Transvertebral anterior cervical foraminotomy: midterm outcomes of clinical and radiological assessments including the finite element method

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Abstract

Purpose The aim of this study was to compare the clinical features, radiological changes, biomechanical effects, and efficacy in patients treated by transvertebral anterior foraminotomy. Preservation of segmental motion and avoidance of adjacent segment degeneration are theoretical advantages of transvertebral anterior foraminotomy. In practice, this procedure is minimally invasive and has shown good clinical results, especially in patients with unilateral cervical radiculopathy.

Method We conducted a retrospective minimum 2-year follow-up study of the cervical spine of patients treated by transvertebral anterior foraminotomy at our institution. Radiological outcomes, which were estimated by measuring disc and functional spinal unit heights, and the angle and range of motion (ROM) from C2 to C7 of the functional spinal unit and adjacent segments were evaluated. Furthermore, a three-dimensional finite element method was used to biomechanically analyze the strength of the postoperative vertebral body.

Results Between 2004 and 2009, 34 patients underwent surgery. The improvement rate was 94.2 %. The average flexion–extension ROM from C2 to C7 was $36.6 \pm 16.6^\circ$. On plain radiographs, the disc height and ROM and height of the functional spinal unit in the operated segment were not significantly decreased relative to the preoperative levels. The finite element method also revealed that there was no difference in strength between the pre- and post-vertebral bodies.

Conclusions These results demonstrate that biomechanical stability was achieved. Transvertebral anterior cervical foraminotomy did not limit motion in the operated and adjacent segments and did not cause a significant decrease in disc and vertebral heights after surgery.

Keywords Motion-preserving effect · Radiculopathy · Transvertebral anterior cervical foraminotomy

Introduction

In patients with unilateral cervical radiculopathy, the potential motion-preserving effects of transvertebral anterior cervical foraminotomy (TVACF) can be beneficial. Because most radiculopathies are caused by focal lesions of the intervertebral foramen, they do not require total discectomy and vertebral fusion. Especially, in patients who have retained physiological alignment, we avoid removal of healthy discs for performing intervertebral fusion. Nonfusion and nondiscectomy can preserve intervertebral motion. Theoretically, TVACF can reduce adjacent intervertebral degeneration compared with intervertebral fusion.

In 1955, Smith and Robinson described anterior cervical discectomy and fusion (ACDF) for cervical disc diseases [1–3]. At present, ACDF is the gold standard for focal cervical disc diseases [4].

Gore et al. [5] reported that ACDF resulted in excellent initial clinical results. However, one-third of patients experienced recurrent pain after a pain-free interval. Complications of this procedure, such as graft donor site pain, and problems around the surgical sight and nonoperated regions have also been reported [3, 5, 6]. In particular, the development of adjacent segment disease after

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this surgery is well recognized. Hilibrand et al. [7] reported that there was a 2.9 % annual incidence of symptomatic adjacent segment disease.

Therefore, compared with ACDF, many anterior cervical discectomy techniques without fusion have been performed to provide the advantages of maintaining intervertebral disc and spinal stability.

Hakuba [8], Scoville et al. [9], and Snyder and Bernhardt [10] reported a transuncodiscal procedure that involved an approach from the anterolateral side. Jho [11, 12] also reported microsurgical anterior cervical foraminotomy (ACF) that involved removal of the uncinat process. However, the disadvantages of ACF involve long-term issues related to disc degeneration and unilateral removal of the uncovertebral joint [13, 14].

Maurice-Williams et al. [15, 16] reported that 25 % of patients had some degree of residual neck pain, 71 % revealed bony fusion, and 13 % showed some degree of flexion deformity after these approaches.

In 1996, TVACF was reported for the first time by Yamada et al. [17] to minimize the complications and shortcomings of cervical discectomy without fusion. In 2003, Jho [11] described his latest technique. We recently modified TVACF, and Choi [18] also described TVACF in 2007, which closely resembled our modification of the procedure.

Four theoretical advantages of this procedure have been proposed. First, it can preserve the intervertebral disc except for the herniated disc because this procedure does not require discectomy to access the herniated mass and osteophyte. As a result, the mobility of the surgical segment is well preserved so that the burden of the adjacent intervertebral discs is decreased [4]. Second, it is less invasive for the anterior longitudinal ligament of the operated segment. Furthermore, it needs less exposure of the vertebral surface and retraction of the trachea and esophagus because of the unilateral procedure [4]. Therefore, patients can be discharged at the earliest [19]. Third, years after surgery, drilled holes often get refilled with new bone. With time, the surgical site becomes more stable. Fourth, bone grafting and an artificial interbody are not needed. Consequently, donor site problems are not the issue [6].

However, there has been no large case series study of TVACF concerning biomechanical alignment. In this paper, we retrospectively review the midterm results obtained with this modified procedure.

Materials and methods

Patient population

A retrospective study of patients treated by TVACF (who underwent surgery from 2002 to 2009) was designed to

evaluate surgical treatment methods. These patients experienced cervical radiculopathy caused by a unilateral herniated cervical disc and an osteophyte, which was complicated with myelopathy in some patients.

The fundamental indications for this surgery were (1) unilateral radiculopathy corresponding with the imaging study that was refractory to conservative therapy for at least 2 months or (2) signs of motor weakness and/or intolerable pain not responding to analgesics. The exclusion criteria were signs of myelopathy only or instability. In addition, severe degenerative change including kyphosis and loss of intervertebral space are excluded. In that case, ACDF might be more useful to correct the alignment than TVACF, and there is no disc and disc space to preserve in the loss of the intervertebral space cases. Moreover, neck pain was not the only indication for this procedure.

Radiological assessment

Dynamic lateral radiographs taken during the pre- and postoperative periods were used to assess overall cervical sagittal balance and morphological changes. Assessment of ROM from C2 to C7 and adjacent segments was performed. Lateral cervical spine radiographs were used to determine the heights of functional spinal unit (FSU) [20] and intervertebral discs. FSU consisted of 2 vertebrae and corresponding intervertebral discs (Fig. 1). We measured the FSU height instead of real disc space height because detection of the end-plate line on plain radiography was difficult, especially of spondylotic changes. The numerical values of FSU and the discs were corrected for radiological magnification errors by comparing transverse distances of the vertebrae on plain radiographs and computed tomography (CT). Lordosis was shown as a negative value, and kyphosis was shown as a positive value. Standard statistical analysis was used for this study.

Finite element method

For the estimation of the strength of postoperative vertebrae, we used a three-dimensional (3D) finite element method (FEM) to analyze the breaking strength of the vertebral body. In this computer simulation study, Mechanical Finder Extended Edition software (RCCM, Tokyo, Japan) was used to perform FEM analysis, which helped derive the contours and bone density from CT images of the actual patient. Figure 2 shows the 3D FEM models.

We selected a hypothetical patient whose age was the same as the mean age of patients in the study. The most frequent lesion was that in C5/6. Therefore, we analyzed a C5 vertebra of a 56-year-old man as a representative example. Using Mechanical Finder software, Young's

Fig. 1 Functional spinal unit (FSU). FSU consists of two vertebrae and an intervertebral disc. This image shows the measurement method used for FSU in this study

modulus of bone was determined. Virtual surgery was performed on the vertebra, for which a tunnel same as that in our TVACF method was created (Fig. 2a, b). Other material properties are shown in Table 1. We added virtual axial loading on the pre- and postoperative vertebrae and estimated fracture strength. The loading condition was defined as uniform axial loading on the vertebral body and facets parallel with the red arrow in Fig. 2c. Constraint was added for the inferior surface of the vertebral body (Fig. 2d). In material nonlinear analysis, we increased the loading strength until 10 solid elements were broken and assigned this as the fracture load.

Operative technique

The patient was placed in the supine position. A lateral radiograph was used to identify the skin incision level. A 3–4 cm transverse skin incision was made at half a level higher than the affected disc level. We approached the anterior surface of the vertebra from the affected side by the usual method. We determined the midline and appropriate keyhole positions by its relationship to the two longus colli muscles (LCM) and anterior longitudinal segment. The affected disc level was exposed; however, we did not expose the lower vertebra of the affected segment.

The keyhole position was above the lower border of the exposed vertebra and the lateral border of the LCM attachment, which had already detached during this procedure. The lateral and caudal side trajectory of the tunnel was decided by the cortical bone and terminal lamina findings of the drilled tunnel wall. The tunnel was approximately 6 mm in diameter and was gradually increased to approximately 10 mm toward the tunnel end in our procedure (Fig. 3). Care was taken to avoid damage to the medial wall of the transverse foramen and to preserve the integrity of the underlying end plate, especially in the anterior two-thirds of the disc (Fig. 4). We could also find cortical bone when we reached the posterior limit of the drill hole. After the posterior bone was drilled to achieve paper-thin thickness, we resected the residual bone and posterior longitudinal ligament. We were then able to visualize the herniated disc fragment and osteospur. We gently removed the disc fragment and osteospur. Subsequently, protuberance of the root or the root itself was confirmed for orientation. After sufficient decompression, cerebrospinal fluid pulsation in the nerve root could be observed. The postoperative protocol involved no unusual procedures. Patients did not need any neck collar.

Results

Between 2004 and 2009, 35 patients underwent surgery. Of the 35 patients, 1 patient underwent the older surgical method in which the keyhole was made at the midpoint. Therefore, there were 34 patients (males, 25; females, 9; average age, 55.2 ± 12.3 years; range, 28–77 years) with a total of 47 lesions (mean follow-up period, 2.5 ± 1.5 years). Only 4 patients were lost to follow-up, and 10 patients were followed up for a short period. Therefore, 20 of the 34 (58.8 %) patients were followed up for at least 2 years (males, 14; females, 6; average age, 55.5 ± 11.4 years; mean follow-up period, 3.3 ± 1.3 years). To determine pre- and postdynamic radiological changes, 12 patients were compared. Before this surgery, laminoplasty was performed in 1 patient. Additional surgery was required in 2 patients.

Preoperative clinical features are shown in Table 2. One patient demonstrated poor outcome because of a sequence of cervical degeneration disease. Other patients improved and remained stable. The improvement rate was 94.2 %.

With respect to surgical locations, 48.9 % of the lesions occurred in C5/6 (Table 3). Single-level TVACF was performed in only 64.7 % of the patients. The rates of double lesion surgery, single TVACF with ACDF, and double TVACF with ACDF are presented in Table 3.

Twelve patients were followed up for at least 2 years (average age, 56.3 ± 9.8 years; mean follow-up period,

Fig. 2 Finite element method (FEM) models. We created a 6-mm-diameter tunnel in the FEM model. The 6-mm-diameter tunnel was made in the lateral side of the vertebra (**a**, **b**). The tunnel was gradually increased to approximately 10 mm toward the tunnel end.

A C5 vertebral model. *Green* imitates the intervertebral disc (**c**). *Red* indicates the loading point, and the *red arrow* indicates the direction of the axial loading. *Blue* indicates the constraint point (**d**)

Table 1 Material property

	Young's modulus	Poisson's ratio	Shell element
Bone	Calculated by bone density	0.4	+
Intervertebral disc, cartilage	20 MPa	0.4	None

3.3 ± 0.6 years). The average pre- and postoperative C2–C7 alignments were not statistically significant. None of the pre- and postoperative differences in ROM from C2 to C7, FSU, and the adjacent segments were statistically significant (Table 4). In addition, no differences were observed between the pre- and postoperative FSU and disc heights in the operated segments (Table 4).

Only 1 patient had mobility in the operated intervertebral levels (>10°), and 1 patient had mobility in the adjacent intervertebral levels. No collapse of the drilled vertebral body was observed in any patient.

In FEM, equivalent stress diagrams with and without a tunnel at 1,000 N are shown in Fig. 5a, b. The model without a tunnel was broken with 2,240 N [(228.4 kilogram-force (kgf))], and the model with a tunnel was broken with 2,180 N (222.3 kgf). Pedicles were the breaking points for both, which are indicated by white arrows in Fig. 5c, d, e, f.

Without a tunnel: 2240 N.

With a tunnel: 2180 N.

In contrast, when we added the axial loading only to the superior surface of the vertebral bodies without facets, the vertebral bodies were very strong; the model without a tunnel was broken with 4,920 N (501.7 kgf) and that with a tunnel was broken with 1,150 N (117.3 kgf). This was sufficiently strong compared with the pedicle fracture strength.

Therefore, we concluded that there was no clinical difference between the fracture strength of the models with and without a tunnel because the strength of the vertebral bodies in both models was stronger than that of the pedicles, although the fracture strength of the vertebral body was lesser in the model with a tunnel than in the model without a tunnel. These data indicate that vertebral body strength was preserved in TVACF.

Fig. 3 Postoperative reconstructed three-dimensional computed tomography image. A 6-mm tunnel window is seen on the *right side* of the C5 vertebra

Fig. 4 Postoperative axial computed tomography image. This image shows preservation of the medial wall of the intervertebral foramen, and the bone defect is a small part of the vertebra

Discussion

This study is an initial case series of TVACF, with exact patient selection. The rate of motor weakness of preoperative symptoms (87.5 %) was higher than that observed in other studies (41–44 %) [19], which enabled a more appropriate patient selection.

Table 2 Clinical features and lesion type

	Number of patients (%)
Preoperative clinical features of 32 patients	
Radicular pain	20 (62.5)
Interscapular pain	2 (6.3)
Sensory disturbance (thermal hyposthesia)	2 (6.3)
Dysesthesia	28 (87.5)
Motor weakness	28 (87.5)
Neck pain	2 (6.3)
Type of pathology (33 patients)	
Radiculopathy	27 (79.4)
Myelopathy	0 (0)
Radiculopathy with myelopathy	6 (17.6)
Type of lesion (34 patients)	
Soft disc herniation	21 (61.8)
Spondylotic osteophyte	11 (32.3)
Soft disc with osteophyte	2 (5.9)

Table 3 Level and surgical method

	Number of patients (%)
Level	
C4/5	4 (8.5)
C5/6	23 (48.9)
C6/7	17 (36.2)
C7/T1	3 (6.4)
Method	
Single	22 (64.7)
Double	7 (20.6)
Single with ACDF	4 (11.8)
Double with ACDF	1 (2.9)
Total 47 lesions in 34 patients	

Table 4 Changes in pre- and postoperative radiography

	Preoperative	Postoperative	
Sagittal alignment			
C2–7	-5.7 ± 11.6	-10.8 ± 13.2	NS
FSU	3.5 ± 4.7	0.6 ± 6.8	NS
ROM			
C2–7	31.6 ± 15.7	36.6 ± 16.6	NS
FSU	5.0 ± 2.7	4.2 ± 3.9	NS
Adjacent segment	3.4 ± 1.7	4.2 ± 2.5	NS
Height			
FSU	33.9 ± 3.0	33.8 ± 3.6	NS
Intervertebral disc	4.9 ± 1.3	4.6 ± 1.9	NS
Follow-up period 3.3 ± 0.6 years

Fig. 5 Finite element method analysis. Equivalent stress diagrams with (a) and without (b) a tunnel at 1,000 N. The white arrows indicate the breaking points. The white points are tensile fracture

elements, and the red points are compression fracture elements (c, d, e, f). Both fracture elements are seen only at the base of the pedicles from the vertebral body

A radiographic study revealed that the parameters of biomechanical stability were completely stable and well preserved. In addition, there was no trend reflecting the possibility of aggravation in the degeneration of the surgical level or adjacent segments. TVACF did not restrict segmental and adjacent segment motion and did not cause a significant decrease in disc and vertebral height after surgery.

With respect to postoperative disc height, our cases showed excellent results in contrast to the results of past studies [18, 20]. The midpoint approach is more likely to increase disc height reduction than the lateral hole approach. Our biomechanical results are excellent compared with those of Yi, who performed the approach from the midpoint. However, Choi demonstrated disc height reduction after TVACF, although he performed almost the same method as

ours. One possible reason for this discrepancy was that we often use a hybrid method, e.g., TVACF with ACDF (Table 2). Hybrid methods allow more appropriate patient selection for TVACF surgery because of multiple options; therefore, we did not persist in performing TVACF.

When TVACF was first introduced, we performed it using the transvertebral approach from the midpoint of the vertebra, similar to the approach used by Noguchi and Matsushita [22]. The advantage of this method is that it allows an approach from bilateral sides. However, we eventually decided that the operated vertebra was fragile and showed spondylotic changes and lateral sclerotic tilt as we gained more experience with the method, as Yi reported. Therefore, we modified the TVACF method. As a result, the new method is less invasive than the old method

because only the unilateral side of a vertebra is required to view the surgical site. Therefore, the indications for this method are restricted to unilateral radiculopathy. Furthermore, because of difficult access from the upper vertebra above the C4/5 segment, we recommend approaching from the lower vertebra in these cases.

In general, various adverse outcomes are observed after TVACF surgery, and there is a need for reoperation. Our series had three reoperations after TVACF. Laminoplasty was performed in one patient after TVACF because of the development of canal stenosis, which was asymptomatic at first surgery. TVACF is a minimally invasive procedure compared with laminoplasty; therefore, both patients and surgeons might prefer only to resolve the symptoms and avoid invasive surgery for asymptomatic lesions.

One patient (2.9 %) required surgery for an adjacent disc disease. This incidence of symptomatic adjacent disc disease was not very high compared with that reported by Hilibrand et al. Fortunately, no immediate complications were observed in any of our patients.

Nakai et al. [21] reported that 4 of 24 patients needed additional simultaneous or subsequent ACDF. In our study, no patients had spontaneous fusion, except for scheduled ACDF cases of hybrid method. We believe this is a result of our precautions to avoid invading the disc component. Wirth et al. [19] reported no significant differences among posterior cervical foraminotomy, ACDF, and ACF. However, the TVACF method, as used in our study, was not included in their study.

Recently, the total disc replacement (TDR) method has been introduced worldwide. This method has the same concept as that of TVACF for preserving intervertebral motion. However, we should be aware of the different biomechanical backgrounds resulting in common advantages [20]. TDR requires insertion of an artificial prosthesis. Patients who have instability at a pathological level need TDR, but for others, TVACF is more suitable. To achieve the fundamental goal of the procedures, the patients' biomechanical abnormalities should be evaluated preoperatively and the treatment strategy selected. In addition, according to FEM analysis, TVACF preserves vertebral body strength. However, these are preliminary data from a pilot series.

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Conflict of interest None.

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