Effects of Dexmedetomidine on Hippocampal Focal Adhesion Kinase Tyrosine Phosphorylation in Physiologic and Ischemic Conditions

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Background: Dexmedetomidine is a potent and selective α2-adrenoceptor agonist that exhibits a broad pattern of actions, including sedation, analgesia, and neuroprotection. Some of these actions (e.g., neuroprotection) may require targets involved in long-term cellular changes. The authors hypothesized that dexmedetomidine increases the expression of active (autophosphorylated) focal adhesion kinase (FAK), a nonreceptor tyrosine kinase playing a pivotal role in cellular plasticity and survival. Therefore, we examined the cellular mechanisms involved in this effect and its sensitivity to oxygen-glucose deprivation (OGD) in rat hippocampal slices.

Methods: The effects of dexmedetomidine on phospho-tyrosine99 FAK phosphorylation were studied first with or without various pharmacologic agents in normoxic conditions, and second in a model of pharmacologic preconditioning of slices subjected to 30 min of OGD followed by 1 h of reperfusion. FAK phosphorylation and caspase-3 activation were examined by immunoblotting. Neuronal death was assessed by propidium iodide fluorescence.

Results: Dexmedetomidine produced a dose-related increase in FAK phosphorylation (187 ± 4%; mean ± SD, from basal level, EC50 = 0.2 μM; 95% confidence interval, 0.09–0.5 μM). This effect was stereoselective and was completely blocked by yohimbine and the combination of the cyclic monophosphate permeant analog 8-bromo cyclic monophosphate and the phosphodiesterase inhibitor 3-isobutyl-1-methylxanthine. It was mimicked by the protein kinase A inhibitor H 89. In contrast, prazosin and the protein kinase C inhibitors chelerythrine and bisindolylmaleimide I were ineffective. OGD induced a significant increase in immunoreactivity of the cleaved caspase-3 17-kd fragment (417 ± 22; P < 0.001), a decrease in FAK phosphorylation (78 ± 12% of control; P < 0.05), and production of significant neuronal death. In OGD conditions, a preconditioning application of dexmedetomidine (0.2 μM, 20-min application, 3 h before anoxia) significantly reduced neuronal death and cleaved caspase-3 expression and significantly attenuated the decrease in phosphorylated FAK content. The dexmedetomidine-induced reduction in caspase-3 expression was significantly decreased by the Src tyrosine kinase inhibitor PP2.

Conclusion: Dexmedetomidine exhibits a preconditioning effect against ischemic injury in hippocampal slices subjected to OGD. Increase in phosphorylation of FAK via stimulation of α2 adrenoceptors and decrease in cleaved caspase-3 expression correlate with dexmedetomidine-induced cell survival.

Dexmedetomidine is a potent and selective agonist of the α2-adrenergic receptors negatively coupled to adenylate cyclase, which exhibits a fascinating spectrum of actions, including a decrease in heart rate and blood pressure, sedation, anesthetic-sparing effects, and analgesia.1-2 Recent reports indicate that dexmedetomidine can be used as a primary sedative in critically ill patients, as well as the sole anesthetic in some surgical patients.3,4 Major advances have been made in the understanding of the mechanisms underlying the sedative/anesthetic action of dexmedetomidine. Elegant experiments using a targeted mutation approach in mice support that the α2A-receptor subtype is responsible for its sedative and analgesic effects.5 Recent data indicate that dexmedetomidine anesthetic action proceeds via activation by α2-adrenergic receptors located on locus ceruleus neurons of a specific γ-aminobutyric acid-mediated pathway involved in a particular stage of sleep named non-rotation eyes movies.6

Dexmedetomidine exhibits potent neuroprotective effects in various experimental models.7,8 However, the cellular effects involved in these actions remain unclear. Recent data support that dexmedetomidine exerts its protective effects via a direct effect of the α2-adrenergic receptor-adenylate cyclase pathway on intracellular signaling cascades rather than an indirect effect through a reduction in the release of excitotoxic glutamate or catecholamines.8-10 This view is further supported by the demonstration of possible antiapoptotic properties of dexmedetomidine.11 Tyrosine protein kinase proteins, such as the nonreceptor tyrosine kinase focal adhesion kinase (FAK), exert a prominent control on signaling pathways and may couple rapid events, such as action potential or neurotransmitter release, to long-lasting changes in synaptic strength and survival.12 The neuronal isoform of FAK is activated by various extracellular signals that use a restricted number of intracellular pathways, and the increase in intracellular Ca2+ and activation of protein kinase C (PKC) family represents a major intracellular step for stimulating FAK phosphorylation.12 Several lines of evidence suggest that the neuronal isoform of FAK exhibits antiapoptotic properties. Also, the FAK-Src complex is in tight connection with the Fyn tyrosine kinase, which plays a key role in the activation of extracellular regulated kinase pathway pro-

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moting cell survival. Alternatively, FAK has been reported to induce an antiapoptotic signal via the Akt-nuclear factor-κB and extracellular related kinase pathways.\textsuperscript{12}

We have recently demonstrated that the protein expression of active (tyrosine phosphorylated) FAK is sensitive to anesthetic agents except ketamine and that the phospholipase C–PKC pathway is involved in this effect.\textsuperscript{13} Alternatively, FAK tyrosine phosphorylation can also be induced via stimulation of receptors (e.g., cannabinoid CB1 receptors) negatively coupled to adenylate cyclase.\textsuperscript{14,15} Therefore, in the current study, we investigated first whether dexmedetomidine affects FAK tyrosine phosphorylation in rat hippocampal slices and the mechanisms involved in this effect. Second, we examined the potential physiologic relevance of these findings in a model of pharmacologic preconditioning of the slices subjected to oxygen–glucose deprivation (OGD).

Materials and Methods

Handling procedures according to the Guide for the Care and Use of Laboratory Animals were followed throughout.\textsuperscript{16} Experiments were performed on male Sprague-Dawley rats (Iffa-Credo, L’Arbresle, France) weighing 250 g and housed on a 12:12-h light:dark cycle with food and water ad libitum. Approval was obtained from the Institutional Animal Care and Use Committee at Paris VII University (Paris, France).

This study, including care of the animals involved, was conducted according to the official edict presented by the French Ministry of Agriculture (Paris, France) and the recommendations of the Helsinki Declaration. Therefore, these experiments were conducted in an authorized laboratory and under the supervision of an authorized researcher (Gressens Pierre, M.D., Ph.D., INSERM U 676, Paris, France).

Experimental Protocol

Animals were killed by stunning (thoracic shock followed by reflex cardiac arrest) and decapitation. Brains were quickly removed; hemispheres were separated until the corpus callosum was observed. The hippocampus of each hemisphere was carefully dissected and incubated in Ca\textsuperscript{2+}-free artificial cerebrospinal fluid (CSF; 4°C; 126.5 mM NaCl, 27.5 mM NaHCO\textsubscript{3}, 2.4 mM KCl, 0.5 mM KH\textsubscript{2}PO\textsubscript{4}, 1.93 mM MgCl\textsubscript{2}, 0.5 mM Na\textsubscript{2}SO\textsubscript{4}, 4 mM glucose, and 11 mM HEPES adjusted to pH 7.4 with 95%/5% [vol/vol] oxygen–carbon dioxide mixture). Hippocampal slices (300-μm thickness each) prepared with a MacIlwain tissue chopper were transferred to polypropylene tubes (three slices per container) containing 1 ml artificial CSF (60 min, 37°C). To avoid tyrosine kinase activation at this step of the experiment, Ca\textsuperscript{2+} was omitted from the medium from the dissection phase until the end of incubation. Slices were incubated for 60 min at 37°C with moderate agitation under a humidified atmosphere of 95%/5% (vol/vol) O\textsubscript{2}/CO\textsubscript{2} until pharmacologic treatments were added together with CaCl\textsubscript{2} and/or an OGD–reperfusion challenge was initiated. Tetrodotoxin (1 μM) was added at the beginning of slice incubation to avoid indirect effects due to neuronal firing.

Slices were transferred to airtight chambers (1 cm\textsuperscript{3} volume, 10 slices per chamber) and superfused at 10 ml/min during 30 min with either the same oxygenated or a glucose-free CSF bubbled with 95% nitrogen–5% containing 5 mM dithionite, an oxygen absorbent, as previously described.\textsuperscript{17,18} Temperature, pH, and partial pressure of oxygen (P\textsubscript{O2}) and carbon dioxide (P\textsubscript{CO2}) were closely monitored. Temperature was servo-controlled to 37°C. After the period of simulated ischemia, slices were recovered in oxygenated buffered CSF for 1 h. The sequence of 30 min of ischemia followed by 1 h was selected according to a preliminary “time-response” study indicating that it provided optimal changes in the content of both FAK and activated caspase-3.

In normoxic normoglycemic conditions, dexmedetomidine and levomedetomidine were applied at various concentrations (10⁻⁷ M to 10⁻³ M) for 5 min. This duration of incubation was determined according to preliminary experiments in which FAK phosphorylation induced by 1 μM dexmedetomidine was plotted against duration of incubation (1, 2, 5, 10, 20, and 30 min) in the presence of the phosphatase inhibitor orthovanadate (1 mM). It corresponded to the point for which the ceiling was reached after a linear increase in phosphorylation between 1 and 5 min. Other pharmacologic agents supposed to increase FAK phosphorylation were applied for 5 min as well. In anoxic–aglycemic conditions, dexmedetomidine was applied as a preconditioning stimulus during 20 min,\textsuperscript{18} and then oxygenation and buffering of the slices were continued for 3 h before the 30-min period of ischemia was induced. This was followed by a 1-h period of reperfusion with oxygen glucose containing CSF. Agents supposed to block the dexmedetomidine (or any other activator)-induced changes in FAK phosphorylation and/or cleaved caspase-3 expression were administered 1 h before dexmedetomidine.

At the end of the experiments, CSF was aspirated, and slices were frozen in liquid nitrogen, homogenized by sonication in 200 μl of a solution of 1% (wt/vol) sodium dodecyl sulfate, 1 mM sodium orthovanadate, and antiproteases (50 μg/ml leupeptin, 10 μg/ml aprotinin, and 5 μg/ml pepstatin) in water at 100°C, and placed in a boiling bath for 5 min. Homogenates were stored at −80°C until processing. To investigate the putative role of phosphatases in the changes observed in FAK phosphorylation, orthovanadate, a tyrosine phosphatase inhibitor, and okadaic acid, a serine–threonine phosphatase inhibitor, were administered at active concentrations (10⁻³ M...
and $10^{-6}$ m, respectively) from the beginning of incubation in physiologic and ischemic conditions.

**Chemicals**

The following agents were studied alone or in combination: dexmedetomidine and levomedetomidine ($10^{-8}$ m to $10^{-5}$ m), tetrodotoxin (1 $\mu$M; Sigma, St-Quentin Fallavier, France), the inhibitors of PKC chelerythrine ($10^{-5}$ m; Sigma) and bisindolylmaleimide 1 ($10^{-5}$ m; Sigma), phorbol 12-myristate 13-acetate (PMA, 0.1 $\mu$M; Sigma), the analog of cyclic adenosine monophosphate (cAMP) 8-bromo cAMP ($4 \times 10^{-3}$ m; Sigma), the inhibitor of phosphodiesterases 3-isobutyl-1-methylxanthine ($10^{-4}$ m; Sigma), methoxamine ($10^{-5}$ m; Sigma), the inhibitor of cAMP-dependent protein kinase H 89 ($10^{-5}$ m; Sigma), prazosin ($10^{-4}$ m; Sigma), yohimbine ($10^{-3}$ m; Sigma), the inhibitor of Src tyrosine kinase 4-aminophenyl-7-(t-buty)pyrazolo[3,4-d]pyrimidine (PP2, $10^{-5}$ m; Calbiochem, Nottingham, United Kingdom), and the phosphatases inhibitors sodium orthovanadate (1 mm; Sigma) and okadaic acid ($10^{-6}$ m; Sigma).

**Immunoblot Analysis**

Protein concentration in the homogenates was determined with a bicinecinic acid–based method, using bovine serum albumin as the standard. Equal amounts of protein (30 $\mu$g) were subjected to 6% (wt/vol) polyacrylamide gel electrophoresis in the presence of sodium dodecylsulfate and transferred electrophoretically to nitrocellulose. For detection of phosphorylated FAK, immunoblot analysis was performed with affinity-purified rabbit antiphosphotyrosine antibodies (monclonal mouse immunoglobulin IgG, clone 4G10; Euromedex). The 17-kd band was considered cleaved residues of the protein (monclonal mouse IgG, clone 447; Euromedex 05-537, Souffelweyersheim, France). Immunoreactive bands were quantified using a computer-assisted densitometer and normalized to $\beta$-actin expression (quantified by using the specific monoclonal antiactin A5316 antibody Sigma) ratio (Cohu High Performance charge-coupled device camera; Gel Analyst 3.01 pci, Paris, France). The validity of the actin control in both physiologic and ischemic conditions was tested by comparing the normalization of data to either actin or total FAK in both physiologic and conditions and OGD.

**Quantification of Cell Death**

Quantification of cell death was performed using two methods: detection of active cleaved caspase 3 by Western blot analysis and quantification of cell death using propidium iodide (PI) fluorescence.

Detection of active cleaved caspase 3 was performed using Western blot analysis (see Immunoblot Analysis) using a rabbit polyclonal IgG anti-caspase 3–specific antibodies detecting both the 32-kd entire protein and the 17-kd fragment produced by cleavage of caspase 3 when activated (Upstate biotechnology, diluted 1:2,000; Euromedex). The 17-kd band was considered cleaved caspase 3 and was taken into consideration in the statistical analysis.

Quantification of cell death and dexmedetomidine neuroprotection was also detected using fluorescent PI (Invitrogen, Cergy-Pontoise, France, P3566). PI binds to DNA by intercalating between the bases with little or no sequence preference and with a stoichiometry of one dye per four to five base pairs of DNA. Once the dye is bound to nucleic acids, its fluorescence is enhanced 20- to 30-fold, the maximal absorption wave for PI being 535 nm and maximal fluorescence emission wave being 617 nm. PI was added to the artificial CSF (2 $\mu$g/ml) in three independent experiments. In each of them, five slices were randomly selected and processed for serial 20-$\mu$m coronal sections cut along the entire hippocampus. Stained cells were examined using a fluorescence microscope equipped with an appropriate filter (UV-2A; Zeiss, Oberkochen, Germany; excitaction, 530 nm; emission, $>$ 600 nm), and images were digitalized. All the slices were analyzed the same time by an observer unaware of treatment assignment. For each experiment, PI fluorescence from five areas of the CA1 subfield were analyzed using Image J 1.31v software.
Houston, TX) COMPAQ computer. For tyrosine phosphorylation or caspase-3 protein expression (15–24 experiments per condition), normality of distributions was first assessed by the Fisher exact test for equality of variances. Statistical analysis was then performed by analysis of variance with the Scheffe post hoc correction for multiple comparisons.

Results (mean ± SD) are expressed as a percentage of control FAK or caspase-3 protein expression. \( P < 0.05 \) was considered the threshold for significance.

Results

Experiments Performed in Physiologic Conditions

Both dexmedetomidine and levomedetomidine produced a significant, concentration-related, similar increase in phosphotyrosine immunoreactivity of both the 125-kd band and the specific FAK one (figs. 1 and 2). However, the \( EC_{50} \) values (maximal effect) were significantly different for dexmedetomidine (0.22 \( \mu \)M [95% confidence interval, 0.09–0.49 \( \mu \)M]; 187 ± 6%) and levomedetomidine (12.5 \( \mu \)M [95% confidence interval, 2.2–17.8 \( \mu \)M]; 186 ± 9%) (\( P < 0.05 \); fig. 2). In contrast, dexmedetomidine did not significantly increase immunoreactivity of total FAK (data not shown). Omitting tetrodotoxin from the incubation medium did not significantly change tyrosine phosphorylation (data not shown). For each dexmedetomidine concentration tested, no significant difference between tyrosine phosphorylation normalized to either total FAK or actin was present (data not shown). In addition, the \( EC_{50} \)s of dexmedetomidine-induced FAK phosphorylation normalized to either total FAK or actin were not significantly different: 0.13 \( \mu \)M (95% confidence interval, 0.05–0.30 \( \mu \)M) and 0.22 \( \mu \)M (95% confidence interval, 0.09–0.49 \( \mu \)M) (data not shown).

The increase in FAK phosphorylation induced by dexmedetomidine (0.2 \( \mu \)M) was completely blocked by the \( \alpha_2 \)-adrenoceptor antagonist yohimbine (10\(^{-5} \) M) and the association of the permeant cAMP analog 8 bromo cAMP (4 \( \times 10^{-3} \) M) and the phosphodiesterase inhibitor 3-isobutyl-1-methylxanthine (10\(^{-4} \) M) (fig. 3). Further, dexmedetomidine effect on FAK phosphorylation was present (data not shown). In addition, the \( EC_{50} \)s of dexmedetomidine-induced FAK phosphorylation normalized to either total FAK or actin were not significantly different: 0.13 \( \mu \)M (95% confidence interval, 0.05–0.30 \( \mu \)M) and 0.22 \( \mu \)M (95% confidence interval, 0.09–0.49 \( \mu \)M) (data not shown).

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DEXMЕDETOMIDINE AND ТYROSINE PHOSPHORYLATION

Fig. 4. Effects of prazosin (10⁻⁴ m), methoxamine (10⁻⁵ m), chelerythrine (10⁻⁵ m), bisindolylmaleimide I (Ro318220, 10⁻⁵ m), and phorbol 12-myristate 13-acetate (PMA, 0.1 μm) on dexmedetomidine (Dex, 0.2 μm)-induced focal adhesion kinase phosphorylation in rat hippocampal slices. Data (mean ± SD) are expressed as a fractional 125-kd tyrosine phosphorylation on actin ratio increase from basal phosphorylation (control: 100%). * P < 0.05 versus control, ** P < 0.01 versus control, *** P < 0.001 versus control. NS = not significant.

mimicked by H 89, but no additivity of these effects was detected (fig. 3). In contrast, the α₁-adrenoceptor antagonist prazosin (10⁻⁴ m) did not affect dexmedetomidine-induced increase in FAK phosphorylation, whereas it completely blocked the effect of methoxamine (10⁻⁵ m) (fig. 4). The structurally distinct inhibitors of PKC, chelerythrine (10⁻⁵ m) and bisindolylmaleimide I (10⁻⁵ m), did not affect dexmedetomidine effect on FAK phosphorylation, whereas they blocked the effect of the PKC activator phorbol 12-myristate 13-acetate (0.1 μm). The combination of dexmedetomidine (0.2 μm) and methoxamine (10⁻⁵ m) produced a significantly additive effect on FAK phosphorylation (fig. 4).

Experiments Performed in Oxygen-Glucose-deprived Slices

PO₂, PCO₂, and pH in the anoxic-aglycemic versus control chambers were the following: 4 ± 2 versus 450 ± 21 mmHg (P < 0.05), 40 ± 3 versus 41 ± 3 mmHg (not significant), and 7.4 ± 0.02 versus 7.4 ± 0.03 (not significant). A 30-min period of OGD followed by 1 h of reperfusion resulted in both a marked decrease in phosphorylated FAK content (78 ± 12% of normoxic-normoglycemic control; P < 0.05) and a significant increase in the 17-kd fragment of caspase-3 immunoreactivity (437 ± 22; P < 0.001; figs. 5A and B). At this time, the intensity of PI fluorescence was significantly increased in comparison with physiologic conditions (5,721 ± 204 vs. 27 ± 1.6; P < 0.001; fig. 6). Application of dexmedetomidine (0.2 μm) during 20 min, 3 h before the anoxic aglycemic challenge, significantly attenuated neuronal death (5,721 ± 204 vs. 2,896 ± 255; P < 0.001; fig. 6) as well as the decrease in phosphorylated FAK content. Also, it significantly reduced 17-kd caspase-3 fragment immunoreactivity. In contrast, coapplication of the Src tyrosine kinase inhibitor PP2 (10⁻⁴ m) together with dexmedetomidine (0.2 μm) significantly, but not totally, reduced the decrease in 17-kd caspase-3 fragment of content (figs. 5A and B). As was the case in physiologic conditions, normalization of data to either actin or total FAK was not significantly different in any case (data not shown). The presence of orthovanadate or okadaic acid from the onset of incubation did not induce any change in FAK phosphorylation or cleaved caspase-3 expression (figs. 7A and B).

Discussion

We have shown that clinically relevant concentrations of dexmedetomidine increase phosphorylation of FAK tyrosine kinase in rat hippocampal slices. This effect is mediated via activation of the α₁-adrenoceptor-adenylate cyclase pathway. We also provide evidence that a preconditioning application of dexmedetomidine attenuates both the decrease in FAK tyrosine phosphorylation and the increase in cleaved caspase-3 expression observed in response to OGD. These effects correlate with a neuroprotective effect of dexmedetomidine observed in the slices.

Methodologic Considerations

Control of PO₂, PCO₂, and pH in the superfusion chambers was satisfactory, because PO₂ of less than 5 mmHg was obtained in the anoxic chambers. Dexmedetomidine induced a concentration-related increase in FAK tyrosine phosphorylation. The specificity of the antityrosine397 FAK antibody for the phosphorylated (active) form of FAK has been demonstrated previously.12,14,21 This represents the first step of FAK activation and oc-
curs by autophosphorylation of the kinase on its tyrosine residue. Our data indicate also that phosphatases were very likely to not play a major role in the reported effects. Also, it was of particular importance to show first that dexmedetomidine actually increased the content of phosphorylated FAK, and not simply the total amount of FAK, and second that the expression of results as normalized to actin concentrations was not af-

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Fig. 5. (A) Effects of dexmedetomidine (Dex, 0.2 μM), PP2 (10\(^{-5}\) μM), and the association of dexmedetomidine and PP2 in presence or absence of orthovanadate (1 mM) during all the procedure in physiologic (normal cerebrospinal fluid [CSF] superfusion during all the procedure) or oxygen-glucose deprivation (OGD) (3 h normal CSF superfusion, 30 min oxygen- and glucose-free CSF superfusion, and 1 h normal CSF superfusion) conditions on focal adhesion kinase phosphorylation. Data (mean ± SD) are expressed as a fractional 125-kd tyrosine phosphorylation on actin ratio increase from basal phosphorylation for physiologic condition (control physiologic: 100%). Western blot bands show total 125-kd tyrosine phosphorylation (PT, 125-kd; upper panels) and phospho-tyrosine focal adhesion kinase (P-Tyr\(^{397}\) FAK; lower panels). (B) Effects of dexmedetomidine (0.2 μM), PP2 (10\(^{-5}\) μM), and the association of dexmedetomidine and PP2, in presence or absence of orthovanadate (1 mM) during all the procedure, in physiologic (normal CSF superfusion during all the procedure) or OGD (3 h normal CSF superfusion, 30 min oxygen- and glucose-free CSF superfusion, and 1 h normal CSF superfusion) conditions on P\(^{17}\) caspase-3 expression. Data (mean ± SD) are expressed as a fractional P\(^{17}\) caspase-3 (P\(^{17}\) C3) increase from basal for physiologic condition (control physiologic: 100%). Western blot bands show P\(^{17}\) caspase 3. MP = molecular probe.
affected by the possible degradation of FAK, but not actin, under OGD. We therefore compared a second standard, i.e., total FAK content, which includes both nonphosphorylated and phosphorylated FAK, to actin content to normalize the data. Our results indicate first that dexmedetomidine actually increased the phosphorylated FAK content, and second that normalization to actin was valid under both physiologic and ischemic conditions.

**Dexmedetomidine Increases FAK Phosphorylation via Activation of \( \alpha_2 \)-Adrenoceptors**

The effect of dexmedetomidine on FAK phosphorylation was likely not to be mediated via \( \alpha_1 \) adrenoceptors. We have previously shown that most of the intravenous and volatile anesthetics increased FAK phosphorylation via activation of the phospholipase C–PKC pathway and that this effect was not shared by the nonimmobilizer F6.\(^\text{13}\) The lack of effect of the structurally distinct PKC antagonists bisindolylmaleimide I and chelerythrine in our study suggests that dexmedetomidine effects on FAK phosphorylation are not mediated by PKC. The pharmacologic approach we used here strongly supports that dexmedetomidine increases FAK phosphorylation by stimulation of \( \alpha_2 \) adrenoceptors. However, the receptor subtype (\( \alpha_{2A} \) or \( \alpha_{2C} \)) involved in this effect was not determined here. Our results are consistent with the previous observation that decreasing adenylate cyclase activity (e.g., via activation of the cannabinoid CB1 receptors) results in an increase in FAK phosphorylation.\(^\text{14,15,22}\) However, the relations between reduced cAMP and protein kinase A activity and FAK phosphorylation remain to be clarified. In some experimental systems, such as fibroblasts or endothelial cell cultures, the role of SHP2, a tyrosine phosphatase controlling FAK phosphorylation, has been suggested.\(^\text{23,24}\) These obser-

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Fig. 6. (Left) Propidium iodide fluorescence on CA1 hippocampal areas (\( \times \)20 magnification). (Right) Propidium iodide fluorescence in physiologic (normal cerebrospinal fluid superfusion during all the procedure) or ischemia (3 h normal cerebrospinal fluid superfusion, 30 min oxygen- and glucose-free cerebrospinal fluid superfusion, and 1 h normal cerebrospinal fluid superfusion) experiments in presence or absence of dexmedetomidine preconditioning. * \( P < 0.001 \).

Fig. 7. (A) Effects of dexmedetomidine (Dex, 0.2 \( \mu \)M), PP2 (10\(^{-5}\) M), and the association of dexmedetomidine and PP2 in physiologic (normal CSF superfusion during all the procedure) or oxygen–glucose deprivation (OGD) (3 h normal CSF superfusion, 30 min oxygen- and glucose-free CSF superfusion, and 1 h normal CSF superfusion) conditions with or without the phosphatases inhibitors orthovanadate (1 mM) or okadaic acid (10\(^{-7}\) M) on focal adhesion kinase phosphorylation. Data (mean ± SD) are expressed as a fractional 125-kd tyrosine phosphorylation on actin ratio increase from basal phosphorylation for physiologic condition (control physiologic: 100%) and OGD condition (control ODG: 100%). * \( P < 0.05 \) versus control, ** \( P < 0.01 \) versus control, *** \( P < 0.001 \) versus control. (B) Effects of dexmedetomidine (0.2 \( \mu \)M), PP2 (10\(^{-5}\) M), and the association of dexmedetomidine and PP2 in physiologic (normal CSF superfusion during all the procedure) or OGD (3 h normal CSF superfusion, 30 min oxygen- and glucose-free CSF superfusion, and 1 h normal CSF superfusion) conditions with or without the phosphatases inhibitors orthovanadate (1 mM) or okadaic acid (10\(^{-7}\) M) on \( \text{P}17 \) caspase-3. Data (mean ± SD) are expressed as a fractional \( \text{P}17 \) caspase-3 increase from basal immunoreactivity for physiologic condition (control physiologic: 100%) and OGD condition (control ODG: 100%). * \( P < 0.05 \) versus control, ** \( P < 0.01 \) versus control, *** \( P < 0.001 \) versus control.
vations are not supported by our data showing insensitivity of FAK phosphorylation to phosphatase inhibitors. In differentiated tissue, such as hippocampal slices from adult rats, changes in cAMP concentrations induced by a Gi-coupled receptor or pharmacologic manipulation of protein kinase A activity seem sufficient to activate a signaling pathway involving FAK, similar to that triggered by integrin-dependent cell adhesion.\(^{12}\) The effect of dexmedetomidine on FAK phosphorylation exhibited a significant degree of stereoselectivity, because the EC\(_{50}\) value observed for FAK phosphorylation by the levogyre medetomidine isomer (levomedetomidine) was significantly greater than that of dexmedetomidine. Interestingly, levomedetomidine has a significantly lower anesthetic potency in various species, which supports physiologic relevance of the present findings.\(^{25,26}\)

**Dexmedetomidine Exhibits a Preconditioning Effect in an In Vitro Model of Neuroprotection**

Consistent with our previous findings, a 30-min period of OGD resulted in a marked increase in the intensity of PI fluorescence.\(^{27}\) This correlated with a decrease in the content of phosphorylated FAK in the slices. This is most likely to be explained by the energy deprivation caused by OGD, because the phosphorylation process is adenosine triphosphate dependent,\(^{28,29}\) or by activation of phosphatase.\(^{30}\) Our results do not support phosphatase stimulation because no difference in FAK phosphorylation or caspase activation was found when both tyrosine phosphatases and serine–threonine phosphatases were inhibited. Energy deprivation induces in hippocampal slices a cascade of events triggered by excitotoxic glutamate and leading to neuronal death by necrosis, apoptosis, or both.\(^{28}\) The increase in the expression of the 17-kd fragment of caspase 3, a key enzyme in the production of apoptotic death, suggests that caspase 3 has been cleaved and activated by the OGD. Brain caspase-3 expression has been found increased when ischemia or hypoperfusion is present.\(^{31,32}\) Therefore, apoptotic cell death was likely to be present in the slices subjected to OGD and reperfusion.

Reduction of cell death by dexmedetomidine correlated with restoration of the content of phosphorylated FAK to physiologic levels. Expression of cleaved caspase 3 was significantly, but not totally, reduced by dexmedetomidine (0.2 \(\mu\)M) under OGD. This is consistent with results previously obtained by Engelhard et al.\(^{11}\) showing that dexmedetomidine enhances the expression of regulatory proteins favoring antiapoptosis and decreases that of proapoptotic ones in rat brains subjected to 30 min of focal ischemia.\(^{13}\) Further, we provide evidence for the first time that dexmedetomidine exerts preconditioning effects toward brain ischemic injury. Activation of the Src-family kinases by FAK autophosphorylation represents a critical step to allow phosphorylation of tyrosine residues in the catalytic and carboxyterminal domain of FAK.\(^{33}\) These residues bind target molecules such as extracellular related kinase and induce their activation.\(^{12}\) We found that the effect of dexmedetomidine on caspase 3 expression in ischemic conditions was significantly reduced by the Src tyrosine kinase inhibitor PP2. This is consistent with previous data showing that adenylate cyclase–mediated cannabinoid-induced increase in FAK-related kinases, such as Fyn, was sensitive to PP2.\(^{28}\) Because reduction of 17-kd caspase 3 elicited by PP2 was only partial (fig. 5B), it is likely that other mechanisms, such as reduction in glutamate release, are involved in dexmedetomidine-induced neuroprotection. Indeed, reduction in glutamate transmission is expected to decrease FAK phosphorylation and can therefore be considered as a potential additional mechanism of dexmedetomidine induced neuroprotection. Altogether, these experiments support that preservation of FAK phosphorylation and inhibition of caspase-3 activation contribute, at least in part, to the neuroprotective effects of dexmedetomidine observed in our model.

**Physiologic Relevance**

The interpretation of the current findings might have some physiologic relevance but also exhibits some limitations. First, caution should always be used when extrapolating in vitro data to the clinical setting. Second, our model allows detecting only short-term protective actions of dexmedetomidine in vitro. It cannot be excluded that the protective effects of dexmedetomidine reported here are no longer present after days or weeks.\(^{34}\) However, our results and data from other groups support that the protective effects of dexmedetomidine against ischemic injury proceed in part via antiapoptotic mechanisms.\(^{11}\) Third, whether dexmedetomidine acts at the pretranscriptional or posttranscriptional level to increase FAK phosphorylation cannot be derived from our data. However, the efficient dexmedetomidine concentrations reported here are low and fairly consistent with those that can be anticipated to be found in the brain of rats protected by this agent against ischemic injury,\(^{8,10}\) or in the plasma of humans treated with this agent.\(^{35,36}\)

In summary, dexmedetomidine exhibits a preconditioning effect against ischemic injury in the hippocampal slice subjected to OGD. Increase in phosphorylation of FAK via stimulation of \(\alpha_2\) adrenoceptors and decrease of cleaved caspase-3 expression correlate with dexmedetomidine-induced cell survival.

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**References**

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