Surgical management of adult spinal deformity is a complex and evolving discipline involving correction of coronal and sagittal imbalance, in addition to establishing spino pelvic harmony between the spine and pelvis in regards to the SVA, PI, PT, LL, and thoracic kyphosis. One of the essential goals in deformity correction is restoration of sagittal balance, which may be accomplished via a number of well-established procedures that involve lengthening the anterior column, shortening the posterior column, or both. Traditional techniques include the Smith-Peterson osteotomy and the pedicle subtraction osteotomy, which are considered closing-wedge osteotomies that correct an average of 15° and 30°, respectively. Vertebral column resection is both an anterior and posterior spine-shortening procedure. Although effective, these techniques may be associated with high degrees of morbidity from wide exposure and significant blood loss.

Anterior longitudinal ligament release using the minimally invasive lateral retroperitoneal transpsoas approach: a cadaveric feasibility study and report of 4 clinical cases

Laboratory investigation

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Object. Traditional procedures for correction of sagittal imbalance via shortening of the posterior column include the Smith-Peterson osteotomy, pedicle subtraction osteotomy, and vertebral column resection. These procedures require wide exposure of the spinal column posteriorly, and may be associated with significant morbidity. Anterior longitudinal ligament (ALL) release using the minimally invasive lateral retroperitoneal approach with a resultant net lengthening of the anterior column has been performed as an alternative to increase lordosis. The objective of this study was to demonstrate the feasibility and early clinical experience of ALL release through a minimally invasive lateral retroperitoneal transpsoas approach, as well as to describe its surgical anatomy in the lumbar spine.

Methods. Forty-eight lumbar levels were dissected in 12 fresh-frozen cadaveric specimens to study the anatomy of the ALL as well as its surrounding structures, and to determine the feasibility of the technique. The lumbar disc spaces and ALL were accessed via the lateral transpsoas approach and confirmed with fluoroscopy in each specimen. As an adjunct, 4 clinical cases of ALL release through the minimally invasive lateral retroperitoneal transpsoas approach were reviewed. Operative technique, results, complications, and early outcomes were assessed.

Results. In the cadaveric study, sectioning of the ALL proved to be feasible from the minimally invasive lateral retroperitoneal transpsoas approach. The structures at most immediate risk during this procedure were the aorta, inferior vena cava, iliac vessels, and sympathetic plexus. The mean increase in segmental lumbar lordosis per level of ALL release was 10.2°, while global lumbar lordosis improved by 25°. Each level of ALL release took 56 minutes and produced 40 ml of blood loss on average. Visual analog scale and Oswestry Disability Index scores improved by 9 and 35 points, respectively. There were no cases of hardware failure, and as of yet no complications to report.

Conclusions. This initial experience suggests that ALL release through the minimally invasive lateral retroperitoneal transpsoas approach may be feasible, allows for improvement of lumbar lordosis without the need of an open laparotomy/thoracotomy, and minimizes the tissue disruption and morbidity associated with posterior osteotomies.

Key Words • extreme lateral interbody fusion • scoliosis • direct lateral interbody fusion • sagittal balance • transpsoas • anterior longitudinal ligament • minimally invasive surgery • lumbar

Abbreviations used in this paper: ALL = anterior longitudinal ligament; LL = lumbar lordosis; ODI = Oswestry Disability Index; PEEK = polyetheretherketone; PI = pelvic incidence; PT = pelvic tilt; SL = segmental lordosis; SS = sacral slope; SVA = sagittal vertical axis; VAS = visual analog scale.
Minimally invasive anterior release for deformity correction

The authors propose an alternative to the above procedures: ALL release through the minimally invasive lateral retroperitoneal transpsoas approach. This approach may provide comparable lordosis correction by lengthening the anterior spinal column with placement of a hyperlordotic cage. This is a relatively new technique; thus there is a paucity of clinical data and information on the surgical anatomy of the ALL. The goal of this cadaveric study is to describe the ALL as it relates to the anterior lengthening procedure, and to determine the procedure’s feasibility. A secondary goal is to show through 4 illustrative cases that ALL release, although technically demanding, should provide increased segmental and global lumbar lordosis in an attempt to restore sagittal balance.

Methods

Study Design

Twelve fresh-frozen human cadaveric torsos were used in the study. The average age was 64 years old (range 35–81 years). There were 9 male and 3 female specimens. The spinal column was intact from the pelvis to T-1 and the limbs had been disarticulated. Specimens were positioned on a radiolucent operating table in the lateral decubitus position and secured with tape at the pelvis and upper rib cage to prevent significant movement.

The lumbar disc spaces (L1–2 through L4–5) were accessed via the minimally invasive lateral retroperitoneal transpsoas approach in the standard fashion. The ALL was dissected from its attachment to the anterolateral border of the vertebral body while making note of surrounding structures and points of insertion.

In addition to the cadaveric dissections, this study also examined 4 patients who underwent ALL release and placement of 30° lordotic interbody PEEK cages (CoRoent XL-Hyperlordotic, NuVasive) using the minimally invasive lateral retroperitoneal transpsoas approach (Fig. 1). All patients had adult spinal deformity with sagittal imbalance via the SVA and spinopelvic parameters. Preoperative and postoperative 3-foot scoliosis radiographs were obtained while patients were standing to evaluate instrumentation and lordosis correction. Operative results, complications, and early outcomes were then assessed. A 4-question VAS and the ODI were used to assess outcome.

Surgical Technique

After induction of general anesthesia and positioning the patient in the lateral decubitus position, fluoroscopy is used to ensure proper orthogonal visualization of the target segment on anteroposterior and lateral views. The skin is marked using fluoroscopic guidance, then incised. The retroperitoneal space is entered after gentle splitting of the abdominal wall muscles and the transversalis fascia. For multilevel surgery we use a single longitudinal skin incision with individual transverse fascial incisions for each level accessed. Serial dilators traverse the psoas muscle and are positioned over the junction of the middle and posterior third of the disc space, using directional electrophysiological monitoring (NV5, NuVasive) to guide dilator placement and minimize the risk of lumbar plexus motor nerve injury. A retractor (MaxAccess, NuVasive) is placed and secured by a table-mounted flexible arm while a shim blade anchors the retractor into the disc space.

An annulotomy and extensive discectomy are then performed, paying careful attention to endplate preparation and preservation. A curved custom retractor is then gently passed along the anterior edge of the ALL and positioned between the large vessels/sympathetic plexus and the ventral aspect of the disc (Fig. 2). The great vessels are not visualized at this point as that amount of dissection would likely place the patient at greater risk than simply placing a 1–2-mm retractor. Using a custom disc blade and intradiscal distractor, the ALL is sectioned in a sequential fashion, easing the curved retractor across to the contralateral side of the disc space. Complete ALL release is confirmed when the adjacent vertebral body endplates are mobilized with minimal resistance and there is an obvious “fish-mouth” opening of the ventral disc space.

Once the endplates are prepared, an appropriately sized PEEK cage is selected. These cages range from 8–18 mm height × 22 mm width × 50–60 mm length × 10–30° lordosis, and are packed with allograft of the surgeon’s preference. The cages are anchored to the adjacent vertebral body with 1 or 2 screws to prevent ventral cage migration into the peritoneal cavity and loss of indirect decompression (Fig. 3).

Results

Cadaveric Study

Using the standard minimally invasive lateral trans-
psosas approach, adequate exposure was obtained to perform an ALL release and placement of a hyperlordotic cage. No peritoneal or retroperitoneal structures, including the bowel, lumbar plexus, aorta, inferior vena cava, iliac vessels, or sympathetic plexus were violated on any of the specimens.

**Anterior Longitudinal Ligament**

The ALL is a strong band of fibers extending along the anterior aspect of the vertebrae. It widens as you move caudally along the spine and is thicker in the thoracic than in the cervical or lumbar region. In the lumbar spine, the ALL traverses the anterior aspect of all vertebral body and disc spaces, and is composed of 3 layers: superficial, intermediate, and deep. The superficial layer traverses 4 or 5 vertebral bodies, while the intermediate layer covers 2 or 3 vertebral bodies. The deep layer of the ALL covers only the individual vertebral bodies and attaches from one vertebral body to the next. The ALL is thinner and wider at the level of the disc but thicker and narrower at the vertebral bodies. Also, it is more strongly adherent to the intervertebral disc than the middle of the vertebral body, making mobilization at the disc space difficult. There are oval apertures at the lateral aspect of the ligament to allow passage of vessels (Fig. 4).1,31,40

**Lumbar/Sympathetic Plexus**

Neural structures at risk during this procedure are similar to those in the standard lateral approach. However, because it courses dorsal to ventral in the psoas major, of all the lumbar plexus nerves, the genitofemoral nerve (L1–2) is especially at risk as it crosses the L2–3 and L3–4 disc spaces. At the caudal end of the L-4 vertebral body, it has moved anteriorly to run along with the sympathetic plexus.

The sympathetic plexus is a paired bundle of nerves running along the anterolateral border of the vertebral bodies in the lumbar spine that functions as part of the autonomic nervous system via fibers to the inferior mesenteric ganglion. The sympathetic plexus lies along the lateral border of the ALL, where it meets the psoas major, and may be encountered during an ALL release (Fig. 5). The sympathetic plexus is in communication with the lumbar plexus, with information arriving at the paravertebral ganglia through the white rami communicantes, and leaving via the gray rami communicantes. These communicating fibers run along the inferolateral aspect of the vertebral body, and generally are not encountered at the disc space where an ALL release is performed.

**Great Vessels**

The aorta and the inferior vena cava lie along the left and right anterior lumbar vertebral body border, respectively. Even when intimately associated with the ALL, there is an adipose-lined anatomical plane allowing dissection dorsal to the great vessels. There are generally 4 paired lumbar (segmental) arteries, which arise from the aorta and course laterally around the vertebral body, thus avoiding the disc space. The aorta bifurcates into the right and left common iliac arteries 18 mm rostral to the L4–5 disc space, while the right and left common iliac veins converge to form the inferior vena cava within 2 mm of the L4–5 disc space (Fig. 6).15

**Illustrative Cases**

Anterior longitudinal ligament release was successfully performed in 4 clinical cases without complication.
or conversion to open techniques (Table 1). Average operating time and estimated blood loss per level of ALL released was 56 minutes and 40 ml, respectively. The mean follow-up was 9 months (range 6–19 months). Average segmental lordosis correction was 10.2° per level of ALL release performed, while average global LL correction was 25° per patient. In all cases, patients showed significant clinical improvement and postoperative images demonstrated adequate placement of the hyperlordotic cages with global sagittal deformity correction.

Case 1

This patient was a 71-year-old woman with low-back pain and bilateral L-4 radiculopathy who had undergone L2–5 interbody fusion with dynamic stabilization 8 years prior to presentation. Preoperative VAS and ODI scores were 36 and 92, respectively. Imaging revealed proximal junctional kyphosis at L1–2, a coronal thoracolumbar Cobb angle of 9°, SVA of 7 cm, LL of 11°, PI of 57°, PT of 35°, SS of 20°, and SL at L1–2 of 3°.

The patient underwent an L1–2 ALL release through a minimally invasive lateral retroperitoneal transpsoas approach. A hyperlordotic PEEK cage was implanted and the posterior hardware was removed in addition to an extension of instrumentation from T-10 to L-5. She tolerated the procedure well with less than 50 ml of estimated blood loss during the lateral portion of the case, and no neurovascular compromise was found. Her postoperative imaging revealed a coronal Cobb angle of 4°, SVA of 3.5 cm, LL of 49°, PI of 59°, PT of 23°, SS of 28°, and SL of 12°. Postoperatively, her VAS score was 25 and ODI score was 60 (Fig. 7).

Case 2

This patient was a 58-year-old man who presented with intractable low-back pain with preoperative VAS and ODI scores of 32 and 70, respectively. Imaging studies revealed adult spinal deformity with a coronal lumbar Cobb angle of 24°, SVA of 7 cm, LL of 21°, PI of 50°, PT of 13°, SS of 30°, and SL at L3–4 of 1°.

He underwent L1–5 minimally invasive lateral retroperitoneal transpsoas interbody fusions with ALL release at L3–4 and placement of a hyperlordotic PEEK cage. This was followed by an L5–S1 minimally invasive transforaminal lumbar interbody fusion in a staged manner, with percutaneous pedicle screw fixation from T-11 to S-1. Both procedures were well tolerated, and the estimated blood loss was less than 25 ml for the lateral portion. His postoperative VAS and ODI scores were 21 and 26, respectively, and imaging revealed a coronal Cobb angle of 7°, SVA of 3.4 cm, LL of 40°, PI of 48°, PT of 9°, SS of 36°, and SL of 12° (Fig. 8).

Case 3

This patient was a 66-year-old man who presented with severe back pain radiating to the right leg with limited ability to ambulate, with preoperative VAS and ODI scores of 22 and 54, respectively. Preoperative imaging showed a thoracolumbar coronal Cobb angle of 54°, SVA of 10 cm, LL of 23°, PI of 67°, PT of 34°, SS of 18°, and SL at L2–4 of 5°.

During Stage 1, the patient underwent minimally invasive lateral interbody fusion from T-12 to L-5 with ALL release at T12–L1, L2–3, and L3–4 with placement of hyperlordotic PEEK cages, along with an L5–S1 anterior lumbar interbody fusion. Stage 2 consisted of T10–S1 posterior percutaneous pedicle screw fixation. Both procedures were tolerated well and without complication, with a total estimated blood loss of less than 100 ml. His VAS and ODI scores improved to 16 and 30, respectively, and imaging revealed a thoracolumbar coronal Cobb angle of 15°, SVA of 3 cm, LL of 50°, PI of 67°, PT of 25°, SS of 40°, and SL at L2–4 of 25° (Fig. 9).

Case 4

This patient was a 58-year-old woman with back pain and preoperative VAS and ODI scores of 40 and 86, respectively. Preoperative imaging revealed adult degenerative scoliosis with an apex at L2–3, Grade 2 anterolisthesis of L–4 on L-5, and degenerative disc changes from L-2.
Fig. 5. Illustrated photograph of cadaveric dissection demonstrating the relationship between the ALL and the sympathetic plexus. Note the complex network of communicating nerves in connection with the sympathetic plexus (rami communicantes). The genitofemoral nerve is also pictured crossing the L2–3 and L3–4 disc spaces from dorsal to ventral. Inset demonstrates the position of the cadaver during dissection.

Fig. 6. Illustrated photograph of cadaveric dissection in the right lateral decubitus position (inset). Note the inferior vena cava (IVC) ventral to the ALL on the contralateral side. The aorta is retracted. Notice also the lumbar segmentary vessel arising from the aorta. The sympathetic plexus is retracted with the aorta and genitofemoral nerve.
Minimally invasive anterior release for deformity correction

### TABLE 1: Preoperative and postoperative clinical and radiographic data for the patient cohort

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* At levels that ALL release was performed.

to L-5. It also revealed a lumbar coronal Cobb angle of 20°, SVA of 7.1 cm, LL of 33°, PI of 56°, PT of 15°, SS of 39°, and SL at L2–4 of 10°.

She underwent an L2–5 lateral minimally invasive interbody fusion with ALL release and placement of hyperlordotic PEEK cages at L2–3 and L3–4, as well as an anterior lumbar interbody fusion at L5–S1, followed by posterior fixation from L-2 to the ileum. Estimated blood loss was less than 50 ml for the first stage, and postoperative VAS and ODI scores were 33 and 46, respectively. Postoperative imaging revealed a lumbar coronal Cobb angle of 11°, SVA of –1 cm, LL of 49°, PI of 55°, PT of 14°, SS of 35°, and SL at L2–4 of 25° (Fig. 10).

**Discussion**

Sagittal spinopelvic harmony is increasingly targeted as a primary goal during the surgical management of adult degenerative scoliosis. Emerging literature has demonstrated that patients who are sagittally imbalanced postoperatively (SVA > 5 cm) tend to have worse clinical outcomes. With a positive sagittal alignment, there is increased stress on the axial musculature, which in turn leads to abnormal degenerative changes in the disc spaces, resulting in further imbalance and serving a self-perpetuating cycle. A high postoperative SVA also increases the risk for pseudarthrosis, adjacent segment disease, and proximal junctional kyphosis. Although currently no practice guidelines exist regarding minimally invasive deformity correction, here are a few key questions that should be addressed during the treatment decision-making process: 1) is the thoracic kyphosis within the normal range of 20–40°; 2) is the lumbar lordosis within 9° of the pelvic incidence; 3) how many degrees of sagittal correction are the goal; 4) are minimally invasive techniques feasible or are traditional open procedures indicated; and 5) if sagittally imbalanced, would a lateral approach with release of the ALL be feasible or is an osteotomy the best option?

Surgical correction of sagittal imbalance can be accomplished with posterior shortening or anterior lengthening techniques, which have varying effects, complication...
rates, and challenges in execution. The posterior shortening techniques, namely Smith-Petersen osteotomy, pedicle subtraction osteotomy, and vertebral column resection, are traditionally used in deformity correction. The Smith-Petersen osteotomy is generally considered a safe technique with low morbidity and is confined to resection of the laminae and articular facets, hinging the middle column in an attempt to stretch an intact ALL. Each millimeter of bone resected provides approximately 1° of correction, with a maximal correction of 10–15°. In contrast, pedicle subtraction osteotomy is a challenging procedure involving all 3 columns and may be associated with significant blood loss. After resection of the posterior elements, the anterior vertebral body is fractured while closing the osteotomy to achieve lordosis. In a vertebral column resection, the entire vertebral segment is resected in an attempt to correct significant rigid spinal deformities. The complications from this procedure are potentially devastating and it generally requires long operative times.

Advances in minimally invasive spine surgery allow for options in the treatment of spinal deformity, as many new techniques may offer similar or even improved clinical and radiographic outcomes with less morbidity than conventional approaches. In particular, the lateral retroperitoneal or retropleural approach allows access to the spine with minimal tissue disruption along a relatively bloodless plane, and has been shown to preserve coronal and sagittal balance. However, in cases of fixed sagittal imbalance, ALL release may be useful to restore proper alignment, as it can potentially provide sagittal correction similar to a Smith-Petersen osteotomy based on this study and other emerging data. This requires further investigation as the technique becomes more frequently used.

The clinical cases in this study demonstrated that VAS and ODI scores improved by an average of 9 and 35 points, respectively. Postoperative sagittal spinopelvic harmony was achieved, with an SVA ≤ 5 cm and PT < 25°. Average segmental lordosis (at the operative level) and LL correction was 10.2° and 25°, respectively. Interestingly, placement of a 30° hyperlordotic cage did not provide an equal amount of segmental lordosis. This is likely due to the intact posterior elements (facet complexes and spinous processes) acting as a hinge, which provides only ventral lengthening without dorsal compression. The dor-

![Fig. 8. Case 2. Left: Preoperative standing lateral radiograph showing LL of 21.4° and PI of 49.5°. Right: Postoperative standing lateral radiograph after placement of lumbar interbody cages at L1–5 and ALL release at L3–4, demonstrating LL of 40° and PI of 48°.](image)

![Fig. 9. Case 3. A: Preoperative standing anteroposterior radiograph demonstrating coronal imbalance (Cobb angle 54°). B: Postoperative standing anteroposterior radiograph demonstrating improved coronal balance (Cobb angle 15°). C: Preoperative standing lateral radiograph demonstrating a PI of 67.1° and PT of 34°. D: Postoperative standing lateral radiograph after T12–S1 interbody fusions and ALL release at L2–3 and L3–4, with percutaneous pedicle screw fixation from T-10 to S-1, demonstrating a PI of 66.7° and PT 25.2°.](image)
Anatomical and Technical Challenges

Releasing the ALL is technically demanding and requires a thorough understanding of the regional anatomy of the lateral retroperitoneal or retropleural approach to the spine. Although it eliminates some complications associated with posterior approaches, it is associated with its own unique set of risks in addition to those related to the standard minimally invasive lateral access. As with other minimally invasive techniques, there is a significant learning curve and will likely foster initial skepticism given the potential catastrophic complications associated with an ALL release. However, the potential benefit to patients is significant and thus should be explored further.

As with preoperative evaluation for any planned lateral retroperitoneal approach, it is essential to evaluate the patient’s MRI to determine the course of the great vessels and where the bifurcation occurs. In addition, care must be taken not to injure the ilioinguinal, iliohypogastric, or lateral femoral cutaneous nerves when accessing the retroperitoneum.

However, given its posterior to anterior course along the iliopsoas muscle at the most frequently accessed levels (L2–3 and L3–4), the genitofemoral nerve is particularly at risk. Depending on its course, opening the retractor may cause a neuropraxia that is likely dependent on both the timing and amount of stretch of the nerve. Risk of injury to this nerve may also occur when performing anterior interspace dissection to reach the ALL. Although the use of directional electrophysiological monitoring can help minimize nerve injury during the lateral approach, the genitofemoral nerve is mainly sensory and unable to be monitored without scrotal or labial electrodes.

Another pitfall comes with dissecting the sympathetic plexus and great vessels off the ALL using the curved custom retractor, which carries the risk of a potentially catastrophic aortic or inferior vena cava injury. The cadaveric dissection in the current study reveals several important pieces of information to assist in navigating the ALL during an ALL release. The target of the retractor blade is the plane of dissection dorsal to the sympathetic plexus/great vessels and ventral to the ALL. However, a unique problem associated with this procedure is dissection in the plane ventral to the sympathetic plexus and dorsal to the great vessels. If this occurs unbeknownst to the surgeon, inadvertent damage may be done to the sympathetic plexus unilaterally. At this point, ramifications of such an injury have been unexamined and require further study. It is likely that injuries occur during these dissections to the gray and white rami communicantes, which connect the sympathetic plexus to the spinal nerve roots. However, given the many overlapping connections existing between these structures, the authors believe that injury at 1 or 2 levels is unlikely to produce any significant clinical consequence.

After reaching the contralateral interspace with the retractor, a fresh no. 11 blade, rather than monopolar electrosurgery, should be used to incise the ALL to prevent thermal injury to the sympathetic plexus and nearby vascular structures. Opening the intradiscal distractor should then produce a “fish-mouth” deformity at the disc space. If this does not occur, it is likely that the ALL is not fully cut. The variety of hyperlordotic cages (10–30°) enables the surgeon to fit each disc space appropriately. The cage should be placed between the anterior and middle third of the disc space, which is anterior to the suggested position of a lumbar interbody cage placed from the lateral decubitus position. The purpose of this is to provide ligamentotaxis of the posterior longitudinal ligament and indirect foraminal decompression at that level. Two transversely oriented screws are used for the sole purpose of securing the cage and preventing ventral migration into the peritoneal cavity. The mechanical stability provided by these screws is likely negligible.

Study Limitations

The authors of this study acknowledge that only 1
operative approach to ALL release has been described in this study. Undoubtedly, other nuances and approaches can be used as the technique evolves, as happens with most surgical procedures. Also, one must be careful and realize that anatomical and physiological variability may exist between a cadaver and a live patient. For example, the vascular structures in a cadaver are generally collapsed and at significantly lower risk of being injured in a dissection. However, to this point at our institution, 12 cases of ALL release have been performed with no vascular injuries. This study focused only on anterior correction, while additional posterior compressive osteotomies may lead to greater segmental and global lordosis, which may be examined in a future study. In addition, fluoroscopic limitations may decrease the accuracy of our measurements.

As with all clinical studies, more data may be collected from a longer follow-up period. However, we believe that the true value of this study is to demonstrate the feasibility of this procedure with respect to deformity correction. Further investigations are necessary to evaluate long-term outcomes of ALL release, and perhaps a prospective study comparing different techniques for deformity correction may be pursued.

Conclusions

Releasing the ALL using the minimally invasive lateral retroperitoneal transpsoas approach may provide an alternative to both anterior lumbar interbody fusion and posterior osteotomies for the restoration of segmental lordosis. Through our clinical cases and cadaveric dissections, we attempt to show that this is a technically challenging yet feasible procedure that should be kept in the armamentarium used to treat spinal deformity. The specific utility of ALL resection and minimally invasive lateral deformity correction will be better understood as more experience is gained with this approach through clinical applications.

Disclosure

Dr. Uribe is a paid consultant and receives research grants from NuVasive, LLC.

Author contributions to the study and manuscript preparation include the following. Conception and design: Deukmedjian, Baaj, Dakwar, Uribe. Acquisition of data: Deukmedjian, Smith, Uribe. Analysis and interpretation of data: Deukmedjian, Smith, Uribe. Drafting the article: Deukmedjian. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Deukmedjian. Statistical analysis: Deukmedjian. Study supervision: Uribe.

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