Computer-Based 3D Simulations to Formulate Preoperative Planning of Bridge Crane Technique for Thoracic Ossification of the Ligamentum Flavum

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Background: The bridge crane technique is a novel surgical technique for the treatment of thoracic ossification of the ligamentum flavum (TOLF), but its preoperative planning has not been studied well, which limits the safety and efficacy of surgery to some extent. The purpose of this study was to investigate the method of application and effect of computer-aided preoperative planning (CAPP) on the bridge crane technique for TOLF.

Material/Methods: This retrospective multi-center included 40 patients with TOLF who underwent the bridge crane technique from 2016 to 2018. According to the utilization of CAPP, patients were divided into Group A (with CAPP, n=21) and Group B (without CAPP, n=19). Comparisons of clinical and radiological outcomes were carried out between the 2 groups.

Results: The patients in Group A had higher post-mJOA scores and IR of neurological function than those in Group B (p<0.05). Group A had shorter surgery time, fewer fluoroscopic images, and lower incidence of complications than Group B. In Group A, there was a high consistency of all the anatomical parameters between preoperative simulation and postoperative CT (p>0.05). In Group B, there were significant differences in 3 anatomical parameters between postoperative simulation and postoperative CT (p<0.05). In Group B, the patients with no complications had higher post-SVOR and lower SVRR and height of posterior suspension of LOC in postoperative CT than those in postoperative simulation (p<0.05).

Conclusions: CAPP can enable surgeons to control the decompression effect accurately and reduce the risk of related complications, which improves the safety and efficacy of surgery.

MeSH Keywords: Computer-Aided Design • Neurosurgery • Spine • Spondylosis

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**Background**

Thoracic ossification of the ligamentum flavum (TOLF) is commonly considered as a primary contributor to thoracic myelopathy in East Asia [1–3]. Due to its progressive feature and poor efficacy for conservative therapy, surgical treatment is usually a preferred choice [4,5]. However, the clinical outcomes of surgical intervention are often unsatisfactory and its risk is also high, which is accompanied by various complications such as cerebrospinal fluid leakage and neurological deficit [6–9].

A novel surgical method named the bridge crane technique was proposed recently to reduce the incidence of complications and improve the efficacy of treatment of severe TOLF [10]. Its core concept lies in the isolation and suspension of the laminae-OLF complex (LOC) for direct decompression of the thoracic spinal cord without resection of the TOLF. Although the idea of the bridge crane technique might seem simple, there are still several unresolved problems in clinical practice. Firstly, the border of the ossified mass is irregular and it cannot be observed directly during the operation. If the range of isolation of LOC is insufficient, the residual ossified lesions can increase the risk of neurologic deterioration and recurrence [11–13]. Conversely, if the range of isolation of LOC is excessive, resection of the facet joints can cause kyphosis [14,15]. It is necessary to position the ossified mass precisely and determine the range of isolation before surgery. Secondly, the decompression effect mainly depends on the posterior shifting of the LOC. The distance of posterior shifting of the LOC is determined by the length of pedicle screws outside the bone, the amount of excision of the spinal processes, and the curvature and position of the transverse connectors. Insufficient length, amount of excision, or curvature can cause incomplete decompression. Conversely, if they are excessive, they can increase the risks of screw loosening and spinal instability [16]. Furthermore, excessive posterior shifting also might lead to dural tears and cerebrospinal fluid (CSF) leakage [17]. Thirdly, the curvature of the longitudinal rods is closely related to the length of pedicle screws outside the bone at each level and the physiological curvature of thoracic spine. However, the curvature is not usually predictable and the surgeon has to bend the rods repeatedly for adaption to the screw grooves, which can increase the risk of rod breakage [18,19]. In clinical practice, it is difficult for surgeons to control so many parameters within appropriate ranges at the same time due to the lack of a quantitative analysis technique. More importantly, surgeons usually lack an effective method to measure the distance of posterior shifting of the LOC and to evaluate the decompression effect accurately during the operation, so the key to a successful operation is good preoperative planning.

Currently, computer-aided design (CAD) technology is applied in the preoperative planning of various surgeries due to its low cost, individuality, accuracy, and repeatability [20–23]. Computer-aided preoperative planning (CAPP), which is based on three-dimensional (3D) anatomical reconstructions and quantitative data analysis, is gradually replacing the traditional approach based on 2D images and surgeon expertise [24,25]. CAPP can provide the visual surgical simulation and optimal operation scheme for the surgeons, which saves operation time, minimizes the surgical risks, and improves clinical outcomes [26–28].

Therefore, the purpose of the present study was to investigate the method of application and effect of CAPP on the bridge crane technique for treatment of thoracic ossification of the ligamentum flavum.

**Material and Methods**

**Patient population**

A retrospective, multi-center study of patients who underwent the bridge crane technique for TOLF was conducted in 3 hospitals (Shanghai Changzheng Hospital, Ningbo No. 906 Hospital of the People’ Liberation Army, and Guangzhou General Hospital of Guangzhou Military Command) from March 2016 to December 2018. The diagnosis of TOLF was based on clinical signs, symptoms, and preoperative computed tomography (CT) scanning. Patients underwent scanning with 1-mm slice thickness (Siemens 64-Slice CT Scanner, Germany). The inclusion criteria were: (1) Thoracic myelopathy and (2) TOLF. The exclusion criteria were: (1) thoracic ossification of the posterior longitudinal ligament (OPLL) (2) spinal surgery, trauma, tumor, deformity, or infection, and (3) incomplete follow-up data. After filtering, 40 patients were enrolled in the study and were divided into Group A (with CAPP, n=21) and Group B (without CAPP, n=19). This study was conducted with approval from the Ethics Committee of our hospital. Written informed consent was obtained from all participants.

**Establishment of 3D model**

The preoperative scanning data of these patients were saved as Digital Imaging and Communications in Medicine (DICOM) files. The DICOM files of these patients were imported into MIMICS Medical 19.0 software (Materialise, Inc., Belgium) [29]. The operating procedures of establishing the spine 3D model are presented in Figure 1A and were as follow: (1) A bone mask was created by setting a thresholding of bone (226-2998 Hounsfield Unit (HU)). (2) The required region (T8–T12) of the bone mask was selected by pressing the Crop mask button. (3) According to the CT value and anatomy, the selected mask (T8–T12) was revised further by pressing the Edit mask button. (4) The mask of spine (T8–T12) was obtained, and then the mask of TOLF

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was obtained by using the same method. (5) The obtained spine mask (T8-12 and TOLF) was converted into a 3D object by pressing the Calculate 3D button. (6) The spine 3D model was saved as Stereolithography (STL) files.

The pedicle screws, nuts, longitudinal rods, and transverse connectors were reconstructed in Pro/Engineer 5.0 software (PTC, Inc., USA) [30]. The operating procedures of establishing the surgical instrument 3D model are shown in Figure 1B and were as follows: (1) A specified mode named mmns_part_solid was opened. (2) By using the Extrude and Geometric tool, the surgical instruments were drawn according to their real shape and size, and the screw threads were inserted into the pedicle screw by pressing the Protrusion button. (3) The obtained surgical instrument 3D model was saved as STL files.

Finally, the STL files of thoracic spine and surgical instruments were imported into 3-matic Medical 11.0 software (Materialise, Inc., Belgium) for subsequent use in virtual surgery [31].

**Surgical simulation**

The virtual surgery was performed in 3-matic Medical 11.0 software. Visualizing, excising, and moving were the main operations of the virtual surgery, which were realized by sequentially...
pressing the Transparency, Trim, and Interactive Translate buttons (Figure 1C).

The procedures of the bridge crane technique in virtual surgery were different from those in real surgery (Figure 2A, 2B2–2D2). Firstly, the transparency of the 3D model was increased to make the ossified mass visible in the coronal plane (Figure 3A, 3B). According to the size and shape of the ossified mass, the LOC was safely isolated. Secondly, the LOC was suspended posteriorly based on the evaluation of spinal canal stenosis (Figure 3C). Thirdly, the physiological curvature of the thoracic spine was measured in the sagittal plane. Two longitudinal rods were bent with a similar curvature. The pedicle screws were placed in the bone as deeply as possible and their length outside the bone was not retained. The rods were installed on pedicle screws, and zero-curvature transverse connectors were installed on the rods (Figure 3D). Then, the spinal processes of the involved laminae were excised and sutures were buried at the base of the LOC (Figure 3E).

Finally, if the values of these parameters were not in the appropriate range or could not meet the demand for complete decompression, they would be adjusted in a specific order until satisfactory data were obtained (Figure 2E2). Firstly, changing the position of the transverse connectors could increase the distance between the LOC and transverse connectors (Figure 2D1, Figure 4E). Secondly, if satisfactory decompression was not yet met, the amount of excision of the spinal processes would be increased to enlarge the extent of posterior suspension. Thirdly, the length of pedicle screws outside the bone were retained appropriately. The curvature of the longitudinal rods should also be adjusted for adaption to the screw grooves according to the changed length of all the pedicle screws outside the bone at each level. Finally, the curvature of the transverse connectors was also increased if the previous steps did not work.
Intraoperative application

During the actual surgery, the spinal processes were first excised according to the amount of excision in CAPP (Figure 2B1). Then, the positioning screws were placed into the pedicles. By using the positioning screws as a reference, the range of LOC isolation was determined according to the preoperative width and length of the LOC. The positioning screws were removed and the pedicle screws were placed according to the preoperative length outside the bone. Two longitudinal rods and the transverse connectors were bent with a planned curvature. The planned positions of the transverse connectors installed on the rods were marked, and then the longitudinal rods and the transverse connectors were installed on the pedicle screws successively, which were fixed by nuts (Figure 2C1). Finally, the sutures were tied to the transverse connectors and the LOC was successfully suspended (Figure 2E1). The caliper and specially-made curvature ruler were used for parameter measurement to ensure that the operation was performed according to the preoperative plan [32].

Clinical assessment

The patients’ preoperative and postoperative neurological function were assessed by a modified Japanese Orthopaedic Association (mJOA) scoring system for thoracic myelopathy [33], as shown in Table 1. Recovery rate (RR) represented recovery degree of neurological function as follows: RR=(postoperative JOA score-preoperative JOA score)/(11–preoperative JOA score)×100%. The criteria for surgical outcomes was defined as follows: Excellent ≥75%, 74% ≥Good ≥50%, 49% ≥Fair ≥25%, and 24% ≥Poor ≥0%. The postoperative mJOA scores of these patients were calculated at the last follow-up. The follow-up period of all the patients was not less than 6 months. The surgical
complications including residual ossified lesion, CSF leakage, neurologic deterioration, and instrumentation-related complications were also recorded.

Radiological assessment

The degree of spinal canal stenosis was assessed by measuring the spinal volume occupation ratio (SVOR) and spinal volume recovery rate (SVRR) [34]. The SVOR and SVRR were measured by using 3-matic software (Figure 4H). SVOR was calculated as: TOLF volume within spinal canal/spinal canal volume×100%. SVRR was calculated as: SVRR=preoperative SVOR–postoperative SVOR. All the radiological methods, including plain radiographs, CT, and MRI, were conducted within 3 days after surgery and at the final follow-up period.

The 8 anatomical parameters – the length and width of LOC, the length of pedicle screws outside the bone, the amount of excision of the spinal processes, the height of posterior suspension of LOC, α=Curvature of the transverse connectors (B, C), β=Curvature of the longitudinal rods (D), r=Position of the transverse connectors (distance between the cranial neighboring pedicle screw and the transverse connector) (E). The distance measurement: press Distance Point to Point_WCS button (F). The curvature measurement: press Angle Line to Line_WCS button (G). The volume measurement (spinal canal volume (yellow) and TOLF volume (red)): press Dimensions button (H). TOLF – thoracic ossification of the ligamentum flavum; LOC – laminae-OLF complex.

To ensure that the intra-observer and inter-observer reliability for radiological assessment was acceptable, 2 independent reviewers measured all the parameters 3 times and calculated their mean values.

Statistical analysis

Statistical data were analyzed using SPSS (version 19.0, SPSS, Inc., Chicago, IL, USA). The results were reported as mean±SD (mean±standard deviation). The independent-samples t test was used to compare clinical and radiological outcomes between Group A and Group B. The Pearson’s chi-square test was used in the comparisons of sex, TOLF type, RR grade, and complications between Group A and Group B. The paired t test was used to compare the anatomical parameters between preoperative simulation and postoperative CT, or postoperative CT and postoperative simulation. p<0.05 was defined as a significant difference.

Results

Table 2 demonstrates the demographic data of patients with TOLF. A total of 40 patients who underwent the bridge crane...
technique were divided into Group A and Group B. There were 21 patients in Group A and 19 patients in Group B. There was no significant difference in preoperative data, including sex, age, symptom duration, follow-up, TOLF extent, and TOLF type, between the 2 groups (p>0.05).

Clinical outcomes

As shown in Table 3, the mean total time for CAPP was 84±25 min (range, 50–125 min). The mean time for establishing the spine 3D model was 46.0±11 min (range, 25–65 min). The mean time for establishing the surgical instrument 3D model was 29±6 min (range, 25–40 min). The mean time for virtual surgery was 27±10 min (range, 15–35 min).

There was no significant difference in blood loss between the 2 groups (p>0.05). However, shorter operation time and fewer fluoroscopic images were obtained in Group A that in Group B (185±29 min vs. 211±42 min, p<0.05; 3.3±0.8 vs. 6.1±1.2, p<0.01). There was no significant difference in pre-mJOA and pre-SVOR scores between the 2 groups (p>0.05).

The mean postoperative mJOA scores in both groups had all increased substantially at final follow-up, and patients in Group A had higher mJOA scores (8.8±1.8 vs. 7.3±2.4) and RR of neurological function (65.7±21.4% vs. 48.2±30.6%) than those in Group B (p<0.05). The distribution of RR grade in Groups A and B was 8/6 for excellent, 9/4 for good, 3/6 for fair, and 1/3 for poor, respectively.

A total of 7 patients had complications, including residual ossified lesion (0 in Group A and 2 in Group B), CSF leakage (1 in Group A and 3 in Group B), and neurologic deterioration (0 in Group A and 1 in Group B). No instrumentation-related complications were observed in either group. The incidence of complications in Group A was lower than in Group B, but the difference was not significant (p=0.07).

Radiological outcomes

There was no significant difference in post-SVOR and SVRR scores between the 2 groups (p>0.05).

| Categories                          | Score (points) |
|-------------------------------------|----------------|
| **Motor function: lower extremity**|                |
| Impossible to walk                  | 0              |
| Need a cane or aid on flat ground   | 1              |
| Need aid only on stairs             | 2              |
| Possible to walk without any aid, but slow manner | 3 |
| Normal                              | 4              |
| **Sensory function: lower extremity**|              |
| Apparent sensory disturbance        | 0              |
| Minimal sensory disturbance         | 1              |
| Normal                              | 2              |
| **Sensory function: Trunk**         |                |
| Apparent sensory disturbance        | 0              |
| Minimal sensory disturbance         | 1              |
| Normal                              | 2              |
| **Bladder function**                |                |
| Urinary retention or incontinence   | 0              |
| Severe dysuria (sense of retention, staining) | 1 |
| Slight dysuria (polakusia, retardation) | 2 |
| Normal                              | 3              |
| Total score                         | 11             |

**Table 1.** Modified Japanese Orthopaedic Association (mJOA) scoring system for the assessment of thoracic myelopathy.

| Categories                              | Score (points) |
|-----------------------------------------|----------------|
| Sex (Male/Female)                       |                |
| Age (year)                              |                |
| Symptom duration (month)                |                |
| Follow-up (month)                       |                |
| TOLF extent (segment)                   |                |
| TOLF type on axial CT (lateral/enlarged/fused/tuberous) | |
| TOLF type on sagittal CT (continuous/noncontinuous) | |
| Group A (n=21)                          | Group B (n=19)  | P value |
| 14/7                                    | 11/8           | 0.57    |
| 51.8±11.1                               | 54.6±9.8       | 0.40    |
| 20.1±10.9                               | 18.3±12.6      | 0.63    |
| 10.2±4.2                                | 11.6±4.7       | 0.33    |
| 3.2±1.1                                 | 3.4±1.2        | 0.53    |
| 0/7±9/5                                 | 1/5/11/2       | 0.46    |
| 19/2                                    | 15/4           | 0.56    |

* Difference was defined as significant when p<0.05. The results were reported as mean±SD (mean±standard deviation).

TOLF – thoracic ossification of the ligamentum flavum.
In the 21 patients in Group A, the anatomical parameters of preoperative design and postoperative CT were compared. There was a high consistency in width and length of the LOC, length of pedicle screws outside the bone, amount of excision of the spinal processes, position of the transverse connectors, height of posterior suspension of LOC, curvature of the longitudinal rods, and curvature of the transverse connectors before and after surgery, as shown in Table 4 (p>0.05).

We performed 3D simulation and surgical design postoperatively for the 19 patients in Group B. The anatomical parameters of postoperative simulation and postoperative CT measurement were compared, as shown in Table 5. There were no significant differences in width of LOC, length of the LOC, position of transverse connectors, height of posterior suspension of the LOC, and curvature of longitudinal rods between postoperative simulation and postoperative CT (p>0.05). However, there were statistically significant differences in the

### Table 3. Comparison of clinical and radiological outcomes between 2 groups.

|                          | Group A       | Group B       | P value |
|--------------------------|---------------|---------------|---------|
| Pre-planning time (minutes) | 84±25         | NA            | NA      |
| Operative time (minutes)  | 185±29        | 211±42        | 0.03*   |
| Blood loss (ml)           | 532±83        | 515±124       | 0.61    |
| No. of fluoroscopies      | 3.3±0.8       | 6.1±1.2       | <0.01*  |
| Pre-mJOA                  | 5.2±1.9       | 4.7±2.0       | 0.41    |
| Post-mJOA (Final visit)   | 8.8±1.8       | 7.3±2.4       | 0.04*   |
| RR                        | 65.7±21.4     | 48.2±30.6     | 0.04*   |
| RR grade (excellent/good/fair/poor) | 8/9/3/1      | 6/4/6/3       | 0.29    |
| Pre-SVOR                  | 13.8±6.0 (4.8–27.9) | 15.7±6.7 (6.6–31.1) | 0.33   |
| Post-SVOR                 | 1.1±2.6 (-3.9–4.9) | 1.7±4.9 (-6.2–8.5) | 0.61   |
| SVRR                      | 12.7±6.3 (3.3–24.7) | 14.1±5.1 (5.2–22.6) | 0.46   |
| Complications             | 1 (4.8%)      | 6 (31.6%)     | 0.07    |
| Residual ossified lesion  | 0             | 2             |         |
| CSF leakage               | 1             | 3             |         |
| Neurologic deterioration  | 0             | 1             |         |
| Instrumentation-related complications | 0       | 0             |         |

* Difference was defined as significant when p<0.05. The results were reported as mean±SD (mean±standard deviation). NA – not applicable; mJOA – modified Japanese Orthopaedic Association; RR – recovery rate; SVOR – spinal volume occupation ratio; SVRR – spinal volume recovery rate; CSF leakage – cerebrospinal fluid leakage.

### Table 4. Comparison of preoperative and postoperative anatomical parameters in Group A.

| Anatomical parameters | Preoperative | Postoperative | t Value (P) |
|-----------------------|--------------|---------------|-------------|
| Width of LOC (mm)     | 17.8±2.5 (12.8–22.4) | 17.9±2.5 (13.1–21.5) | 0.64         |
| Length of LOC (mm)    | 55.4±14.5 (33.7–79.8) | 55.8±13.3 (35.6–77.5) | 0.40         |
| Length of pedicle screws outside the bone (mm) | 17.3±1.9 (14.5–20.0) | 17.2±1.6 (14.5–19.1) | 0.55         |
| Amount of excision of the spinal processes (mm) | 7.1±1.4 (5.0–9.4) | 7.0±1.3 (5.8–9.3) | 0.54         |
| Position of the transverse connectors (mm) | 12.9±2.9 (6.2–17.0) | 13.0±2.7 (7.5–16.6) | 0.62         |
| Height of posterior suspension of LOC (mm) | 7.3±1.4 (4.5–9.1) | 7.4±1.4 (4.7–9.4) | 0.22         |
| Curvature of the longitudinal rods (°) | 8.8±5.7 (0.0–16.0) | 8.9±5.9 (0.0–17.3) | 0.74         |
| Curvature of the transverse connectors (°) | 14.5±10.9 (0.0–30.0) | 14.0±10.9 (0.0–33.3) | 0.15         |

The results were reported as mean±SD (mean±standard deviation). LOC = laminae-OLF complex.
Table 5. Comparison of the anatomical parameters regarding postoperative simulation and postoperative CT in Group B.

| Anatomical parameters                             | Postoperative simulation | Postoperative CT | t Value (P) |
|---------------------------------------------------|--------------------------|------------------|-------------|
| Width of LOC (mm)                                 | 19.4±2.5 (15.2–23.8)     | 19.2±2.8 (13.1–24.0) | 0.58        |
| Length of LOC (mm)                                | 53.8±14.5 (36.0–82.7)    | 55.4±14.2 (39.6–82.1) | 0.07        |
| Length of pedicle screws outside the bone (mm)    | 17.9±1.7 (14.5–20.5)     | 16.5±1.7 (14.5–20.4) | 0.01*       |
| Amount of excision of the spinal processes (mm)   | 7.6±1.5 (5.0–10.4)       | 8.7±1.7 (6.0–12.4)  | 0.02*       |
| Position of the transverse connectors (mm)        | 9.4±2.6 (6.5–15.2)       | 10.2±2.2 (6.5–14.6) | 0.30        |
| Height of posterior suspension of LOC (mm)        | 7.5±1.3 (5.0–9.5)        | 7.2±1.5 (4.4–9.8)  | 0.39        |
| Curvature of the longitudinal rods (°)            | 11.5±6.2 (0.0–19.6)      | 13.6±6.9 (0.0–22.9) | 0.24        |
| Curvature of the transverse connectors (°)        | 17.2±9.5 (0.0–30.0)      | 9.4±7.9 (0.0–24.8) | 0.02*       |

* Difference was defined as significant when p<0.05. The results were reported as mean±SD (mean±standard deviation).

LOC – laminae-OLF complex.

Table 6. Comparison of the radiological parameters regarding the decompression effect between postoperative simulation and postoperative CT in Group B (the patients with no complications, n=14).

| Radiological parameters                             | Postoperative simulation | Postoperative CT | t Value (P) |
|-----------------------------------------------------|--------------------------|------------------|-------------|
| Post-SVOR                                           | 0.3±1.8 (–2.2–3.1)       | 2.5±3.6 (–3.8–7.4) | 0.03*       |
| SVRR                                                | 15.2±5.9 (7.1–26.0)      | 13.0±4.1 (5.2–20.7) | 0.03*       |
| Height of posterior suspension of LOC (mm)          | 7.4±1.3 (5.0–9.5)        | 6.9±1.0 (5.0–8.8)  | 0.04*       |

* Difference was defined as significant when p<0.05. The results were reported as mean±SD (mean±standard deviation).

SVOR – spinal volume occupation ratio; SVRR – spinal volume recovery rate; LOC – laminae-OLF complex.

Discussion

Thoracic ossification of the ligamentum flavum (TOLF) was first reported by Polgar in 1920 [35]. Its main feature is ectopic...
osteogenesis of the thoracic ligamentum flavum, which leads
to compression of the thoracic spinal cord. TOLF has gradu-
ally become the primary cause of thoracic myelopathy for East
Asian people, especially for Japanese, and whites [36]. Once
this disease is diagnosed, surgical decompression is gener-
ally considered the most effective treatment. The current sur-
gical treatment methods include laminectomy and fenesta-
tion. Nevertheless, these methods usually need to invade the
spinal canal and remove the ossified mass directly, which can
damage the spinal cord [37]. The high risk of early complica-
tions such as neurological deficits and cerebrospinal fluid (CSF)
leakage are also why it is hard to achieve satisfactory clinical
outcomes using these surgical methods [6–9].

To reduce the risk of complications and improve the safety
of surgical procedures, a novel surgical technique named the
bridge crane technique has been used to treat severe TOLF [10].
The idea of the surgical technique is to isolate and suspend
the TOLF with the help of the instrument, similar to lifting ma-
terial vertically with the help of a bridge crane machine when
building a bridge. This surgical method to restore the original
volume of the spinal canal by suspending instead of resect-
ing the TOLF can avoid invading the spinal canal and damag-
ing the spinal cord. The reconstruction of the remaining lami-
nae and TOLF as autologous bones can continue to maintain
the stability of the thoracic spine.

The key procedure of the bridge crane technique is longitudi-
nal and transverse osteotomy, and posterior suspension of the
isolated TOLF. The range of longitudinal and transverse oste-
otomy (width and length of the laminae-OLF complex (LOC))
determines whether the TOLF can be isolated completely, and
the decompression effect depends on the distance of posterior
suspension of isolated LOC (the combination of 4 parameters).
Any inappropriate value or combination of the parameters can
increase the risk of complications. In Group B (without CAPP),
2 major complications were observed. Firstly, 2 patients with
residual ossified lesion were observed to have an insufficient
width of the LOC. One of these 2 patients also experienced
neurological deterioration. TOLF often originates from the bi-
lateral vertebral and articular processes, so LOC insufficient
width is like to cause a residual ossified lesion [38]. Secondly,
3 patients with CSF leakage were observed. Their postoper-
ative SVOR were –6.2%, –7.0%, and –5.1%. Considering that
TOLF often adheres to the dura mater and even causes dural
ossification, we suspected that excessive posterior suspension
had led to dural tearing and CSF leakage [15].

Due to the invisible surgical procedure, complete isolation and
precise posterior suspension can be a challenge for surgeons.
To solve the above problems as much as possible, computer-
aided design (CAD) was used in our preoperative planning. With
the help of 3 different types of CAD software we formulated
an efficient and feasible process of CAPP and its intraoper-
ative application for the bridge crane technique. In the pro-
cess, the 3D models of thoracic spine and surgical instruments
were reconstructed by using Mimics and Pro/Engineer soft-
ware based on the actual CT data and physical data. The pre-
cision of reconstruction has been widely recognized and has
been reported in previous studies [39,40]. Then, the transpar-
cy of the spine model was increased and TOLF hidden in the
spinal canal was revealed. The visualization of the 3D mod-
el can help surgeons precisely position and isolate the ossifi-
ced mass completely. Furthermore, surgeons can also change
the surgical sequence to obtain an optimal planning for pre-
cise posterior suspension. In practice, the distance of poste-
rior suspension of isolated LOC is easily determined accord-
ing to the thickness of the TOLF, but the amount of excision
of spinal processes is difficult to determine at first. In actual
surgery, the surgeons can only estimate the amount of exci-
sion of spinal processes based on experience and then roughly
evaluate the decompression effect by reduplicated fluoroscopy,
which can increase the surgical risks and radiation exposure
of patients. In virtual surgery, surgeons can easily determine
the suspension distance and then adjust other parameters
based on the suspension situation. In addition, the specially-
made measurement tools and intraoperative procedure can
help surgeons perform the operation accurately according to
the preoperative planning. We compared the main param-
ters in preoperative planning with those in postoperative CT
and found there was a high consistency of the 8 main param-
eters (p>0.05), which demonstrated that the effectiveness and
reliability of the CAPP process and its intraoperative applica-

To further explore the utility and effect of CAPP, the clinical out-
comes of the 2 groups were compared. As the results show, the
patients in Group A obtained higher mJOA scores and RR of neu-
rological function than those in Group B (p<0.05). The following
2 factors might have contributed to the above results. Firstly,
the incidence of complications in Group A was far lower than in
Group B (4.8% vs. 31.6%). Secondly, incomplete decompression

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might have occurred in some patients in Group B. Spinal volume parameters about such as SVOR and SVVR are the most important indicators for prognosis of decompression surgery [34,45]. After exclusion of patients with complications in Group B, those with no complications obtained higher post-SVOR and lower SVRR and height of posterior suspension of LOC in postoperative CT than those in postoperative simulation (p<0.05). This demonstrated that complete TOLF isolation and precise posterior suspension were achieved with the aid of CAPP, which minimized the risks of incomplete decompression, CSF leakage (excessive decompression), and residual ossified lesions. In addition, Group A had shorter operation time and fewer fluoroscopic images than Group B (p<0.05). We also found that CAPP can help surgeons minimize operation time by avoiding repeated intraoperative attempts and operations, including bending the rods, performing fluoroscopy, and adjustment of other parameters, as well as minimizing radiation exposure of patients.

We also found that there were statistically significant differences in some anatomical parameters between postoperative simulation and postoperative CT in Group B (p<0.05). As the results showed, the spinal decompression was achieved by a larger amount of excision of the spinal processes instead of increasing the length of pedicle screws outside the bone and curvature of the transverse connectors. In many cases, it was insufficient to rely solely on the amount of excision of the spinal processes. Therefore, more parameters need to be involved in the operation for complete decompression. In clinical practice, it is difficult for surgeons to control the length of pedicle screws outside the bone and curvature of the transverse connectors during surgery. However, our research has solved the critical clinical problem. The precise and controllable multi-parameter-related decompression can be achieved by quantitative preoperative planning.

One of the CAPP technologies – computer-aided virtual surgery technology – was used in our study. Currently, virtual surgery and 3D-printing technologies are the main means utilized for preoperative planning [20]. Their advantages, including better clinical outcomes, less blood loss, shorter operation time, and fewer fluoroscopic images, were reported in the previous studies, most of which were also presented in the present report [46,47]. Compared with 3D-printing technology, the advantages of virtual surgery technology lie in more convenient surgical simulation, less preoperative planning time, shorter hospital stay, and no extra cost [47]. However, dealing with the 3D images by the 2D method (using the mouse) is its biggest shortcoming. Conversely, 3D-printing technology can provide a physical model for the surgeon to perform anatomical operations, which is more similar to the real surgery [48].

In recent years, some novel technologies such as virtual reality (VR) and mixed reality (MR) have developed and are already used in preoperative planning. VR technology lacks the shortcoming of virtual surgery technology and enables the surgeon to obtain surgical experience similar to the real physical environment by using 3D interactive devices, but if fails to give the surgeon a “real-touch” experience [49,50]. As an improvement of VR technology, MR technology can combine the virtual surgery with the perception of the real environment, such as vision and touch, which provides an almost real surgical experience [51,52]. However, whether VR and MR technologies can improve surgical results and patient outcomes needs to be confirmed [49].

The present study has certain limitations. Firstly, the sample size was not large enough and we speculated that this was the main reason for finding no statistically significant difference in complications between the 2 groups. Secondly, the follow-up time was too short, which might be why we observed no instrumentation-related complications. Thirdly, CAPP requires the surgeons to have computer skills or spend time mastering these skills, which might be a challenge for some surgeons. Finally, the bridge crane technique is a novel treatment approach for TOLF, and its long-term follow-up outcomes have not been reported yet. Therefore, the clinical value and advantages of the surgical technique need further evaluation, although we have presented some clinical outcomes here.

**Conclusions**

The process of CAPP and its intraoperative application for the bridge crane technique are reliable and feasible. CAPP can enable surgeons to control the decompression effect accurately and reduce the risk of related complications, which improves the safety and efficacy of the bridge crane technique for the treatment of TOLF. Nevertheless, studies with more patients and longer follow-up are needed to further prove the effectiveness of CAPP and the bridge crane technique itself.

**Conflict of interest.**

None.
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