RESEARCH ARTICLE

Relationship between Spinal Cord Volume and Spinal Cord Injury due to Spinal Shortening

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Abstract

Vertebral column resection is associated with a risk of spinal cord injury. In the present study, using a goat model, we aimed to investigate the relationship between changes in spinal cord volume and spinal cord injury due to spinal shortening, and to quantify the spinal cord volume per 1-mm height in order to clarify a safe limit for shortening. Vertebral column resection was performed at T10 in 10 goats. The spinal cord was shortened until the somatosensory-evoked potential was decreased by 50% from the baseline amplitude or delayed by 10% relative to the baseline peak latency. A wake-up test was performed, and the goats were observed for two days postoperatively. Magnetic resonance imaging was used to measure the spinal cord volume, T10 height, disc height, osteotomy segment height, and spinal segment height pre- and postoperatively. Two of the 10 goats were excluded, and hence, only data from eight goats were analyzed. The somatosensory-evoked potential of these eight goats demonstrated meaningful changes. With regard to neurologic function, five and three goats were classified as Tarlov grades 5 and 4 at two days postoperatively. The mean shortening distance was 23.6 ± 1.51 mm, which correlated with the d-value (post-pre) of the spinal cord volume per 1-mm height of the osteotomy segment (r = 0.95, p < 0.001) and with the height of the T10 body (r = 0.79, p = 0.02). The mean d-value (post-pre) of the spinal cord volume per 1-mm height of the osteotomy segment was 142.87 ± 0.59 mm³ (range, 142.19–143.67 mm³). The limit for shortening was approximately 106% of the vertebral height. The mean volumes of the osteotomy and spinal segments did not significantly change after surgery (t = 0.310, p = 0.765 and t = 1.241, p = 0.255, respectively). Thus, our results indicate that the safe limit for shortening can be calculated using the change in spinal cord volume per 1-mm height.

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Introduction

The treatment of severe spinal deformities, namely scoliosis and kyphosis, is complicated by altered anatomy, severe rotation of the vertebrae, and limited flexibility of the spinal column [1, 2]. Vertebral column resection (VCR), which shortens the spinal column, is a generally accepted technique for correcting severe spinal deformities [3–5]. However, spinal cord injury (SCI) may occur in cases of excessive spinal shortening [6–8]. The relationship between the amount of shortening and SCI is important for reducing intra- and postoperative neurologic complications. Kawahara et al. [9] reported that the so-called “dangerous range of shortening” was greater than two-thirds of the vertebrectomy length in a dog model. In addition, Hitesh et al. [10] reported that shortening of ≥104.2% of the height of one vertebral body at the thoracolumbar level induced SCI, whereas shortening of ≤73.8% of the height of one vertebral body did not cause SCI in a pig model. However, the safe limits reported in these previous studies were based on the vertebral body height and not on the spinal cord itself, which may yield different findings in different animals. Moreover, to our knowledge, no previous study has examined the relationship between spinal cord volume (SCV) and SCI in gradual spinal shortening surgery. Hence, in the present study, we aimed to utilize a goat model to investigate the relationship between changes in SCV and SCI due to spinal shortening, and to quantify the SCV per 1-mm height in order to clarify the safe limit for shortening.

Materials and Methods

Animals

This study was carried out in strict accordance with the recommendations provided in the guide for the care and use of laboratory animals by the authority of the People’s Republic of China, and the study protocol was approved by the animal ethics committee at Guangzhou General Hospital of Guangzhou Military Command (permit number: 2014–0112). All goats were purchased from Sui Northern experimental animal farms and bred in the animal center of Guangzhou General Hospital of Guangzhou Military Command. Ten goats (age, 24–36 months) with an average body weight of 28 ± 2.21 kg (range, 25–32 kg) were used in this experiment. The study animals underwent fasting for 24 hours prior to anesthesia. General anesthesia was induced in each goat with an injection of 0.15 mL/kg of xylazine hydrochloride and 10 mL of 3% pentobarbital sodium before endotracheal intubation. Anesthesia was maintained by administration of 2–4 mL of 3% pentobarbital sodium, according to the condition of each animal [11]. All experiments were performed under the supervision of veterinarians, and all efforts were made to minimize suffering.

Surgical preparation and positioning

After induction of anesthesia, each goat received an intravenous drip of 5% glucose solution with 240,000 units of gentamicin in order to prevent infection. Each goat was monitored by using a rectal temperature probe and by recording arterial blood pressure. Body temperature was maintained between 36°C and 37°C by using a heating pad when necessary. Arterial blood pressure was maintained by increasing the amount of administered fluid when the pressure decreased. Subsequently, the animals were placed in a prone position on a radiolucent table, and the desired level of surgery (T8-12) was marked using a C-arm image intensifier (Fig 1).

Preparation for neuromonitoring

The somatosensory-evoked potential (SSEP), which is an electrical response signal in the scalp or spine evoked by stimulating the somatosensory afferent peripheral nerves, was measured by
a qualified electrophysiology technician using the Neuron-Spectrum System (Neurosoft, Russia), and the neuromonitoring data were read and analyzed by a neurophysiologist. A stimulating electrode was placed on the left posterior tibial nerve, and a recording electrode was placed at -0.5 cm and 0.2 cm from the intersection of the ear lines and median sagittal line. The placement of the recording electrodes corresponded to the left hindlimb sensory projection area of the cortex. A reference electrode was placed on the hard palate, and pulses of constant stimulation current (20 Hz, 0.2 ms duration) were subsequently delivered. The baseline SSEP amplitude of the first positive wave and baseline peak latency were measured before the experiment. A decrease in the SSEP of more than 50% from the baseline amplitude of the first positive wave or a delay of more than 10% relative to the baseline peak latency was considered an abnormal result [12].

Surgical procedure

A midline longitudinal incision extending from T7-12 was created, and the vertebral laminae were exposed from T8-12. A total laminectomy was performed from T9-11, and 4.5 x 22-mm single-axis pedicle screws were fixed into the vertebrae at T8, T9, T11, and T12. The SSEP was monitored during screw insertion. A rod of suitable length was fixed to the pedicle screws on the right side for temporary fixation. The T10 vertebral body and adjacent discs were resected completely using a curette and osteotome, while carefully avoiding any injury to the dura or spinal cord. After the osteotomy was completed, the rod on the right side was removed, and two rods of suitable length were assembled on each side (Fig 2A). At this time, the SSEP was recorded again, and compared with the baseline amplitude (Fig 3A). Any decrease in the SSEP amplitude during the osteotomy was considered to represent an accidental iatrogenic SCI, and these animals were not included in the analysis.

The spinal column was shortened simultaneously on both sides by using a click-type stopper at 1-mm intervals. After every 3 mm of closure, the procedure was ceased for 60 seconds and the SSEP was recorded. The lengths on the right and left sides were measured using a vernier caliper (Fig 2C), and the mean value of these two measurements was determined. The limit for
changes in SCV was defined as the point at which the SSEP was decreased by 50% from the baseline amplitude or delayed by 10% relative to the baseline peak latency (Fig 3B); spinal column shortening was ceased upon reaching this limit. The shortened distance was maintained for 5 minutes after the development of spinal injury. Thereafter, the final distance on each side was measured to determine if there was any recovery of the SSEP. If there was no recovery, the compression was released every 3 mm until recovery of SSEP was observed. Subsequently, the final distance on each side was measured. A wake-up test, which was used to assess the animal’s motor functions, was carried out by discontinuation of the anesthetic to exclude false-negative and false-positive SSEP results. During this test, the movement of the lower extremities and sensory response to mechanical stimulation of the goat were assessed. Subsequently, the goat was anesthetized again. At the final stage of the experiment, the osteotomy site was fixed with a bone graft, and the pedicle screws were tightened at the rods in this position (Fig 2B). Two days after surgery, a postoperative neurologic examination was conducted.

Postoperative neurologic examination

The spine was shortened by 21.4–25.6 mm in eight goats. Neurologic function was evaluated two days after surgery according to the Tarlov scoring system as follows [13, 14]: grade 0, complete paraplegia with no hind extremity motion; grade 1, minor joint movements; grade 2,
major joint movements; grade 3, the animal can stand; grade 4, the animal can walk; and grade 5, the animal can climb a 20°-inclined plane.

**SCV measurement**

In all animals, magnetic resonance imaging (MRI; Siemens, Germany) of T9-11 (2-mm slice thickness) was conducted preoperatively and three days postoperatively (Fig 4). The MRIs were saved as DICOM 3.0 files and downloaded to a personal computer. The T10 body height, disc height (defined as the length from the lower endplate of T9 to the upper endplate of T10), osteotomy segment height (defined as the length from the lower endplate of T9 to the upper endplate of T11), and spinal segment height (defined as the length from the upper endplate of T9 to the lower endplate of T11) were measured pre- and postoperatively using an MRI workstation (Fig 5). Data of all the regions (DICOM) were imported into Materialise Interactive

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**Fig 4. Pre- and postoperative magnetic resonance images (MRIs) of T9-11.** (A) Preoperative MRI showing a normal signal at the T8-12 spinal cord. (B) MRI three days postoperatively showing successful complete resection of the T10 vertebral body and adjacent discs and a normal signal at the T8-12 spinal cord.

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**Fig 5. Schematics demonstrating the shortening process.** (A) T8-12 were exposed, and single-axis pedicle screws were inserted into the vertebrae at T8, T9, T11, and T12. The T10 height (defined as the length from the upper to lower endplates of T10), disc height (defined as the length from the lower endplate of T9 to the upper endplate of T10), osteotomy segment height (defined as the length from the lower endplate of T9 to the upper endplate of T11), and spinal segment height (defined as the length from the upper endplate of T9 to the lower endplate of T11) were measured. (B) The T10 vertebral body and adjacent discs were resected completely, and laminectomy of T9-11 was performed. (C) The spinal column was shortened, and the spinal cord was buckled.
Medical Image Control System version 15.01 software (Mimics; Materialise, Leuven, Belgium) in order to reconstruct and calculate the SCV. Mimics software can separate the spinal cord, reconstruct it, and use the reconstruction to calculate the SCV. The volumes of the osteotomy and spinal segments were measured pre- and postoperatively (Fig 6). Each value was measured in triplicate, and the mean value of these three measurements was determined and used for the analysis.

Data analysis

The paired Student’s t test was used to compare the pre- and postoperative mean volumes, as well as to compare the mean shortening distance resulting in an SSEP change along with the mean d-value (postoperative minus preoperative value) of the osteotomy segment height. Spearman’s correlation test was used to analyze the relationship between the bilateral shortening distance and other parameters, such as the d-value of the osteotomy segment volume, the d-value of the spinal segment volume, T10 body height, spinal segment height, and disc height. A correlation was considered strong, good, or fair if r = 0.80–0.99, 0.60–0.79, or 0.50–0.59, respectively. For all analyses, P ≤ 0.05 was considered significant.

Preliminary study

Prior to this study, a preliminary study was performed to determine the reliability of the measured values. We measured the volume of T8-12 in six goats after the induction of anesthesia by using a previously described method; thereafter, all goats were sacrificed, and the spinal cords were removed and assessed using MRI. The SCV was measured on MRI using Mimics software. In addition, the SCV was also measured using Archimedes’ drainage method. This preliminary study demonstrated that the results measured using these two different methods were consistent (r = 0.986, p < 0.001) (Fig 7). Thus, the method of SCV measurement using MRI and the Mimics software was determined to be reliable.
Results

Two of the 10 goats were excluded due to changes in the SSEP during the osteotomy or due to postoperative infection. The SSEP of the remaining eight goats (3 female, 5 male) showed meaningful changes; the SSEP of five goats was decreased by 50% from the baseline amplitude and was delayed by 10% relative to the baseline peak latency, whereas the SSEP of the remaining three goats was decreased by 50% from baseline amplitude but was delayed by less than 10% relative to the baseline peak latency. During the wake-up test, all four limbs of all eight goats could move. With regard to neurologic function, five goats were classified as Tarlov grade 5 and three were classified as Tarlov grade 4 at two days after surgery. Data obtained from these eight goats were analyzed.

Intraoperatively, the mean T10 body height, preoperative osteotomy segment height, preoperative spinal segment height, postoperative osteotomy segment height, postoperative spinal
segment height, disc height, d-value of the osteotomy segment, and spinal cord shortening distance were 22.1 ± 1.69 mm, 28.9 ± 1.88 mm, 78.7 ± 7.14 mm, 5.4 ± 0.46 mm, 62.0 ± 6.16 mm, 4.1 ± 0.60 mm, 23.6 ± 1.51 mm, and 23.6 ± 1.52 mm, respectively (Table 1). The paired Student’s t test used to compare the mean osteotomy segment d-value and mean shortening distance did not reveal any statistical significance (t = -0.076, p = 0.941).

The mean pre- and postoperative volumes of the osteotomy and spinal segments were 952.50 ± 71.63 mm³ and 950.30 ± 64.57 mm³, and 2433.60 ± 138.24 mm³ and 2471.87 ± 140.96 mm³, respectively (Table 2). No significant differences between the mean pre- and postoperative volumes of the osteotomy segment (paired Student’s t test; t = 0.310, p = 0.765) and spinal segment (paired Student’s t test; t = 1.241, p = 0.255) were observed.

The mean pre- and postoperative SCVs per 1-mm height of the osteotomy segment were 33.03 ± 1.25 mm³ and 175.91 ± 1.19 mm³, respectively. Moreover, the mean pre- and postoperative volume at the levels of the osteotomy site and spinal segment did not significantly differ (paired t test; osteotomy site: t = 0.310, p = 0.765; spinal segment: t = 1.241, p = 0.255).

Table 1. Lengths of the spinal segments.

| Goat No. | T10 body height | Osteotomy segment | Spinal segment | Preoperative (mm) | Postoperative (mm) |
|----------|-----------------|-------------------|---------------|------------------|-------------------|
|          | T10 body height | Osteotomy segment | Spinal segment | Disc height (mm) | d-value of the osteotomy segment (post-pre) (mm) | Shortening distance (mm) |
| 1        | 24.4            | 30.4              | 86            | 5.4              | 67                | 4.1              | 25                | 25                |
| 2        | 20              | 28.1              | 72.4          | 5.5              | 57.9              | 3.1              | 22.6              | 22.3              |
| 3        | 20.9            | 27                | 73            | 5.2              | 57.3              | 3                | 21.8              | 21.5              |
| 4        | 20.2            | 26.2              | 74.8          | 4.8              | 59.4              | 4.6              | 21.4              | 21.8              |
| 5        | 22.7            | 31.8              | 87.2          | 6.2              | 70.8              | 3.5              | 25.6              | 25.4              |
| 6        | 22.7            | 29.7              | 77.1          | 5.4              | 59.8              | 2.9              | 24.3              | 24.2              |
| 7        | 24.2            | 30                | 88            | 5.8              | 69.6              | 3.2              | 24.2              | 24.5              |
| 8        | 21.7            | 28.1              | 71.3          | 4.9              | 54.5              | 3.4              | 23.2              | 24.2              |
| Mean     | 22.1            | 28.9              | 78.7          | 5.4              | 62                | 4.1              | 23.5              | 23.6              |
| Std. Dev.| 1.69            | 1.88              | 7.14          | 0.46             | 6.16              | 0.6              | 1.51              | 1.52              |

Comparison of the mean osteotomy site d-value and mean spinal cord shortening distance showed no statistical significance (t = -0.076, p = 0.941).

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Table 2. Volumes of the spinal cord segments.

| Goat No. | Preoperative (mm³) | Postoperative (mm³) |
|----------|-------------------|-------------------|
|          | Osteotomy segment | Spinal segment    | Osteotomy segment | Spinal segment    |
| 1        | 943.42            | 2618.16           | 940.42           | 2616.20           |
| 2        | 974.00            | 2504.52           | 962.30           | 2498.24           |
| 3        | 915.77            | 2355.05           | 900.00           | 2367.22           |
| 4        | 845.96            | 2568.43           | 884.20           | 2490.20           |
| 5        | 1082.52           | 2695.13           | 1080.30          | 2683.20           |
| 6        | 949.47            | 2561.71           | 921.20           | 2560.10           |
| 7        | 1028.18           | 2682.60           | 1021.70          | 2279.40           |
| 8        | 880.66            | 2283.20           | 892.30           | 2280.40           |
| Mean     | 952.50            | 2533.60           | 950.30           | 2471.87           |
| Std. Dev.| 71.63             | 138.24            | 64.57            | 140.96            |

The mean preoperative and postoperative volume at the levels of the osteotomy site and spinal segment did not significantly differ (paired t test; osteotomy site: t = 0.310, p = 0.765; spinal segment: t = 1.241, p = 0.255).

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postoperative SCVs per 1-mm height of the spinal segment were 32.29 ± 1.85 mm³ and 40.99 ± 1.84 mm³, respectively. The mean d-value (post-pre) of the SCV per 1-mm height of the osteotomy segment was 142.87 ± 0.59 mm³ (range, 142.19–143.67 mm³), whereas the corresponding value of SCV per 1-mm height of the spinal segment was 8.7 ± 0.09 mm³ (range, 8.61–8.84 mm³), with the osteotomy segment changing more substantially than the spinal segment (Table 3).

Spearman’s correlation test demonstrated a strong correlation between the bilateral shortening distance with the d-value (post-pre) of SCV per 1-mm height of the osteotomy segment (r = 0.95, p < 0.001) and a good correlation with T10 body height (r = 0.79, p = 0.02), whereas no correlation with the d-value (post-pre) of SCV per 1-mm height of the spinal segment was observed (r = -0.26, p = 0.53) (Table 4). Although the spinal segment height and disc height showed good correlations with the shortening distance (r = 0.60 and 0.61, respectively), no statistical significance was observed (p = 0.10 and 0.21, respectively).

**Table 3. Unit volumes of the spinal cord (1-mm).**

| Goat No. | Osteotomy segment |    | Spinal segment |    |
|---------|-------------------|----|----------------|----|
|         | Preoperative      | Postoperative | d-value (post-pre) | Preoperative | Postoperative | d-value (post-pre) |
| 1       | 31.03             | 174.71         | 143.67           | 30.44         | 39.08          | 8.63             |
| 2       | 34.66             | 177.09         | 142.43           | 34.59         | 43.26          | 8.66             |
| 3       | 33.92             | 176.11         | 142.19           | 32.26         | 41.10          | 8.84             |
| 4       | 32.54             | 174.88         | 142.34           | 34.45         | 43.09          | 8.64             |
| 5       | 33.54             | 177.21         | 143.67           | 30.23         | 38.95          | 8.72             |
| 6       | 32.12             | 175.00         | 142.88           | 33.67         | 42.28          | 8.61             |
| 7       | 34.24             | 177.44         | 143.20           | 30.22         | 38.88          | 8.66             |
| 8       | 32.22             | 174.82         | 142.60           | 32.48         | 41.29          | 8.81             |
| Mean    | 33.03             | 175.91         | 142.87           | 32.29         | 40.99          | 8.70             |
| Std. Dev.| 1.25             | 1.19           | 0.59             | 1.85          | 1.84           | 0.09             |

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**Discussion**

Although various osteotomy techniques can be used to correct severe spinal deformities, VCR is the only effective technique to manage severe rigid spinal deformities caused by coronal or sagittal decompensation [15–18]. However, several studies have reported neurologic complications in an average of 14.3% (range, 1.2–17.1%) of VCR cases [3, 6, 18–20]. Such complications may be related to excessive shortening of the spinal cord. The current study investigated the effects of changes in SCV due to spinal shortening during posterior VCR on spinal cord function in eight goats in order to determine the safe limit for spinal shortening.

**Table 4. Correlations between morphometric factors and distraction distance.**

| Morphometric factor         | R Value (p-value)* |
|-----------------------------|--------------------|
| d-value per 1-mm height of osteotomy segment | 0.95 (<0.001) |
| d-value per 1-mm height of spinal segment | -0.26 (0.53) |
| T10 body height             | 0.79 (0.02)       |
| Spinal segment height       | 0.62 (0.10)       |
| Disc height                 | 0.61 (0.21)       |

*Spearman’s correlation analysis
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This experiment utilized young goats aged between 24 and 36 months. The goat spine is similar to the human spine in many aspects, including the structure and biomechanics of the thoracic and lumbar vertebrae [21, 22]. There are 12 dorsal and 6–8 lumbar vertebrae in goats. The spinal cord terminates at the L6 level in goats; however, in humans, it terminates near the L1-2 level. In this study, we chose T10 as the site of VCR, which matches the T9-10 level in humans; the surgical level was located precisely by using the 12th rib of the goat as a marker.

SSEP can be utilized to continuously evaluate sensory neural pathways during surgery, without obstructing the surgeon, even when muscle relaxants are employed intraoperatively [23, 24]. However, relatively high rates of false-negative and false-positive results have been reported [25]. Some of the influencing factors, including hypothermia, hypotension, and inhalation anesthesia, can be avoided [26]. In this study, the body temperature and arterial blood pressure of each goat were monitored to eliminate the effects of low body temperature and blood pressure instability on the conduction velocity. In addition, intravenous anesthesia was used to reduce the influence of inhalation anesthesia on SSEP. Further, in this study, similar to in the study by Strahm et al [27], no anesthesia drugs were given during the spinal shortening in order to ensure the accuracy of detecting SSEP. Finally, the functional status of the spinal cord was evaluated by using the wake-up test after confirming the presence of SCI based on the SSEP changes, in order to reduce the risk of false-negative and false-positive SSEP results [28, 29].

Mimics software is an image-processing tool that connects two-dimensional image data with three-dimensional image engineering. It is widely used in the clinical setting because of its powerful three-dimensional imaging technology and its ability to compute irregular volumes [30, 31]. By using the software configuration function according to a certain value of regional growth, the spinal cord can be easily separated from the surrounding tissue, including the cerebrospinal fluid, so as to accurately calculate the SCV. However, there is no previous report on the use of the Mimics software to measure SCV. Conversely, the Archimedes drainage method has been widely used to measure the volume of irregular objects, by measuring the discharge water volume when an irregular object is totally immersed in water. Thus, the SCV can be accurately calculated by this method by using a fine graduated cylinder. Our preliminary study showed that the results using the Archimedes' drainage method and Mimics software correlated well (r = 0.986, p < 0.001), and confirmed that the method of SCV measurement on MRI by the Mimics software was reliable.

In this study, when the spinal column was shortened, SCI was defined as the occurrence of decreased amplitude or delayed peak latency of the SSEP. The mean shortening distance was 23.6 ± 1.55 mm; it strongly correlated with the d-value (post-pre) of SCV per 1-mm height of the osteotomy segment and showed a good correlation with T10 body height. The maximum value of the change in SCV per 1-mm height was based on the osteotomy segment, and its safe limit was found to be 142.75 ± 0.68 mm³. The safe limit for shortening was approximately 106% of the vertebral height, and the volumes of the spinal segment and osteotomy segments were not significantly changed after surgery. If the preoperative SCV per 1-mm height of the osteotomy segment is known, its corresponding postoperative value can be calculated. Thus, the safe limit for shortening can be calculated preoperatively. In addition, several studies have reported the use of computer-aided design rapid prototyping to preoperatively simulate the operation [30, 32]. Combining computer-aided design prototyping and calculation of the shortening distance preoperatively may help develop a better osteotomy scheme as a means to improve the success of surgery and to reduce the risk of neurologic complications.

Kawahara et al. [9] reported that shortening by more than two-thirds of the vertebral height caused compression and spinal cord deformity due to buckling of the dura in a dog model, while Hitesh et al. [10] reported that SCI was induced upon shortening by 104% of the
vertebral height in a pig model. Different results may be seen in different animals, and it has been speculated that this may be largely related to the laminectomy length. In Kawahara’s study, laminectomy was performed from the caudal region of the upper vertebra to the cranial region of the lower vertebra, whereas total laminectomy was performed from the upper vertebra through the lower vertebra in Hitesh’s study. In this study, the osteotomy site was T10, and total laminectomy was performed from T9 through T11. Furthermore, a sheep cadaveric study [33] reported that, during full-length shortening, the mean kink of the spine in the sagittal plane was 92.4° for two-level hemilaminectomy of T11 and T13, 24.6° for complete laminectomy of T11 with hemilaminectomy of T13, and 20.2° for two-level complete laminectomy. The authors reported that it was possible to avert kinking of the spine by applying the proper laminectomy technique for full-length shortening. In this study, we determined the safe limit for shortening by using the SCV per 1-mm height of the osteotomy segment. However, SCI may result from local changes in SCV per 1-mm height even before this safe limit is reached. Of note, the calculated safe limit was based on total laminectomy of T9-11; thus, the morphology should be carefully observed during the actual operation. On the other hand, the previous study described the extent of spinal shortening in relation to the mean body height of the relative vertebrae. However, altered anatomy, such as hemivertebrae or block vertebrae, is often observed at the osteotomy site in cases of severe spinal deformity. Such altered anatomy may lead to alterations of the spinal cord length, spinal morphology, and/or SCV. Therefore, it may be better to use the safe limit of the change in SCV per 1-mm height to calculate the shortening distance, which is relative to the SCV itself, rather than the shortening distance relative to the mean body height of the involved vertebrae.

The main limitation of the present study was that the data were based on a goat model, and the translational value for humans may be limited. However, this study revealed a strong correlation between SCV and SCI due to spinal shortening, and the same phenomenon may occur in the human spinal cord. In the future, to confirm the results of this animal experimental study, a series of severe spinal deformity cases need to be reviewed in order to elucidate the safe limit for shortening in humans.

Conclusion
The shortening distance strongly correlated with the d-value (post-pre) of SCV per 1-mm height of the osteotomy segment, and showed a good correlation with the T10 body height. The maximum value of the change in SCV per 1-mm height was based on the osteotomy segment, and its safe limit was found to be $142.87 \pm 0.59 \text{ mm}^3$. Thus, our results indicate that the safe limit for shortening can be calculated by using the change in SCV per 1-mm height, and this may be helpful for reducing the risk of neurologic complications in VCR.

Author Contributions
Conceived and designed the experiments: XYM FQ JCY. Performed the experiments: XYM JCY FQ JJX QLY YSX XZ HSH LHX. Analyzed the data: FQ QLY YSX. Contributed reagents/materials/analysis tools: XZ HSH LHX. Wrote the paper: FQ JCY JJX.

References
1. Liljenqvist UR, Link TM, Halm HF. Morphometric analysis of thoracic and lumbar vertebrae in idiopathic scoliosis. Spine (Phila Pa 1976). 2000; 25:1247–53.
2. Weinstein JN, Rydevik BL, Rauschning W. Anatomic and technical considerations of pedicle screw fixation. Clin Orthop Relat Res. 1992; 284:34–46. PMID: 1395312
3. Hamzaoglu A, Alanay A, Ozturk C, Sarier M, Karadereler S, Ganiyusufoglu K. Posterior vertebral column resection in severe spinal deformities: a total of 102 cases. Spine (Phila Pa 1976). 2011 Mar 1; 36 (5):E340–4. doi:10.1097/BRS.0b013e3182015712 PMID: 21325930

4. Lenke LG, O'Leary PT, Bridwell KH, Sides BA, Koester LA, Blanke KM. Posterior vertebral column resection for severe pediatric deformity: minimum two-year follow-up of thirty-five consecutive patients. Spine (Phila Pa 1976). 2009 Sep 15; 34(20):2213–21.

5. Wang Y, Zhang Y, Zhang X, Huang P, Xiao S, Wang Z, et al. A single posterior approach for multilevel modified vertebral column resection in adults with severe rigid congenital kyphoscoliosis: a retrospective study of 13 cases. Eur Spine J. 2008 Mar; 17(3):361–72. doi:10.1007/s00586-007-0566-9 PMID: 18172699

6. Suk SI, Chung ER, Lee SM, Lee JH, Kim SS, Kim JH. Posterior vertebral column resection in fixed lumbosacral deformity. Spine (Phila Pa 1976). 2005 Dec 1; 30(23):E703–10. PMID: 16319740

7. Shimode M, Kojima T, Sowa K. Spinal wedge osteotomy by a single posterior approach for correction of severe and rigid kyphosis or kyphoscoliosis. Spine (Phila Pa 1976). 2002 Oct 15; 27(20):2260–72. doi:10.1097/00007632-200210150-00031 PMID: 12394904

8. Dabney KW, Ehrenshteyn M, Agresta CA, Twiss JL, Stem G, Tice L, et al. A model of experimental spinal cord trauma based on computer-controlled inter-vertebral distraction: characterization of graded injury. Spine (Phila Pa 1976). 2004 Nov 1; 29(21):2357–64 PMID: 15507795

9. Kawahara N, Tomita K, Kobayashi T, Abdel-Wanis ME, Murakami H, Akamaru T. Influence of acute shortening on the spinal cord: an experimental study. Spine (Phila Pa 1976). 2005 Mar 15; 30(6):613–20. PMID: 15770174

10. Modi HN, Suh SW, Hong JY, Yang JH. The effects of spinal cord injury induced by shortening on motor evoked potentials and spinal cord blood flow. J Bone Joint Surg. 2011; 93:1781–1789. doi:10.2106/JBJS.I.01794 PMID: 22005863

11. Lin HC, Tyler JW, Wallace SS, Thurmon JC, Wolfe DF. Telazol and xylazine anesthesia in sheep. Cornell Vet. 1993 Apr; 83(2):117–24. PMID: 8467697

12. Dawson EG, Sherman JE, Kanim LE, Nuwer MR. Spinal cord monitoring. Results of the Scoliosis Research Society and the European Spinal Deformity Society survey. Spine (Phila Pa 1976). 1991 Aug; 16(8 Suppl):S361–4. PMID: 1785088

13. Bohilman HH, Bahnuike E, Raskulinecz G, Field G. Mechanical factors affecting recovery from incomplete cervical spinal cord injury: a preliminary report. Johns Hopkins Med J. 1979; 145:115–25. PMID: 470290

14. Im Tarlov, Klinger H. Spinal cord compression studies. II. Time limits for recovery after acute compression in dogs. AMA Arch Neurol Psychiatry. 1954 Mar; 71(3):271–90. 15. PMID: 13123590

15. Bridwell KH. Decision making regarding Smith-Petersen vs. pedicle subtraction osteotomy vs. vertebral column resection for spinal deformity. Spine (Phila Pa 1976). 2006 Sep 1; 31(19 Suppl):S71–8. PMID: 1704088

16. Zhang HQ, Li JS, Liu SH, Guo CF, Tang MX, Gao QL, et al. The use of posterior vertebral column resection in the management of severe posttuberculous kyphosis: a retrospective study and literature review. Arch Orthop Trauma Surg. 2013 Sep; 133(9):1211–8. doi: 10.1007/s00402-013-1794-6 PMID: 23812354

17. Lenke LG, O'Leary PT, Bridwell KH, Sides BA, Koester LA, Blanke KM. Posterior vertebral column resection for severe pediatric deformity: minimum two-year follow-up of thirty-five consecutive patients. Spine (Phila Pa 1976). 2009 Sep 15; 34(20):2213–21.

18. Suk SI, Chung ER, Kim JH, Kim SS, Lee JS, Choi WK. Posterior vertebral column resection for severe rigid scoliosis. Spine (Phila Pa 1976). 2005 Jul 15; 30(14):1682–7. PMID: 16025041

19. Lenke LG, Sides BA, Koester LA, Hensley M, Blanke KM. Vertebral column resection for the treatment of severe spinal deformity. Clin Orthop Relat Res. 2010 Mar; 468(3):687–99. doi: 10.1007/s11999-009-1037-x PMID: 19727995

20. Qiu Y, Wang S, Wang B, Yu Y, Zhu F, Zhu Z. Incidence and risk factors of neurological deficits of surgical correction for scoliosis: analysis of 1373 cases at one Chinese institution. Spine (Phila Pa 1976). 2008 Mar 1; 33(5):519–26.

21. Braun JT, Hoffman M, Akuz E, Olgilvie JW, Brodke DS, Bachus KN. Mechanical modulation of vertebral growth in the fusionless treatment of progressive scoliosis in an experimental model. Spine (Phila Pa 1976). 2006 May 20; 31(12):1314–20. PMID: 16721292

22. Qin J, He X, Wang D, Qi P, Guo L, Huang S, et al. Artificial cervical vertebra and intervertebral complex replacement through the anterior approach in animal model: a biomechanical and in vivo evaluation of a successful goat model. PLoS One. 2012; 7(12):e52910. doi: 10.1371/journal.pone.0052910 PMID: 23300816
23. Hermanns H, Lipfert P, Meier S, Jetzek-Zader M, Krauspe R, Stevens MF. Cortical somatosensory-evoked potentials during spine surgery in patients with neuromuscular and idiopathic scoliosis under propofol-remifentanil anaesthesia. Br J Anaesth. 2007 Mar; 98(3):362–5. PMID: 17237215

24. Chandanwale AS, Ramteke AA, Barhate S. Intra-operative somatosensory-evoked potential monitoring. J Orthop Surg (Hong Kong). 2008 Dec; 16(3):277–80. PMID: 19126889

25. Hilibrand AS, Schwartz DM, Sethuraman V, Vaccaro AR, Albert TJ. Comparison of transcranial electric motor and somatosensory evoked potential monitoring during cervical spine surgery. J Bone Joint Surg Am. 2004; 86:1248–53. PMID: 15173299

26. Weinstein SL. Somatosensory evoked potentials. J Bone Joint Surg Am, 2000; 82A (10): 1517–1518

27. Strahm C, Min K, Boos N, Ruetsch Y, Curt A. Reliability of perioperative SSEP recordings in spine surgery. Spinal Cord. 2003 Sep; 41(9):483–9. PMID: 12934088

28. Gunnarsson T, Krassioukov AV, Sarjeant R, Fehlings MG. Real-time continuous intraoperative electromyographic and somatosensory evoked potential recordings in spinal surgery: correlation of clinical and electrophysiologic findings in a prospective, consecutive series of 213 cases. Spine (Phila Pa 1976). 2004 Mar 15; 29(6):677–84. PMID: 15014279

29. Schwartz DM, Auerbach JD, Dormans JP, Flynn J, Drummond DS, Bowe JA et al. Neurophysiological detection of impending spinal cord injury during scoliosis surgery. J Bone Joint Surg Am. 2007 Nov; 89(11):2440–9. PMID: 17974887

30. Yang JC, Ma XY, Lin J, Wu ZH, Zhang K, Yin QS. Personalised modified osteotomy using computer-aided design-rapid prototyping to correct thoracic deformities. Int Orthop. 2011 Dec; 35(12):1827–32. doi: 10.1007/s00264-010-1155-9 PMID: 21125271

31. Yang JH, Chang M, Kwak DS, Wang JH. Volume and contact surface area analysis of bony tunnels in single and double bundle anterior cruciate ligament reconstruction using autograft tendons: in vivo three-dimensional imaging analysis. Clin Orthop Surg. 2014 Sep; 6(3):290–7. doi: 10.4055/cios.2014.6.3.290 PMID: 25177454

32. Metzler P, Geiger EJ, Alcon A, Ma X, Steinbacher DM. Three-Dimensional Virtual Surgery Accuracy for Free Fibula Mandibular Reconstruction: Planned Versus Actual Results. J Oral Maxillofac Surg. 2014 Jul 30.

33. Alemdaroğlu KB, Atlhan D, Cimen O, Kılıç CY, İlter S. Morphometric effects of acute shortening of the spine: the kinking and the sliding of the cord, response of the spinal nerves. Eur Spine J. 2007 Sep; 16(9):1451–7. PMID: 17426990