A spatial model of nanosized titanium dioxide material was created using Discovery Studio Visualizer software, versions 2.0 and 2.5. A search for and analysis of possible sites of its docking to the extracellular part of GABA<sub>B1a</sub> receptor subunit were performed using the algorithm for molecular docking PatchDock. The dimensions of the obtained TiO<sub>2</sub> nanoparticle surface were (18.925 × 3.785 × 19.028) Å. Four potentially possible sites of TiO<sub>2</sub> docking to the extracellular part of GABA<sub>B1a</sub> receptor subunit of GABA<sub>B</sub> were identified. The TiO<sub>2</sub> nanoparticle demonstrated high affinity of docking to one of the receptor sites with the geometric shape complementarity score of 12562, taking the following values in other sites: 10746; 10370; 10204. The approximate interface area of complex of the extracellular part of GABA<sub>B1a</sub> receptor subunit of GABA<sub>B</sub> with TiO<sub>2</sub> for the site with the highest geometric shape complementarity score was 1949.80 Å, and for others – 1273.20 Å, 1261.10 Å and 1170.30 Å, respectively. The evaluation of atomic contact energy demonstrated the following values for the sites of TiO<sub>2</sub> nanoparticle docking: 362.92; 173.93; 340.63 and 224.61. The nature of connections, stabilizing the sites of TiO<sub>2</sub> docking to the extracellular part of GABA<sub>B1a</sub> receptor subunit of GABA<sub>B</sub>, was analyzed in accordance to their amino acid composition.

**Keywords:** TiO<sub>2</sub> nanoparticles, GABA<sub>B</sub> receptor, molecular docking, PatchDock.

**INTRODUCTION**

It is known that in the form of nanoparticles, many substances acquire fundamentally new physical and chemical properties and are quite active in that state regarding the biological objects, whose macromolecules are also at the level of the nanometer dimensions, revealing their function via the formation of supermolecular complexes. These materials include titanium dioxide (TiO<sub>2</sub>), whose use in the form of nanoparticles has considerably extended in modern highly technological production processes in different sectors of economy, in particular, in food production and pharmacology [21]. According
to literature data [3, 4, 5, 14, 27], TiO$_2$ is a polar adsorbent, whose most active centers are superficial hydroxyl groups, capable of dissociating and forming positively and (or) negatively charged adsorption centers. It was shown [18] that TiO$_2$ particles are capable of adsorbing on its surface aminoacids, in particular, histidine (Fig. 1).

![Fig. 1. Histidine adsorption on the surface of TiO$_2$ nanoparticles [18]. Amino acids are bound to the surface of TiO$_2$, which creates conditions for intramolecular transfer of a proton onto the carboxyl group of adsorbed histidine. In addition, the imidazole ring may interact via π-orbitals with titanium atoms, located on the surface, and the amino acid may form H-bonds with superficial atoms of oxygen [4] ](image)

Taking that into consideration, it was interesting to investigate molecular mechanisms of interaction between TiO$_2$ nanoparticles and molecules of proteins-receptors, in particular, metabotropic GABA$_B$ receptor [2, 11] whose the mediator is a known transmitter of the central nervous system, γ-aminobutyric acid, that participates in control over blood circulation, implemented by neurons of dorsomedial and ventrolateral divisions of medulla oblongata [23, 24, 26]. To solve this issue by the molecular docking method, the search for binding sites of TiO$_2$ particles and the extracellular part of GABA$_B$ receptor was performed. The aim of our work was also to construct the spatial structure of TiO$_2$ particle, using Discovery Studio Visualizer software 2.0 and 2.5 of versions. The construction of the spatial structure of full-size GABA$_B$ receptor (Fig. 2), the investigation of its molecular dynamics and estimation of the energy of nonvalent interactions in the model of the complex of GABA$_B$ receptor with lipid bilayer membrane was performed in our previous work [19].

**MATERIALS AND METHODS**

In order to construct a spatial structure of TiO$_2$ nanoparticle, its crystal modification, anatase, was used [10]. A remarkable specificity of the modification of this nanoparticle material is a system of channels, oriented parallel to the plane of the crystallographic face. The channels in the cross section form a square with the side of 3.35 Å. The anatase structure has a form of three-dimensional chains made of TiO$_6$ octahedra. Each octahedron contains a central ion Ti$^{4+}$ surrounded by six anions O$^{2-}$. Four anions are located in the equatorial plane, and two – in the axial points. The equatorial connections
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**Fig. 2.** Spatial structure of GABA\(_B\) receptor. This is a heterodimer consisting of two subunits (GABA\(_{B1\alpha}\) and GABA\(_{B2}\)) [22]. In its turn, each subunit consists of the extracellular part (\(\beta\)-elements successively interchanging \(\alpha\)-helices forming unique “claws”); the transmembrane part (containing seven successively connected \(\alpha\)-helices); the intracellular part (containing the part, that serves for the formation of the superhelical structure) [8, 9, 22]

in the anatase are 1.980 Å, axial ones – 1.985 Å [7]. In our work, according to [16] the spatial structure of titanium dioxide nanoparticle was constructed using Discovery Studio Visualizer software 2.0 and 2.5 of versions (Accelrys Software Inc. – http://accelrys.com/). PatchDock, a geometry-based molecular docking algorithm, was used in a search for interaction sites of the extracellular part of GABA\(_B\) receptor and the TiO\(_2\) nanoparticle [6, 25]. This algorithm consists of three main stages: Molecular Shape Representation, Surface Patch Matching and Filtering and Scoring. PatchDock computes the three-dimensional transformations of one of two molecules with respect to the other with the goal of maximizing surface shape complementarity while minimizing the number of steric clashes. Docking programs adapted to native conditions, consequently these programs are used at physiological pH. The service is available at http://bioinfo3d.cs.tau.ac.il/PatchDock/. The visualization and analysis of the contact surfaces were performed using Discovery Studio Visualizer software 2.0 and 2.5 of versions.

**RESULTS AND DISCUSSION**

According to the catalog, the receptor subunit of gamma-aminobutyric acid, type B, was indicated in the work as GABA\(_B\)\(_{1\alpha}\) [1], where \(\alpha\) relates to the subunit isoform, and \(\beta\) indicates its number. The spatial structure of the extracellular part of GABA\(_B\)\(_{1\alpha}\) subunit (15–592 amino acid residues) was obtained via the molecular simulation of the full-size GABA\(_B\) receptor, that was conducted in our previous studies (Fig. 3, A) [19]. The three-dimensional structure of the TiO\(_2\) particle (Fig. 3, B) was simulated using Discovery Studio Visualizer software 2.0 and 2.5 of versions. Taking into consideration the data about the crystallography of anatase, the following parameters of the elementary cluster of TiO\(_2\) were used in our work: \(A = B = 3.785\) Å; \(C = 9.514\) Å, where \(A, B, C\) – lengths of the crystalline grid. \(a = b = \gamma = 90^\circ\), where \(a, b, \gamma\) – dimensions of crystal angles. The spatial symmetry group (the combination of symmetry transformations, remarkable for atomic structure of crystals) of titanium dioxide, is \(I4(1)/amd\) [7, 12]. The dimensions of the surface of TiO\(_2\) nanoparticle obtained after the simulation of the spatial structure, were as follows: \((18.925 \times 3.785 \times 19.028)\) Å.
A search for and analysis of the interaction sites of TiO$_2$ and the extracellular part of the GABA$_{B1a}$ receptor subunit was performed using PatchDock web-service. The input parameters for the docking were the PDB coordinate file for the extracellular part of the GABA$_{B1a}$ receptor subunit and the TiO$_2$ nanoparticle. Clustering of RMSD (Root-mean-square deviation) was chosen as 4.0 Å. Clustering of RMSD is a positive number that specifies the radius of the RMSD clustering in angstroms. This value is used in the final clustering stage of the algorithm. It ensures that the distance between any of two output solutions will be at least the specified clustering of RMSD value. The default value for this parameter is 4 Å [25]. Complex Type was chosen as protein–small ligand. In the case of protein–small ligand docking, the algorithm uses a parameter set optimized for small-size molecules. Potential binding sites of the receptor and the ligand, respectively, were not chosen. A web page that presents the solutions is automatically generated. The output of PatchDock is a list of candidate complexes between extracellular part of GABA$_{B1a}$ receptor subunit and TiO$_2$. The geometric score (Score), the atomic contact energy (ACE) [28], the size of interface area (Area) and the actual rigid transformation of the solution for the four binding sites are shown in Table 1. The atomic contact energy is used to estimate the contribution of the desolvation energy to the scoring function. The ACE score of a pair of protein atoms is defined as the free energy difference between two protein-atoms and water contacts and the sum of a protein-atom to protein-atom contact and a water to water contact. Presented transformations are 3D transformations that include 3 rotational angles and 3 translational parameters. These transformations are applied on the TiO$_2$ nanoparticle.

The results of the molecular docking of the TiO$_2$ nanoparticle demonstrate that the latter induces four potential sites of different affinity for its binding to the extracellular part of GABA$_{B1a}$ of GABA$_B$ receptor subunit. According to data of the estimations of PatchDock web-service, TiO$_2$ possessed high affinity of binding to one of receptor sites with the geometric shape complementarity score of 12562, and in other sites – 10746;
10370; 10204. The approximate interface area of the complex of the extracellular part of subunit GABA<sub>B1α</sub> of GABA<sub>B</sub> receptor and TiO<sub>2</sub> for one of sites is 1949.80 Å, and for others – 1273.20 Å, 1261.10 Å and 1170.30 Å, respectively. This value is in distinct correlation with the geometric shape complementarity score. It was determined that the level of affinity as a result of strong intramolecular interaction in the site of the protein-receptor binding TiO<sub>2</sub>, the distribution within the site of amino acids forming long-term electrostatic hydrogen bonds, hydrophobic interactions are determined by their location on the receptor molecule, namely, the first one – on the side, opposite the slit between the lobes 1 (LB1) and 2 (LB2) closer to N-terminal part, the second one – in the slit between LB1 and LB2, the third one – on the surface of the receptor macromolecule near the slit between LB1 and LB2 and the fourth one – on the side, opposite the slit between LB1 and LB2 closer to the zone of their binding. The sites were numbered according to the reduction in their affinity degree.

Table 1. Docking analysis of the extracellular part of GABAB1a subunit and TiO<sub>2</sub> complex

| No sites | Score  | Area    | ACE     | Transformation |
|---------|--------|---------|---------|---------------|
| 1       | 12562  | 1949.80 | 362.92  | 0.17 0.54 0.68 36.67 -5.22 64.30 |
| 2       | 10746  | 1273.20 | 173.93  | -2.34 -0.06 -0.04 14.29 21.48 64.11 |
| 3       | 10370  | 1261.10 | 340.63  | -1.41 -0.93 2.29 35.09 31.20 90.90 |
| 4       | 10204  | 1170.30 | 224.61  | 0.23 0.03 -0.05 14.30 -9.71 41.04 |

It was established (Fig. 4) that the amino acid composition and environment of the first binding site include the following amino acids: Trp37, Glu38, Val74, Thr92, Arg95, Cys96, Arg98, Gly116, Gly117, Asp118, Leu119, Pro120, Leu122, Pro153, Lys154, Pro155, His156, Arg258, Arg277, Gln278, Pro281, Gln503, Thr504, Asp507, Gln508, Tyr510, Arg511, Asn514, Asp528, Ala529, Ser530. The evaluation of the atomic contact energy demonstrated its value for this site of TiO<sub>2</sub> nanoparticle binding to be 362.92.

The analysis of the amino acid composition of the site with the highest affinity of binding TiO<sub>2</sub> (the first site) demonstrated that the variety of its composition includes all currently known amino acids with polar charged radicals capable of forming long-term electrostatic charges (the charge of the amino acid radical is indicated in brackets): Glu38 (-), Arg95 (+), Arg98 (+), Asp118 (-), Lys154 (+), His156 (+), Arg258 (+), Arg277 (+), Asp507 (-), Arg511 (+), Asp528 (-) with prevailing amino acids, whose radicals have a positive charge. Among these amino acids, arginine and lysine are amino acids with high occurrence degree and the least conformational entropy of the side chain (as the estimation of the amino acid ability of forming the helix), for which Gibbs free energy (∆G) is (-0.68) kJ/mol and (-0.65) kJ/mol, respectively (calculated via changes in the temperature of the helix-coil transition while injecting a specific amino acid into the standard amino acid sequence of peptide), according to literature data [20]. As for glutamic and asparagine acids which are in this site composition, at the expense of the carboxylic group of side chains they are well-adsorbed on the surface of anatase [15]. The stabilization of the position of TiO<sub>2</sub> particle in this site of binding to the protein-receptor
GABA\_B\_1, in addition to the electrostatic interactions, is affected by the hydrogen bonds, whose formation, as seen from the model, is facilitated by the following polar uncharged amino acids: Thr92, Cys96, Gln278, Gln503, Thr504, Gln508, Tyr510, Asn514 and Ser530. \( \Delta G \) of these amino acids is in the range of (-0.07) – (-0.35) kJ/mol. Noteworthy it is the presence of cysteine in the list of the mentioned amino acids, as high polarization capacity of the electronic envelope of its sulfur atom makes it an active center of interacting with reagents and, as may be assumed, – with TiO\_2 in particular. The amino acid composition of this binding site also contains the hydrophobic amino acids, including four residues of proline. It is known [13, 20] that proline (\( \Delta G = +3 \) kJ/mol) is the only cyclic amino acid whose amino group is not free and is a part of heterocycle, so this amino acid does not participate in the formation of the hydrogen bond. Proline binds to the polypeptide chain via covalent bonds and forms its clear link with the open access of peptide bonds. According to literature data [18] regarding the capability of TiO\_2 to form bonds both with amino groups of amino acid residues in protein and to its peptide bonds, they may become an additional place of interacting with nanoparticles. As stated above, the affinity of the first binding site acquires the value exceeding the value of this parameter for all three following sites. The results of estimating the approximate interface area of complex for each binding site of TiO\_2 allowed revealing similar regularities (Table 1).

The following binding site (Fig. 5) for TiO\_2 particle and its environment includes such amino acids: Gly181, Trp182, Cys246, Ser247, Ser248, Ser270, Ser271, Gln314, Thr316, Val318, Ser345, Tyr367, Glu368, Thr369, Arg372, Lys373, Trp395, Ala397, Ile403, Tyr404, Asp405, Pro406, Ser407, Glu459, Gly462, Gly463, Phe464, Gln465, Glu466. The estimations of ACE for this site performed using PatchDock web-server, demonstrated that it acquires the value of 173.93.
Fixing of the TiO₂ nanoparticle in the second binding site located in the slit between LB1 and LB2 of the extracellular part of the receptor, also occurs with the participation of the electrostatic interactions, ensured by polar radicals of amino acids, whose number is almost twice smaller than in the first site located opposite the slit between LB1 and LB2 close to N-terminal part (Glu368 (-), Arg372 (+), Lys373 (+), Asp405 (-), Glu459 (-), Glu466 (-)), which may be related to a low, compared to aqueous environment, value of the dielectric constant of the environment in the “claws” of receptor macromolecule. This site has fewer amino acids with a small value of conformational entropy: only one amino acid, arginine, and one amino acid, lysine, whose Gibbs free energy, as stated above, is (-0.68 and 0.65 kJ/mol). ΔG for other polar charged amino acids of this binding site takes the values from (-0.15) to (-0.27) kJ/mol. The analysis of obtained results demonstrated that a considerable number of bonds with TiO₂, formed at the second binding site, are hydrogen bonds, whose formation is promoted by the radicals of polar uncharged amino acids (Cys246, Ser247, Ser248, Ser270, Ser271, Gln314, Thr316, Ser345, Tyr367, Thr369, Tyr404, Ser407, Gln465), among which the prevalence in amount is attributed to the capping amino acid serine which is known to be the most reactive amino acid due to its functionally active hydroxyl group [17]. As stated above, cysteine is another amino acid among polar uncharged ones whose reactive capability is ensured by the sulfur atom with high polarization capacity of its electronic envelope. ΔG for the abovementioned amino acids is in the range of (-0.17) to (-0.35) kJ/mol. On contrary to the first binding site of TiO₂, a group of the hydrophobic amino acids in its composition contains one amino acid proline instead of four. In terms of quantity, the number of the hydrophobic and non-polar amino acids in both sites is practically the same.
The composition and environment of the third site (Fig. 6) of binding TiO$_2$ particle includes the following amino acids: Tyr171, Met178, Gln189, Pro190, Glu193, Asn200, Glu210, Leu211, Lys212, Leu213, Ile214, His215, His216, Asp217, Lys219, Lys227, Tyr228, Glu231, Asn235, Pro237, Arg453, Leu454, Arg456. The ACE value for this site is 340.63.

![Fig. 6. The third site of TiO$_2$ binding to the extracellular part of GABA$_B_{1a}$ of GABA$_B$ receptor subunit (Score – 10370, Area – 1261.10, ACE – 340.63)](image)

The forces ensuring the binding of TiO$_2$ particle in the third site located at the surface of the receptor macromolecule near the slit between LB1 and LB2, are mostly presented with the electrostatic interactions at the expense of radicals of the following amino acids: Glu193 (-), Glu210 (-), Lys212 (+), His215 (+), His216 (+), Asp217 (-), Lys219 (+), Lys227 (+), Glu231 (-), Arg453 (+), Arg456 (+). The content of uncharged and hydrophobic amino acids at this site are of the same order as the ones at the site with high affinity, but, on contrary to all other binding sites, non-polar amino acids are completely absent.

It was determined (Fig. 7) that the amino acid composition of the fourth site of binding TiO$_2$ nanoparticle and the environment is as follows: Ile32, His34, Pro35, Gly39, Gly40, Ile41, Tyr43, Ala53, Asn55, Arg68, Lys299, Glu302, Lys303, Trp304, Gly305, Lys307, Glu332, Ala333, Gly334, Lys557, Asp558, Asp559, Trp562. The ACE value for this site is 224.61.

The comparison of the binding site with the lowest affinity (the fourth binding site), located opposite the slit between LB1 and LB2 closer to the zone of their connection. The binding site with the highest affinity demonstrates that on contrary to a second one, the content of polar uncharged amino acids, whose radicals participate in the formation of hydrogen bonds, is presented by two amino acids only: tyrosine and asparagine with the highest conformational entropy of the side chain ($\Delta G$ takes the values of (-0.17 and -0.11) kJ/mol). As for polar uncharged amino acids, whose radicals form electrostatic interactions, when compared against the site of high affinity of binding TiO$_2$, its composition...
also includes such amino acids as arginine and lysine, that have the least conformational freedom and a high value of Gibbs free energy. The composition of the fourth site is as following: His34 (+), Arg68 (+), Lys299 (+), Glu302 (−), Lys303 (+), Lys307 (+), Glu332 (−), Lys557 (+), Asp558 (−), Asp559 (−). The binding site under consideration also has non-polar amino acids, whose number regarding the site of comparison increases more than twofold: Gly39, Gly40, Ala53, Gly305, Ala333, Gly334. Glycine with the value of ΔG = 0 kJ/mol, similar to proline (ΔG = +3 kJ/mol), causes destabilizing impact on the polypeptide chain, whereas the amino acid alanine does not have any conformational freedom (ΔG = -0.77 kJ/mol). As for hydrophobic amino acids, their number does not differ from their content at other binding sites for TiO₂. Fig. 8 shows the ratio of content of polar charged amino acids to polar uncharged amino acids in the sites of TiO₂ binding to the extracellular part of GABA₁α subunit.

Fig. 7. The fourth site of TiO₂ binding to the extracellular part of GABA₁α of GABA B receptor subunit (Score – 10204, Area – 1170.30, ACE – 224.61)

Fig. 8. The ratio of content of polar charged amino acids to polar uncharged amino acids (vertical axis) in sites of the nanosized TiO₂ material binding to the extracellular part of GABA₁α subunit. 1, 2, 3, 4 are numbers of binding sites

Thus, the molecular docking of TiO₂ nanoparticle to the extracellular part of GABA₁α of GABA B receptor subunit was performed using PatchDock web-service. The results of these studies demonstrated that TiO₂ in the form of nanosized material is capable of forming a supermolecular structure via interaction with the extracellular part of GABA₁α of GABA B receptor subunit, and it may be assumed that this will be accompanied by modulations in its spatial organization.
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MOLECULAR DOCKING OF NANOSIZED TITANIUM DIOXIDE MATERIAL TO THE EXTRACELLULAR PART OF GABA\textsubscript{B}-RECEPTOR

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Сконструйовано просторову модель нанорозмірного матеріалу діоксиду титану за допомогою програми Discovery Studio Visualizer версій 2.0, 2.5, проведено пошук і аналіз можливих сайтів його зв'язування із зовнішньоклітинною частиною субодиниці ГАМК\textsubscript{B1a} рецептора ГАМК\textsubscript{B} за допомогою алгоритму для молекулярного докінгу PatchDock. Розміри поверхні одержаної наночастинки TiO\textsubscript{2} становили (18,925 x 3,785 x 19,028) Å. Встановлено чотири потенційно можливі сайти зв'язування TiO\textsubscript{2} із зовнішньоклітинною частиною субодиниці ГАМК\textsubscript{B1a} рецептора ГАМК\textsubscript{B}. Наночастинці TiO\textsubscript{2} була притаманна висока афінність зв'язування з одним із сайтів рецептора зі значенням параметра оцінки комплементарності геометричної форми 12562, в інших сайтах приймаючи значення: 10746; 10370; 10204. Орієнтовна площа інтерфейсу комплексу зовнішньоклітинної частини субодиниці ГАМК\textsubscript{B1a} рецептора ГАМК\textsubscript{B} з діоксидом титану для сайту з найбільшим значенням параметра оцінки комплементарності геометричної форми 12562, в інших сайтах приймаючи значення: 10746; 10370; 10204. Орієнтовна площа інтерфейсу комплексу зовнішньоклітинної частини субодиниці ГАМК\textsubscript{B1a} рецептора ГАМК\textsubscript{B} з діоксидом титану для сайту з найбільшим значенням параметра оцінки комплементарності геометричної форми становила 1949,80 Å, а для інших – 1273,20 Å, 1261,10 Å та 1170,30 Å, відповідно. Розрахунки енергії атомного контакту підтвердили, що для сайтів зв'язування наночастинки TiO\textsubscript{2} ця енергія набуває таких значень: 362,92; 173,93; 340,63 та 224,61. Проаналізовано характер зв'язків, які стабілізують сайти зв'язування TiO\textsubscript{2} із зовнішньоклітинною частиною субодиниці ГАМК\textsubscript{B1a} рецептора ГАМК\textsubscript{B} відповідно до їхнього амінокислотного складу.

Ключові слова: наночастинки TiO\textsubscript{2}, ГАМК\textsubscript{B} рецептор, молекулярний докінг, PatchDock.
МОЛЕКУЛЯРНЫЙ ДОКИНГ НАНОРАЗМЕРНОГО МАТЕРИАЛА ДИОКСИДА ТИТАНА С ВНЕКЛЕТОЧНОЙ ЧАСТЬЮ ГАМК₆-РЕЦЕПТОРА

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Была сконструирована пространственная модель наноразмерного материала диоксида титана с помощью программы Discovery Studio Visualizer версий 2.0, 2.5, проведены поиск и анализ возможных сайтов его связывания с экстрацеллюлярной частью субъединицы ГАМК₆₁а рецептора ГАМК₆ с помощью алгоритма для молекулярного докинга PatchDock. Размеры поверхности полученной наночастицы TiO₂ составили (18,925 × 3,785 × 19,028) Å. Установлены четыре потенциально возможных сайта связывания TiO₂ с экстрацеллюлярной частью субъединицы ГАМК₆₁а рецептора ГАМК₆. Наночастица TiO₂ показала высокую аффинность связывания с одним из сайтов рецептора со значением параметра оценки комплментарности геометрической формы 12562, в других сайтах принимая значения: 10746; 10370; 10204. Ориентировочная площадь интерфейса комплекса экстрацеллюлярной части субъединицы ГАМК₆₁а рецептора ГАМК₆ с диоксидом титана для сайта с наибольшим значением параметра оценки комплментарности геометрической формы составила 1949,80 Å, а для других – 1273,20 Å, 1261,10 Å и 1170,30 Å, соответственно. Расчеты энергий атомного контакта показали, что для сайтов связывания наночастицы TiO₂ она приобретает следующие значения: 362,92; 173,93; 340,63 и 224,61. Проанализирован характер связей, которые стабилизируют сайты связывания TiO₂ с экстрацеллюлярной частью субъединицы ГАМК₆₁а рецептора ГАМК₆ в соответствии с их аминокислотным составом.

Ключевые слова: наночастицы TiO₂, ГАМК₆ рецептор, молекулярный докинг, PatchDock.

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