Morphometric effects of acute shortening of the spine: the kinking and the sliding of the cord, response of the spinal nerves

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Abstract Spinal shortening is performed for a wide spectrum of diseases. This study was designed to investigate the morphologic effects of shortening on the spinal cord, to enlighten the amount and direction of the sliding of the cord, the alteration of the angles of the roots, and to identify the appropriate laminectomy length. Total vertebrectomy of T12 was applied to ten sheep models after spinal instrumentation. Gradual shortening was applied to five sheep; then, the degree and direction of the sliding of the spinal cord and the angles of the adjacent roots were measured. On five other sheep, additional sagittal sectioning was performed via excision of the pedicles. Measurements were taken at different laminectomy lengths to record kinking of the spinal cord with gradual shortening. The mean sliding of the spinal cord was 9 mm cranially and 7.8 mm caudally. T11 spinal nerves became more vertical caudally, and T12 spinal nerves achieved an ascending position with gradual shortening. Both T11 and T12 spinal nerves were sharply bent in the foramen and on the pedicle of T13, respectively. In full-length shortening, the mean kink of the spine in the sagittal plane was 92.4° for two levels of hemi-laminectomies, 24.6° for complete laminectomy of T11 with hemilaminectomy of T13, and 20.2° for two levels of complete laminecto-

mies. The slippage of the cord is dominant in the earlier stages and kinking is dominant in later stages of shortening. Increasing the laminectomy length by only a half or one level prevents excessive kinking and compressions at the upper and lower margins of the laminectomy. In the later stages of shortening, the spinal nerves near the vertebrectomy site are at risk because of the sharp bending of the nerves. This study describes the mechanism of the sliding and kinking of the cord due to gradual shortening of the spine, which might be useful in spinal surgery procedures. It also states that it is possible to avoid excessive kinking by planning the appropriate technique of laminectomy style in full-length shortening.

Keywords Spinal shortening · Kinking · Sliding · Spinal cord · Spinal nerves

Introduction

Spinal column shortening may be indicated in congenital spinal deformities [8, 10, 12–15], primary [4, 5] or secondary malignant tumors [3, 9], benign aggressive tumors [16], kyphotic deformities [15], fixed sagittal imbalance [1], and flatback deformity [6, 11] of the spine.

In a recent research, Kawahara et al. [7] reported the morphometric and physiological effects of acute spinal column shortening on the spinal cord. Their study describes the spinal kinking in gradual shortening of the spine. They stated that shortening of more than two-thirds of a single vertebral segment is characterized by kinking of the spinal cord and neurological dysfunction. They stated that shortening greater than

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two-thirds of the vertebrectomy length was the “dangerous range”. They attributed neurological dysfunction, in terms of morphologic deformation of the cord, decreased spinal cord blood flow, and obstruction of the anterior spinal artery, to excessive kinking. However, they used models with limited laminectomy and did not consider that the length of the laminectomy would affect the degree of kinking. Also, to our knowledge, there is no previous study that describes the mechanism of sliding and kinking of the cord in gradual spinal shortening.

Our study was designed on sheep models to investigate and to specify the morphologic effects of spinal column shortening on the cord, to enlighten the amount and direction of the sliding of the cord, the nature of kinking, and the alteration of the angles of the roots, and the effects of the laminectomy length on the degree of kinking.

Materials and methods

Spinal column models of ten female fresh Merino sheep cadavers including the cervical region and pelvis were prepared and used in this study. The age of the sheep was between 8 and 11 months. The proximal edge of the spinal cord was glued to the bone at the upper cervical region to prevent uncontrolled caudal sliding of the cord. Anterior spinal instrumentation was performed from the left side with screws passing through T10 and L1 levels with a single rod that was bent to fit the normal kyphosis. The height of T12 was measured, including the adjacent discs. The 12th rib was extracted from both sides, without causing any spinal nerve injury. Total laminectomy of T12 and upper half hemilaminectomy of T13 and lower hemilaminectomy of T11 were performed. The dura was sacrificed at the level of laminectomy in all models in order to observe and measure accurate sliding and kinking of the cord and the origin of the roots and their angles. The arachnoidea was spared in all models. The pathways of the spinal nerves of T11 and T12 were dissected without stripping them from the soft tissue. The initial outlet angles of the T11–T12 spinal nerves with horizontal plane were measured by goniometry. Then, vertebrectomy to the T12 level and excision of the adjacent discs were performed with great caution, without disturbing the integrity of any of the spinal nerves.

The initial position was assigned as stage 1, 25% shortening of the gap as stage 2, 50% shortening as stage 3, 75% shortening as stage 4 and 100% shortening (full-length shortening) as stage 5.

On the first five sheep, the upper and lower end-points of the T11 and T13 hemi-laminectomies and the same levels of the cord were marked by a marker in order to measure the slippage (Fig. 1). Then, gradual shortening was performed by shortening of the space by 25, 50, 75, and 100% of its length. At each stage, the direction and amount of slippage were measured with a caliper compass with 0.1 mm accuracy and then the angles of the T11–T12 spinal nerves in the horizontal plane were measured at their outlet from the spinal cord with 1° accuracy. Also, the bending of the spinal nerves was measured at foramen for T11 roots and on the pedicles of the T13 for T12 roots. The measurements were applied by measuring the angle between the proximal part of the nerve and distal part of the nerve due to foramen (for T11 roots) or pedicle (for T12 roots) with 1° accuracy. Each measurement was performed accurately by the four authors simultaneously. Measurements were executed considering the native kyphosis and acquired kinking.

On the other five sheep, after anterior spinal instrumentation with a single rod from the left side, two levels of hemi-laminectomies and total T12 vertebral resection were performed. Transverse processes and the pedicles of the right side of T11 and T13 were excised to maintain a direct sagittal view. The degree of kinking of the spinal cord was determined by measuring the angle between the proximal and distal segments of the cord at the vertebrectomy level for each shortening stage for the following laminectomy styles: (1) T11–T13 hemilaminectomy (one laminectomy length), (2) T11 complete laminectomy with T13 hemilaminectomy (one-and-a-half laminectomy length), and (3) T11–T13 complete laminectomy (two laminectomy length) (Fig. 2).

Statistical analysis was applied by using the SPSS 11.5 package program. Descriptive statistics were shown as mean values $\pm$ standard deviations. Repeated measures of variance analysis were used in comparisons of repeated measurements within a group. When there was significant difference, Bonferroni multiple comparison test was used to identify the measurements, which had caused the difference. $p < 0.05$ was accepted value for significance. The differences between caudal sliding and cranial sliding and the difference between right-side roots and left-side roots were tested by paired *t* test with Bonferroni correction.

Results

The mean spinal column shortening distance was 25.4 ± 3.05 mm by T12 vertebrectomy including two adjacent discs.

Fig. 1 Note the slippage of the cord by gradual shortening. The distances of the markers to the upper and lower laminectomy margins are measured to understand the amount of the slippage at each shortening stage. The positions of the origins of the spinal nerves are altered by the slippage of the cord. The angles of the T11 and the T12 roots were altered due to shortening. **a** Stage 1 (original position), the angle of root with the horizontal plane was shown. **b** Stage 2 (25% shortening), the sliding of the cord is caudal. **c** Stage 3 (50% shortening) caudal sliding is still

dominant. T12 roots are stretched on the pedicle of the lower vertebra. **d** Stage 4 (75% shortening), the stretched T12 roots decelerate the caudal sliding and cranial sliding becomes dominant. Both T11 and T12 spinal nerves are extremely stretched because of the bending on their pathways; T11 nerves in their foramen and T12 nerves on the pedicles of the T13 vertebra (showed with arrows). **e** Stage 5 (full-length shortening), accelerated kinking is dominant in this stage with decelerated sliding toward both direction

Sliding of the spinal cord

There was sliding of the cord both cranially and caudally (Table 1). The sliding was greater to the caudal direction than the cranial direction in stages 2 and 3. This was statistically significant in stage 2 ($p < 0.001$). In stages 4 and 5, the total sliding was higher cranially (9 ± 0.42 mm) than caudally (7.8 ± 0.33 mm), but the differences were not significant ($p > 0.0125$).

The mean of 8.6 ± 1.92 mm of shortening of the cord was tolerated within the two levels of hemi-laminectomies levels by either bending or kinking in stage 5.

Position and the path of the T11 and T12 spinal nerves

By gradual shortening of the cord, the sliding of the cord had altered the origin of the spinal nerves and their angle of outlet from the cord. The outlet angles of the spinal nerves with horizontal plane were noted in Table 2. T11 (the upper adjacent level to total vertebrectomy) spinal nerves became more vertical, with gradual shortening reaching $67.6 \pm 2.41^\circ$ on the right

and $68.4 \pm 1.40^\circ$ on the left at full-length shortening. At both the right and left side, the difference of the outlet angles of T11 nerves was significant through the stages ($p = 0.018$ for the right, $p = 0.017$ for the left). The difference was significant in all pairwise comparisons. There was no significant difference between the right and left side with the Bonferroni correction ($p > 0.01$). They had a sharp bend at the level of the foramen reaching $62.2 \pm 1.92^\circ$ on the right and $59.6 \pm 2.07^\circ$ on the left at stage 5 (Fig. 1, Table 3). At both the right and the left side, the difference of the bending angles of T11 nerves was significant (at the level of foramen) through the stages with $p = 0.025$ and 0.017 , respectively.

The origin of the T12 (the level of total vertebrectomy) spinal nerves displaced caudally, which had an ascending position (shown by negative values in Table 2), reached $-48.2 \pm 2.17^\circ$ on the right and $-48.6 \pm 1.14^\circ$ on the left in stage 5 (Fig. 1e). At the left side, the difference of the outlet angles of T12 nerves was significant through the stages ($p = 0.025$), where at the right side there was no significance, $p = 0.07$). They had a sharp bend over the pedicles of T13, reaching

Fig. 2 The kinking of the cord at full-length shortening for different laminectomy styles in the sagittal plane. The angle between the proximal and the distal parts of the angulation was measured. **a** T11 and T13 hemilaminectomy (one laminectomy length), the angle of the kinking was shown in the figure. Arrows indicate the compression of the cord at the upper and lower laminectomy level. **b** Complete T11 laminectomy and T13 hemilaminectomy (one-and-a-half laminectomy length). **c** Complete T11 and T13 laminectomy (two laminectomy length)

42.6 ± 1.52 on the right and 44 ± 3.16 on the left at full-length shortening (Table 3). At both the right and the left side, the difference of the bending angles of T12

Table 1 The sliding direction and amounts for the shortening stages

Shortening stages	Cranial direction		Caudal direction	
	Mean (mm)	SD	Mean (mm)	SD
1	0		0	
2	3.3	0.26	4.4	0.26
3	6	0.43	6.7	0.45
4	8.3	0.50	7.4	0.23
5	9	0.42	7.8	0.33

nerves (at the level of the pedicle of T13) was significant through the stages with $p < 0.001$ and $p = 0.003$, respectively.

The T12 spinal nerves also translated posteriorly with increased kinking, and they contacted the posterior wall of the facsett and were compressed in this region.

Kinking of the cord

The kinking response of the cord from three different laminectomy styles is shown in Table 4. The models with two hemi-laminectomies had a greater amount of kinking, reaching $23.2 \pm 2.49^\circ$ at stage 4 and $92.4 \pm 2.70^\circ$ at stage 5. At the upper and lower edges of the laminectomy, there was obvious compression to the cord at this stage (Fig. 2a). In the first three stages, kinking was negligible as the shortening was tolerated mostly by sliding, whereas in the last two stages the sliding decreased and the kinking greatly increased. The kinking of the cord was altered significantly by adding either half or complete laminectomies within stages 3, 4, and 5 with p values of <0.01 , <0.001 , and <0.001 , respectively.

When a half more laminectomy was added (T11 complete laminectomy and T13 half laminectomy), the kinking markedly decreased to $10 \pm 2.45^\circ$ at stage 4 ($p < 0.01$) and $24.6 \pm 1.82^\circ$ at stage 5 ($p < 0.001$) (Fig. 2b). There was no compression to the cord at the edges of the laminectomy in this style of laminectomy. Two levels of complete laminectomies (T11–T13 complete laminectomy) showed results of 5.4 ± 1.14 kinking at stage 4 ($p < 0.05$) and $20.2 \pm 2.39^\circ$ at stage 5 ($p = 0.001$) (Fig. 2c). Thus, in stages 4 and 5 the differences were all significant among all three types of laminectomies.

Discussion

Our experiment was applied to young female sheep between 8 and 11 months old. As there are close similarities to the human spine, the sheep spine has been found to be a reliable model for experiments related to structure and biomechanics of the thoracic and the lumbar spine in many aspects [17, 18]. There are 14 dorsal and 7 lumbar vertebrae in Merino sheep. The spinal cord terminates at the level of L7 in Merino sheep, whereas in humans it terminates near the L1/L2 level. The natural kyphosis of the sheep thoracic spine is continuous through the lumbar region. We used T12 level in our shortening experiments, which matches with T8–T9 level in humans. The age of the sheep can

Table 2 The angles of the spinal nerves with the horizontal plane for different shortening stages

Shortening stages	T11 right		T11 left		T12 right		T12 left	
	Mean (°)	SD	Mean (°)	SD	Mean (°)	SD	Mean (°)	SD
1	24.6	1.14	23.4	1.14	17	2.55	17	1.58
2	14.4	0.89	12.2	1.48	−4	2.55	−6.2	3.19
3	44.8	1.48	45	1	−37.4	3.44	−37.4	3.36
4	56.8	1.79	56.6	1.82	−46	2.74	−46.4	3.85
5	67.6	2.41	68.4	1.14	−48.2	2.17	−48.6	1.14

Table 3 The angulation of the spinal nerves; at their foramen for T11 spinal nerves and on the pedicles of the lower vertebra for T12 spinal nerves

Shortening stages	T11 right		T11 left		T12 right		T12 left	
	Mean (°)	SD	Mean (°)	SD	Mean (°)	SD	Mean (°)	SD
1	6.2	0.84	6.2	0.84	0	0	0	0
2	12.8	1.30	13	1.87	0	0	0	0
3	25.6	1.52	25.6	1.95	1	1.41	1.4	1.95
4	42	2.55	42	1.73	31.2	1.64	30.6	2.07
5	62.2	1.92	59.6	2.07	42.6	1.52	44	3.16

Table 4 The degrees of kinking of the cord due to laminectomy lengths

Shortening stages	T11 and T13 hemilaminectomy		T11 complete and T13 hemilaminectomy		T11 and T13 complete laminectomy	
	Mean (°)	SD	Mean (°)	SD	Mean (°)	SD
1	0		0		0	
2	0		0		0	
3	10.6	2.41	0.4	0.89	0	
4	23.2	2.49	10	2.45	5.4	1.14
5	92.4	2.70	24.6	1.82	20.2	2.39

be matched with the adolescent period in humans, while interpreting the elasticity of the neural structures and the soft tissue.

The procedures that shorten the spine have attracted great interest in the past decade. Techniques applying a lesser amount of shortening, like pedicle subtraction osteotomy or Smith–Peterson osteotomy, have been considered safer [7]. These techniques are preferable, especially for the correction of deformities, as they avoid excessive shortening of the spinal column with enhanced stability by bone-to-bone contact [1, 6, 11]. However, for primary or secondary malignant tumors, only total vertebrectomy has the chance of being curative [3–5, 9].

The optimal amount of shortening is yet to be defined. The greatest single effort has been made by Kawahara et al. [7] who carried out a morphometric and physiological study to investigate this problem. They proved the adverse effects of kinking of the spinal cord and mostly attributed the functional deficits to excessive kinking of the spine in the following as-

pects: the morphological disturbance of the cord, the decreased spinal cord blood flow, and the obstruction of the anterior spinal artery. The majority of their cases with full-length shortening resulted in paraplegia. They finally defined shortening greater than two-thirds of the vertebral segment as the “dangerous range”. They also showed occlusion of the anterior spinal artery, which is placed ventrally and dorsally at the mouth of the kinking in the full-length shortening position.

It is rational that excessive morphological deformation of the cord would affect the blood flow adversely. Excessive kinking would result in stretching on the dorsal veins and crinkling at the ventral veins of the cord. Thus, less kinking of the cord would result in relaxation of the veins of the cord and the blood flow supply of the cord would benefit from the realignment of the cord.

However, Kawahara et al. used models with limited laminectomy (hemi-laminectomies of upper and lower adjacent vertebra) and did not consider that the length of the laminectomy would affect the degree of kinking.

Both in their study and in our models of full-length shortening combined with two levels of hemi-laminectomied models, there were compressions of the spinal cord at the upper and lower boundaries of the laminectomy levels, in addition to a mean kinking of $92.4 \pm 2.7^\circ$. As the effects of compression on the spinal cord are well defined, these compressions probably play a critical role in neurological injury (Fig. 2a) [2]. However, in our study, by adding another half level of laminectomy, both the upper and lower compressions subsided and the mean kinking decreased to just $24.6^\circ \pm 1.82$. Furthermore, at stage 4 the kinking decreased to only $10 \pm 2.45^\circ$ and $5.4 \pm 1.14^\circ$ with one-and-half length laminectomy and two complete laminectomies, respectively. This acute decrease in the kinking suggests that a one-and-a-half laminectomy length or two complete laminectomies might be useful in avoiding neurological injury in many cases, even with complete shortening of the vertebral segment. This laminectomy length avoids excessive kinking of the cord and compressions at the laminectomy margins at all stages of shortening, thus giving increased stability of the spine by permitting bone-to-bone contact of the adjacent vertebral bodies. Despite the very promising results of this morphometric experiment, the functional outcomes need to be studied in living animals to confirm the parallelism of the reduced morphologic deformation with improved neurological outcome. Such a study with different levels of laminectomy will also help in understanding the level of the deformation that can be tolerated by the spinal cord.

To our knowledge, there is no previous study in the literature that analyzes the morphology and the post-operative functions of the spinal nerves. In our study, the sliding of the spinal cord definitely altered the positions of the origin of the spinal nerves, thus changing their outlet angles while exiting from the cord. The origin of T11 roots (the roots of the upper adjacent vertebra) slid cranially and the root became more vertical in the caudal direction. Likewise, T12 roots (the origins of the roots of the total vertebrectomy) level slid caudally into an ascending position. These facts caused sharp bending at the foramen for T11 roots and over the pedicle of the lower adjacent vertebra for T12 roots. These sharp bendings and stretching may deteriorate the functions of the roots. The nerve roots of the upper adjacent level would benefit from additional facett bone resection to realign their pathways and to be released.

There are no previous studies of sliding of the cord and its direction. In the first three stages, kinking was negligible as the shortening was tolerated mostly by sliding of the cord, while in the last two stages the

slippage was substituted by increased kinking. The sliding of the cord tended to be caudally at stages 2 and 3 (Fig. 1b, c). However, at stage 4 the sliding had a tendency to be cranial (Fig. 1d). Finally, at stage 5, the sliding was considerably reduced, but the kinking was accelerated (Fig. 1e). We observed that the position and the direction of the spinal nerves determined this phenomenon and would like to describe the mechanism of sliding and kinking of the cord. The T11 roots (roots of the upper adjacent vertebra) were in close contact with the bone in its own foramen. On the other hand, T12 roots (the spinal nerves of the total vertebrectomy level) are free with no initial bone contact. In the earlier stages of shortening, T11 roots became stretched much earlier than the nerves at the level of the vertebrectomy, hence the cord slid caudally (Fig. 1b, c). At the later stages, T12 roots come in contact with the pedicle after sliding caudally and getting strained, as their former descending pathways were forced into an ascendant direction and began to resist the caudal slippage (Fig. 1d). As the T11 roots were in a relatively relaxed position, the cord slid cranially at stage 4 shortening. After this stage, as both T11 and T12 roots became excessively strained, the sliding considerably decelerated, and shortening resulted with an accelerated kinking of the cord (Fig. 1e).

Conclusion

The kinking was negligible in the first three stages as the shortening was tolerated mostly by sliding, while in the last two stages the sliding decelerated and the kinking increased greatly. The amount of kinking is highly dependent on the length of the laminectomy. This is a promising study that results with an expectation of protection of neurological function, as it demonstrates that excessive structural deformation of the cord can be competently addressed by additional removal of laminar bone. However, the physiological effects of this phenomenon will remain unknown until a new study investigates the different levels of laminectomies that can be done on living animals with acute spinal shortening.

Two levels of hemi-laminectomies seem sufficient to prevent excessive kinking in the shortening about three-fifth shortening of the segment level. One-and-a-half length of laminectomy and two-level lengths of laminectomy avoid excessive kinking at stages 4 and 5, respectively.

The sliding of the cord in the cranial and caudal directions due to the shortening of the column alters the position of the origins of the spinal nerves. Spinal

nerves of the upper adjacent level of the vertebrectomy are bent and stretched in their own foramen, while the spinal nerves of the vertebrectomy level are bent and stretched on the pedicle of the lower adjacent vertebra in the later stages of shortening. The functions of these nerves are at risk because of these sharp curvatures and straining of the nerves, even if they can be spared under surgery.

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