Original Article

C1-C2 arthroplasty for craniovertebral junction instability: A preliminary proof of concept in human cadavers

ABSTRACT

Background: The atlantoaxial complex contributes to significant neck movements, especially the axial rotation. Its instability is currently treated with various C1-C2 fusion techniques. This however, considerably hampers the neck movements and affects the quality of life; a C1-C2 motion preserving arthroplasty could potentially overcome this drawback.

Objectives: We evaluate the range of motion (ROM) of lateral C1-C2 artificial joints in cadaveric models.

Materials and Methods: This is an *in vitro* cadaveric biomechanical study. After C1-C2 arthroplasty through a posterior approach, the C1-C2 ROM was tested in 4 fresh-frozen human cadaveric specimens, before and after destabilization.

Results: The mean axial rotation demonstrated after the placement of C1-C2 joint implants was 15.46 degrees on the right and 16.03 degrees on the left side; the prosthesis provided stability, with 46% of the baseline C1-C2 axial rotation on either side. The ROM achieved in the other axes was less compared with that of intact specimens. To initiate rotation, a higher moment of 1.5 Nm was required in the presence of joint implants compared to 0.5 NM in unimplanted specimens.

Conclusions: In our preliminary ROM evaluation, the C1-C2 arthroplasty appears to be stable and provides about half of the range of atlantoaxial rotation. It has the potential for joint motion preservation in the treatment of atlantoaxial instability resulting from lateral C1-C2 joint pathologies.

Keywords: Artificial joints, atlantoaxial, biomechanics, C1-C2, craniovertebral junction, kinematics, neck rotation, prosthesis

INTRODUCTION

The atlantoaxial area with its intricate anatomy is the most mobile segment of the spine providing significant range of neck movements, particularly rotation, and this very fact also makes it vulnerable to instability.[1-3] The atlantoaxial dislocation (AAD) can arise from various pathologies, with differing etiology according to geographic regions. For instance, while the trauma, degenerative, and inflammatory diseases are its common causes in the western nations, congenital craniovertebral junction (CVJ) anomalies with an underlying C1-C2 facet joint deformity remain the usual reason in the Asian continent.[4-6] Regardless of the etiology, the most common operation performed for AAD has been the CVJ fusion.[4-6] Although this treatment method has been time tested with excellent reported outcomes, one of its important disadvantages is neck movement restriction, a matter of concern from the patients' perspective. Thus, an

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artificial C1-C2 joint prosthesis that overwhelms this specific drawback, yet simultaneously stabilizes the CVJ region is likely to be a boon for the AAD patients.

In this paper, we report our preliminary biomechanical evaluation of a novel C1-C2 facet replacement implant in the human cadaveric spine.

MATERIALS AND METHODS

Four fresh-frozen cadaveric head-and-neck specimens extending from the intact occiput to T2 were procured. The specimens naturally thawed at the room temperature. The occiput (C0) to C3 segment was excised from the specimen, and the muscles were dissected with careful preservation of the osteo-ligamentous structures. Each specimen was potted using Bondo (3M, Maplewood, MN), a 2 part epoxy resin, maintaining the neutral upright position and keeping the C3 parallel to the horizontal plane. Screws were drilled through the C3 to augment its anchorage in the cement. A fiberglass plate was fixed on the top of cut surface of the occiput and held in position with screws drilled through it into the petrous bones. The plate itself had a loading adaptor where the torque transducer could be fixed.

Motion analysis

Each of the potted specimens was fixed on the test rig located in the field of view of the Optotrak (NDI, Waterloo, Canada) motion capture system [Figure 1]. The torque transducer was attached to the loading adapter mounted on the occiput (C0) end. A set of three light emitting diode markers were affixed to the occipital bone, bilateral C1 lateral mass and the C2 body for recording the spatial locations in response to the moment applied using the Optotrak motion capture system. This system utilizes infrared cameras to track the spatial locations of the three light-emitting diodes affixed to the vertebrae, in response to the applied loads.

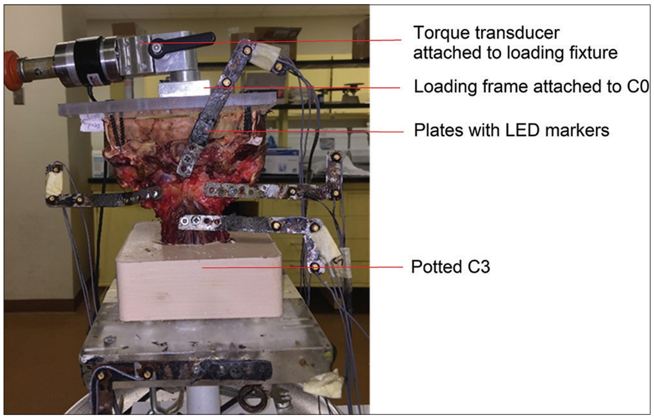

Figure 1: Experimental setup of range of motion testing of C1-C2

Initially, the intact specimen was subjected to pure moments applied by the torque transducer in steps of 0, 0.5, 1, 1.5, and 2 Nm in flexion, extension, right and left lateral bending, and right and left axial rotation, and the position data were captured at each load step. Following the testing of intact specimen, the C1-C2 capsule was cut and all ligaments including the transverse ligament were severed to simulate a destabilised CVJ model. The C1-C2 joint cartilage was removed and the facets were drilled to create appropriate space for placing the prosthesis; sizers were used to assess the adequacy of drilling. Appropriate grooves were made on the C1-C2 facetal surfaces to engage the prosthesis. The prosthesis was then simultaneously introduced in both C1-C2 joints to slide along the precut grooves. The posterior plates of the prosthesis were fixed to the surface of the C1 lateral mass and C2 isthmus, using lateral mass and pedicle screws respectively [Figure 2].

The position data recorded for each vertebra were transformed into angular rotation referenced to the base plate using the rigid body transformation. The rotation of the vertebra was plotted against the applied load to characterize the load-displacement behavior of the segment. The angular displacement across the segments for the intact and instrumented cases was obtained. The mean of the range of motion (ROM) of all the cases was computed.

RESULTS

Figure 3 represents the comparison of ROM (rotation, flexion-extension and lateral bending) achieved in the intact and postarthroplasty C1-C2 specimens, at a moment of 2 Nm. The mean axial rotation noted in the presence of joint implants was 15.46° on the right and 16.03 ° on the left side. The prosthesis thus offered stability, preserving 46% of the baseline C1-C2 axial rotation (mean; right, 46.4° and left, 46.6°) seen with intact joints on either side. The other range of movements, when compared with that of intact specimen was relatively less. The initiation of rotation after the implant

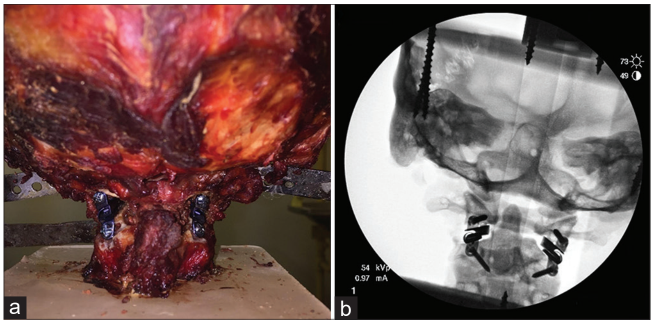

Figure 2: Cadaveric (a) and fluoroscopic images (b) following C1-C2 arthroplasty

placement required a torque of 1.5 Nm compared to 0.5 NM in unimplanted specimens [Figure 4].

DISCUSSION

The C1-C2 joint complex consists of a median atlanto-Odontoid and 2 lateral facet joints. This along with its surrounding ligaments plays an important role in neck movements contributing to nearly 50% of total range of neck rotation, with the usual range being approximately 23°–45°.[1-3] A damage or abnormality of any of these joints and/or ligamentous structures can predispose to C1-C2 subluxation. Following trauma, the AAD usually results from disruption of the transverse ligament or a dens fracture.[7] Only infrequently, the lateral joint complex is involved. However, in patients with congenital CVJ instability, the anatomic orientation of these C1-C2 lateral facet joints is the major determinant of disease progression.[2,4,6,8] In these, the C1-C2 joints may be congenitally oblique which over a period give rise to progressive slippage of the C1 over C2 and the treatment therefore, aims at their multiplanar remodelling with fixation. Though this treatment is well established, its major downside has been the cervical spine movement limitation. At times, an adjacent segment degenerative disease as seen after any other spinal arthrodesis is also a possibility.

Recently, few attempts have been made to overcome this problem, by innovations of artificial C1-C2 joints.[9-15] These strive to restore CVJ stability and simultaneously preserve the C1-C2 movements as close to that seen in a nondiseased spine. For this purpose, an atlanto-odontoid joint prosthesis has been described, and was inserted in cadaveric specimens through a trans-oral approach.[9-11] However, this corridor in patients has a relatively higher risk of infections and cerebrospinal fluid leak, and other inherent approach-related complications. Overcoming these demerits, Shen *et al*. reported the use of an artificial atlanto-Odontoid joint which can be fixed through a posterior approach.[12] Similarly, another posterior C1-C2 restricted nonfusion fixation device consisting of multi-axial fixed connector with atlas-axis connecting rod systems, and preserving the rotation and lateral bending movements has been developed by Chen *et al*.[13] The above mentioned posterior motion-preserving prostheses can be useful in indications such as nonunion of dens fractures and injuries involving transverse ligament disruption. Nevertheless, these may not be appropriate for congenital AAD patients in whom the primary pathology lies in the lateral facetal joints. Also, their utility in cases with inflammatory and degenerative etiology affecting the lateral joints may be limited.

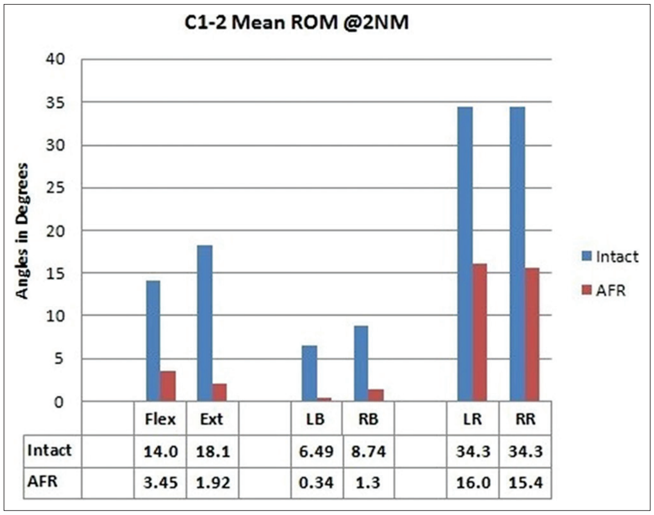

Figure 3: Range of motion between intact and implanted specimens at a moment of 2 Nm. AFR - Artificial facet replacement; LB - Left bending; RB - Right bending; LR - Left rotation; RR - Right rotation

Normal atlantoaxial joint configuration and function

Knowledge of the kinematics of the normal C1-C2 joint helps to understand the underlying dynamics of an artificial C1-C2 facet replacement. Normally, the C1 inferior facet is concave and the C2 superior facet is convex.[2,16] The anatomy of a C1-C2 joint is naturally designed such that it allows concomitant movements in various planes. Apart from serving the predominant neck rotation, the C1-C2 joint concurrently allows several other movements which in turn facilitate its degree of rotation.[2] The rotational movement indeed is coupled with vertical C2 motion as well as some amount of lateral-tilt, lateral-translation and flexion-extension at the C1-C2 area. These movements are not possible with a concavo-convex bony facet configuration. However, the presence of intervening cartilage surfaces with a convex on convex configuration makes these movements happen.[2,16] Additionally, the C1-C2 joint capsules, and the structural integrity of the dens with C1 anterior arch along with adjacent ligaments permit controlled C1-C2 movements, while limiting motion beyond the physiological range.[1,3,16]

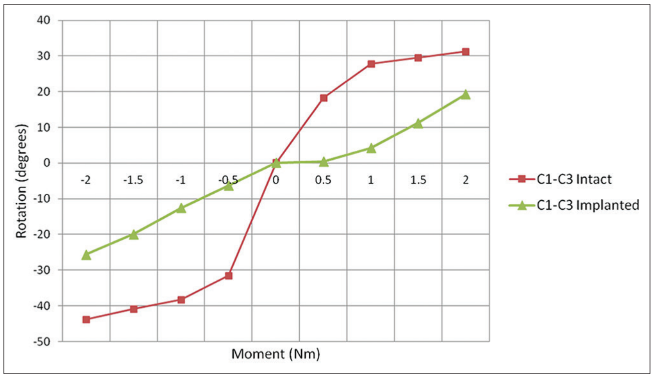

Figure 4: Comparison of torque needed to initiate rotation between intact and implanted specimens. Note that rotation started at 1.5 NM after facet replacement compared to 0.5 NM in unimplanted specimens

The current C1-C2 facet joint design performance and futuristic implications

An ideal C1-C2 facet prosthesis has to be as close to the design and functionality of naturally occurring joint, and relevant attempts are on its way.[14,15] Goel *et al*. proposed a ball and socket type of joint with the aim of restoring joint mobility.[14] Such prosthesis can provide some flexion extension but only a few degrees of axial rotation. Also, the biomechanical testing of this prosthesis is yet to be reported. In this initial cadaveric experiment, we have focused on the biomechanical evaluation of a prototype of lateral facetal joints that closely mimic the naturally occurring joints. With our current C1-C2 joint design, the rotation seems to be slightly less ideal, and needs further modification. In addition, this design requires refinement to preserve the other C1-C2 movements such as flexion-extension and lateral bending as well. Furthermore, the force needed to overcome the inertia for the desired amount of rotation appears to be higher than that of the naturally occurring joints; this could be due to absence of the muscular forces that assist smooth neck movements *in vivo*. Besides, accompanying C1 assimilation and C2-3 fusion, a frequent anomaly seen in congenital AAD patients can alter the joint stress and performance, and needs consideration. It is also likely that the actual loading force in real life differs from that seen *in vitro* conditions. In short, the described C1-C2 prosthesis has to be subjected to further *in vitro* and *in vivo* testing before it can be actually put into clinical use.

Currently, there remains a challenge to construct a lateral C1-C2 joint prosthesis that very closely resembles the natural joints. At present, a near-normal structural design simulating the joint cartilage has been identified; an ultrahigh molecular weight polyethylene composition of the cartilage has shown improved gliding effects while reducing corrosion. Further biomechanical evaluation such as its wear and tear properties and endurance testing is being carried out.

CONCLUSIONS

The artificial C1-C2 lateral joint appears to be a promising motion-preserving strategy, with its initial biomechanical evaluation demonstrating reasonable rotational movements in this cadaveric study. However, it requires further extensive evaluation before it can find its clinical utility.

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Conflicts of interest

There are no conflicts of interest.

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