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Computer-assisted virtual operation planning in anterior controllable anterior-displacement and fusion surgery for ossification of the posterior longitudinal ligament based on actual computed tomography data

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ABSTRACT

Objectives: To investigate the effect of computer-assisted virtual operation planning (CAVOP) on anterior controllable anterior-displacement and fusion (ACAF) surgery for ossification of the posterior longitudinal ligament (OPLL).

Patients and methods: A total of 25 patients with OPLL were enrolled in the study from September 2017 to December 2017. Preoperative Computed tomography (CT) scanning data were input into Mimics software to reconstruct three-dimensional (3D) models of actual cervical OPLL.Preoperative simulation of each surgical procedure and measurement of main parameters for intraoperative decision were conducted. Postoperative CT were used to test the clinical value of the preoperative planning. Width of vertebrae-OPLL complex (VOC), thickness of resected vertebral body (VB), height of intervertebral spacer, and length of screws and anterior plate were analyzed.

Results: There were no significant differences between the length of screws, width of VOC, and thickness of anterior resection of vertebrae in preoperative CT and postoperative CT. Statistical differences were found between preoperative and postoperative height of intervertebral space and length of anterior plate.

Conclusion: A virtual ACAF surgical procedure for OPLL is feasible and useful clinically in surgical planning. It may provide a valuable tool for surgeons in formulating an appropriate surgical plan.

1. Introduction

Ossification of the posterior longitudinal ligament (OPLL) is frequently related to cervical myelopathy [1,2]. Patients with progressive myelopathy require surgical treatment [3]. Anterior and posterior decompression are two main surgical strategies used for the treatment of OPLL. The anterior decompression surgery could gain a direct decompression and satisfactory neural function recovery [4]. However, it is more technically demanding and involves in more complications [5].

We have previously reported a novel technique named anterior controllable anterior-displacement and fusion (ACAF) as an alternative surgical technique for traditional anterior decompression surgery [6]. The idea of ACAF is to isolate and hoist the vertebrae-OPLL complex (VOC) ventrally to restore the space of the spinal canal and thus achieve direct decompression of the neural elements without resection of the OPLL [7].

The key procedures of ACAF are isolation of the VOC from the surrounding bony tissue and ventrally hoisting of the isolated VOC. The treatment principles of ACAF might seem simple, but this surgery often involves several specific and difficult issues. The lateral border of VOC should be wide enough to include the OPLL. However, the risk of damaging vertebral artery or cervical pedicle would be increased when the border of the VOC was too wide [8]. The amount of resection at each anterior vertebral body is determined by the thickness of the OPLL at each level. All of these data are vital for performing the surgery. However, the OPLL cannot be observed directly in ACAF and these data are hard to be obtained intraoperatively. Thus, preoperative planning is with paramount importance in ACAF surgery.

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Computer-assisted virtual operation planning (CAVOP) has been reported to help improving surgical precision in individual dental surgery, maxillofacial surgery, liver resection, and acetabular fracture reduction [9–12]. The purpose of our study was to explore the application methods and clinical value of virtual operation planning in ACAF for the treatment of OPLL.

2. Materials and methods

2.1. Patients and data acquisition

We retrospectively reviewed patients with OPLL who were treated with ACAF in our institute from September 2017 to December 2017 and twenty-five patients were included in this study. Exclusion criteria were as follows: 1) patients with a history of previous cervical surgery. 2) cervical tumor, trauma, and infection. 3) cervical myelopathy due to other causes such as disc herniation. All patients underwent preoperative and postoperative computed tomography (Sensation 64, Siemens Medical Solutions, Germany) scanning. This study was conducted with approval from the Ethics Committee of our hospital. Written informed consent was obtained from all participants.

2.2. Establishment of three-dimensional model

The original patient data were input with the Digital Imaging and Communications in Medicine (DICOM) format, and the thickness of the fault was set as 1 mm to obtain a vivid virtual OPLL cervical spine. The cervical vertebrae were identified semi-automatically based on DICOM data using the MIMICS software. Every level from C2 to C7 of each patient was separated and reconstructed into a three-dimensional (3D) model for further parameter calculation. 3D model was created automatically. Firstly, identification of the vertebra was conducted by using a threshold of 226–3071 HU for the detection of bone. Secondly, each vertebra was detached from the other vertebrae using both axial and sagittal slice images. Thirdly, the region of vertebra was isolated using the same threshold, and a 3D model was created (Fig. 1).

2.3. Virtual operation planning

All virtual objects with all parts of it can be independently and freely moved, removed, and fixed in a 3D plane. The cervical spine was placed in a supine position. Firstly, bilateral osteotomies for the complete isolation of the VOC were conducted. Secondly, the VOC were moved ventrally to gain restoration of the AP diameter of the spinal canal. An anterior cervical plate and screws were installed. Resection of the anterior vertebral bodies of the VOC was then performed (Fig. 2).

2.4. Main observation parameters

On the preoperative planning model, the width of bilateral osteotomies for VOC isolation was recorded (Fig. 3). The levels of VOC, height for the intervertebral spacer, thickness of anterior resected vertebral body (VB), length of screws, length of anterior plate was recorded on the preoperative model after the CAVOP (Table 1). The time needed for creation of a patient's individual digital model were measured.

Follow-up was conducted in all patients for at least 3 months. Japanese Orthopaedic Association (JOA) score were used to assess the degree of disability. An improvement rate (IR) of neurologic function was calculated as IR = (postoperative JOA score – preoperative JOA score / 17 – preoperative JOA score) ×100%. Surgical outcome was defined by the IR as follows: excellent (IR > = 75%), good (75% > IR > = 50%), fair (50% > IR > = 25%), and poor (IR < 25%). All patients underwent postoperative CT within 2–4 days

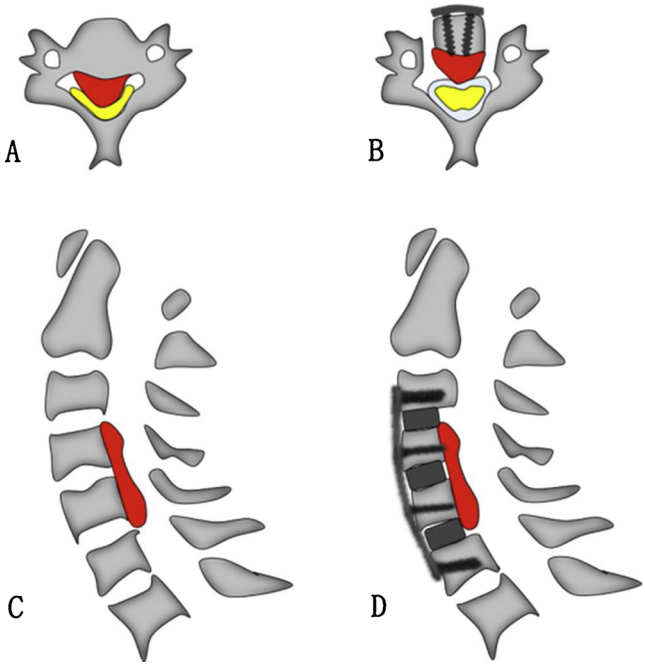

Fig. 1. Illustration of the procedures of the ACAF technique. Axial plane (A) and sagittal plane (C) of cervical spine demonstrating the huge OPLL mass; the completely isolated VOC and the antedispacement of the OPLL achieved by gradually tightening the screws in each vertebra at the same pace (B, D). ACAF: anterior controllable anterior-displacement and fusion; OPLL: ossification of the posterior longitudinal ligament; VOC: vertebrae-OPLL complex.

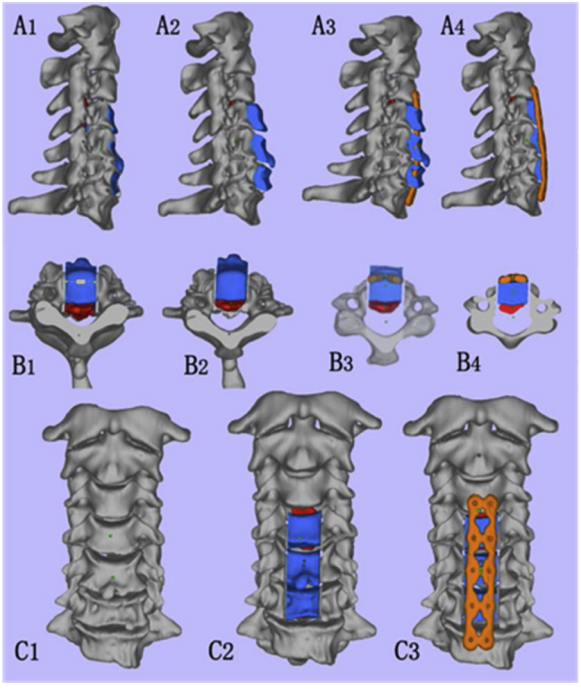

Fig. 2. Illustration of the virtual operation planning on a three-dimensional model. Intact model (C1); bilateral osteotomies for the complete isolation of the VOC (A1, B1, C2); Anterior-displacement of the VOC to gain restoration of the AP diameter of the spinal canal (A2, B2); Installation of an anterior cervical plate(A3, B3); Resection of the anterior vertebral bodies of the VOC (A4, B4, C3). VOC: vertebrae-OPLL complex; AP: anteroposterior.

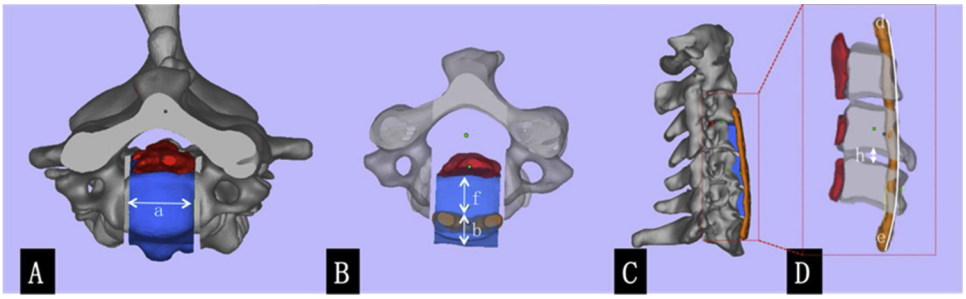

Fig. 3. Illustration of the main observation parameters. Preoperative width of VOC is measured after the bilateral osteotomies on the axial plane (A); Preoperative thickness of anterior resected VB (b) and length for screws (f) were measured after the anterior-displacement of VOC on the axial plane (B); Preoperative height for intervertebral spacer (h), preoperative length of anterior plate was measured on the sagittal plane (C, D). VOC: vertebrae-OPLL complex; VB: vertebral body.

after surgery. The main observation parameters of the preoperative virtual operation planning were then assessed on the postoperative CT to evaluate the effects of the CAVOP.

Radiologic assessments in this study were investigated by two radiologists who were blind to this study using the same conditions and the same systems, and interclass coefficient was analyzed.

2.5. Statistical analysis

Statistical analysis was performed using SPSS. Preoperative and postoperative main observation parameters which were related and paired were compared using pair *t*-test The level of significance was set at $p < 0.05$.

3. Results

3.1. Demographic and clinical data of patients

Twenty-five patients (16 males and 9 females) were finally enrolled in this study. The mean age of patients in this study was 61.3 ± 6.2 years old (43–68). The mean operative time was 124.7 min (range, 90–156 minutes), with the mean blood loss of 215.8 milliliters (range, 150–400 milliliters). The mean JOA score increased from 8.6 ± 2.1 (range, 5–13) at preoperation to 14.6 ± 2.0 (range, 10–16) at the 3-month follow-up. The average IR was 67.2% ± 12.3% (Table 2).

Table 2
Clinical data of the patients.

Item	Patients
Number of patients (male/female)	25 (16/9)
Age (years old)	61.3 ± 6.2(43-68)
Time for preoperative planning (min)	
3D model establishment	35.7 ± 6.5(20-60)
Virtual operation planning	17.2 ± 5.3 (10-35)
Measurement of the parameters	5.3 ± 0.9(4-8)
Operative time (min)	124.7 ± 15.4 (90-156)
Blood loss (ml)	215.8 ± 25.2 (150–400)
JOA score	
Before surgery	8.6 ± 2.1 (5–13)
3 months after surgery	14.6 ± 2.0 (10–16)
IR 3 month after surgery, %	67.2 ± 12.3 (41.7–88.9)

Measurement data are expressed as the mean ± standard deviation (range), JOA: Japanese Orthopaedic Association; IR: improvement rate.

3.2. Evaluation of software operation time

Establishment of the 3D model was the most time-consuming in preoperative planning. The average time used for 3D model establishment was 35.7 min (20–60 min). The mean time used for the virtual ACAF planning was 17.2 min (10–35 min). The mean time used for measuring the parameters was 5.3 min (4–8 min)

Table 1
Definition of anatomical parameters.

Parameters	Remarks
a = Preoperative width of VOC	Preoperative width of VOC in each level is the distance between the medial borders of bilateral osteotomies on the virtual operative planning model. The preoperative width of VOC of each case is the average value obtained from each level of OPLL.
a' = Postoperative width of VOC	Postoperative width of VOC in each level is the distance between the medial borders of bilateral osteotomies on the postoperative CT. The postoperative width of VOC of each case is the average value obtained from each level of OPLL.
b = Preoperative thickness of resected VB	Preoperative thickness of resected VB in each level is the distance between the ventral surface of the anterior plate and anterior border of the VB on the virtual operative planning model. The preoperative thickness of anterior resected VB of each case is the average value obtained from each level of OPLL.
b' = Postoperative thickness of resected VB	Postoperative thickness of resected VB in each level is the differences between the anterioposterior diameter of the preoperative and postoperative VB. The postoperative thickness of anterior resected VB of each case is the average value obtained from each level of OPLL.
h = Preoperative height for intervertebral spacer	Preoperative height for the intervertebral spacer in each level is the average height of the anterior, middle and posterior part of the intervertebral space on the virtual operative planning model. Preoperative height for the intervertebral spacer of each case is the average value obtained from each level of OPLL.
h' = Postoperative height for intervertebral spacer	Postoperative height for the intervertebral spacer is the height of the intervertebral spacer used in actual surgery. Postoperative height for the intervertebral spacer of each case is the average value obtained from each level of OPLL.
f = Preoperative length for screws	Preoperative length for the screws in each level is the distance between the ventral surface of the anterior plate and posterior border of the VB on the virtual operative planning model. The preoperative length for the screws of each case is the average value obtained from each level of OPLL.
f' = Postoperative length for screws	Average length of the screws used in actual surgery.
l = Preoperative length of anterior plate	Length of anterior plate on the virtual operative planning model.
l' = Postoperative length of anterior plate	Length of anterior plate used in actual surgery.

VB: vertebral body, OPLL: ossification of the posterior longitudinal ligament, VOC: vertebrae-OPLL complex, mm: millimeter.

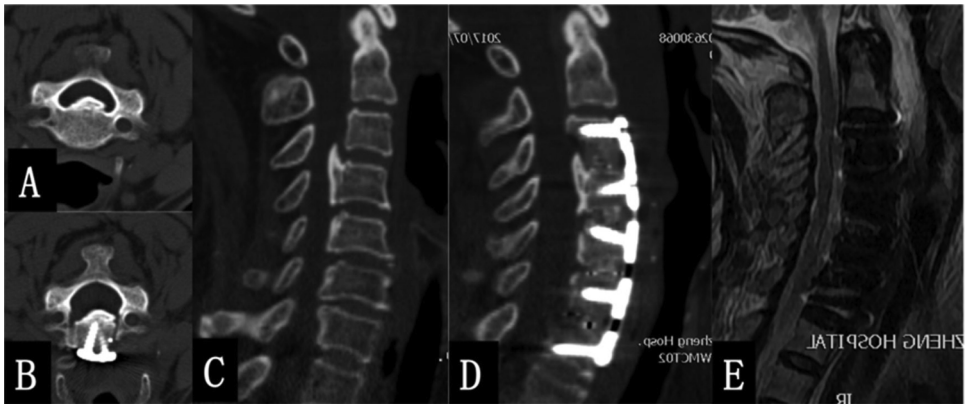

Fig. 4. Radiologic information of the demonstrating case. Preoperative CT demonstrated C4-6 segmental type OPLL (A, C). Postoperative CT demonstrated satisfactory anterior-displacement of VOC from C4 to C6 (B, D); Postoperative T2-weighted MRI demonstrated satisfactory decompression has been achieved (E). OPLL: ossification of the posterior longitudinal ligament; ACAF: anterior cervical corpectomy and fusion; CT: computed tomography; VOC: vertebrae-OPLL complex; MRI: magnetic resonance images.

3.3. Case present

A 56-year-old man experienced walking disturbance for 3 years with numbness in left hands for 1 year. Neurological examination revealed a motor deficit of his limbs with 4 of 5 muscle strength. In addition, the patient had clumsiness of both hands and sensation decrease in limbs and trunk. The JOA score is 11. The knee and ankle-jerks reflex are hyperactive, and Hoffman and Babinski sign is positive. CT demonstrated C4-6 multilevel segmental-type OPLL (Fig. 4). MRI revealed the spinal cord was compressed from C4/5 to C6. After 3D reconstruction of the cervical spine model, the virtual ACAF planning was performed. The width of bilateral osteotomies for VOC isolation was 15 mm. The height of intervertebral space was 5 mm, thickness of anterior resected VB was 3 mm, and length of anterior plate was 72 mm.

After general anesthesia, patient was placed in a supine position. A right lateral incision was implemented to expose C3-C7. Firstly, discectomies of C3/4, C4/5, C5/6 and C6/7 were carried out. In the levels of C3/4 and C6/7, the posterior longitudinal ligament was resected to facilitate the further hoisting of the VOC. On the contrary, no resection of the posterior longitudinal ligament was needed in the levels of C4/5 and C5/6. Secondly, resection of the anterior vertebral bodies of the C4, C5 and C6 was performed by Leksell rongeur and high-speed burr. The amount for the resection of anterior vertebral body was determined by the data gained from the CAVOP. Intervertebral spacers filled with autogenic bone harvested from the former procedure were inserted at each level. Thirdly, the anterior cervical plate was placed from C3 to C7. The screws were installed after proper drilling and taping on the remaining vertebral bodies. After the placement of the plate and screws, the VOC was temporarily stabilized. Fourthly, a 2-mm high-speed cutting burr was used to thin the bilateral corticocancellous bone from C4 to C6 and 1 mm Kerrison rongeurs was used to remove the posterior vertebral wall on the bottom of the troughs for the complete isolation of the VOC. Fifthly, the VOC was hoisted via gradually tightening the screws in C4, C5 and C6 vertebra. Lastly, autogenic bone was graft into the bilateral troughs to obtain further fusion of the VOC with the surrounding bone.

After the surgery, the patient got immediate release of numbness of left hand. MRI showed satisfactory decompression of the spinal cord (Fig. 4). A neck collar was used for 3 months. He recovered without any complication related to the surgery. At 3-month's follow-up, the patient's JOA was increased to 15. Flexion and extension views of lateral plain X ray after 3 months of the operation were performed to ensure no pseudoarthrosis exists.

3.4. Evaluation of postoperative effects

In 25 cases with planned VOC levels, 24 cases adopted the planned VOC levels completely. One patient underwent ACAF with one level less than the preoperative planning. The average preoperative width of VOC was 16.6 mm. The average preoperative height for intervertebral spacer was 4.7 mm. Preoperative thickness of resected VB was 4.7 mm. Preoperative length for the screws was 13.2 mm. Preoperative length of anterior plate was 70.5 mm. The average postoperative width of VOC was 15.9 mm. Postoperative height of intervertebral space was 5.5. Postoperative thickness of resected VB was 4.9 mm. Postoperative length for the screws was 13.6 mm. Postoperative length of anterior plate was 76.2 mm. Statistical differences were found between preoperative and postoperative height of intervertebral space and length of anterior plate (Table 3).

3.5. Inter-observer reliability

Inter-observer reliability was excellent for all cervical radiographic parameters in the two independent observers.

4. Discussion

Ossification of the posterior longitudinal ligament (OPLL) has been recognized as one of the most common causes of severe cervical myelopathy in East Asian population. There are two main surgical strategies used for the treatment of OPLL and can be broadly divided into anterior and posterior decompression surgery. The posterior decompression surgery is safer than the anterior decompression surgery for it needs no resection of the ventral compression component. However, the effect of the indirect posterior decompression relies much on the cervical lordosis alignment. In cases with bad cervical lordosis or severe OPLL lesion, the neurological improvement is always diminished [13].

The anterior decompression surgery removes the compressive component and directly relieves the cervical spinal cord with a proven satisfactory clinical outcome [14,15]. However, when dealing with severe OPLL, the anterior decompression becomes a technical challenge [16]. The incidence rate of complications includes cerebrospinal fluid leakage, hardware failure, or neural injury was reported higher than that of posterior decompression surgery [17].

We have previously reported a novel technique named anterior controllable anterior-displacement and fusion (ACAF) as an alternative surgical technique for ACCF. The technique gained satisfactory clinical outcome with less complications according to the preliminary result [18]. The idea of ACAF is to isolate and "actively transport" the OPLL ventrally to restore the normal volume of the spinal canal and thus achieve direct decompression of the spinal cord and nerve roots. The remaining vertebral body and OPLL mass are then served as autogenous bones for the reconstruction of the cervical spine.

The key procedure of ACAF is bilateral longitudinal osteotomies and ventrally hoisting of the isolated VOC. The lateral border of VOC should be wide enough to include the OPLL. However, the risk of damaging vertebral artery or cervical pedicle would be increased when the border of the VOC was too wide [19]. The amount of resection at each anterior

Table 3
Clinical pre and postoperative data of the main observation parameters.

Parameters	Preoperative	Postoperative
Level of VOC	3.2 ± 0.3(2-4)	3.1 ± 0.3(2-4)
Height for the intervertebral spacer (mm)	4.7 ± 0.4(3.3-7.5)	5.5 ± 0.6(4.0-7.0)*
Width between the osteotomies (mm)	16.6 ± 1.3 (14.4-20.1)	15.9 ± 2.1(13.2-19.5)
Thickness of resected VB (mm)	4.7 ± 1.2 (3.2-7.5)	4.9 ± 1.1 (3.3-7.8)
Length for the screws	13.2 ± 1.5 (11.5-19.3)	13.6 ± 1.3 (12-18)
Length of the plate (mm)	70.5 ± 5.0 (65.0-84.0)	76.2 ± 4.6 (68.0-86.0)*

Level of VOC was counted as the average number of antedisplaced vertebrae. Measurement data are expressed as the mean ± standard deviation (range). *P < 0.05 (compared with preoperative data).
VB: vertebral body, VOC: vertebrae-OPLL complex, mm: millimeter.

vertebral body is determined by the thickness of the OPLL at each level. All of these data are vital for performing the surgery. However, the OPLL, pedicle and vertebral artery cannot be observed directly during the surgery. Our previous anatomy study showed that UP could be served as an anatomic landmark for longitudinal osteotomies in ACAF surgery. However, preoperative measurement of CT images of each case should be conducted for an individual-dependent surgical planning of ACAF [8].

Computer technology has been widely used in spine surgery. Spinal technology involves imaging, navigation, and robotics, collectively known as “image-guided therapy” [20]. Imaging coupled with navigation enhances visualization of irregular anatomy, enabling the surgeons to perform quicker and safer hand movements with increased accuracy. Even though computer technology holds great potential for performing spinal surgery, it requires the use of expensive surgical assistance instruments, and is rarely applied in daily cervical spine surgery, especially in the current cost-effective era [21,22].

The Computer-assisted Virtual Operation Planning (CAVOP) has been used in pelvic tumors, maxillofacial surgery, and pelvic fractures. Giovinco et al. reported the usage of CAVOP in the preparation for the surgical reconstruction of a deformed Charcot foot [23]. This CAVOP provided an affordable and reproducible, personalized preoperative plan, and allowed the surgeons to practice and refine the surgical approach in the preoperative setting. In pelvic-acetabular surgeries, CAVOP could be used in simulating the reduction for acetabular fractures and calculating the trajectory and size of the screws using real CT scan data [24]. These studies have demonstrated that surgeons can obtain an optimal operative plan on their computers using the exported CT data of the patients and achieve satisfactory results via an interactive operation planning tool. However, the use of CAVOP has been relatively rare in spine surgery.

After using Mimics software to simulate an ACAF surgery in cervical OPLL model, we find the actual ACAF surgery more simplified as each step of the procedure has been simulated in the CAVOP (Fig. 2). No attention is required during the CAVOP on osteotomies and surgical risks such as iatrogenic injury of neural elements or vertebral artery. On the contrary, the key data required for the operation are accurately obtained through virtual operation in the clear view of the anatomical structure (Fig. 3). For example, the width of OPLL and location of transverse foramen can be directly observed in the cross -section plane of cervical model. The optimal width of VOC can be easily determined with thorough decompression and the least risk of vertebral artery injury.

As shown in the results, the patients underwent ACAF have all gained satisfactory outcome. The decompression effect of ACAF depends on the extent of anterior-displacement of VOC. In actual operation, intraoperative CT reconstruction can be done with O-arm to confirm the space between the anterior plate and remaining VB is enough for anterior-displacement of VOC. However, effect of radiation for the patient is a big concern for the use of intraoperative CT. In virtual surgery, we can change the sequence of the surgical procedure. Firstly, anterior-displacement of the VOC is conducted. An anterior plate with satisfying length is selected. Thus, the amount of the anterior resection of the VB is naturally determined and served as an important parameter for the intraoperative procedure.

The selection of the length of screws in each segment is also an important issue in ACAF operation. To increase the purchase of the screws, we tend to use the longest screw without damaging the spinal cord. However, the risk of perforating the posterior wall of the VB together with the concern of over exposure of radiation makes the accurate selection of the optimal length of screws difficult. While in the CAVOP, the length for the screws can be directly measured after the anterior-displacement of VOC and installation of anterior plate. The length for the screws gained from CAVOP can then be used in the actual operation, which might help decrease the number of intraoperative fluoroscopic imaging and optimize the length of screws.

According to the results, there is a high consistency between the data in preoperative design and the data in actual operation, which indicates that CAVOP can accurately assist surgery. The CAVOP may be helpful to reduce the time of operation. The time saving effect of CAVOP may be caused by the accurate selection of the width of VOC, so as to reduce the time wastage used in osteotomy of the pedicle, hemostasis of the intervertebral foramen vein, adjustment and replacement of the intervertebral spacer, anterior plate and screws.

However, it is important for a surgeon to keep in mind the difference between virtual and real conditions. The difference is mainly due to the difference of body position. Virtual data were obtained from preoperative CT. When CT was taken, the patient was awake and in natural supine position. While during operation, the patient was under general anesthetic. The paraspinal muscles were completely relaxed. Meanwhile, the cervical curvature was adjusted to an over extend position. In this way, the cervical curvature in actual surgery is usually larger than the cervical curvature in CAVOP. Therefore, the length of anterior plate used in surgery is larger than that in the CAVOP. Another discrepant data is the height of the intervertebral spacer. Our result is that the height of the intervertebral spacer in actual surgery is 1 mm more than that in the CAVOP. In addition to the former mentioned increase in the curvature of the cervical spine and the increase in the height of the intervertebral body, the trimming of the end plate is also an important reason for the difference.

This present study has several limitations. First, the patient sample was small and the duration of follow-up was relatively short. More studies with more patients and longer -term follow-up will be required in the future. Secondly, in this study, the length for screws, neurologic recovery, blood loss, and operative time of ACAF with CAVOP could not be directly compared with those associated with ACAF without CAVOP. Prospective, randomized, controlled studies may be required to adequately investigate these issues.

5. Conclusion

A virtual ACAF surgical procedure for OPLL is feasible and useful clinically in surgical planning. It may provide a valuable tool for surgeons in formulating an appropriate surgical plan. Our study may serve

as an impetus for exploring the use of computer-assisted virtual operation planning in clinical applications for cervical spine surgery.

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Conflict of interest

The authors declare that they have no conflict of interest.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent

Informed consent: "Informed consent was obtained from all individual participants included in the study."

Acknowledgment

The Manuscript submitted does not contain information about medical device(s)/drug(s).

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