Endogenous opioids have been shown to produce beneficial effects in experimental stroke. To evaluate both neurophysiological and biochemical parameters, we induced massive cerebral ischemia in 11 rabbits according to the method standardized in our laboratory, using microspheres injected through the internal carotid artery. Binding studies were performed in the 11 embolized, in nine control, and in five sham-operated rabbits using the appropriate concentration of \(^{3}H\)dynorphin A (1–8). Neurophysiological parameters were evaluated under baseline conditions and 1 hour after embolization, surgical preparation, or sham operation in 17 rabbits. Comparison of visual readings of the electroencephalograms and analyses of the quantified electroencephalograms under baseline conditions and after embolization indicated a marked and statistically significant \((p<0.01)\) increase in bilateral delta activity; histologic examination confirmed bilateral brain edema. Binding studies on \(\kappa\)-opioid receptors indicate that 1 hour after embolization there were significantly more \((28\%)\) \(\kappa\)-opioid receptors \((B_{\text{max}})\) in six embolized rabbits than in five sham-operated animals. No significant changes were observed in the affinity parameters, particularly in the dissociation constant \((K_{d})\). Our results indicate a role for endogenous dynorphin peptides in the pathogenesis of stroke. (Stroke 1990;21:943–947)
previous described model of massive cerebral ischemia induced in rabbits.21

Materials and Methods

Using 25 New Zealand white rabbits weighing 3.0–3.5 kg, we isolated and then cannulated the right common carotid artery after occlusion of all its external branches. Embolization through a catheter inserted in the internal carotid artery was carried out in 11 rabbits by means of 10 microspheres, 0.3–0.35 mm in diameter, suspended in 1 ml of a sterile solution containing physiological saline plus 1% xanthan gum and perfused by a constant perfusion pump for 60 seconds (flow rate of 62 ml/hr). The five sham-operated rabbits received carotid injections of 1 ml of the vehicle. The nine control rabbits received no carotid injections. We performed all surgical procedures with the rabbits under anesthesia (10–15 minutes duration) with 4% halothane and used 2% xylocaine locally to ensure their pain-free conditions.

We prepared another group of 17 rabbits (six sham-operated and 11 embolized) for electroencephalography (EEG) according to the stereotactic method of Monnier and Gangloff22 to study the motor, sensorimotor, and visual cortices of both hemispheres. All electrophysiological variables were evaluated for 30 minutes at baseline conditions and 1 hour after surgical preparation and carotid injection. The quantified EEG analysis was calculated on-line using a Nova 4/c, 16-bit minicomputer of the Data General series (Westboro, Massachusetts) equipped with a 12.5-megabyte hard disk, a 512-kilobyte floppy disk, hardware multiply-divide, and an analog-to-digital conversion board and then evaluated by means of a minicomputer, according to the method standardized in our laboratory.21 We considered the power density spectrum and four frequency bands (0.15–3.7, 3.7–7.2, 7.2–12.2, and 12.2–20.2 Hz) for both the right and left cortices. Somatosensory evoked potentials (SEPs) were obtained by unilateral stimulation of the right and left median nerves. The data were evaluated by two-factor analysis of variance23 to examine the factors treatment, time within a treatment, rabbit, and the treatment × rabbit interaction. All the in vivo experiments were carried out in strict accordance with the “Guiding Principles in the Care and Use of Laboratory Animals” of the American Physiological Society.

The binding studies were conducted 1 hour after surgical preparation or carotid injection to avoid the presence of necrotic tissue to a significant extent even if it cannot be excluded that pathologic processes were developing. The 25 rabbits were decapitated and their brains were homogenized as described by Quirion and Filapi.24 For 16 rabbits (five controls, five sham-operated, and six embolized) 1.0 ml homogenized right frontoparietal cortex (12 mg/ml) was increased to 2.0 ml with solutions of the unla- beled ligand dynorphin A (1–8) plus [3H]dynorphin A (1–8) (specific activity 25.5 Ci mmol at 1, 3, 5, 7, 10, and 15 nM). Binding was assayed in the remaining nine rabbits (four controls and five embolized) in the presence of a saturating concentration of U 69593 (10–8 M), a specific κ-opioid receptor ligand.25 Specific binding was calculated as the difference in radioactivity bound in the presence and absence of 10–4 M unlabeled dynorphin A. The mixture was incubated for 1 hour at 0° C, filtered, and washed three times with cold buffer. The protein content was measured according to the method of Lowry et al.26 Kin and Bmax were calculated using the methods of Munson and Rodbard.27 The control, sham-operated, and embolized groups were compared using analysis of variance as modified by Scheffé.23

For histologic examination, the brains of all 17 rabbits were fixed in 12% formalin solution. Five coronal sections were prepared and stained with hematoxylin and eosin and Luxol fast blue for myelin.

Results

Neither the control nor the sham-operated rabbits showed any changes in the parameters considered. All 11 embolized rabbits developed massive bilateral edema. At the time of the binding assay no ischemic lesions were evident; they were detectable histologically only later.
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TABLE 1. Kinetic Variables of K-Opioid Receptors in Rabbit Brain

<table>
<thead>
<tr>
<th>Group</th>
<th>n</th>
<th>$B_{max}$ (fmol/mg protein)</th>
<th>$K_d$ (nM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>5</td>
<td>181.66±12.61</td>
<td>3.42±0.18</td>
</tr>
<tr>
<td>Sham-operated</td>
<td>5</td>
<td>193.77±16.06</td>
<td>4.22±0.32</td>
</tr>
<tr>
<td>Embolized</td>
<td>6</td>
<td>247.90±15.54*</td>
<td>3.77±0.26</td>
</tr>
</tbody>
</table>

Data are mean±SEM.  
*p<0.005 different from control and sham-operated according to Munson and Rodbard.27

cortical components. In all the 11 embolized rabbits the subcortical components ($N_1$ and $P_1$) were delayed (Figure 3).

Histologic results showed that the 11 embolized rabbits developed massive bilateral brain edema without histologic evidence of ischemic lesions. According to histologic localization of the ischemic sites previously described,21 samples of the right frontoparietal cortex submitted to biochemical determinations showed that our experimental stroke significantly increased $B_{max}$ without changing $K_d$ (Table 1). In the experiments using $10^{-8}$ M U 69593, no changes were observed in the kinetic properties of K-opioid receptors in embolized rabbits compared with controls (Table 2).

Discussion

Experimental intravascular embolization in rabbits seems to be a valuable model of stroke that reproduces a pattern of massive cerebral edema commonly found during the course of ischemic insult to the brain. Previously we standardized a different model of stroke by injecting different amounts of microspheres into the internal carotid artery.21 The pathologic picture ranged from a single infarct, ipsilateral to the injection and localized in the frontoparietal area to massive brain edema. In that study, cerebral blood flow was monitored by the clearance curve of xenon-133. Rabbits submitted to massive embolization demonstrated a critical decrease (>80%) in gray matter blood flow. These neurophysiological results

**Figure 2.**  Bar graphs of quantified electroencephalogram analysis in rabbits: power density spectrum (PDS) and relative power in four frequency bands. MC, motor cortex; SC, sensorimotor cortex; shaded bars, baseline conditions; cross-hatched bars, 1 hour after embolization. *p<0.05 different from baseline by analysis of variance.

**Figure 3.**  Typical somatosensory evoked potentials of rabbit under baseline condition (Bas) (top) and 1 hour after embolization (1 h) (bottom). R, right hemisphere (stimulation of left median nerve); L, left hemisphere (stimulation of right median nerve); $N_1$ and $P_1$, subcortical components; $N_2$ and $P_2$, $N_3$ and $P_3$, $N_4$ and $P_4$, cortical components.
indicate the existence of brain damage since the increase in delta activity is typical of this pathology. In particular, SEP recordings showed a loss of cortical components, indicating a primary cortical lesion.

Recent evidence suggests a role for endogenous opioid peptides in the pathogenesis of cerebral ischemia and shock. These findings are based mainly on the demonstration that the opiate antagonist naloxone improves neurologic recovery. However, these results have not been confirmed by other investigators. Even if there are no clear reasons to explain the apparently contradictory findings with naloxone, some hypotheses can be made. Naloxone is effective only at very high doses, reflecting actions of non-μ-opioid receptors. Beneficial doses of naloxone are nearly three times those used to reverse morphine effects in animals. For these reasons, it has been suggested that other opiate receptors, such as δ- and κ-opioid receptors, could be involved. Studies using opiates acting at κ sites showed beneficial effects in a rabbit model of spinal stroke. Moreover, it has been demonstrated that dynorphin concentrations increase following traumatic thoracic spinal cord injury in rats. The increase in dynorphin concentrations is located to the ischemic site and is closely correlated with the degree of damage and neurologic deficits. Dynorphin is considered to be the endogenous neuropeptide with selectivity for κ-opioid receptors. Because of these findings, it has been suggested that dynorphin is the pathologic opioid involved in cerebral ischemia. McIntosh and coworkers showed that κ-opioid agonists exacerbate hypoperfusion after brain injury, but no data are available regarding changes in κ-opioid receptor binding after cerebral ischemia.

Our results indicate that massive cerebral ischemia in rabbits significantly increases the number of κ-opioid receptors without changing the dissociation constant. The increase in Bmax is localized at the ischemic site in the frontoparietal cortex since this brain area is the most affected by embolization. Even if [3H]dynorphin A (1-8) also binds to μ- and δ-opioid receptors, our experiments using saturating concentrations of the specific κ-opioid agonist U 69593 clearly demonstrate that only κ-opioid receptors are modified during brain ischemia. In fact, no changes in the number of [3H] dynorphin binding sites were detected in the ischemic tissue under these experimental conditions.

In conclusion, our results suggest that κ-opioid receptors and dynorphin-related peptides appear to be involved in this model of cerebral ischemia. Therefore, specific κ-opioid antagonists might possess greater therapeutic efficacy than nonselective opiate antagonists such as naloxone in the treatment of cerebral ischemia.

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