The Effect of Fentanyl Anesthesia and Intrathecal Naloxone on Neurologic Outcome Following Spinal Cord Injury in the Rat

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Whereas opiate receptor agonists have resulted in spinal cord damage; opiate receptor antagonists have demonstrated protection against spinal cord injury. Because opioids are used in clinical anesthesia, the effect of an opiate antagonist was evaluated on neurologic outcome in a rat model of spinal cord injury occurring during opioid anesthesia. One day prior to spinal cord injury, a catheter was inserted into the spinal subarachnoid space with the tip at T8. On the day of spinal cord injury a balloon tipped catheter was inserted in the epidural space with the tip at the thoracolumbar junction. Spinal cord injury was produced by balloon inflation during one of the following states: 1) group 1 (A/S), injury was produced in awake rats and saline was administered in the subarachnoid space immediately following injury; 2) group 2 (F/S), injury was produced during a fentanyl/nitrous oxide (N2O) anesthetic, and subarachnoid saline administered; and 3) group 3 (F/Nx), injury was produced during a fentanyl/N2O anesthetic, and subarachnoid naloxone (1 mg/kg) was administered immediately following injury. Dose-response curves describing the relationship between the duration of balloon inflation and the percentage of animals with a persistent neurologic deficit were constructed and compared for differences by use of a group t test. The duration of balloon inflation required to produce a neurologic deficit was greater in both the F/S and F/Nx groups than in the A/S group (P < 0.05). There was no difference between the F/S and F/Nx groups. In summary, in rats receiving a fentanyl/N2O anesthetic, neurologic outcome was improved compared with the awake state. The administration of naloxone in the subarachnoid space adjacent to injury did not further improve neurologic outcome. These results do not support the supposition that opioid anesthesia produces an adverse effect upon neurologic outcome following a compressive spinal cord injury. (Key words: Anesthetics, gases: nitrous oxide. Anesthetics, intravenous: fentanyl. Antagonists, opiates: naloxone. Spinal cord: injury.)

ANESTHESIOLOGISTS are called upon to manage patients at risk for spinal cord injury. These injuries may occur either by extension of an antecedent injury or as a result of a primary intraoperative injury. One factor that may influence the extent of injury and is meaningful to anesthetic management concerns the effect of opioids on spinal cord injury.1-7 Opiate receptor antagonists (of which naloxone has been the most extensively studied) have repeatedly produced beneficial effects on spinal cord injury.1-7 In addition, dynorphin, an endogenous kappa opiate, results in paraplegia when administered in the spinal canal.8,9 The above findings have led to a concern that opioid anesthesia may produce a harmful effect upon intraoperative spinal cord injury. We addressed this possibility in a previous study and found that a fentanyl-based anesthetic did not result in a detrimental effect on neurologic outcome.10 However, because spinal cord injury is mediated by multiple factors,7,11-16 it is possible that fentanyl produces both favorable and detrimental effects upon specific pathophysiologic components of spinal cord injury. If this were true, it may be postulated that despite an overall favorable effect by fentanyl/N2O on spinal cord injury (possibly through improved perfusion pressure and autoregulation), there may be a deleterious influence of fentanyl/N2O on the pathophysiologic process (possibly a decrease in postinjury spinal cord blood flow). If this deleterious component were reversed by opiate antagonism, an even more favorable neurologic outcome may result in the course of spinal cord injury occurring during fentanyl/N2O anesthesia. The present study evaluated the hypothesis that any detrimental effect of opioid anesthesia upon spinal cord injury might be prevented by local opiate receptor antagonism.

Methods

Approval was obtained from the Institutional Animal Research Committee. Male, Sprague-Dawley rats (n = 77) of similar weights (300–350 g) were surgically prepared as follows:

**DAY 1 PREPARATION**

Each rat was anesthetized with N2O (65%) and isoflurane (1.0–1.5%) via a face mask. A PE-10 catheter was inserted into the spinal subarachnoid space via the atlantooccipital membrane.17 The tip of the catheter was positioned at T8 (verified at necropsy). The incision was infiltrated with 0.25% bupivacaine. Each rat was allowed a 24-h anesthetic recovery period with systematic neu-
DAY 2 PREPARATION

Following verification of normal neurologic function a tail artery catheter was inserted during N<sub>2</sub>O/isoflurane anesthesia via a face mask. A midline laminectomy was performed at L3–4, and a 2-Fr Fogarty<sup>ab</sup> balloon tipped catheter was secured in the epidural space, with the tip at the thoracolumbar junction. The incisions were closed and infiltrated with 0.25% bupivacaine. The preparatory period was 30–45 min. A 120-min anesthetic recovery period was allowed, and normal neurologic function was verified prior to production of the spinal cord injury by epidural balloon inflation.

SPINAL CORD INJURY

Physiologic parameters (pH, P<sub>aco2</sub>, P<sub>ao2</sub>, mean arterial pressure, serum glucose, and hematocrit) were monitored before, during, and immediately following spinal cord insult. Temperature was monitored rectally and servocontrolled at 37° C with a heat lamp. Awake animals were kept in an oxygen enriched atmosphere (F<sub>1O2</sub> ≈ 35–40%). Anesthetized animals received an F<sub>1O2</sub> of 35%. Each rat was randomized to one of the following anesthetic treatments during spinal cord injury:

Group 1 (awake [n = 22]). Each rat was awake and unrestrained during spinal cord insult.

Group 2 (fentanyl–N<sub>2</sub>O [n = 22]). A fentanyl (57 µg/kg subcutaneously)/N<sub>2</sub>O (65%) anesthetic was administered during spinal cord insult.

Group 3 (fentanyl–N<sub>2</sub>O [n = 22]). An identical fentanyl/N<sub>2</sub>O anesthetic was delivered as in group 2.

The fentanyl/N<sub>2</sub>O dose was roughly equivalent to 1.3 MAC. In the fentanyl groups, animals were placed in a 2.5-l plexiglass box and anesthetic induction was begun with 65% N<sub>2</sub>O/35% O<sub>2</sub>. A sedative anesthetic plane was achieved with N<sub>2</sub>O (≈ 1 min), and the fentanyl dose was injected. A 5-min period was allowed and each rat in the fentanyl groups was orotracheally intubated and their lungs mechanically ventilated with a Harvard<sup>®</sup> rodent ventilator. An additional 10-min period of fentanyl equilibration was allowed (total of 15 min) before spinal cord injury.

When anesthetic equilibration was achieved (or after an equivalent period in awake animals), the epidural balloon was inflated with a constant volume of air (0.1 ml), and inflation maintained over varying times of 0, 6, 12, 24, or 42 min. In animals at the lower inflation times (0, 6, 12, and 24 min) an additional simulated period of balloon inflation was allowed to maintain a constant 42-min period for this portion of the study. Immediately following spinal cord insult the epidural and arterial catheters were quickly removed (<10 min) during a N<sub>2</sub>O (65%)/isoflurane (1%) anesthetic. The N<sub>2</sub>O/isoflurane anesthetic was administered to all three groups for less than 10 min (by face mask to the awake group and via the endotracheal tube in the two fentanyl anesthetized groups). At the conclusion of arterial and epidural catheter removal (10 min following the spinal cord insult) either naloxone (1 mg/kg) or preservative free saline was administered in the spinal subarachnoid space as follows:

Group 1 (awake/saline [n = 22]). Each rat in the awake group received 30 µl of preservative-free saline (37° C) via the spinal subarachnoid catheter.

Group 2 (Fentanyl–N<sub>2</sub>O/saline [n = 22]). Each rat in this fentanyl–N<sub>2</sub>O anesthetized group received 30 µl of preservative-free saline (37° C) via the spinal subarachnoid catheter.

Group 3 (Fentanyl–N<sub>2</sub>O/naloxone [n = 22]). Each rat in this fentanyl–N<sub>2</sub>O anesthetized group received naloxone powder (1 mg/kg [Du Pont Pharmaceuticals, Inc.]) reconstituted in 30 µl of pH buffered, preservative-free saline (37° C) via the spinal subarachnoid catheter.

Each rat was awake, with spontaneous ventilation 5 min following discontinuation of the N<sub>2</sub>O/isoflurane anesthetic. Each rat was examined for the presence or absence of hindlimb paralysis by an investigator blinded to treatment. The exam was performed at a similar time each day for seven postinsult days. Hindlimb paralysis was defined as the lack of spontaneous or purposeful movement of either hindlimb. A flicker of movement did not qualify as movement. A rat exhibiting a purposeful response to paw pinch without spontaneous movement was not graded as paralyzed.

During the recovery period nursing care was given as follows:

1. Each rat was kept in a thermally controlled rodent intensive care cage for 72 h. Subsequently, one standard rodent cage was allotted to each rat (also in a thermally controlled environment).

2. Bladders were voided twice daily using a Credé maneuver, and intramuscular gentamicin (1 mg · kg<sup>−1</sup> · day<sup>−1</sup>) was administered.

3. Each rat was bathed and weighed daily.

4. Subcutaneous fluids (0.9% NaCl) were administered depending upon the presence and magnitude of weight loss.

5. Each rat had ad libitum access to water and Tekland<sup>®</sup> rat chow.

Statistical analysis was performed on the physiologic data using an analysis of variance. The relationship between the duration of balloon inflation and the number of animals with a neurologic deficit on recovery day 7 was determined by constructing dose–response curves with a logistic function of: P = D<sup>y</sup>/(D<sup>y</sup> + D<sub>50</sub>). P is the probability of a neurologic deficit, D the duration of
TABLE 1. Physiologic Data (mean ± SD)

<table>
<thead>
<tr>
<th></th>
<th>Awake/S</th>
<th>Fentanyl/S</th>
<th>Fentanyl/Nx</th>
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</thead>
<tbody>
<tr>
<td>Weight (g)</td>
<td>322 ± 16</td>
<td>314 ± 12</td>
<td>324 ± 17</td>
</tr>
<tr>
<td>Mean arterial pressure (mmHg)</td>
<td>113 ± 17</td>
<td>110 ± 14</td>
<td>109 ± 10</td>
</tr>
<tr>
<td>$P_{aCO_2}$ (mmHg)</td>
<td>40 ± 3</td>
<td>38 ± 3</td>
<td>38 ± 3</td>
</tr>
<tr>
<td>$P_{aO_2}$ (mmHg)</td>
<td>120 ± 26</td>
<td>113 ± 17</td>
<td>116 ± 21</td>
</tr>
<tr>
<td>pH (units)</td>
<td>7.41 ± 0.03</td>
<td>7.41 ± 0.02</td>
<td>7.42 ± 0.03</td>
</tr>
<tr>
<td>Hematocrit (%)</td>
<td>43 ± 2</td>
<td>42 ± 2</td>
<td>43 ± 3</td>
</tr>
<tr>
<td>Serum glucose (mg/dl)</td>
<td>128 ± 14</td>
<td>139 ± 24</td>
<td>144 ± 31</td>
</tr>
</tbody>
</table>

S represents the group that received subarachnoid saline following spinal cord injury. Nx represents the group that received subarachnoid naloxone (1 mg/kg) following spinal cord injury.

One was excluded because of a neurologic deficit following insertion of the epidural catheter. Seven rats died in the postinsult period. Two of the rats that died were in the awake/saline group, two in the fentanyl/saline group, and three in the fentanyl/naloxone group. All of the deaths in the postinsult period occurred in paralyzed animals.

There were no between groups differences in the physiologic data (weight, pH, $P_{aCO_2}$, $P_{aO_2}$, hematocrit, serum glucose, mean arterial pressure, and temperature [see table 1]).

The neurologic results are presented as dose–response curves in figure 1. The duration of balloon inflation is plotted against the percentage of animals with a persistent neurologic deficit (hindlimb paralysis). There was a significant decrease in the incidence of hindlimb paralysis in the fentanyl/saline and fentanyl/naloxone groups compared with that in the awake/saline group (right shift in the dose–response curve). There was no difference between the fentanyl/saline and fentanyl/naloxone group. When the neurologic results are examined as a duration of balloon inflation required to produce a deficit in 50% of animals (ET$_{50}$, tables 2 and 3), identical differences are observed.

Discussion

The present study indicates that an opioid-based anesthetic administered during spinal cord injury does not result in a detrimental effect upon neurologic outcome. Intrathecal naloxone (1 mg/kg), administered immediately following a spinal cord insult produced during fentanyl anesthesia, did not influence neurologic outcome.

In the present study, spinal cord injury may have been affected by physiologic factors. However, because no between groups differences were present, these factors should not have affected the relative position of the dose–response curves. It should be noted that the physiologic data were monitored only through the immediate postinjury period, and differences may have existed later in the postinsult period (although none were observed in pilot evaluations of this spinal cord injury model).
A potential mechanism explaining why the awake animals had a poorer neurologic outcome than anesthetized animals is the state of stress. In comparing the awake state with the anesthetized state, a prediction may have been made that catecholamine levels would have been higher in awake animals. Because increased catecholamine levels can produce deleterious effects upon spinal cord injury, this issue should be addressed when explaining the observed decrease in spinal cord injury during fentanyl/N_{2}O anesthesia. However, based upon serum glucose as an indicator of stress, it is unlikely that significant differences were present. Prior to spinal cord injury each animal spent 120 min in a quiescent environment. The only maneuver necessary to produce injury was inflation of the epidural balloon without otherwise disturbing the animal. In a previous study, the awake control group also had the lowest serum glucose level. Accordingly, it is plausible that in this model of spinal cord injury, catecholamine levels are not elevated in awake animals (although this has yet to be verified).

One concern was the removal of the arterial and epidural catheters. Because noxious stimuli were present during removal, anesthesia was required. This would not have been a methodologic problem had all groups been anesthetized. However, one group was awake during the spinal cord injury. Consequently, a standardized anesthetic regimen of 60% N_{2}O and 1% isoflurane was administered to all study groups during catheter removal (<10 min). An additional concern involved potential spinal cord toxicity by naloxone. In pilot studies we did not observe histologic evidence of spinal cord toxicity by a 1 mg/kg intrathecal dose of naloxone.

The objectives of the present study were to determine both the effect of opioid anesthesia on spinal cord injury and that of naloxone on spinal cord injury during opioid anesthesia. The intrathecal route of naloxone administration was chosen to maintain the fentanyl/N_{2}O anesthetic state. Studies that have shown a positive effect of naloxone on spinal cord injury have been restricted to the systemic route of administration, and have employed relatively large doses (2–10 mg/kg). Accordingly, one intent of the present study was to administer the largest naloxone dose (1 mg/kg) that did not result in either behavioral (arousal, agitation, etc.) or physiologic perturbations (increase in heart rate, blood pressure, and respiratory rate).

A second intent of the study was to design the dose of naloxone to antagonize spinal cord opiate receptors in parallel to the pharmacokinetic binding profile of fentanyl. In this manner, any deleterious effect fentanyl anesthesia might have on spinal cord injury via opiate receptors would be competitively blocked. In the rat, naloxone and fentanyl have comparative CNS partition coefficients and CNS elimination half-lives (60 min for naloxone and 45 min for fentanyl). Accordingly, the observation that neurologic outcome was not different between the fentanyl/naloxone and fentanyl/saline groups does not support the contention that a fentanyl anesthetic produces a deleterious effect on neurologic outcome via direct opioid receptor mechanisms. However, if the dose, duration, or timing of the naloxone dose had been specifically designed to influence spinal cord injury, a beneficial affect of naloxone may have been observed.

Another consideration is the elimination of potential beneficial systemic effects of naloxone by the intrathecal route of administration; this appears unlikely. In addition, if naloxone were to affect spinal cord injury via mechanisms in CNS regions above the injury, it is plausible that the local intrathecal delivery of naloxone may have resulted in different naloxone concentrations in these regions compared with the systemic delivery of naloxone.

Do the results of the present study contradict previous findings that opioid receptor antagonism produces a beneficial effect upon postinjury spinal cord blood flow and neurologic outcome? We believe they do not. The present observations may be attributable to a negligible interaction of fentanyl at spinal cord kappa receptors. A proposed mechanism explaining the interaction between opioid receptor agonists, such as dynorphin, opioid receptor antagonists, and spinal cord injury has been developed by Faden et al. Following spinal cord injury there is a proliferation and up-regulation of spinal opioid recep-

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**Table 2. Epidural Balloon Inflation Time (mean ± SE) Required to Produce a Neurologic Deficit in 50% of Animals (D_{50}) and the Slope (±SE) of the Balloon Inflation Time versus Percentage of Rats with a Persistent Neurologic Deficit**

<table>
<thead>
<tr>
<th>Group</th>
<th>D_{50} (min)</th>
<th>95% Confidence Bound (min)</th>
<th>Slope</th>
<th>95% Confidence Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Awake/S</td>
<td>6.2 ± 1.7</td>
<td>2.7–9.7</td>
<td>2.8 ± 1.6</td>
<td>−0.5–6.1</td>
</tr>
<tr>
<td>Fentanyl/S</td>
<td>16.9 ± 5.2*</td>
<td>6.1–27.7</td>
<td>1.8 ± 0.9</td>
<td>−0.1–3.7</td>
</tr>
<tr>
<td>Fentanyl/Nx</td>
<td>12.3 ± 3.1*</td>
<td>5.8–18.8</td>
<td>2.3 ± 1.0</td>
<td>0.2–4.4</td>
</tr>
</tbody>
</table>

* Significant difference between the awake group compared with both fentanyl groups (P < 0.05).

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**Table 3. The Number of Animals at Each Epidural Balloon Inflation Time That were Normal (not paralyzed) and Abnormal (hindlimb paralysis)**

<table>
<thead>
<tr>
<th>Inflation Time</th>
<th>Awake/S (n = 22)</th>
<th>Fentanyl/S (n = 22)</th>
<th>Fentanyl/Nx (n = 22)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
<td>Abnormal</td>
<td>Normal</td>
</tr>
<tr>
<td>0 min</td>
<td>3</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>6 min</td>
<td>3</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>12 min</td>
<td>1</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>24 min</td>
<td>0</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>42 min</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>
tors of the kappa subtype. A release of endogenous opiates also occurs, which acts at the up-regulated opioid receptors and results in a decrease in spinal cord blood flow and a worse neurologic outcome. If opioid receptor antagonists mediate spinal cord injury via kappa opioid receptors, it is plausible that the lack of a beneficial effect of naltrexone upon spinal cord injury may have been due to an insufficient action of fentanyl at kappa receptors. If the anesthetic dose of fentanyl did not significantly interact at kappa receptors, the pathologic milieu necessary to demonstrate a naltrexone reversible component of injury secondary to the opioid anesthetic would not have been present.

The clinical correlate of the present model may be the patient susceptible to an intraoperative insult from an unstable spine and impingement of bone or ligamentous elements on the spinal cord. This study provides no data to support the restriction of anesthetic doses of opioids during spinal cord injury in such a patient group. The precise mechanisms whereby spinal cord protection was afforded by opioid-based anesthesia and not by naloxone, and their anesthetic interactions, may be multiple, complex, and require additional study.

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