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Transient cervical nerve root compression modulates pain: Load thresholds for allodynia and sustained changes in spinal neuropeptide expression

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Abstract

Nerve root compression produces chronic pain and altered spinal neuropeptide expression. This study utilized controlled transient loading in a rat model of painful cervical nerve root compression to investigate the dependence of mechanical allodynia on load magnitude. Injury loads (0–110 mN) were applied quasistatically using a customized loading device, and load thresholds to produce maintained mechanical allodynia were defined. Bilateral spinal expression of substance P (SP) and calcitonin gene-related peptide (CGRP) was assessed 7 days following compression using immunohistochemistry to determine relationships between these neuropeptides and compression load. A three-segment change point model was implemented to model allodynia responses and their relationship to load. Load thresholds were defined at which ipsilateral and contralateral allodynia were produced and sustained. The threshold for increased allodynia was lowest for acute (day 1) ipsilateral responses (26.29 mN), while thresholds for allodynia on day 7 were similar for the ipsilateral (38.16 mN) and contralateral forepaw (38.26 mN). CGRP, but not SP, significantly decreased with load; the thresholds for ipsilateral and contralateral CGRP decreases corresponded to 19.52 and 24.03 mN, respectively. These thresholds suggest bilateral allodynia may be mediated by spinal mechanisms, and that these mechanisms depend on the magnitude of load.

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Keywords: Nerve root; Cervical; Load; Neck pain; Threshold

1. Introduction

The annual incidence of neck pain among adults ranges 14–50% (Côté et al., 2004; Fejer et al., 2005) affecting up to 71% of people in their lifetime (Côté et al., 1998, 2000). Individuals may suffer from chronic pain throughout their lives, resulting in large societal costs (Rempel et al., 1992; Côté et al., 2004). Cervical spine motions decrease the intervertebral foramen (Nuckley et al., 2002) causing transient impingement of the nerve roots and radicular pain when motions exceed the normal range, as can occur in accidents and sports injuries (Krivickas and Wilbourn, 2000; Torg et al., 2002).

Nerve root compression can produce tissue damage, edema, membrane leakage, and Wallerian degeneration, as well as changes in neuropeptide expression and spinal glial activation (Olmaker et al., 1989; Pedowitz et al., 1992; Colburn et al., 1997, 1999; Hashizume et al., 2000; Winkelstein et al., 2001a; Kobayashi et al., 2005a,b). These responses result in bilateral sensitivity (Hubbard and Winkelstein, 2005) and central sensitization: a heightened responsiveness and reduced threshold for afferent inputs to the central nervous system (Woolf and Walters, 1991; Ji et al., 2003). Canine lumbar root compression for 1 h produces endoneurial edema but only for loads above 15 gf (147.2 mN; Kobayashi et al., 1993; Kobayashi and Yoshizawa, 2002), suggesting a load threshold for producing neural pathology. While those studies provide insight into physiologic responses for nerve root loading and their dependence on biomechanics, injury mechanics and

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cellular/molecular outcomes have not been investigated in the context of pain. Models of persistent pain from root compression have not used controlled loading mechanics (Winkelstein et al., 2001b, 2002; Winkelstein and DeLeo, 2002, 2004; Sekiguchi et al., 2003, 2004). Previous work in our lab has shown that transient compression of the rat cervical nerve root with 10 gf (98.1 mN) produces persistent mechanical allodynia, and suggested that 10 gf is above the load threshold for producing bilateral behavioral hypersensitivity in rats (Hubbard and Winkelstein, 2005). Currently, there is an incomplete understanding of the role of compression severity in transient nerve root loading for producing either acute or persistent mechanical allodynia, and no study has identified tissue loading thresholds for behavioral outcomes in the cervical spine.

The neuropeptides substance P (SP) and calcitonin gene-related peptide (CGRP) have been studied extensively for their contributions to nociception (Oku et al., 1987; Cridland and Henry, 1989; Kawamura et al., 1989; Levine et al., 1993; Bennett et al., 2000; Kobayashi et al., 2004, 2005a,b; Aoki et al., 2005). SP is released from axon terminals upon C-fiber stimulation (Malcangio et al., 2000), and its expression in the superficial laminae of the spinal cord decreases after lumbar neural injuries (Munglani et al., 1996; Malmberg and Basbaum, 1998; Allen et al., 1999). CGRP affects nociception by promoting the release, and slowing the metabolism of SP (Allen et al., 1999; Meert et al., 2003). Allodynia increases following intrathecal CGRP administration and decreases after administration of a CGRP antagonist (Oku et al., 1987; Cridland and Henry, 1989; Bennett et al., 2000). Despite studies characterizing the temporal expression of spinal SP and CGRP (Cahill andCoderre, 2002; Jang et al., 2004), the dependence of these neuropeptides on nerve root compression load and persistent behavioral hypersensitivity is not fully understood.

In this study, a statistical model is used to identify load thresholds governing allodynia and spinal neuropeptide responses. To quantify changes in behavioral outcomes, mechanical allodynia (response to a stimulus which is not normally painful) is measured, which has clinical relevance as a pain outcome and is a sensitive measure in rodent models (Colburn et al., 1999; Tabo et al., 1999; Bennett et al., 2000). It is hypothesized that bilateral mechanical allodynia will depend on load magnitude above a defined threshold. We further hypothesize that altered spinal SP and CGRP expression can be modeled by similar load thresholds, which will match the thresholds for mechanical allodynia.

2. Materials and methods

Experiments were performed using male Holtzman rats (250–350 g; Harlan Sprague-Dawley, Indianapolis, IN) housed with a 12–12 h light–dark cycle and free access to food and water. All experimental procedures were approved by an Institutional Animal Care and Use Committee.

2.1. Surgical procedures

Surgical procedures were performed under halothane inhalation anesthesia (4% induction, 2% maintenance) and were adapted from published methods (Hubbard and Winkelstein, 2005; Rothman et al., 2005). After the spinal cord and right roots were exposed, a customized loading device with microcompression platens (0.7 mm width) applied compression to the C7 dorsal root proximal to the dorsal root ganglion (DRG, Fig. 1(A)). Platen displacement was measured by an LVDT (5 mm travel distance, 0.25% sensitivity; RDP, Pottstown, PA), and the applied load was recorded by a load cell (490 mN, 0.15 mN resolution; Omega, Stamford, CT). Mechanical data were recorded at 10 Hz using LabVIEW (National Instruments, Austin, TX). Digital video (Qimaging, Burnaby, British Columbia) monitored the nerve root during compression.

The right C7 dorsal root was compressed transversely through its diameter to prescribed loads ranging 0–110 mN ($n = 25$), with loads distributed across that range. Due to considerable stress relaxation for

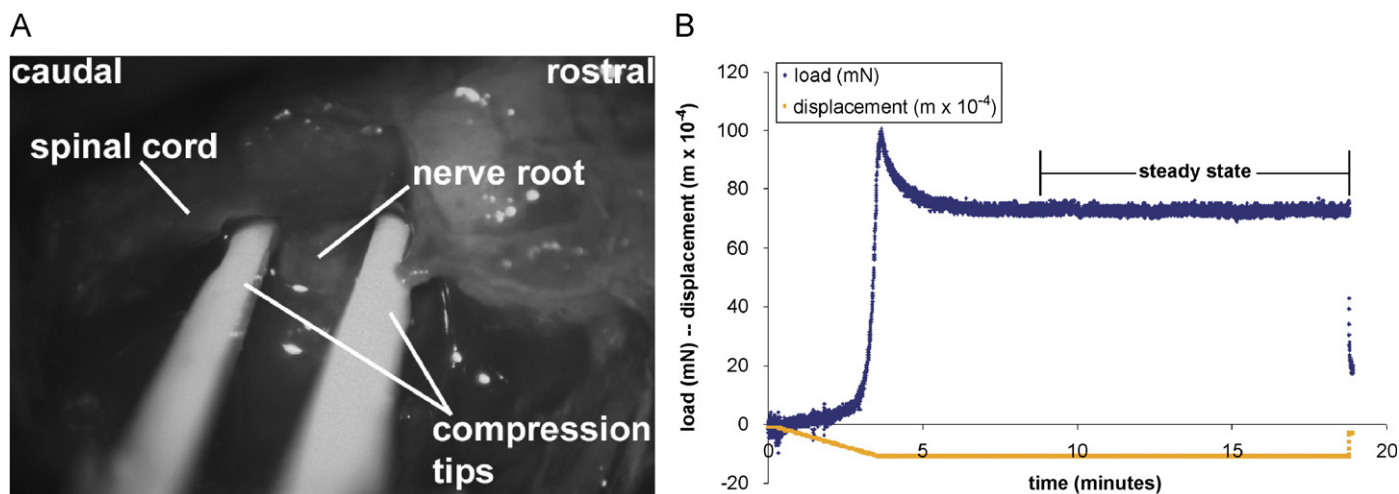


Fig. 1. (A) Surgical exposure of right C7 dorsal root showing anatomy and compression platens inserted prior to load application. (B) Mechanical data (load and displacement) during compression of the C7 nerve root (rat #194). Steady-state load (71.32 mN) was defined as the average load measured between 5 and 15 min after the peak load was reached.

dynamic compression of neural tissue (Miller et al., 2000; Gefen and Margulies, 2004; Coats and Margulies, 2006; Cheng and Bilston, 2007), quasistatic loading (0.004 mm/s) was implemented. Upon reaching a predetermined peak load, platen displacement was held for 15 min. The load relaxed approximately 20% within the first 5 min of the hold period (Fig. 1(B)). Steady-state load was reported as the average load measured between 5 and 15 min during compression. Sham procedures were performed with the same surgical technique but without tissue compression ($n = 4$). Wounds were closed using 3–0 polyester suture and surgical staples.

2.2. Mechanical allodynia

All rats were evaluated for bilateral forepaw mechanical allodynia on days 1, 3, 5, and 7 following surgical procedures (Ramer et al., 2000; Lee et al., 2004; Hubbard and Winkelstein, 2005; Rothman et al., 2005). Prior to surgery, baseline measurements were recorded for two consecutive days. A single tester performed all allodynia testing and was blinded to the applied compression load.

For each session, following 20 min of acclimation to the testing environment, rats were stimulated on the plantar surface of each forepaw using three von Frey filaments (13.7, 19.6, and 39.2 mN, Stoelting, Wood Dale, IL). Each testing session consisted of three rounds of 10 stimulations on each forepaw, separated by 10 min. The total number of paw withdrawals was summed for each forepaw with each filament.

2.3. Spinal cord tissue preparation and immunohistochemistry

Rats were euthanized on day 7 by an overdose of sodium pentobarbital (40 mg/kg) and transcardially perfused with 200 ml of phosphate buffered saline (PBS) followed by 200 ml of 4% paraformaldehyde in PBS. Spinal cord tissue was harvested and placed in 4% paraformaldehyde for 1 h, then in 30% sucrose for 5 days before freeze mounting in OCT (Fisher, Fairlawn, NJ) and storage at -80°C . Axial sections (20 μm) immediately rostral to the C7 root insertion were sectioned for free-floating immunohistochemistry. Sections were blocked in 2% normal goat or donkey serum. Polyclonal antibodies against CGRP (1:4000; Bachem, San Carlos, CA) and SP (1:2000; Chemicon, Temecula, CA) were applied to tissue sections in PBS-T (0.3% triton). Goat anti-rabbit (1:1000; Vector, Burlingame, CA) or donkey anti-rabbit (1:1250; Chemicon, Temecula, CA) secondary antibodies were applied for CGRP or SP immunostaining, respectively. All antibody dilutions were previously optimized (Rothman et al., 2005). Sections were exposed to 3,3'-diaminobenzidine for color development (Vector Labs, Burlingame, CA).

Representative bilateral tissue sections for SP and CGRP from each rat were imaged at $50\times$ to quantify immunostaining. Within a 350×750 pixel area including the superficial laminae, pixels with a staining intensity above a predetermined mean threshold for positive immunoreactivity in normal tissue were quantified (Abbadie et al., 1996; Malmberg and Basbaum, 1998; Rothman et al., 2005). For densitometry, reactive pixels were only detected in laminae I and II. The number of pixels above threshold was reported as a percentage of the total in the region and averaged for the sections analyzed for each rat.

2.4. Data and statistical analyses

Mechanical allodynia was analyzed by groups defined by average steady state compression loads. Rats were divided into four groups ($n = 6$ or 7 per group) in addition to shams ($n = 4$), based on average steady state load ($\pm\text{SD}$, Table 1). Allodynia responses were averaged for each group to provide mean ipsilateral and contralateral responses and analyzed by a two-way analysis of variance (ANOVA) with repeated measures to determine significant effects of load over time. A one-way ANOVA with post-hoc Bonferroni correction compared means at each time point. These

Table 1
Applied nerve root compression load

Rat ID	Peak load (mN)	Average peak load (mN) ^a	Steady-state load (mN)	Average steady state load (mN) ^a
195	31.20	21.80 ± 6.31	5.30	10.89 ± 6.49
217	26.87		22.07	
219	16.88		9.22	
220	14.24		7.06	
221	19.82		15.11	
222	21.76		6.77	
175	89.37	57.35 ± 17.15	32.86	37.18 ± 7.28
176	54.35		37.96	
198	54.35		37.08	
200	61.41		38.55	
201	62.36		51.31	
218	34.08		33.65	
223	45.56		28.55	
178	87.70	85.27 ± 10.29	74.26	66.71 ± 7.45
194	98.79		71.32	
196	88.28		72.10	
197	90.64		58.76	
199	74.97		56.41	
214	71.26		67.36	
177	114.09	108.04 ± 4.70	108.99	98.10 ± 6.96
212	106.07		97.90	
213	108.75		92.31	
215	105.19		90.64	
216	101.61		95.65	
224	112.51		103.20	

^aAverage loads \pm standard deviation.

statistical analyses were performed using SYSTAT v10.2 (Richmond, CA). Allodynia data are presented as mean ($\pm\text{SEM}$), with significance at $p < 0.05$.

Thresholds to initiate and sustain allodynia were determined using injury load as a continuous variable. Applied load for shams was defined as 0 mN. Ipsilateral and contralateral allodynia on days 1 and 7 and over the entire post-operative period (total allodynia) were specifically analyzed with respect to load. For each behavioral data set, a Bayesian three-segment change point model was fit to the load–allodynia relationship (Muggeo, 2003) because of its utility to fit the apparent segmented response of allodynia and load, with flat responses for the low-load and higher-load ranges. Such a model enables the identification of the change points between the segments, providing load thresholds for allodynia. The three segments included minimum and maximum allodynia responses, and a linear segment between the extremes. The first change point corresponded to the load above which allodynia was elevated over sham, representing a threshold to produce allodynia. The second change point indicated the load above which allodynia reached a maximum. Additional details of this model are in supplementary Appendix A (Bacon and Watts, 1971; Cowles and Carlin, 1996; Gelfand and Smith, 1990).

Bilateral spinal SP and CGRP immunoreactivity were also analyzed with respect to load. This approach tested if the relationship between neuropeptide expression and load also followed the three-segment model. Further, if that model did fit the neuropeptide data, change points were determined for altered neuropeptide expression at day 7. Compressive load was compared to the average percent immunoreactivity for each neuropeptide in the ipsilateral and contralateral dorsal horns, separately. Thresholds are reported as a mean followed by the 95% credible interval in parentheses, with significance determined by the exclusion of 0 from the credible interval.

3. Results

3.1. Mechanical allodynia

Average loads for the compression groups [10.89 mN (± 6.49), 37.18 mN (± 7.28), 66.71 mN (± 7.45), 98.10 mN (± 6.96)] were significantly different from each other ($p < 0.0001$, Table 1). Qualitative trends in allodynia between groups were similar for testing with all filaments. Responses elicited by the 39.2 mN filament were the most robust and are presented in detail here. Compression by 10.89 or 37.18 mN did not produce ipsilateral allodynia significantly greater than sham; sham surgeries did not produce allodynia different from baseline on any day (Fig. 2(A)). Following a 66.71 mN load, ipsilateral allodynia was significantly elevated over sham on day 1 ($p < 0.023$) and did not decrease between days 3 and 7. Compression with 98.10 mN produced ipsilateral allodynia

that was significantly increased over sham on days 1, 3, and 5 ($p < 0.02$) and was not significantly different than that following a 66.71 mN load on any day (Fig. 2(A)). Ipsilateral mechanical allodynia produced by 66.71 and 98.10 mN loads was significantly greater than that for the 10.89 mN load group on days 1 and 5 ($p < 0.03$).

Contralateral mechanical allodynia was significantly elevated over sham only for 98.10 mN compression, on days 5 and 7 ($p < 0.03$; Fig. 2(B)). Contralateral allodynia for a 98.10 mN load was also significantly greater than that for 37.18 and 10.89 mN compressions on days 5 ($p < 0.05$) and 7 ($p < 0.005$), respectively. Sham procedures did not produce any contralateral allodynia.

While bilateral allodynia was graded according to load group (Fig. 2), a three-segment change point model quantified the relationship between allodynia and load (Table 2). Ipsilateral allodynia at day 1 demonstrated a robust increase between the first and third segments

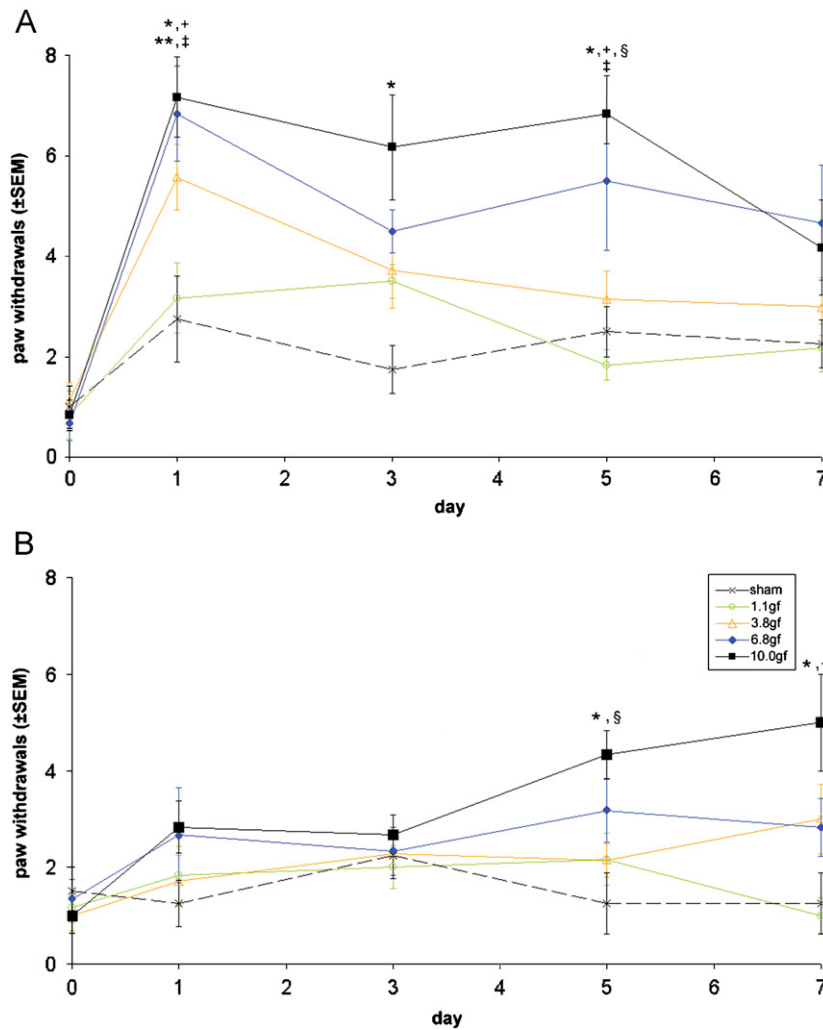


Fig. 2. Ipsilateral (A) and contralateral (B) mechanical allodynia assessed with a 39.2 mN von Frey filament, reported as frequency of paw withdrawals. Data are grouped into four average load groups according to steady state compression load. Similar trends were observed with the other filaments. A significant increase relative to sham is indicated by (*) for the 98.10 mN group and (**) for the 66.71 mN group. A significant increase relative to the 10.89 mN group is indicated by (+) for the 98.10 mN group and (†) for the 66.71 mN group. The 98.10 mN group significantly elevated above the 37.18 mN group is indicated by (§).

(Fig. 3(A)). Ipsilateral allodynia was produced above a load of 26.29 mN (1.57, 65.43) at day 1 (Table 2, Fig. 3(A)). The second change point was identified at 48.95 mN (22.66, 92.12), indicating the load above which allodynia was maximum. The corresponding increase in allodynia between the first and third segments [3.73 paw withdrawals, (2.01, 5.39)] was statistically significant (Table 2). Similarly, for ipsilateral paw withdrawals on day 7 and for total allodynia (Figs. 3(B) and (C)), the corresponding first and

second change point loads were 38.16 mN (2.75, 92.70) and 54.35 mN (6.57, 104.38) for day 7, and 22.86 mN (1.18, 65.04) and 76.32 mN (47.48, 106.14) for total allodynia (Table 2). While the increase in ipsilateral allodynia between the two change points was not significant at day 7, the increase in total allodynia was significant. Contralateral allodynia at day 1 did not vary with load (Table 2, Fig. 3(D)); however, both day 7 and total allodynia were well fit (i.e. a significant increase in

Table 2
Change point model parameters

Outcome measure		First change point (mN)	Second change point (mN)	Change in outcome measure (paw withdrawals, % positive pixels)
Allodynia	Ipsilateral—day 1	26.29	48.95	3.73*
	Ipsilateral—day 7	38.16	54.36	1.73
	Ipsilateral—total	22.86	76.32	13.60*
	Contralateral—day 1	48.36	57.98	0.96
	Contralateral—day 7	38.26	66.02	2.94*
	Contralateral—total	52.09	76.81	6.85*
Spinal neuropeptide reactivity	SP—ipsilateral	36.00	46.11	−2.32
	SP—contralateral	41.01	50.03	−1.53
	CGRP—ipsilateral	19.52	28.35	−3.04*
	CGRP—contralateral	24.03	34.53	−3.37*

SP = substance P; CGRP = calcitonin gene-related peptide.

*Significant change in outcome measure between first and second change points.

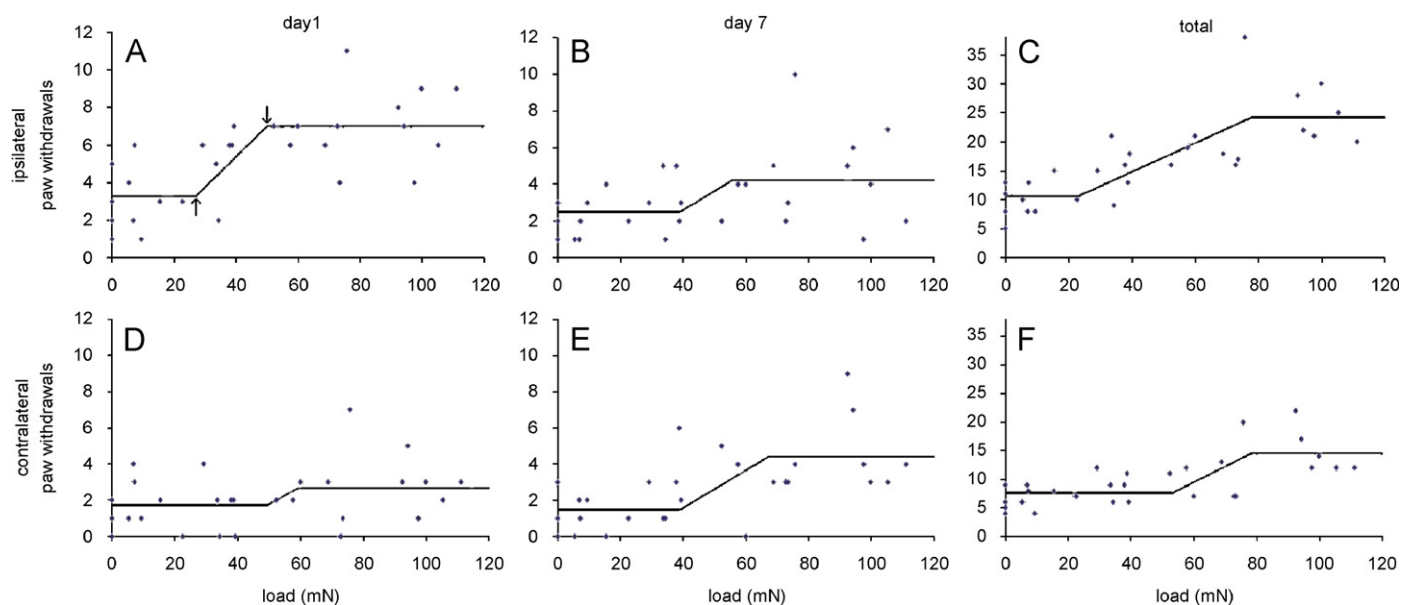


Fig. 3. Mechanical allodynia on days 1 (A, D) and 7 (B, E) after compression, and total allodynia (C, F) as a function of applied nerve root load magnitude. Ipsilateral (A–C) and contralateral (D–F) mechanical allodynia are shown for stimulation with a 39.2 mN von Frey filament. Superimposed on each plot is the corresponding three-segment change point model with the segments having no difference from sham, a linear increase in allodynia with load, and the maximum allodynia responses. The first and second change points are indicated by arrows in panel (A).

allodynia between change points) by the three-segment model and significantly increased with load (Table 2, Figs. 3(E) and (F)). At day 7, contralateral allodynia greater than sham (0 mN) was produced above 38.26 mN (2.55, 85.45) and plateaued for loads over 66.02 mN (26.78, 103.30, Fig. 3(E)). The analogous thresholds for total allodynia were slightly higher than those for day 7: 52.09 mN (5.89, 73.97) and 76.81 mN (49.64, 102.12, Table 2, Fig. 3(F)).

3.2. Spinal neuropeptides

Bilateral dorsal horn SP and CGRP immunostaining generally decreased with increases in applied root load (Fig. 4). Sham surgeries did not alter either neuropeptide relative to uninjured, naïve rats. Also, immunostaining in the deeper laminae was unchanged for all procedures. While the three-segment model did capture the minor decrease in SP immunoreactivity with load, this decrease was neither robust nor significant (Table 2, Figs. 4(A)–(C)). However, bilateral changes in CGRP immunoreactivity did depend significantly on load, with a response to low loads similar to sham, followed by a linear decrease as load increased, reaching a lower plateau. The change points for ipsilateral and contralateral decreases in CGRP immunoreactivity were 19.52 mN (2.16, 46.21) and 24.03 mN (3.14, 46.40), respectively (Table 2).

4. Discussion

This is the first study to quantify the effect of transient nerve root compression magnitude on modulating behavioral outcomes, or to establish load thresholds for persistent mechanical allodynia and sustained changes in spinal neuropeptides. In general, loads to initiate ipsilateral allodynia (i.e. day 1) were less than those to produce maintained allodynia (i.e. day 7, total allodynia, Table 2,

Figs. 3(A)–(C)). Differences in these thresholds for acute and maintained allodynia indicate that some loads may be sufficient only to transiently affect sensitivity while greater loads may initiate mechanisms that lead to persistent hypersensitivity. The dependence of allodynia on load at day 7 was not significant primarily due to the relative variability in responses observed at that time point. Considering results from the entire testing period, a significant increase in total allodynia was determined using the model (Table 2). From both the day 7 and total allodynia relationships to load, nerve root compression as low as 22.86 mN can lead to persistent allodynia. Above 76.32 mN, allodynia is not further modulated by applied load (Table 2, Figs. 3(A)–(C)), corroborating previous work showing no difference in allodynia for 10 gf (98.10 mN) or 60 gf (588.60 mN) compression loads (Hubbard and Winkelstein, 2005). Contralateral allodynia exhibited a late onset, consistent with previous studies (Tabo et al., 1999; Hunt et al., 2001; Rutkowski et al., 2002; Araujo et al., 2003; Hubbard and Winkelstein, 2005). The load threshold for contralateral allodynia at day 7 (38.26 mN) matched that to produce ipsilateral allodynia (38.16 mN, Table 2). The load of 38.26 mN required to produce bilateral allodynia at day 7 after compression implies that persistent pain may not be maintained for loading below this threshold. Further, the manifestation of contralateral allodynia at day 7 suggests that a central, spinal mechanism may contribute to the maintenance of pain.

The three-segment model is supported for use with the current application based on both experimental and statistical evidence (Spiegelhalter et al., 2002). A previous study applying compression loads above 100 mN suggested that a non-linear relationship may exist between nerve root load and resulting allodynia (Hubbard and Winkelstein, 2005). This implied that a critical load for establishing allodynia may exist, beyond which behavioral sensitivity is

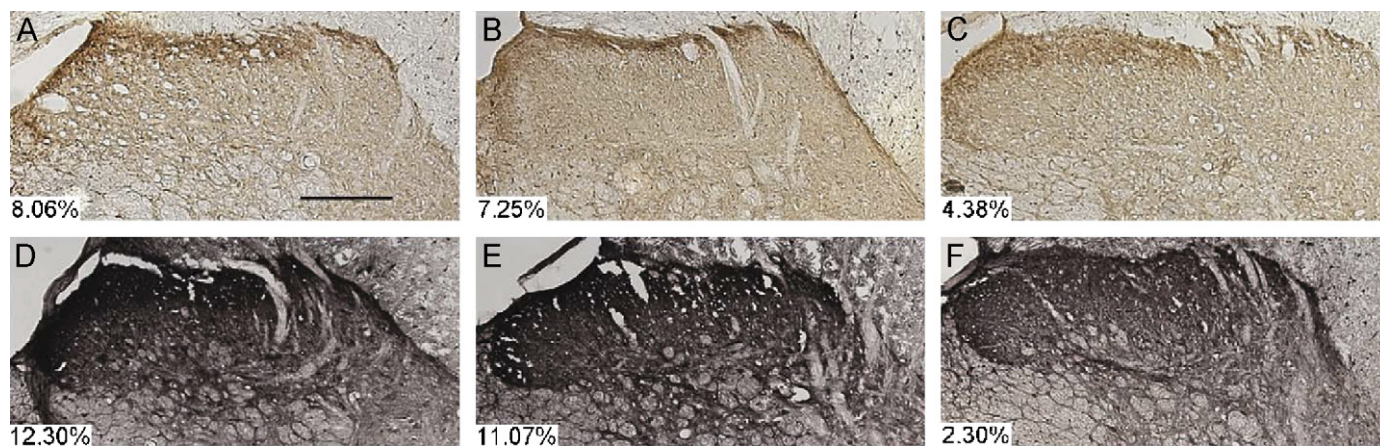


Fig. 4. Representative images for the ipsilateral spinal cord dorsal horns (laminae I–IV) labeled for substance P (A–C) or calcitonin gene-related peptide (D–F) immunoreactivity at day 7 after nerve root compression: sham (A, D), 10.89 mN (B, E), and 98.10 mN (C, F). Positive immunolabeling assessed by densitometry was confined primarily to laminae I and II. Individual densitometry measures for these images are indicated in each panel. A slight decrease in substance P staining after compression with a high load is apparent (C), and a more robust decrease is evident for CGRP immunoreactivity (F). Contralateral immunostaining followed similar trends for all groups. Scale bar in (A) = 200 μ m.

not modulated by load. Using a statistical measure for model appropriateness (deviance information criterion), it was found that for all cases relating allodynia to load, a linear regression model was not superior to the change point model. Moreover, the change points defined by this model identify potential load thresholds at which compression of the nerve root can produce and maximize mechanical allodynia (Table 2). It must be noted that for cases in which loads are applied only within the linear region between the change points, a linear regression would be a simpler, and possibly more appropriate, model.

Spinal SP and CGRP demonstrated differences at day 7 following transient nerve root compression. The thresholds for decreased ipsilateral CGRP immunoreactivity were lesser than those for contralateral changes at day 7 (Table 2). Additionally, bilateral CGRP thresholds were below those thresholds for producing allodynia on day 7 (Table 2), suggesting that additional spinal responses likely contribute to pain maintenance. Spinal SP did not significantly depend on load but did correspond closely with thresholds for allodynia at day 7 (Table 2), and may indicate different mechanistic roles for SP and CGRP in pain. Nonetheless, the dependence of CGRP immunoreactivity on load strongly implicates a decrease in this neuropeptide in the superficial laminae as contributing, at least partially, to sustained allodynia.

Previous investigations of spinal SP or CGRP provide conflicting evidence for their involvement in the onset and maintenance of pain. Although our findings corroborate reports of decreases in SP or CGRP in the superficial laminae following neural injury (Munglani et al., 1996; Malmberg and Basbaum, 1998; Swamydas et al., 2004; Kobayashi et al., 2005a, b), increased CGRP has also been implicated in mediating elevated behavioral sensitivity (Oku et al., 1987; Cridland and Henry, 1989; Christensen and Hulsebosch, 1997; Bennett et al., 2000). Decreases in spinal neuropeptides may result from increased peptide utilization in the spinal cord, increased receptor internalization, decreased synthesis in the DRG, or breakdown of anterograde axonal transport at the injury site (Kobayashi et al., 2005a, b; Allen et al., 1999; Cahill and Coderre, 2002). In our study, damage to unmyelinated afferents may have reduced axonal transport in the dorsal root, leading to a depletion of CGRP in the superficial laminae. Alternatively, axonal damage may have affected production of SP and CGRP in the DRG as a result of neuronal dysfunction or diminished neurotrophic transport (Kirita et al., 2007). With previous studies suggesting neuropeptide expression in the dorsal horn is unchanged or increased as early as 1 day after nerve root compression (Kobayashi et al., 2005a; Rothman et al., 2005), the depletion of CGRP in the superficial laminae at day 7 may reflect a spinal accommodation following an initial increase in spinal CGRP. Assessment of temporal expression of neuropeptides in the dorsal horns is necessary to define their roles following painful injury. Axonal damage assessment in the compressed nerve root and local

neuropeptide and neurotrophin localization following transient compression are also needed to understand the mechanistic relationship between these injury pathways. Lastly, studies are needed to quantify early expression of these and other regulatory proteins in the spinal cord and DRG in order to elucidate the specific mechanisms dependent on load for painful nerve root injury.

The compression device used in this study applied displacements that produced loads across the range of 0–110 mN via quasistatic motor-controlled displacement. These measured loads were smaller and more repeatable than those imposed by prefabricated clips or forceps used previously in lumbar radiculopathy models (Kobayashi et al., 1993; Kobayashi and Yoshizawa, 2002; Sekiguchi et al., 2003). Two-second forceps compression in a rat model produced ipsilateral allodynia for at least 1 week, but without contralateral allodynia (Sekiguchi et al., 2003). The lack of contralateral hypersensitivity in that model emphasizes the role of mechanics in producing varied behavioral outcomes. In models of chronic nerve root ligation, a linear relationship between allodynia and tissue strain was suggested, providing a strain-threshold for persistent allodynia (Winkelstein et al., 2001b, 2002; Winkelstein and DeLeo, 2002, 2004). However, those studies assumed that the ligation applied constant strain over the post-operative period. The present study utilized platen displacement to apply desired compression loads; tissue strains were not calculated here. However, the strain threshold for persistent mechanical allodynia following chronic lumbar root ligation (Winkelstein and DeLeo, 2004) was determined to be much lower (22.2% tissue compression) than the tissue deformations through the diameter of the root estimated in the present model (~90%), suggesting that the load threshold for painful transient root compression is higher than that for chronic compression. Moreover, allodynia at day 7 after transient compression indicates that behavioral hypersensitivity persists even after the removal of the painful stimulus. Maintained allodynia has also been demonstrated previously in a model of transient compression, with behavioral hypersensitivity lasting at least 2 weeks after injury (Rothman et al., 2007).

In summary, this injury model enables examination of the *in vivo* mechanics for painful nerve root compression and defines predictive load thresholds governing behavioral hypersensitivity and sustained cellular responses. Further, this model offers potential utility for identifying specific thresholds to activate other pathways responding to persistent pain (e.g. macrophage recruitment, cytokine release, neurotrophin release), both locally and in the central nervous system. Results for ipsilateral mechanical allodynia support a higher threshold for maintenance of pain compared to its onset (Table 2, Figs. 3(A)–(C)). The similarity in thresholds for ipsilateral and contralateral allodynia at day 7 further supports central mechanisms as contributing to persistent pain. This was substantiated by bilateral decreases in spinal CGRP at day 7 for loads above

24.03 mN. By defining pain symptoms and spinal neuro-peptide expression in the context of injury mechanics, these findings define potential factors contributing to cervical radiculopathy and supply evidence for a direct role of mechanics in modulating painful outcomes for transient cervical nerve root compression.

Conflict of interest

There are no conflicts of interest for any authors with any aspect of this study.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.jbiomech.2007.09.026](https://doi.org/10.1016/j.jbiomech.2007.09.026).

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