Developmental Age Influences the Effect of Epidural Dexmedetomidine on Inflammatory Hyperalgesia in Rat Pups


Background: Epidural α2-adrenergic agonists produce analgesic effects in children and adults, but efficacy and safety have not been established in neonates and infants. The aim of this study was to determine the effect of epidural dexmedetomidine on sensory processing, reversal of inflammatory hyperalgesia, and sedation during early development in rats.

Methods: In rat pups aged 3, 10, and 21 postnatal days, mechanical withdrawal thresholds of the hind limbs were measured at baseline and after unilateral inflammation due to carrageenan. The effect of epidural dexmedetomidine on withdrawal thresholds was measured for 90 min after injection, and dose-response curves were constructed for each age group. The duration of the righting reflex was measured to assess sedation. The effects of epidural and systemic administration of dexmedetomidine were compared.

Results: At all ages, carrageenan-induced hyperalgesia was reversed by doses of epidural dexmedetomidine that did not affect the threshold of the contralateral paw or prolong the righting reflex. Higher doses of epidural dexmedetomidine affected baseline nociception in the contralateral paw and produced sedation but had no effect when given systemically. Reversal of hyperalgesia and sedation were produced by lower doses of epidural dexmedetomidine in the youngest pups.

Conclusions: Spinally mediated selective reversal of inflammatory hyperalgesia by epidural dexmedetomidine can be achieved at all ages; relatively lower doses are effective in early life, but the therapeutic window is narrow. These data have implications for the use and dosing of epidural α2 agonists in neonates and infants.

Epidural analgesia is frequently used in neonates, infants, and children for the management of acute postoperative pain.1–3 Increasingly, nonopioid spinally acting analgesics are being added to local anesthetics and opioids with the aim of improving the quality or prolonging the duration of analgesia or to reduce side effects because lower doses are required with combination therapy.4,5 In rats, it has recently been shown that significant age-related changes occur in response to epidurally administered opioids6 and local anesthetics,7 which is consistent with the developmental regulation of receptors and channels in the central nervous system during early life.8

Clonidine is an α2-adrenergic agonist that produces spinally mediated analgesia in both laboratory9 and clinical studies.10 In pediatric practice, 1–2 μg/kg clonidine has been shown to prolong analgesia when added to caudal epidural local anesthetic injections,5,11 and 0.08–0.12 μg·kg⁻¹·h⁻¹ clonidine produces a dose-related analgesic effect when added to lumbar epidural infusions.12 However, clinical trials have recruited children older than 6–12 months, and there are no controlled data for epidurally administered clonidine in neonates and infants younger than 6 months. Recently, case reports of side effects after administration of caudal clonidine to neonates13–15 raise the possibility that the response to epidural α2 agonists is developmentally regulated.

Dexmedetomidine has greater selectivity for the α2 receptor and is more potent than clonidine.16 In adult animals, dexmedetomidine has antinociceptive and anti-hyperalgesic effects after systemic and spinal administration.17 In isolated neonatal rat spinal cord, dexmedetomidine inhibits ventral root responses to stimulation of the dorsal root,18,19 suggesting an effect on spinal nociceptive transmission, but the in vivo efficacy of spinally administered dexmedetomidine has not been compared at different developmental ages.

The aim of the current study was to examine the effect of postnatal age on the response to epidural dexmedetomidine in rats. We wished to determine whether (1) dose related analgesia could be demonstrated at all ages (2) a direct spinal analgesic action was evident at all ages, (3) reversal of inflammatory hyperalgesia could be achieved without nonspecific sensory effects, and (4) age is a significant factor in analgesic efficacy.

Materials and Methods

All experiments were performed with approval of the Royal North Shore Hospital and University of Technology Sydney Animal Care and Ethics Committee, New South Wales, Australia, in accordance with the Australian Code of Practice for the Care and Use of Animals for Scientific Purposes, 1990, or under personal and project licenses in accordance with the United Kingdom Animal Code of Practice for the Care and Use of Animals for Scientific Purposes, 1990.
(Scientific Procedures) Act 1986. Litters of male and female Sprague-Dawley rat pups on the 3rd (P3), 10th (P10), and 21st postnatal days (P21) were obtained from Gore Hill Laboratories (Sydney, Australia) or the Biologic Services Unit, University College London (London, United Kingdom). Animals were randomly assigned to treatment groups.

**Flexion Withdrawal Thresholds and Righting Reflex Duration**

The mechanical threshold for hind-limb withdrawal was determined using calibrated nylon monofilaments (von Frey hairs) that exert logarithmically increasing stimulus strength, expressed linearly on a scale of 1–20 as the von Frey hair number. The range of hairs used in this study applied forces from 1.1 g (von Frey hair 9) to 22 g (von Frey hair 15). Pups were lightly restrained on a flat bench surface, and each von Frey hair was applied to the dorsal surface of the hind paw five times at 1-s intervals, and the number of evoked flexion withdrawals was recorded. The maximum force applied was that which evoked five withdrawal responses. The mechanical withdrawal threshold of both hind paws was determined at the following time points: baseline (time = t = 0); immediately before epidural injection (time = t0); and then 15, 30, 45, 60, and 90 min after epidural injection.

The duration of the righting reflex was measured to assess sedation. Each animal was placed on its back on a flat bench surface, and the time taken for the animal to turn and place all four paws on the bench was measured. The average of two measurements was taken at each time point. A maximum cutoff time of 20 s was allowed.

**Hind-paw Inflammation**

Inflammation was induced by injection of a 2% solution of lambda carrageenan (Sigma, St. Louis, MO) into the left hind paw. Rat pups were briefly anesthetized with 2–4% halothane in oxygen, and injections were made into the midpoint of the plantar surface of the hind paw using a 30-gauge sterile needle and a calibrated syringe. The volumes of injectate were 5, 10, and 20 μl at P3, P10, and P21, respectively, to provide a dose approximating 10 mg/kg at all ages.7

**Epidural Injection Technique**

Three hours after hind-paw injection, animals were briefly anesthetized with halothane and oxygen. Using a 30-gauge needle and calibrated 100-μl glass Hamilton syringe, epidural injections were made between the lower lumbar vertebrae using a loss-of-resistance technique.6,7 Solutions of saline and varying concentrations of epidural dexmedetomidine (0.5–10 μg/ml; Abbott Australasia Pty Ltd, Kurnell, Australia) were prepared and coded. The same investigator, who was blinded to the epidural solution, performed all epidural injections and sensory testing. By using the same volume (2 μl/g) of different concentrations of drug, equivalent doses per gram body weight could be given without compromising blinding. All solutions contained 1% Evans Blue as a marker. After an overdose of intraperitoneal pentobarbital (100 mg/kg) at the end of each experiment, a laminectomy was performed, and the spinal cord was dissected. Data were only included from animals in which epidural placement could be confirmed by midline extradural spread of solution across low thoracic and lumbar segments, and dural puncture was excluded by lack of cerebrospinal fluid and spinal cord staining.

**Dose and Age Groups**

The maximum tolerated epidural concentration of dexmedetomidine was determined for each age group in pilot experiments. After 20 μg/kg (i.e., 2 μl/g of 10 μg/ml) at P3 and 40 μg/kg (i.e., 2 μl/g of 20 μg/ml) at P10 and P21, animals were markedly sedated, the withdrawal reflex could not be elicited, and the respiratory rate was visibly reduced. Data were therefore obtained from saline controls, four doses of dexmedetomidine in P3 pups (1, 2, 4, and 10 μg/kg), and five doses in P10 and P21 pups (1, 2, 4, 10, and 20 μg/kg). The sample size was six to eight for each treatment group.

The effect of systemic administration of dexmedetomidine was assessed by intraperitoneal injection of 10 μg/kg dexmedetomidine at P3 and 20 μg/kg at P10 and P21 (n = 4 in each group) 3 h after hind-paw carrageenan. The hind-paw injection technique and the testing protocol were as outlined above.

**Statistical Analysis**

For each test condition, the number of withdrawal responses was plotted against von Frey hair number. Because each increase in von Frey hair number corresponds to a logₐ increase in applied force, a sigmoidal stimulus–response curve with variable slope was constructed using nonlinear regression (GraphPad Prism versions 3 and 4; GraphPad, San Diego, CA). The midpoint of the curve (50% maximum force) was determined and designated the threshold.20,21 Changes in threshold were analyzed in von Frey hair number units as previously described.7 Treatment groups were compared with one-way analysis of variance and Tukey post hoc comparison, two-way analysis of variance with time and treatment as variables, or two-tailed Student t test as appropriate (GraphPad Prism versions 3 and 4). P < 0.05 was designated as statistically significant.

**Results**

**Effect of Postnatal Age and Carrageenan**

**Inflammation on Mechanical Withdrawal Thresholds**

The baseline mechanical withdrawal threshold increased with postnatal age, consistent with previous
Effect of Epidural Dexmedetomidine on Baseline Sensory Processing

At all ages, the dose of epidural dexmedetomidine that reversed inflammatory hyperalgesia did not affect the threshold of the contralateral paw (fig. 2). Fifteen minutes after epidural injection, the threshold of the contralateral paw was significantly increased above baseline by 10 μg/kg dexmedetomidine in P3 pups and by 20 μg/kg in P10 and P21 pups ($P < 0.05$, two-way analysis of variance). The threshold of the contralateral paw did not differ significantly from baseline after lower doses of epidural dexmedetomidine.

Effect of Systemic Dexmedetomidine on Carrageenan-induced Hyperalgesia

The maximum epidural dexmedetomidine dose (10 μg/kg at P3 or 20 μg/kg at P10 and P21) had no effect when given systemically. The mechanical withdrawal threshold was significantly higher 15 and 30 min after epidural administration when compared with the same dose by the intraperitoneal route ($P < 0.05$; fig. 4). At these doses, intraperitoneal dexmedetomidine had no effect on the hyperalgesia produced by carrageenan, because threshold values remained low and did not differ significantly from the control epidural saline group. The duration of the righting reflex was also not significantly increased after these doses of intraperitoneal dexmedetomidine in any age group (data not shown).

Effect of Epidural Dexmedetomidine on the Righting Reflex

The dose of epidural dexmedetomidine that reversed carrageenan-induced hyperalgesia did not produce significant sedation as assessed by prolongation of the righting reflex. The righting reflex becomes more coordinated and rapid with increasing postnatal age ($P < 0.01$). Within each age group, the baseline times to right (mean ± SEM) did not differ across treatment groups and were $4.36 ± 0.39$, $1.91 ± 0.08$, and $0.71 ± 0.02$ s at P3, P10, and P21, respectively. Epidural dexmedetomidine increased the duration of the righting reflex at all ages in a time- and dose-dependent manner, because effects were more prolonged and occurred at lower doses in younger animals (fig. 5). In P21 rat pups, the lowest dose that significantly prolonged the duration of the righting reflex was 20 μg/kg epidural dexmedetomidine ($P < 0.01$), whereas in P3 pups, doses of 2, 4, and 10 μg/kg dexmedetomidine were sufficient to prolong the reflex ($P < 0.05$). In four of six animals in both the P10 20-μg/kg group and the P3 10-μg/kg group, epidural dexmedetomidine prolonged the righting reflex beyond the 20-s cutoff period. This degree of effect was not seen at any dose or time in P21 pups.

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Fig. 1. Mechanical withdrawal threshold and response to inflammation at different developmental ages. The mechanical withdrawal threshold (von Frey hair number [vFH]) of the ipsilateral and contralateral paw is represented at baseline and 3 h after hind-paw injection of carrageenan (ipsilateral post carrageenan; contralateral post carrageenan). The withdrawal threshold increases with increasing postnatal age. At each age, the threshold of the ipsilateral injected paw after carrageenan was significantly lower than in all other groups. Data points = mean ± SEM. ** $P < 0.01$, one-way analysis of variance with Tukey post hoc comparison; n = 32–40 in all groups.
Discussion

We have shown that epidural dexmedetomidine has a dose-dependent and developmentally regulated analgesic effect in rat pups. Selective reversal of hyperalgesia can be achieved at all ages, without affecting the threshold of the contralateral paw or causing significant prolongation of the righting reflex. The dose of epidural dexmedetomidine required to reverse hyperalgesia is lower in the youngest pups, which are also more sensitive to the sedative effects. The analgesic effect of epidural dexmedetomidine is spinally mediated, because systemic administration of the same dose has no effect.

*α₂*-Adrenergic receptors are functionally coupled to G proteins from early in development and have an inhibitory influence on neuronal activity. *α₂*-Adrenoceptors within the spinal cord are present on the terminals of primary afferents, interneurons, and descending noradrenergic fiber pathways from cell groups A5, A6 (locus ceruleus), and A7 (subceruleus) in the pons. This spina is mediated, because systemic administration of the same dose has no effect. 

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Fig. 2. Change in withdrawal threshold after inflammation and epidural dexmedetomidine at ages P21, P10, and P3 (n = 6–8 in all groups). Data are represented as the change in von Frey hair number (mean ± SEM) from the baseline value (−180 min) and for 90 min after epidural injection of saline or dexmedetomidine (1–20 μg/kg) in the ipsilateral (A, C, and E) and contralateral (B, D, and F) hind paw. At all ages, the threshold in the ipsilateral paw is reduced 3 h after hind-paw carrageenan (t = 0), and increasing doses of dexmedetomidine progressively reverse inflammatory hyperalgesia. High doses of epidural dexmedetomidine increase the threshold above baseline in both the ipsilateral and the contralateral paw.

DEVELOPMENTAL AGE AND EPIDURAL DEXMEDETOMIDINE

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point mutation (D79N) of the α2A receptor suggest that this subtype is important for antinociceptive effects.\textsuperscript{26,27} Receptor protein and messenger RNA (mRNA) have been isolated in rat dorsal root ganglia\textsuperscript{28–30} and in the superficial dorsal horn.\textsuperscript{26,31} Dexmedetomidine has greater potency and increased selectivity for the α2A receptor than clonidine.\textsuperscript{32,33} In adult animals, dexmedetomidine produces dose-related antinociceptive effects in response to thermal and mechanical stimuli.\textsuperscript{33,34} In our study, high doses of epidural dexmedetomidine increased the mechanical withdrawal threshold of the hind paw above baseline (i.e., had an antinociceptive effect) at all ages. However, we also wished to determine whether selective reversal of inflammatory hyperalgesia could be achieved at lower doses without affecting sensory transmission in the contralateral paw. In adult animals, dexmedetomidine attenuates carrageenan-induced hyperalgesia\textsuperscript{24,25} at doses lower than required to produce antinociceptive effects.

Reversal of inflammatory hyperalgesia was achieved at all postnatal ages by doses of epidural dexmedetomidine that did not alter the threshold of the contralateral paw. This suggests that in early development, antihyperalgesic effects of α2 agonists can be achieved at doses that have no effect on baseline sensory processing. In addition, the dose required for both antihyperalgesic and antinociceptive effects was lower in the youngest pups, suggesting an increased sensitivity to dexmedetomidine in early life.

Dexmedetomidine has greater potency and increased selectivity for the α2 receptor than clonidine.\textsuperscript{52,53} In adult animals, dexmedetomidine produces dose-related antinociceptive effects in response to thermal and mechanical stimuli.\textsuperscript{53,54} In our study, high doses of epidural dexmedetomidine increased the mechanical withdrawal threshold of the hind paw above baseline (i.e., had an antinociceptive effect) at all ages. However, we also wished to determine whether selective reversal of inflammatory hyperalgesia could be achieved at lower doses without affecting sensory transmission in the contralateral paw. In adult animals, dexmedetomidine attenuates carrageenan-induced hyperalgesia\textsuperscript{24,25} at doses lower than required to produce antinociceptive effects.

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In all age groups, the maximum epidural dose had no effect on mechanical withdrawal thresholds or inflammatory hyperalgesia when given by the intraperitoneal route, suggesting that the effect of epidural dexmedetomidine is spinally mediated.

A major advantage of the decreased dose requirement with spinal administration is the potential for reduced side effects when compared with systemic administration. Several studies have shown that the therapeutic window is narrow after systemic administration of $\alpha_2$ agonists, because sedative and motor side effects often occur within the same dose range as analgesia. Because both analgesia and sedation are mediated by the $\alpha_{2A}$ receptor, development of a subtype selective drug is unlikely to decrease the likelihood of side effects. In the current study, doses of epidural dexmedetomidine...
that reversed inflammatory hyperalgesia did not significantly prolong the righting reflex. The righting reflex has been used in previous studies with adult animals to assess the sedative effects of dexmedetomidine.\textsuperscript{39,40} Other methods of assessing sedative or motor activity, such as the rotarod\textsuperscript{36} or activity in an open field,\textsuperscript{54} are not applicable to P3 pups, which have a low level of spontaneous activity. Although the righting reflex is less coordinated in young pups and the baseline time to right is longer, a dose-related increase with higher doses of dexmedetomidine could be seen at all ages.

Developmental changes in nociceptive processing, receptor distribution, and descending inhibitory mechanisms\textsuperscript{8,41} may influence the response to $\alpha_2$ agonists. The relative contribution of primary afferent, spinal cord, and descending pathway mechanisms to $\alpha_2$-adrenergic analgesia has not been determined during development. Descending inhibitory pathways in the dorsolateral funiculus do not inhibit dorsal horn activity in the first postnatal week,\textsuperscript{42} and although noradrenergic-immunoreactive fibers are visible in the dorsal horn at P3, the density of innervation does not reach adult levels until P30.\textsuperscript{15} However, radioligand binding of the agonists $[^{3}H]$RX821002 and $[^{3}H]$rauwolscine demonstrate a predominance of $\alpha_2A$ binding sites in both neonatal and adult spinal cord,\textsuperscript{44} and binding sites for $[^{3}H]$dexmedetomidine have been identified in neonatal spinal cord (P1–2).\textsuperscript{45} Messenger RNA for the $\alpha_2A$ receptor is present in prenatal dorsal horn cells,\textsuperscript{46} and moderate levels have been detected in dorsal horn slices at P1–3 and P21 and high levels have been detected at P5–14.\textsuperscript{47} The effect of postnatal age on the density and distribution of $2A$ receptor protein expression in the spinal cord or the expression of $\alpha_2$-adrenergic receptor mRNA and protein in the dorsal root ganglion has not been systematically investigated. Postnatal changes in receptor distribution may contribute to developmental changes in sensitivity to analgesics, as shown for opioids.\textsuperscript{20} In adult animals, comparison of effects after intracerebroventricular and intrathecal administration suggests the spinal cord as the predominant site mediating analgesia.\textsuperscript{48,49} In isolated neonatal spinal cord (PO–6), dexmedetomidine depresses the ventral root potential evoked by substance P\textsuperscript{18} or electrical stimulation of the dorsal root.\textsuperscript{19} This suggests that local spinal cord mechanisms may mediate analgesic effects in early development, but dose-related effects at different postnatal ages have not previously been tested in vivo. Our study demonstrates reversal of inflammatory hyperalgesia by epidural dexmedetomidine at all postnatal ages, with an increased functional sensitivity in the youngest pups.

Lower doses of epidural dexmedetomidine prolonged the righting reflex in the youngest pups, suggesting an age-related sensitivity to side effects. The sedative effects of $\alpha_2$ agonists are mediated in the locus ceruleus,\textsuperscript{17} and therefore, an increased pharmacodynamic sensitivity, increased central redistribution, or increased dural penetration may contribute to this effect. The blood–brain barrier is functional at birth,\textsuperscript{50} and no age-related differences in dural penetration after epidural morphine were found in rat pups.\textsuperscript{51} The locus ceruleus is a specific area with high expression of $\alpha_2$ mRNA throughout postnatal development,\textsuperscript{47} and levels of $\alpha_2$-receptor binding are high and already near adult levels at P1.\textsuperscript{52} The relatively high level of $\alpha_2$ receptor in the developing brainstem may contribute to increased sedative effects in early life. In P3 pups, although the dose of epidural dexmedetomidine that reverses hyperalgesia is less than that associated with sedation (1 vs. 2 $\mu g/kg$), the therapeutic window is relatively narrow. With increasing postnatal age, there was a change from a 2- to a 10-fold difference between the dose associated with reversal of hyperalgesia and the dose that produced sedation (as illustrated in fig. 6). Sedation was also produced at doses lower than required for antinociception, suggesting a specific increased sensitivity to sedation in early life that differs from a nonspecific effect on sensory processing. By P21, only doses that have antinociceptive effects produce sedation and are much higher than the dose required for reversal of inflammatory hyperalgesia. Some overlap between analgesia and side effects is seen in infants and children because caudal clonidine (1–2 $\mu g/kg$) prolongs analgesia and is associated with mild sedation,\textsuperscript{5,11} whereas clinically significant sedation and cardiovascular changes are produced by higher doses (5 $\mu g/kg$).\textsuperscript{53} However, a tendency to increased side effects from epidural $\alpha_2$ agonists in early life is reflected in clinical reports of apnea, oxygen desaturation, and bradycardia in neonates\textsuperscript{15–17} given doses of caudal clonidine (1.25–2.2 $\mu g/kg$) that are tolerated by older children. Although these side effects cannot be specifically attributed to caudal clonidine, particularly because two of the neonates were born preterm (32 and 36 weeks’ postconcep-


