

# Repurposing FDA Approved Drugs as JNK3 Inhibitor for Prevention of Neuroinflammation Induced by MCAO in Rats

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**Background:** Stress-associated kinases are considered major pathological mediators in several incurable neurological disorders. Importantly, among these stress kinases, the c-Jun NH2-terminal kinase (JNK) has been linked to numerous neuropathological conditions, including oxidative stress, neuroinflammation, and brain degeneration associated with brain injuries such as ischemia/reperfusion injury. In this study, we adopted a drug repurposing/reprofiling approach to explore novel JNK3 inhibitors from FDA-approved medications to supplement existing therapeutic strategies.

**Materials and Methods:** We performed in silico docking analysis and molecular dynamics simulation to screen potential candidates from the FDA approved drug library using the standard JNK inhibitor SP600125 as a reference. After the virtual screening, dabigatran, estazolam, leucovorin, and pitavastatin were further examined in ischemic stroke using an animal rodent model of focal cerebral ischemia using transient middle cerebral artery occlusion (t-MCAO). The selected drugs were probed for neuroprotective effectiveness by measuring the infarct area (%) and neurological deficits using a 28-point composite score. Biochemical assays including ELISA and immunohistochemical experiments were performed.

**Results:** We obtained structural insights for dabigatran, estazolam, and pitavastatin binding to JNK3, revealing a significant contribution of the hydrophobic regions and significant residues of active site regions. To validate the docking results, the pharmacological effects of dabigatran, estazolam, leucovorin, and pitavastatin on MCAO were tested in parallel with the JNK inhibitor SP600125. After MCAO surgery, severe neurological deficits were detected in the MCAO group compared with the sham controls, which were significantly reversed by dabigatran, estazolam, and pitavastatin treatment. Aberrant morphological features and brain damage were observed in the ipsilateral cortex and striatum of the MCAO groups. The drugs restored the anti-oxidant enzyme activity and reduced the levels of oxidative stress-induced p-JNK and neuroinflammatory mediators such as NF- $\kappa$ B and TNF- $\alpha$  in rats subjected to MCAO.

**Conclusion:** Our results demonstrated that the novel FDA-approved medications attenuate ischemic stroke-induced neuronal degeneration, possibly by inhibiting JNK3. Being FDA-approved safe medications, the use of these drugs can be clinically translated for ischemic stroke-associated brain degeneration and other neurodegenerative diseases associated with oxidative stress and neuroinflammation.

**Keywords:** re-purposing, in silico docking, JNK3 kinase, MCAO stroke, JNK3 inhibitors, neuroinflammation, brain degeneration

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## Background

For neurological disorders, stroke is globally a prominent cause of mortality and is estimated to become the fourth most conspicuous disability caused due to heart

diseases by 2020.<sup>1-3</sup> The pathological cascade of ischemic stroke is triggered by the blockage of a cerebral artery either by thrombus and/or emboli, and accounts for ~87% of all stroke cases, triggering neurological and psychological conditions.<sup>4</sup> Currently, thrombolytics that act by vascular recanalization are approved by the FDA, but only 15% of patients benefit from the minimal therapeutic window (3–4.5 h) and show increased intracerebral hemorrhage (ICH).<sup>5,6</sup> Therefore, during the last decade, numerous neuroprotectant development programs have been executed to target early pathological processes, including oxygen and energy shortages, calcium influx, oxidative stress, free radicals, excitotoxicity, inflammatory/immunological processes, and apoptotic neurodegeneration, yet none of these attempts have successfully passed clinical trials. Thus, it is a challenging task to effectively manage stroke in clinical scenarios.

Recent studies on the pathological processes of stroke have revealed that oxidative stress is associated with inflammation that is initiated early in the stroke. Therefore, the identification of critical disease-modifying molecules that are implicated in injury, and the development of therapeutics against them may be a promising therapeutic strategy. The c-Jun NH2-terminal kinase (JNK) signaling pathway mediates the stress-induced inflammatory cascade and is implicated in mitochondrial apoptosis.<sup>7</sup> JNK is an important member of the MAPK family involved not only in apoptotic pathways,<sup>8</sup> but also in cell regulating mechanisms such as cell proliferation, and gene expression.<sup>9</sup> JNK (as p-JNK) activates apoptotic cell death by transcriptional and posttranscriptional modification and it is involved in numerous pathophysiological mechanisms not only in stroke,<sup>10</sup> but other chronic neurodegenerative disorders, such as Parkinson's and Alzheimer's.<sup>10-12</sup> Several reports have demonstrated that active JNK is involved in the phosphorylation of tau proteins including in stroke<sup>13</sup> and traumatic brain injury.<sup>14,15</sup> Furthermore, JNK3 knockout mice are remarkably resistant to kainic acid-induced excitotoxicity<sup>16</sup> and attenuated neuronal death in the global ischemia-hypoxia model.<sup>17</sup> Knocking out of the JNK3 gene condenses the apoptotic Bim and Fas activity after stroke and with parallel less cytochrome c release following oxygen-glucose deprivation.<sup>17</sup> Furthermore, the peptide JNK inhibitor, D-JNKI also showed a remarkable neuroprotective effect in both the transient and permanent middle cerebral artery occlusion (MCAO) model of stroke.<sup>18</sup> Based on this literature survey, we proposed that the JNK pathway could

represent a potential therapeutic target for the treatment of ischemic stroke.

The latest research work on a dozen inhibitors, including JNK3, has significantly enhanced our understanding of the signaling cascade in several related neurodegenerative models. One specific inhibitor, SP600125, a reversible ATP-competitive anthrapyrazolone, exhibited a 300-fold increase in selectivity for JNK over extracellular signal-regulated kinases such as ERK and p38 MAPKs. It decreases ischemic-reperfusion injury in the brain.<sup>19</sup> However, it has limitations in terms of safety and translation for use in the clinic.

Similarly, other de novo drug innovations and developments for stroke remain a prolonged, risky, and costly process. Notably, ~90% of drugs have failed during development due to the lack of efficacy or safety concerns.<sup>20</sup> Collectively, it takes ~13-15 years and USD 2.6 billion to bring a new drug to the market. These parameters and enormous expenditures coupled with other obstacles in novel drug development demand the use of substitute methodologies, including drug re-profiling or repositioning. This innovative paradigm in drug development is cost-effective and time-saving and has known safety profiles.<sup>21</sup> Drug reprofiling implies a new therapeutic intervention due to a reinvestigation of the existing drug,<sup>22</sup> and the most recent example is that of dimethyl fumarate (Tecfidera<sup>®</sup>) for multiple sclerosis, which was initially used for psoriasis.<sup>23</sup> Moreover, ropinirole and amantadine are now indicated for Parkinson's disease and were initially developed for the treatment of hypertension and influenza, respectively.<sup>24</sup> For drug repositioning, activity-based drug reprofiling includes the screening of the parent drug, whereas in silico drug reprofiling utilizes data banks and virtual screening to scientifically probe the interaction network between ligands and proteins.<sup>25</sup> Computational or in silico drug-repurposing can greatly speed up the traditional drug discovery and development process by automatically integrating and evaluating thousands of drugs and ailments.<sup>26</sup> However, to date, systematic and comprehensive computational approaches to identify and validate FDA-approved drug repositioning for ischemic stroke have not been undertaken. Here, we applied a repurposing approach for FDA-approved medication and present a novel drug discovery strategy using the JNK3-pathway as a specific target by using a combined computational drug-repositioning system and its experimental validation to rapidly identify repositioned drug candidates for clinical translation studies in the treatment of ischemic stroke.

## Materials and Methods

### Virtual Screening and Docking Analysis

#### Ligands Preparation

About 600 FDA-approved clinical drugs were randomly selected from <https://www.drugbank.ca/>. The upper threshold was selected based on two factors: first, the number of FDA drugs involved in bond formation with the active site residues of JNK3, and second, by the number of hydrogen bonds formed between the FDA drugs and JNK3 active residues. Moreover, a general selection criteria was set, and drugs were selected based on several factors, including local market availability, literature accessibility, and the relative role of the drugs in neurodegenerative disorders including BBB penetration. Moreover, protein-based drugs, elemental drugs, and drugs with intact patency were also excluded. The 2D structures of compounds were retrieved from the PubChem database.<sup>27</sup> The scrutinized compounds were then subjected to geometry optimization using the Avogadro tool<sup>28</sup> to evaluate the protonation and stereoisomerization properties.

#### Identification of JNK3 Active Site

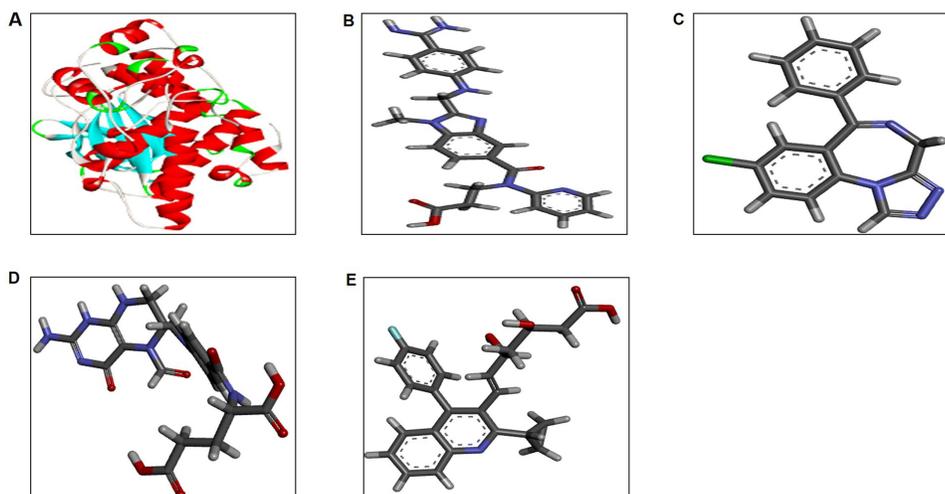
The crystal structure of JNK3 (PDB ID: 3TTI) was retrieved from PDB (<http://www.rcsb.org>), as shown in (Figure 1A).<sup>29</sup> The structure was evaluated by MolProbity, followed by refinement using WinCoot.<sup>30</sup> Subsequently, geometry optimization was performed using Yasara.<sup>31</sup> The JNK3 active site was identified as reported previously.<sup>32</sup> The ligand-binding pocket of JNK3 containing the active site consists of two residues, Glu147 (2.8 Å), and the main chain nitrogen of Met149 (2.8 Å).

#### Docking Studies on JNK3 with Selected FDA Approved Drugs

To identify new potential drugs for ischemic stroke, ~600 drugs were virtually screened using AutoDock Vina 4.2 to assess their binding potential against JNK3 with reference to the standard JNK3 inhibitor SP600125.<sup>33</sup> The grid map was adjusted to aid the molecular docking process with an exhaustiveness of 8. The dimensions of the grid were  $147 \times 272 \times 191$  points for the ligand with 0.375 Å spacing between the grid points. To compare and identify the best candidates, the compounds were redocked through the PatchDock approach. The hydrophobic and electrostatic interactions were mapped using LigPlus and UCSF Chimera 1.11.2.<sup>34</sup> Consequently, four drugs, ie, dabigatran, estazolam, leucovorin, and pitavastatin, with the lowest binding energy were selected for further in vivo and molecular mechanism studies. The 2D structures of dabigatran, estazolam, leucovorin, and pitavastatin are shown in (Figure 1). Binding residues, interactions (ie hydrophobic, hydrogen bonds, and electrostatic), and bonds were also deeply examined using Discovery Studio Visualizer.<sup>35</sup>

#### Molecular Dynamics (MD) Simulation

Molecular dynamics (MD) simulations were performed by utilizing the JNK3 bound inhibitors (Dabigatran, Estazolam, and Pitavastatin) to evaluate the interaction profile in terms of dynamics and to further dichotomize between these bound states using the Groningen Machine for Chemical Simulations (GROMACS) 5.0.7. For the structural and topological illustration, the force field



**Figure 1** The 3D structure of protein and ligand molecules (A) JNK3 (PDB ID: 3TTI). Structures of the selected FDA approved drugs (B) dabigatran, (C) estazolam, (D) leucovorin, and (E) pitavastatin.

parameterization PRODRG tool<sup>36</sup> was used. All MD simulations were performed using the GROMOS96 43A1 force field<sup>37</sup> to acquire an equilibrated system. The systems were solvated using the SPC216 water model in a periodic box (1 nm) followed by energy minimization (steepest descent algorithm for 500 steps), via tolerance of 1000 kJ/mol Å<sup>2</sup> to remove initial steric clashes. The energy-minimized systems were treated for a 1000 ps equilibration run under constant pressure and temperature conditions to relax the systems. Finally, MD simulations were run for a 50 ns time scale under constant temperature (300 K) and pressure (1 atm). The Particle Mesh Ewald (PME) algorithm was used in all calculations to dissect electrostatic interactions. The stability and time-dependent behavior of each system were investigated at different nanoscale intervals. GROMACS modules such as *g\_rms*, *g\_rmsf*, *g\_energy*, and *g\_hbond* functions were utilized to analyze the stability and behavior of each system. All MD trajectories were analyzed using the UCSF Chimera ver. 1.11.2, and Discovery Studio Visualizer.<sup>35</sup>

## Experimental Studies

### Chemicals and Reagents

The services of different biotechnological companies were hired to provide chemicals and reagents, such as MP Biomedicals LLC (USA) and Sigma-Aldrich Co. (USA) from which we obtained all consumables (solids and liquids). Phosphate buffer saline (PBS) tablets were used for the morphological analyses or fresh buffers were prepared for use in each experiment. The HPLC grade (99%) pharmaceutical drugs (dabigatran, estazolam, leucovorin, and pitavastatin) for use as raw materials were supplied by a local pharmaceutical manufacturer. The primary antibodies TNF- $\alpha$  (sc-52B83), p-NF- $\kappa$ B (sc-271908), p-JNK (sc-6254), and HO-1 (sc-13691), and immunohistochemistry related consumables such as ABC Elite kit (sc-2018), and 3,3-diaminobenzidine powder (DAB; sc-216,567), and the JNK inhibitor SP600125 (sc-200635) were purchased by Santa Cruz Biotechnology, USA. The goat anti-mouse IgG H&L (HRP) (ab6789) were purchased from Abcam UK. The ELISA kit for p-JNK was acquired from Shanghai Yuchun Biotechnology, China (cat. No. SU-B30586).

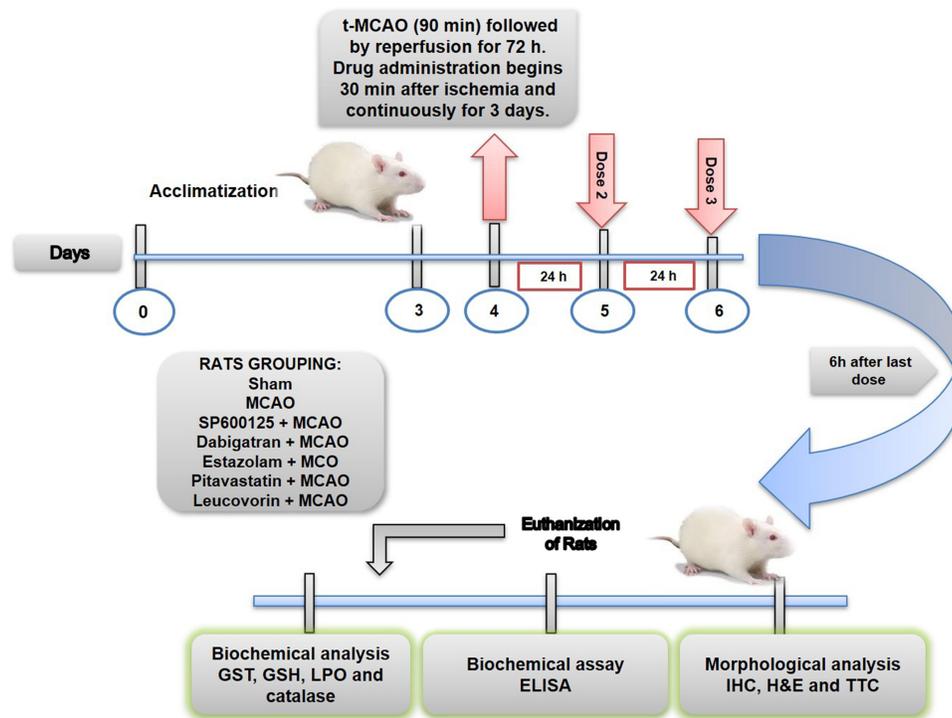
### Animals and Drug Treatment

Male Sprague Dawley rats weighing 250–300g were housed three per cage under a 12 hour light/dark cycle with free access to water and food at the animal house of the Riphah Institute of

Pharmaceutical Sciences (RIPS) using standard laboratory protocols (temperature: 22±1°C; humidity: 50%±10%). All experimental procedures were carried out as per the guidelines of the Institute of Laboratory Animal Resources. The animals were kept for some days at the facility before the experimental procedures, and the body weights were checked every alternate day throughout the study. As middle cerebral artery occlusion (MCAO) is a stressful and invasive procedure, supplementary procedures were adopted to minimize animal suffering such as the use of a heating pad and fluid replenishment. Further, we strictly followed the approved protocols and guidelines of the research and ethical committee (REC) of the Riphah Institute of Pharmaceutical Sciences (RIPS), Islamabad (Approval ID: Ref. No. REC/RIPS/2018/09), which are similar to the ARRIVE guidelines with minor exemptions.<sup>38</sup> Two cohorts of animals were used for the experiments, and 7 different experimental groups were used (Figure 2): (1) the vehicle administered sham group, also called the control group (n=17), and (2) the vehicle + transient-MCAO (t-MCAO) group. The vehicle used was saline with 3% DMSO, and transient (t-MCAO) was conducted for 90 min, followed by reperfusion for 3 days (72 h; n=17), (3) dabigatran (100 mg/kg) group/Dabi + t-MCAO (n=17), (4) estazolam (10 mg/kg) group/Esta + t-MCAO (n=17), (5) leucovorin (7.5 mg/kg) group/Leuc + t-MCAO (n=17), (6) pitavastatin (20 mg/kg) group/Pita + t-MCAO (n=17), and (7) SP600125 treated group/SP+t-MCAO (n=15). The drugs were dissolved in saline with 3% DMSO and were administered intraperitoneally (I/P) after ischemia (30 min), followed by 3 consecutive days (Figure 2). Due to the invasive surgical procedure, a total of 9 rats died, including in the t-MCAO group (3 rats), Dabi + t-MCAO and Leuc + t-MCAO (2 rats each), and the Esta + t-MCAO and Pita + t-MCAO groups (1 rat each). Therefore, the n-number per group was rectified with more animals. Multiple factors may cause this fatality, which includes but is not limited to BBB outflow, hypothalamic failure, or edema, as reported previously. Rats were sacrificed after 72 h, and the brain samples were collected.

### t-MCAO Surgery

An I/P administered mixture of xylazine and ketamine was used for animal anesthesia before the surgical procedures. Subsequently, the ocular ointment and heating pad were used to avoid eye dryness and maintain body temperature. The protocols for MCAO surgery used in our lab are well established.<sup>39–41</sup> Briefly, rats were placed in a supine position, and the neck area was shaved and disinfected using 70% ethanol. After disinfection, a midline incision was



**Figure 2** Schematic plot for the in vivo study design. Rats were first acclimatized to the environment before stroke induction. Following drug administration after MCAO, rats were subjected to neurobehavioral analysis, and subsequently, tissues were collected for biochemical analysis or for preparing brain sections for 2,3,5-triphenyl tetrazolium chloride staining, followed by their histological analysis.

made, and the underlying soft tissues were retracted to expose the vessels. The right common carotid artery was exposed and temporarily knotted using thin black 6/0 silk. The external carotid artery (ECA) was exposed, tied permanently, and ligated near the bifurcation point. A blue nylon filament (3/0) with a blunted and rounded tip was inserted through the opening of the external carotid artery and extended into the internal carotid artery up to 18–19 mm until it blocked the origin of the middle cerebral artery. Small resistance to nylon advancement also indicates MCA occlusion. The nylon filament was tied in place with the lumen of the artery, and the skin was sealed. After a 90 min occlusion period, the nylon filament was gently pulled back using forceps, and the filament was secured at the open end of the ECA to resume blood flow through the MCA. The sham group was subjected to the same surgical procedure, excluding filament insertion. No significant adverse effects were observed in the drug-treated animal groups. After the surgery, all animals were euthanized using CO<sub>2</sub>, and the brain was extracted and stored.

Although the experiment was conducted with skill and accuracy, the absence of blood flow measurements using the Doppler effect remained a limitation. Animals

showing no sloppy movement, circling behavior, or depressed signs were excluded from the study.

### Neurobehavioral Testing

To evaluate the extent of neurological damage and sensorimotor changes, a modified 28-point neuro score testing was done at 24, 48, and 72 h post-surgery. The composite score consisted of several subtests, with a cumulative score of 28.<sup>39</sup> A low score indicated severe injury, whereas no or less damage indicated a high score.

### Staining and Histological Preparation

After behavioral assessments, rats were anesthetized and decapitated. The brain tissue was carefully isolated and sliced into 2 mm thick coronal sections from the frontal lobe. The brain slices were stained using 2% 2,3,5-triphenyl tetrazolium chloride (TTC), which delineated the red and white infarcted areas. The TTC stained sections were then photographed on a white background paper sheet and analyzed using ImageJ to measure the infarct area. To counterbalance brain edema, the following formula was used for percent infarction:

$$\text{Corrected infarct area} = \frac{[\text{left hemisphere area} - (\text{right hemisphere area} - \text{infarct area})]}{100}.$$

The thick stained brain slices were stored in 4% paraformaldehyde for later use in the morphological analysis. For this purpose, the slices were embedded in paraffin and trimmed to thin 4  $\mu\text{m}$  sections using a Leica rotary microtome (First cohort).

### Hematoxylin and Eosin (H&E) Staining

H&E staining was performed according to previously published protocols. Briefly, the sections on non-coated slides were deparaffinized and rehydrated using xylene and a graded ethanol series. The rehydration step was completed using distilled water, and the slides were dipped for 10 min in a Coplin jar containing hematoxylin to stain the nucleus. Next, the slides were kept under running water and traced for nuclear staining using a compound microscope. If nuclear staining was not appropriate, the staining time with hematoxylin was increased. Slides were next dipped in 1% HCl for a few seconds, rinsed with water, and then rinsed with 1% ammonia water followed by a water rinse. Next, the slides were dipped in eosin solution for 5 min, rinsed with water, and air-dried. The slides were then dehydrated in graded ethanol, fixed in xylene, and covered with coverslips. Using light microscopy (Olympus, Japan), 5 images per slide were taken using the same threshold intensity, and ImageJ was used to quantify the number of distorted, vacuolated, infiltrated, and surviving neurons.

### Immunohistochemical Staining and Analysis

We used coated slides for immunohistochemical studies as previously described.<sup>41</sup> The slides were subjected to deparaffinization and hydration protocols as discussed above for H&E staining. To unlock the antigenic epitopes from paraformaldehyde, proteinase K was applied to the tissue, followed by a rinse with PBS. After hydration, the slides were not allowed to dry at any stage of immunohistochemical analysis. Before blocking with normal goat serum (NGS), slides were treated with  $\text{H}_2\text{O}_2$  to deplete peroxidase activity. After blocking for an appropriate time primary antibodies for mouse anti-phosphorylated-c-Jun N-terminal kinase (p-JNK), mouse anti-p-nuclear factor- $\kappa\text{B}$  (NF- $\kappa\text{B}$ ), mouse monoclonal anti (HO-1), and mouse monoclonal anti-TNF- $\alpha$  (1:100; Santa Cruz Biotechnology) were used with an overnight incubation at 4°C in a humidified chamber. The following morning, the slides were removed and kept for 1 h at room

temperature in a humidified chamber. After rinsing with PBS, a biotinylated secondary antibody (goat anti-mouse; the selectivity of the serum depends upon the source of the secondary antibody) was used and the ABC reagent (SCBT USA) as applied for 1 h in a humidified chamber. Slides were washed with PBS and stained with DAB solution. Slides were dried, dehydrated in an ascending ethanol series, fixed with xylene, and covered using coverslips. The neuronal positive cells derived via staining with the various primary antibodies were quantified at the same threshold intensity using ImageJ and the staining intensity was expressed as the relative integrated density of the samples relative to the control.

### Enzyme-Linked Immunosorbent Assay (ELISA)

p-JNK expression was quantified using a rat p-JNK ELISA kit as per the manufacturer's instructions. Approximately 50 mg of tissue sample was homogenized in PBS (2500  $\mu\text{L}$  + PMSF as a protease inhibitor), followed by centrifugation at 15,000 rpm, and the supernatant was collected. The protein concentration was measured using a BCA kit (Elabscience) and the same quantity of protein was added to each well to determine the protein concentration of p-JNK, using an ELISA microplate reader (BioTek ELx808). The resultant cytokine concentration (pg/mL) were normalized to the total protein content (pg/mg total protein).

## Antioxidant Assays

### Antioxidant Enzyme Analysis

The level of non-enzymatic glutathione (GSH) and the enzymatic activity of glutathione S-transferase (GST) was determined as previously discussed.<sup>39</sup> After homogenizing brain tissue samples (cohort 2) the supernatant was collected. For the assay, the stock of 0.2 M sodium phosphate buffer was prepared using  $\text{Na}_2\text{HPO}_4 \cdot 2\text{H}_2\text{O}$  and  $\text{NaH}_2\text{PO}_4$ , (pH 8). For the sample loading, sodium phosphate buffer (153  $\mu\text{L}$ ), freshly prepared 1 mM DTNB (40  $\mu\text{L}$ ), and supernatant (6.6  $\mu\text{L}$ ) were sequentially mixed. After 15 min, the absorbance of this mixture was measured at 412 nm using a spectrophotometer. A mixture of DTNB solution and phosphate buffer alone served as the control, and phosphate buffer was used as a blank measurement sample. The absorbance was expressed in  $\mu\text{mol}$  GSH/g of the sample. To detect the GST activity,<sup>42</sup> a stock of 0.1 M potassium phosphate buffer was prepared using  $\text{KH}_2\text{PO}_4$  and  $\text{KH}_2\text{PO}_4$  in a 1:2 ratio (pH 6.5). For the assay, 1 mM GST and 1 mM CDNB were prepared. For the assay, GST

solution, CDNB, potassium buffer, and tissue homogenate were mixed (1:1:27:1) and the optical density was recorded at 340 nm. The phosphate buffer was used as a blank and the assay mixture without homogenate was used as a control. The GST activity was calculated using the extinction coefficient of the product and expressed as  $\mu\text{moles}$  of CDNB conjugated/minute. Catalase activity was measured by mixing 3 mL of  $\text{H}_2\text{O}_2$  and 0.05 mL of tissue supernatant. The absorbance activity was measured at 240 nm relative to a blank containing 3 mL of PBS. The absorbance is proportional to the  $\text{H}_2\text{O}_2$  level, which is degraded by catalase. This measure of  $\text{H}_2\text{O}_2$  breakdown is expressed as  $\mu\text{moles}$  of  $\text{H}_2\text{O}_2$  decomposed per milligram of protein/min.<sup>43</sup>

### Determination of the Lipid Peroxidation (LPO) in Tissue

Increased LPO is an indirect indicator of neurological damage and can be determined by measuring the levels of thiobarbituric acid reactive substances (TBARS). The LPO assay was performed as reported previously, with slight modifications. Tissue supernatant (40  $\mu\text{L}$ ) was added to a freshly prepared solution of ferric ammonium sulfate and incubated for 30 min at 37°C. Next, 75  $\mu\text{L}$  of thiobarbituric acid (TBA) was added to this mixture and the absorbance was immediately measured at 532 nm using a microplate reader. TBARS levels were expressed as Tbars nM/min/mg protein.<sup>44</sup>

### Statistical Analysis

ImageJ was used to analyze the histological and TTC data. Behavioral analysis was performed using a grouped two-way analysis. All the data are expressed as means  $\pm$  SEM and were analyzed using one-way or two-way ANOVA followed by the post hoc Bonferroni multiple comparison test using the GraphPad Prism 6 software.  $P < 0.05$  indicates a significant difference. \* and # indicate a significant difference compared to sham-operated controls and MCAO, respectively.

## Results

### In-Silico Analysis

#### Structural Evaluation of JNK3

The evaluation tool indicated the efficacy and reliability of the JNK3 structures. Overall, 97% of the favored region was noticed in the Ramachandran plot of the regions were favored. Subsequently, outliers and poor rotamers were corrected to refine the model. Table 1 illustrates the scores

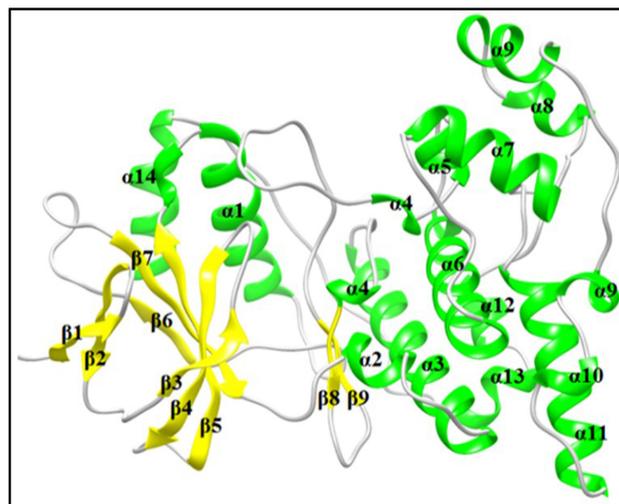
**Table 1** Structural Evaluation of JNK3

Parameters	Pre-Optimization	Post-Optimization
Poor rotamers	41	4
Favored rotamers	232	301
Ramachandran outliers	2	3
Ramachandran favored	309	328
C $\beta$ deviations >0.25Å	1	0
Bad bonds	0	7/2833
Bad angles	0	11/3838

for the seven parameters of the refined structures as obtained from the MolProbity server. The refined 3D structure of JNK3 is shown (Figure 3).

### Binding Analysis

The drug-receptor poses through the docking analysis with the lowest energy values were selected for detailed binding pattern characterization (Tables 2 and 3). To demonstrate the integrity of the resultant complex, the adjoining residues in the proximity of the JNK3 active site were assessed comprehensively. Dabigatran exhibited binding to JNK3 with a score of  $-9.2$  kcal/mol, and the Ile70, Ala74, Val78, Lys93, Arg107, Glu111, Met149, Asn194, Val196, and Met219 residues were actively involved. Ile70, Ala74, Val78, and Val196 formed  $\pi$ -alkyl interactions with dabigatran, whereas  $\pi$ -sulfur and  $\pi$ -cationic interactions were identified in dabigatran binding to Met219 and Arg107 residues of JNK3, respectively. The further evaluation indicated that the JNK3-estazolam complex exhibited a binding energy value of  $-8.9$  kcal/mol.



**Figure 3** The refined 3D structure of JNK3. The 3D structural architecture of JNK3 is shown.  $\alpha$ -helices and  $\beta$ -sheets are colored in green and yellow, and the linker region is colored in gray.

**Table 2** E-Values and Interacting Residues of JNK3 with Dabigatran, Estazolam, and Pitavastatin, and Leucovorin

Ligands	Energy Values (kcal/mol)	Hydrogen Bonding	Van Der Waals and Other Forces
Dabigatran	-9.2	MET-149 THR-226	ALA-74 ARG-107 VAL-78 ILE-70 LYS-93 GLU-111 ASN-194 VAL-196 MET-219
Estazolam	-8.9	MET-146 MET-149	SER-72 LYS-191 ASN-194 VAL-224 VAL-225 THR-226 ALA-74
Pitavastatin	-8.3	ASN-152 GLY-71 GLY-76 GLN-75 ASN-194	VAL-78 VAL-196 LEU-206 ALA-9 MET-146
Leucovorin	-8.7	MET-149 ALA-74 ASN-194 LYS-191 THR-226	LYS-93 VAL-78

**Abbreviations:** TYR, tyrosine; ARG, arginine; MET, methionine; ALA, alanine; VAL, valine; SER, serine; LYS, lysine; LEU, leucine; GLY, glycine; THR, threonine; ASN, asparagine.

Binding analysis of the best fit revealed the involvements of the Val78, Lys93, Asn152, Lys191, Ser193, and Arg230 residues. Specifically, a  $\pi$ -alkyl interaction was observed with Ala74. Furthermore, VanDer Waals interactions were observed with the Ser72, Lys191, Asn194, Val224, Val225, and Thr226 residues. JNK3-pitavastatin complex exhibited a binding energy value of -8.3 kcal/mol, with a favorable number of hydrogen bonding interactions via the Gln75, Asn152, Gly71, Gly76, and Asn194 residues. Pitavastatin formed a  $\pi$ -sigma interaction with Val78, Val196, and Leu206, and  $\pi$ -alkyl bond with Ala9. Moreover, Met146 residue was involved in binding to the aromatic ring of pitavastatin via a  $\pi$ -sulfur linkage. Generally, the structural insights for dabigatran, estazolam, and pitavastatin binding to JNK3 revealed a significant

**Table 3** Top 10 Ranked Compound Produced from Virtual Screening Including the Binding Energy of the Co-Crystallized Ligand

Ligands	Energy Values (kcal/mol)	Hydrogen Bonding	Van Der Waals Forces
SP600125	-8.2	MET-149 GLU-147	ALA-91 LEU-206 VAL-78 VAL196
Alprazolam	-9.2	MET-149	ALA-91 LYS-93 MET-146 VAL-196
Apomorphine	-8.6	MET-149 ASP-150	ALA-91 LEU-206 MET-146 VAL-196
Bosutinib	-8	MET-149 GLN-155	ILE-70 LEU-206 VAL-78
Brigatinib	-7.5	MET-149 ILE-70	ALA-74 GLN-155 VAL-78
Dabigatran	-9.2	MET-149 THR-226	ALA-74 ARG-107 VAL-78
Estazolam	-8.9	MET-146 MET-149	SER-72 LYS-191 ASN-194 VAL-224 VAL-225
Indinavir	-9.1	MET-149 SER-72	ALA-74 GLY-71 LYS-93 VAL-225
Leucovorin	-8.7	MET-149 ALA-74 ASN-194 LYS-191 THR-226	LYS-93 VAL-78
Ofloxacin	-9.2	MET-149	ALA-91 LYS-93 MET-146 LEU-206 VAL-78
Pemetrexed	-9	MET-149 GLN-155 ILE-70 LEU-144	ALA-91 LYS-93 MET-146 VAL-78

(Continued)

**Table 3** (Continued).

Ligands	Energy Values (kcal/mol)	Hydrogen Bonding	Van Der Waals Forces
Pimozide	-10	MET-149 SER-193	ALA-91 LYS-93 MET-146 VAL-78 VAL-196
Pitavastatin	-8.3	MET-146 ASN-152 GLY-71 GLY-76	VAL-78 VAL-196 LEU-206
Triazolam	-9	MET-149	ALA-91 ILE-70 LYS-93 VAL-196

**Abbreviations:** TYR, tyrosine; ARG, arginine; MET, methionine; ALA, alanine; VAL, valine; SER, serine; LYS, lysine; LEU, leucine; GLY, glycine; THR, threonine; ASN, asparagine; GLU, glutamic acid; ASP, aspartic acid; ILE, isoleucine; GLN, glutamine; ARG, arginine; GLY, glycine.

contribution of the hydrophobic regions and residues of the active site regions, consistent with the binding pattern of previously known inhibitors.

The C-terminal domain of JNK3 contains a flexible activation loop, typically 20–30 residues in length and contains a conserved Asp-Phe-Gly (“DFG”) motif. ATP docking site of kinase exhibited remarkable conformational flexibility to facilitate small molecule inhibitors. As all three compounds preferentially bind to the DFG-out conformation (Figure S1), they contain ‘type II’ binding mode.

### MD Simulation Analysis

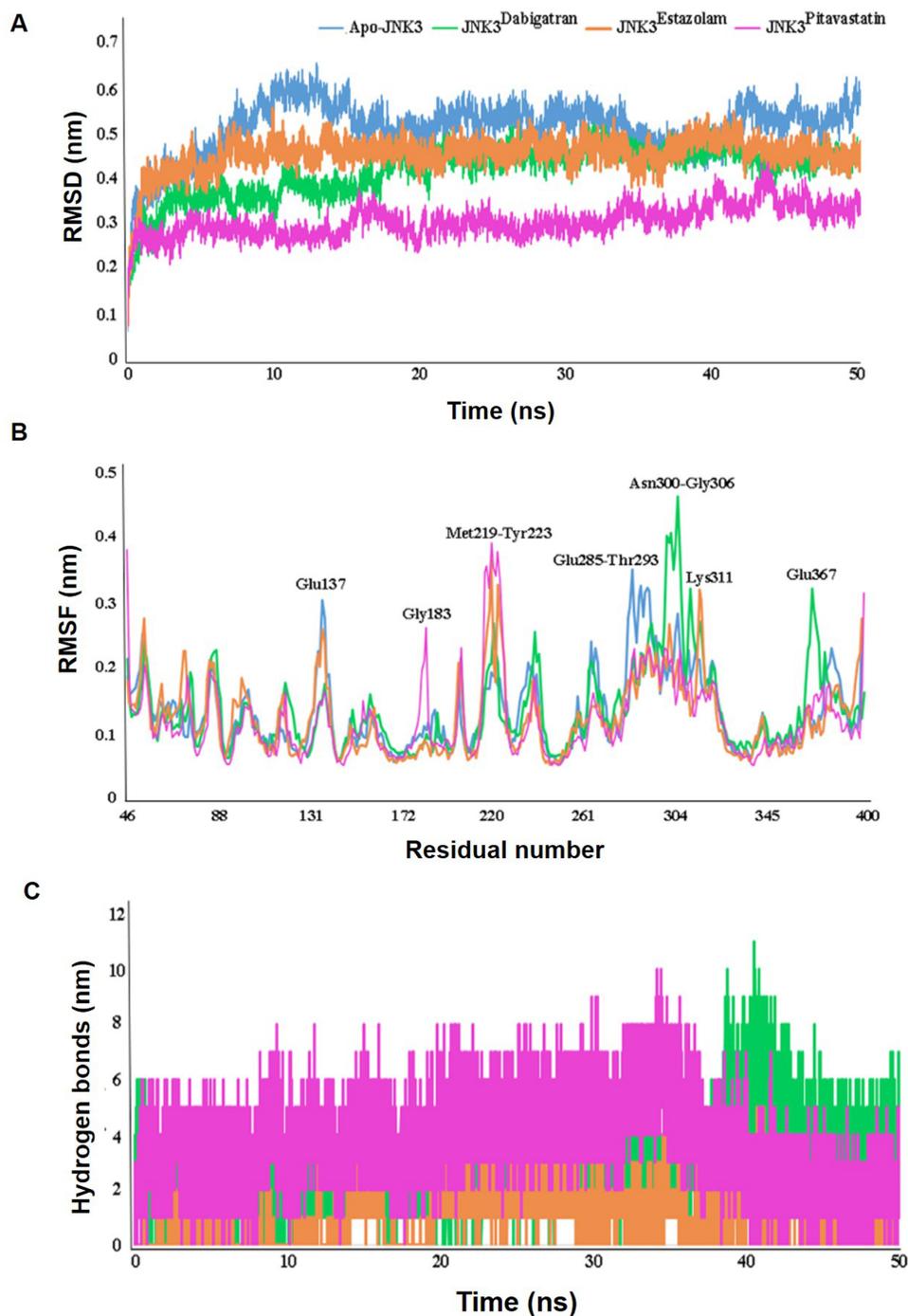
The JNK3<sup>Dabigatran</sup>, JNK3<sup>Estazolam</sup>, and JNK3<sup>Pitavastatin</sup> complexes were evaluated further via MD simulation to examine the durability, folding characteristics, conformational modifications, and structural dynamics of JNK3 inhibition relative to apo-JNK3. These characteristics were explored for each simulated system using the root mean square deviations (RMSD) (Figure 4A), root mean square fluctuations (RMSF) (Figure 4B), hydrogen bonding, and energy plots (Figure 4C) analyses. The RMSD value indicated a stable interaction profile. The average RMSD values among the C-alpha atoms of individual complexes and apo-JNK3 were approximately 0.43nm, indicating that the system was stable (Figure 4A). RMSF plots indicated the residual flexibility upon binding of JNK3 to inhibitors throughout the simulation time. RMSF values

showed the extent of each residual fluctuation, denoted by the peak elevation (Figure 4B). For JNK3<sup>Dabigatran</sup>, the fluctuations observed in the Asn300-Gly306 and Gln367 residues were in the range of 0.46nm. In the case of JNK3<sup>Estazolam</sup>, significant fluctuations were detected near the binding residues (Met219-Tyr223). For JNK3<sup>Pitavastatin</sup>, a loop region (Met219-Tyr223) exhibited major fluctuations up to 0.36nm (Figure 4B). Furthermore, critical residues involved in binding (Gln75, Val78, Asn194, Val196, and Leu206) were quite stable. Minimal variations were noted in the secondary structure elements of JNK3, indicating high stability during interactions. The binding characteristics of JNK3 with dabigatran, estazolam, and pitavastatin were then analyzed by plotting intermolecular hydrogen bond (Figure 4C), and more hydrogen bonds were recorded for JNK3<sup>Pitavastatin</sup> as compared to JNK3<sup>Dabigatran</sup> and JNK3<sup>Estazolam</sup> systems (Figure 4C).

Next, JNK3-inhibitor complexes were analyzed by energy calculation. As depicted in the energy plot, all complexes were perfectly balanced and stable throughout MD simulations (Figure 5A–C). JNK3<sup>Pitavastatin</sup> and JNK3<sup>Dabigatran</sup> systems demonstrated higher energy values in the range of -1800 kJ/mol, relative to JNK3<sup>Estazolam</sup> (Figure 5C). The LJ-SR energy value is considered stable in the range of -2000 to -1400 kcal/mol.

### Conformational Analysis

To characterize the underlying conformational switches in JNK3<sup>Dabigatran</sup>, JNK3<sup>Estazolam</sup>, and JNK3<sup>Pitavastatin</sup> complexes, PDB files were generated at 10, 20, 30, 40, and 50 ns (Figure 5). Moreover, substantial conformational alterations were witnessed in the vicinity of the binding pocket (Figure 6). SP600125 binding and its residues involvement were taken as reference (Figure 6A and E). Particularly, widening of the binding cavity was evident to accommodate estazolam (Figure 6C), whereas dabigatran and pitavastatin settled well into the hollow cavity (Figure 6B and D). Upon dabigatran binding, the variable regions from His219-Tyr223 were significantly twisted inward, and Arg230 moved downward (Figure 6F), resulting in a conformation suitable for the entrance of the inhibitor inside the cavity. Upon estazolam binding, the Lys191 residue of JNK3 was significantly twisted towards the inhibitor to improve the interaction (Figure 6G). Similarly, Asn152 and Cys154 residues were significantly twisted outward (Figure 6G), thus creating a doorway for the appropriate

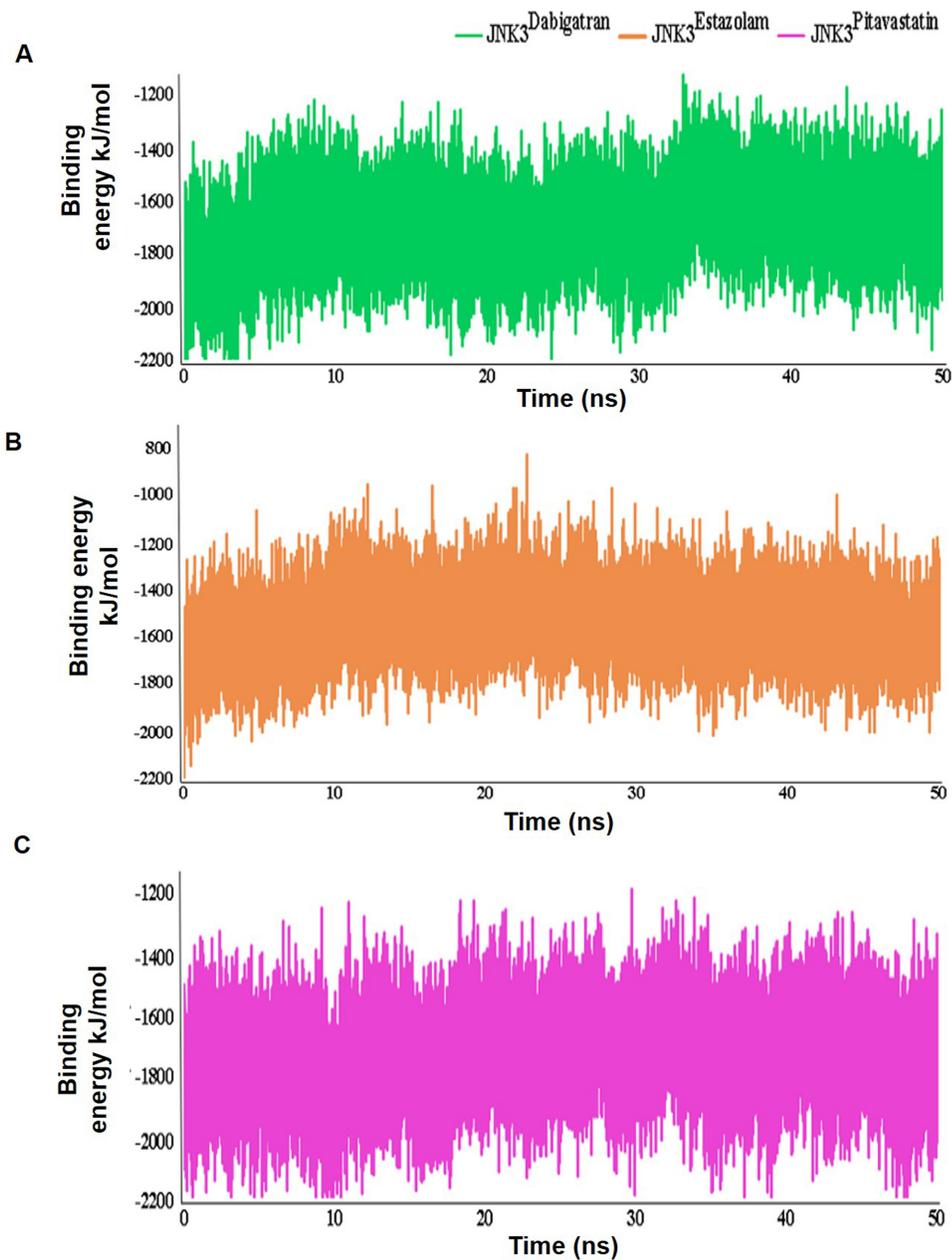


**Figure 4** Time-dependent analysis of MD trajectories of apo and inhibitor bound states of JNK3. **(A)** RMSD plots were made via the least square fitting method using the backbone of the  $\alpha$ -carbons. **(B)** Relative RMSF plot of apo-JNK3 (blue), JNK3<sup>Dabigatran</sup> (green), JNK3<sup>Estazolam</sup> (orange), and JNK3<sup>Pitavastatin</sup> (pink). **(C)** Time versus intermolecular hydrogen bonding pattern for the 50 ns MD simulation.

entrance of inhibitor inside the cavity, and aiding in the interaction via hydrophobic associations.

Upon binding of pitavastatin, Ser72 was significantly pushed outward (Figure 6H) to open the pocket that mediated a conformational space accessed by the inhibitor. These structural arrangements altered the placement of the

Gln75 and Asn194 residues, which were bent towards the inhibitor to increase the binding affinity and stabilize the interactions through hydrogen bonding. Overall, the interaction pattern of the inhibitors and JNK3 suggested that the Ile70, Val78, and Val196 residues in the binding cavity sustained the binding stability of JNK3.



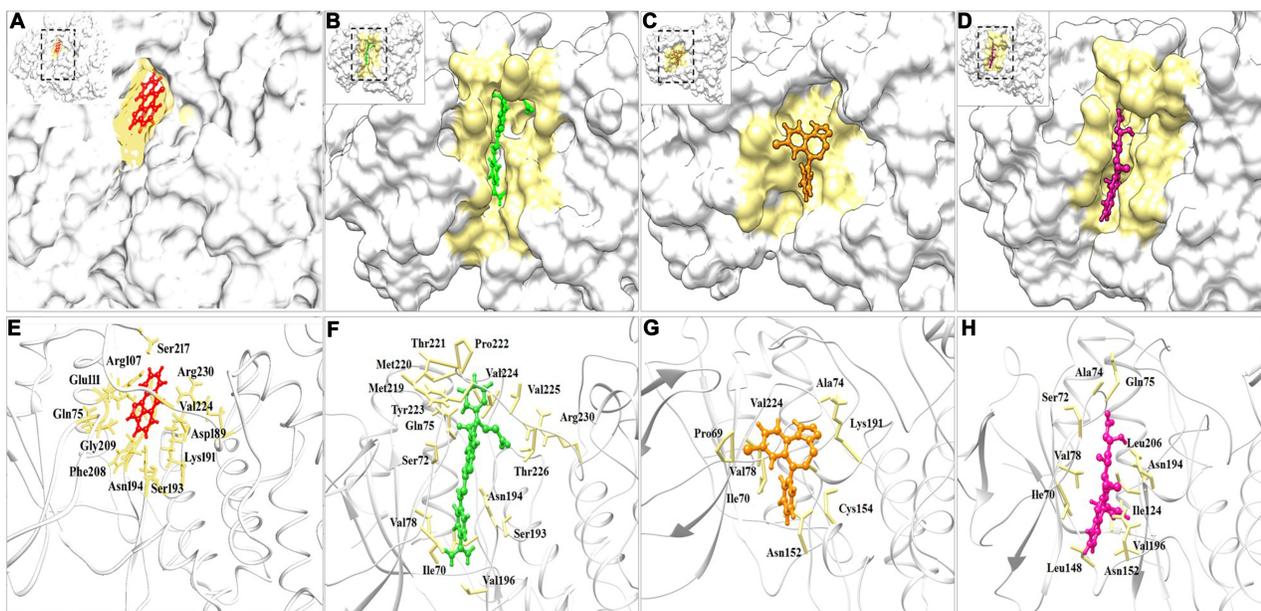
**Figure 5** Time versus binding energy plots for 50 ns MD simulation. The LJ-SR binding energy profile of the (A) dabigatran-JNK3, (B) estazolam-JNK3, and (C) pitavastatin-JNK3 complexes.

### Docking and Stimulation Analysis of Leucovorin

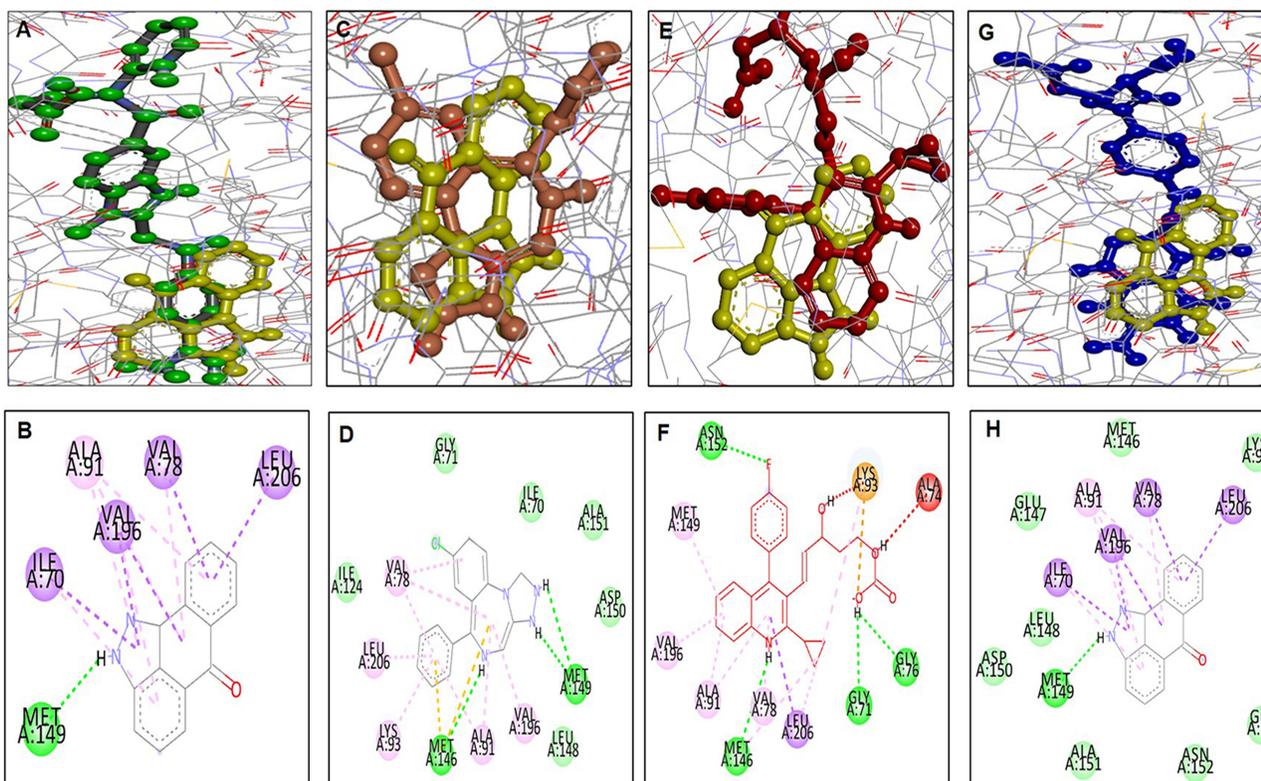
The docking analysis of leucovorin is shown (Figure 7). During the simulation, leucovorin failed to maintain its position in the cavity and lost its orientation. Furthermore, the superimposed 3D pose analysis and 2D depictions for dabigatran (green, Figure 7A and B), estazolam (orange, Figure 7C and D), pitavastatin (pink, Figure 7E and F), and leucovorin (blue, Figure 7G and H), SP600125 (yellow) on JNK3 were also shown (Figure 7).

### The Relative Effects of FDA Approved Drugs and JNK3 Inhibitor on Brain Infarction and Neuronal Cell Loss

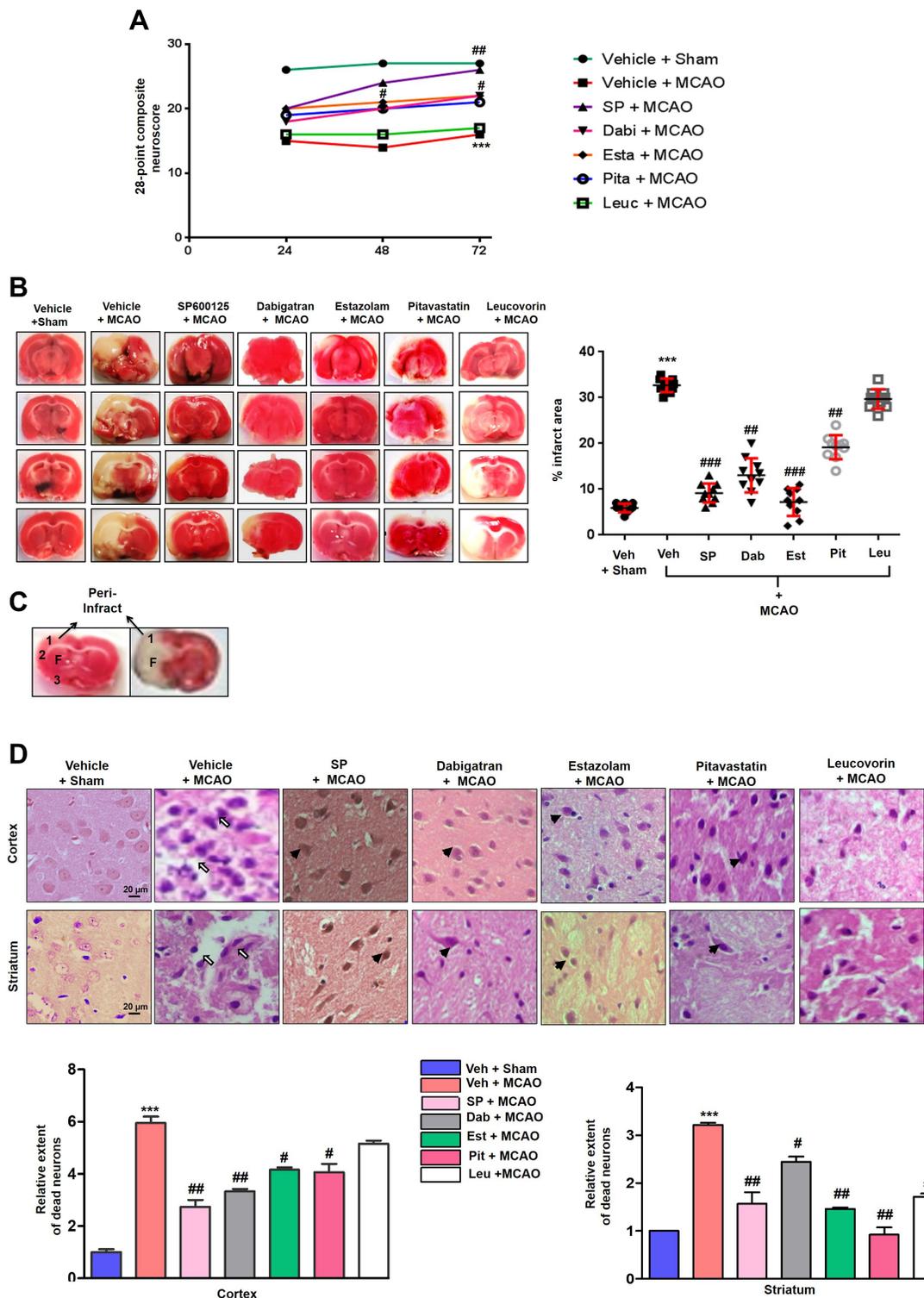
To validate the docking results, the pharmacological effects of dabigatran, estazolam, leucovorin, and pitavastatin on MCAO were tested in parallel with the JNK inhibitor SP600125. Sensorimotor functions were evaluated using a 28-point composite scoring method at 3-time intervals (1, 2, and 3 days) post-t-MCAO. As shown in Figure 8A, significant sensory-motor deficits were noticed in the MCAO group than in the sham controls ( $p < 0.001$ ),



**Figure 6** Surface view of RBX1 binding cavity orientation. (A) SP600125-JNK3, (B) Dabigatran-JNK3, (C) Estazolam-JNK3, and (D) Pitavastatin-JNK3. (E–H) SP600125, dabigatran, estazolam, and pitavastatin are indicated in red, green, orange, and pink colors respectively.



**Figure 7** Docking and superimposed orientation of FDA drugs and SP600125 on JNK3. The post-docking study was pictured using DSV in 2D and 3D poses. The superimposed pose analysis and 2D depictions for dabigatran (green, B), estazolam (orange, D), pitavastatin (pink, F), and leucovorin (blue, H), while 3D images are shown (A, C, E, G) respectively for dabigatran, estazolam, pitavastatin, and leucovorin. SP600125 is demarcated by yellow colour in 2D images.



**Figure 8** The effect of test drugs on MCAO induced neurodegeneration (A) The 28 point composite scoring. The test drugs significantly reduced neurological deficits. \*\*\*Indicates  $p < 0.001$  relative to sham group and # $p < 0.05$ , ### $p < 0.01$  compared to the MCAO rats. Data are presented as mean  $\pm$  SEM and were analyzed using a grouped two-way ANOVA ( $n = 10$ /group). SP600125 treated rats had a higher cumulative score whereas leucovorin treated rats had the least scores. The composite scores of dabigatran, pitavastatin, and estazolam treatment were comparable after 72 h of MCAO. (B) Brain coronal sections were stained with TTC after 72 h of MCAO. Data are presented as mean  $\pm$  SEM and were analyzed by one-way ANOVA ( $n = 10$ /group). \*\*\* or ####Indicates  $p < 0.001$ , and ###Represents  $p < 0.01$ . The TTC sections were made from the same cohort as the behavioral (first cohort). (C) Coronal sections were separated by the frontal cortex (1), parietal cortex and insular cortex (2), and the piriform cortex (3). The region of interest is indicated by the square I and F. (D) Representative photomicrograph of H&E staining showing the extent of the surviving neurons in the cortex and striatum. H&E stained slides from coronal sections were prepared (first cohort). Arrowhead indicates relatively intact neurons in the treated groups while the open arrows indicate the swelled and vacuolated forms. Magnification 40x, scale bar = 20  $\mu$ m, ( $n = 7$ /group). \*\*\*Indicates  $p < 0.001$ , and the symbols ### and #Represent  $p < 0.01$  and  $p < 0.05$ .

**Abbreviations:** Veh, vehicle; SP, SP 600125; Dab, Dabigatran; Est, Estazolam; Pit, Pitavastatin, Leu, Leucovorin.

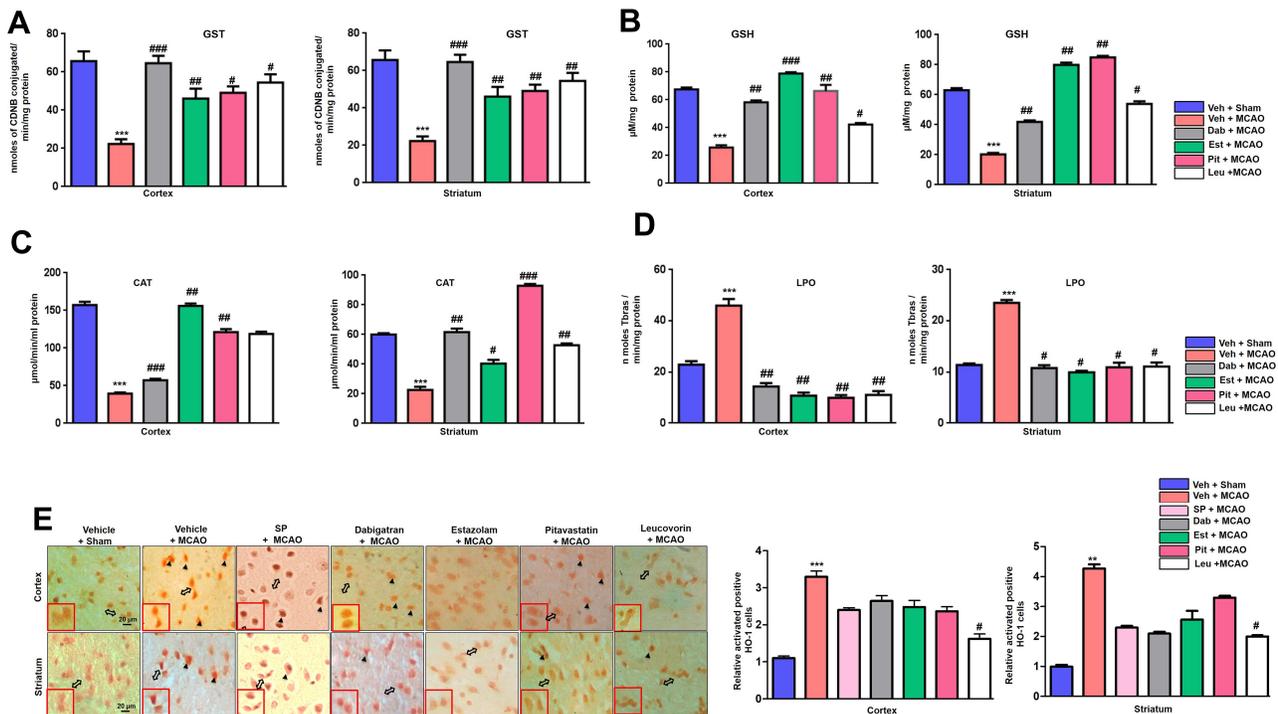
which was significantly reversed by treatment with dabigatran ( $p < 0.05$ ), estazolam ( $p < 0.05$ ), and pitavastatin ( $p < 0.05$ ) (Figure 8A). Treatment with SP600125 resulted in significant improvement ( $p < 0.01$ ), whereas the leucovorin-treated group did not show any improvement.

An increase in cumulative scores were observed in the pitavastatin, dabigatran, and estazolam-treated groups on the 2nd and 3rd-day post-ischemia, suggesting a constant recovery in sensorimotor function after MCAO. To further validate the neuroprotective effects of dabigatran, estazolam, pitavastatin, and leucovorin, TTC staining was performed to differentiate the infarct core from the intact tissue and penumbra, and to delineate the infarct size (Figure 8B and C). Considerable changes were observed at 72 h of t-MCAO ( $p < 0.001$ ) relative to the sham-operated group (Figure 8B). The corrected infarcted areas for pitavastatin, dabigatran, estazolam, and SP600125 treated groups were 13.5% ( $p < 0.01$ ), 19.65% ( $p < 0.001$ ), 25.49% ( $p < 0.01$ ), and 23.80% ( $p < 0.001$ ), respectively (Figure 8B), whereas treatment with leucovorin did not result in a significant reduction

in infarct size. Furthermore, we distinguished between intact and necrotic neuronal cells in the cortex and striatum using H&E staining. Distinct changes were detected 72 h after t-MCAO in the cortex and striatal region of the t-MCAO and sham-operated groups ( $p < 0.001$ ; Figure 8D). Aberrant morphological features characterized by variation in color staining and neuronal structure, and in immune cell permeation were observed in the ipsilateral brain of t-MCAO groups (Figure 8D). Dabigatran, estazolam, and pitavastatin treatment attenuated the damage ( $p < 0.05$ ) in the corresponding areas.

### The Effects of FDA Approved Drugs on Endogenous Antioxidant Enzymes and Oxidative Stress Markers

As first-line indicators of oxidative damage, the levels of enzymatic and non-enzymatic oxidants such as GST and GSH were measured in brain tissues. MCAO induced reactive oxygen species (ROS) along with the exhaustion of GSH and GST in the cortical and striatal homogenates (Figure 9A and B). Treatment with dabigatran, estazolam, pitavastatin, and leucovorin increased the levels of GSH



**Figure 9** The effects of FDA approved drugs on endogenous antioxidant enzymes and oxidative stress markers (A and B) Histograms showing the results of the GST and GSH assays in the cortical and striatum homogenates from rat brains. (C) Histograms showing the CAT level in the cortical and striatum homogenates from rat brains. (D) Histograms showing the results of the LPO assay and MDA analyses in the cortical and striatum homogenates from the rat brain. The samples were collected from the second cohort. The results are represented as the means  $\pm$  SEM ( $n = 7$  rats/group) for three independent and reproducible experiments. The data were analyzed by one-way ANOVA followed by the post hoc Bonferroni multiple comparison test. The symbols \*\*\* or #### indicate significant differences at  $p < 0.001$ , whereas # and ## indicate significant difference at  $p < 0.05$  and  $p < 0.01$ , respectively. (E) The effect of dabigatran, estazolam, leucovorin, and pitavastatin on HO-1 in the cortex and striatum was analyzed via immunohistochemistry. Scale bar = 20  $\mu$ m, magnification 40 $\times$ , ( $n = 7$ /group). HO-1 exhibited nuclear localization. Arrowhead indicated either HO-1 expression (MCAO group) in the nucleus while double open arrow indicated magnified cells. The slides were prepared from the first cohort of animals. \*\*\* or \*\* indicate  $p < 0.001$  or  $p < 0.01$  respectively, while # indicate  $p < 0.05$ .

and GST, in the cortical and striatal homogenates, respectively (Figure 9A and B). Further, treatment with dabigatran, estazolam, pitavastatin, and leucovorin restored the level of CAT in both homogenates (Figure 9C). Oxidative stress and ROS generated early in MCAO induced the formation of several detrimental products, including malondialdehyde (MDA), which can be measured by TBARS. Therefore, we performed an LPO assay to assess the degree of damage induced by LPO products in both homogenates of the MCAO group, which were increased relative to the sham group (Figure 9D). Dabigatran, estazolam, pitavastatin, and leucovorin treatment attenuated LPO in the cortex and striatum (Figure 9D).

To further complement these results, we performed an immunohistochemical analysis of the antioxidant heme oxygenase (HO-1). The effect of the drugs on HO-1 expression was not significant, although we observed intergroup variability for the effect of the drugs on the striatum compared to the cortex (Figure 9E).

### The Reprofiled Drugs Attenuated JNK Expression and Downstream Neuroinflammatory Mediators

To determine the effects of dabigatran, estazolam, pitavastatin, and leucovorin on p-JNK, changes in p-JNK were analyzed via ELISA assays. As shown in Figure 10A, p-JNK was significantly decreased in dabigatran, estazolam, and pitavastatin-treated groups in the cortex and striatum homogenates compared to the MCAO model ( $p < 0.01$ ). To validate the ELISA findings, immunostaining was performed, and the results indicated that these compounds attenuated the cytoplasmic expression of p-JNK in the frontal cortex and striatum (Figure 10B). TNF- $\alpha$  and its receptors are known to activate the nuclear factor- $\kappa$ B (NF- $\kappa$ B) pathway and is an essential transcriptional controller of genes associated with cellular inflammation and proliferation.<sup>45</sup> We studied TNF- $\alpha$  and p-NF- $\kappa$ B expression by immunohistochemical analysis and observed elevated expression of p-NF- $\kappa$ B and TNF- $\alpha$  in the ischemic group ( $p < 0.01$ , Figure 11A and B). Moreover, treatment with dabigatran, estazolam, pitavastatin, and leucovorin decreased the expression of p-NF $\kappa$ B and TNF- $\alpha$  in the cortex and striatum.

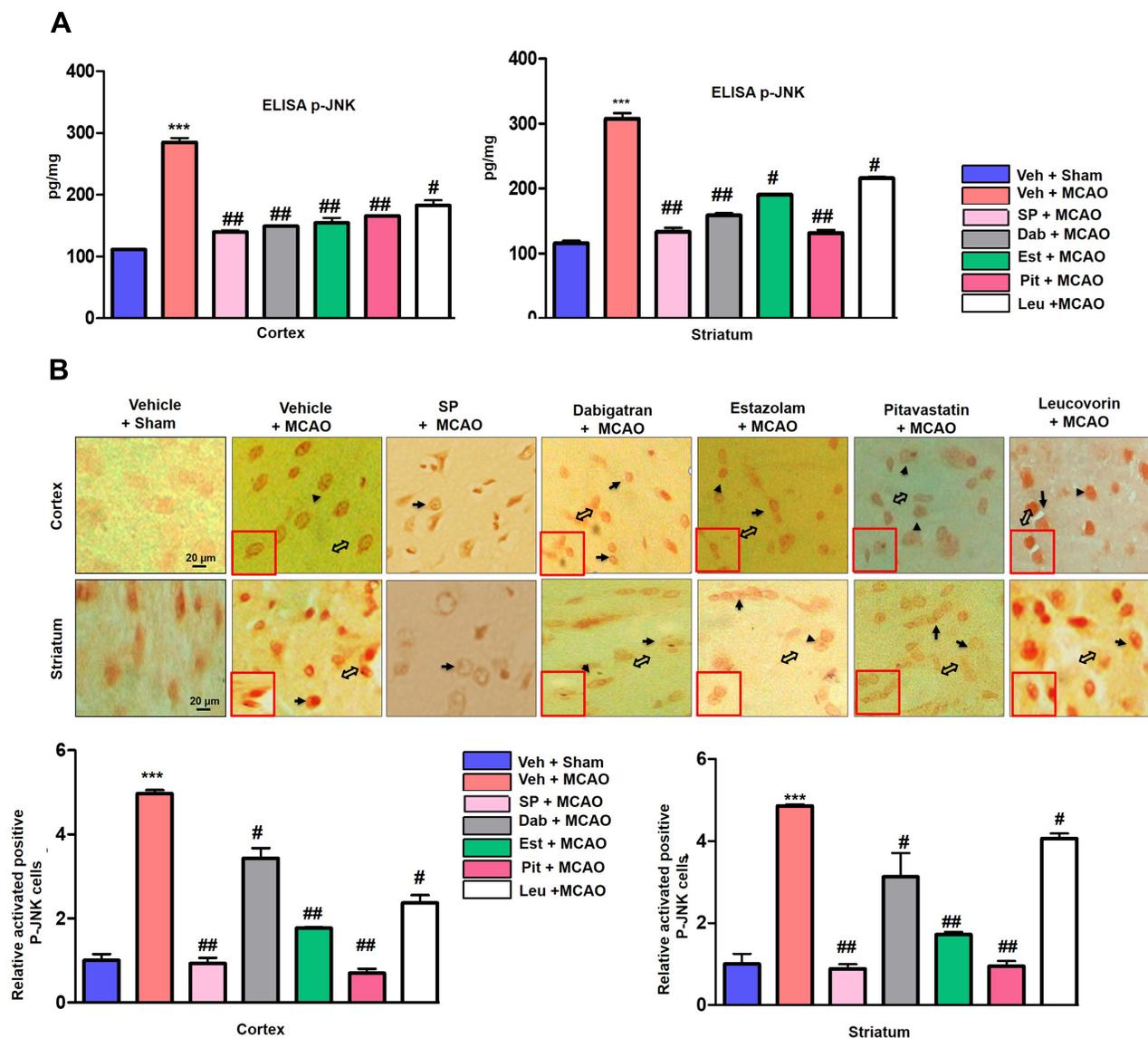
## Discussion

Ischemic brain injury perturbs the activity of numerous proteins in several physiological cascading pathways. Among them, JNK is a prominent mediator of pathological events and is associated with neuroinflammation and

neurodegeneration.<sup>46</sup> JNK3 inhibition or downregulation is associated with favorable outcomes in several related animal stroke models.<sup>47,48</sup> Keeping in mind these considerations, we demonstrated the neuroprotective effects of four structurally and pharmacologically different drugs, dabigatran, estazolam, pitavastatin, and leucovorin, in an ischemic stroke model using JNK3 as the target protein by adopting a drug reprofiling approach (Figure 12).

Drug repurposing and reprofiling may serve as a rewarding approach as it provides substitutes for conventional drug discovery and development methods, in addition to a cost-effective approach.<sup>21,22</sup> Docking and molecular simulation (GROMACS) are integral components of target-based strategies when using the reprofiling approach. In molecular docking, interactions between the potential target for a given drug or the potential drug for an anticipated target can be determined through the structural input of drug(s) and target(s).<sup>36</sup> Molecular dynamics are used to scale time-dependent post-docking conformational changes and the binding stability of individual protein-drug complexes in a real-time environment, enabling the identification of false positives from true positives. In this study, the putative drug compounds dabigatran, estazolam, and pitavastatin demonstrated a superior affinity for JNK3, which was similar to the reference drug SP600125.

Pitavastatin reduces the risk of cerebral ischemic stroke and decreases the risk of oxidative damage, as observed via *in vitro* and *in vivo* analysis.<sup>49</sup> Our results showed that pitavastatin treatment reduced the infarct area and significantly improved neurological functions, accompanied by decreased p-JNK expression. The results are in accordance with previous reports, which demonstrated that statins significantly reduced the infarct volume size by up to 38.18%.<sup>50</sup> Moreover, pitavastatin (10  $\mu$ M) significantly blocked the phosphorylation of three MAPKs, i.e. extracellular-signal-regulated kinase (ERK), c-Jun N-terminal kinase (JNK), and the p38 MAPK induced by C-reactive protein (CRP) (10  $\mu$ g/mL).<sup>51</sup> Furthermore, preclinical studies and clinical trials have shown the neuroprotective effects of statins after acute cerebral infarction, and these act by reducing the expression of neuroinflammatory mediators such as TNF- $\alpha$  and IL-1 $\beta$ .<sup>52</sup> In clinical practice, statins are administered orally; however, we administered pitavastatin I/P, in a manner similar to studies in which pitavastatin showed anticonvulsant and neuroprotective effects in ischemic injury.<sup>53,54</sup> Moreover, we also performed the *in silico* testing of other statin members, namely atorvastatin, fluvastatin, lovastatin, pravastatin,

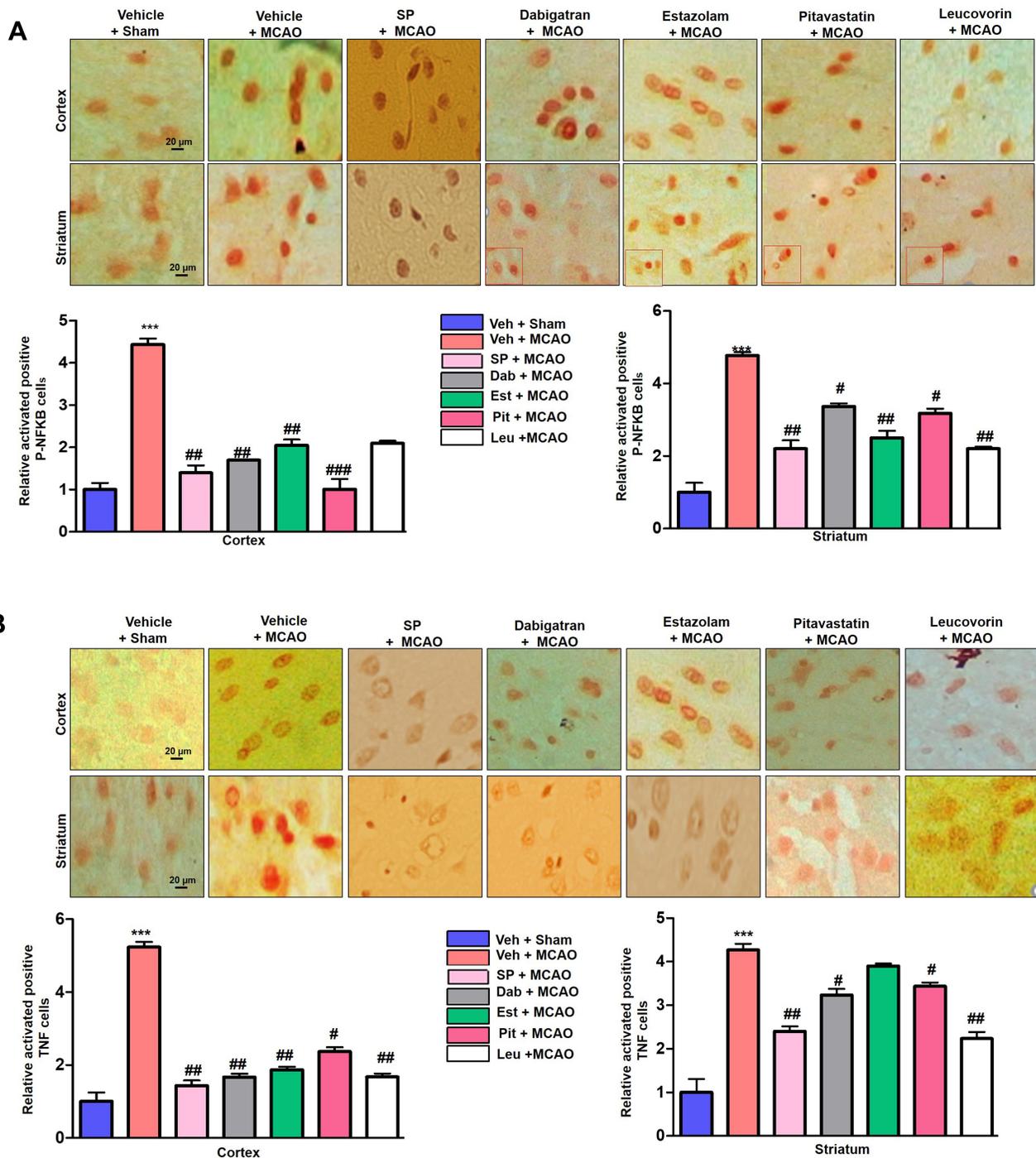


**Figure 10** The effect of dabigatran, estazolam, leucovorin, and pitavastatin on activated JNK3 in the cortex and striatum. **(A)** Histograms representing the JNK levels assayed via ELISA using extracts from the cortex and striatum. A one way ANOVA was used for the analysis ( $n = 7/\text{group}$ ). The samples were collected from the 2nd cohort of animals.\*\*\* indicates  $p < 0.001$ , \*\*#Represents  $p < 0.01$ , #Indicates  $p < 0.05$ . **(B)** The effect of dabigatran, estazolam, leucovorin, and pitavastatin on p-JNK in the cortex and striatum was analyzed via immunohistochemical analysis. Scale bar = 20  $\mu\text{m}$ . p-JNK exhibited cytoplasmic localization; the double open arrow shows magnified cells, while the arrowheads show p-JNK expression and the arrow show no expression. The samples were collected from the first cohort ( $n = 7/\text{group}$ ). \*\*\*Indicates  $p < 0.001$ , \*\*#Represent  $p < 0.01$ , #Indicates  $p < 0.05$ .

rosuvastatin, and simvastatin, and none of these formed a stable complex with JNK3. Atorvastatin attenuated ischemic stroke-induced neuronal toxicity by inhibiting NF- $\kappa\text{B}$ , as described in previous studies.<sup>43</sup>

Several studies have demonstrated that JNK3 inhibition attenuates the infarction area and neuronal death after ischemia.<sup>46</sup> The significance of JNK3 in ischemia is further supported by studies using JNK3 null mice.<sup>55</sup> Dabigatran is clinically used for stroke prevention in patients with atrial fibrillation, and the drug has shown

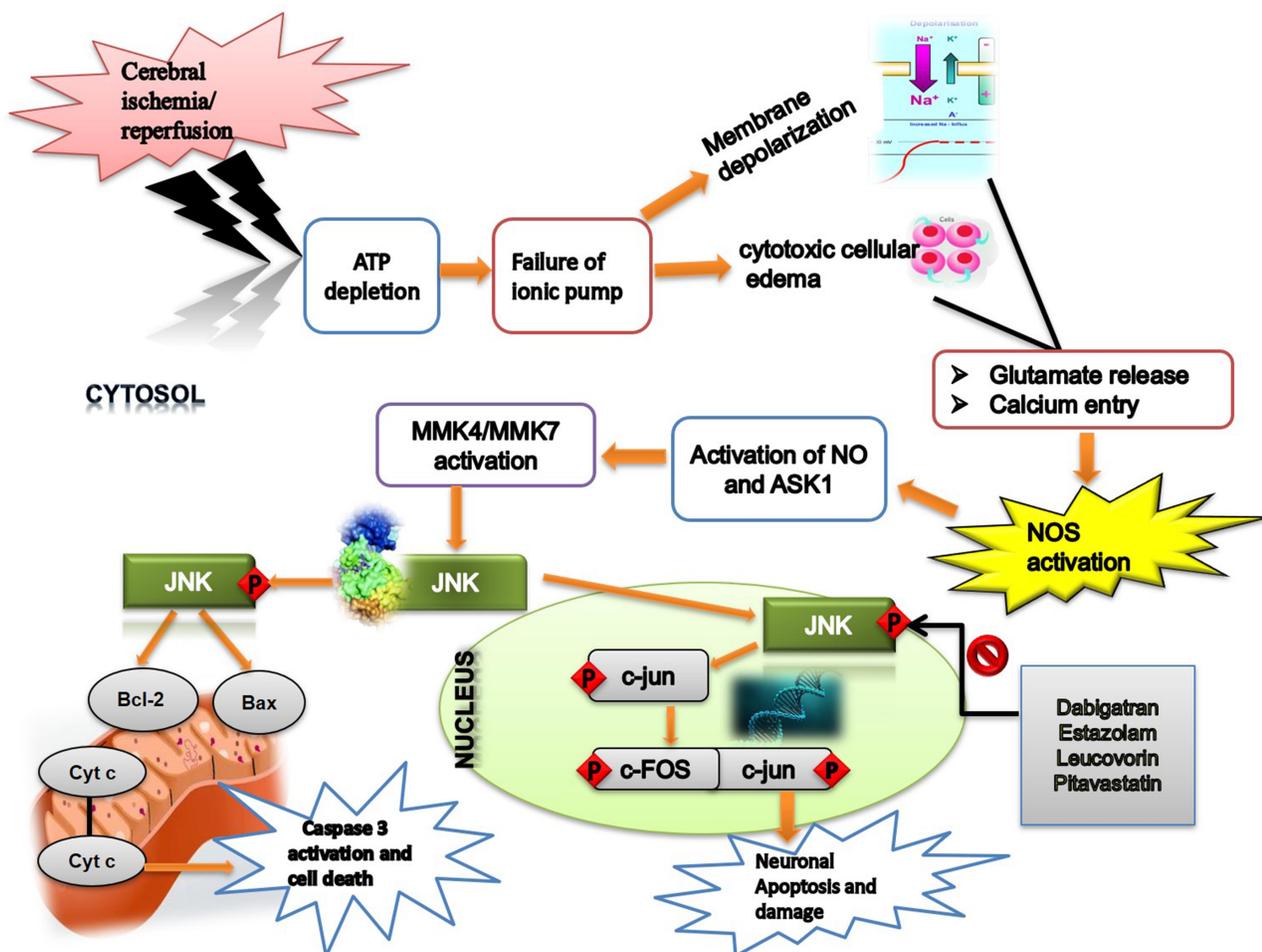
superior clinical properties over warfarin,<sup>56</sup> due to its lower tendency for drug-drug interactions and no predicted inhibitory effects on cytochrome P450 (CYP), which makes routine coagulation monitoring unnecessary.<sup>57</sup> Further, 110 mg dabigatran showed similar effects to that of warfarin, whereas 150 mg dabigatran reportedly reduced the risk of ischemic stroke, intracranial hemorrhage, and death.<sup>58</sup> Besides these reports, few studies are available on the safety of dabigatran in ischemic stroke patients.<sup>58-60</sup> Moreover, other studies do not recommend



**Figure 11** The effect of the dabigatran, estazolam, leucovorin, and pitavastatin neuroinflammatory mediators. **(A)** The representative immunohistochemical staining of p-NF-κB in the cortex and striatum are shown. p-NF-κB exhibited nuclear localization; the arrowhead indicates no or less expression in the neuronal nucleus and the thin arrow indicates localization to the nucleus. Scale bar = 20 μm. One-way ANOVA was used to analyze the data (n = 7/group). \*\*\* and #### indicate p < 0.001, ### Represents p < 0.01, #Indicates p < 0.05. The slides were prepared from the first cohort of animals **(B)** Representative immunohistochemical analysis of TNF-α in the cortex and striatum. Scale bar = 20 μm. One-way ANOVA was used to analyze the data (n = 7/group) \*\*\*Indicates p < 0.001, ### Represents p < 0.01, #Indicates p < 0.05.

the concurrent therapy of rt-PA with dabigatran in stroke patients, and the effect of dabigatran must be antagonized before thrombolysis with tPA.<sup>61</sup> A recent study demonstrated that intraperitoneal dabigatran therapy does not

increase the risk of hemorrhage after thrombolysis irrespective of the dose, species (rat, mice), frequency of drug administration (single vs multiple), type of MCAO (filament vs thromboembolic), and duration of recanalization



**Figure 12** The graphical representation illustrates the underlying antioxidant and anti-inflammatory mechanisms of the re-profiled drugs against MCAO-induced brain injury using JNK3 as a target.

(2 h vs 3 h).<sup>62</sup> Thus, our results support these observations. In another study, dabigatran reduced proinflammatory cytokine expression, decreased thrombus formation, and reduced CD68-immunoreactivity in ischemic lesions without increasing the rate of intracranial hemorrhage.<sup>63</sup> Similarly, no increased risk of hemorrhage was seen with dabigatran anticoagulation in the ischemic stroke model.<sup>64</sup> Further studies may be required to evaluate the effect of dabigatran in ischemic stroke.

Estazolam is a sedative-hypnotic drug that modulates the activity of GABA receptors. As per our literature survey, no study has described the neuroprotective role of estazolam in ischemic stroke. Previous studies have demonstrated the inhibitory effect of GABA on NMDA receptor-mediated NO production in ischemic brain injury,<sup>65</sup> whereas muscimol (GABA<sub>A</sub> agonist) and baclofen (GABA<sub>B</sub> agonist) have shown neuroprotective effects. Moreover, it has been shown that GABA<sub>A</sub> and GABA<sub>B</sub>

receptor co-activation intensely increased Akt (protein kinase B) activation and inhibited apoptosis signal-regulating kinase 1 (ASK1) activation. Combination therapy with muscimol and baclofen subdued MKK4/MKK7-JNK signaling activation, indicating that the GABA<sub>A</sub> and GABA<sub>B</sub> receptor activators could deter the ASK1-c-Jun N-terminal protein kinase (JNK) pathway via the PI-3K/Akt cascade.<sup>66</sup> Several studies have demonstrated the neuroprotective effects of GABAergic drugs in brain ischemic injuries.<sup>67,68</sup> In another study, chlorthalidone (a GABA modulator) decreased the brain infarct volume 1h after occlusion.<sup>69</sup> Midazolam also plays a neuroprotective role in the ischemic brain.<sup>70</sup> We evaluated the most common benzodiazepine midazolam in silico and found that it did not form any standard bond with JNK3. Although the results from these animal models raise the possibility of their clinical application, several independent clinical trials have failed to find the

beneficial effects of GABAergic drugs in stroke.<sup>71</sup> Liu et al, 2016 in a clinical review regarding the use of GABA agonists for acute stroke in clinical patients concluded that there was no evidence to support the use of GABA receptor agonists (chlormethiazole or diazepam) for acute stroke.<sup>70</sup>

Folinic acid (leucovorin) is prescribed as a supplement to counteract the deleterious effects of drugs such as pyrimethamine, trimethoprim, and methotrexate (MTX), which are associated with folic acid depletion.<sup>72</sup> Our simulation studies (data not shown) indicated a loss of complex formation after docking, which was further validated by in vivo analyses. Several studies have demonstrated the neuroprotective role of leucovorin in various neurodegenerative models,<sup>73</sup> though none have demonstrated the protective effects of leucovorin against ischemic stroke. Accumulating evidence indicates that cytokines and chemokines mutually interact and aggravate oxidative stress during ischemic injury.<sup>74</sup> Therefore, JNK3 inhibitors may act as protective agents by minimizing oxidative stress and inflammatory reactions in ischemic injury.

Our study has several limitations. First, we did not strictly follow the STAIR criteria to test our findings in two or more laboratories, replication in another species, or consideration of sex differences. Moreover, our experimental studies suggest the presence of neuroprotective effects, which are not indicated in some cases based on clinical data. Similarly, dabigatran does not cross the BBB, which suggests the possibility of indirect effects on JNK3 or the presence of alternative mechanisms for brain protection that may reduce infarction and impact JNK3 activity after tissue damage.

## Conclusions

Our results showed that the FDA-approved drugs dabigatran, estazolam, and pitavastatin can inhibit p-JNK in a manner similar to the standard SP600125, as indicated by our docking simulations. Further, in vivo experiments illustrated that these drugs mitigated the infarct area and were associated with enhanced motor outcomes. JNK is a critical player in mediating cell death signaling via apoptotic pathways and is associated with immune responses, and thus could be induced by multiple proinflammatory cytokines such as TNF- $\alpha$  and NF $\kappa$ B. Moreover, we demonstrated the inhibitory effects of these drugs on the feedback mechanism that exists between inflammatory cytokines and activated p38/JNK, where the activation of one pathway activates the other, suggesting critical roles for p38/JNK in

inflammation. Based on our results, we suggest conducting further extensive studies to delineate the underlying protective mechanisms of these drugs in translational and clinical studies using multiple animal strains with associated comorbid conditions.

## Author Contributions

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published, and agree to be accountable for all aspects of the work.

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## Disclosure

The authors report no conflicts of interest in this work.

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