A biomechanical evaluation of occipitocervical instrumentation: screw compared with wire fixation

R. JOHN HURLBERT, M.D., PH.D., F.R.C.S.(C), NEIL R. CRAWFORD, PH.D., WON GYU CHOI, M.D., AND CURTIS A. DICKMAN, M.D.

The University of Calgary Spine Program, Foothills Hospital and Medical Centre, and Spinal Biomechanics Research Laboratory, Barrow Neurological Institute, Phoenix, Arizona

Object. The purpose of this study was to compare cable techniques used in occipitocervical fixation with two types of screw fixation. The authors hypothesized that screw fixation would provide superior immobilization compared with cable methods.

Methods. Ten cadaveric specimens were prepared for biomechanical analyses by using standard techniques. Angular and linear displacement data were recorded from the occiput to C-6 with infrared optical sensors after conditioning runs. Specimens underwent retesting after fatiguing. Six methods of fixation were analyzed: Steinmann pin with and without C-1 incorporation; Cotrel-Dubousett horseshoe with and without C-1 incorporation; Mayfield loop with C1–2 transarticular screw fixation; and a custom-designed occipitocervical transarticular screw-plate system. Sublaminar techniques were extended to include C-3 in the fusion construct, whereas transarticular techniques incorporated the occiput, C-1, and C-2 only.

All methods of fixation provided significant immobilization in all specimens compared with the nonconstrained destabilized state. Despite incorporation of an additional vertebral segment, sublaminar techniques performed worse as a function of applied load than screw fixation techniques. Following fatiguing, these differences were more pronounced. The sublaminar techniques failed most prominently in flexion–extension and in axial rotation. On gross inspection, increased angular displacement associated with loosening of the sublaminar cables was observed.

Conclusion. Occipitocervical fixation can be performed using a variety of techniques; all bestow significant immobilization compared with the destabilized spine. All methods tested in this study were susceptible to fatigue and loss of reduction and were weakest in resisting vertical settling. Screw fixation of the occiput–C2 reduces the number of vertebral segments that are necessary to incorporate into the fusion construct while providing superior immobilization and resistance to fatigue and vertical settling compared with sublaminar methods.

Key Words • occipitocervical • craniocervical • fixation • instability • instrumentation • biomechanics

Occipitocervical stabilization for complex atlantoaxial or occipitocervical instability presents the spine surgeon with many challenges and issues. The several fixation techniques available involve both external orthoses and internal fixation devices. Although the classic approach of onlay bone graft augmented by external halo immobilization has proven useful, recent advances in instrumentation have allowed for construction of cable-rod and screw-plate constructs fashioned specifically for the craniocervical junction. Of these implantable devices, those most commonly used require placement of occipital and sublaminar cables to anchor the device against the cranium and spine surfaces.

Single-stranded wiring can be prone to loosening and failure; multistranded cables have provided improved resistance to stress fatigue. The disadvantages of such devices create the potential for neurological injury due to sublaminar cable placement. This can be particularly worrisome when a congenitally narrow spinal canal or cervical spondylosis coexists with instability. It is also common for these methods to require incorporation of between three and five cervical segments.

The method of screw fixation has been shown to confer distinct biomechanical advantage over other methods in providing stability across a fusion construct, leading to higher rates of fusion in both animal and human studies. With the successful application of this technology to other parts of the spine, it seemed reasonable to predict benefit when applied to an unstable portion at the occipitocervical junction. The purpose of this experiment was to compare the biomechanical stabilizing characteristics of occipitocervical wiring with screw fixation techniques in vitro, using destabilized, cadaveric human cervical spines. We hypothesized that screw fixation would provide superior immobilization compared with cable methods, despite requiring incorporation of fewer motion segments.

Materials and Methods

Cadaver Preparation

Ten freshly frozen head and neck cadaveric specimens were obtained for biomechanical analyses. Review of medical history, detailed inspection, and x-ray films verified that the cadavers were free from congenital or other pathological conditions affecting the
Biomechanics of occipitocervical fixation

spinal column. Skin and muscles were sharply dissected from each cadaver, with preservation of bones and spinal ligaments. Mandibles were disarticulated and removed. The maxilla and top of the cranium were resected by oscillating saw, preserving the sphenoid, temporal, and occipital bones.

To model the clinical circumstances of occipitocervical stabilization in the specimens appropriately, it was important to model vertical as well as horizontal instability. Hence, we devised a method to allow “cranial settling” to occur between the occiput and C-2. Horizontal occipitocervical instability was created by removing the anterior arch of C-1, the odontoid process, and the apical,alar, and transverse ligaments. Vertical occipitocervical instability was created by drilling away the articular surfaces between C-1 and C-2 with 3 to 4 mm of adjacent bone on each side of the joint space so that the total C1–2 gap was 10 mm. This was performed on each side of midline. Ten-millimeter-thick spacers were subsequently inserted between C-1 and C-2 to preserve vertical height and alignment during instrument creation, using a uniform vertical gap in all specimens (Fig. 1). Both spacers were removed prior to load application and testing.

For each cadaveric preparation, the C-6 vertebral bodies were fixed in metal potting fixtures by using methylmethacrylate. On test days, a specimen was thawed and the occipital bone was bolted to the testing table. All testing was performed with the specimen in an inverted position. Three 4- to 6-mm-long end-threaded stainless steel surgical guidewires were placed into each bony segment (occiput–C6), and infrared emitters were rigidly affixed to each guidewire. Specimens were wrapped in gauze sponges and irrigated with normal saline solution to keep them moist throughout the test period.

Six methods of fixation were analyzed: Contoured Steinmann pin with and without C-1 incorporation; Cotrel-Dubousset (CD) horseshoe (Sofamor Danek, Memphis, TN) with and without C-1 incorporation; Mayfield loop with C-1–2 transarticular screw fixation (OMI Surgical Products, Inc., Cincinnati, OH); and a custom-designed occipitocervical transarticular (OCTA) screw-plate system (Fig. 2). All sublaminar methods (Steinmann pin and CD horseshoe) included C-3 vertebra in the stabilization construct (occiput–C3). Both screw-plate techniques incorporated only the occiput, C-1, and C-2. The OCTA system differed from the Mayfield loop in that fully threaded C1–2 transarticular screws were used to anchor the fixation device to the spine, coupled by a more firmly constrained, meshed interface, whereas the Mayfield loop was anchored to C-1 and C-2 by partially threaded transarticular lag screws, coupled to the plate by a custom-designed clamp (Apfelbaum plate). In neither of these screw fixation methods was the ring of C-1 wired into the construct.

For sublaminar cable fixation techniques, small laminotomy defects were created in the ligamentum flavum adjacent to the ring of C-1 and the laminae of C-2 and C-3 to allow placement of the multistranded stainless steel cables, which were tightened to 40 lbs to secure the contoured rods to bony surfaces. Rods were contoured flush to the skull and cervical spine to minimize stress risers in the construct. When screw fixation to the occiput was required (using CD horseshoe, Mayfield loop, or OCTА plate), bicortical screw purchase was attained with each of three identical titanium 3.5-mm-diameter screws. Partially threaded 3-mm-diameter or fully threaded 3.5-mm-diameter transarticular screws were placed across C-1 and C-2 for the Mayfield and OCTA systems, respectively.

Data Acquisition

Nonconstraining torsional loads were applied to the potted C-6 segment through six physiological directions of motion (flexion–extension; left and right lateral bending; and left and right axial rotation). In addition, linear forces were applied in axial compression and distraction. Angular and linear displacement for each motion segment was measured using a three-dimensional tracking device (Optotrak model 3020; Northern Digital, Waterloo, ON, Canada). Loads were applied quasistatically by using a hydraulic pump system (Mini Bionix model 858; MTS Systems Corporation, Minneapolis, MN) coupled to the C-6 vertebra through a series of pulleys.¹ Data were recorded on an IBM-compatible personal computer by using software developed in our laboratory. Specimens were tested in the normal and destabilized states, and then again after each type of instrumentation was placed. All specimens underwent instrumentation first with Steinmann pin and CD horseshoe (randomly assigned) with and without C-1 incorporation (also randomly assigned). Each specimen then underwent screw fixation first with the Mayfield loop and then the OCTА plate, with each specimen serving as its own control. Data were collected following three preconditioning runs (0–1.5 Nm torsional loads; 0–70 N compression and distraction loads) for each testing phase. In addition, for each of the stabilization constructs, data were again recorded after fatiguing through 1000 cycles in seven of the eight directions (excluding axial distraction). These forces were chosen to approximate roughly the weight of a 5-kg head acting on the craniovertebral junction over several days or weeks.

Statistical Analyses

Data were normalized by defining the middle of the neutral zone as having an angular displacement of 0°. Angular displacement and translational data from the occiput–C1 and from C1–2 were combined to allow comprehensive reporting on motion from occiput–C2 (in keeping with our model of vertical instability). Descriptive statistics were explored for all data with variance expressed as standard error of the mean. Statistical comparisons were made using analysis of variance (ANOVA) or repeated-measures ANOVA. Post hoc examinations were performed using the Student-Newman-Keuls (repeated-measures) or Dunnett’s (ANOVA) methods to further determine differences between individual groups.¹ All tests were two tailed. We considered a probability value of less than or equal to 0.05 to represent statistical significance.

Results

Complete biomechanical testing was performed for both the Steinmann pin and CD horseshoe (without C-1) fixation groups in all 10 specimens. Because of bony or ligamentous failure after initial testing, we examined the OCTА plate in nine, the Steinmann pin and CD horseshoe (with C-1) in eight, and the Mayfield loop in seven cadavers. All fixation methods provided a significant degree
of immobilization from the occiput to C-2 compared with the normal and destabilized states (Fig. 3). However, during the course of testing, small degrees of cable loosening occurred, likely due to a wearing effect at the bone–cable interface or cable creep. We did not note any evidence of screw loosening or backout.

Examination of load displacement data revealed various degrees of immobilization that depended on the type of fixation used. In general, the fully wired construct (Steinmann pin) allowed the most motion, followed by the combined screw and wire construct (CD horseshoe). Complete screw systems (OCTA plate and Mayfield loop) provided the highest degree of immobilization through the six directions of angular displacement, most pronounced in axial rotation and least pronounced in lateral bending. Incorporation of C-1 with sublaminar cables into the instrumented segments conferred considerable, further stability but still much less than when incorporated through transarticular screws (OCTA plate and Mayfield loop).

Fatigue stressing caused loosening in all methods of fixation (screws and cables). However, the degree of loosening was directly related to the degree of stability conferred on the spine by each type of instrumentation in the prefatigue state. For example, most loosening was observed in the Steinmann pin construct without C-1 incorporation, an intermediate amount in the CD horseshoe construct without C-1, and the least loosening in the OCTA and Mayfield loop systems. Both the OCTA and Mayfield fixation systems demonstrated significantly less fatigue than the other methods ($H = 160.771$, df 5, $p < 0.001$; ANOVA on ranks).

Postfatigue testing demonstrated similar relationships...
among the different techniques of instrumentation compared with prefatigue values (Fig. 4). Repeated-measures ANOVA demonstrated a highly significant interaction between response to load and fixation device for flexion–extension (F = 4.787, df 65,727, p < 0.001), axial rotation (F = 4.896, df 65,727, p < 0.001), and lateral bending (F = 2.539, df 65,713, p < 0.001). Least constraint was observed in the completely cabled construct without incorporation of C-1. Once again, the cable techniques incorporating C-1 performed better than those incorporating only C-2 and C-3. Post-hoc statistical analyses proved screw fixation (OCTA and Mayfield) to be superior to all types of cable fixation in flexion and extension, axial rotation, and in compression and distraction. In lateral bending the Steinmann pin with C-1 incorporation exhibited stiffness approaching that of the OCTA plate and Mayfield loop systems; however, the latter two remained statistically superior to all other methods.

Measurements of linear displacement (translation) were performed, referencing the body of C-2 to the anterior midline of the foramen magnum and to the anterior tubercle of C-1 (which was estimated following odontoid resection). Translational data were obtained after fatigue, while moving the cadavers through the six angular directions of displacement, and while moving the cadavers in axial compression and distraction. Trends similar to those observed in measurements of angular displacement were seen (Fig. 5). Sublaminar techniques without incorporation of C-1 tended to exhibit more linear displacement than the same techniques when C-1 incorporation was included. In all cases, however, both the OCTA plate and Mayfield loop proved superior to other methods in pre- and postfatigue testing paradigms (p < 0.05, one-way ANOVA on ranks).

Most pertinent for clinical applications, vertical instability was assessed by loading the specimens in axial compression and distraction from 0 to 70 N, mimicking the effect of gravity on a 5-kg cranium (Fig. 5D). In pre- and postfatigue states, the four sublaminar techniques allowed, on average, 4 to 6 mm of displacement. Incorporation of C-1 provided a degree of further stability as did screw fixation to the occiput. Screw fixation with the OCTA plate or Mayfield loop restricted vertical instability to 1.3 ± 0.3 mm even after fatigue. It is important to note that, among the eight directions in which translation was tested, all fixation methods performed most poorly in compression and distraction tests.

Stiffness for normal and stabilized specimens was calculated after fatigue by using a least-squares line fit to estimate the slope of the load–deformation curve within
the elastic zone (loads ≥ 0.5 Nm for angular forces and ≥ 30 N for linear forces; Fig. 6). In flexion–extension, lateral bending, and axial rotation, only the OCTA plate and Mayfield loop provided significantly increased stiffness compared with the normal state (p < 0.05, one-way ANOVA on ranks). Under distraction and compression mean stiffness values were less than those of intact specimens when fixation was undertaken with any of the four sublaminar cable techniques. Only the OCTA plate and Mayfield loop demonstrated stiffness greater than normal (noninstrumented, intact) preparations. Combined stiffness for both the Steinmann pin without C-1 and the CD horseshoe with C-1 incorporation were statistically inferior to normal controls (p < 0.05, one-way ANOVA on ranks). Combined stiffness values for the OCTA plate and Mayfield loop were significantly superior to the other fixation techniques.

**Discussion**

Clinical indications for occipitocervical instrumentation typically involve occipitoatlantal or occipitoatlantoaxial instability. Clearly vertical instability, such as that seen in the reduced state (posttraction) of cranial settling or basilar invagination, provides the highest demands on any construct used to facilitate an arthrodesis in this region. Following reduction, a defect or gap is created in the anterior column that prevents transmission of axial loads through the articular surfaces of the spine. As a result, high mechanical stresses are placed on any device...
Biomechanics of occipitocervical fixation

utilized to fix the occiput to the cervical spine while maintaining this gap. We have reported the first biomechanical study that critically evaluates the stability of different types of occipitocervical fixation devices. We have also provided the first report of a method designed to model vertical instability in vitro.

It has been established in other regions of the spine and peripheral skeletal system that screw fixation provides superior stability compared with nonscrew techniques. Our results confirm that this remains the case in the occipitocervical region. Neither increasing the degree of constraint through the coupling device that connects the occipital plate to the transarticular screws nor using fully threaded transarticular screws provided significant additional immobilization. Although increased stiffness was observed in the OCTA compared with the Mayfield loop systems in each of the directions tested, this difference was not statistically significant. Therefore, the key element in providing maximum immobilization at the cranio cervical junction is screw purchase (as opposed to wire fixation) into both the occiput and the atlantoaxial complex, largely independent of the coupling device. Cyclical loading for the purpose of fatiguing the fixation devices further demonstrated the superior stiffness of the screw systems.

The screw fixation devices we tested involved placement of C1–2 transarticular screws. As is commonly the case in instances of advanced rheumatoid occipitocervical degeneration and/or destruction, placement of transarticular screws is not always possible. However, the degree of fixation we observed was not overtly related to the use of partially threaded (Mayfield loop) or fully threaded (OCTA plate) transarticular screws. Hence, it is possible that screws placed into the pars interarticularis of C-2 might provide similar stability to such constructs without crossing the articular interface. Although one would prefer to wire C-1 to the loop or plate in such a circumstance, the effect of excluding C-1 completely when making use of screw techniques remains grounds for further biomechanical studies.

Screw fixation of the occiput to the cervical spine has been described clinically. The earliest description of occipitocervical screw fixation was in 1988. A small fragment “T” plate was contoured to bridge from the midline of the occiput to the spinous process of C-2 and was fixed with screws on either end. Nonunion was observed in one of 13 patients available for follow-up examination. A modified lateral mass plate (inverted “Y” plate) has been used to anchor C1–2 transarticular screws to the base of the occiput. An extended series of patients was recently reported by the same group, detailing improved fusion rates and neurological outcome compared with a retrospective cohort of onlay graft and wiring. Loosening of a

cant only after occipital and C1–2 transarticular screw fixation (with OCTA plate and Mayfield loop). B: Similarly in lateral bending and axial rotation, only the OCTA plate and Mayfield loop conferred significantly more stiffness on specimens than in their normal state. C: Mean stiffness in distraction and compression for occiput–C2 immobilized by sublaminar cables was less than the stiffness in intact or normal state. Only the OCTA plate and Mayfield loop increased stiffness compared with the normal state.

Fig. 6. Graphs depicting stiffness of normal and instrumented specimens. A: A trend toward increased stiffness through flexion-extension was observed for all fixation methods compared with normal controls and this difference was statistically signifi-
A transarticular screw was observed in two patients, but neither required revision during their mean follow-up period of 24 months.

Bilateral lateral mass or pelvic reconstruction plates have also been used to bridge the occipitocervical junction. In 1993 Smith, et al., described a technique of screw fixation from the occiput extending to C-2 and below. Instead of using transarticular screws through the C1–2 joint space, the authors placed 20- to 22-mm screws into the pars interarticularis only. They reported a solid bony union in all 14 patients after a mean follow-up period of 11.7 months. Asymptomatic screw backout was noted in four patients. Sasso, et al., published their results after using a similar technique of bilateral lateral mass plates with C1–2 transarticular screws in 23 patients, with an average follow-up period of 50 months. Solid bony union was attained in all patients. There were no complications from the occipital screws. Postoperative atlantoaxial alignment was lost in one patient.

Clinical evaluation of the Mayfield loop has not yet been reported. In the principal author’s experience, however, it has thus far proved a useful adjunct for occipitocervical fusion. Nonetheless, despite the apparent biomechanical superiority of the Mayfield loop and OCTA plate, the clinical implications of this study remain to be defined.

Conclusions

Occipitocervical fixation can be performed using a variety of techniques; all bestow significant immobilization compared with the destabilized spine. All methods we tested were susceptible to fatigue and loss of reduction, and all were weakest in resisting vertical settling. Screw fixation of the occiput to C-2 reduces the number of vertebral segments that it is necessary to incorporate into the fusion construct while providing superior immobilization and resistance to fatigue and vertical settling compared with sublaminar methods.

References


Address reprint requests to: R. J. Hurlbert, M.D., University of Calgary Spine Program, Foothills Hospital and Medical Centre, 1403 29th Street N.W., Calgary, Alberta, Canada T2N 2T9. email: jhurlber@acs.ucalgary.ca.