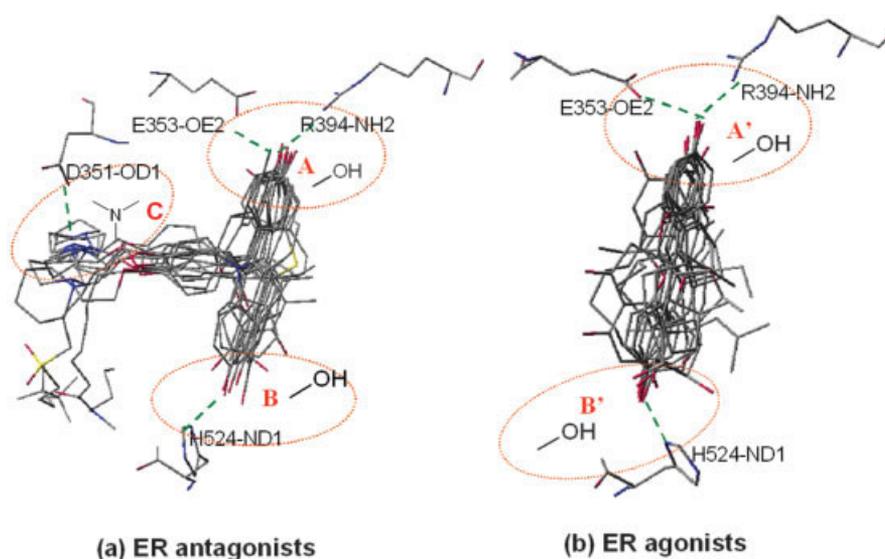


Fig. 6. The binding-site pharmacological consensus are identified by overlapping the docked conformations of (a) 10 known ER antagonists and (b) 10 known ER agonists against the reference proteins 3ert and 1gwr, respectively. (a) Four pharmacological interactions were identified and circled as A (phenolic hydroxyl group), B (phenolic hydroxyl group), and C (piperidine nitrogen). (b) Three pharmacological interactions were identified and circled as A' (phenolic hydroxyl group) and B' (phenolic hydroxyl group). The dashed lines indicate the hydrogen bonds formed between the ligand and the target protein. These pharmacological interactions are consistent with those evolved from X-ray structures.

Mining Pharmacological Consensuses

GEMDOCK evolves the binding-site pharmacological consensus and ligand preferences from both known active ligands and the target protein to improve screening accuracy. We used the premise that previously acquired interactions (hot spots) between ligands and the target protein can be used to guide the selection of lead compounds for subsequent investigation and refinement. When known active ligands were available, GEMDOCK used a pharmacophore-based scoring function [Eq. (1)]. On the other

hand, LP_{elec} and LP_{hb} were set to zero, and GEMDOCK used a purely empirical-based scoring function [Eq. (2)] if known active compounds were not available.

For each known active ligand, GEMDOCK first yielded 5 docked ligand conformations by docking the ligand into the target protein, and only the docked ligand conformation with the lowest energy was retained for pharmacological consensus analysis. The protein–ligand interactions were extracted by overlapping these lowest energy docked conformations, and the interactions were classified into 2

different types, including hydrogen-bonding and hydrogen-charged interactions. After all of the protein–ligand interactions were calculated, and the atom interaction-profile weight of the target protein representing the pharmacological consensus of a particular interaction was given as

$$Q_j^k = \frac{f_j^k}{N}, \quad (5)$$

where N is the number of known active compounds and f_j^k is the total interaction number of an atom j (in a protein) interacting with an atom of known active ligands with the interaction type k (e.g., hydrogen-bonding or hydrogen-charged interactions). In this work, an atom j (in a protein) was considered to interact with an atom i (in a ligand) if the distance between the atoms j and i ranges from $(V_1 + V_2)/2$ to $(V_3 + V_4)/2$, where V_1, \dots, V_4 are given in Figure 5. An atom j in the reference protein was considered a hot-spot atom when Q_j^k was more than 0.5.

The pharmacophore-based interaction energy (E_{pharma}) between the ligand and the protein is calculated by summing the binding energies of all hot spot atoms:

$$E_{pharma} = \sum_{i=1}^{lig} \sum_{j=1}^{hs} CW(B_{ij})F(r_{ij}^{B_{ij}}), \quad (6)$$

where $CW(B_{ij})$ is a pharmacological weight function of a hot spot atom j with interaction type B_{ij} , $F(r_{ij}^{B_{ij}})$ is defined as in Eq. (3), lig is the number of heavy atoms in a screened ligand, and hs is the number of hot spot atoms in the protein. The $CW(B_{ij})$ is given as

$$CW(B_{ij}) = \begin{cases} 1.0 & \text{if } Q_j^k \leq 0.5 \text{ or } B_{ij} \neq k \\ 1.5 + 5(Q_j^k - 0.5) & \text{if } Q_j^k > 0.5 \text{ and } B_{ij} = k \end{cases}. \quad (7)$$

Q_j^k is the atomic pharmacological profile weight [Eq. (5)] and k is the interaction type of the hot spot atom j .

We evolved the ligand preferences (E_{ligpre}) from known ligands to reduce the deleterious effects of screening ligand structures that are rich in charged or polar atoms. Docking methods using energy-based scoring functions are often biased toward such compounds, which abound with charged and polar atoms (i.e., hydrogen donor or acceptor atoms) because the pair-atom potential of the electrostatic energy and hydrogen bonding energy is always larger than the steric energy. For example, the atomic pairwise potential energies of the electrostatic, hydrogen bond, and steric potential were set to -5 , -2.5 , and -0.4 in this work. The ligand preference (E_{ligpre}) is a penalty value for those screened ligands that violate the electrostatic or hydrophilic constraints. The E_{ligpre} is given as

$$E_{ligpre} = LP_{elec} + LP_{hb}, \quad (8)$$

where LP_{elec} and LP_{hb} are the penalties for the electrostatic (i.e., the number of charged atoms of a screened ligand) and hydrophilic (i.e., the fraction of polar atoms in a screened ligand) constraints, respectively. LP_{elec} is defined as

$$LP_{elec} = \begin{cases} 10NA_{elec} & \text{if } NA_{elec} > UB_{elec} \\ 0 & \text{if } NA_{elec} \leq UB_{elec} \end{cases}, \quad (9)$$

where $UB_{elec} = \theta_{elec} + \sigma_{elec}$.

NA_{elec} is the number of charged atoms of a screened ligand and UB_{elec} is the upper bound number of charged atoms derived from known active compounds. θ_{elec} is the maximum number of charged atoms among known active compounds, and σ_{elec} is the standard deviation of the charged atoms of known active compounds. LP_{hb} is defined as

$$LP_{hb} = \begin{cases} 5NA_{hb} & \text{if } r_{hb} > Ur_{hb} \\ 0 & \text{if } r_{hb} \leq Ur_{hb} \end{cases}, \quad (10)$$

where $r_{hb} = \frac{NA_{hb}}{NA_t}$ and $Ur_{hb} = \theta_{hb} + \sigma_{hb}$.

r_{hb} is the fraction of polar atoms (i.e., the atom type is both, donor, or acceptor) in a screened ligand, and Ur_{hb} is the upper bound of the fraction of polar atoms calculated from known active ligands. NA_{hb} and NA_t are the number of polar atoms and the total number of the heavy atoms of a screened ligand, respectively. θ_{hb} and σ_{hb} are the maximum ratio and the standard deviation of the ratios of polar atoms evolved from known ligands, respectively.

In order to reduce the deleterious effects of biasing toward the selection of high molecular weight compounds, we formulate a normalization strategy defined as

$$E_{bind}^{MW} = \frac{E_{bind}}{(NA_t)^K}, \text{ where } K = \begin{cases} 0.5 & \text{if } \mu_{mw} \leq 15 \\ 0.5 - \frac{0.45(\mu_{mw} - 15)}{25} & \text{if } 15 < \mu_{mw} \leq 40 \\ 0.05 & \text{if } \mu_{mw} > 40 \end{cases}, \quad (11)$$

where E_{bind} is the empirical binding energy [Eq. (2)], NA_t is the total number of the heavy atoms in a screened ligand, and μ_{mw} is the mean of the number of heavy atoms in known active compounds. When the normalization strategy is applied, the energy function [Eq. (1)] is given as

$$E_{tot} = E_{bind}^{MW} + E_{pharma} + E_{ligpre}. \quad (12)$$

Flexible Docking Algorithm

Here, we present the outline of our molecular docking method that is a generic evolutionary method enhanced from our original technique.¹⁰ The core idea of our evolutionary approach was to design multiple operators that cooperate using the family competition model, which is similar to a local search procedure. The rotamer-based mutation operator, a discrete operator, is used to reduce the search space of ligand structure conformations. The Gaussian and Cauchy mutations, continuous genetic operators, search the orientation and conformation of the ligand relating to the center of the target protein.

After the ligand database and the target protein were prepared and the pharmacological preferences were evolved, we first specified the crystal coordinates of the protein atoms from the PDB and assigned a formal charge

and atom type for each protein atom. GEMDOCK then automatically decides the search cube of a binding site based on the maximum and minimum values of coordinates among these selected protein atoms. For each ligand in the database, GEMDOCK takes the atomic coordinates from the ligand database and assigns a formal charge and atom type for each atom. It then sequentially predicts the binding conformation and estimates the binding affinity for each ligand. Finally, GEMDOCK ranks these docked ligand conformations for use in the postdocking analysis.

Our docking method works as follows: It randomly generates a starting population with N docked structures by initializing the orientation and conformation of the ligand relating to the center of the target protein. Each solution is represented as a set of 3 n -dimensional vectors (x^i, σ^i, ψ^i) , where n is the number of adjustable variables of a docking system and $i = 1, \dots, N$, where N is the population size. The vector x is the adjustable variables representing a particular orientation and conformation space of a ligand to be optimized, in which x_1, x_2 , and x_3 are the three-dimensional (3D) location of the ligand relating to the center of the target protein; x_4, x_5 , and x_6 are the rotational angles of the ligand relating to axes; and x_7 to x_n are the twisting angles of the rotatable bonds inside the ligand. σ and ψ are the step-size vectors of decreasing-based Gaussian mutation and self-adaptive Cauchy mutation. In other words, each solution x is associated with some parameters for step-size control. The initial values of x_1, x_2 , and x_3 are randomly chosen from the feasible box, and the others, from x_4 to x_n , are randomly chosen from 0 to 2π in radians. The initial step size σ is 0.8 and ψ is 0.2. After GEMDOCK initializes the solutions, it enters the main evolutionary loop, which consists of 2 stages in every iteration: decreasing-based Gaussian mutation and self-adaptive Cauchy mutation. Each stage is realized by generating a new quasi-population (with N solutions) as the parent of the next stage. These stages apply a general procedure “FC_adaptive” with only different working population and the mutation operator.

The FC_adaptive procedure employs 2 parameters, namely, the working population (P , with N solutions) and mutation operator (M), to generate a new quasi-population. The main work of FC_adaptive is to produce offspring and then conduct the family competition. Each individual in the population sequentially becomes the “family father.” With a probability p_c , this family father and another solution that is randomly chosen from the rest of the parent population are used as parents for a recombination operation. Then the new offspring or the family father (if the recombination is not conducted) is operated by the rotamer mutation or by differential evolution to generate a quasi-offspring. Finally, the working mutation is operated on the quasi-offspring to generate a new offspring. For each family father, such a procedure is repeated L times, called the family competition length. Among these L offspring and the family father, only the one with the lowest scoring function value survives. Since we create L children from one “family father” and perform a selection, this is a family competition strategy. This method avoids

the population prematureness but also keeps the spirit of local searches. Finally, the FC_adaptive procedure generates N solutions because it forces each solution of the working population to have one final offspring. In the following, genetic operators are briefly described. We use $a = (x^a, \sigma^a, \psi^a)$ to represent the “family father” and $b = (x^b, \sigma^b, \psi^b)$ as another parent. The offspring of each operation is represented as $c = (x^c, \sigma^c, \psi^c)$. The symbol x_j^s is used to denote the j th adjustable optimization variable of a solution s , $\forall j \in \{1, \dots, n\}$.

Recombination operators

GEMDOCK implemented modified discrete recombination and intermediate recombination. A recombination operator selected the “family father (a)” and another solution (b) randomly selected from the working population. The former generates a child as follows:

$$x_j^c = \begin{cases} x_j^a & \text{with probability 0.8} \\ x_j^b & \text{with probability 0.2} \end{cases}.$$

The generated child inherits genes from the “family father” with a higher probability 0.8. Intermediate recombination works as

$$w_j^c = w_j^a + \beta(w_j^b - w_j^a)/2,$$

where w is σ or ψ based on the mutation operator applied in the FC_adaptive procedure. The intermediate recombination only operated on step-size vectors and the modified discrete recombination was used for adjustable vectors (x).

Mutation operators

After the recombination, a mutation operator, the main operator of GEMDOCK, is applied to mutate adjustable variables (x). Gaussian and Cauchy Mutations are accomplished by first mutating the step size (w) and then mutating the adjustable variable x :

$$\begin{aligned} w_j' &= w_j' A(\cdot) \\ x_j' &= x_j + w_j' D(\cdot), \end{aligned}$$

where w_j and x_j are the i th component of w and x , respectively, and w_j is the respective step size of the x_j , where w is σ or ψ . $A(\cdot)$ is evaluated as $\exp[\tau'N(0, 1) + N_j(0, 1)]$ if the mutation is a self-adaptive mutation, where $N(0, 1)$ is the standard normal distribution, $N_j(0, 1)$ is a new value with distribution $N(0, 1)$ that must be regenerated for each index j . When the mutation is a decreasing-based mutation $A(\cdot)$ is defined as a fixed decreasing rate $\gamma = 0.95$. $D(\cdot)$ is evaluated as $N(0, 1)$ or $C(1)$ if the mutation is, respectively, Gaussian or Cauchy. For example, the self-adaptive Cauchy mutation is defined as

$$\begin{aligned} \psi_j^c &= \psi_j^a \exp[\tau'N(0, 1) + \tau N_j(0, 1)], \\ x_j^c &= x_j^a + \psi_j^c C_j(t). \end{aligned}$$

We set τ and τ' to $(\sqrt{2n})^{-1}$ and $(\sqrt{2\sqrt{2n}})^{-1}$, respectively, according to the suggestion of evolution strategies. A random variable is said to have the Cauchy distribution $[C(t)]$ if it has the density function: $f(y; t) = (t/\pi)/(t^2 + y^2)$, $-\infty < y < \infty$. In this article, t is set to 1. Our decreasing-

TABLE I. Pharmacological Weights of Hot Spot Atoms of the ER-Antagonist and ER-Agonist Complexes Evolved by Overlapping Docked Conformations of Known Active Ligands

Residue ID ^a	Atom ID ^b	Hot spots weight [$CW(B_{ij})$]		Interaction type (hot spots)
		ER-antagonist complex	ER-agonist complex	
E353	OE2	3.0	3.1	H-bond (OH \leftrightarrow O) (phenolic hydroxyl) ^{26,29-32}
R394	NH2	2.9	3.1	H-bond (OH \leftrightarrow N) (phenolic hydroxyl) ^{26,29-32}
H524	ND1	2.4	3.4	H-bond (OH \leftrightarrow N) ^{26,29-32}
D351	OD1	2.2	— ^c	H-bond (N \leftrightarrow O) (dimethylamino group) ^{26,31} and piperidine nitrogen ^{29,30}

^aOne-letter amino acid code, with the residue sequence numbered as in the PDB.

^bAtom name in the PDB.

^cD351-OD1 is not a hot spot atom in the ER-agonist reference complex.

TABLE II. Ligand Preferences Evolved from Known Active Ligands Screen Lead Compounds for the ER-Antagonist and ER-Agonist Complexes

Ligand name	Electrostatic preferences [Eq. (9)]			Hydrophilic preferences [Eq. (10)]			Molecular weight [Eq. (11)]	
	θ_{elec}	σ_{elec}	UB_{elec}	θ_{hb}	σ_{hb}	Ur_{hb}	μ_{mw}	K
ER antagonist	2.0	0.63	2.63	0.15	0.02	0.17	34.0	0.16
ER agonist	0	0	0	0.25	0.06	0.31	21.4	0.38

based Gaussian mutation uses the step-size vector σ with a fixed decreasing rate $\gamma = 0.95$ and works as $\sigma^c = \gamma\sigma^a$ and $x_j^c = x_j^a + \sigma^c N_j(0, 1)$.

Our rotamer mutation is only used for x_7 to x_n to find the conformations of the rotatable bonds inside the ligand. For each ligand, this operator mutates all of the rotatable angles according to the rotamer distribution and works as $x_j = \gamma_{ki}$ with probability p_{ki} , where γ_{ki} and p_{ki} are the angle value and the probability, respectively, of i th rotamer of k th bond type including sp^3-sp^3 and sp^3-sp^2 bond. The values of γ_{ki} and p_{ki} are based on the energy distributions of these 2 bond types.

RESULTS AND DISCUSSION

Parameters of GEMDOCK

In our studies, GEMDOCK parameters in the flexible search phase included the initial step sizes ($\sigma = 0.8$ and $\psi = 0.2$), family competition length ($L = 2$), population size ($N = 200$), and recombination probability ($p_c = 0.3$). For each ligand screened, GEMDOCK optimization stopped either when the convergence was below a certain threshold value or the iterations exceeded the maximal preset value of 60. Therefore, GEMDOCK generated 800 solutions in one generation and terminated after it exhausted 48,000 solutions for each docked ligand. The average GEMDOCK docking run took 135 s using a Pentium 1.4-GHz personal computer with a single processor.

Mining the Pharmacological Consensus

Figure 6 and Table I show the pharmacological interaction preferences (hot-spot atoms), and Table II shows the ligand preferences. We evolved these pharmacological consensuses and steric binding interactions by overlapping the docked ligand conformations, yielded by GEMDOCK, of all known active compounds. Figure 6(a and b)

shows the overlap of 10 docked poses of 10 known active ligands in the vicinity of the ER-antagonist target protein and ER-agonist target protein, respectively. The dashed lines indicate the hydrogen bonds formed between the ligand and the reference proteins. For the ER-antagonist target protein, 4 binding-site pharmacological interactions were identified and circled as A (hydroxyl group)^{26,29-32}, B (hydroxyl group)^{26,29-31}, and C (dimethylamino group)^{26,31} or piperidine nitrogen^{29,30}. These interactions, evolved from docked conformations, are consistent with the interactions evolved from superimposing 3 X-ray structures with that from related studies.^{26,29-31} As shown in Table I, the pharmacological weights [$CW(B_{ij})$] defined in Eq. (7)] and the interaction type for the ER-antagonist complex included E353-OE2 (3.0), R394-NH2 (2.9), H524-ND1 (2.4), and D351-OD1 (2.4). For the ER-agonist target protein, 2 binding-site pharmacological interactions were identified (e.g., A' hydroxyl group and B' hydroxyl group). The pharmacological weights and the interaction type for the ER-agonist complex included E353-OE2 (3.1), R394-NH2 (3.1), and H524-ND1 (3.4). These interactions are also consistent with those evolved by superimposing 4 X-ray structures [Fig. 6(b)].

For screening ER antagonists and agonists, Table II shows the parameter values of ligand preferences evolved from known ER antagonists (Fig. 2) and agonists (Fig. 3). These ligand preferences improve the screening accuracy by reducing the deleterious effects of ligand molecular weights and ligand structures that are rich in charged or polar atoms. The electrostatic parameter values [see Eq. (9)] for ER antagonists included the maximum number of charged atoms ($\sigma_{elec} = 2.0$), standard deviation of the charged atoms ($\sigma_{elec} = 0.63$), and upper bound number of charged atoms ($UB_{elec} = 2.63$). For the hydrophilic preferences [see Eq. (10)], the maximum ratio (θ_{hb}) was 0.15, the

TABLE III. Comparing GEMDOCK and GOLD With Respect to Docking 7 Ligands Back Into Respective Complexes and Reference Proteins

Ligand ID	GEMDOCK				GOLD	
	Native protein ^b		Reference protein ^c		Native protein ^b	Reference protein ^c
	E_{tot}^d	E_{bind}^d	E_{tot}	E_{bind}		
EST01 (1err.RAL ^a)	0.66	0.65	1.37	1.36	1.02	1.68
EST02 (3ert.OHT)	0.60	0.75	0.60	0.75	1.15	1.15
EST03 (1hj1.AOE)	1.41	1.05	3.27	3.35	5.07	3.92
ESA01 (1gwr.EST)	0.66	0.64	0.66	0.64	0.54	0.54
ESA02 (1l2i_ETC)	0.61	0.48	0.62	0.69	0.55	0.76
ESA03 (1qkm.GEN)	0.69	1.53	3.32	4.83	0.24	7.16
ESA04 (3erd.DES)	0.67	0.51	1.44	1.43	1.10	1.76

^aFour characters followed by 3 characters (separated by a period) denote the PDB code and the ligand name in the PDB, respectively.

^bThe RMSD value for docking each ligand back into its respective complex.

^cThe RMSD value for docking each ligand into its reference complex, 3ert for ER antagonists (e.g., EST01 ~ EST03) and 1gwr for ER agonists (e.g., ESA01 ~ ESA04).

^d E_{tot} and E_{bind} are defined in Eq. (1).

standard deviation (σ_{hb}) of the ratios was 0.02, and the upper bound ratio ($U_{r_{hb}}$) of polar atoms was 0.17. For molecular weight [see Eq. (11)], the mean of heavy atoms (μ_{mw}) was 21.6 and linear normalization parameter K was 0.16. In contrast, for ER agonists the values of UB_{elec} and $U_{r_{hb}}$ were 0 and 0.31, respectively, and K was 0.38.

Evaluation of Virtual Screening Accuracy

Some common factors were used to evaluate the screening quality, including coverage (the percentage of active ligands retrieved from the database), yield (the percentage of active ligands in the hit list), false-positive (FP) rate, enrichment, and goodness-of-hit (GH). The coverage (true positive rate) is defined as A_h/A (%), A_h/T_h (%) is the yield (hit rate), and the FP rate is defined as $(T_h - A_h)/(T - A)$ (%). The enrichment is defined as $(A_h/T_h)/(A/T)$. A_h is the number of active ligands among the T_h highest ranking compounds, which is called the hit list, A is the total number of active ligands in the database, and T is the total number of compounds in the database. The GH score is defined as³³

$$GH = \left(\frac{A_h(3A + T_h)}{4T_h A} \right) \left(1 - \frac{T_h - A_h}{T - A} \right). \quad (13)$$

The GH score contains a coefficient to penalize excessive hit list size and, when evaluating hit lists, is calibrated by weighting the score with respect to the yield and coverage. The GH score ranges from 0.0 to 1.0, where 1.0 represents a perfect hit list (i.e., containing all of, and only, the active ligands). In the data sets for screening the ER agonists or ER antagonists, A and T are 10 and 1000, respectively. Here, we also took the averages of hit rates, enrichments, GH scores, and FP rates. For example, the averages of the hit rates and enrichments are defined as $(\sum_{i=1}^A i/T_h^i)/A$ and $(\sum_{i=1}^A (i/T_h^i)/(A/T))/A$, respectively, where T_h^i is the number of compounds in a hit list containing i active compounds.

Molecular Recognition of ER-Antagonist and ER-Agonist Complexes

We tested GEMDOCK¹⁰ on a highly diverse data set of 100 protein–ligand complexes proposed by Jones et al.⁶ and on 2 cross-docking ensembles of protein structures. Upon consideration of the solutions at the first rank, in 79% of these complexes, the docked lowest energy ligand structures had root-mean-square deviations (RMSDs) below 2.0 Å with respect to the corresponding crystal structures. The success rate increased to 85% if the structured water molecules were retained. In contrast, GOLD⁶ yielded a 71% success rate in identifying the experimental binding model based on the GOLD assessment categories, and the rate was 66% if based on the top-ranked solutions with RMSD values of less than 2 Å. FlexX⁷ achieved 70% and 46.5% success rates for solutions at any rank and the first rank, respectively.

The main objective of this study was to evaluate whether the new scoring function was applicable to both molecular docking and ligand scoring during VS. First, GEMDOCK was evaluated by docking each ligand of 7 ER complexes in the PDB into its respective complex and into its reference protein. Table III shows the overall predicted accuracies of GEMDOCK and GOLD. Ten independent docking runs were performed for each active compound, and the docked ligand conformation with the lowest energy was used to calculate RMSD values for ligand heavy atoms between the docked conformation and the crystal structure. The RMSD values of 7 docked conformations (docking each ligand back into its respective complex) were less than 2.0 Å. When these ligands were docked into the reference protein using GEMDOCK, all docked conformations had an RMSD of less than 2.0 Å except for EST03 and ESA03 (genistein). EST03 docked well in the binding site, with the exception of the long acyclic side-chain. The agonist ESA03 could not be docked into its corresponding pose in the reference protein (1gwr) due to a fundamental differ-

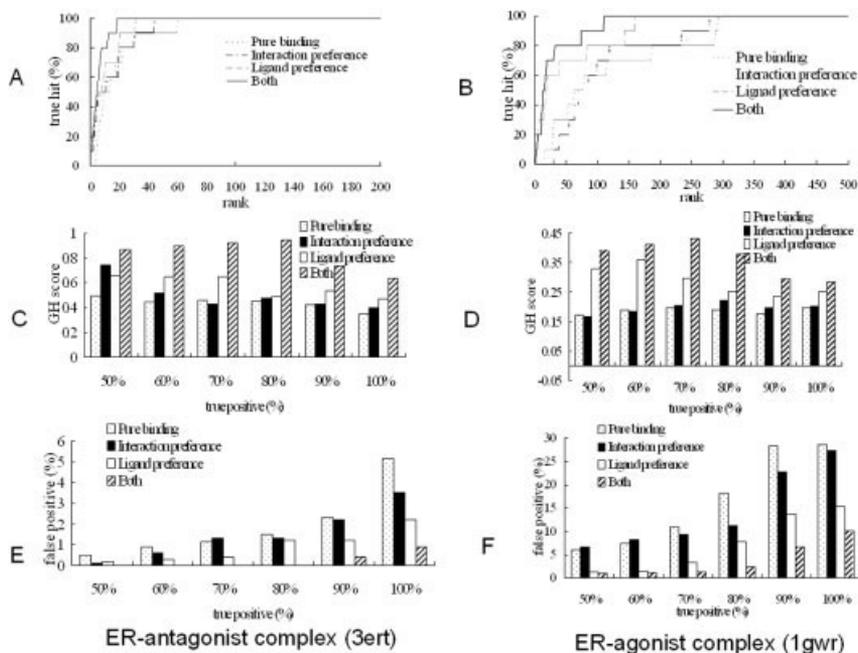


Fig. 7. GEMDOCK screening accuracies of ER antagonists and ER agonists assessed by (A and B) true hits, (C and D) GH scores, and (E and F) the false-positive rates against different true-positive rates ranging from 50% to 100%. The performance of GEMDOCK was consistently superior when using both ligand preferences and pharmacological-interaction preferences.

TABLE IV. GEMDOCK Screening Accuracies Using Different Combinations of Pharmacological Preferences on the Data Set Proposed by Bissantz et al.¹⁴

Measure factor	ER antagonists (reference protein: 3ert)				ER agonists (reference protein: 1gwr)			
	Pure binding ^a	Interaction preference ^b	Ligand preference ^c	Both ^d	Pure binding ^a	Interaction preference ^b	Ligand preference ^c	Both ^d
Average hit rate (%)	34.88	57.93	71.58	92.19	6.94	7.52	25.02	45.66
Average enrichment	34.88	57.93	71.58	92.19	6.94	7.52	25.02	45.66
Average false-positive rate (%)	1.32	0.94	0.56	0.13	7.83	6.34	2.56	0.75
Average GH score	0.39	0.57	0.67	0.83	0.17	0.18	0.32	0.48

^{a,b,c,d}Using E_{bind} , $E_{bind} + E_{pharma}$, $E_{bind} + E_{ligpre}$ and E_{top} respectively, for the scoring function. These energy terms are defined in Eq. (1).

ence between the binding site of ER α (1gwr) and ER β (1qkm). As shown in Table III, GEMDOCK and GOLD yielded results of equal quality, and GEMDOCK yielded similar results regardless of whether the pharmacological preferences (i.e., E_{pharma} and E_{ligpre}) were considered.

Virtual Screening of ER Antagonists and ER Agonists

We compared the overall accuracy of GEMDOCK using 4 variations of energy terms to screen ER antagonists and agonists from a data set of 1000 compounds proposed by Bissantz et al.¹⁴ (Fig. 7 and Table IV). Each variation combined 3 scoring terms applied in GEMDOCK: binding energy (E_{bind}), pharmacological interaction preferences (E_{pharma}), and ligand preferences (E_{ligpre}). For example, the approach “Pure binding” used only the binding energy (E_{bind}) as the scoring function; the approach “Interaction preference” integrated E_{bind} and E_{pharma} for the scoring

function; “Ligand preference” integrated E_{bind} and E_{ligpre} for the scoring function; and “Both” integrated E_{bind} , E_{ligpre} , and E_{pharma} for the scoring function. The parameter values for interaction preferences (E_{pharma}) and ligand preferences (E_{ligpre}) are shown in Tables I and II, respectively. The various ranks of 10 known active ligands in the ligand screening database are shown in Table V, and the comparison of results obtained with other methods is shown in Table VI.

As shown in Table IV and Figure 7, GEMDOCK generally improves the screening quality when both interaction preferences and ligand preferences are considered. The latter was more important than the former for this data set. For the ER antagonists that were screened, average hit rates were 92.19% (Both), 71.58% (Ligand preference), 57.93% (Interaction preference), and 34.8% (E_{bind}). The average GH scores were 0.83 (Both), 0.67 (Ligand preference), 0.57 (Interaction preference), and 0.39 (E_{bind}). Fig-

TABLE V. Ranks of 10 Known ER Antagonists and 10 Known ER Agonists Using GEMDOCK With Different Combinations of Pharmacological Preferences on the Data Set Proposed by Bissantz et al.¹⁴

ER antagonists (reference protein: 3ert)					ER agonists (reference protein: 1 gwr)				
Ligand ID ^a	Pure binding ^b	Interaction preference ^c	Ligand preference ^d	Both ^e	Ligand ID ^f	Pure binding	Interaction preference	Ligand preference	Both
EST01	9	3	3	3	ESA01	87	57	33	8
EST02	23	31	21	13	ESA02	25	49	7	6
EST03	10	20	20	8	ESA03	31	32	3	3
EST04	15	12	7	4	ESA04	220	116	99	29
EST05	6	6	1	1	ESA05	128	97	53	20
EST06	7	5	4	6	ESA06	101	73	41	14
EST07	32	21	9	7	ESA07	53	53	16	7
EST08	18	4	11	5	ESA08	45	102	9	26
EST09	5	1	2	2	ESA09	43	38	10	5
EST10	61	45	32	19	ESA10	97	66	37	11

^aDefined in Figures 2 and 3, respectively.

^{b,c,d,e}Using E_{bind} , $E_{bind} + E_{pharma}$, $E_{bind} + E_{ligpre}$ and E_{tot} respectively, for the scoring function. These energy terms are defined in Eq. (1).

TABLE VI. Comparing GEMDOCK With Other Methods on Screening the ER Antagonists by False-Positive Rates (%) on the Data Set Proposed by Bissantz et al.¹⁴

True positive (%)	GEMDOCK ^a	GEMDOCK ^b	Surflex ^c	DOCK ^c	FlexX ^c	GOLD ^c
80	1.5 (15/990) ^d	0.0 (0/990)	1.3	13.3	57.8	5.3
90	2.3 (23/990)	0.4 (4/990)	1.6	17.4	70.9	8.3
100	5.2 (51/990)	0.9 (9/990)	2.9	18.9	— ^e	23.4

^aGEMDOCK without pharmacological interactions and ligand preferences (e.g., E_{bind} for the scoring function).

^bGEMDOCK with pharmacological interactions and ligand preferences (e.g., E_{tot} for the scoring function).

^cDirectly summarized from the references.^{1,35}

^dThe false-positive rate from 990 random ligands (percentage).

^eFlexX could not calculate the docked solution for EST09.

ure 7(C and E) shows that the GH scores and FP rates of the true positive rates ranged from 50% to 100%. For the ER agonists that were screened, average hit rates were 45.66% (Both), 25.02% (Ligand preference), 7.52% (Interaction preference), and 6.94% (E_{bind}). The average GH scores were 0.48 (Both), 0.32 (Ligand preference), 0.18 (Interaction preference), and 0.17 (E_{bind}). Figure 7(D and F) shows the GH scores and FP rates with different true positive rates ranging from 50% to 100%.

The screening accuracy of GEMDOCK for ER antagonists was better than that of ER agonists on this data set. These results might be caused by using the same 990 random compounds proposed by Bissantz et al.¹⁴ for these 2 screens. When they prepared the random ligand set, only the chemical reagents of the ER-antagonist complex were eliminated and therefore the ER-agonist-like compounds might be selected. For example, GEMDOCK screened two ligands, MFCD00012742 and MFCD00002206 (Table VII), which are similar in structures to ESA03 and ESA04 (Fig. 4), respectively. At the same time, the numbers of the ligands that violate the ligand preferences (e.g., LP_{elec} and LP_{hb} shown in Table II) of ER antagonists and ER agonists are 400 and 289 compounds, respectively. The MFCD compounds were the random ligands in the data set.

GEMDOCK was superior to other approaches (Surflex, DOCK, FlexX, and GOLD) for screening the ER antagonists (Table VI). All of these methods were tested using the same reference protein and screening database with true-positive rates ranging from 80% to 100%. When the true

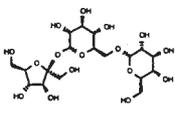
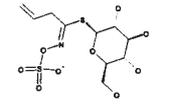
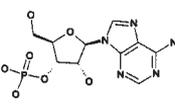
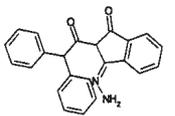
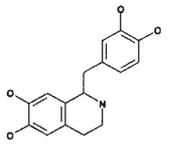
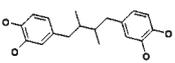
positive rate was 90%, the FP rates were 2.3% (GEMDOCK without pharmacological preferences), 0.4% (GEMDOCK with pharmacological preferences), 1.6% (Surflex), 17.4% (DOCK), 70.9% (FlexX), and 8.3% (GOLD).

The Influences of Pharmacological Preferences

When using interaction energy scoring alone for choosing ligands, docking methods (e.g., GEMDOCK and GOLD) favor the selection of not only highly charged polar compounds but also high molecular weight compounds. Figures 8 and 9 show the influences of the ligand structures and molecular weight, respectively, when the binding scoring (E_{bind}) alone was used in GEMDOCK. The docking energy of a ligand with charged or polar atoms is often lower than the energy of a noncharged ligand when the docked conformations are similar. For example, the docking energies are -76.86 for ESA01-C (r_{hb} is the smallest), -91.32 for ESA01, and -99.64 for ESA01-COO (with charged atoms, and r_{hb} is the largest) when the docked positions of these ligands are similar (Fig. 8). At the same time, ESA01 and ESA01-COO form the pharmacological interactions shown in Figure 6(B) (e.g., A' phenolic hydroxyl group and B' phenolic hydroxyl group). In contrast, ESA01-C has no polar atoms to form these pharmacological interactions. We obtained these ligand structures (EAS01-C and ESA01-COO) using the 3D structure generator CORINA.³⁴

Tables VII and VIII show the effect of pharmacological preferences of some typical ligand structures on screened

TABLE VII. GEMDOCK Ranks Using Different Combinations of Pharmacological Preferences for Some Typical Ligands on Screening ER Agonists on the Data Set Proposed by Bissantz et al.¹⁴

Ligand ID in ACD	Ligand structure	NA_{elec} ^a	r_{hb} ^b	Pure binding ^c	Interaction preference ^d	Ligand preference ^e	Both ^f
MFC00006630		0.00	0.47	5	172	911	850
MFC00006616		3.00	0.45	3	1	900	828
MFC00005746		3.00	0.52	4	2	925	889
MFC00003783		0.00	0.15	54	270	13	165
MFC00012742		0.00	0.24	10	6	2	1
MFC00002206		0.00	0.18	13	11	1	4

^aNumber of charged atoms in a screened ligand [Eq. (9)].

^bThe fraction of polar atoms in a screened ligand [Eq. (10)].

^{c,d,e,f}Using E_{bind} , $E_{bind} + E_{pharma}$, $E_{bind} + E_{ligpre}$ and E_{tot} respectively, for the scoring function. These energy terms are defined in Eq. (1).

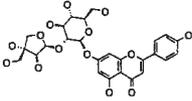
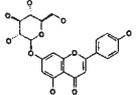
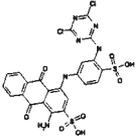
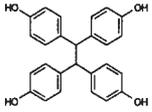
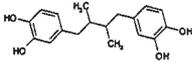
ER agonists and antagonists, respectively. When the binding energy (E_{bind}) alone was used to screen ER agonists, GEMDOCK selected 2 ligands, MFC00012742 (first) and MFC00002206 (fourth), which are similar in structure to ESA03 and ESA04, respectively, and satisfy the ligand preferences. Due to higher numbers of polar atoms at critical sites, these ligands formed greater numbers of pharmacological interactions compared with known active ligands. At the same time, GEMDOCK was able to exclude ligands such as MFC00006630 ($r_{hb} = 0.47$), MFC00006616 ($r_{hb} = 0.45$ and $NA_{elec} = 3$), and MFC00005746 ($r_{hb} = 0.52$ and $NA_{elec} = 3$) that violate the ligand preferences of known ER agonists (Table II). For example, their r_{hb} values were larger than the upper bound ratio ($Ur_{hb} = 0.31$) of polar atoms or the upper bound number ($UB_{elec} = 0$) of charged atoms. When the penalty for the ligand preferences (E_{ligpre}) was considered, the ranks of MFC00006630 (911th), MFC00006616 (900th), and MFC00005746 (928th) lagged substantially. Ligands such as MFC00003783 lagged (244th), since it is unable to interact with 3 important residues [Glu353, Arg394, and His524; Fig. 6(B) in the reference protein].

GEMDOCK yielded similar results when the ER antagonists were screened (Table VIII). When the binding energy (E_{bind}) alone was used, the ranks of ligands

MFC00016941 ($r_{hb} = 0.35$), MFC00016787 ($r_{hb} = 0.32$), and MFC00001218 ($r_{hb} = 0.34$) were 8th, 51st, and 13th, respectively. When both E_{bind} and ligand preferences (E_{ligpre}) were considered for the scoring function, the ranks of these ligands were 661st (MFC00016941), 747th (MFC00016787), and 954th (MFC00001218) since their r_{hb} values were larger than the upper bound ratio (e.g., $Ur_{hb} = 0.17$ in Table II) derived from known ER antagonists. These total scoring values were penalized by hydrophilic preferences [i.e., LP_{hb} in Eq. (10)]. Ligand MFC00001218 was also penalized by the electrostatic preferences [i.e., LP_{elec} in Eq. (9)], because the number of charged atoms ($NA_{elec} = 6$) was larger than the upper bound ($Ur_{elec} = 2.63$ in Table II). The screening of ligand MFC00010009, which has no polar atoms to form pharmacological interactions [Fig. 6(A)], often fell behind when GEMDOCK used both E_{bind} and E_{pharma} for the scoring function. In contrast, ligands MFC00002371 and MFC00002206 yielded good ranks for various combinations of energy terms, since they are able to form binding-site pharmacological interactions and satisfy the ligand preferences.

Figures 9 and 10 show the effect of molecular weight on screening accuracy. A docking method using energy-based scoring alone is often biased toward large molecular

TABLE VIII. GEMDOCK Ranks Using Different Combinations of Pharmacological Preferences for Some Typical Ligands When Screening ER Antagonists on the Data Set Proposed by Bissantz et al.¹⁴

Ligand ID in ACD	Ligand structure	NA_{elec} ^a	r_{hb} ^b	Pure binding ^c	Interaction preference ^d	Ligand preference ^e	Both ^f
MFC00016941		0	0.35	8	2	661	260
MFC00016787		0	0.32	51	8	747	319
MFC00001218		6	0.34	13	17	954	937
MFC00010009		0	0.00	88	430	5	57
MFC00002371		0	0.13	40	19	16	12
MFC00002206		0	0.18	37	30	46	20

^aNumber of charged atoms in a screened ligand [Eq. (9)].

^bFraction of polar atoms in a screened ligand [Eq. (10)].

^{c,d,e,f}Using E_{bind} , $E_{bind} + E_{pharma}$, $E_{bind} + E_{ligpre}$ and E_{tot} respectively, for the scoring function. These energy terms are defined in Eq. (1).

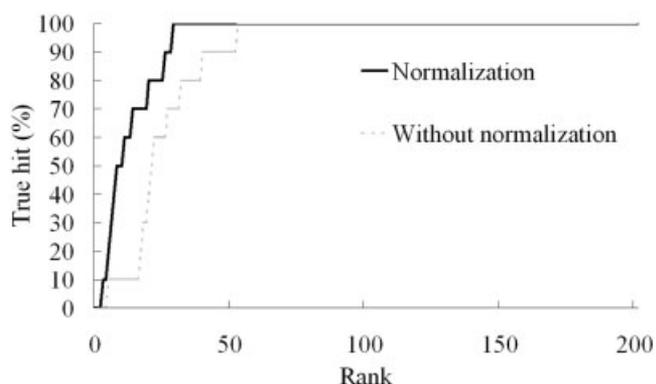


Fig. 10. The accuracy of GEMDOCK for screening ER agonists, assessed using scoring functions with molecular-weight normalization (solid line) and without molecular-weight normalization (dash line).

weight ligands, because the overall van der Waals interaction energy is summed over all pairs of ligand and target protein atoms within a specified cutoff distance. Figure 9(a) shows that ESA01 (blue) and EST03 (yellow) have a

common group A, and that EST03 has an additional substructure group (side-chain B). The van der Waals force of a large ligand (e.g., EST03) is often larger than that of a small ligand (e.g., ESA01). In this case, EST03 acquires additional van der Waals force from side-chain B, as shown in Figure 9(b). For example, when using E_{bind} alone for docking a ligand into the reference protein (3ert), GEMDOCK yielded docking energies of -127.27 for EST03 and -82.82 for ESA01. Figure 10 shows the true hits obtained by GEMDOCK when screening ER agonists without (dashed line) or with molecular weight normalization [solid line; defined in Eq. (11)]. When GEMDOCK applied molecular weight normalization and pharmacological preferences to screen ER agonists, the average hit rate was 45.66%, the average FP rate was 0.75%, and the GH score was 0.48. In contrast, these averages were 21.18%, 2.02%, and 0.29, respectively, when molecular weight normalization was not considered.

Figure 11 shows the true hits of GEMDOCK using the cleaned lists and the original data set proposed by Bissantz et al.¹⁴ For each test case (ER antagonists and ER ago-

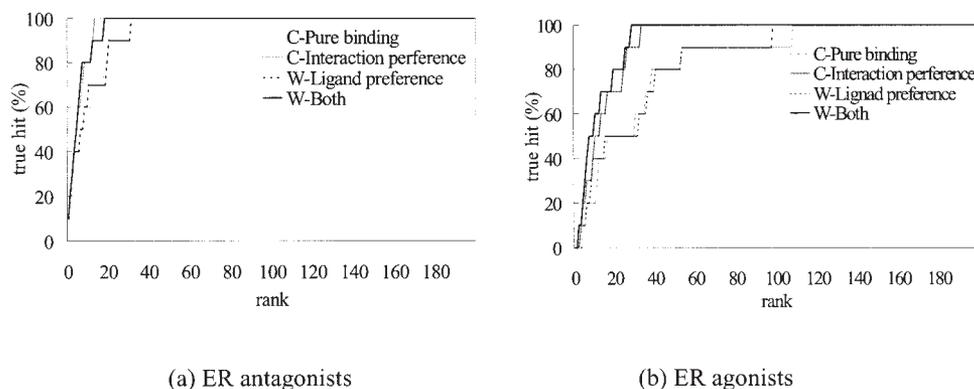


Fig. 11. The accuracy of GEMDOCK for screening (a) ER antagonists and (b) ER agonists, assessed using the cleaned ligand sets (C-Pure binding and C-Interaction preference) and the ligand set proposed by Bissantz et al.¹⁴ (W-Ligand preference and W-Both).

nists), we prepared the cleaned list by filtering the original set in order to eliminate the ligands that violate the electrostatic (LP_{elec}) or hydrophilic constraints (LP_{hb}). These two cleaned lists, including the known active compounds, consist of 590 and 701 compounds for screening the ER antagonists and ER agonists, respectively. As shown in Figure 11, the true hits (gray lines) of GEMDOCK using E_{bind} (C-Pure binding) and $E_{bind} + E_{pharma}$ (C-Interaction preference) as the scoring functions on the cleaned lists are similar to those (black lines) of GEMDOCK using $E_{bind} + E_{ligpre}$ (W-Ligand preference) and $E_{bind} + E_{ligpre} + E_{pharma}$ (W-Both) as scoring functions, on the original set, respectively. Using GEMDOCK on the cleaned sets, average GH scores were 0.82 (Interaction preference) and 0.66 (Pure binding) for ER antagonists, and average GH scores were 0.41 (Interaction preference) and 0.29 (Pure binding) for ER agonists. These experiments indicated that the pharmacological interaction preferences were able to improve the GH scores for both the cleaned lists and original set; moreover, the ligand preferences might improve the screening accuracy of a scoring function and become the filters to prepare a ligand database.

In summary, we developed a near-automatic tool with a novel scoring function for VS by making numerous modifications and enhancements to our original techniques. By integrating a number of genetic operators, each having a unique search mechanism, GEMDOCK seamlessly blends the local and global searches so that they work cooperatively. The key aspect of the present work is that our new scoring function uses pharmacological interaction preferences to select the ligand structures that form pharmacological interactions with target proteins; furthermore, the scoring function applies ligand preferences to select ligand structures that are similar to known active ligands. Our scoring function is indeed able to enhance the accuracy during flexible docking and improves the screening utility by reducing the number of FPs during the postdocking analysis. Our results demonstrate the applicability and adaptability of GEMDOCK for virtual screening.

REFERENCES

1. Lyne PD. Structure-based virtual screening: an overview. *Drug Discov Today* 2002;7:1047–1055.
2. Shoichet BK, McGovern SL, Wei B, Irwin J. Lead discovery using molecular docking. *Curr Opin Chem Biol* 2002;6:439–446.
3. Doman TN, McGovern SL, Witherbee BJ, Kasten TP, Kurumbail R, Stallings WC, Connolly DT, Shoichet BK. Molecular docking and high-throughput screening for novel inhibitors of protein tyrosine phosphatase-1B. *J Med Chem* 2002;45:2213–2221.
4. Kubinyi H. QSAR and 3-D QSAR in drug design: 1. Methodology. *Drug Discov Today* 1997;2:457–467.
5. Kuntz ID, Blaney JM, Oatley SJ, Langridge R, Ferrin TE. A geometric approach to macromolecular-ligand interactions. *J Mol Biol* 1982;161:269–288.
6. Jones G, Willett P, Glen RC, Leach AR, Taylor R. Development and validation of a genetic algorithm for flexible docking. *J Mol Biol* 1997;267:727–748.
7. Kramer B, Rarey M, Lengauer T. Evaluation of the FlexX incremental construction algorithm for protein–ligand docking. *Proteins* 1999;37:228–241.
8. Ewing TJ, Makino S, Skillman AG, Kuntz ID. DOCK 4.0: search strategies for automated molecular docking of flexible molecule databases. *J Comput Aided Mol Des* 2001;15:411–428.
9. Morris GM, Goodsell DS, Halliday RS, Huey R, Hart WE, Belew RK, Olson AJ. Automated docking using a Lamarckian genetic algorithm and empirical binding free energy function. *J Comput Chem* 1998;19:1639–1662.
10. Yang J-M, Chen C-C. GEMDOCK: a generic evolutionary method for molecular docking. *Proteins* 2004;55:288–304.
11. Gohlke H, Hendlich M, Klebe G. Knowledge-based scoring function to predict protein–ligand interactions. *J Mol Biol* 2000;295:337–356.
12. Weiner SJ, Kollman PA, Case DA, Singh UC, Ghio C, Alagona G, Profeta SJ, Weiner P. A new force field for molecular mechanical simulation of nucleic acids and proteins. *J Am Chem Soc* 1984;106:765–784.
13. Gehlhaar DK, Verkhivker GM, Rejto P, Sherman CJ, Fogel DB, Fogel LJ, Freer ST. Molecular recognition of the inhibitor AG-1343 by HIV-1 protease: conformationally flexible docking by evolutionary programming. *Chem Biol* 1995;2:317–324.
14. Bissantz C, Folkers G, Rognan D. Protein-based virtual screening of chemical databases: 1. Evaluation of different docking/scoring combinations. *J Med Chem* 2000;43:4759–4767.
15. Stahl M, Rarey M. Detailed analysis of scoring functions for virtual screening. *J Med Chem* 2001;44:1035–1042.
16. Langer T, Krovat EM. Chemical feature-based pharmacophores and virtual library screening for discovery of new leads. *Curr Opin Drug Discov Dev* 2003;6:370–376.
17. Fradera X, Knegtel RMA, Mestres J. Similarity-driven flexible ligand docking. *Proteins* 2000;40:623–637.
18. Hindle SA, Rarey M, Buning C, Lengauer T. Flexible docking

- under pharmacophore type constraints. *J Comput Aided Mol Des* 2002;16:129–149.
19. Pegg SC-H, Haresco JJ, Kuntz ID. A genetic algorithm for structure-based de novo design. *J Comput Aided Mol Des* 2001;15:911–933.
 20. Muegge I, Martin YC, Hajduk PJ, Fesik SW. Evaluation of PMF scoring in docking weak ligands to the FK506 binding protein. *J Med Chem* 1999;42:2498–2503.
 21. Yang J-M. Development and evaluation of a generic evolutionary method for protein–ligand docking. *J Comput Chem* 2004;25:843–857.
 22. Good AC, Cheney DL, Sitkoff DF, Tokarski JS, Stouch TR, Bassolino DA, Krystek SR, Li Y, Mason JS, Perkins TD. Analysis and optimization of structure-based virtual screening protocols: 2. Examination of docked ligand orientation sampling methodology: mapping a pharmacophore for success. *J Mol Graph Model* 2003;22:31–40.
 23. Joseph-McCarthy D, Thomas BEI, Belmarsh M, Moustakas D, Alvarez JC. Pharmacophore-based molecular docking to account for ligand flexibility. *Proteins* 2003;51:172–188.
 24. Miller CP. SERMs: evolutionary chemistry, revolutionary biology. *Curr Pharm Des* 2002;8:2089–2111.
 25. Dutertre M, Smith CL. Molecular mechanisms of selective estrogen receptor modulator (SERM) action. *J Pharmacol Exp Ther* 2000;295:431–437.
 26. Shiau AK, Barstad D, Loria PM, Cheng L, Kushner PJ, Agard DA, Greene GL. The structural basis of estrogen receptor/coactivator recognition and the antagonism of this interaction by tamoxifen. *Cell* 1998;95:927–937.
 27. van Lipzig MM, ter Laak AM, Jongejan A, Vermeulen NP, Wameling M, Geerke D, Meerman JH. Prediction of ligand binding affinity and orientation of xenoestrogens to the estrogen receptor by molecular dynamics simulations and the linear interaction energy method. *J Med Chem* 2004;47:1018–1030.
 28. Warnmark A, Treuter E, Gustafsson JA, Hubbard RE, Brzozowski AM, Pike AC. Interaction of transcriptional intermediary factor 2 nuclear receptor box peptides with the coactivator binding site of estrogen receptor alpha. *J Biol Chem* 2002;277:21862–21868.
 29. Brzozowski AM, Pike AC, Dauter Z, Hubbard RE, Bonn T, Engstroem O, Oehman L, Greene GL, Gustafsson JA, Carlquist M. Molecular basis of agonism and antagonism in the oestrogen receptor. *Nature* 1997;389:753–758.
 30. Renaud J, Bischoff SF, Buhl T, Floersheim P, Fournier B, Halleux C, Kallen J, Keller H, Schlaeppli JM, Stark W. Estrogen receptor modulators: identification and structure-activity relationships of potent ER-alpha-selective tetrahydroisoquinoline ligands. *J Med Chem* 2003;46:2945–2957.
 31. Gust R, Keilitz R, Schmidt K. Synthesis, structural evaluation, and estrogen receptor interaction of 2,3-diarylpiperazines. *J Med Chem* 2002;45:2325–2337.
 32. Garg R, Kapur S, Hansch C. Radical toxicity of phenols: a reference point for obtaining perspective in the formulation of QSAR. *Med Res Rev* 2001;21:73–82.
 33. Fisher LS, Guner OF. Seeking novel leads through structure-based pharmacophore design. *J Braz Chem Soc* 2002;13:777–787.
 34. Sadowski J, Gasteiger J, Klebe G. Comparison of automatic three-dimensional model builders using 639 X-ray structures. *J Chem Inform Comput Sci* 1994;34:1000–1008.
 35. Jain AN. Surflex: fully automatic flexible molecular docking using a molecular similarity-based search engine. *J Med Chem* 2003;46:499–511.