

Theme Issue Article

Effects of a semi-synthetic N-,O-sulfated glycosaminoglycan K5 polysaccharide derivative in a rat model of cerebral ischaemia/reperfusion injury

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Summary

Heparin and low molecular weight heparins may reduce brain damage evoked by ischaemia/reperfusion (I/R) injury, although their use is hampered by the risk of haemorrhage. Chemical and enzymatic modifications of K5 polysaccharide have shown the possibility to produce heparin-like compounds with low anticoagulant activity and strong anti-inflammatory effects. Using a rat model of transient cerebral I/R, we investigated the effects of an epimerised N-,O-sulfated K5 polysaccharide derivative, K5-N,OSepi, on the infarct size, motor activity and injury caused by ischaemia (30 min) and reperfusion. Reperfusion was allowed for 60 min or 1–5 days. Rats reperused for 5 days showed an infarct volume of $30.7 \pm 3.1\%$ and K5-N,OSepi (0.1–1 mg/kg) caused dose-dependent reduction in infarct size (maximum at 1 mg/kg: $13.1 \pm 2.1\%$ infarct volume). This effect was associated with a significant improvement in motor performance. In the rat

hippocampus, one of the brain areas most sensitive to I/R injury, I/R induced a robust increase in myeloperoxidase (MPO) activity, a marker of neutrophil infiltration, that was halved by K5-N,OSepi administration ($66.38 \pm 7.75 \mu\text{U MPO/tissue g}$, $30.78 \pm 5.67 \mu\text{U MPO/tissue g}$, respectively). K5-N,OSepi drastically reduced the expression of cyclooxygenase-2, inducible-nitric-oxide-synthase and intercellular-adhesion-molecule-1. I/R-induced activation of nuclear factor- κB was attenuated by drug treatment. Furthermore, K5-N,OSepi administration was associated with a significant modulation of apoptosis markers, such as Bid and Bcl-2. In conclusion, the results demonstrated that the sulfated semi-synthetic K5 derivative K5-N,OSepi protects the brain against I/R injury by disrupting multiple levels of the apoptotic and inflammatory cascade, including inhibition of NF- κB activation.

Keywords

Heparin-like derivative, hippocampus, cerebral ischaemia/reperfusion, inflammation

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Introduction

Ischaemic cerebrovascular diseases have a major impact on the public health of every nation. Cerebral ischaemia is defined as a reduction in cerebral blood flow, sufficient to cause a metabolic or functional deficit. The characteristics of brain injury depend on the severity and the duration of cerebral blood flow (CBF) reduction. Although reperfusion following transient ischaemia leads to restoration of CBF, there is compelling evidence to support the notion that reperfusion may exacerbate the injury initially caused by ischaemia, producing a so-called “cerebral ischaemia/reperfusion (I/R) injury”. Inflammation and neutrophil infiltration significantly contribute to the tissue injury evoked by

reperfusion of the ischaemic organ (1). The release of pro-inflammatory cytokines, increased expression of endothelial adhesion molecules and chemotactic factors, activation of microglia, and infiltration of leukocytes have recently emerged as important determinants of post-ischaemic inflammation, which contributes to the progression of brain damage (2). Therefore, interventions aimed at suppressing post-ischaemic inflammatory reactions are an emerging therapeutic strategy for the treatment of cerebral I/R injury.

Heparin, low-molecular-weight heparins and heparin-like compounds have been widely employed in acute stroke and their ability to reduce brain injury after I/R has been clearly demonstrated. However, their potential for causing haemorrhage con-

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tinues to arouse caution (3, 4). Although heparin's mechanism of action for brain protection has been thought to be dependent on its anticoagulant property, recent findings suggest that heparin's anti-inflammatory properties may play a more important role than its anticoagulant property (5–7). In recent years, chemical and/or enzymatic modifications of K5 polysaccharide have shown the possibility of producing biotechnological heparin-like compounds of bacterial origin with defined and selected chemical-biological features, also designated as bioheparin (8). In particular, considerable efforts have been made to develop heparin derivatives with a low anticoagulant activity, while retaining strong anti-inflammatory effects. O-desulfated non-anticoagulant biotechnological heparins have been demonstrated to inhibit translocation of the transcription nuclear factor-kappaB (NF- κ B) from the cytoplasm to the nucleus in human endothelial cells (9) and to the production of interleukin (IL)-1 β , IL-6 and tumor necrosis factor (TNF)- α by lipopolysaccharide (LPS)-stimulated mononuclear cells, with no effect on the anti-inflammatory cytokine IL-10 (10). In addition, non-anticoagulant heparin-like derivatives have been demonstrated to be effective in reducing organ injury in a few *in vivo* models of coronary, hepatic and renal injury (11–13). However, the effects of heparin-like semi-synthetic derivatives on cerebral I/R injury have not yet been investigated. Thus, this study was designed to investigate the effects of an epimerised N,O-sulfated K5 polysaccharide derivative, K5-N,OSepi, on infarct size, the degree of inflammation, and apoptosis caused by cerebral I/R in the rat. K5-N,OSepi was obtained by N-deacetylation/N-sulfation of K5 polysaccharide and epimerisation of K5 with the enzyme glucuronyl C5 epimerase and O-sulfation (10). This compound has been previously demonstrated to be endowed with anti-inflammatory and anti-adhesive effects but it is devoid of any anti-coagulant activity (8, 10). In addition, we investigated whether the protective actions of K5-N,OSepi are partially mediated through the reduction of the inflammatory response associated with cerebral I/R injury.

Materials and methods

Animals and surgery

Male Wistar rats (Harlan-Italy; Udine, Italy) weighing 210 to 230 g were housed in a controlled environment at $25 \pm 2^\circ\text{C}$ with alternating 12 hour (h) light and dark cycles. They were provided with a Piccioni pellet diet (n.48, Gessate Milanese, Milano, Italy) and water *ad libitum*. All rats were acclimatised in our animal facility for at least 1 week prior to experiments and stressful stimuli were avoided. Animal care was in compliance with Italian regulations on the protection of animals used for experimental and other scientific purposes (D.M. 116/92) as well as with the Guide for the Care and Use of Laboratory Animals as adopted and promulgated by the U.S. National Institutes of Health. The experimental protocol, approved by the Turin University Ethics Committee, was performed as described elsewhere (14, 15). Briefly, rats were anaesthetised with *i.p.* injection (30 mg/kg) of Zoletil 100 (mixture of tiletamine and zolazepam, Laboratoires Virbac, Carros Cedex, France), which was supplemented as needed. Anaesthetised rats were placed onto a thermostatically controlled heating pad, a rectal temperature probe was inserted and body temperature was monitored and maintained at

37°C . Both common carotid arteries were exposed over a mid-line incision and a dissection was made between the sternocleidomastoid and the sternohyoid muscles, parallel to the trachea. Each carotid artery was freed from its adventitial sheath and vagus nerve, which was carefully separated and maintained. Ischaemia was achieved by clamping the bilateral common carotid arteries for 30 minutes (min) using non-traumatic artery clamps (Micro Bulldog Clamps, Harvard Apparatus Ltd., Kent, UK). During ischaemia, the animals were monitored for body temperature, respiration pattern, loss of righting reflex, unresponsiveness, corneal reflexes, and fixed and dilated pupils. Re-circulation of blood flow was established by releasing the clips and restoration of blood flow in the carotid arteries was confirmed by careful observation. Reperfusion was allowed for 1 h, 24 h or 5 days. Post-surgery, the animals were kept for at least 3 h in a 37°C incubator to ensure that postoperative recovery was satisfactory. Thereafter, they were group-housed under temperature- and light-controlled conditions with food and water *ad libitum*. At the end of the reperfusion, the anaesthetised rats were killed by decapitation after aortic exsanguination. Sham-operated rats underwent identical surgical procedures except that no artery clamps were applied. After decapitation, the forebrain was rapidly dissected at 0°C and the whole hippocampus from both hemispheres was removed and transferred to an appropriate ice-chilled homogenising medium for biochemical assays.

Preparation of the N-, O-sulfated K5 polysaccharide

The precursor of the compound K5-N,OSepi is the capsular K5 polysaccharide obtained from *Escherichia coli* strain 010:K5:H4, a polymer with the structure [-4)-GlcA β 1-4 GlcNAc-(1-n in which the disaccharidic unit formed by D-glucuronic acid and N-acetylglucosamine is linked by a α 1 \rightarrow 4 bond. This structure is a kin to N-acetylheparosan, the natural precursory polymer of heparin and of heparan sulphate from mast cells. The purified K5 polysaccharide was prepared as described by Manzoni et al. (16). N, O-sulphated K5 polysaccharide was obtained by chemical N- and O- sulfation of the K5 polysaccharide followed by the enzymatic epimerisation with the enzyme glucuronyl C5 epimerase and O- sulfation, according to the method described by Gori et al. (10). Briefly, the K5 polysaccharide was treated with 2M sodium hydroxide at 50°C for 18 h and, after neutralisation, the solution was added with sodium carbonate and pyridine sulphur trioxide and maintained at 55°C for 6 h. The reaction product was treated with the enzyme glucuronyl C5 epimerase immobilised on a CNBr Sepharose 4B resin (Pharmacia, Uppsala, Sweden) in 25 mM Hepes buffer, pH 6.5, 50 mM CaCl_2 at 37°C . The epimerised product was then purified by ultrafiltration, precipitated with ethanol and passed through a cation-exchange resin. The O-sulfation was performed by treating the product with tetrabutylammonium hydroxyde in N,N-dimethylformamide and with pyridine sulphur trioxide at 50°C for 24 h. The product was finally depolymerised to the desired molecular weight by controlled nitrous acid deamination as described by Horton and Philips (17).

Biochemical characterisation of the K5 derivative

The structural profile of the compound was characterised by nuclear magnetic resonance ($^1\text{H-NMR}$ and $^{13}\text{C-NMR}$) analysis;

the sulfate content was obtained by sulphate/carboxyl ratio analysis and molecular weight determination was performed by HPLC (High Performance Liquid Chromatography) analysis according to described methods (18). The compound used in these experiments had an average molecular weight of 6,000 Da, a sulphate/carboxyl ratio of 4.0 and an iduronic acid/glucuronic acid ratio of 0.8. K5-N,OSepi was also tested for their antithrombotic/anticoagulant activity, showing no anti-factor Xa activity.

Drug treatments

Animals were randomly allocated into different groups: I/R groups (n = 8 per group); K5-N,OSepi groups (the drug was administered in the dose-range 0.1 – 1 mg/kg at beginning of reperfusion, after 6 h reperfusion and until day 5, n = 8 per group); Sham (the common carotid arteries were exposed but not occluded, n = 8). An additional group of rats received K5-N,OSepi (1 mg/kg i.v.) prior to the sham operation (n = 4). Ischaemia lasted 30 min, while reperfusion was allowed for 1 hour, 24 hours or 5 days.

Determination of infarct volume

At 1 or 5 days of reperfusion, the rats were killed with an overdose of Zoletil 100 (mixture of tiletamine and zolazepam) and decapitated. The rats' brains were immediately removed and placed in ice-cold saline for 5 min. Each brain was then placed in a brain matrix and coronal sections were cut into 2-mm slices. Brain slices were immediately immersed in 2% 2,3,5-triphenyltetrazolium chloride monohydrate (TTC) solution (in saline) at 37°C for 30 min, followed by 4% paraformaldehyde solution. The infarct area and hemisphere area of each section were traced and quantified by an image analysis system (Inquiry; Loats, Westminster, MD, USA) and expressed as the percentage infarct area of the whole brain.

Physical performance test: Rota-rod (motor coordination)

An Omni rotor (Omnitech Electronics Inc., Columbus, OH, USA) was used to evaluate the rats' motor coordination by testing the ability of rats to remain on a revolving rod. The rotor consisted of a rotating rod (75 mm diameter), which was divided into four compartments, permitting testing of four rats at a time. The apparatus automatically recorded the time to 0.1 seconds (s) when the rats fell off the rotating shaft. The speed was set at 10 rpm and the cut off time was 180 s.

Tissue extracts

Cytosolic and nuclear extracts were prepared by the Meldrum method (19). Briefly, rat hippocampi were homogenised at 10% (w/v) in a Potter Elvehjem homogeniser (Wheaton, Millville, NJ, USA) using a homogenisation buffer containing 20 mM HEPES, pH 7.9, 1 mM MgCl₂, 0.5 mM EDTA, 1% NP-40, 1 mM EGTA, 1 mM dithiothreitol (DTT), 0.5 mM Phenylmethyl Sulphonyl Fluoride (PMSF), 5 µg/ml aprotinin, 2.5 µg/ml leupeptin. Homogenates were centrifuged at 1,000 g for 5 min at 4°C. Supernatants were removed and centrifuged at 15,000 g at 4°C for 40 min to obtain the cytosolic fraction. The pelleted nuclei were resuspended in extraction buffer containing 20 mM HEPES, pH 7.9, 1.5 mM MgCl₂, 300 mM NaCl, 0.2 mM EDTA,

20% glycerol, 1 mM EGTA, 1 mM DTT, 0.5 mM PMSF, 5 µg/ml aprotinin, 2.5 µg/ml leupeptin. Next, the suspensions were incubated on ice for 30 min for high-salt extraction followed by centrifugation at 15,000 g for 20 min at 4°C. The resulting supernatants containing nuclear proteins were carefully removed and the protein content was determined using a BCA protein assay following the manufacturers' instructions. Samples were stored at –80°C until use.

Western blot analysis

About 15 µg total proteins were loaded. Proteins were separated by 8% sodium dodecyl sulphate-polyacrylamide gel electrophoresis (SDS-PAGE) and transferred to a polyvinylidenedifluoride (PVDF) membrane, which was then incubated with SuperBlock blocking buffer. Membranes were incubated with primary antibody (rabbit anti-inducible-nitric-oxide-synthetase [iNOS], rabbit anti-cyclooxygenase-2 [COX-2], rabbit anti-Bcl-2, rabbit anti-Bax, goat anti-Bid, goat anti-S100B, goat anti-intercellular adhesion molecule-1 [ICAM-1], mouse anti-NF-κB p65). Blots were then incubated with a secondary antibody conjugated with horseradish peroxidase and developed with the ECL detection system. The immunoreactive bands were visualised by autoradiography and the density of the bands was evaluated densitometrically using Gel Pro[®]Analyser 4.5, 2000 software (Media Cybernetics, Silver Spring, MD, USA). The membranes were stripped and incubated with β-actin monoclonal antibody and subsequently with an anti-mouse antibody to assess gel-loading homogeneity.

Myeloperoxidase activity

Myeloperoxidase (MPO) activity was used as an indicator of polymorphonuclear leukocytes infiltration into the hippocampus. At the specified reperfusion time, hippocampi were obtained and weighed and each piece homogenised in a solution containing 0.5% (w/v) hexadecyltrimethyl-ammonium bromide dissolved in 10 mM potassium phosphate buffer (pH 7) and centrifuged for 30 min at 20,000g at 4°C. An aliquot of the supernatant was then allowed to react with a solution of 1.6 mM tetramethylbenzidine and 0.1 mM H₂O₂. The rate of change in absorbance was measured spectrophotometrically at 650 nm. MPO activity was defined as the quantity of enzyme degrading 1 µmol of peroxide per min at 37°C and was expressed in milliunits per gram of wet tissue.

Materials

Unless otherwise stated, all compounds were purchased from the Sigma-Aldrich Company Ltd. (St. Louis, MO, USA). The K5 derivative K5-N,OSepi was kindly provided by INALCO RSM S.p.A (Montale, Pistoia, Italy). The BCA Protein Assay kit and SuperBlock blocking buffer were from Pierce Biotechnology Inc. (Rockford, IL, USA) and PVDF was from the Millipore Corporation (Bedford, MA, USA). Goat polyclonal antibody against ICAM-1 and S100B, horseradish peroxidase-conjugated donkey anti-goat IgG, mouse monoclonal antibody against NF-κB p65 and rabbit polyclonal antibodies against Bcl-2 and Bax were from Santa Cruz Biotechnology (Santa Cruz, CA, USA). Rabbit polyclonal antibody against COX-2 was from the Cayman Chemical Company (Ann Arbor, MI, USA). The anti-mouse and

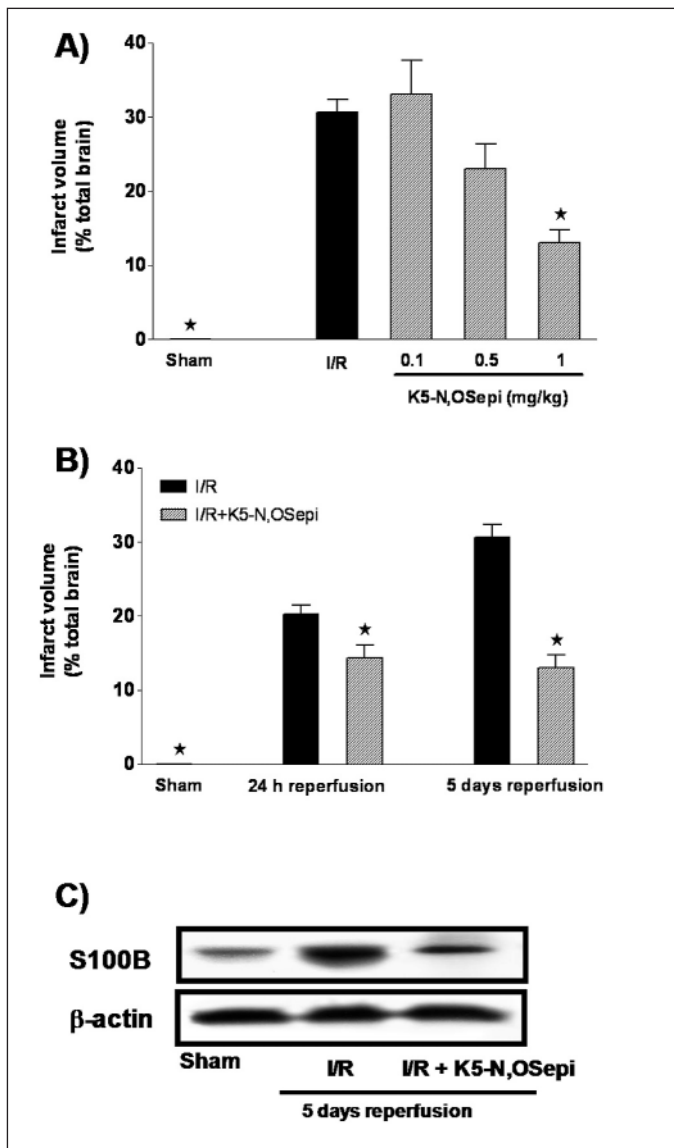


Figure 1: Effects of K5-N,OSepi administration on infarct volume and hippocampal S100B expression. Dose-response effects of K5-N,OSepi against infarct volume induced by 30 min of cerebral ischaemia followed by 5 days of reperfusion (A). Effects evoked by K5-N,OSepi treatment (1 mg/kg) on cerebral infarct volume were evaluated at both 24 h and 5 days reperfusion (B). Data are means \pm SEM of four animals/group. Panel C shows the effects of K5-N,OSepi (1 mg/kg) on S100B protein expression, measured subsequent to I/R (30 min/5 days) on fresh cytosolic fractions of hippocampus. The immunoblot of S100B protein expression and the corresponding β -actin are representative of three separate experiments. \ll $p < 0.05$ versus I/R.

anti-rabbit Ig horseradish peroxidase-linked whole antibodies and Luminol ECL detection reagents were from Amersham (Buckinghamshire, UK).

Statistical analysis

All values in both the text and figures are expressed as mean \pm standard error of the mean (S.E.M.) for n observations. One-way analysis of variance with Dunnett's post test was performed

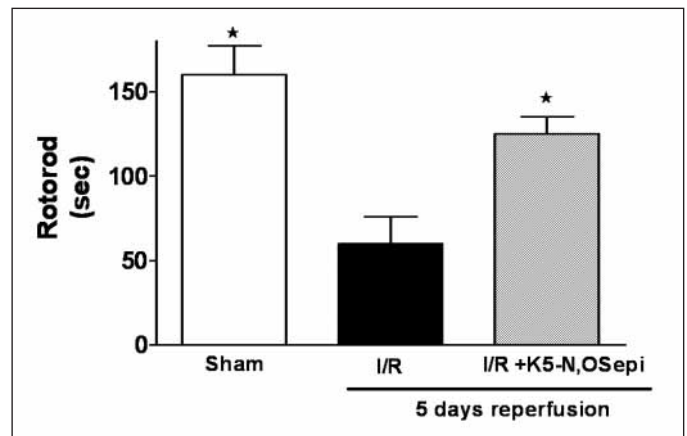


Figure 2: Effects of K5-N,OSepi administration on motor performance measured by Rota-rod Test at 5 days reperfusion. Rats that received K5-N,OSepi (1 mg/kg) during reperfusion (I/R+K5-N,OSepi) showed better motor coordination than rats that underwent ischaemia and reperfusion only (I/R). Data are means \pm SEM of five animals/group. \ll $p < 0.05$ versus I/R.

using GraphPad Prism version 4.02 for Windows (GraphPad Software, San Diego, CA, USA) and p -values below 0.05 were considered to be significant.

Results

Effect of K5-N,OSepi on cerebral infarction and motor performance

In comparison with the brain sections obtained from sham-operated rats, those rats that had been reperused for 5 days showed an infarct volume of $30.7 \pm 3.1\%$. As shown in Figure 1A, administration of K5-N,OSepi during reperfusion induced a dose-dependent reduction in the I/R-induced infarct volume in the range of 0.1–1 mg/kg, with a maximum effect at 1 mg/kg ($13.1 \pm 2.1\%$). The mean size of ischaemic lesions in vehicle-treated animals was larger after 5 days of reperfusion than 24 h reperfusion (Fig. 1B). Interestingly, the mean size of the ischaemic area in the rats treated with K5-N,OSepi (1 mg/kg) was reduced by 30% when measured after 24 h reperfusion and almost 60% when measured at 5 days reperfusion. Consequently, 1 mg/kg, the most effective dose, was taken as the reference dose and endpoints were determined at 5 days of reperfusion in all subsequent experiments.

S100B, a calcium binding protein, which has been recognised as a marker of neuronal damage (20), was barely detectable in the hippocampi of sham-operated animals. Animals subjected to cerebral I/R exhibited a two-fold increase in this protein marker when measured at 5 days reperfusion (Fig. 1C). Treatment of animals with K5-N,OSepi almost completely prevented this rise in S100B levels, so that values of S100B measured in animals treated with K5-N,OSepi were similar to those measured in sham-operated animals.

Consistent with the results of cerebral infarction, treatment with K5-N,OSepi resulted in a significantly better motor performance at 5 days of reperfusion (Fig. 2), when compared with

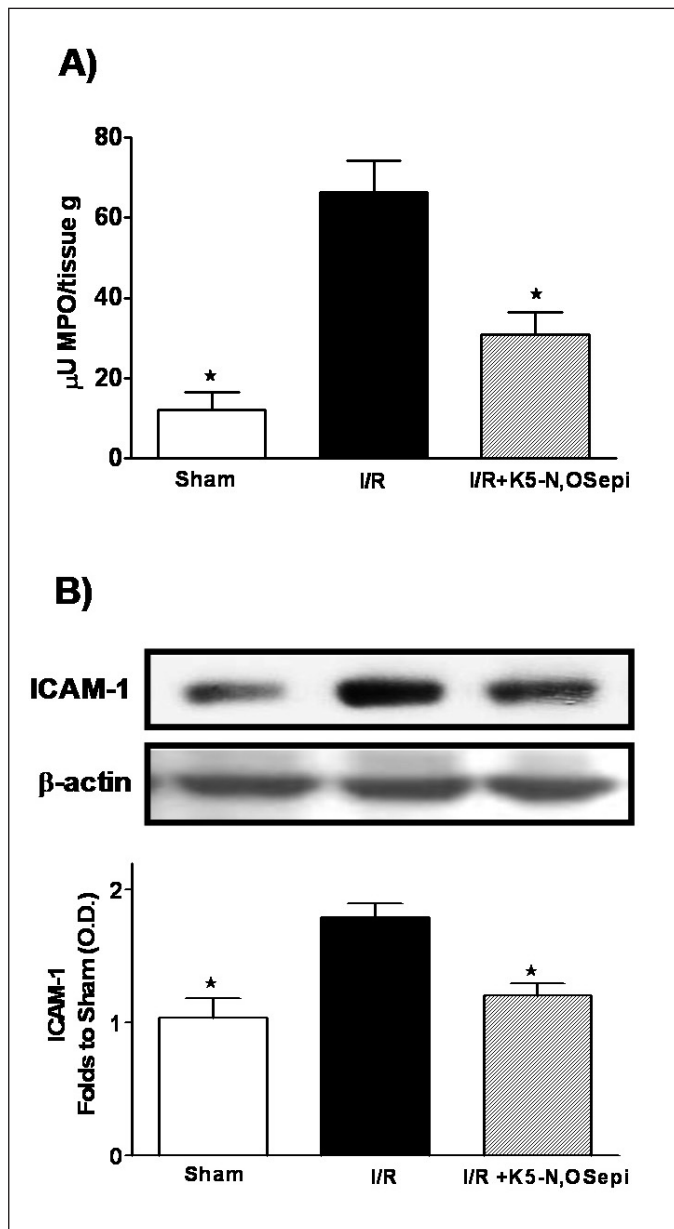


Figure 3: K5-N,OSepi prevents I/R-induced neutrophil infiltration in the rat hippocampus. Myeloperoxidase (MPO) activity (A) and ICAM-1 expression (B) were measured in hippocampi homogenates of sham-operated rats (Sham) and rats that underwent 30 min ischaemia and 5 days reperfusion (I/R). K5-N,OSepi (1 mg/kg) was administered during reperfusion (I/R + K5-N,OSepi). Each immunoblot is from a single experiment and is representative of three separate experiments. Densitometric analysis of the bands is expressed as relative optical density (O.D.), corrected for the corresponding β -actin contents and normalised using the related sham-operated band. Data are means \pm SEM of three separate experiments for Western Blot and four animals/group for MPO. $\ll p < 0.05$ versus I/R.

I/R controls. The results obtained from the rota-rod showed a drastic impairment in motor activity in the I/R group over sham values. K5-N,OSepi administration evoked a significant improvement in balance and coordination compared to the I/R group.

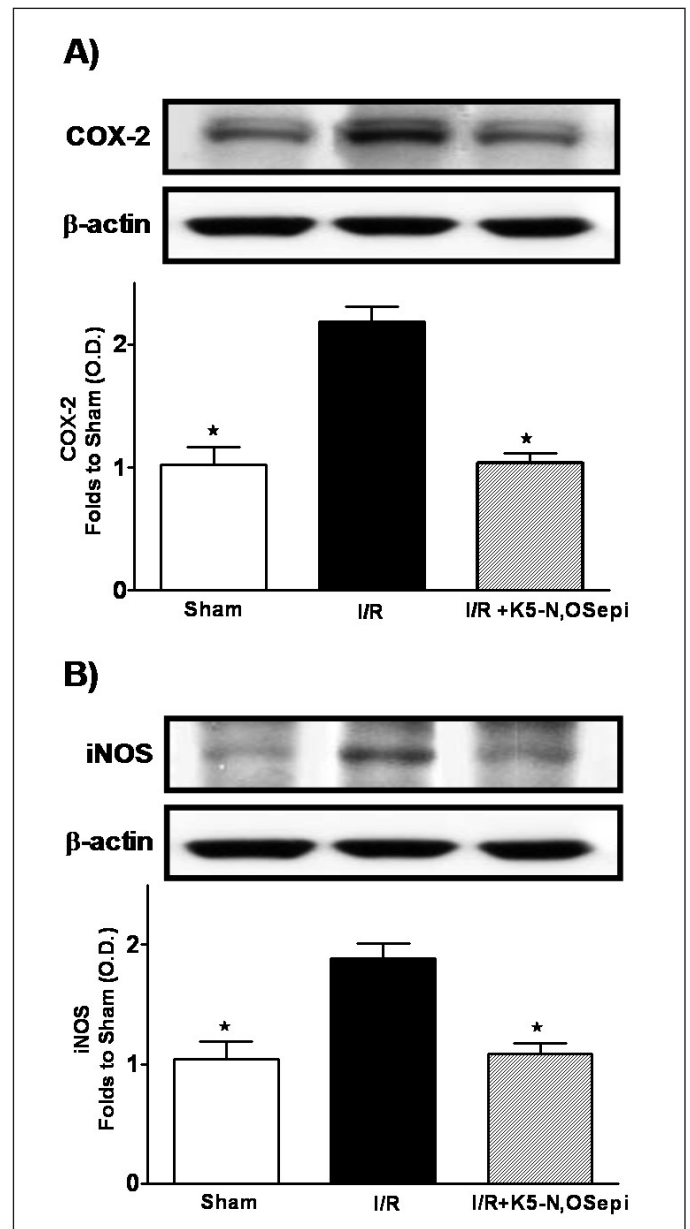


Figure 4: Alterations in hippocampal expression of COX-2 (A) and iNOS (B) induced by K5-N,OSepi administration. Rats were subjected to 30 min ischaemia and 5 days reperfusion (I/R). K5-N,OSepi (1 mg/kg) was administered during reperfusion (I/R + K5-N,OSepi). Each immunoblot is from a single experiment and is representative of three separate experiments. Densitometric analysis of the bands is expressed as relative optical density (O.D.), corrected for the corresponding β -actin contents and normalised using the related sham-operated band. Data are means \pm SEM of three separate experiments. $\ll p < 0.05$ versus I/R.

Effects of K5-N,OSepi on neutrophil infiltration

The improvement in the outcome of I/R injury was associated with a reduced neutrophil infiltration measured in reperused hippocampi at 5 days of reperfusion. As shown in Figure 3A, cerebral I/R caused a robust increase in hippocampal MPO activity, a specific marker of local neutrophil activity, in comparison with sham-operated rats ($66.38 \pm 7.75 \mu\text{U MPO/tissue g}$, 12.04 ± 4.42

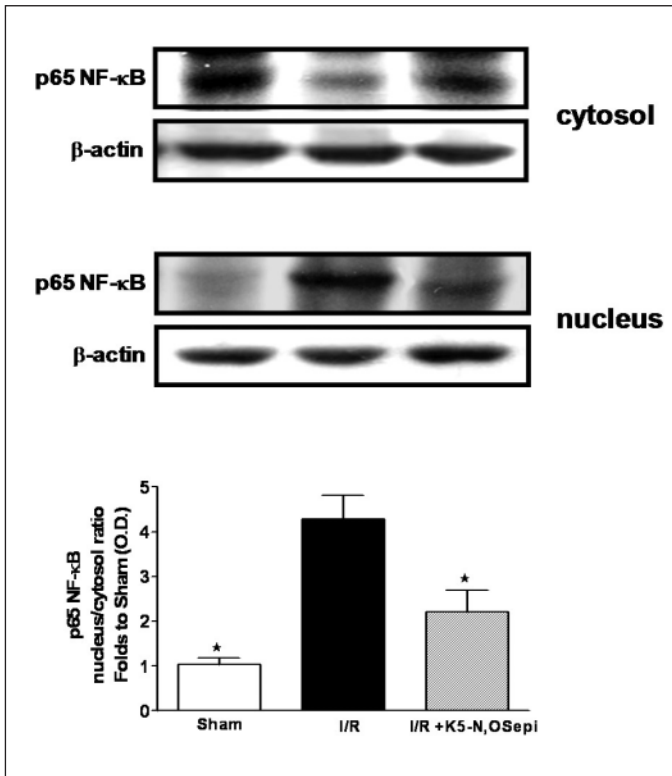


Figure 5: K5-N,OSepi prevents the nuclear translocation of p65 NF-κB evoked by cerebral I/R injury. NF-κB translocation from the cytosol to the nucleus was evaluated in the hippocampus of rats subjected to the surgical procedure alone (Sham) or rats subjected to 30 min ischaemia and 1 h reperfusion and treated with vehicle (I/R) or K5-N,OSepi (1 mg/kg, I/R + K5-N,OSepi). NF-κB p65 subunit levels were measured in both cytosol and nuclear fractions and the results are expressed as nucleus/cytosol ratio. Densitometric analysis is expressed as relative optical density (O.D.) of the bands, corrected for the corresponding β-actin contents and normalised using the related sham-operated band. Data are means ± SEM of three separate experiments. * $p < 0.05$ versus I/R.

μU MPO/tissue g, respectively, $p < 0.05$). In K5-N,OSepi-treated animals, the MPO activity was halved (30.78 ± 5.67 μU MPO/tissue g, $p < 0.05$). The adhesion molecule ICAM-1, which is the endothelial ligand for the neutrophil receptor CD11b/CD18, was scarcely detectable in the hippocampus from sham-operated animals and its expression was strongly induced by 5 days of reperfusion (Fig. 3B). Administration of K5-N,OSepi drastically reduced the increase in ICAM-1 expression afforded by transient cerebral I/R ($p < 0.05$).

Administration of K5-N,OSepi to sham-operated rats had no significant effect on all the markers measured in the present study when compared to sham-operated rats only (data not shown).

K5-N,OSepi reduced the expression of inflammatory markers evoked by cerebral I/R

Densitometric analysis of the autoradiograms detected low COX-2 and iNOS protein levels in the hippocampi obtained from sham-operated animals (Fig. 4). Rats that had undergone transient cerebral ischaemia followed by 5 days of reperfusion

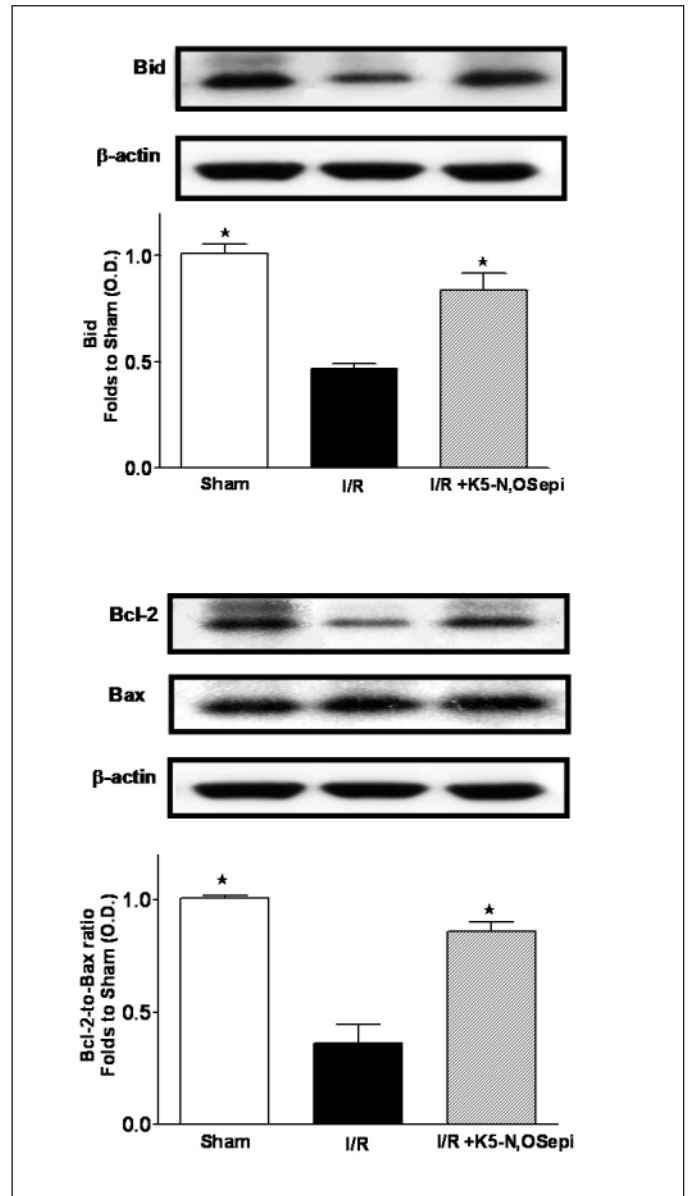


Figure 6: Effects of K5-N,OSepi on expression of apoptosis markers in the hippocampus of rats that underwent I/R injury. Representative Western blot and corresponding densitometric analysis of the bands showing expression of Bid (A), Bcl-2 and Bax (B) at 5 days reperfusion in the presence or absence of K5-N,OSepi treatment (1 mg/kg). The reduction in Bid expression as well as Bcl-2 to Bax ratio evoked by I/R was completely reversed by K5-N,OSepi. Each immunoblot is from a single experiment and is representative of three separate experiments. The data from bands densitometric analysis are means ± SEM of three separate experiments. * $p < 0.05$ versus I/R.

exhibited a significant ($p < 0.05$) increase in the expression of COX-2 and iNOS (Fig. 4A and B, respectively). Administration of K5-N,OSepi did not affect basal COX-2 and iNOS protein levels, but prevented the increase in expression caused by I/R, bringing the hippocampal protein levels of these inflammatory markers back to values similar to those measured in sham-operated animals.

K5-N,OSepi prevented the nuclear translocation of the NF- κ B p65 subunit induced by cerebral I/R injury

Western blot analyses were performed on rat hippocampi to elucidate whether NF- κ B activation was involved in K5-N,OSepi protective mechanisms. Measurement of the nuclear translocation of the p65 subunit NF- κ B from the cytosolic to the nuclear fraction of tissue extracts obtained from rats subjected to I/R injury showed higher levels of p65 subunit in the nucleus in comparison with sham-operated rats, thus suggesting NF- κ B activation secondary to I/R (Fig. 5). The rise in the nucleus/cytosol ratio of the NF- κ B p65 subunit was observed at 1 h but not at 24 h of reperfusion (data not shown). K5-N,OSepi administration attenuated the rise in the nucleus/cytosol ratio hence, indicating reduced translocation of p65 to the nucleus ($p < 0.05$; Fig. 5).

Effects of K5-N,OSepi on markers of apoptosis

Using an antibody against the intact form of the pro-apoptotic protein Bid, Western blot analysis revealed that hippocampi obtained from rats subjected to I/R showed a significant reduction in Bid expression, when compared to sham-operated rats (Fig. 6A), thus demonstrating its activation by cleavage of intact Bid into truncated forms of Bid. The administration of K5-N,OSepi prevented the I/R-induced activation of Bid, when compared to control rats. The basal expression of Bcl-2 protein, a well-known suppressor of apoptosis, was significantly reduced by I/R and this effect was abolished by exogenous K5-N,OSepi administration. On the contrary, the levels of the mitochondrial apoptotic protein Bax showed no significant quantitative differences among different groups, not being changed either by I/R or by K5-N,OSepi pre-treatment. Therefore, the Bcl-2-to-Bax ratio, which was calculated as an index of apoptosis signalling, was significantly reduced in animals subjected to I/R in comparison with sham-operated rats and this effect was attenuated by treatment with K5-N,OSepi (Fig. 6B).

Discussion

The effects of heparin for patients with ischaemic cerebrovascular diseases have been investigated in clinical trials, however, the efficacy and safety of heparin use in cerebral I/R injury remain debatable and depend on a balance between benefits, such as reduction of infarct volume, and risks, such as cerebral haemorrhage (3, 4). Thus, heparin-like derivatives without a bleeding tendency could represent an effective pharmacological strategy to reduce the brain damage induced by I/R. K5-N,OSepi is an epimerised N-deacetylated and N- and O-sulfated heparin-like molecule obtained by chemical and enzymatic modifications of the capsular K5 polysaccharide from *Escherichia coli*. This K5 derivative shows a limited anticoagulant/antithrombotic activity in comparison to heparin (8). This may be due to the influence of the O-sulfated glucuronic acid residues present in sulfated K5 derivatives but not in extracted heparin. On the other hand, the enzymatic modification of K5 by C5-epimerase produces a conformational change in the molecule and enables its anti-inflammatory activity, suggesting that epimerisation is necessary for the anti-inflammatory activity of the O-sulfated molecules (10). The results reported here demonstrated that the heparin-like de-

rivative K5-N,OSepi attenuates cerebral I/R injury *in vivo*, reducing infarct size. This protective effect is further confirmed by data on hippocampal expression of S100B, a member of the S100 family of calcium-binding proteins, which is mainly expressed in the brain (21). Clinical studies indicate that an increase in the levels of S100B correlates with impairment of hippocampal function as well as cerebral infarct size (20). In our study, K5-N,OSepi administration was able to reverse the significant increase in S100B protein level seen in rats that had undergone cerebral I/R injury. We also document a marked correlation between infarct size and impairment of motor coordination and, most notably, we show that the decrease in infarct size evoked by K5-N,OSepi was associated with improved motor coordination.

In search of the mechanism(s) underlying the protective action of K5-N,OSepi, we investigated whether K5-N,OSepi may affect the inflammatory response associated with cerebral I/R injury, as its pivotal role in the pathogenesis of ischaemic cerebrovascular diseases is well known (22). We focused our investigation on the hippocampus, one of the brain areas most sensitive to I/R injury (23). We recently observed (14) that 30 min ischaemia followed by 1 h reperfusion causes significant oxidative stress, whereas the inflammatory response is partially delayed (by at least 24 h) in the rat hippocampus. During cerebral reperfusion, expression of adhesion molecules such as ICAM-1 in endothelial cells is a fundamental requirement for the recruitment of neutrophils into cerebral tissue (24). A number of reports have shown that inhibition of ICAM-1 expression during reperfusion is accompanied by a suppression of recruited leukocytes into the ischaemic brain parenchyma (25–27). We have already reported that heparin and partially desulfated heparins reduce neutrophil adhesion to vascular endothelium (28). The present results demonstrate that administration of K5-N,OSepi can suppress the expression of ICAM-1 and, thus, significantly reduce neutrophil migration out of the vessels. The measurement of MPO activity was selected as a marker of tissue neutrophil infiltration and, in agreement with previous reports (29, 30), the results show that cerebral I/R evoked a strong increase in MPO activity. The elevated activity of MPO was inhibited by K5-N,OSepi treatment. Therefore, we can speculate that the decreased cerebral neutrophil infiltration may have significantly contributed to the reduced cerebral injury after 5 days reperfusion in rats treated with K5-N,OSepi. Two important enzymes involved in the ischaemic inflammatory cascade, iNOS and COX-2, were up-regulated by I/R and, most notably, K5-N,OSepi administration protected the rat hippocampus from I/R-induced iNOS and COX-2 over-expression. The current findings are in keeping with a recent paper showing that an O-sulphated heparin-like K5 derivative blunted inflammatory markers, including the generation of prostaglandins and cytokines, in a rat model of carrageenan-induced pleurisy (31). In the present study, the reduction of the inflammatory response evoked by K5-N,OSepi at 24 h reperfusion was associated with the early inhibition of the proinflammatory nuclear transcription factor NF- κ B measured at 1 h reperfusion. Experimental evidence indicates that NF- κ B plays a fundamental role in the development of I/R injury (32) and we and others have recently reported NF- κ B to be activated in the hippocampi of rats undergoing I/R (33, 34). Here, we show that K5-N,OSepi attenu-

ates the nuclear translocation of NF- κ B p65, which may account for the observed reduction in the expression of COX-2, iNOS and ICAM-1, all of which are NF- κ B-dependent proteins. As previously suggested (9, 35), these results are consistent with the possibility that non-anticoagulant heparin-like molecules may bind electrostatically to cell membranes of different cells and internalise into the cytosolic compartment, thus preventing translocation of NF- κ B from cytoplasm to the nucleus. Therefore, the observed reduction of inflammatory responses and the improvement of cerebral injury after K5-N,OSepi treatment are due, at least in part, to the reduction of NF- κ B activation. However, further study is required to determine the mechanism(s) more precisely.

Another important factor that contributes to the development of I/R-induced cerebral injury is apoptosis. In response to oxidative load in the mitochondria, the outer membrane of mitochondria becomes permeabilised, resulting in the translocation of Bax from cytosol to the mitochondria and the release of cytochrome c normally confined to the mitochondrial intermembrane space. The translocation of those proapoptotic proteins is controlled by the Bcl-2 family proteins (36). In examining the expression of key apoptotic related molecules in the hippocampi of rats at 5 days of reperfusion, we found that Bid (a pro-apoptotic marker) is activated during cerebral I/R injury and is attenuated with K5-N,OSepi administration. Activation of Bid depends on its proteolytic processing into truncated forms of tBid. Bid activation has been shown both *in vivo* following cerebral I/R and *in vitro* in primary cultured mouse neurons (37), whereas deletion of this molecule by gene targeting has been demonstrated to provide significant neuroprotection (38). We also determined the effects of K5-N,OSepi administration on the ratio of Bcl-2-to-Bax expression, a reliable index of apoptotic signalling. Bcl-2 acts as an antiapoptotic regulator by preventing or delaying the release of cytochrome c, perhaps through its ability to influence the creation, maintenance, and function of mitochondrial mem-

brane channels (39). In contrast, Bax (a 21-kDa protein coimmunoprecipitated with Bcl-2) is a promoter of cell death, and its pro-apoptotic function is directly antagonised by Bcl-2 through formation of the Bcl-2/Bax heterodimer (40). Overexpression of Bcl-2 has been demonstrated to reduce the impact of various neurological insults, including I/R injury (41) and several reports have shown a decreased Bcl-2-to-Bax ratio after I/R injury (42). Our results confirmed that cerebral I/R injury caused the suppression of Bcl-2 without associated change in Bax expression, resulting in a decreased Bcl-2-to-Bax ratio to 0.37-fold of the control. Most notably, we observed a significant increase in Bcl-2-to-Bax ratio in the hippocampi of K5-N,OSepi-treated rats, indicating the antiapoptotic capacity of the heparin derivative after cerebral I/R injury.

In conclusion, our results show that post-ischaemic administration of K5-N,OSepi attenuates cerebral I/R injury. This protective effect can be attributed, at least in part, to its ability to inhibit neutrophil infiltration and suppress the inflammatory response by preventing activation of the proinflammatory transcription factor NF- κ B. The mitochondrial apoptotic pathway may represent a further potential target for heparin-like compounds. Overall, our results provide a new understanding of the effects of new heparin derivatives, with low anticoagulant and high anti-inflammatory activities, in post-ischaemic injury and may offer a potential new therapeutic strategy for acute brain injury. However, further investigation is warranted for a better assessment of the pharmacodynamics and safety of a therapy with heparin-like derivatives in conditions associated with cerebral I/R injury.

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