Development and Achievement of Cervical Laminoplasty and Related Studies on Cervical Myelopathy

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Abstract:

Cervical laminoplasty (CL) is one of the surgical methods via the posterior approach for treating patients with multilevel affected cervical myelopathy (CM). The main purpose of CL is to decompress the cervical spinal cord by widening the narrowed spinal canal, combined with preserving the posterior anatomical structures to the degree possible and preserving the widened space stably. During the development and improvement of spine surgeries including CL, various studies on CM have progressed and useful achievements have been obtained: (1) posterior cervical spine fixation systems that can be used in combination with CL simultaneously have been developed; (2) various materials to stably maintain the enlarged spinal canal have been developed; (3) the main influential factors on the surgical results are the inner factors of the patients, such as the patient's age and the disease duration; (4) various surgical methods to preserve the function of the posterior cervical muscles have been tried to avoid postoperative kyphotic changes of the cervical spine; (5) postoperative complications, such as C5 palsy and axial pain, have been examined, and the countermeasures have been tried; (6) K-line on lateral X-ray films has been applied to evaluate the indication of CL in patients with CM due to ossification of the posterior longitudinal ligament (OPLL) preoperatively; and (7) the method and idea of CL have been adapted to surgeries at the thoracic and lumbar spine. However, some issues remain to be resolved, such as the deterioration of neurological findings, especially in patients with continuous or mixed-type OPLL, the postoperative kyphotic-directional alignment change of the cervical spine, C5 palsy, and axial pain.

Keywords:

Cervical spine, Laminoplasty, Posterior decompression, Cervical myelopathy, Kyphosis

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Principles and History of Cervical Laminoplasty

Previously in Japan, laminectomy was performed commonly as posterior cervical decompression surgery for patients with cervical myelopathy (CM). However, constriction of the dura mater caused by extradural scar formation, progressive spinal deformity (kyphotic or sigmoid-type curvature), especially in relatively younger patients, postoperative progression of ossification of the posterior longitudinal ligament (OPLL), and spinal instability have been reported as a consequence in some cases[1-4]. These problems had been thought to be caused by the inevitable postoperative lack of the posterior anatomical structures. Although all these problems do not always deteriorate the neurological condition, some patients with progressive deformity had required early spinal fusion[3].

To resolve these issues occurring in laminectomy, cervical laminoplasty (CL) has been tried and developed. The main purpose of CL is to decompress the cervical spinal cord by widening the narrowed spinal canal, combined with preserving the posterior anatomical structures as much as possible and to preserve the widened space stably. The preservation of the posterior anatomical structures as much as possible is especially characteristic.

Various methods of CL have been developed and improved in Japan since "expansive lamina-Z-plasty", which was first proposed by Oyama and co-workers[5] in 1973. The fundamental surgical methods of most CL had been completed in the 1980s in Japan. Thereafter, various types of CL were performed in many hospitals, thus replacing the previous laminectomy. Recently, these have been performed gradually around the world as one of the surgical methods

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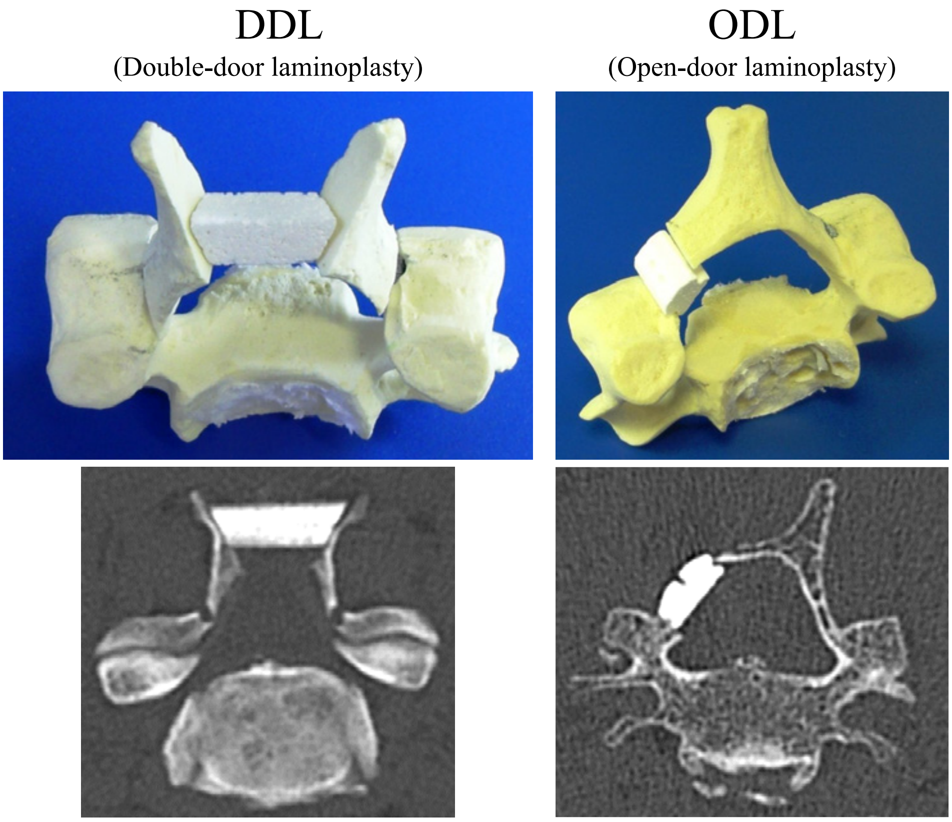

Figure 1. Pictures of a plastic model (upper) and computer tomographic films (lower) of DDL and ODL

via the posterior approach for treating patients with multilevel affected CM[6-9].

At present, the surgical methods of CL are divided broadly into two types from the viewpoints of the site of osteotomy: double-door laminoplasty (DDL)[10-15] and open-door laminoplasty (ODL)[16-19] (Fig. 1). In DDL, osteotomy is performed at the central spinous process and lamina. In ODL, osteotomy is performed at one side of the lamina-facet junction. The surgical techniques and methods of CL are referred to in other articles.

During the development and improvement of spine surgeries including CL thereafter, various studies on CM have progressed, and new surgical and assessment methods have been added, resulting in better surgical results.

Why was CL developed in Japan? There may be two reasons for this: a narrower spinal canal and a high prevalence rate of OPLL in the Japanese population. In Japanese people, the average anteroposterior (AP) diameter of the cervical canal at the C5 level is 16 mm in males and 15 mm in females[20,21]. These are narrower than those in people of western countries[22]. In Japan, the AP diameters of less than 14 mm in males and 13 mm in females are diagnosed as narrow canal stenosis, which has tendency of causing CM.

Since 1960, when Tsukimoto[23] reported one case of OPLL, many Japanese researchers have paid attention to OPLL. There are many reports on the high prevalence rate of cervical OPLL in Japan: 1.9%[24] and 3.7%[25] on lateral X-ray films, and 6.3%[26] on positron emission tomography and computed tomography. Matsunaga et al.[27] retrospectively reported that the prevalence of OPLL in the general Japanese population older than 30 years is 1.9% - 4.3%. This prevalence rate of cervical OPLL is higher among the Japanese than among Caucasians[25].

Mechanism of CM

In general, CM is related to a narrowed spinal canal, which may be congenital and/or acquired. In Japan, most patients with CM have acquired type due to cervical spondylosis and/or OPLL. Within the narrowed spinal canal, the spinal cord may be compressed due to both static and dynamic stress mechanisms. In chronic anterior and posterior compression, forces impact the spinal cord over a long period of time. As a result, the spinal cord gradually becomes degenerated and atrophied histologically, causing neurological symptoms.

These mechanisms have been revealed by biomechanical experimental studies using the cervical spinal cords of bovines[28] and rabbits[29]. Ichihara et al.[28] revealed that the mechanical property of the gray matter is more rigid, although more fragile, than the white matter, and estimated that the specific areas of the CM, that is, the gray matter and the posterolateral portion of the white matter, are finally affected.

Clinically, the histological changes within the spinal cord in patients with OPLL are revealed to be more significant in the gray matter than in the white matter[30]. In the gray matter, flattened anterior horn cells, loss and degeneration of the nerve cells, growth of the glial cells, and fibrous gliosis are revealed. In the white matter, demyelination can be seen mainly at the lateral and posterior funiculus. Although distinct obstruction of the small arteries within the spinal cord is not seen, fibrous degeneration of the adventitia in the small veins, with narrowing of the lumen is revealed. These histological findings may indicate that CM due to OPLL is caused by mechanical stress and secondary circulatory disturbance.

Ogino et al.[31] reported the results of a clinicopathological study of nine patients with cervical spondylotic myelopathy as follows: at the site of cord compression, the posterolateral white matter (lateral corticospinal tracts) first suffered from minor compression and anterior horn cell loss or localized infarction of the gray matter was associated with severe compression, and infarction eventually extended over the entire gray matter. Finally, the whole lateral white matter was destroyed. Degeneration of the posterior white matter, particularly in the central region, was seen in cases with severe compression.

Mizuno et al.[32] investigated the relationship between the findings of magnetic resonance imaging (MRI) and the pathology of the spinal cord in CM. In the boomerang-shaped spinal cord on MRI, major pathological changes were restricted to the gray matter, and the white matter was relatively well preserved. In the triangular-shaped spinal cord, in which compression forces might impact the spinal cord circumferentially, pathological changes were more severe, and both the gray matter and white matter were involved. There were severe pathological changes over more than one segment, and degeneration of both the descending and ascending tracts at the posterior column was observed.

The relationship between the affected levels of the spinal cord and roots and the neurological findings and symptoms in CM has been investigated[33-36]. Ono and co-workers[35,36] reported a characteristic finding named “myelopathy hand” as pyramidal tract involvement, in which loss of power of adduction and extension of the ulnar two or three fingers without sensory loss or spastic quadriparesis occurs, and the pathological regions are thought to be the C7, C8, or T1 spinal cord segments at C5-6 and C6-7 disk levels.

To summarize, in CM, the gray matter and the posterolateral portion of the white matter tend to be mainly affected.

Treatment of CM

In general, myelopathy may be caused primarily by two compression mechanisms: static and dynamic. Therefore, the main purpose of treatment of CM is to first decrease the compression mechanical stress. At the cervical spine where extension movement tends to be the main mechanism causing dynamic compression, the conservative treatment of reducing its movement using a collar is effective. For patients in whom the conservative treatment is not so effective, surgical intervention to decrease the stress caused mainly by the static mechanism (decompression surgery) must be introduced as the next step.

As for decompression surgery, there are two approaches: anterior and posterior. While considering which approach must be selected, not only the degree of the width (AP diameter) of the spinal canal and the number of intervertebral disks involved but also the pathologies of anterior space-occupying lesions (SOLs) and the alignment of the cervical spine must be assessed.

In general, the selection of an approach depends mainly on the degree of the width of the spinal canal. For patients with wide a spinal canal, a single intervertebral disk lesion, such as disk herniation, is usually operated via the anterior approach. For patients with a narrow spinal canal, surgery via the posterior approach is usually selected because multi-level decompression can be performed easily because of the shallow and wide surgical field. Besides, the volume of bleeding during surgery is less than that in the anterior approach, in which the volume of bleeding from the extradural veins often becomes a lot, especially in cases of OPLL. Even after indirect decompression via the posterior approach, such as CL, the spinal cord can be shifted posteriorly and separated from the OPLL. Usually, in most patients, the alignment of the cervical spine is lordotic; therefore, the spinal cord can be separated from anterior SOL more effectively.

However, in patients with large-volume SOLs, such as continuous or mixed-type large OPLL protruding into the spinal canal, indirect decompression via the posterior approach is inadequate, and direct decompression via the anterior approach is certainly reasonable even though it is technically demanding because of the deep and narrow surgical field, the working space is limited, and there is the possibility of high-volume bleeding during the direct procedure on the OPLL.

The alignment of the cervical spine is also one of the issues to consider when selecting the surgical approach. In patients with severe kyphotic alignment of the cervical spine, the effect of posterior shift of the spinal cord may be limited in posterior decompression; therefore, anterior decompression is usually selected or sometimes posterior decompression is added after that.

On the other hand, Abumi et al.[37,38] have developed a cervical pedicle screw fixation system that can reduce the kyphotic alignment of the cervical spine posteriorly because of its rigid fixation property. However, in patients with a narrow spinal canal combined with severe kyphotic alignment, posterior decompression of the spinal cord such as CL, followed by reduction of kyphotic alignment and stabilization can be simultaneously performed. According to Abumi et al., in patients in the flexible kyphosis group, the average preoperative kyphosis of 28.4 degrees improved to 5.1 degrees at the final follow-up, and in patients in the rigid or fixed kyphosis group, the preoperative kyphosis of

30.8 degrees improved to 0.5 degrees at the final follow-up[38].

As the cervical pedicle screw system is somewhat technically demanding[39], a lateral mass screw system[40,41] is sometimes performed instead, even though the fixation property is less than that of the pedicle screw system.

With regard to comparisons of surgical results between anterior and posterior approaches, there are many reports from Japan[42-46], other Asian countries[7,9,47-49], and Western countries[50-57]. Many issues such as complications, reoperation, postoperative deformity of the cervical spine, neurological recovery, and deterioration have been discussed. Besides, the comparisons of surgical results between anterior and posterior approaches are sometimes discussed from medico-economical standpoints[52,53]. Although it is necessary to recognize the problems involved in each approach, it is not so simple to decide the superiority or inferiority of the two approaches. It may be reasonable to select an appropriate approach based on the individual conditions of patients, and it is thought best for a surgeon to perform surgery carefully by his or her most familiar method[58].

Various Materials Used in CL

During the development of CL, various materials to maintain the enlarged spinal canal stably have also been developed in place of previous autologous bone (iliac bone[10], spinous process[11,17]); hydroxyapatite spacer[12,14,18,19,58-62], titanium plate and screw[63,64], thread[16], and so on. Although autologous bone has a high quality of bone union, the size, and configuration are individual and not always uniform. In harvesting the iliac bone, another incision must be made and complications such as gluteal nerve injury may occur. In contrast, a hydroxyapatite spacer and titanium plate and screw have uniform size and shape; therefore, they are easy to handle. The operation time can be decreased in comparison with adding the iliac bone harvest. However, they are commercially expensive and complications such as loosening and displacement may occur, probably because of malfitting to the implanted site and fragility of fixation[65].

Neurological Changes after CL

a. *Neurological recovery*

With regard to the surgical results of CL, neurological recovery rates have been reported to be about 60%-70% in the literature[66-76], although the surgical methods and techniques of CL and the methods of assessment may differ, and the recovery rates must be strictly divided between two causes of CM: cervical spondylosis and OPLL[77]. This recovery rate is almost the same as that of laminectomy[78,79]. This is probably because the effect of posterior decompression of the spinal cord itself is almost the same in both CL and laminectomy.

As long as decompression surgery is undertaken untraumatically, the surgical results are thought to depend on the viability of the spinal cord of the patients at the time of surgery. In other words, the role of decompression surgery is thought to provide a new circumstance in which the spinal cord can recover additional viability thereafter. It has been revealed that the influential factors on the surgical results are the age of the patients[80], the neurological findings just before surgery[81-83], the duration of the diseases, and accompanying injuries to the cervical spine[31,66-76]. All these are the inner factors of the patients.

From these results, it is naturally estimated that the milder the neurological findings before surgery, the better the surgical results that can be expected. Therefore, it is important that surgical intervention be made before the neurological conditions deteriorate. In general, the pathological changes within the spinal cord can be estimated to some extent from the neurological conditions, such as muscle weakness and atrophy and the obvious severity of spasticity causing disability of handling eating utensils and/or walking. In contrast, prophylactic decompression surgery should not be considered for patients with only slight neurological findings because these findings often recover even after conservative treatment[84,85].

b. *Deterioration of physical function after CL*

For a long time after surgery, the physical functions may deteriorate gradually in some patients. One of the reasons for this deterioration is thought to be the worsening of the neurological functions: a worsening of the function of the spinal cord itself with aging, *de novo* formation and/or progression of thickness of the OPLL, degenerative changes at the thoracic and/or lumbar vertebral levels, progression of the kyphotic alignment of the cervical spine, adjacent intervertebral disk changes, and so on[66-77].

With regard to the rate of progression of OPLL after surgery, 66%[67], 70%[68], and 73%[69] have been reported for more than 10 years of follow-up. Younger age at the time of operation and continuous or mixed-type OPLL are highly predictive of the progression of OPLL[68,69]. Seichi et al. reported that the occupancy rate of OPLL was higher in patients with neurological deterioration[77], and the main cause of neurological deterioration in patients with OPLL was a minor injury of the spinal cord at the remnant site of OPLL[66].

Of course, the deterioration of physical functions after surgery does not always relate to the deterioration in neurological functions, and it is sometimes due to other factors, such as the natural decrease of muscle power and deterioration in the joint function of extremities with age. Accordingly, the precise evaluation of surgery for CM after a long follow-up is sometimes difficult to perform with confidence.

Local Complaints around the Cervical Spine after CL

a. Postoperative kyphotic-directional alignment change of the cervical spine

In posterior decompression surgery, the control of the postoperative kyphotic-directional alignment change is one of the important challenges[18,86,87]. The postoperative kyphotic-directional alignment change does not relate so much to the deterioration of neurological findings in cervical spondylotic myelopathy, but to the deterioration of neurological findings in some cases of OPLL[67,77].

One method of solution in DDL is to recover the tension of the posterior cervical muscles and the nuchal ligament as much as possible by preserving the spinous process as long as possible as an anterior support and re-suturing the semispinalis cervicis muscles that had been detached earlier from the C2 spinous process before closure[87]. By using this method[88], it was revealed that the postoperative kyphotic-directional alignment change could be restricted by about 10 degrees in about 70% of patients, whether the preoperative cervical spine was lordotic or kyphotic.

In ODL, the procedures of preserving the funicular section of the nuchal ligament attached to the C6 and/or C7 spinous processes, in addition to all muscles attached to the C2 and C7 spinous processes and the subaxial deep extensor muscles on the hinged side, have been performed[18,89].

Shiraishi[12] developed a new surgical technique that preserved the attachments of the semispinalis cervicis and multifidus muscles on the cervical spinous processes and limited the damage to the attachments of the interspinous and rotator muscles. Comparing his method (skip laminectomy: SL) with ODL, the average postoperative range of neck motion was maintained at 98% of the preoperative measurement in SL and 61% in ODL, and the average atrophy rate of the deep extensor muscles was 13% in SL and 59.9% in ODL. In SL, there was no significant difference between the pre- and postoperative cervical curvature index according to Ishihara's method[73].

b. Postoperative C5 palsy

Postoperative C5 palsy is defined as *de novo* or aggravating muscle weakness mainly at the C5 region, with slight or no sensory disturbance after cervical surgery. Even now, the precise cause of C5 palsy has not yet been revealed, probably because multiple factors are related to its occurrence. At present, the uncertain causes are divided from the viewpoint of the time of onset and the kinds of nerve tissue involved[90].

During surgery, the spinal cord and/or the nerve root may be damaged by the direct compression of a retractor and/or high friction heat of the tip of an air-drill[91]. After surgery, the spinal cord and/or the nerve root may be distracted and/or compressed by adjacent anatomical structures, such as the facet joint and the vertebral body under a new circumstance, in which the cervical spine alignment is more or less changed, especially when the patients start rehabilitation after bed rest.

With regard to the kinds of nerve tissue involved, there are two theories: the segmental spinal cord disorder theory and the nerve root injury theory. In the theory of segmental spinal cord disorder, it is thought that nerve tissues, especially the anterior horn cells, may be damaged due to ischemia before CL and/or recirculation after CL. At the time of acute recirculation, the nerve cells may be chemically damaged by reactive oxygen[92,93]. In contrast, in the theory of nerve root injury, the anterior rootlet or nerve root may be mechanically compressed and/or distracted[58,94-101].

From the side of the theory of nerve root injury[58,96,98,100], various countermeasures have been proposed, such as the intermittent relaxation of tension of the hooks to the muscles during surgery, prophylactic foraminotomy to decompress the C5 nerve root, prevention of excessive posterior shift of the spinal cord, and prevention of excessive lordotic alignment of the cervical spine. These countermeasures have proved to be effective in decreasing the rate of C5 palsy.

c. Axial pain after CL

In a narrow sense, axial pain is defined as pain and a feeling of stiffness around the neck and shoulders after cervical surgery[102]. It must be clearly discriminated from pain caused by nerve tissues, such as the spinal cord and nerve roots. According to Duetzmann et al.[103], who systematically reviewed 103 studies on CL from 2003 to 2013, the percentage of patients who complained of postoperative axial pain was 30% at a mean follow-up of 51 months. Axial pain has significant negative correlations with health-related quality of life[104].

Axial pain usually occurs when a patient starts to sit up in bed, and often decreases on sitting and standing, and conversely improves on lying down[105]. In the beginning, the cause was thought to be related to resection of the posterior deep muscles of the cervical spine at the time of approach. However, later, it was thought that the release of deep muscles from the C7 spinous process may be likely related to this axial pain. After resection of the rhomboid minor muscle and the trapezius muscle from the tip of the C7 spinous process, the scapula rotates adductly on sitting and standing[105]. This rotation of the scapula may induce pain and the feeling of stiffness around the neck and shoulders.

To prevent axial pain, the operation level of CL has been limited from C3 to C6 and the C7 lamina has been cut in a dome-shape when involved[106,107]. However, even after this countermeasure, some patients continue to have complaints. There are also controversies regarding the effectiveness of preservation of the attachment of the nuchal ligament to the C6 spinous process to reduce postoperative axial pain[108,109].

Recently, it has been thought that the cause of axial pain is possibly not single but multiple[109-114]. Wang et al.[112] reviewed 1,297 cases in 26 studies and concluded that potential sources of axial pain include the cervical disk, musculature, facet joints, spinal cord, and nerve roots; and to prevent postoperative axial pain, various trials are important, such as early postoperative range of motion exercise, shorter or no application of external immobilization, less surgical exposure, avoiding detachment of the semispinalis cervicis muscle from the C2 spinous process, and reconstructing the extensor musculature as anatomically as possible.

K-Line on Lateral X-ray Films

In CL, the spinal cord is decompressed by shifting posteriorly. However, in cases with a large OPLL or even a small OPLL combined with kyphosis of the cervical spine, the effect of decompression may be incomplete. Fujiyoshi et al.[115] proposed the K-line to predict the degree of the postoperative posterior shift of the spinal cord. They defined the K-line as a line that connects the midpoints of the spinal canal at the C2 and C7 vertebral levels on lateral X-ray films in a neutral position. The K-line (-) is defined as the situation where the tip of the OPLL exceeds the K-line. They concluded that a sufficient posterior shift of the spinal cord and neurological improvement will not be obtained in the K-line (-) group.

Thereafter, modified K-lines using MRI[116,117] and different assessment methods of K-line in flexion[118] or extension positions[119] have been reported. From the results of these preoperative investigation using the K-line, the surgical methods have been changed from CL to anterior decompression and fusion[120] or posterior decompression and instrumented fusion[121]. The K-line is one of the useful practical markers for deciding the surgical approach and methods in patients with OPLL[122].

Adaptation to Surgeries at the Thoracic and Lumbar Spine

For OPLL at the upper thoracic level (C7/T1-T3/T4), Tsuzuki and co-workers[123,124] performed conjoint laminoplasty from the upper cervical level to the upper thoracic level (expansive laminoplasty; one kind of ODL) to separate the spinal cord from the OPLL posteriorly to the extent possible. For OPLL at the middle thoracic level (T4/T5-T7/T8), they performed a staged operation via the posterior approach alone. The first stage is expansive laminoplasty, and the second stage is laminoplasty from the upper thoracic level to the middle thoracic level about 1 month later.

For ossification of the yellow ligament (OYL), the level of ossification and the affected lamina are partially or totally resected via the posterior approach. In total laminectomy, there are two approaches similar to ODL and DDL. In the ODL-like method, the thinned lamina with OYL is gradually declined opposite side of longitudinal severity of the inner cortex and finally resected. In the DDL-like method, the thinned lamina with OYL is centrally split and opened symmetrically and finally resected. Both methods can be performed safely because the affected lesions are lifted without compressing the spinal cord[125].

For patients with lumbar spinal canal stenosis, spinous process-splitting laminectomy, in which the approach is similar to DDL, has been performed[126,127].

Conclusion

During and after the development and improvement of spine surgeries including CL, various studies on CM have progressed, and useful achievements have been obtained. CL can be performed safely and stable surgical results are maintained for a long period, of more than 10 years. However, patients with a large prominence-type OPLL and severe kyphotic alignment of the cervical spine are relatively contraindicated because of the possibility of inadequate posterior shift of the spinal cord. This possibility can be predicted to some extent using a K-line before surgery. Recently, even in patients with a narrow spinal canal combined with severe kyphotic alignment, the reduction of kyphotic alignment and stabilization following CL can be performed simultaneously by using the cervical pedicle screw system or lateral mass screw system in some patients.

Even now, some issues remain to be resolved: the deterioration of neurological findings, especially in patients with continuous or mixed-type OPLL, the postoperative kyphotic-directional alignment change of the cervical spine that may relate to its relative invasiveness to the posterior muscles, C5 palsy, and axial pain.

Conflicts of Interest: The authors declare that there are no relevant conflicts of interest.

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