Biomechanial and Clinical Aspect on Fixation Techniques in the Cervical Spine

BY
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Abstract

The present work is analyzing the general biomechanical aspects of fixation techniques in the upper and lower cervical spine along with clinical implications.

The in vitro biomechanical properties of five different posterior atlanto-axial fixation techniques are compared. They provided for either a one, two or three-point fixation between atlas and axes. A new device, the C1 claw was biomechanically tested, which allow for fixation without the need for a structural bone graft. The three-point reconstructions indicated superior biomechanical properties compared to all others.

The new C1 claw device was clinically evaluated in a series of 26 patients treated with a posterior C1-C2 fusion. There were no clinical or radiological failures in the series, Twenty-one patients out of twenty-three with any length of follow up either showed a solidly healed fusion or a healed fracture.

Destructive flexion (DF) injuries in the lower cervical spine treated with anterior plate alone were analyzed with respect to healing rate and complications in a consecutive series of 36 patients. Results indicated that DF injury stage 1 and 2 according to Allen and Ferguson healed without complication, whereas DF injuries stage 3 had a high frequency of failure, needing an additional posterior fixation.

The in vitro biomechanical properties of four different fixation techniques for a destructive flexion injury stage 3 were analyzed. The result indicated that anterior plate alone for fixation of a DF injury stage 3 is insufficient supporting the clinical finding in the previous study.

Adjacent level motion was analyzed following a one segment fusion in the lower cervical spine. Motion was found to increase in adjacent levels possibly contributing to accelerated degeneration.

Keywords: Biomechanics, Atlanto-axial fusion, Destructive flexion injuries, cervical spine, adjacent level motion

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This thesis is based on the following papers, which will be referred to in the text by their Roman numerals:


To my lovely wife  Eva

and our wonderful daughters

Frida, Josefin and Fanny
Introduction

Historical Background

The oldest known description of vertebral fractures is from the Edwin Smith surgical papyrus, which is almost 5000 years old. In this writing, spinal injuries are described as an “ailment not to be treated”. In the Greek “Golden Era” when more modern teachings of medicine were introduced, Hippocrates described a way of treating spinal injuries with axial distraction while an anterior force was applied to the gibbus.

Paul of Aegina performed the first reported surgical procedure, laminectomy for a spinal cord injury, in the 7th century. There are no reports of spinal instrumentation until the second half of the 18th century, when interspinous wiring for cervical and thoraco-lumbar fractures were developed. However, it is not until the last 70 years that surgery has become a method of treating cervical spine instabilities in a wider perspective (1).

Basic biomechanics of the cervical spine

Anatomically and functionally the cervical spine may be divided in two parts; the upper part consisting of occiput, atlas (C1) and axis (C2), and the subaxial or lower cervical spine, consisting of C3-C7.

Occiput and axis are sometimes described as two rotating squares with atlas as a bearing between them. The joints between atlas and axis are almost horizontal and therefore allow for a wide range of motion in rotation, which is approximately 60° (2), whereas rotation between occiput and atlas is completely prevented by the geocentric anatomy of the articulation. Taking this in consideration, a fixation between atlas and axis will render the patient a 50% restriction of cervical spine rotation.

Both joints, occiput-C1 and C1-C2, participate in flexion extension. Extension at occiput-C1 is one of the largest single motions in the spine, about 30°. Lateral bending occurs at occiput-C1, but is almost negligible at C1-C2.

Motion in the subaxial cervical spine occurs at all levels and in all six degrees of freedom, however, most of the flexion-extension motion occurs in the central region with the C5-C6 considered to have the greatest range. It is believed that there may be some causal relationship between this observation and the incidence of cervical spondylosis at that interspace. The loss of motion due to degeneration or posttraumatic changes has been observed to
result in compensatory increase of motion in adjacent segments (3). Range of motion in axial rotation and lateral bending tend to be smaller in the more caudal segments.

**Coupled motion**

The term *coupled motion* denotes that motion about one axis consistently occurs simultaneously with motion about another axis (rotation or translation). In vitro, it occurs in the thoracic and lumbar spine, but is most dramatic in the cervical spine. Two kinds of coupled motion are especially well known in the cervical spine, axial rotation in the same direction as applied lateral bending, and lateral bending in the same direction as applied axial rotation.

**Clinical instability of the cervical spine**

White and Panjabi (4) defined clinical instability as “the loss of the ability of the spine under physiologic loads to maintain relationship between vertebrae in such a way that the spinal cord or nerveroots are not damaged or irritated and deformity or pain does not develop”. In the upper cervical spine instability is quite well understood and defined both clinically by Jefferson, Cornich, Effendi and Anderson Dálonzo (5,6,7,8) and biomechanically by Spence, Fielding and Schartzer (9,10,11).

Instability in the lower cervical spine, however, is somewhat more difficult to define, which is reflected by the many classification systems existing (12,13). Basically these classification systems regard the cervical spine as a construct made up of two or three columns. The two-column theory proposed by White and Panjabi (14) defines one anterior column as the vertebral body, the disc and the anterior and posterior longitudinal ligament, and a posterior column as the ligaments and osseous structures posterior to the posterior longitudinal ligament. Furthermore they define a motion segment as two adjacent vertebrae and the intervening soft tissues. If a motion segment has all the anterior elements and one posterior element or all the posterior elements and one anterior element intact it will remain stable under physiologic loads. However, if all the anterior or posterior elements are not functional the motion segment should be considered unstable (15). They developed a checklist for the diagnosis of clinical instability of the lower cervical spine based on the radiological findings and the neurological status. In addition to disruption of the anterior or posterior elements, horizontal translation of >3,5mm or sagittal plane rotation >11° more than the adjacent level in a motion segment, were given point values as
well as medullary or nerveroot damage. Instability was considered when a critical point value was exceeded (16).

The three-column theory introduced by Denis (17) defines a third intermediate column as the posterior part of the vertebral body, the posterior annulus fibrosus and the posterior longitudinal ligament. Instability was defined as disruption of the anterior or the posterior column as well as the intermediate column.

Allen and Ferguson (18) presented a mechanistic classification system of injuries to the lower cervical spine in 1982. They defined six groups, or phylogenies, of injuries based on the direction of the major injury vector, which produce the initial failure within each phylogeny. These groups were compressive flexion, vertical compression, distractive flexion, compressive extension distractive extension and lateral flexion. In each phylogeny they defined a minor injury vector which produced associated tissue failure. They stated in their work that “Instability in the lower cervical spine is an ethereal subject badly in need of rigorous definition”. Furthermore they strongly rejected the idea that neurological injury should be considered a factor in the assessment of stability, and disapproved of the idea of having a “checklist” that would provide a rational analysis of an injury. In their opinion the skeletal injury, the neurologic injury, associated injuries, medical disorders and unique individual factors should be analyzed in each case to determine acute, and risk for late instability.

Recent work by Argensson et al (19) defines more than one major injury vector in each phylogeny. For example in distractive flexion injuries, the major injury vector would be distraction-flexion in injuries with subluxation or bilateral facet joint dislocation, whereas rotation also would be a major injury vector in the distractive flexion injury with unilateral facet joint dislocation, thus, creating an asymmetrical lesion.

**Fixation techniques of the cervical spine**

The purpose of surgical intervention of the cervical spine in general is to decompress neurological structures if so is necessary, realign the cervical spine and to stabilize a possible unstable motion segment. These purposes may be obtained in more than one way, using anterior or posterior approach to the cervical spine. However, as an anterior approach may allow for decompression and superior realignment of the cervical spine compared to a posterior approach, an anterior fixation might be inferior to a posterior instrumentation. These considerations along with individual physiologic demands must be weighed against each other before a decision can be made on how to treat the patient.
It may be useful to discuss the upper and lower cervical spines separately as the anatomical and functional considerations are quiet different. To simplify the understanding on various fixation techniques, the cervical vertebrae may be looked upon as rings that should be fixed to each other. One can apply the fixation devices at one, two or three points around the circumference of these rings, thus 1-, 2-, and 3-point fixation.

The upper cervical spine

There are various indications for fixation of the upper cervical spine such as fractures, rheumatoid arthritis, metastasis and ligamentous injuries. Anterior screw fixation introduced by Böhler (20) is almost exclusively used for fracture of the odontoid process of axis, whereas posterior fixation techniques can be an alternative for all other mentioned disorders. Gallie (21), in 1939, introduced a posterior wiring technique that depended on a structural bone graft. Over the years, numerous different techniques have been developed. For example, double looped wiring with two bone grafts introduced by Brooks-Jenkins (22) and the Halifax clamps (23). These constructs were one-point fixations and had a failure/non union rate of about 10-15%, which was considered secondary to failure of the bone graft (24). In 1979 Magerl and Seeman (25) introduced a transarticular (TA) screw fixation technique, which in combination with a posterior wiring between C1 and C2 form a three-point fixation. At present, this construct is by many spinal surgeons considered as the golden standard for posterior fixation of C1-C2 (26,27). In large clinical studies this technique has shown a negligible pseudarthrosis rates (28).

In a point of view remark, P Rooper (29), discussed the issue why posterior wiring techniques failed. He addressed the need for studying one-point fixation techniques that did not depend on structural bone grafts,
before accepting three-point fixations using TA screws, as the procedure of choice for C1-C2 fixations. His concern was mainly that the TA screw technique is technically demanding and requires considerable experience. There are numerous reports of screws penetrating the vertebral artery (VA) (30,31), sometimes with fatal consequences to the patient (32).

At Uppsala University Hospital the C1 claw had been developed, that could be used attached to TA screws (Fig.1) or in combination with pedicle screws in C2 or sublaminar hooks. The latter being 1-point fixations without the need for structural bone graft. However, there were no biomechanical studies done comparing these constructs using the C1 claw to already existing reconstruction techniques.

![Figure 1. The C1 claw, a special device for C1-C2 fixation.](image)

**The lower cervical spine**

Numerous fixation techniques and devices have been developed over the years for stabilizing the lower cervical spine. The first techniques introduced were for posterior fixation. The wire technique introduced by Gallie for the upper cervical spine was also applicable in a modified way for use in the lower cervical spine. The posterior wire technique has been developed over the years introducing different types of cables secured to the posterior lamina and spinal processes (33,34,35,36), and is still the operative method of choice in many spine centers. However, these techniques provide for one-point fixations and were depending on a structural bone graft. To avoid this, various plates were developed for posterior fixation of the cervical spine. The problem has been to find safe screw placements to secure the plates to
the posterior aspect of the cervical spine. An insertion technique in the lateral mass to avoid injury to the vertebral artery and the nerve root have been described in the literature by Roy-Camille and others, and is well excepted (37,38). Others have recommended sublaminar hooks connected to rods to stabilize the spine. In recent years pedicle screw fixation in the cervical spine has been reported (39) providing for excellent screw fixation, however difficult to perform and with potential risk of vertebral artery injury (40).

Robinson and Smith (41) in 1955, followed by Cloward (42) 1958 and Bailey & Badgely (43) 1960 introduced the anterior approach to the cervical spine. The anterior approach allowed for anterior decompression and realignment of the cervical spine. Later on, a small fragment plate was used to secure the motion segment to allow early mobilization. The anterior fixation technique was originally designed for degenerative diseases, but further development with screws that locked to the plate (44,45) made it useful also in patients with injuries to the lower cervical spine.

It has for a long time been a debate whether or not a fusion in the spine will have influence on adjacent levels and in what way. In the lumbar spine several biomechanical studies have indicated that a fusion at one level will lead to increased motion and intradiscal pressure in adjacent levels, and this effect increase with multiple level fusion (46). The question is whether these findings will have influence on the degenerative process that would take place in spite of a fusion. Some authors suggest that this increase of motion and intradiscal pressure is within the adjacent motion segments physiologic range and therefore does not influence on the natural history of degeneration (47). Others mean that increase in intradiscal pressure may disturb the microcirculation near the endplates and influence on the nutritional diffusion to the disc, which lacks a true blood supply (48).

The effect on adjacent levels following fusion in the cervical spine is not well understood, and there are few studies reported on the issue. One biomechanical study by Eck et al. (48), reported on increased motion and intradiscal pressure in adjacent levels following fusion. The intradiscal pressure increased gradually with increased motion. However the specimen were only tested in flexion-extension. To reach a better understanding on the consequences in adjacent levels further studies needed to be done.

**Anterior or posterior approach to the cervical spine**

In this overwhelming amount of fixation techniques, it has become quiet a challenge for the surgeon to choose the best way to treat the patient. The first issue to be addressed of course is if the problem can be solved by conservative or non-operative treatment. If the answer is no, then the second
question to be asked is if the procedure should be done from the anterior or posterior aspect of the spine.

Some general aspects of the two approaches may be stated initially. There are several advantages with the anterior as opposed to the posterior approach in trauma patients. The patient is treated in a supine position. The potentially dangerous maneuver of turning a patient with an unstable cervical spine injury over to prone position is, thus, avoided.

Anterior approach allows for removal of the disc. Many cervical spine injuries, especially distractive-flexion injuries, are associated with traumatic disc herniations (49,50,51). Reducing the dislocation may lead to injury of the spinal cord, as the disc may dislodge into the spinal canal, which has been reported in several articles (52,53). This dreaded complication is avoided by removing the disc prior to reduction, which is made possible by an anterior approach.

Furthermore, anterior approach is more atraumatic than posterior, and complications are rare. Anterior approach has also proven to render patients less neck problem compared to posterior surgery (54,55). “Stand alone” short level posterior fixation, on the other hand, may in trauma patients result in kyphosis of the affected segment due to subsequent disc degeneration with reported increase in complaints of cervical pain (56). An anterior plate fixation with an appropriate bone graft in the disc space is technically simple, and the fusion is under direct compression, thus allowing optimal fusion healing.

In the upper cervical spine, anterior approach is most common for anterior screw fixation of acute fracture of the odontoid process. There are some other rare cases when posterior approach is not possible due to anatomical considerations when the approach must be individually chosen, but in most other cases the posterior approach is the most common.

In the lower cervical spine the choice between anterior or posterior approach may be more difficult to make. For degenerative diseases such as disc herniations, foraminal stenosis and cervical spinal stenosis, both approaches may give access to address the problem. In most cases anterior approach with the Smith Robinsson technique will allow for decompression of the spinal cord and nerveroots. However, many surgeons suggest that if the procedure will exceed more than 2 motion levels, a posterior approach with decompression and fixation is advisable.

In trauma patients, anatomical and biomechanical aspects must be taken in consideration. The general idea has been that if the injury is predominantly in the posterior column, then a posterior approach and fixation is recommended, and the opposite if the injury is in the anterior column. However, numerous clinical studies have reported excellent results when treating cervical spine injuries with both predominantly posterior and anterior injuries with single anterior approach and fixation (57,58,59,60,61,62). Ulrich et al. (63) even stated that anterior approach
should be the primary and preferred one for a traumatized unstable lower cervical spine. It involves fewer problems with regard to surgical technique, unrestricted additional cord decompression can take place, implant fixation is technically simple and the fusion is under direct compression. However, combined techniques, anterior and posterior, are indicated for highly unstable or particularly complex injuries (64,65,66). Posterior fixation seems, therefore, to be more appropriate for degenerative, rheumatoid or tumorous instabilities than for traumatic instabilities.

**Highly unstable subaxial cervical spine injuries**

As mentioned above, the anterior approach and fixation has proven successful in treating lower cervical spine injuries in most cases. However, some authors have reported on failure in single stage fixation. The failure to recognize the presence of three-column instability resulted in failure of the stabilization (66). Mechanism of injury most frequently identified in this group was the distractive flexion (DF) pattern. Thus, the problem might be to identify and understand the biomechanical and anatomical complexity of these injuries, in order to choose the accurate fixation technique in each single case.

DF-injuries account for about 10 % of all injuries to the lower cervical spine (67). As the injuries mainly involves posterior soft tissue such as ligaments and parts of the intervertebral disc, and not bone the healing potential with conservative treatment is poor (68,69). The severity of DF injuries range from mild subluxations to dislocations with the vertebrae totally displaced anteriorly, the latter obviously with all posterior ligaments ruptured. Therefore thorough anatomical and biomechanical understanding of these injuries is mandatory to obtain optimal results (70).

At Uppsala University Hospital, DF injuries had been treated with anterior approach and fixation according to a study protocol. We observed failure in fixation in some patients with bilateral facet joint dislocation. A consecutive series of 36 patients was examined and subdivided according to the Allen-Ferguson classification (18). Furthermore we decided to perform a biomechanical study to investigate the biomechanical properties of a DF injury with bilateral facet joint dislocation stabilized with anterior plate alone. As this injury is presumably highly unstable and therefore perhaps in need for an additional posterior fixation, three different posterior fixation techniques were also tested in combination with the anterior plate, in order to find a clinical recommendation on how to stabilize these injuries.
Aims of the present study

- To quantify and compare the in vitro biomechanical properties of five different atlanto-axial posterior fixation techniques providing for one, two and three-point reconstructions. To determine whether a non-bone graft dependent one-point fixation could afford stability levels equivalent to a three-point reconstruction at the atlanto-axial interspace.
- To evaluate the radiological healing and possible complication of the new fixation device for posterior atlanto-axial fusion in a consecutive clinical series of patients.
- To analyze the outcome in terms of healing rate and complications in a consecutive series of patients treated for distractive flexion injuries with anterior plate alone.
- To quantify and compare the in vitro biomechanical properties of four different fixation techniques in a distractive flexion injury stage 3, in order to find data that can be used to form a clinical recommendation.
- To investigate the effect on motion in adjacent levels following a one level fusion at C5-C6 using different fixation techniques providing successively decreased motion in the fused segment.
Materials

Biomechanical in vitro studies (Paper I, IV and V)

Preparation and Experimental groups

Sixteen human cervical spines, in two groups of eight in each one, (C0-Th1) were utilized in the current study. Eight spines were used in the C1-C2 study (Paper I), and the other group of eight spines was used in the study with four different fixation techniques at C5-C6 (Paper IV and V). The cervical spines were harvested from fresh human cadavers, frozen immediately in double-wrapped plastic bags and stored at -20°C until testing. Pre-experimentation radiographs were obtained to identify and exclude any specimen that demonstrated spinal pathology. Before biomechanical testing, the specimen were thawed to room temperature and the surrounding soft tissue and muscles were dissected off the cervical spines, with care being taken to preserve bone, spinal ligaments, intervertebral discs and the facet joint capsules.

Clinical consecutive study on C1-C2 fusion (Paper II)

The material consisted of 26 patients (14 woman), with mean age of 73 (range 37-93) years, treated with C1-C2 fusion. The indications were odontoid fracture in 18 patients, rheumatoid instability in 6 and odontoid non-union and os odontoideum with myelopathy in 1 each.

Clinical consecutive study on DF injuries (Paper III)

During the years 1987-1997, 399 cervical spine injuries were treated surgically at the Uppsala University Hospital. Of these, thirty-six patients (6 women) with DF-injuries were treated according to the study protocol. Mean age of patients were 51 (16-88) years. The most frequent cause of injury was traffic accident. The DF injuries were classified according to Allen and Ferguson (18). There were six stage one (DF injury stage 1; “flexion sprain” facet subluxation with divergence of the spinous processes), one of which involved two levels. Seventeen stage two, (DF injury stage 2; unilateral facet joint dislocation), three of which involved subluxation on the adjacent level.
leading to surgery on two levels. Thirteen stage three injuries (DF injury stage 3; bilateral facet joint dislocation with ≤50% vertebral body displacement anteriorly). No patient in the series had a stage four injury (DF injury stage 4; floating vertebrae or translation >50% anteriorly). Neurological status was classified according to the American Spinal Injury Association’s modified Frankel’s grading (71). Quadriplegia were present in nine of the thirty-six patients; one of the six in DF injury stage 1, three of the seventeen in DF injury stage 2, and five of the thirteen in DF injury stage 3.
Summary of Papers

Biomechanical in vitro Studies (Paper I, IV and V)

Methods
In the first biomechanical study (Paper I) comparing five different posterior fixation techniques at C1-C2, the segment between C3 and C4 was rigidly fixed by placing bone screws between the vertebral bodies and adjoining facets. The specimens were then mounted with cross transfixing pins and polyester resin at C3-C4 superiorly and the skull rigidly fixed in a container with cross transfixing pins inferiorly. This left the segments C0-C1, C1-C2 and C2-C3 unconstrained between the fixation jigs. Care was taken to ensure that there was no impingement at the motion segments. An inverted orientation was used as it allowed for more accurate alignment of the loading fixture and therefore more accurate alignment of the loading axes. This orientation also reduced the risk for unwanted secondary moments caused by the weight of C3-C4 and the fixture, as compared with a placement with the much larger skull base and loading fixture placed superiorly.

In the second biomechanical testing (Paper IV and V) The C3-C4 and C7-T1 motion segments were rigidly fixed by placing bone screws between the vertebral bodies and between adjoining facets. Care was taken to ensure that there was no impingement between the facets at the C4-5-6-7 motion segments. The specimens then were mounted with cross transfixing pins and polyester resin at C3-4 superiorly and C7-T1 inferiorly. This left the segments C4-C5, C5-C6 and C6-C7 unconstrained between the fixation jigs, so that the motion segment C5-C6 and the adjacent levels could be analyzed.

To enable each specimen to serve as its own control, the specimens were first tested biomechanically 1) while intact (control) after which they were tested 2) after destabilization and reconstruction. In the first study the destabilization was performed mimicking an odontoid fracture Andersson-dÁlonzo type II (8).

Spinal Constructs (Paper I)
After destabilization each of the spinal specimens were reconstructed in the following order:
1. Supralaminar hooks over C2-laminae and a rod under the spinous process of C2, in combination with C1 claw, one-point fixation (HC) (Fig.2).
2. Pedicle screws in C2 in combination with C1 claw, one-point fixation (PC) (Fig.3).
3. Bilateral C1-C2 transarticular screws, two-point fixation (Magerl) (M) (Fig 4).
4. Bilateral C1-C2 transarticular screws combined with a posterior wire fixation (modified Gallie) using structural bone graft, three-point fixation (MG) (Fig 5).
5. Bilateral C1-C2 transarticular screws in combination with the C1 claw, three-point fixation (MC) (Fig 6).
In the second study the instability model created before the reconstruction consisted of a distractive flexion injury stage 3 at C5-C6 level. Transecting the supraspinous ligament, interspinous ligament, facet joint capsules, ligamentum flavum, posterior longitudinal ligament, and the posterior half of annulus fibrosus created this. The facet joints were dislocated and subsequently reduced. The only remaining ligament bridging the C5-C6 vertebrae was the anterior longitudinal ligament and the anterior half of annulus fibrosus, which however, was plastically deformed enough to allow the dislocation-reduction maneuver.

**Spinal Constructs (Paper IV and V)**

After destabilization each of the spinal specimens were reconstructed and tested in the following order.

1. Anterior plate with tricortical interbody bone graft (AP) (Fig 7)
2. Anterior plate+ Bohlman triple wire reconstruction (APW) (Fig 8)
3. Anterior plate+transfacet screws (APT) (Fig 9)
4. Anterior plate+pedicle screw/rod instrumentation (APP) (Fig10)
The specimens were kept moistened copiously with saline during the mechanical testing, which never exceeded 8 hours (72).

**Biomechanical Testing**

All biomechanical testing was performed on a biaxial material testing machine (MTS 858 Bionix Test System, Minneapolis, MN.) The non-destructive biomechanical testing included axial rotation (±1.5 Nm, 50 N preload), flexion/extension (±1.5 Nm), and lateral bending (±1.5 Nm) loading modes. These are the most commonly used maximum loading modes for cervical spines. During loading, unconstrained three-dimensional segmental motion was measured using an optical motion analysis system (Optotrak 3020; Northern Digital, Waterloo, Ontario, Canada). At the time of testing each vertebra was provided with a specially designed plexiglas marker containing three light-emitting diodes (LEDs) arranged in a noncollinear manner. Six moments of flexion, extension, right and left lateral bending and right and left axial torque was applied in three equal load steps to a maximum of 1.5 Nm. Each load step was applied for 30 seconds to minimize the viscoelastic effects. Each moment was applied three times to its maximum value, unloading completely between the load cycles. The three-dimensional displacement of the LED markers attached to each moving vertebrae were measured on the third load cycle.

In the C1-C2 study, because of the wide range of motion (ROM), after destabilization and reconstruction, mainly caused by increased motion in adjacent levels, the tests in lateral bending and flexion/extension had to be done in displacement control, whereas for axial rotation we did the tests in load control. In the C5-C6 study all tests were done in load control.

**Results**

**Paper I**

In the C1-C2 study (Paper I) the stiffness data (degree/Nm) from the intact spine in axial rotation, flexion-extension and lateral bending was normalized to 100 % (control) and the reconstructions were compared to that condition. Stiffness (degree/Nm) at C1-C2 was statistically compared using a one-way analysis of variance and Sheffe’s post hoc test.

**Axial Rotation**
Under axial rotation all C1-C2 reconstructions indicated significantly higher stiffness than the intact spine (p<0.0001). The two and three-point reconstructions provided higher stiffness than the one-point reconstruction with pedicle screws combined with C1 claw: PC vs. M, MG and MC (p<0.05). Both three-point reconstructions provided higher stiffness than the reconstruction with hook-rod combined with the C1 claw: HC vs. MG and MC (p<0.05)

Flexion-Extension
During flexion extension, higher stiffness levels were observed in one and three-point fixations when compared to the intact spine at p<0.05.

Lateral Bending
In lateral bending, no significant differences between the six groups were indicated, although the trend was that two and three-point reconstructions (including transarticular screws) provided greater stability than one-point reconstructions.

Paper IV
In the C5-C6 study (Paper IV) the stiffness data (degrees/Nm) at C5-C6 from the intact spine in axial rotation, flexion-extension and lateral bending was normalized to 100% (I). The reconstructions were then compared to the normalized intact spine condition as well as to the other fixation techniques. Intergroup data comparison was statistically compared using a one-way analysis of variance (ANOVA) and Student-Newman-Keuls (SNK) test. A “p” value of 0.05 or less was considered statistically significant.

Axial Rotation
Under axial rotation testing the one and two point reconstruction techniques (anterior plate: AP and anterior plate plus Bohlman triple wire: APW) did not differ in stiffness from intact spine. When the three-point reconstructions were tested (anterior plate plus transfacet screws: APT and anterior plate plus pedicle-screw rod construct: APP) stiffness increased and was significant different from the other three conditions (I, AP and APP) (p<0.05).

Flexion-Extension
During flexion extension testing all reconstructions (AP, APW, APT and APP) provided higher stiffness properties compared to intact spine (I)(p<0.05). Compared to the one point fixation (AP) stiffness was further increased when the two and three-point reconstructions (APW, APT and APP) stabilized the C5-C6 segment (p<0.05).
**Lateral Bending**
Following destabilization and reconstruction with the one and two-point constructs (AP and APW) stiffness was markedly decreased in lateral bending testing compared to intact spine. However, stiffness increased with the three-point fixation techniques (APT and APP) and differed significantly from the other two constructs (AP and APW) (p<0.05). Although the three point reconstructions tended to be stiffer than intact condition no significant differences were detected.

**Paper V**
In the adjacent level study (Paper V), range of motion data (degrees) at C4-C5, C5-C6 and C6-C7 from the intact spine in axial rotation, flexion-extension and lateral bending were grouped. Range of motion data from the reconstructed segment C5-C6 plus adjacent level motion in C4-C5 and C6-C7 using the four reconstruction techniques stabilizing the C5-C6 segment was then compared to the intact spine condition. Intergroup data comparison was statistically compared using a one-way analysis of variance (ANOVA) and Student t-test. A “p” value of 0.05 or less was considered statistically significant.

**Axial rotation**
Under axial rotation testing, motion in adjacent levels increased at C4-C5 when the anterior plate alone was stabilizing the C5-C6 segment and in C6-C7 with the three combination techniques (AW, AT and AP) stabilizing C5-C6 (p<0.05).

**Flexion-extension**
In flexion extension, motion in the adjacent level above the fixation, C4-C5, did not change following fixation at C5-C6. Motion in adjacent level below the fixation, C6-C7, increased following the first and last instrumentation (p<0.05).

**Lateral bending**
In lateral bending testing, adjacent level motion at C4-C5 increased when anterior plate plus transfacet screws stabilized C5-C6. No differences in range of motion was detected at the adjacent level below the instrumentation (p<0.05).
Clinical Studies (Paper II and III)

Posterior fusion at C1-C2 with new fixation device (Paper II)

Methods
The 26 patients were all operated on with the new fixation device using the C1 claw, which consists of two counter-positioned moveable hooks designed to grip around the posterior C1 arch. The shaft of the claw device is connected to the bone screw with a screw link and a double loop connector. When assembled, all parts of the device are mechanically locked to each other to form a rigid implant, and thereby not depending on a structural bone graft.

Postoperatively, the patients were mobilized in a semiflexible plastic collar of Aspen type for the first 6-12 weeks.

The patients were followed clinically and with plain radiographs for an average of 15 (range 3-27) months. The radiographs were evaluated for signs of secondary displacement, instrument failure and fusion healing. Bony union was evaluated on plain film according to a three-grade scale:

1. Definitely healed: bone trabeculae were seen to bridge the fusion area and could be visualized all the way from the C1 arch to the C2 arch without discontinuity (Fig 11).
2. Not healed, but without signs of healing disturbances: bone trabeculae could not be seen bridging the fracture or fusion area, but there were no sign of mechanical failure of the fixation.
3. Established non-union: the fracture line was still visible, a radiolucent zone was seen across the fusion mass or around a screw, there was an obvious implant failure, there was a change in alignment or there were other signs indicating non-union.

Fig 11. Healed fusion at C1-C2 using the C1-claw device.
Results
There were no neurological or vascular complications related to the surgery. No secondary displacement occurred and no re-operation was necessary to perform in the series. In two patients the transarticular C1-C2 screws cut out dorso laterally in the isthmus of C2 and had to be redirected.

Twenty-one patients out of twenty-three with any length of follow up either showed a solidly healed fusion or a healed fracture. The other two patients were judged as “not healed but without signs of healing disturbances”. Two patients died shortly after the index operation from unrelated causes and one patient was lost to radiographic follow up, but had a clinically satisfactory outcome up until 24 months when he died.

Distraction flexion injuries treated with anterior plate alone
(Paper III)

Methods
The 36 consecutive patients in the series were classified according to the Allan and Fergusson mechanistic classification system. There were six (6) DF injuries stage 1, seventeen (17) DF injuries stage 2 and thirteen (13) DF injuries stage 3. Surgery was performed with the patient in a supine position. Skull traction (4 kg) was applied with an ACE Trippi Wells tongue and the head resting in a neutral position in a headrest. A left sided anterolateral approach was utilized as well as a lateral projection fluoroscopi. The disc was excised together with any remnants of the posterior longitudinal ligament and intraspinal disc fragments. The spine was manipulated in axial traction and flexion until the facet joints were reduced. Finally, an anterior fusion was performed with autologuos iliac crest bone graft and stabilization with the CSLP device. The patients wore a stiff-neck collar for 6 weeks following surgery.

Patients were followed clinically and with plain radiographs until decided healed. Follow up varied between 5 months and 6 years (mean 15 months). Patient’s records were reviewed for clinical remarks and complications. Radiographs in four standard projections (AP, lateral, left and right oblique) were obtained and reviewed by an independent radiologist. A fusion was considered healed without loss of correction, if the alignment was unaltered from previous films, there were no signs of loosening of the implant, and bridging bone could be seen across the fusion.
Results

Remarks and complications
There were no peroperative deaths or postoperative infections. No patient deteriorated in his or her spinal cord injury. One patient developed unilateral recurrent laryngeal nerve palsy secondary to the surgical approach, one patient complained of transient dysphagia, and one patient had an injury of the lateral cutaneous femoral nerve as a result of bone graft harvesting.

Radiographic results
DF injury stage 1: Solid fusion healing was demonstrated in all six patients (6/6).

DF injury stage 2: Solid fusion healing was demonstrated in fifteen out of seventeen patients (15/17). Two of the three patients with two level injuries developed non-union at one of the levels. One patient was successfully reoperated with a new anterior fusion. The other patient was free of symptoms and no reoperation was considered necessary.

DF injury stage 3: Solid fusion healing without loss of alignment was seen in six out of thirteen patients (6/13). Redisplacement or loss of alignment occurred in seven out of thirteen patients (7/13). In five of these patients redislocation was obvious already on the postoperative radiograph obtained within forty-eight hours from surgery. Four patients with redisplacement were successfully reoperated with posterior fixation. In two other patients, both with neurological injury grade A according to Frankel, displacement was noted but was considered not to cause any clinical problems why no additional surgery was performed. Both these patients subsequently healed their fusion but with persistent displacement. The seventh patient was lost to follow up as he was transported abroad directly after the postoperative radiograph was obtained.

Thus, five reoperations were performed in the series, one in a patient with a two-level DF injury stage 2, and in four patients with DF injury stage 3. The risk of developing a mechanical insufficiency is significantly higher in DF injury stage 3 than in a DF injury stage 2 (p=0.0492, Fisher’s exact test).
Fig 12. MRI shows a distractive flexion injury stage 3 at C6-C7 (A and B). Initial treatment with anterior plate failed with redislocation (C). Reoperation with additional posterior fixation using a cervical pedicle/rod instrumentation (D).
General Discussion

This thesis investigates the biomechanical and clinical aspects of atlanto-axial and subaxial fixation techniques. Consequently, we will start to discuss the biomechanical and clinical aspects of posterior atlanto-axial fusion (Paper I and II) followed by the biomechanical and clinical aspects of one segment fusion in the subaxial cervical spine (Paper III, IV and V).

Biomechanical aspects of posterior atlanto-axial fusion

Some general aspects on biomechanical in vitro studies may be stated initially. There are certain limitations with an in vitro study. The cadaveric cervical spines are of high age and therefore preexisting degenerative changes that will have influence on cervical spine motion (73). Another obvious fact is the lack of musculature, which has been shown to have certain stabilizing functions in the cervical spine (88).

Posterior fixation techniques between C1 and C2 principally differ biomechanically depending on if they provide for a one, two or three point fixation.

The one-point fixations provide for good stability in flexion-extension, however depending on a structural bone-graft in wire and cable reconstructions. Axial rotation and lateral bending motion is not well controlled with a one-point fixation, even when using non bone graft dependent fixation techniques as shown in study I.

A two-point fixation is achieved by introducing bilateral TA C1-C2 screws. This fixation will restrict motion in rotation and lateral bending, but poorly in flexion extension.

When combining these two techniques, TA screws and a posterior one-point fixation, a three-point reconstruction is achieved. This provides restriction of motion in all degrees of freedom. In clinical practice the most common one-point fixation used in combination with TA screws is a modified Gallie technique. The drawback of using this technique is that it depends on a structural bone graft and a wire has to be passed under the C1 arch into the spinal canal with a possible risk of spinal cord injury.

Using the C1 claw device, which grips around the posterior aspect of the C1 arch and is firmly connected to the TA screws, solves these two problems. No instruments are passed into the spinal canal and the reconstruction does not depend on a structural bone graft. In our biomechanical study comparing five different posterior C1-C2 fixation techniques (Paper I), the three-point reconstructions provided the highest
stiffness values. The C1 claw-TA screw combination provided stiffness values equivalent to the traditional 3-point fixation using TA screws in combination with the modified Gallie technique.

**Clinical aspects of posterior atlanto-axial fusion**

In order to achieve a successful C1-C2 fusion, a mechanical stability between the vertebrae combined with bone grafting is necessary. The fixation techniques according to Gallie and Brook-Jenkins, which provide for a 1-point fixation has shown an unacceptable high failure rate when used alone (74,75). These techniques depend on a structural bone graft fixed in compression by cables or wires. The stability relies on the integrity of the bone block and its ability to withstand compressive forces, which is necessary for preservation of tension in the wire. In an elderly patient the bone may be osteoporotic. As a 1-point fixation merely restricts motion in flexion-extension, the unrestricted motion, particularly in rotation in combination with an osteoporotic bone graft will lead to fixation failure.

When the Gallie technique was combined with TA screws, a 3-point reconstruction was achieved. In addition to preventing motion in flexion-extension provided by the Gallie wiring, the TA screws restricted motion in rotation and lateral bending, and the pseudarthrosis rate in C1-C2 fusion was negligible. However, the reconstruction still depends on a structural bone graft to maintain tension in the wire, which is necessary to restrict motion in flexion-extension until healing, and a wire must be passed into the spinal canal.

In our clinical study, we have presented a new device, the C1 claw, which when attached to the TA screws provide for a 3-point fixation. It does not depend on a structural bone graft and no instruments are passed into the spinal canal, thus a safer procedure. The early results showed no evident clinical or radiographic failure in the entire series, and no serious complications related to the use of the device were encountered.

The argument against using a 3-point fixation at C1-C2 is the use of TA screws and the risk of injury to the vertebral artery when the screws are inserted (76,77,78). In a study of patients requiring a C1-C2 fusion, 23% was found not suited for TA screw on one side at least due to anatomical variations of the vertebral artery (79). There are reports of secondary medullar or cerebellar infarction, and even death caused by vertebral artery injury (32). However, in a survey of 1318 patients having undergone C1-C2 fusion, 2492 TA screws were used, only two patients exhibited subsequent neurological deficit from known or suspected vertebral artery injuries. The risk of neurological deficit from vertebral artery injury in this study was estimated to 0,1 % per screw (32).
A preoperative CT scan with reconstructions can provide information about the anatomical suitability for TA screws and hereby reduce the risk of screw penetration and vertebral artery injury. If only one side can be utilized, a unilateral TA screw in combination with a 1-point reconstruction has shown to provide sufficient stability for C1-C2 fusion to heal (80). If TA screws can not be used on either side, the C1 claw can be used in combination with pedicle screws in C2, or hooks around the C2 lamina as an alternative method, although not providing stability equivalent to a 3-point reconstruction.

**Biomechanical and clinical aspects on anterior fixation in highly unstable DF injuries**

Anterior approach has many advantages when treating injuries in the subaxial cervical spine as mentioned earlier. In our investigations we have tried to understand the anatomical and biomechanical reasons for failure or success when treating subaxial injuries with anterior plate alone. The crucial point seems to be how the instantaneous axes of rotation is shifted due to the soft tissue injury involved. As the degree of posterior soft tissue injury increase, the instantaneous axes of rotation will be shifted anteriorly, to a point where an anterior plate alone cannot stabilize the motion segment.

The anatomical structure that seems to be most important in this united action with the anterior plate is the posterior longitudinal ligament (PLL). If there are some remnants left of the PLL that can provide a posterior tension band mechanism, an anterior plate alone will be sufficient. This hypothesis is supported by our findings in the clinical study on DF injuries (Paper III), where DF injury stage 1 and 2 are sufficiently treated by anterior plate alone, as the PLL is intact in this injury pattern (81).

In DF injury stage 3 and 4, Vaccaro et al. (82) found in an MRI study, that the PLL plus the posterior musculature, inter and supraspinous ligament, facet capsule, ligamentum flavum and anterior longitudinal ligament are disrupted. In addition, it has been observed that these injuries are commonly associated with traumatic disc herniations (83,84). Under these circumstances the instantaneous axes of rotation will be situated almost at the position of an anterior plate as no posterior tension band mechanism exists. Consequently, a high failure risk is to be expected. In our series we observed redislocation in 50% of our patients with a DF injury stage 3.

We observed that patients who had sustained a DF injury stage 3, and also had a tetraparesis were at higher risk of redislocation than the ones with intact neurology. It seems logical to assume that these patients, with neurological deficit, had a more extensive soft tissue injury. It has been
shown that the posterior musculature plays an important role in stabilizing the cervical spine in flexion (88), and perhaps this musculature, if partly intact, as can be expected in the neurological intact patients, could provide a sufficient tension band, in spite of a disrupted PLL.

The same metaphor as we used when discussing C1-C2 fusion can be applied also in the subaxial cervical spine, considering the two vertebrae as two separate rings. In a DF injury stage 3, there would be no intact structures holding these rings together, except for the surrounding musculature. An anterior plate alone would provide for a 1-point fixation, but with the instantaneous axes of rotation located at the position of the plate with a consequently high failure risk. Thus, for an optimal biomechanical situation the DF injuries should probably be stabilized from the back, a standpoint supported by several biomechanical studies using both human and bovine spines (85,86,87).

In our biomechanical study this circumstance was also clearly indicated, as an anterior plate alone could not restrict motion to a higher level than the intact spine tested. However, when adding a posterior instrumentation, shifting the instantaneous axes of rotation posteriorly, the motion segment was stabilized. A posterior wire reconstruction in combination with the anterior plate provided for a 2-point fixation, stabilizing the segment in flexion-extension, but poorly in axial rotation and lateral bending, thus needing an external support for fusion healing. When adding transfacet screws or a pedicle screw/rod construct to the anterior plate, a 3-point fixation was achieved. These reconstructions restricted motion in all degrees of freedom (Fig 13).

![Figure 13. Schematic drawing illustrating one, two and three-point reconstructions. Anterior plate alone A, anterior plate combined with Bohlman tripple wire B, and anterior plate with a pedicle/screw rod construct C.](image_url)
Anterior approach and fixation has many benefits as described previously and should be the primary option when treating injuries to the cervical spine. However, in cases when a highly unstable discoligamentous injury is suspected, as in DF injury stage 3 and 4 with spinal cord injury, a combination of anterior and posterior fixation is recommended.

Biomechanical effect of cervical spine fusion on adjacent level motion

In our investigation on adjacent level motion, we studied the effect of one segmental fusion, using four different fixation techniques with successively decreased motion in the fused segment. The hypotheses was that the cervical spine would try to remain the same range of motion irrespective of a fusion administered restricting motion in one segment, and as motion decreased in the fused segment with more rigid fixation techniques, adjacent level motion would increase.

It was clearly indicated in the present study that adjacent level motion increased as a result of one segment fixation. These results were most evident in axial rotation and flexion extension testing, but also occurred in lateral bending. However, the adjacent level motion did not correspond with gradually increasing motion as the motion in the instrumented segment decreased as a result of more rigid reconstruction techniques.

It has previously been demonstrated in a biomechanical in vitro study that adjacent level motion and intradiscal pressure increased following one segment anterior plate fixation in the cervical spine (48). As displacement is a result of applied load, these findings suggests that additional load is shifted over to adjacent segments. This additional load may lead to increased motion and intradiscal pressure. How adjacent segments will react to this greater load may be due to individual flexibility. The distribution between increased motion and intradiscal pressure may be depending on the degree of degenerative changes present in the adjacent segment. In degenerated segments additional load may not lead to increased motion but perhaps increased intradiscal pressure, leading to accelerated degeneration. These ideas are somewhat supported by Hilibrandt et al. (89) in a clinical study. They found in a long term follow up study, that the greatest risk factors for degenerative disease in adjacent levels following one level arthrodesis for spondylosis with radiculopathy or myelopathy was: involvement of the fifth or sixth vertebra in the fusion and evidence of pre-existing degeneration in adjacent segment at the time of surgery.

In our study, the greatest increase of range of motion in adjacent levels occurred between intact condition and the first reconstruction, anterior plate alone. As range of motion in the fused segment decreased with successively
more rigid fixation techniques, the range of motion was unaltered in adjacent levels, except for one case in lateral bending. It therefore seems logical to assume that the adjacent levels had reached the plateau phase on the load-displacement curve, where no significant changes in motion would be detected when the same load was applied. Whether intradiscal pressure was increased under these conditions can only be speculated, as it was not measured in the study.

The first reconstruction technique used for stabilizing the C5-C6 segment following destabilization was anterior plate alone. Under this condition, range of motion in the fused segment did not differ from intact spine except under flexion-extension testing where it decreased and consequently adjacent level motion increased. This finding is in agreement with the hypothesis that decreased motion in the fused segment would lead to increased motion in adjacent segment. However, it is more difficult to explain why motion was increased in adjacent level in axial rotation and lateral bending following fixation with anterior plate alone. Under these conditions, the anterior plate reconstruction in the fused segment indicated equal range of motion as intact condition. One explanation may be that the segment as a whole, in all six degrees of freedom was restricted in motion compared to intact. The phenomenon coupled motion is well documented throughout the spine, but is most dramatic in the cervical spine (90). This phenomenon may have contributed to our findings.

The clinical implication of the increased motion in adjacent segment, and intradiscal pressure as shown in previous studies, is whether these responses to fusion in the cervical spine will lead to accelerated degeneration in adjacent segments.

The normal nutrition supply to the disc is managed by diffusion through the extracellular matrix from peripheral bloodvessels and vertebral endplates, as the disc lacks a true blood supply. Increased mechanical demands and age are factors known to affect this nutritional diffusion mechanism and lead to disc degeneration (91,92). However, it is still obscure if the findings in the present and previous studies; increased adjacent level motion and intradiscal pressure in adjacent levels following fusion, will alter the natural history process of cervical spine degeneration. Modern technology with disc substitutes, where the motion is kept intact following surgical interventions for degenerative cervical spine diseases may prove different responses in adjacent levels (93,94). However, this is yet to be seen in biomechanical and long-term clinical evaluations.
Conclusions

- The conclusion of the analyzes of the in vitro biomechanical properties of one, two and three point fixations at the atlanto-axial segment is that:
  - **One-point fixations** result in high stiffness in flexion-extension, whereas the stiffness in axial rotation and lateral bending is lower, using new non-bone graft dependent fixation devices.
  - **Two-point fixation** results in high stiffness in all motion directions except in flexion-extension. The reasons probably being that the screws are located close to the axis of rotation in this motion direction.
  - **Three-point fixations** result in high stiffness levels in all degrees of freedom. The combination of transarticular screws with the C1-claw device results in equivalent stiffness as the traditional 3-point fixation technique, but without the need of structural bone graft and the use of cerclage wire in the spinal canal. From a biomechanical viewpoint the 3-point fixation technique is the method of choice for C1-C2 fusion.

- The early results of posterior C1-C2 fusion with the C1 claw of the Olerud Cervical Fixation System seem promising. There were no clinical or radiological failures in the series, and no serious complications related to the use of the device were encountered.

- DF injury stage 1 and 2 on one level seems to heal without complication with anterior plate fixation alone. DF injury stage 3 and 4 treated with anterior plate fixation alone with the CSLP device using monocortical screw purchase will not be sufficient. From a neurological risk point of view an anterior disc excision prior to reduction is beneficial, but the fixation needs to be supplemented by a posterior fixation, especially in patients with severe neurological injury.

- The conclusion of the analyzes of the in vitro biomechanical properties of four different fixation techniques in a distractive flexion injury stage 3 is that:
  - **Anterior plate alone**, with monocortical screw purchase, result in equal stability as the intact spine, thus allowing equal range of
motion in all degrees of freedom as intact spine tested under the given load.

Anterior plate combined with the Bohlmans triple wire technique increased stability in flexion-extension but not in axial rotation and lateral bending.

Anterior plate combined with transfacet screws, or a pedicle screws-rod device, improved stability in all degrees of freedom.

We believe these findings disqualify the use of anterior plate alone, using monocortical screw purchase, for fixation of DF injuries stage 3, if it can be expected that all structures responsible for the posterior tension band mechanism are torn. In these situations the present biomechanical study substantiates the use of anterior decompression and fixation combined with a posterior tension band reconstruction.

Transfacet screws or pedicle screw/rod constructs may be an alternative to wire fixation and lateral mass screws in cases with unusual anatomy or absent lamina, when additional posterior fixation is needed for fixation in highly unstable DF injuries stage 3 and 4. The limitation being that the transfacet screw technique is difficult to apply above C4.

- Adjacent level motion increased as a result of one level cervical spine fusion. These findings were more prominent in the level below the fused segment. As the range of motion stepwise decreased in the fused segment, due to more rigid reconstruction techniques, no additional increase of motion was detected in the adjacent segments as the segments presumably were loaded to their physiological limits. The additional load, shifted over from the fixed segment to adjacent levels, however, not contributing to increased motion, may contribute to increased intradiscal pressure, leading to accelerated degeneration in adjacent levels.
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