A Novel Technique of Odontoidoplasty and C1 Arch Reconstruction: Anatomical and Biomechanical Basis

BACKGROUND: Transoral odontoidectomy and resection of the anterior C1 arch destabilize the atlantoaxial joint and risk its stability.

OBJECTIVE: To preserve stability in such cases we devised and evaluated a proof-of-concept study. The arch and dens were dissected and decompression was performed on cadavers. The dens was replaced with an odontoid screw, and the C1 arch was replaced with a rib-graft substitute using miniplates. We assessed the biomechanical strength of the C1 ring and 3D occipitoatlantoaxial flexibility before and after the repair.

METHODS: Five silicon-injected fixed cadaver heads were dissected. The arch of C1 and dens were preserved and reconstructed using odontoid screws and miniplates. Once the feasibility of the technique was established, we biomechanically tested 6 cadaveric occiput-C2 specimens in 3 phases: (1) intact/normal range of motion (ROM), (2) after transection of dens and C1 arch, and (3) with odontoidoplasty using odontoid screws and C1 arch reconstruction.

RESULTS: After odontoidectomy and arch removal, angular ROM increased significantly in all directions of loading. Resection increased flexion-extension at the occiput-C1 and at C1-C2 by 21% and 129%, respectively. Reconstruction slightly increased flexion-extension stability (16% and 107%, respectively) relative to normal. With 70 N applied compression, the C1 ring separation was 1145% greater than normal. After reconstruction, the separation was only 89% greater than normal (statistically significant, \( P = .002 \)).

CONCLUSION: C1 arch reconstruction with or without odontoidoplasty restores only partial angular stability of the atlantoaxial joint but provides restoration of the ability of the C1 lateral masses to resist splaying, often observed as postodontoidectomy cranial settling.

KEY WORDS: Atlantoaxial fixation, Biomechanical analysis, C1 arch reconstruction, Odontoidoplasty

Arthrodesis of the craniocervical junction is challenging because it is difficult to apply fixation hardware to the small, yet highly mobile atlantoaxial joints. Clinical studies have shown that transoral odontoidectomy potentiates pathologic instability; 45 to 90% of patients subsequently require internal stabilization primarily at C1-C2.\(^1,2\)

Consensus on the optimum fixation method to achieve atlantoaxial fusion after odontoidectomy is debatable. Most researchers and clinicians have focused on posterior surgical approaches to the atlantoaxial joint.\(^3-8\) Others have argued that direct anterior decompression should be combined with anterior instrumentation and posterior wire fusion for better stability.\(^9\) Recently, the biomechanical properties of transoral atlantoaxial plating systems have been compared.\(^10-12\) With these systems, good bony purchase is difficult to achieve anteriorly, especially working through a small transoral surgical exposure.

Few studies have addressed the option of avoiding fusion altogether after odontoidectomy. One study proposed an artificial C1-2 joint,\(^13\) but to our knowledge no studies have assessed reconstruction of osteotomized bony fragments. The purpose of this in vitro pilot study was to...
establish the feasibility of C1 arch and/or odontoid reconstruction after odontoidectomy in cadavers and then evaluate the biomechanical stability of the partially reconstructed C1-2 joint.

METHODS

The methods consist of 2 phases: (A) anatomic dissection of the silicon-injected specimens to test the feasibility of the technique, and (B) biomechanical evaluation of a separate group of specimens to assess the stability of the construct.

Anatomically Studied Specimens

Cadaveric dissections were performed in 5 specimens to establish the feasibility of this technique for clinical application (Figure 1). Specimens were from 2 males and 3 females (mean age, 78 years; range, 68-87 years). A standard transoral approach was performed in each cadaver as described by Crockard et al.14 Once the arch of C1 and the body of C2
were identified with fluoroscopic guidance, the soft tissue around the C1 arch was dissected without opening the C1-2 facet joint capsule, instead of drilling as for a classic odontoidectomy procedure. Under an operating microscope and using the smallest fluted drill bit with a high-speed pneumatic drill (The Anspach Effort, Inc., Palm Beach Gardens, Florida), the arch was cut about 6 mm left and right of midline. The anterior articulation between the dens and C1 was opened carefully, and the intact arch was removed. Next, the cruciate, alar, and apical ligaments
were dissected sharply and transected. A high-speed drill was used to make a U-shaped osteotomy at the base/body of the dens to simulate a type III odontoid fracture. By alternating drilling with sharp dissection, the odontoid peg was carefully removed en bloc along with a rim of the C2 body. Care was taken to avoid breaching the dura (Figure 1B–D).

Next, reconstruction was performed in 2 stages. Both stages/procedures can be performed independently of each other (that is to say, only the C1 arch can be reconstructed or only dens screws can be used). First, odontoidoplasty was performed by inserting a cannulated odontoid screw to reattach the odontoid peg to the body of C2 under biplanar fluoroscopic monitoring, using standard odontoid screw fixation techniques. Second, miniplates and screws were used to replace the original osteotomized portion of the C1 arch. The C1 arch can still be reconstructed when odontoidoplasty is not possible (Figure 1 E and F).

Once the feasibility of this procedure was confirmed in this group of cadavers, we tested the construct for biomechanical stability on a separate group of specimens.

**Biomechanically Tested Specimens**

Six unembalmed human cadaver specimens (skull with attached cervical spine through C-2) from 4 males and 2 females (mean age, 53 years; range, 38-63 years) were then studied. To ensure absence of spinal disease, all specimens were x-rayed, their medical histories reviewed, and DEXA scans obtained to ensure the absence of osteoporosis. The testing setup was similar to that used in previous studies of the craniocervical junction.

**Biomechanical Testing**

Nonconstraining, nondestructive pure-moment loading was applied to the fixture on C2 in the inverted specimen through a system of cables and pulleys in conjunction with a standard servohydraulic test system (MTS, Minneapolis, Minnesota), as described previously (Figure 2A). Pure moments were applied about the appropriate anatomic axes to induce flexion, extension, left and right axial rotation, and left and right lateral bending. In each direction of loading, before collecting data, 3 preconditioning cycles of 1.5 Nm were applied for 60 seconds each. During data collection, loads were applied quasistatically in 0.25-Nm increments (each increment held 45 seconds) to a maximum of 1.5 Nm. Specimens also underwent vertical compression loading in which a spherical fixture on the piston of the servohydraulic test frame compressed the flat distal surface of the potting fixture on C-2 (Figure 2B). The position of the specimen was adjusted anteroposteriorly and laterally to minimize bending during compression. The specimens were preconditioned at 70 N for 3 cycles (60 seconds each) before data were recorded. During the data collection cycle, loads were applied quasistatically in 10-N increments (each increment held 45 seconds) to a maximum of 70 N.
During pure-moment and compressive loading, 3-dimensional spinal movement was measured using an optical tracking system (Optotrak 3020; Northern Digital, Waterloo, Ontario, Canada). Infrared-emitting diodes were rigidly attached to the ends of 1.25-mm, end-threaded, stainless steel surgical guide wires that had been inserted into 3 locations in the skull base and into 3 locations in the C-2 vertebral body and cut to an average of 4 cm. Three infrared-emitting diodes were similarly attached to the left lateral and right masses of C-1 to track the 2 halves separately as 2 rigid bodies. A digitizing probe (an accessory to the Optotrak system) was used to establish a Cartesian coordinate system at each spinal level with respect to its neutral orientation. \(^{24}\)

For pure-moment tests, angular motion at C0-C1 and C1-C2 was determined from marker coordinate data by use of the tilt/twist method. \(^{17}\) For vertical compression tests, the linear displacement of a point on the midsagittal midheight anterior tubercle of C-1 was established with the digitizing probe relative to the left lateral mass of C1 and tracked relative to the right lateral mass of C-1. \(^{23}\)

All specimens were tested in 3 phases, as follows: (1) intact/normal range of motion (Figures 3A and 4A); (2) after transection of the C-1 anterior arch and odontoidectomy, in which the entire odontoid process and the transverse ligament were removed (Figures 3B and 4B); and (3) after odontoidoplasty with use of an odontoid screw (Figures 3C and 4C) and C1 arch reconstruction with a rib graft substitute affixed to the remaining portion of the C1 anterior arch with miniplates and screws (Figures 3D and 4D).

**Surgical Technique**

The surgical procedure to create instability (step 2 of the testing sequence) was identical to that used in the anatomic feasibility portion of the study.
Odontoid Reconstruction Technique

A cannulated 40-mm odontoid screw (Medtronic Inc., Memphis, TN) was used (Figures 5 and 6). Procedures described by Dickman et al.\textsuperscript{16} were used to place the odontoid screw over a stainless steel guide wire from the anteroinferior border of the body of C2 and across the fracture site to capture the distal fragment of the dens. The fracture was reduced manually under fluoroscopic guidance.

C1 Arch Reconstruction

Once the odontoid screw was in place, a graft was fashioned from rib that had been harvested from thoracic cadaveric specimens (Figures 3D, 4D, and 6). The graft was carefully sized to the width and shape of the defect in the arch. Then, 2 miniplates (14 mm long, 0.6 mm thick; Codman, Raynham, Massachusetts) and 4 screws (1.7 mm diameter, 5 mm long) were used to secure the graft to the
remaining arch. Care was taken not to oversize the graft and splay the lateral masses of C1 (Figure 6).

During the initial trial period of testing, phase 3 was split and sub-tested as follows: (i) only the reconstructed arch was tested, (ii) only the reconstructed dens was tested, (iii) a combination of both was tested. Because the results of individual tests (i and ii) were the same as the combined test (iii), we then formally tested the combination of arch and dens reconstruction in all specimens.

RESULTS

Data Analysis

From the acquired data, the parameters quantified included angular range of motion (ROM), the lax zone (LZ), and stiff zone (SZ) to assess C0-C1 and C1-C2 angular motion, and linear ROM to assess translation of the left C1 lateral mass relative to the right C1 lateral mass. The LZ and SZ are components of the ROM (LZ + SZ = ROM). The LZ is the portion of the ROM in which the ligaments are not under substantial stress, whereas the SZ is the portion of the ROM in which the ligaments are experiencing loading and increasing displacement is met with increasing resistance. Smaller values of LZ, SZ, and ROM indicate increased stability. The angle demarcating the transition from LZ to SZ was calculated by extrapolating the load-deformation slope at data points corresponding to 0.75, 1.00, 1.25, and 1.50 Nm to zero load using the method of least squares. The data were analyzed using one-way repeated-measures analysis of variance followed by Holm-Sidak pairwise comparisons to assess whether differences in mean LZ, SZ, or ROM among conditions were statistically significant. Probability values less than .05 were considered significant.

FIGURE 5. Schematic illustration of the steps of odontoidoplasty and C1 arch repair using a rib-graft substitute. A, intact specimen. B, after transection of the C-1 anterior arch. C, after en bloc odontoidectomy, in which the entire odontoid process and ligaments were removed. D, after odontoidoplasty using odontoid screw and C1 arch reconstruction using a rib-graft substitute with miniplates. Used with permission from Barrow Neurological Institute.

FIGURE 6. Bone fragments and hardware for C1 arch repair and odontoidoplasty. Miniplates are attached to the rib graft. A 40-mm cannulated odontoid screw (bottom) was used to reattach the odontoid. Used with permission from Barrow Neurological Institute.
Angular motion at C0-C1 and C1-C2 significantly increased after odontoidectomy (Figures 7 and 8, Table 1). Lateral translatory separation of the left and right C1 lateral masses during compression increased 1145% relative to normal ($P = 0.001$; Figure 9, Table 1). After odontoidoplasty, atlantoaxial angular motion was reduced only moderately, by an average of 6% ($P > 0.10$; Figures 7 and 8, Table 1), which was more suboptimal than expected (negative result). After C1 arch reconstruction, translatory splaying was significantly reduced 89% relative to normal (ie, from 1.1 to 0.2 mm; $P = .002$; Figure 9, Table 1).

DISCUSSION

Anatomic and Biomechanical Considerations

Anatomically, the atlantoaxial joints are biconvex, making rotation at C1–C2 in its neutral position intrinsically unstable after an odontoidectomy procedure.$^{8,26-31}$ Biomechanically, odontoidectomy significantly increases ROM at C1–C2.$^1$ Odontoidectomy eliminates the buttressing action of the dens against the posterior aspect of the C1 anterior arch and transverse ligaments. It also disrupts the tension bands formed by other ligaments. Odontoidectomy requires transection of the anterior arch of C1; the posterior arch of C1, which has a thin cross-sectional area, especially at the arterial sulcus, must then alone resist the lateral force exerted by vertical compression.

Reconstruction Considerations

C1 Arch Reconstruction

During the initial cadaveric dissections, the osteotomized portion of the C1 arch was used for C1 reconstruction. However, the fit of this bone piece was imperfect because some bone was lost during drilling, even though the smallest bit possible was used. In a pilot specimen preceding full biomechanical testing, the amount of C1 lateral mass splaying associated with use of the osteotomized C1 arch piece was compared with use of a carefully shaped graft fashioned from rib (Figure 6). The lateral mass splayed by 0.86 mm with the replaced arch piece but only by 0.27 mm (69% reduction) when the rib graft was used. Thus, rib graft$^{32-34}$ was used for all specimens undergoing biomechanical tests. An additional advantage of using rib graft is that it can be shaped as a wedge,
which helps prevent the graft from subsiding posteriorly past C1 toward the spinal canal. Transoral odontoidectomy is universally performed, and C1 arch reconstruction is a simple and effective way to minimize cranial settling. In previous biomechanical studies of reconstructed CVJ specimens using posterior hardware, vertical translation was either not studied or was found to be present despite adequate fixation.\textsuperscript{3-8,21,23,35} Thence, in clinical settings, the original osteotomized arch or a graft substitute can be used for reconstruction, even when an additional anterior or posterior approach is performed for spinal stabilization to reduce translatory splaying, thus augmenting posterior instrumentation and fusion.

**Odontoid Reconstruction**

Types II and III odontoid fractures are commonly repaired in patients with odontoid screws.\textsuperscript{16,32,36,37} We simulated a type III odontoid fracture because the type III fracture is more stable and leaves a larger surface area to which the dens can be reattached (Figures 5 and 6). Because the initial biomechanical results of the study were not encouraging for odontoidoplasty, we do not recommend this procedure at this time. Future concrete evidence is needed before this procedure should be adopted.

**Biomechanical Implications**

Odontoidectomy produced distinct alterations in motion at C0-C1 and C1-C2 and in force-deformation responses in the lateral masses of C1. The many significant increases in biomechanical motion parameters indicate significant instability. Repair by arch reconstruction and/or odontoidoplasty only partially restored angular stability but provided restoration of the C1 arch to resist splaying. Integrity of the C1 ring is vital in preventing cranial settling.\textsuperscript{23} Our results confirmed this finding, showing that reconstruction of the anterior arch improved resistance to splaying of the C1 lateral masses (Figure 9, Table 1). Involvement of the dens is unrelated to C1 splaying; thus, a simple C1 arch reconstruction should still help prevent vertical compression.

**Clinical Considerations**

En bloc resection of the odontoid was problematic and time consuming in the cadaveric dissections, and the stability of the odontoid reattachment was suboptimal based on the biomechanical testing. Thus, reattaching the odontoid peg is not recommended based on the data accumulated. However, the osteotomized arch can still be used for reconstruction of the C1 arch, which can prevent vertical compression and may help to augment posterior instrumentation and fusion. Basilar invagination, platybasia, ventral extradural/soft tissue tumors, clival tumors, rheumatoid arthritis, and Pott disease may be some of the potential indications for reconstruction of the C1 arch.

**Study Limitations**

In vitro testing has inherent limitations. One challenge was to recreate the mouth opening of a normal adult in a cadaver. Many factors such as the integrity of the temporomandibular joint, trismus, macroglossia, dentition, and jaw length are involved with mouth opening. In this study we did not investigate the contribution of muscles to the stability of the craniovertebral junction. Another limitation is our small sample, which reduced the power of the statistical analysis and increased the probability of incorrectly finding no significant differences.

**CONCLUSIONS**

A proof-of-concept study was undertaken to restore stability of the atlantoaxial joint. Our results demonstrate that odontoid reconstruction does not confer any biomechanical benefit after resection. Based on our experience, it cannot be proposed as a stabilizing technique. Risks are likely to outweigh any perceived benefit and we therefore do not recommend its use in the clinical arena. Nevertheless, C1 arch reconstruction can still prevent lateral splaying of C1, which commonly follows an odontoidectomy because of cranial settling. Further biomechanical evaluation of this technique with other posterior atlantoaxial instrumentations and fusion is needed to explore the stability and strength of the construct and to determine
whether the amount of instability present after reconstruction is clinically prohibitive.

Disclosure

The authors have no personal financial or institutional interest in any of the drugs, materials, or devices described in this article.

REFERENCES


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aROM, range of motion; SZ, stiff zone; LZ, lax zone.
bBolded values indicate significant differences.
Acknowledgments

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COMMENTS

The authors present an interesting series of patients with a rare peripheral nerve lesion. The cases are well-described and illustrated. Some of these patients present with a clinical scenario that is very reminiscent of the Parsonage Turner syndrome, or brachial neuritis, with severe spontaneous pain followed by the palsy with some delay. Perhaps these patients should undergo imaging, such as MR neurography or ultrasonography, and maybe some should be explored and decompressed. The authors’ technique of epineurectomy and “detorsion,” with selected resection and primary suture repair seems to have been very successful in these patients, even after a substantial delay up to 17 months following onset of the palsy. We would have added intraoperative nerve action potentials (NAPs) to assist with the decision whether to simply perform neurolysis or to resect the lesion and repair it. I suspect that these torsional lesions may not be as rare as the sparse literature would suggest. Undoubtedly, some surgeons have seen these hourglass-type constrictions and concluded that these were unusual traumatic neuromas. As the intraoperative photos show, the torsional nature of the lesion may not become apparent until the epineurium is opened and resected.

Eric L. Zager
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This paper describes torsion injury to particular nerves in 5 patients that were all surgically explored and repaired, all with detorsion following epineurectomy and 3 with an additional primary repair. The clinical presentation in several cases was also consistent with a diagnosis of brachial neuritis or Parsonage Turner syndrome. These findings suggest that some patients may have a surgically treatable cause. Hopefully as imaging with MRI and/or ultrasound continues to evolve it may become obvious of the Parsonage Turner syndrome, or brachial neuritis, with severe spontaneous pain followed by the palsy with some delay. Perhaps these patients should undergo imaging, such as MR neurography or ultrasonography, and maybe some should be explored and decompressed. The authors’ technique of epineurectomy and “detorsion,” with selected resection and primary suture repair seems to have been very successful in these patients, even after a substantial delay up to 17 months following onset of the palsy. We would have added intraoperative nerve action potentials (NAPs) to assist with the decision whether to simply perform neurolysis or to resect the lesion and repair it. I suspect that these torsional lesions may not be as rare as the sparse literature would suggest. Undoubtedly, some surgeons have seen these hourglass-type constrictions and concluded that these were unusual traumatic neuromas. As the intraoperative photos show, the torsional nature of the lesion may not become apparent until the epineurium is opened and resected. The authors present an interesting series of patients with a rare peripheral nerve lesion. The cases are well-described and illustrated. Some of these patients present with a clinical scenario that is very reminiscent of the Parsonage Turner syndrome, or brachial neuritis, with severe spontaneous pain followed by the palsy with some delay. Perhaps these patients should undergo imaging, such as MR neurography or ultrasonography, and maybe some should be explored and decompressed. The authors’ technique of epineurectomy and “detorsion,” with selected resection and primary suture repair seems to have been very successful in these patients, even after a substantial delay up to 17 months following onset of the palsy. We would have added intraoperative nerve action potentials (NAPs) to assist with the decision whether to simply perform neurolysis or to resect the lesion and repair it. I suspect that these torsional lesions may not be as rare as the sparse literature would suggest. Undoubtedly, some surgeons have seen these hourglass-type constrictions and concluded that these were unusual traumatic neuromas. As the intraoperative photos show, the torsional nature of the lesion may not become apparent until the epineurium is opened and resected.

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Garavah et al have presented an innovative clinical strategy for limiting the need for dorsal stabilization following transoral cervicomedullary junction decompression in selected cases, while minimizing range of motion loss. This technique is most certainly technically demanding. Its use, in addition, will be very limited since transoral approaches are much less frequently employed than in years past. Regardless, the authors are to be congratulated for their creativity and objective assessment.

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