Evaluation of Spinal Toxicity and Long-term Spinal Reflex Function after Intrathecal Levobupivacaine in the Neonatal Rat


ABSTRACT

Background: Neuraxial anesthesia is utilized in children of all ages. Local anesthetics produce dose-dependent toxicity in certain adult models, but the developing spinal cord may also be susceptible to drug-induced apoptosis. In postnatal rodents, we examined the effects of intrathecal levobupivacaine on neuropathology and long-term sensorimotor outcomes.

Methods: Postnatal day 3 (P3) or P7 rat pups received intrathecal levobupivacaine 2.5 mg/kg (0.5%) or saline. Mechanical withdrawal thresholds and motor block were assessed. Spinal cord tissue analysis included apoptosis counts.

Results: Intrathecal levobupivacaine produced spinal anesthesia at P3 and P7. No increase in apoptosis or histopathological change was seen in the cord or cauda equina. In the P3 saline group, activated caspase-3 (mean ± SEM per lumbar cord section 6.1 ± 0.3) and Fluoro-Jade C (12.1 ± 1.2) counts were higher than at P7, but were not altered by levobupivacaine (P = 0.62 and P = 0.11, two-tailed Mann–Whitney test). At P35, mechanical withdrawal thresholds, thermal withdrawal latency, and electromyographic reflex responses did not differ across P3 or P7 levobupivacaine or saline groups (one way ANOVA with Bonferroni comparisons). Intrathecal bupivacaine at P3 did not alter gait.

Conclusion: Single dose intrathecal levobupivacaine 0.5% did not increase apoptosis or produce spinal toxicity in neonatal rat pups. This study provides preclinical safety data relevant to neonatal use of neuraxial local anesthesia.

What We Already Know about This Topic

- Spinally injected local anesthetics can cause neurotoxicity, and general anesthesia during infancy enhances apoptosis in rodents.
- Safety regarding these potential toxicities of spinal local anesthetics in infant animals has had limited testing.

What This Article Tells Us That Is New

- In 3- and 7-day-old rats, intrathecal injection of 0.5% levobupivacaine produced temporary spinal anesthesia, but did not increase apoptosis or result in histologic or behavioral neurotoxicity.

PINAL anesthesia in neonates and infants is well established in pediatric practice.1,2 Large case series report safe and effective anesthesia and analgesia,3–8 including use in high-risk infants.9,10 Neuraxial anesthesia may have particular advantages in preterm-born neonates who are susceptible to postoperative apnea or have coexisting respiratory disease.1,11,12
Persistent neurological deficits are rare following pediatric regional anesthesia,\(^1\) but in fact there has been limited detailed follow-up in this patient group.\(^1,14,15\) Transient neurological symptoms following spinal anesthesia have been reported in adults\(^6,17\) and children,\(^2\) but neonates and infants are unable to report these symptoms. Models have been established for evaluating local anesthetic toxicity in adult animals,\(^18\) and the importance of also evaluating nerve root histopathology in developmental studies has been emphasized.\(^19\) A recent study reported no histopathologic change in white matter tracts within lumbar spinal cord sections following intrathecal racemic bupivacaine at postnatal day (P)7, 14, or 21.\(^20\) As \textit{in vivo} studies in adult animals show variable neurotoxicity with different local anesthetics,\(^21–23\) further preclinical evaluation of different preparations during early development is also needed.

Neuraxial anesthesia and analgesia in neonates and infants avoids or reduces exposure to general anesthetic agents that have been reported to increase neuronal apoptosis in the developing rodent and primate brain, with associated adverse long-term cognitive outcomes.\(^24,25\) Apoptosis in the central nervous system has a temporal profile that varies across brain regions, with different time windows for increased susceptibility to the pro-apoptotic effects of certain drugs.\(^26\) Prolonged general anesthesia, but not intrathecal bupivacaine, at P7 increases apoptosis in both cortex and spinal cord, but neither intervention produced long-term motor deficits.\(^20\) As our previous work demonstrated higher baseline apoptosis in the cord at P3/4, predominantly in the dorsal horn,\(^27–29\) we have included a younger age group and evaluation of sensory outcomes in our toxicity studies. As different local anesthetics produce varying degrees of apoptosis in neuronal cell cultures,\(^30,31\) evaluation of additional preparations in \textit{in vivo} developmental models will further define the safety profile of spinal anesthesia in early life.

Levobupivacaine, the S (-)-enantiomer of bupivacaine, produces reliable and effective spinal anesthesia in neonates\(^32,33\) and children,\(^34\) and is also widely used for single-shot caudal blocks\(^35,36\) and perioperative epidural infusions\(^37,38\) in pediatric practice. Compared with the same dose of racemic bupivacaine, levobupivacaine has an improved systemic toxicity profile after intravenous administration\(^39\) and reduced neurotoxicity following intrathecal administration in some,\(^23\) but not all,\(^40\) adult animal studies. Our developmental model of spinal toxicity had sufficient sensitivity to demonstrate a relatively wide safety margin following morphine\(^27\) and clonidine,\(^29\) but adverse outcomes following ketamine,\(^28\) and will now be the basis for further evaluation of local anesthetic toxicity in the neonatal spinal cord.

The current study evaluates spinal toxicity following intrathecal levobupivacaine in neonatal (P3 and P7) rat pups. Evaluation includes behavioral analysis, quantification of apoptosis, and histopathological evaluation of spinal cord and cauda equina. Functional outcomes in early adulthood (P35) included sensory withdrawal thresholds, and electromyographic responses to suprathreshold stimuli during anesthesia. Gait analysis following neonatal intrathecal bupivacaine is also presented.

**Materials and Methods**

**Animals**

Experiments were carried out according to protocols approved by Institutional Animal Care and Use Committee of University of California, San Diego, La Jolla, California. Pregnant Holtzman Sprague–Dawley rats (Harlan, Indianapolis, IN) were housed in accordance with the National Institute of Health guidelines in a 12-h light–dark cycle and with free access to standard food and water. Dams were monitored, and the day of birth of pups noted. Pups were randomly assigned to treatment groups containing equal numbers of males and females at P3 or P7. Body weights of the rat pups were between 8–11 g at P3 and 12–18 g at P7.

Additional experiments evaluating long-term spinal reflex function were performed in the United Kingdom under personal (Dr. Walker) and project licences in accordance with the requirements of the United Kingdom Animal (Scientific Procedures) Act 1986. Sprague–Dawley dams and litters were bred in-house in the Biological Services Unit University College London and were maintained on a 12-h light–dark cycle at constant ambient temperature with free access to food and water. Pups were randomly assigned to treatment groups at P3 or P7. Litters were restricted to a maximum of 12, with pups weaned into same-gender cages at P21 and maintained until P35.

For all experimental interventions, rat pups were kept on a heating pad to maintain body temperature. Care was taken to minimize the duration of maternal separation and handling of pups, and this was the same for both control and treatment groups. Due to the need to confirm correct intrathecal placement and motor block, experimenters were aware of treatment allocation during initial behavioral testing. Animals for long-term evaluation of spinal reflex function were coded following injections to ensure that the investigator was blinded to initial treatment allocation during testing at P35. Similarly, tissue sections were coded and the experimenter was unaware of treatment allocation at the time of analysis.

**Intrathecal Injections and Solutions**

Percutaneous intrathecal injections were performed as previously described.\(^27\) Under brief isoflurane anesthesia (3%) with oxygen and room air via a nose cone, 0.5% levobupivacaine hydrochloride (Chirocaine 50 mg/10 ml; Abbott Laboratories Limited, Maidenhead, Berkshire, United Kingdom) or sterile saline was injected intrathecally at the L4–L5 or L5–L6 intervertebral space using a 30-gauge needle connected to a microinjector and Hamilton syringe. The volume of the injectate was 0.5 μl/g body weight, which produces spread over low thoracic and lumbar segments in rat pups.\(^27\) Our pilot experiments confirmed that this volume of local
anesthetic produced reliable motor block of the hind limbs. Dose escalation was precluded as we restricted analysis to a clinically available 0.5% preparation, and higher volumes (1 μl/g) were associated with impaired respiration and increased mortality, consistent with previous reports following 0.5% bupivacaine.20,27

Behavioral Testing and Assessment of Spinal Reflex Function

Acute Effects. In rat pups, baseline mechanical withdrawal threshold was determined using calibrated von Frey filaments which apply logarithmically increasing pressure (0.4–15 g). Each von Frey filament was applied five times at 1 s intervals to the dorsal surface of the hindpaw.41 The number of evoked withdrawal responses to each stimulus of increasing intensity was recorded until a given stimulus evoked five responses, or a suprathreshold cutoff pressure was reached (10 g at P3; 15 g at P7). Following injection and recovery from anesthesia, pups were assessed for visible motor block (failure of hip flexion, dragging of hind limbs, and no response to a suprathreshold mechanical stimulus). Animals were only retained for further analysis if dense motor block was apparent following levobupivacaine, and motor function was normal following saline. Motor block scores (0 = no movement; 1 = partial block, and 2 = full movement) for the left and right hind limbs were added to give a total score between 0 and 4 for each animal.20 Mechanical withdrawal thresholds were measured in both hind limbs at 15, 30, 45, and 60 min following injection, and at 24 h or 7 days prior to tissue analysis.

Spinal Reflex Function at P35. Separate groups of P3 and P7 animals received intrathecal 0.5% levobupivacaine 0.5 μl/g or saline as described earlier. Spinal cord function was assessed at 5 weeks of age (P35) by evaluating hind limb withdrawal responses to mechanical and thermal stimuli, with the experimenter blinded to initial treatment group.29 Following habituation on an elevated mesh platform, mechanical stimuli (electronic von Frey device; Dynamic Plantar Aesthesiometer, Ugo Basile, Comerio, Italy) was applied to the mid-plantar surface of the hindpaw. The threshold was averaged from three measures of the force (0–50 g; ramp 20 g/s) required to produce hind limb withdrawal. Thermal withdrawal latency was determined using a modified Hargreaves Box (University Anesthesia Research and Development Group, University of California, San Diego, La Jolla, California) with a glass surface (maintained at 30°C) on which the rats were placed in individual Plexiglas (Altuglas, Los Angeles, CA) cubicles. The thermal nociceptive stimulus from a focused projection bulb positioned below the glass surface was directed to the mid-plantar hindpaw. Latency was defined as the time required for the paw to show a brisk withdrawal as detected by photodiode motion sensors that stopped the timer and terminated the stimulus. In the absence of a response within 20 s, the stimulus was terminated (cutoff time). Thermal latency was the average of three measures from each hindpaw.

To assess sensorimotor reflex function to both threshold and suprathreshold stimuli, flexor reflex electromyography recordings from the biceps femoris muscle were performed as previously described.42,43 In brief, animals were anesthetized with halothane (2–4%) in oxygen and a tracheal tube was inserted to facilitate mechanical ventilation (Small Animal Ventilator, Harvard Apparatus Ltd, Kent, United Kingdom). Halothane was reduced to 0.9% in oxygen for 30 min to ensure equilibration to a stable plane of anesthesia, and maintained at this concentration during electromyography recordings. Animals were placed in a spinal frame with the left hindpaw secured on a fixed platform. Heart rate was continuously monitored and body temperature was monitored with a rectal probe and maintained with a thermostatically controlled heat source. Bipolar electromyography electrodes (Ainsworks, London, United Kingdom) comprising stainless steel 30-gauge needles with a central copper wire core were placed through a small skin incision into the belly of the biceps femoris muscle. Electromyography responses to mechanical hindpaw stimuli were processed (Neurolog System, Digitimer Ltd, Welwyn Garden City, United Kingdom) and recorded in 12-s epochs (PowerLab 4S, AD Instruments, Castle Hill, Australia). von Frey hairs were sequentially applied to the plantar surface of the hindpaw up to a maximum of hair number 20 (180 g) to quantify the response to suprathreshold stimuli.

Gait Analysis at P35. In separate experiments, gait analysis was performed at P35 following intrathecal injection of 0.5% bupivacaine at P3. These experiments were performed in conjuction with our previous experiments evaluating effects of intrathecal morphine27 and ketamine,28 but the local anesthetic results have not been previously reported. Gait analysis was performed as the animal crossed the glass runway of the CatWalk® system (Noldus Information Technology, Wageningen, The Netherlands). Animals commenced a daily training paradigm at P22–25, with runway crossings toward food rewards at the farther end. At P35, runway crossings were recorded and included in analysis if the maximal time for crossing the 60-cm-long section of the runway used for gait recording was ≤2 s, and there were no intermediate stops during the crossing. Three crossings per animal were analyzed using the CatWalk 7.1.6 software (Noldus Information Technology).

Spinal Cord Tissue Preparation and Staining

Tissue analysis was performed either 24 h or 7 days following injection. Rat pups were terminally anesthetized with an intraperitoneal injection of 100 mg/kg pentobarbital and transcardially perfused with saline followed by 4% paraformaldehyde. Following laminectomy, the spinal cord and cauda equina were dissected, postfixed in 4% paraformaldehyde overnight, then transferred to 30% sucrose, and stored at +4°C. Transverse sections of lumbosacral spinal cord (7 and 14 μm) were cut using a cryostat (Leica CM 1800, San Marcos, CA), mounted

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on slides (Fisher SuperFrost Plus, Fisher Scientific, Houston, TX), and stored at −30°C. Using our previously described protocols, we assessed histopathology with hematoxylin and eosin staining 24 h and 7 days postinjection, apoptosis with activated caspase-3 immunohistochemistry and Fluoro-Jade C staining at 24 h, and glial reactivity by staining with microglial (ionized calcium-binding adapter molecule 1; Iba1) and astrocytic (glial fibrillary acidic protein) markers 7 days following injection. For histopathological evaluations of the nerve roots, cauda equina was cut from the spinal cord 24 h and 7 days following injection and transferred into 2.5% glutaraldehyde in 0.1 M phosphate buffer.

Activated Caspase-3. Immunohistochemistry with an antibody to activated caspase-3, the final member of an intracellular cascade activated during programmed cell death, was performed on tissue 24 h postinjection. Tris-buffered saline was used for initial washes and between steps. Slides were incubated in 3% peroxidase in methanol for 10 min, blocked with 0.3% Triton X-100 and 5% normal goat serum in Tris-buffered saline for 1 h at room temperature, and then incubated overnight at 4°C with rabbit monoclonal anti-activated caspase-3 (1:100; Cell Signaling, Danvers, MA). Biotinylated goat antirabbit secondary antibody (Vector, Burlingame, CA) was applied at 1:250 for 30 min at room temperature, followed by avidin–biotin–peroxidase complex (ABC reagent; Vector Laboratories, Burlingame, CA) for 30 min. Staining was developed with 3,3'-diaminobenzidine (DAB; Vector Laboratories, Burlingame, CA) for 8 min and then the slides were counterstained with hematoxylin, dehydrated, and cover-slipped (Permount, Fischer SP15, Fair Lawn, NJ). At least four sections from each animal were counted for caspase-3 immunoreactive cells under the light microscope.

Fluoro-Jade C. Fluoro-Jade C staining was performed in 14-μm sections of spinal cord 24 h following injection using an established protocol. Slides were immersed in 1% sodium hydroxide in 80% ethanol, rinsed with 70% ethanol, and then incubated in 0.06% potassium permanganate. Sections were stained with 0.0002% Fluoro-Jade C (Millipore, Temecula, CA) and 0.01% 4,6-diamidino-2-phenylindole (Molecular Probes, Eugene, OR) dissolved in 0.1% acetic acid, cleared with CitriSolve (Fisher Scientific, Waltham, CA) and 0.01% 4,6-diamidino-2-phenylindole (Molecular Probes, Eugene, OR). At least four sections from each animal were imaged using standardized exposures and an Olympus BX51 microscope with appropriate wavelength fluorescence illuminator (Olympus America, Inc., Center Valley, PA) equipped with a digital camera and image-capture software. The mean intensity of immunofluorescence within a fixed size region of interest in the dorsal horn and background intensity was calculated using Image Pro Plus software (Media Cybernetics Inc., Silver Spring, MD).

Hematoxylin and Eosin. Seven-micron sections of spinal cord from 24-th to 7-day survival groups were stained with hematoxylin (Gill No.2; Sigma Aldrich, St. Louis, MO) and eosin (Eosin Y solution Alcoholic; Sigma Aldrich, St. Louis, MO). At least four nonconsecutive sections per animals were evaluated for histopathological changes (degenerating neurons, tissue necrosis, inflammation, or other changes) by a neuropathologist experienced in the evaluation of neonatal neurological injury and spinal toxicity (Dr. Grafe). Neurotoxicologic evaluation of nerve roots of the cauda equina was performed 24 h or 7 days after saline or levobupivacaine administration in P3 and P7 pups (n = 4 per group, total = 32 animals). Cauda equina was cut from the spinal cord and transferred into 2.5% glutaraldehyde in 0.1 M phosphate buffer. The nerve roots were rinsed with 0.1 M phosphate buffer, postfixed in 1% osmium tetroxide, dehydrated in serial concentrations of alcohol, and embedded in araldite resin according to the recommended procedure. Transverse, 1-μm-thick sections were cut on an automated Leica RM2065 microtome and stained with methylene blue-azure II for light microscopy. Images were taken using Openlab 4.04 software (Improvision, Waltham, MA) and examined for pathological change by an investigator experienced in nerve pathology (Dr. Shubayev).

Statistical Analysis
For determination of mechanical withdrawal thresholds in rat pups, the number of withdrawal responses was plotted against the mechanical stimulus (force expressed as grams on log10 scale). A sigmoidal stimulus–response curve was constructed using nonlinear regression curve fit, and the mid point of the curve (50% effective force; EF50) was designated as the mechanical withdrawal threshold, as previously described. For graphical display, data within the group were pooled for evaluation of EF50 at 15 min as motor block resulted in either no response to the maximum mechanical threshold or submaximal responses (i.e., less than 5/5 responses to the maximum mechanical stimulus; figs. 1 and 2). To allow analysis of the effect of time and treatment, individual threshold values for each animal
were calculated at baseline, 30, 45, 60 min, and 24 h, and the maximum applied force was designated the threshold if motor block was present at 15 min. Repeated measures two-way ANOVA with Bonferroni post hoc test was used to evaluate differences between levobupivacaine and saline groups. Thresholds 7 days following injection of levobupivacaine or saline at P3 or P7 were compared with unpaired two-tailed Student t test. In P35 rats, mechanical withdrawal thresholds and thermal latencies were the mean of three values for each hindpaw. As data were obtained at the same age, and were normally distributed (Kolmogorov–Smirnov test) continuous variables, all treatment groups were compared with one-way ANOVA with Bonferroni post hoc comparisons. In addition, thresholds and latencies were compared with two-way ANOVA with gender and treatment as variables, and age at time of injection and treatment as variables. The duration of the electromyography response was outlined from the display of the raw data and the integral of the root mean square of the signal was calculated (electromyography response; Chart, Powerlab AD Instruments, Castle Hill, Australia). The electromyography response was plotted against the von Frey hair number (mechanical stimulus) and the area under the stimulus–response curve calculated to quantify the overall "reflex response."42 For tissue sections, measures from the display of the raw data and the integral of the root mean square of the signal was calculated (electromyography response; Chart, Powerlab AD Instruments, Castle Hill, Australia). The electromyography response was plotted against the von Frey hair number (mechanical stimulus) and the area under the stimulus–response curve calculated to quantify the overall "reflex response." For tissue sections, measures from at least four nonconsecutive sections were averaged for each animal, with analysis based on n = number of animals and comparison with two-tailed Mann–Whitney test. Statistical analysis was performed using Prism Version 5.0 (GraphPad, San Diego, CA) and P < 0.05 was considered statistically significant.

Results

Intrathecal Levobupivacaine Produces Sensory and Motor Blockade in Rat Pups

Body weights of rat pups were between 8–11 g (mean ± SEM, 9.75 ± 0.24) at P3 and 12–18 g (15.74 ± 0.39) at P7. Baseline mechanical withdrawal thresholds were lower at P3 than P7 (1.9 ± 0.2 g, n = 20 vs. 2.7 ± 0.3, n = 19; P < 0.05 unpaired two-tailed t test) but did not differ significantly between saline versus levobupivacaine groups within age groups (1.9 ± 0.2 vs. 2.0 ± 0.3, P = 0.66 at P3; 2.5 ± 0.3 vs. 2.8 ± 0.4, P = 0.41 at P7). Dense motor block of the hind limbs and failure of hip flexion were apparent 5 min following intrathecal levobupivacaine, when animals had recovered from anesthesia. Fifteen minutes following injection, bilateral block (motor score 0/4) was apparent in 4/9 P3 pups and 6/10 P7 pups; unilateral block (motor score 1/4) in 4/9 P3 and 3/10 P7 pups; and one animal at each age had partial motor response to a suprathreshold mechanical stimulus (motor score 2/4). Animals in which correct intrathecal placement could not be confirmed by early dense motor block, or that had a motor score of 3 or 4 at 15 min, were precluded from further analysis. Motor deficits were not apparent in any saline-treated animals.

Fifteen minutes following levobupivacaine in P3 (fig. 1) and P7 pups (fig. 2), the mechanical stimulus–response curve was shifted to the right and the maximal response was reduced due to complete motor block in the majority of animals. Within-group pooled thresholds were higher in levobupivacaine versus saline groups 15 min following intrathecal injection at both P3 (11.3 ± 1.1 vs. 2.0 ± 0.1 g, P < 0.001, two-tailed unpaired two-tailed Student t test) and P7 (14.9 ± 1.6 vs. 2.4 ± 0.2 g, P < 0.001). Analysis of individual values with time similarly demonstrated significant differences at 15 min (P < 0.001 in P3 and P7 animals; two-way repeated measures ANOVA with Bonferroni posttest). Values did not differ between saline and levobupivacaine groups at other time points to 24 h in P3 pups, but sensory block was more prolonged in P7 pups with higher mechanical withdrawal thresholds at 30 min in the levobupivacaine versus saline group (5.3 ± 1.1 vs. 2.8 ± 0.7 g, P < 0.05, two-way repeated measures ANOVA with Bonferroni posttest). Withdrawal thresholds increased with age, but there were no statistically significant differences between groups 7 days following injection of levobupivacaine or saline at P3 (8.4 ± 1.4 vs. 5.8 ± 0.6; P = 0.11) or P7 (15.1 ± 2.4 vs. 19.0 ± 3.6 g; P = 0.38; unpaired two-tailed Student t test).

Intrathecal Levobupivacaine, Apoptosis, and Glial Reactivity

The number of activated caspase-3 positive cells in the lumbar spinal cord (fig. 3A) did not differ between saline and levobupivacaine groups 24 h following injection at P3 or P7 (fig. 3B). Similarly, the number of Fluoro–Jade C positive cells was not altered by intrathecal levobupivacaine (fig. 3C). Consistent with our previous studies, levels of apoptosis were higher at P3 than P7, and were predominantly distributed in the dorsal horn (fig. 3, B and C).

Microglial Iba1 staining 7 days after injection was higher in the P7 saline versus levobupivacaine group (P < 0.05, two-tailed Mann–Whitney test), but P7 levobupivacaine did not differ from animals receiving saline or levobupivacaine at P3 (P = 0.22, Kruskal–Wallis test with Dunn’s multiple comparisons; fig. 4, A and B). Intrathecal levobupivacaine at either P3 or P7 did not alter the intensity of staining with the astrocytic marker glial fibrillary acidic protein 7 days after injection when compared with saline control groups (fig. 4, C and D).

Histopathological Evaluation in the Spinal Cord and Cauda Equina

There was no evidence of necrosis, gliosis, or inflammation in saline or levobupivacaine groups at any time point. Scattered apoptotic cells were seen in all animals. These were present in greatest numbers in the youngest age group (i.e., P3 animals with 24-h survival) but did not differ between saline and levobupivacaine groups (5.7 ± 0.6 vs. 7.2 ± 1.8 per section, respectively, P = 0.6, Mann–Whitney two-tailed test). At all older ages and time points (P8, P7
plus 24 h; P10, P3 plus 7 days; and P14, P7 plus 7 days), the mean number of apoptotic cells was less than two per section in both saline and levobupivacaine groups.

Multiple intact myelinated axons were observed in the endoneurium of the cauda equina in both levobupivacaine and saline treatment groups in postnatal age P3 and P7 pups (fig. 5). Mild endoneurial edema, particularly in the subperineurial and perivascular spaces, was observed in all groups. Enlarged cytoplasm of activated Schwann cells, characteristic of their morphology during developmental remodeling of myelin in the nerves of P3 and P7 rat pups, was observed in both treatment groups. There were no apparent differences between saline and levobupivacaine groups in either P3 or P7 pups.

**Intrathecal Levobupivacaine and Spinal Reflex Function in Early Adulthood**

Spinal reflex responses at P35 were not altered by neonatal spinal anesthesia. Mechanical withdrawal threshold (fig. 6A) and thermal withdrawal latency (fig. 6B) did not differ significantly between groups receiving intrathecal saline or levobupivacaine at either P3 or P7 (P = 0.1 and 0.051 respectively, one-way ANOVA with Bonferroni post hoc comparisons).

At P35, males weighed more than females (131 ± 4.5 vs. 116 ± 4.1 g), and there was a significant main effect of gender (F1,11 = 6.2, P = 0.03), but not of treatment (F1,11 = 2.38, P = 0.15; two-way ANOVA with gender and treatment as variables) on body weight. There was no main
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Fig. 2. Mechanical withdrawal thresholds of postnatal day (P)7 rat pups prior to (baseline) and at intervals (15, 30, 45, 60 min, and 24 h) following intrathecal injection of saline or 0.5 μl/g of 0.5% levobupivacaine. Graphs represent the log10 stimulus–response relationship between number of hind limb withdrawal responses (0–5) and mechanical stimulus (grams, g) applied with graded von Frey hairs. Thresholds were higher in the levobupivacaine versus saline group at 15 min (log EC50 14.9 g 95% CI, 11.8–18.0 versus 2.4 g; 95% CI, 2.0–2.9) and to a lesser degree at 30 min (log EC50 5.1 g 95% CI, 4.3–6.0 versus 2.5 g; 95% CI 2.1–3.0). Data points = pooled mean ± SEM for saline (n = 9) and levobupivacaine (n = 9) groups.

Discussion

Single dose intrathecal levobupivacaine produced reliable sensory and motor blockade in neonatal rat pups at

effect of intrathecal treatment (saline or levobupivacaine; F1,11 = 0.64, P = 0.44) or gender (F1,11 = 0.05, P = 0.83) on mechanical withdrawal threshold. Similarly, there was no main effect of treatment (F1,11 = 0.39, P = 0.54) or gender (F1,11 = 0.51, P = 0.49) on thermal withdrawal latency at P35 (two-way ANOVA with treatment and gender as variables). Age at time of injection (P3 or P7) did not influence mechanical withdrawal threshold (F1,28 = 6.6, P = 016) or thermal withdrawal latency (F1,28 = 3.4, P = 0.08) in early adulthood (two-way ANOVA with age at time of injection and treatment as variables).

Spinal reflex sensitivity to suprathreshold mechanical stimuli, quantified from the area under the mechanical stimulus versus electromyography response relationship (fig. 6C), did not differ between animals receiving intrathecal levobupivacaine or saline at P3 or P7 (P = 0.87, one-way ANOVA with Bonferroni post hoc comparisons; fig. 6D).

Gait analysis using the CatWalk® runway system at P35 was not altered by prior intrathecal injection of 0.5% bupivacaine at P3. Static (paw print area) and dynamic gait parameters (regularity index, duty cycle, stride length, and base of support) did not differ from animals that received intrathecal saline at P3 (table 1) or age-matched naïve controls (as previously reported).27

Single dose intrathecal levobupivacaine produced reliable sensory and motor blockade in neonatal rat pups at
postnatal day 3 (P3) and P7. Intrathecal levobupivacaine did not increase apoptosis in the spinal cord, or produce histopathological change in the cord or cauda equina. Neonatal spinal anesthesia did not adversely affect spinal cord function in young adulthood (P35), as sensory withdrawal reflex thresholds, electromyographic responses to suprathreshold hindpaw stimuli, and gait did not differ from litter-mate controls receiving intrathecal saline.

Neuraxial local anesthetics can be used as an alternative to general anesthesia, or as a supplemental technique for perioperative analgesia, in children of all ages, and case series in neonates and infants have recently been summarized. Excessive absorption or inadvertent vascular injection can result in systemic toxicity and neurological and cardiovascular complications. As a result, there is increasing...
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use of the stereoisomers levobupivacaine or ropivacaine, which have wider therapeutic windows than racemic bupivacaine.\textsuperscript{50,51} Levobupivacaine 0.5\% produced reliable motor and sensory blockade in P3 and P7 pups. Duration of sensory block was shorter in younger animals (P3 < P7), as seen following bupivacaine (P7 < P21).\textsuperscript{20} Similarly, duration of intrathecal local anesthetic block in infants is less than adults, and postulated to be due to age-dependent differences in relative volume and more rapid turnover of cerebrospinal fluid.\textsuperscript{52}

Serious neurological complications following neuraxial techniques in children are rare,\textsuperscript{1,53} but complication rates are higher in neonates.\textsuperscript{54} Although technical issues in small patients may be a factor, specific evaluation of the relative safety of neuraxial drugs in early development is essential. Use of spinal analgesia in neonates is increasing in some centers\textsuperscript{7,8} and may be further encouraged to reduce exposure to general anesthetics and the potential risk of increased neuronal apoptosis in the developing brain.\textsuperscript{24,55} However, the developing spinal cord is also susceptible to apoptosis, which

\begin{figure}
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\includegraphics[width=\textwidth]{histologic_sections.png}
\caption{Histologic sections of cauda equina nerves 24 h or 7 days after intrathecal injection of saline or levobupivacaine in postnatal day (P)3 and P7 pups. Transverse, 1-μm-thick, plastic-embedded sections stained with methylene blue-azure II at x1400 magnification. Intact myelinated axons, mild endoneurial edema, and activated Schwann cells characteristic of an age-appropriate proliferative phenotype were observed in all sections.}
\end{figure}
is increased following prolonged general anesthesia at P7,20,56 and analgesic doses of intrathecal ketamine at P3.28 By contrast, intrathecal bupivacaine 3.5 mg/kg did not increase neuronal apoptosis or produce histopathological change in spinal cord white matter following injection at P7, P14, or P21.20 Similarly, intrathecal levobupivacaine 2.5 mg/kg did not increase apoptosis at P7, but additionally we found no adverse effect at the younger age of P3, when baseline apoptosis is higher in spinal cord.28,29 This was confirmed using three different but complementary methods: antibodies to activated caspase-3 (an enzyme in the apoptotic cascade expressed once the neuron is committed to cell death)57, Fluoro-Jade C staining (which labels degenerating neurons)44 and identification of apoptotic cells under high power microscopy.

Clinical concerns regarding local anesthetic toxicity followed reports of cauda equina syndrome with continuous spinal anesthesia and high local concentrations of lidocaine

**Table 1.** Gait Parameters at Postnatal Day (P)35 after Intrathecal Treatment at P3

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Print Area</th>
<th>Regularity Index</th>
<th>Duty Cycle</th>
<th>Stride Length</th>
<th>Base of Support</th>
</tr>
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<tbody>
<tr>
<td>Saline*</td>
<td>40.3 ± 3.5</td>
<td>99.8 ± 0.2</td>
<td>54.1 ± 1.4</td>
<td>107.5 ± 2.1</td>
<td>27.6 ± 0.7</td>
</tr>
<tr>
<td>Bupivacaine</td>
<td>40.5 ± 1.9</td>
<td>99.7 ± 0.3</td>
<td>57.7 ± 1.0</td>
<td>99.6 ± 3.5</td>
<td>31.0 ± 0.93</td>
</tr>
</tbody>
</table>

* Saline data previously reported.27

base of support = distance between two hindpaws measured perpendicular to walking direction; duty cycle = ratio between stance duration and full step cycle duration (stance phase duration/stance + swing phase duration); P = postnatal day; Print area = surface area of floor contacted by hindpaw; regularity index = index for degree of interlimb coordination during gait; stride length = distance between placement of hindpaw and subsequent placement of same paw.

Fig. 6. Spinal reflex responses to hindpaw stimuli in young adulthood are not altered by prior intrathecal levobupivacaine. (A), Mechanical withdrawal threshold at postnatal day (P)35 following intrathecal (IT) injection on postnatal day 3 (P3 IT) or 7 (P7 IT) of saline or 0.5% levobupivacaine (l-bupi). Data points = box and whiskers (5–95 percentile); n = 6–8 all groups. Values did not differ significantly across treatment groups (P = 0.10 one-way ANOVA). (B) Thermal withdrawal latency at P35 following IT saline or levobupivacaine at P3 or P7. Data points = box and whiskers (5–95 percentile); n = 6–8 all groups. (P = 0.051 one-way ANOVA). (C) (i): Example of electromyography (EMG) recordings in biceps femoris at P35 in response to increasing mechanical stimuli (von Frey hair, vFh 17–20), and (ii) plot of stimulus–response relationship for quantification of area under the curve (AUC) to threshold (vFh 18) and suprathreshold (vFh 19 and 20) stimuli. (D) The quantified reflex response (AUC EMG) did not differ between animals treated with saline or levobupivacaine at P3 or P7 (P = 0.87 one-way ANOVA). Data points = mean ± SEM; n = 6 per group.
or tetracaine. Transient neurological symptoms (pain in the gluteal region and radiating to legs which usually resolves by the 5th postoperative day) may occur following spinal anesthesia; most commonly following lidocaine (relative risk about seven times higher than bupivacaine), but there is insufficient data to compare rates associated with levobupivacaine or ropivacaine. Although there has been limited detailed evaluation, transient neurological symptoms (tingling in the feet) have been reported following spinal anesthesia in children. Such symptoms and subtle motor deficits cannot be detected in neonates and infants. This emphasizes the need to evaluate comparative local anesthetic toxicity in developmental models.

Local anesthetic toxicity has been evaluated using in vivo and in vitro models. In cell cultures, including adult dorsal root ganglion neurons from rodents and human neuroblastoma cell lines, concentration-dependent toxicity has consistently been shown. Local anesthetics produce mitochondrial injury, caspase activation, apoptosis, increased calcium influx, and necrosis at higher concentrations. Although selective sensitivity to lidocaine has been reported, cellular toxicity has been shown following most local anesthetics, and apoptotic potency correlated with lipid solubility rather than chemical structure. However, in vitro models may overestimate neurotoxicity as isolated cells in culture are more vulnerable (no diffusion barriers and no vascular clearance of drug), and duration of exposure to high concentrations is often more prolonged. Local anesthetics impaired outgrowth of developing neurites (increased growth cone collapse) in cultured dorsal root ganglion neurons from chick embryo, but there has been limited evaluation in developmental models.

In adult rabbits and rodents, intrathecal local anesthetics can produce signs of spinal toxicity, but results vary with dose and drug. Spinal histopathology (increased macrophage infiltration, axonal degeneration, and myelin changes) followed intrathecal 10% lidocaine but not equi-effective bupivacaine. Levobupivacaine 5% 0.12 µl/g (approximately 0.6 mg/kg) did not produce histology in adult rat, but a higher dose (approximately 2.8 mg/kg) produced white matter injury that was similar to procaine but greater than following ropivacaine. Vacuolization and degeneration of neurons in the gray matter have also been demonstrated following 10% lidocaine, and to a lesser degree following tetracaine, 2% bupivacaine, and 2% ropivacaine. In cauda equina, histopathology in adult rodents was greater following 6.9 mg/kg lidocaine (10%) than after equi-effective 1.5 mg/kg bupivacaine (2.1%). Similar injury scores were reported following high dose bupivacaine or levobupivacaine (approximately 10 mg/kg total dose). The current study found no differences in spinal cord or cauda equina histology between intrathecal levobupivacaine and saline groups administered at either P3 or P7. However, rat pups received a lower dose per body weight (2.5 mg/kg) and were exposed to a lower drug concentration as a consequence of both the injectate concentration (0.5%) and further dilution in the relatively greater cerebrospinal fluid volume in pups (8.8 µl/g at P5, 4 µl/g at P30). Intrathecal injectates of 0.5 µl/g produce spread over thoracic and lumbar segments in rat pups, and higher volumes of local anesthetic can produce significant respiratory compromise. Consistent with a previous evaluation of intrathecal bupivacaine at P7, P14, and P21, the maximum dose of levobupivacaine at P3 or P7 did not increase apoptosis or produce histopathology. As spinal catheters and prolonged infusions are not practical in these small pups, we have suggested intrathecal dose escalation and calculation of a therapeutic index (maximum tolerated or minimum toxic dose/analogic dose) to evaluate comparative spinal toxicity in developmental models. The current dose of levobupivacaine produced reversible motor and sensory block without toxicity, but dose escalation was limited by side effects. Therefore, the therapeutic index is greater than 1, but we cannot exclude toxicity at higher concentrations or doses of levobupivacaine.

Assessing effects of neonatal exposure on long-term spinal cord function can include several parameters. Prolonged general anesthesia at P7 increased apoptosis in the spinal cord, but did not impair motor performance at P30 (assessed by time on the Rotarod apparatus). However, as apoptosis in the postnatal cord is greatest in the dorsal horn, increased apoptosis may also influence sensory function. Intrathecal ketamine at P3 increased apoptosis, reduced mechanical withdrawal threshold, and altered static, but not dynamic, gait parameters at P35. Local anesthetics may have additional toxic effects unrelated to developmental apoptosis that influence both motor and sensory outcomes. In adult animals, changes in thermal tail flick latency, mechanical paw pressure withdrawal threshold, and motor function have been shown 4–7 days following doses of local anesthetic that produce tissue histopathology. Here, single intrathecal doses of 2.5 mg/kg levobupivacaine at either P3 or P7 did not produce persistent changes in spinal reflex withdrawal to mechanical or thermal stimuli, and did not alter quantified electromyography responses to suprathreshold mechanical stimuli. Intrathecal bupivacaine 3.75 mg/kg at P7 did not alter motor function (time on the Rotarod) at P30. The CatWalk system allows analysis of sensorimotor coordination and both static and dynamic components of gait. Following intrathecal bupivacaine at P3, gait parameters at P35 did not differ from our previously reported values in age-matched naïve or P3 intrathecal saline control animals. Local anesthetics and spinal analgesics are commonly coadministered to improve analgesia or reduce local anesthetic requirements, but some analgesics enhance local anesthetic toxicity in cell culture models. Ropivacaine-induced decreases in neuronal viability (adult dorsal root ganglion cell culture) were potentiated by midazolam, but...
not clonidine or buprenorphine.\textsuperscript{62} Midazolam and ketamine both increased locidane toxicity (human neuroblasto
toma and rat astrocyte cultures), but sufentanil, clonidine, epinephrine, and neostigmine had no effect.\textsuperscript{70} Our \textit{in vivo}
studies demonstrated increased neuronal apoptosis in the neonatal cord following ketamine,\textsuperscript{28} but not clonidine\textsuperscript{29} or morphine.\textsuperscript{22} Further \textit{in vivo} developmental studies evaluating age- and dose-dependent analgesic efficacy, spinal cord and nerve root histology, and long-term function following combinations of spinal analgesics and local anesthetic would allow further comparison of the safety profile of current clinical regimens.

In conclusion, single doses of 0.5\% intrathecal levobu-
pivacaine produce reliable spinal anesthesia in P3 and P7 neonatal rat pups, but do not increase apoptosis or produce histopathological changes in the spinal cord or cauda equina. This study provides further preclinical safety data relevant to the use of spinal anesthesia in neonates, and supports the use of neuraxial anesthesia as a comparison group\textsuperscript{71} for evaluat-
ing outcomes following surgery and anesthesia in early life. Furthermore, these results add to a growing body of data that validate the neonatal rat as a robust model for assessing the pathogenic propensity of neuraxial agents throughout postnatal development, and the requirement for preclinical evaluation of toxicity as part of the rational development of neonatal neuraxial therapeutics.\textsuperscript{1}

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ANESTHESIOLOGY REFLECTIONS FROM THE WOOD LIBRARY-MUSEUM

From Chloroform to Extract of Meat: Chemist and Entrepreneur Liebig

Nine years after independently discovering chloroform, Baron Justus von Liebig synthesized a meat substitute in 1840 that was eventually marketed as “Liebig’s Extract of Meat.” A Belgian engineer encouraged Liebig to open a processing plant in Fray Bentos, Uruguay, to generate the extract from cattle carcasses otherwise underutilized after processing for leather. In a time period before refrigeration when meat costs were high, this German–Belgian–Uruguayan collaboration prospered. As part of its advertising campaign, the company produced a colorful series of collectible trading cards. “Extracted” from the final card (in a series of six saluting “The Life of Liebig”) are images of Baron Liebig himself (left) and of his factory in Uruguay (right). In 1979 the factory closed. It is now a museum celebrating how a German chemist and a Belgian engineer founded a company which economically revitalized the nation of Uruguay and nutritionally supplemented the diets of people worldwide. (Copyright © the American Society of Anesthesiologists, Inc.)

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