Pier Paolo Maria Menchetti
Editor

Cervical Spine

Minimally Invasive and Open Surgery

I.S.L.A.S.S.

International Society Laser and Percutaneous Procedures in Spinal Surgery

Springer

Cervical Spine

Pier Paolo Maria Menchetti
Editor

Cervical Spine

Minimally Invasive and Open Surgery

Springer

Editor
Pier Paolo Maria Menchetti, MD, FRCS
Spine Center
Rome American Hospital
Rome
Italy

ISBN 978-3-319-21607-2 ISBN 978-3-319-21608-9 (eBook)
DOI 10.1007/978-3-319-21608-9

Library of Congress Control Number: 2015955473

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

To my parents

Preface

Arthrosis of the discs in the cervical spine negatively affects daily activities in the adult population. In light of the growing incidence of this pathology, we believed that offering an overview of surgical approaches to cervical spine treatment might help the medical community to adopt the most appropriate solution to this pathology.

A book on the state of the art of cervical spine surgery, both conventional and minimally invasive, may be of interest to surgeons (both expert and young) as well as clinicians with little or no experience of this field of surgery. Owing to contributions from various highly trained specialists from all over the world, this book aims to provide the reader with essential knowledge of the most advanced surgical cervical spine techniques and their applications.

I believed that it was also important to present a chapter about new anesthesiology methods applied in the minimally invasive field, as general anesthesia is usually not required; in fact mild sedation allows one to safely operate on patients with chronic cardiopulmonary diseases or compromised general conditions.

Most of the chapters concern the osteodiscoarthritis pathology, which is mainly responsible for chronic cervical and/or radicular pain in the forth to sixth decades of life, with step by step presentation of either the most advanced MISS (endoscopy) or the standard procedures such as ACDF (anterior cervical decompression and fusion) using cages or autologous bone, posterior approach to axis instability, minimally invasive stabilization systems, and cervical disc arthroplasty. Looking to the future, chapters about the role of materials in cervical spine fusion and the biomechanical engineering evaluation in cervical tribology are also presented.

I would like to thank all the authors because of the high scientific value of their contributions. This handbook is forwarded by ISLASS (International Society Laser and Percutaneous Procedures in Spinal Surgery), a multidisciplinary society devoted to the standard and the most innovative procedures in spinal surgery.

Rome, Italy — Pier Paolo Maria Menchetti, MD, FRCS

Contents

Contributors

Ronald H.M.A. Bartels Department of Neurosurgery, Radboud University Medical Center, Nijmegen, The Netherlands

Benedikt W. Burkhardt Department of Neurosurgery, Faculty of Medicine, Saarland University Medical Center and Saarland University, Homburg-Saar, Germany

Francesco Cacciola Department of Neurosurgery, University of Siena, Siena, Italy

Angelo Chierichini Department of Anesthesiology, Institute of Anesthesiology, Critical Care and Pain Medicine, Catholic University of the Sacred Heart, Rome, Italy

Riccardo Ciarpaglini Spinal Unit, Department of Orthopedics Surgery, Fribourg Cantonal Hospital, Fribourg, Switzerland

Cesare Colosimo Department of Radiological Sciences, Radiology/Neuroradiology Institute, Catholic University of Sacred Heart, Polyclinic A. Gemelli, School of Medicine, Rome, Italy

Antonella Conti Orthopaedics Department, University of Palermo, Palermo, Italy

Alessandro Maria Costantini Department of Radiological Sciences, Radiology/Neuroradiology Institute, Catholic University of Sacred Heart, Polyclinic A. Gemelli, School of Medicine, Rome, Italy

Giuseppe Costanzo Department of Orthopedics and Neurosurgery, Polo Pontino University "Sapienza", Rome, Italy

Ronel D'Amico Department of Radiological Sciences, Radiology/ Neuroradiology Institute, Catholic University of Sacred Heart, Polyclinic A. Gemelli, School of Medicine, Rome, Italy

Antonio D'Arienzo Orthopaedics Department, University of Palermo, Palermo, Italy

Michele D'Arienzo Orthopaedics Department, University of Palermo, Palermo, Italy

Castelli Daniele Dipartimento delle discipline chirurgiche, oncologiche e stomatologiche, University of Palermo, Palermo, Italy

Roberto Delfini Division of Neurosurgery, Department of Neurology and Psychiatry, University of Rome "Sapienza", Rome, Italy

Maurizio Domenicucci Department of Neurological and Psychiatric Sciences, Neurosurgery, University "Sapienza", Rome, Italy

Carlo Doria Orthopaedic Department, University of Sassari, Sassari, Italy

Giles Dubois Service de Neurochirurgie, Clinique de l'Union, St Jean, France

Paolo Fornaciari Spinal Unit, Department of Orthopedics Surgery, Fribourg Cantonal Hospital, Fribourg, Switzerland

Luciano Frassanito Department of Anesthesiology, Institute of Anesthesiology, Critical Care and Pain Medicine, Catholic University of the Sacred Heart, Rome, Italy

Stefan Freudiger Department of Biomedical engineering, Ingenieurbüro Flugwesen und Biomechanik IFB AG, Bremgarten, Switzerland

Massimiliano Gallo Orthopaedic Department, University of Sassari, Sassari, Italy

Ralf Klein Department of RadiMed Laser, RadiMed GmbH, Bochum, Germany

Alessandro Landi Division of Neurosurgery, Department of Neurology and Psychiatry, University of Rome "Sapienza", Rome, Italy

Antonio Leone Department of Radiological Sciences, Radiology/ Neuroradiology Institute, Catholic University of Sacred Heart, Polyclinic A. Gemelli, School of Medicine, Rome, Italy

Alain Lerch Service de Neurochirurgie, Clinique de l'Union, St Jean, France

Carlo Logroscino Department of Orthopaedics and Traumatology, Catholic University of Rome, "A. Gemelli" University Hospital, Rome, Italy

Nicola Di Lorenzo Departmentof Neurosurgery, University of Florence, Florence, Italy

Gianluca Maestretti Spinal Unit, Department of Orthopedics Surgery, Fribourg Cantonal Hospital, Fribourg, Switzerland

Alberto Maleci Neurosurgery Department, University of Cagliari, Cagliari, Italy

Giulia Letizia Mauro Dipartimento delle discipline chirurgiche, oncologiche e stomatologiche, University of Palermo, Palermo, Italy

Bruce M. McCormack Department of Neurosurgery, University of California, San Francisco, CA, USA

Pier Paolo Maria Menchetti Minimally Invasive Spinal Surgery Department, Spine Center, Rome American Hospital, Rome, Italy

Department of Orthopaedics, University of Palermo, Palermo, Italy

Massimo Miscusi Department of Orthopedics and Neurosurgery, Polo Pontino University "Sapienza", Rome, Italy

Luigi Aurelio Nasto Department of Orthopaedics and Traumatology, Catholic University of Rome, "A. Gemelli", University Hospital, Rome, Italy

The Centre for Spinal Studies and Surgery, Queen's Medical Centre Nottingham University Hospitals NHS Trust, Nottingham, UK

Joachim M.K. Oertel Department of Neurosurgery, Faculty of Medicine, Saarland University Medical Center and Saarland University, Homburg-Saar, Germany

Daniele Peri Biomedical Engineering Department, University of Palermo, Palermo, Italy

Giovanni Peri Anatomy Department, University of Palermo, Palermo, Italy

Paolo Perrini Neurosurgical Department, Azienda Ospedaliero Universitaria Pisana (AOUP), Pisa, Italy

Marco Pileggi Department of Radiological Sciences, Radiology/ Neuroradiology Institute, Catholic University of Sacred Heart, Polyclinic A. Gemelli, School of Medicine, Rome, Italy

Alessandro Ramieri Department of Orthopaedics, Don Gnocchi Foundation ONLUS, Milan, Italy

Antonio Sanfilippo Dipartimento delle discipline chirurgiche, oncologiche e stomatologiche, University of Palermo, Palermo, Italy

Stefano Santoprete Department of Anesthesiology, Institute of Anesthesiology, Critical Care and Pain Medicine, Catholic University of the Sacred Heart, Rome, Italy

Dalila Scaturro Dipartimento delle discipline chirurgiche, oncologiche e stomatologiche, University of Palermo, Palermo, Italy

Kris B. Siemionow Department of Orthopaedic Surgery, University of Illinois, Chicago, IL, USA

Frank Sommer Department of Spine Unit, Medical Center of Spinal Disorders, Munich/Taufkirchen, Germany

Biagio Valentino Anatomy Department, University of Palermo, Palermo, Italy

Anatomy of the Cervical Spine

1

Michele D'Arienzo, Giovanni Peri,
Biagio Valentino, Antonella Conti,
Antonio D'Arienzo, and Daniele Peri

The vertebral column, or spine, consisting of a coordinated series of 33–34 vertebrae separated from each other by intervertebral disks, is divided in five segments or sections: cervical, dorsal, lumbar, sacral and coccygeal [1–7].

The cervical section is made up of 7 vertebrae, the thoracic section of 12 vertebrae the lumbar section of 5 vertebrae, the sacral of 5 vertebrae which are fused together and the coccygeal section is made up of 4–5 vertebrae.

Functionally, vertebrae form a single structure designed to maintain the upright posture and balance against the gravity, to allow the locomotion and every other kinetic movement in relation to forces applied and to resistance.

This is because the two basic requirements of the spine are rigidity, for the static efficiency and protection of spinal cord and spinal nerves, and flexibility for the kinematics of spine.

Spine consists of physiological curves, cervical and lumbar lordosis, thoracic and sacral kyphosis, which greatly increase the resistance to the stress of axial compressions compared to a rectilinear column (up to ten times).

The cervical section, "cervical vertebrae C1-C7", whose length varies from 15 to 16 cm in women and from 18 to 19 cm in men which 1/4 is represented by the thickness of the intervertebral disks, presents a lordodic mobile anteriorly convex curvature of about 36° that varies according to modifications of the other spinal curves and it's more accentuated in elderly.

The cervical segment supports the head allowing at the same time large freedom of movement and it also protects the upper section of spinal cord, vertebral arteries and cervical and brachial plexa.

Cervical vertebrae, according to their peculiarities, can be grouped in:

- Superior group made up by C1-C2 vertebrae
- Inferior group made up by C3-C7 vertebrae

So in the cervical spine a superior section and an inferior section can be recognized.

Superior Cervical Spine

C1 is also known as atlas and C2 as axis and they have different peculiarity from the other vertebrae.

Atlas is ring-like shaped and it's made of an anterior arch which have a median tubercle and

M. D'Arienzo, MD (✉) • A. Conti • A. D'Arienzo
Orthopaedics Department, University of Palermo, Palermo, Italy
e-mail: michele.darienzo@unipa.it

G. Peri • B. Valentino
Anatomy Department, University of Palermo, Palermo, Italy

D. Peri
Biomedical Engineering Department, University of Palermo, Palermo, Italy

P.P.M. Menchetti (ed.), *Cervical Spine: Minimally Invasive and Open Surgery*,
DOI 10.1007/978-3-319-21608-9_1

an anterior convex facet; It's also made of a posterior arch which consists of a median tubercle too and to lateral masses. It has no body and no spinous process.

Both of lateral masses presents a concave superior articular facet which articulates with occipital condyles and a flat inferior articular facet which articulates with the axis.

Medially, the lateral masses present a little rafe in which the atlas transverse ligament inserts and divides in two halves the vertebral foramen: one anterior half for the tooth ad a posterior half for the spinal cord.

Axis is the second cervical vertebra whose structure is similar to the other cervical vertebrae. The most distinctive characteristic is this strong conic process, called odontoid process or tooth which is placed vertically on the superior surface of the vertebral body presenting two articular facets, an anterior one and a posterior one.

This process, with its anterior articular facet, articulates with the articular facet of the anterior arch of the atlas and, with its posterior articular facet, with the atlas transverse ligament. Vertebral foramen is smaller than in the other vertebrae and it's triangular.

Inferior Cervical Spine

Inferior cervical spine is made up of five vertebrae (C3-C7) which have different morphogenetic characteristics that are similar to each other.

They consist of a smaller articular body developed in transversal direction. The body has also two faces, superior and inferior, and also has at the lateral extremities two rafes directed superiorly called spinosus processes.

Two pedicles are directed backward and transverse processes are located anteriorly. Each of these processes consists of two roots, an anterior one and a posterior one which are linked by a bony lamina.

On the base of the two transverse processes there is a hole, the transverse foramen. The transverse channel is made of all the transverse foramina and it's crossed by the vertebral vessels and by the vertebral nerve.

Articular processes, superior and inferior, are located posteriorly to the pedicles and articulate with the upper and lower vertebra. Superior articular process ends with an articular facet facing backward while the inferior one with an articular facet facing forward.

Spinous processes are short and bifid with the exception of the 7th cervical vertebra which it' called prominent whose spinous process is long and not bifid and palpable on the base of the neck and it's an important landmark if you are looking for upper and lower vertebrae. The 7th vertebra has also a smaller transverse foramen through which only the vein ad the transverse process passe.

Sixth cervical vertebra is characterized for the anterior tubercle of the transverse process which is more developed and prominent (Chassaignac tubercle): landmark for the common carotid (ligature), for the inferior tiroid artery and for the vertebral artery (Figs. 1.1, 1.2, and 1.3).

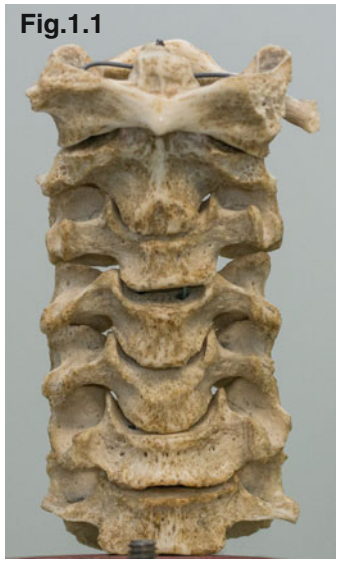
Cervical Spine Joints

Joints between vertebrae are made for making spine mobile.

Vertebrae which make up the different part of the spine have joints that allow to the different parts of spine different movements.

Two sections of cervical spine, "superior cervical spine", which includes occipital bone, atlas and axis and the "inferior cervical spine" which extendes from the inferior edge of the axis to the superior edge of the first thoracic vertebra, have different joints that functionally complete each others allowing movements like rotation, inclination, flexion, extension of the head.

The occipito-atlas joints realize flexion-extension movements on sagittal plane and inclination on frontal plane. They involve occipital bone condyles and the concave articular facets located on lateral masses of the atlas. These joints, defined condylartrosis, have two axis of movement and two grades of freedom. This joint is made of two bones and a fibrous capsule, covered



Figs. 1.1, 1.2, and 1.3 Sixth cervical vertebra is characterized for the anterior tubercle of the transverse process which is more developed and prominent (Chassaignac tubercle): landmark for the common carotid (ligature), for the inferior tiroid artery and for the vertebral artery

by a synovial membrane, which insert in the boundary of the occipital condyles and on the border of the superior articular facet of the atlas. The articular capsule medially is thin and lateral is thicker and it is enforced by the anterior atlas-occipital membrane which extends from the posterior edge of the foramen magnum to the superior edge of the posterior arch of the atlas.

The anterior atlas-occipital membrane has a fibrous band where origins the anterior longitudinal ligament and the posterior occipital membrane is crossed by the first cervical nerve and by the vertebral artery.

Between the occipital condyle and the atlas the first pair of spinal nerves emerge and they will form the cervical plexus.

This joint alone realizes almost the 50 % of the flexion and extension of the head involving for the rest the whole cervical section.

The atlas-axis joint is a diartrosis with no inter vertebral disk between C1 and C2. It's formed by the atlas, axis lateral joints atlas-axis medial joint and atlas-odontoid.

The lateral atlas-axis joint is a diartrosis of artrodia type and it's made by the inferior articular facets of the lateral masses which are slightly concave and by the superior articolar facets of the axis which are slightly convesse. The articular capsule is inserted on the lateral edges of the articular cartilagines and it's enforced anteriorly by the anterior longitudinal ligament and posteriorly by the yellow ligaments and postero medially by the accessorius ligament which arises from the posterior section of the body of the axis and insert on the posterior face of the lateral masses of the atlas.

The medial atal-axis joint is a pivot joint between the posterior facet of the anterior arch of the atlas covered by articular cartilage ad the articular facet of the odontoid covered also by articular cartilage.

The joint is stabilized posteriorly by a fibrous lamina, the "transverse ligament" which surrounds the tooth.

And extendes between the two lateral masses of the atlas realizing in this way a osteo-fibrous ring made anteriorly by the anterior arch of the atlas and posteriorly by the transverse ligament.

From the medial section of the ligament start some fibers that go up to insert on the basilar part of the occipital bone, superior longitudinal ligament, and down on the posterior face of the axis, inferior longitudinal ligament (Fig. 1.4) [9, 10]

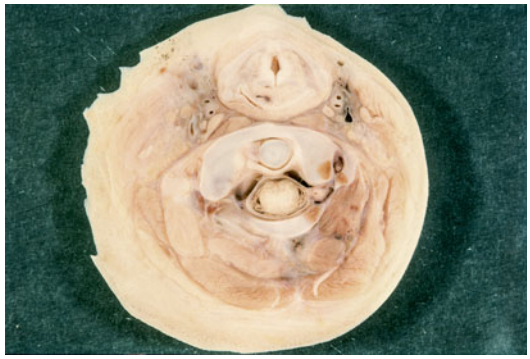


Fig. 1.4 From the medial section of the ligament start some fibers that go up to insert on the basilar part of the occipital bone, superior longitudinal ligament, and down on the posterior face of the axis, inferior longitudinal ligament

The articulation of the "inferior cervical spine" are artrodial joints and between the vertebral bodies intervertebral disks are present.

This section is specialized in flexion -extension movements and lateral flexion: lateral flexion is made by c3-c5 joint while flexion-extension by the C4-C6.

In the inferior cervical spine the joints have common features to the whole spine except sacrum. There are inter-somatic junctions between vertebral bodies esured by the presence of the intervertebral disk and the zigoapofisary joints between the superior articular processes of a vertebra and the inferior articular processes of the lower vertebra. The intersomatic joints are sinartrosis of sinfisys type which are made between the surface of the body of a vertebra and the inferior one of the body of the upper vertebra covered by ialine cartilage.

The shape of the disks is like the one of the vertebral bodies whose is in between and contribute on the flexion-extension movement and lateral flexion of this section and to form the cervical lordosis so the diskes are thicker anteriorly. Discs and vertebral bodies are united and stabilized by the anterior and posterior longitudinal ligaments.

The anterior longitudinal ligament is a fibrous tape which arises from the occipital bone and from th body of the axis and running in the inside of the vertebral channel, it inserts on the posterior surface of the vertebral bodies.

The intervertebral disk is made by a central part called nucleus polposus and by a peripheral part called annulus fibrous. Nucleus polposus is made by a deformable and incompressible gel made by mucopolysaccharides and water. Hydrophilic properties of proteoglycans depend on quantity and quality of mucopolysaccharides.

Idrophily of nucleus polposus determines vertebral resistance to mechanical loading whilst fibro-cartilaginous ring which it's made by anular fibres, allows flexion movements.

These structural features of disk are very important especially following spinal trauma because herniae of nucleus polposus into the specus vertebralis may happen with compression of nerve roots.

Zigoapofisary joints are artrodiae that allow movements of slipping between superior and inferior vertebral processes of two close vertebrae. Superior articular processes, covered by ialine cartilage, run up and backward whilst inferior one run down and forward and are covered by a thin articular capsule that ends on the edge of articular cartilage.

We distinguish:

Intrinsic Muscles of the *Cervical Spine*, *in which muscles have their attachment only* on the vertebrae:

- Interspinous muscles
- Intertrasversarii cervici muscles
- Multifidus muscle
- Short and long rotator muscles
- Semispinalis Capitis muscle
- Spinalis cervicis muscle
- Longissimus Cervicis muscle
- Longus cervicis muscle
- Inferior obliquus cervicis muscle

Extrinsic muscles, in which muscles have their insertion both in cervical spine and in other skeletal segments:

- Spinalis capitis muscle
- Semispinalis capitis muscle
- Longissimus capitis muscle
- Iliocostalis muscle
- Rectus capitis major and minor muscles

- Obliquus capitis superior muscle
- Rectus capitis anterior and lateral muscle
- Levator scapulae muscle
- Splenius capitis and cervicis muscles
- Serratus posterior superior muscle
- Rhomboideus minor muscle
- Trapezius muscle

Neck proprii muscles (excluding cervical spine):

- Suprahyoid muscles: digastric, stylohyoid, mylohyoid and geniohyoid
- **Infrahyoid muscles**: **omohyoid**, **sternocleidohyoid**, **sternothyroid and sternohyoid muscles**
- Sternocleidomastoid muscle
- Platysma muscle

Muscles in the head and neck realize movements of the head and the neck: flexion, extension, lateral deviation and rotation,

Different positions and features of insertion make these muscles can arrange different movements. Another job it's maintain, with the thoracic muscles, the standing of the head and neck.

Vessel Architeture

Artery Network

The neck blood supply is ensured by external carotid and by subclavian arteries [8].

Esternal carotid artery gives:

Occipital artery which surrounds the external edge of the mastoid process sliding under sternocleido-mastoideus muscle, longissimus capitis, latissimus capitis, splenius muscle and semispinalis muscle to end on occipital mucle; during walk borders on hypogloxal nerve which passes laterally and with accessorius nerve which stays medially.

Superior thyroid artery

Subclavian artery gives: vertebral arteries are originally located between scalenus anterior and longus colli then goes back and goes in to foramen trasversarius of the sixth cervical vertebra, then into transverse channel and arises from the hole of transverse process of atlas making a medially concave curve, then surrounds the lateral mass making a second curve anteriorly concave, then goes into the posterior occipito-atlas membrane, dura madre, arachnoids and finally crossing great occipital foramen reaches the cranium. The second curve is located in a triangle delimited from rectus capitis posterior and from obliquus capitis superior and inferior. At its origin artery comes close with inferior thyroid artery and with nerve and vessel of the neck which crossed it anteriorly. It' s also important that the artery comes close to spinal nerves at the beginning of intervertebral holes. In fact osteoarthritis of uncinate processes can compromise normal functions of both artery and nerve. During its course vertebral artery is divided in vertebra-medullary artery and posterior meningeus artery. Thyroid cervical trunk: we talk about one of its collateral branch: arteria cervicalis ascendent that come close with anterior scalenum and frenic nerve; from this artery muscular branches and vertebral-medullar branches arise; artery ends by third cervical vertebra. Costo-cervical trunk: we talk about one of its collateral branch: i.e. arteria cervicalis profunda. This artery goes between transverse process of 7th cervical vertebra and the neck of first rib to end in deep muscles of nape. Transverse artery of the neck is the outermost of the subclavia collaterals. It aries from the interscalenic portion and contributes with its branches to supply muscles of neck and nape ant supply the trunks of brachial plexus as well (Fig. 1.6).

Venous Network

Vnous network of neck is made superficially by anterior giugular veins system, posterior giugular veins system and external giugular veins system and deeply by venous trunks tireolinguofacialis of internal giugular veins and subclaviae veins.

Linfatic Network

Linfatic network is made up by a superficial linfatic network that receives afferents from superficial cervical lymph nodes and of a deep system that receives afferents from deep cervical lymph nodes.

Both superficial and deep system go to jugular trunk that on the right side ends in the junction of the internal jugular and subclavian veins, called the venous angle. On the left side it joins the thoracic duct.

Innervation

Innervation of cervical spine is pertinence of cervical plexus.

Cervical plexus is made up by the anasthomosys of ventral branches of the first four cervical nerves and by an anasthomotyc branch of fifth one that form some arches: the atlantoid arch, the axial and the cervical arches.

Plexus is located deeply and it's close to transverse process of cervical spine; it's near to the vessels and nerves in the neck laterally and to the deep lymphatic nodes of latero-cervical chain anteriorly, medially with glossopharingeus, vagus, accessorius, hypoglossal and with superior and medium cervical ganglia.

From cervical plexus arise:

Superficial branches that made up the superficial plexus; we talk about small occipital nerve that arises from C2-C3 and innerves the skin of the lateral portion of the occipital region.

Deep muscular branches that make up deep cervical plexus. We talk about discendent cervical nerve (C1-C2-C3) which is very close with the discendent branch of and f hypoglossal frenic nerve which is very close to the scalenus nerve. This is the place to find the frenic nerve to perform surgery.

Nerves of nape are represented by posterior branches of eight cervical nerves.

The first cervical branch, called suboccipital nerve is only a motor nerve. This nerve divides itself from the spinal trunk by the atlas reef for vertebral artery, then goes into the occiput triangle delimited by posterior magnus rectus capitis and obliquus superior and inferior capitis.

It also contributes to form cervical plexus with an anasthomotic branch which sends to C2: in the triangle this nerve is close to with one of vertebral artery branches.

The second branch arises from the second cervical trunk, posteriorly to the atlas-axis joint. This nerve, once reached the inferior edge of great obliquus muscle, divides in two branches, one more lateral and thinner, the other one ticker and more medial which distribute to muscles that are close to them. The medial branch, going up, ends in a gap between semispinal muscle and trapezium muscle. After going over the nucal line of insertion of the trapezium, become subcuticular and by the name of great occipital nerve (arnold's) is exclusively sensitive and ends in the skin of the occipital region, place that can hurt (nevralgia).

The 3rd branch arises from the 3d cervical trunk, right after it emerges from the coniugation hole, contributing with its branches to the innervations of nucal muscles.

The branches from 4th to 8th thinner than the others arise from the trunk by the exit from the coniugation hole. Then give a lateral motor branch and a medial mixed.

The medial branch of the 4th, after giving muscolar branches, goes up, goes into the splenium muscle and trapezium and as 3rd occipital nerve exclusively sensitive ends to the skin of the nape.

Nerve branches coming from the brachial plexus contribute also to innervate this region. The brachial plexus is made up by the last four cervical nerves, one anhastomotic branch of the 4th cervical nerve and an anastomotic nerve of the first thoracic nerve.

An important contribution to the innervations of the neck is given by some cranial nerves: by hypoglossal nerve which forms an anastomosys with the discontent cervical nerve. From this anastomosys branches for subdeltoidei muscles and accessories nerve arise.

This nerve during its walk seems to be in touch with the early cervical nerves, expecially with the first one.

This nerve, after arising from the jugular hole divides in an inner branch, which is in touch with the vagus nerve, and in an external branch that walking in oblique direction go down laterally backward. After it reaches the posterior face of the sternocleidomastoideus muscle it innerves

this one and continuing its walk in the upper clavicular region reaches the anterior edge of the trapezium where it ends.

Topographic Organization

Structural components of the neck are covered by a system of fasciae: the medial and deep superficial cervical fascia. These fasciae, being in touch with the structures they meet during their walk, contribute to form connectival spaces of the neck in which they receive the faringo-laringo.tracheal channel and the vascular space with nerve and vessels of the neck (carotid, internal jugular and vagus).

Fasciae of neck as they are disposed on different planes, allow to locate a succession of planes with particular for any region of the neck features.

In the antero- lateral region, beneath the cutaneous and subcuticular plane, two muscle fasciae planes and one muscle-bone plane can be found. The first one is made by the sternocleidomastoideus muscle and over-ioideum muscles surrounded by superficial fascia.

The second one is made up of omoioideum muscle and interioideum muscles covered by medial cervical fascia.

Muscle-bony plane is made up of prevertebral muscles: longus colli, rectus capitis anterior and rectus capitis lateralis and of scalene muscles covered by deep cervical fascia.

In posterior region of the nape, under skin and subcutaneus plane, four muscle-fascial planes and an osteo-fibrous plane can be found: the first one is made up by trapezium muscle covered by superficial cervical fascia, the second one is made up by spleni and levetor scapulae muscles and by superior fascia of rhomboid muscle and posterior dentatus; the third one is made up by three muscles which are orientated in longitudinal direction: longus colli in lateral position, longus capitis in intermedial position and semispinalis capitis muscle located medially. The fourth plane is made up by rectus posteriori and rectus oblique of the head and by cervical spine intrinseci muscles and finally the 5th plane is made up by the flake of the occipital bone and by the cervical spine with its junctions. This plane is in connection with the cervical part of the orthosympathetic system laterally near to the deep cervical fascia made by the sympathetic branches of cervical superior, medium and inferior ganglia. The cervical superior ganglius corresponds to the second cervical vertebra; the medium ganglius, which can be missing sometimes, corresponds to the 5th and 6th cervical vertebra, the inferior cervical ganglius, called star-shaped, corresponds to the 7th cervical vertebra and to the first thoracic vertebra.

From all these ganglia nerves which made visceral plexa of the neck arise:

The cervical superior ganglius correspone to the transverse processes of the second and third cervical vertebra, laterally to the faringe, anteriorly to the longus capitis muscle and posteriorly to the vessels and nerves of the neck.

The medium cervical ganglius and the star-shaped ganglius contribute to the built of the ansa of Vieussens around the subclavia (Figs. 1.4 and 1.5).

Vertebral channel

Across the osteo-fibrous plane the neural space that contain the spinal cord and its cover membrane can be reached.

One of the ways to access the vertebral channel is the laminectomy. Across this the neural space delimitated by osteofibrous walls can be reached.

From the inside to the outside we can see:

The epidural space which is closed cranially from the fusion of the dura madre with the periostium which surrounds the occipital hole, and caudally from the sacral-coccygeal ligaments that close the sacral iatus.

In the epidural space the roots of the spinal nerves with vessels and epidural nerves run. The epidural adipose tissue spreads around the dural sac and accumulates on lateral and posterior parts where the epidural space is wider.

Dura mater is a very strong fibrous membrane that extends like a cilindric sac from the occipital hole to the second sacral vertebra where it ends in the dural cone which continues in the filum terminalis that inserts on the coccyx.

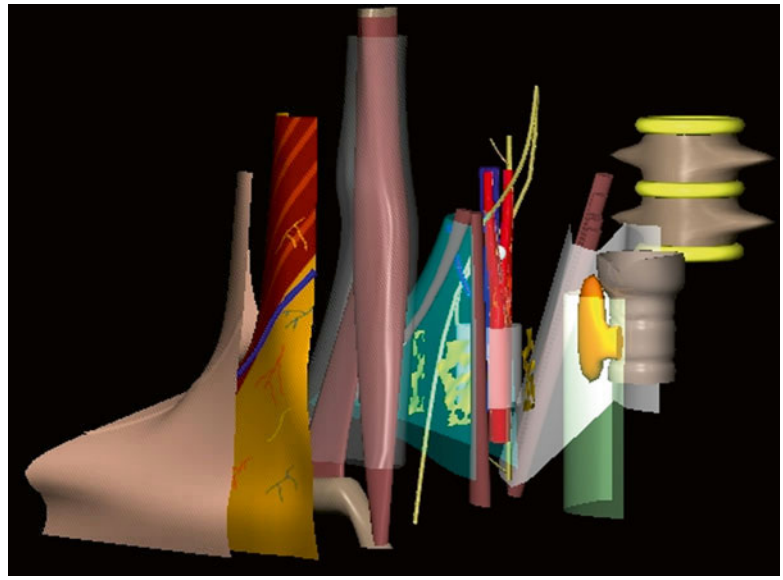


Fig. 1.5 From the skin, progression of the anatomical structures around cervical spine

Arachnoid is a thin membrane that it's modeled on the inner face of the dural sac and it's separate from that by a tiny virtual space (subdural space). Arachnoid delimitates on the inside the subarachnoid space which is the space between the aracnoid and the pia mater and it's extendend for all the length of the spinal cord.

Sub aracnoide space is filled with an amount of fibrous filaments where vessels run each others. This space contains cerebrospinal fluid and it's crossed by the roots of the spinal nerves which are separate from the denticolar ligaments.

Pia mater is a very thin fibrous membrane that covers the spinal cord: from there the denticular ligaments and the anterior and posterior septa arise. Pia mater is close with the epinervium of the spinal nerves and it's rich of blood vessels, linfatic vessels and sentitive nerve terminations which also arises from sensitive corpuscles.

The spinal cord is divided in neuromeres that correspond to the origin of a couple of spinal nerves roots that made the spinal nerve which is covered by dura mater, run into the intervertebral hole.

Spinal cord peripherally is made up by fascia of mielinic nerve fibers which are organized in anterior, lateral and posterior cords that are delimitated by the median, anterior and posterior split and by the lateral, anterior and posterior grooves.

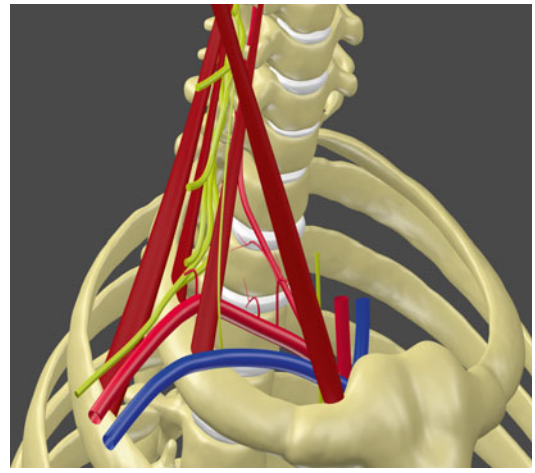
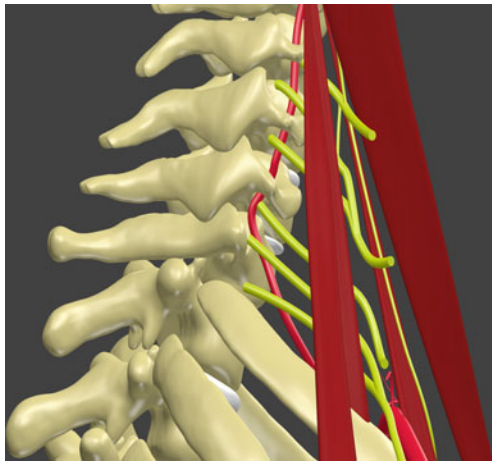
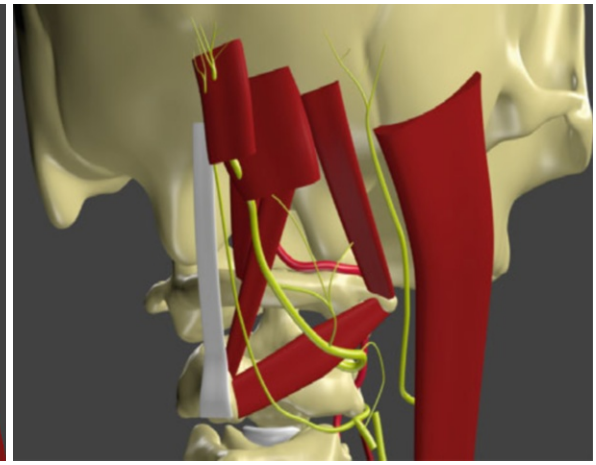


Fig. 1.6 Transverse artery of the neck is the outermost of the subclavia collaterals. It aries from the interscalenic portion and contributes with its branches to supply muscles of neck and nape ant supply the trunks of brachial plexus as well

Centrally the spinal cord presents the neural component organized in two symmetric lateral masses that are linked centrally by the grey commissure which is crossed by the central channel or ependymal channel.

Two lateral masses present an anterior territory that contains motor neurons and a posterior nerve that contain sensitive nerves.





Figs. 1.7 and 1.8 Brachial plexus, subclavia artery and dorsal scapular arteries

In the thoracic-lumbar section there is a lateral protrusion that contains neurons of the simphatethic system.

Cervical cord in C4-T1 presents a conic bump flat in anterior-posterior direction in which is located the brachial plexus. In this place the anterior corn is larger than the other on top and the posterior horn is thinner that the one on top of it (Figs. 1.3 and 1.4) [9, 10].

Dissection Anatomy

When you make a dissection or perform surgery on the muscle-fascial planes of the neck, you must pay attention, when skin and underlying plane are prepared, to the third occipital nerve, to the great occipital and to the occipital artery that appear on the top of the trapezium muscle: when you arrive on the second and the third plane in the space between the trapezium and splenium you must be careful to the small occipital nerve which it's located laterally to the splenium muscle and to the third occipital nerve which it's located laterally to the nucal ligament. In this space the great occipital nerve and the occipital artery can easily seen between the splenium capitis muscle and semispinalis capitis.

When the underlining plane is prepared attention must be payed to the vertebral artery, the suboccipital nerve and the dorsal root of the second cervical nerve with its ganglium, another space that must be attentioned is that one located between the trapezium and the elevator of the scapula where the vascular pedicle and the accessories nerve run.

Finally, when scalenic muscles are prepared attention must be payd to the trunks of brachial plexus, subclavia artery and dorsal scapular arteries (Figs. 1.6, 1.7 and 1.8).

References

1. Lanz Wachsmuth W. Anatomia pratica. Padova: Piccin; 1978.
2. Paturet G. Traité d'Anatomie Humaine. Paris: Masson; 1951.
3. Platzer W. Atlas of topographical anatomy. Stuttgart: Thieme; 1985.
4. Poirier P, Charpy A. Traité d'Anatomie Humaine. Paris: Masson; 1912.
5. Joannes W, Yocochi R-C, Lutjen-Drecoll Elke. Atlante a Colori di Anatomia. Quinta edizione. Piccin, Padova; 2003.
6. Rouvière H. Anatomie Humaine. Descriptive Topographique et Functionelle. Paris: Masson; 1974.
7. Testut L, Jacob O. Trattato di Anatomia Topografica con applicazioni Medico-Chirurgiche. Torino: UTET; 1968.
8. Peri G, et al. Development of software in the study of carotid. Anat Embryol. 2001;106(4):273–82.
9. Pozzi Mucchi R. Trattato italiano di tomografia computerizzata. Gnocchi, Napoli; 1997. p. 3–109.
10. Svakhine N, Ebert DS, Stredney D. Illustration motifs for effective medical volume illustration. IEEE Comput Graph Appl. 2005;25(3):31–9. doi:10.1109/MCG.2005.60.

2 Functional Anatomy and Biomechanics of the Cervical Spine

Alessandro Ramieri, Maurizio Domenicucci, Massimo Miscusi, and Giuseppe Costanzo

Introduction

The head-neck system consists of seven cervical vertebrae and has a unique anatomy and motion to accommodate the needs of a highly mobile head-torso transitory zone. From a kinematical point of view, this system is very complex. Normally, the spine mainly functions as a coupled unit, and neck kinematics can be analyzed by studying head movement relative to the upper body. Cervical motion in every plane is checked by anatomic restraints that protect the spinal cord and accompanying vascular structures. The head can be regarded as a platform that houses the sensory apparatus for hearing, vision, smell, taste: the cervical spine constitutes a device that support this sensory platform, moving and orientating it in the three-dimensional space. Any disturbance of anatomy and mechanical properties can lead to clinical symptoms. Also age-related changes can modified cervical anatomy and alignment, drastically reducing range of motion [1, 2].

A. Ramieri, MD PhD (✉)
Department of Orthopaedics, Don Gnocchi Foundation ONLUS, Milan, Italy
e-mail: alexramieri@libero.it

M. Domenicucci, MD
Department of Neurological and Psychiatric Sciences, Neurosurgery, University "Sapienza", Rome, Italy

M. Miscusi, MD • G. Costanzo, MD
Department of Orthopedics and Neurosurgery, Polo Pontino University "Sapienza", Rome, Italy

Basic Concepts

To analyze, understand and correct the various malfunction of the spine, it is essential recognize his normal function. While physical principles and laws rule the entire spine, kinematics can studied the normal range of motion (ROM) of each segment in the three-dimensional space, without the influence of other internal or external forces. Normally, this range is expressed by translation and rotation in three planes. Too much motion should be considered as structural damage of the spine, while too little motion may accompany stiffness and pain. Motion segment is the "Functional Spine Unit" or FSU that consists of two adiacent vertebrae and the interconnecting soft tissue, devoid of musculature. Forces applied to the spine can always be separated into component vectors: infact, a vector defines the force oriented in a fixed and well-defined direction in three-dimensional space. If a force vector acts on a lever, known as "moment arm", a bending moment is generated. This bending moment applied to a point in the space causes rotation about an axis: this axis is defined "instantaneous axis of rotation" or IAR. Using the standard Cartesian coordinate system for the spine (x, y, z), 12 potential movements about the IAR can be considered: 2 translational and 2 rotational along or around each axes. When a cervical segment moves, there is an IAR passing through or close to the vertebral body (*see below*). In other terms,

P.P.M. Menchetti (ed.), *Cervical Spine: Minimally Invasive and Open Surgery*,
DOI 10.1007/978-3-319-21608-9_2

6° of freedom exist about each IAR, i.e. each FSU has 6° of freedom. When an FSU is loaded, the motion behavior is affected by the choice of the point at which the load or torque is applied. Balance point is achieved when an axial load creates nearly pure compression and the out of plane is minimized. Any loading out of this point causes a moment and induces bending. More specifically, if an axial load is applied at the point of the IAR, the result is an equal (in magnitude) but opposite (in direction) reaction force (Newton third's law) that may symmetrically deform the vertebral body. Instead, if the load is applied in a plane at some distance from the IAR, bending moment is generated by an interaction of forces and asymmetric deformation of the vertebral body can occur in any plane. This phenomenon introduces the concept of "couple", a pair of forces, equal and opposite, having a lines of action that are parallel but that do not coincide. If the resultant is zero, no translational movement occurs and the FSU is in equilibrium. Rotation can occurs if the couple is unopposed. As stressed by Benzel [3], couple is different from "coupling". This term indicates the phenomenon whereby a movement of the spine obligates a separate motion about another axis. In the lower cervical spine is typical that the lateral bending results in axial rotation of the spinous processes away from the concave side of the direction of the bend. This is due to the orientation of the facets and the presence of the uncovertebral joints (Fig. 2.1).

The IAR can be considered similar to the COR (centre of rotation), first described by Penning [4] and more recently applied by Smith [5]. This method describes the motion behavior of the vertebral body respect to the adjacent one, defining the axis and the point about which vertebrae rotate. IAR or COR should be considered dynamic because nearly any motion of the FSU is a coupled motion. As spinal movement occurs, infact, the point about which adjacent vertebrae rotate varies during the motion. An extension of the COR approach provides an helical axis of motion (HAM) that defines a three-dimensional movement when rotation is superimposed on translation. The resultant component of motion is described by the translational movement vector called HAM.

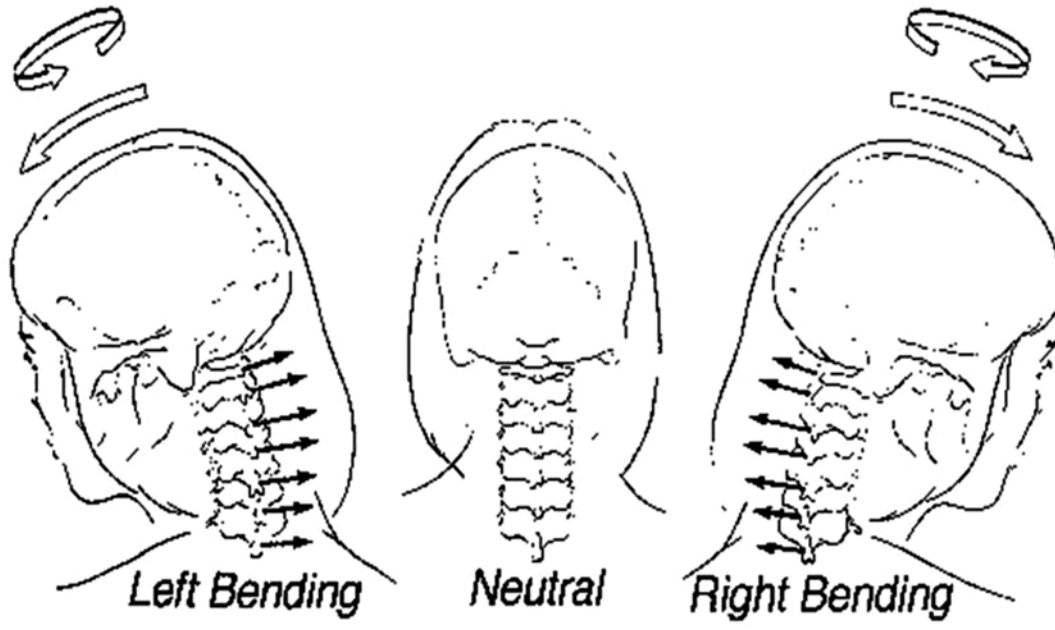


Fig. 2.1 Coupling phenomenon i.e. axial rotation of the spinous processes away from the concave side of the direction of the lateral bending. *Arrows* just above the head show the lateral bending on the *left* and *right*, while the ring *arrow* and *black arrows* suggest contralateral rotation of the spinous processes of the lower cervical spine (From White and Panjabi Ref. [37], with permission)

Summary of Biomechanical Terms

Translation Motion of a rigid body in which each straight line through any pair of its points remains parallel to itself

Rotation Motion of a rigid body in which each straight line does not remain parallel but develops an angle of rotation between initial position (A1–B1) and final position (A2–B2) (Fig. 2.2).

Centre of Rotation or instantaneous axis of rotation (IAR) It is a fixed point obtained by the intersection of the line perpendicular to the motion plane and the translational vector (e.g. A1–A2 see Fig. 2.2)

Degrees of freedom They define the position of an object in the space by a number of independent coordinates organized in a coordinate system (i.e. Cartesian system)

Range of motion (ROM) Extent of physiological movement, measured from a neutral position of the spine, when the internal stresses and the musculature effort to hold the posture are minimal. Physiological ROM can be divided into two parts: neutral zone and elastic zone

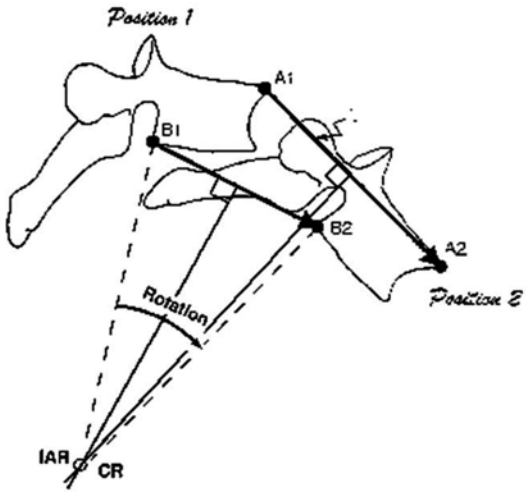


Fig. 2.2 Vertebral motion, defined by translation vectors A1–A2 and B1–B2, is a rotation about the instantaneous axis (*IAR*). IAR is obtained by the intersection of the lines perpendicular to the motion plane and the translational vectors (From Panjabi et al. [1], with permission)

Neutral zone (NZ) First part of ROM within which displacement of a biological tissue is produced against minimal internal resistance. The NZ is defined by flexibility of the tissue.

Elastic zone (EZ) That part of ROM, measured from the end of the NZ up to the elastic limit, in which displacement is produced against internal resistance. The EZ represents the stiffness of the biological tissue

Plastic zone (PZ) It is the zone of trauma and failure of the biological tissue. When the elastic limit is reached, permanent deformation/displacement can occur. The tissue will fail if further forces are applied

Force Any action that tends to change the state of rest or motion of a body to which it is applied. Force is a vector quantity that has magnitude and direction. The unit of measure for the magnitude of force is newtons (N).

Work and Energy Work is the product of force time distance and energy is the work done. The unit of measure is newton-meter (N-m) or joule (J)

Stress It is the force applied to an object (load)

Strain It is the response of the object to the stress (deformation)

Viscoelasticity It is the time-dependent property of a such material to rate of loading or deformation. Bones, ligaments, tendons, passive muscles demonstrate viscoelastic behavior. Because of this, their stress-strain curves are dependent on the rate of loading

Elastic modulus (Young's modulus) It is the ratio between stress and strain, representing the elastic properties of a body that is stretched or compressed

Coupling It is the phenomenon whereby a movement of the spine on a plane obligates a separate motion about another axis (see Fig. 2.1)

Functions of the Cervical Spine

The craniovertebral junction (C0–C1), the upper (C1–C2) and the lower cervical spine (C3–C7) have distinct anatomic and kinematic features and must be described separately. Fundamental to understanding the behavior of the cervical spine is an appreciation of how each segment contributes to the total function in relation to its specific characteristics. For descriptive purposes, the cervical spine can be divided in five units, each with unique morphology that determines its kinematics and its percentage of contribution to the entire function. In anatomical terms, the units are: the occipito-cervical junction (C0–C1), the atlas (C1), the axis (C2), C2–C3 junction, C3–C7 levels. Main anatomical characteristics of the upper compared to the lower cervical spine include the absence of the intervertebral disc, the absence of the ligamentum flavum, and the distinct shape between C1 and C2.

Occipitoatlantoaxial Complex (C0–C2)

Biomechanically Relevant Anatomy

The foramen magnum (FM) is located in the occipital bone, which has three parts: – the squamosal portion in the dorsal aspect; – the clival portion located anteriorly; the condylar part, connecting these two portions, that includes the occipital condyle, posterior margin of the jugular foramen and the hypoglossal canal. Occypital condyle receives the C1 lateral mass. The most posterior margin of the foramen magnum is called “opisthion”, while the “basion” represents its most anterior midline. C1 differs from the other cervical vertebra by being a ring shape and lacks a vertebral body and a spinous process. It has two thick lateral masses which are situated at the anterolateral part of the ring. C2 has many attributes of the more caudal cervical vertebrae, but its transitional nature dictates a complicated anatomy configuration. Odontoid process represents its rostral extension: this fundamental structure originates by the developmental fusion process between the caudal part of the C1 somite and the cranial part of the C2 somite. The odontoid process begins to fuse with the body of C2 at 4 years of age and at 7 years of age the fusion is completed. In about one-third of adults, a remnant of cartilaginous tissue will be present between the odointoid and the C2 vertebral body. The pars interarticularis projects from the lamina in a rostral and ventral direction to attach to the lateral masses. C1 allows the odontoid process of C2 between its lateral masses. In other terms, odontoid occupies the usual position of the vertebral body [6]. Odontoid articulates with the dorsal aspect of the ventral portion of the C1 arch by an anterior oval facet and posteriorly with the transverse ligament that is attaches to the tubercles on the medial aspect of the C1 ring. The lateral masses of C1 articulate with the occipital condyles and C2 by kidney-shaped articulations, while C2 is directly connected to the occiput by the alar and apical ligaments and the tectorial membrane. In a sense, C1 functions as an intermediate “fulcrum” that regulates movement between the occiput and C2 [7]. The special arrangements of the occipitoatlantoaxial ligaments are remarkable to allow for complex motion, yet provide stability to this area. Infact, the capsules of the C1–C2 lateral facets surround the articular surfaces and are reinforced by ligaments and lateral fibers that pass in a rostral direction from the tectorial membrane [8]. There are ligaments between the C1 anterior arch and the odontoid and behind it: the cruciate ligament that has a vertical component from the rim of the FM to the midportion of the C2 vertebral body; the apical ligament from the rim of the FM to the tip of the odointoid process; the alar ligaments from the lateral anterior rim of the FM to the dorsal aspect of the odontoid. The cruciate ligament is considered one of the most important ligament of the human body and its rupture, identified by high resolution MRI, can lead to craniocervical instability. As stated by Quercioli [9], pioneer of

occipito-atlanto-axial biomechanics, the integrity of the transverse and occipitoaxial ligaments is the essential condition for maintaining a stable odontoid process in the axis.

Normal Kinematics

The occipitoatlantoaxial complex is the most mobile of the axial skeleton [10]. This functions as a single unit, considering C1 as a *cradle* for the occiput and C2 as a *washer* between the skull and the cervical spine. This complex is responsible for 40 % of total cervical flexion-extension and 60 % of total cervical rotation.

C0–C1 Joint

The atlanto-occipital joint allows flexion-extension and minimal degrees of lateral flexion and rotation, while the atlanto-axial joint works in coupled, rotation plus minimal lateral bending (Table. 2.1). C1 flexion-extension (e.g. nodding movements) are possible because the C1 superior articular surfaces are concave whereas the occipital condyle are convex. Flexion is achieved by the condyles rolling forwards and sliding backwards across the anterior walls of the notches. A converse combination of movements occurs in extension. Axial forces apply by the mass of the head and the muscles prevent upward displacement, maintaining the condyles nestled on the floor of their cavities. The total normal range of flexion-extension at the atlanto-occipital joint has been described as having a mean value between 14 and 35°, a range from 0 to 25° or a mean value of 14° with a standard deviation of 15° [3, 11, 12]. During these movements, a minimal anterior or posterior translation was observed [13]. Moreover, other restraints to flexion are fixed by the impaction against the skull base, tension of the posterior muscles and capsules and contact of the submandibular tissues against the throat. Extension is limited by compression of the suboccipital muscles against the occiput. Rotation and lateral flexion of atlanto-occipital joint are extremely limited, approximately 5°, due to the depth of the atlantal notches in which the occipital condyles rest. In biomechanical terms, during axial rotation to one side, the contralateral occipital condyle contacts the anterior wall of its atlantal notch, while ipsilateral condyle impacts the corresponding atlantal posterior wall. Therefore, joint stability stems largely from the depth of the C1 notches: their side walls prevent lateral translation, the front and back walls prevent anterior and posterior dislocation.

The IAR for the C0–C1 articulation has not been defined, although x-axis is considered to pass through the mastoids and the z-axis to be 2–3 mm above the tip of the odontoid process [14]

Table 2.1 Movements allowed in the craniocervical region, according to Benzel [3]

Joint	Motion	ROM (degrees)
C0–C1	Flexion/extension	25
	Lateral bending (unilateral)	5
	Axial rotation (unilateral)	5
C1–C2	Flexion-extension	25
	Lateral bending (unilateral)	5
	Axial rotation (unilateral)	40

C1–C2 Joint

The atlanto-axial complex is composed by two lateral facet joints, the unique atlantodental articulation and the joint between the posterior surface of the odontoid and the transverse ligament. Stability at this highly mobile articulation is primarily dependent on ligamentous structures, because the lateral joint capsules, in contrast to that of the atlantooccipital joint, are loose. Its foremost rule is to bear the axial load of the head and atlas and to transmit this load into the remainder of the cervical spine. For this function, C2 laterally presents wide superior articular facets that support the lateral masses of C1 and form the lateral atlanto-axial joints. The centrally-placed odontoid process acts as the "pivot" and forms the atlanto-axial median joint. In order to achieve axial rotation, the anterior arch of the atlas spins and glides around the pivot. Therefore, this movement is anteriorly restrained by the

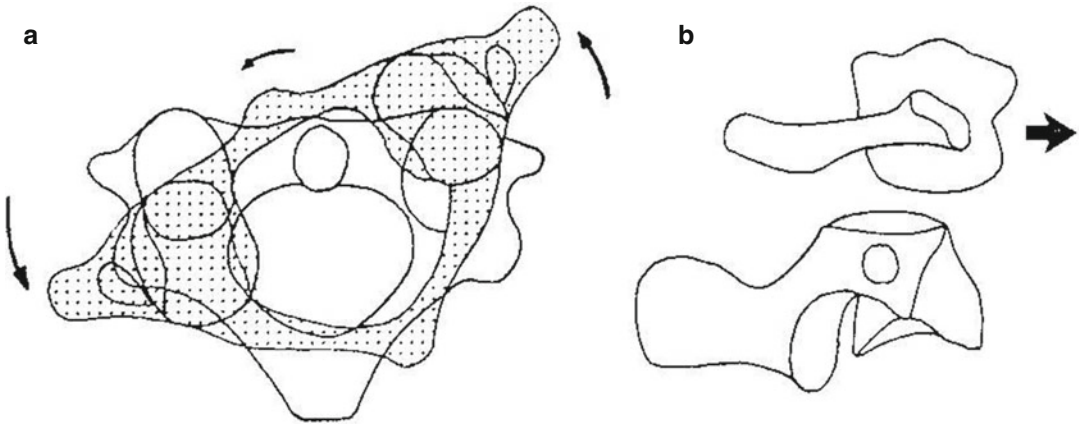


Fig. 2.3 C1–C2 axial rotation. (**a**) (axial view): the anterior arch of C1 glides around the odontoid process (*arrows*); (**b**) (sagittal view): the lateral mass of C1 subluxates (*arrow*) forwards across the superior articular process of C2 (From Bogduk and Mercer [13], with permission)

median atlanto-axial joint and inferiorly by the lateral atlanto-axial joints, that also subluxate. In particular, the ipsilateral lateral mass of C1 slides backwards and medially, while the contralateral lateral mass slides forwards and medially (Fig. 2.3). During axial rotation, the lateral atlanto-axial joints glide across their osseous flat surfaces. But the articular cartilages both of the atlantial and the axial facets are convex in the sagittal plane, rendering the joint biconvex in structure. In addition to these anatomical features, the spaces formed anteriorly and posteriorly by the detachment of the articular surfaces, are filled by large intra-articular meniscoids: these serve to keep a film of synovial fluid on articular surfaces. In the neutral position, the summit of the atlantial convexity rests on the convexity of the axial facet, i.e. the apex of the C1 inferior facets is balanced on the apex of the C2 superior facets. As the C1 rotates, the ipsilateral atlantial facet slides down the posterior slope of the respective axial facet, while the contralateral one slides down the anterior slope of axial facet. Upon reversing the rotation, C1 rises back onto the summit of the facets. In conclusion, C1 axial rotation requires anterior displacement of one lateral mass and a reciprocal posterior displacement of the opposite lateral mass. If the articular cartilages are asymmetrical, a small amplitude of lateral bending may accompany axial rotation: the side of coupling depends on the bias of asymmetry [15], but however this movement is considered negligible [16][1]. Principal structures that restrain axial rotation are the alar ligaments and the joint capsules: at the limits of rotation, the lateral atlanto-axial joints are almost subluxated. The normal ranges of rotation of C1 on C2 are varied (see Table 2.1): 32° e 56.7 in cadaveric studies [17a, 18], over 75° using x-ray [19] and 43° using CT [17b] in healthy adults. Recently, some authors [20], measuring in vivo by MRI normal kinematics of the upper cervical spine in neutral position and during Dvorak's flexion-rotation test, reported respectively 77.6° and 65° of C1–C2 segmental rotation. Sagittal plane motion (flexion-extension) in C1–C2 has been reported by several authors to be on average of 11° and may be facilitated by the rounded tip of the odontoid process [21–23]. More recently, this value has been confirmed by a descriptive study based on computer-aided measurements from lateral flexion-extension radiographs [24]. The

[1] Although not a physiological movement, lateral bending at the C1-C2 joint is assessed by some manipulative proceedings. While C2 superior articular facets slope inferiorly and laterally, C1 lateral translation must be accompanied by ipsilateral side bending. Minimal lateral translation can occur during lateral flexion of the entire cervical spine. Restraints to this motion are the contralateral alar ligament and the impaction of the contralateral lateral mass onto the lateral aspect of the odontoid process.

biconvex nature of the atlanto-axial articulation means that cervical spine flexion and extension often create motion in the direction opposite that being experienced in the atlas [25]. In other terms, when the entire cervical spine is flexing, C1 extends and when the cervical spine extends, C1 flexes. This paradoxical coupling motion is possible because C1 is sandwiched between the head and C2, undergoing a passive movement. Infact, in neutral condition, C1 is balanced precariously on the convexities of its articular cartilages, but when an axial compression load is applied, C1 starts to move. If the line of compression is anterior to the balance point, C1 moves into flexion. On the contrary, when the line is posterior, C1 will extend. This paradox is governed essentially by the muscles acting on the head and it can be observed even if the rest of the cervical spine is flexed. The restraint to C1 flexion/extension have never been formally established. No ligaments are disposed to limit this motion: essentially C1 is free to flex or extend until the posterior arch hits the occiput or the neural arch of C2, respectively. C1 backward sliding is limited by the impaction of its anterior arch against the odontoid process, while forward slipping is prevented by the transverse and the alar ligaments. Subluxation or dislocation implies destruction of both ligaments. Up to 3 mm of anterior translation of C1 on C2, as measured by anterior atlantodental interval (AADI), is considered normal. As the AADI increases to 5 mm or greater, the transverse and accessory ligaments are disrupted. When the transverse ligament is damaged, also rotary dislocation can occur at 45° of rotation, rather than 65° in normal condition.

The IAR for the C1–C2 sagittal plane motion is located in the region of the middle third of the odontoid. During axial rotation, it is located in the centre of the odontoid.

C2–C3 Junction or Vertebroaxial Joint [26]

Although the C2–C3 junction is often considered together with the rest of the lower cervical spine, this joint offers some peculiar differences in morphology. A pillar view of the region[2] reveals that the body of the axis looks like a deep "root" into the typical cervical spine (Fig. 2.4), securing the upper cervical spine in the remaining cervical column. Moreover, in such view, the unique orientation of the C2–C3 zygoaphophysial joints is seen: they are inclined medially, by about 40° [26], and downward [27], while they are typically transversal at lower levels. The processes of both sides form a notch, cradling the inferior articular processes of the axis. This architecture implies that C2–C3 joints operate in a different manner from that of lower cervical segments, nevertheless further differences are open to discovery. The main kinematic expression occurs during axial rotation plus lateral bending. According to Mimura et al [19], C2–C3 axial rotation is similar to that of the lower segments, with mean value of 7° compared to 5, whereas lateral flexion is sig-

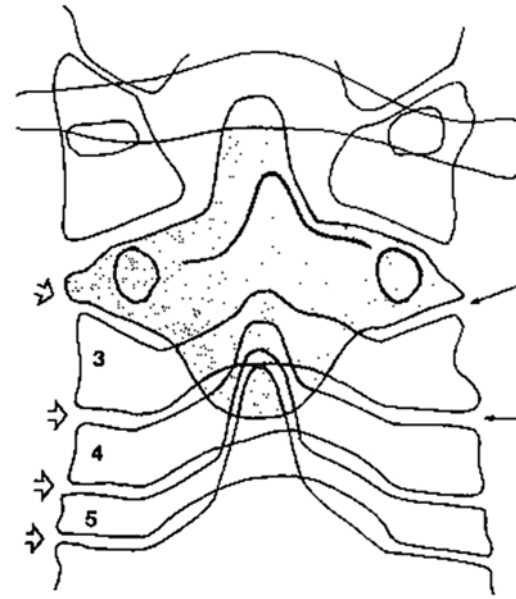


Fig. 2.4 Pillar view of the upper cervical spine, showing the unique morphology of C2 and architecture of the C2–C3 joints (see text). All *arrows* indicate the orientation of the interarticular space for each level (From Bogduk and Mercer [13], with permission)

[2] The "pillar view" is a cervical postero-anterior radiographic projection achieved by directing the beams upwards and forwards essentially along the planes of the lower zigoapophysial joints.

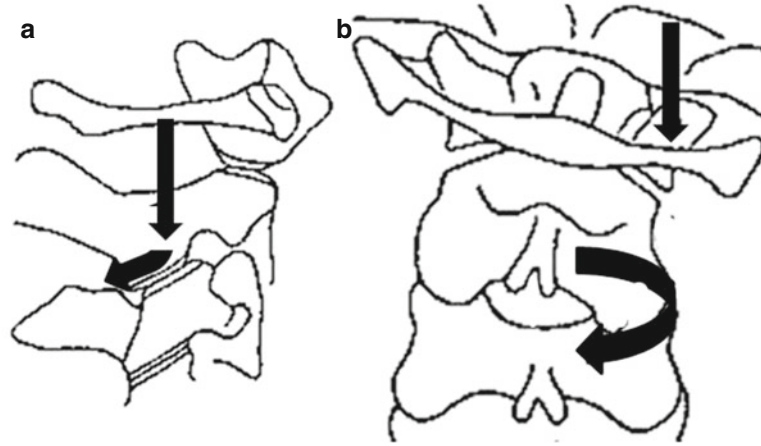


Fig. 2.5 Axial compression force is applied during lateral bending of the head (*Vertical black arrows*); (**a**) (sagittal view): the inferior articular process of C2 slides downward and backword along the superior articular process of C3 (*Black oblique arrow*); (**b**) (coronal view): C2 rotates towards the direction of the side bending due to the backward articular displacement (*ring arrow*)

nificantly different, with mean value of −2° at C2–C3 compared to 6 at C3–C4 and C4–C5 levels. In other terms, instead of tilting towards the same side, C2–C3 joint rotates towards the direction of the side bending (Fig. 2.5). The IAR for the C2–C3 sagittal motion is located lower than in the other cervical levels due to the lower location of the superior articular process of C3 (see below Fig. 2.7).

Mid and Lower Cervical Spine (C3–C7)

Biomechanically Relevant Anatomy and Kinematics

The middle and lower cervical spine segments have essential similar anatomic and functional features and can be effectively represented by the FSU: two vertebral bodies, the disc, the facet joints with associated ligamentous and capsular structures. Each vertebra consists of 3 pillars that forms 3 parallel columns for the load-bearing functions of the cervical spine . The anterior pillar is the vertebral bodies, which are united by interposed discs to form the anterior column. The two posterior columns are formed by the articular pillars: the superior and inferior facets are opposed to one another and united by a joint capsules. Their specific orientations allow to bear the weight of the segments above and prevent dislocation. The facet joints are the principal restraints against forward translation. End-plates of the vertebral bodies, that are stacked on one another, separated by the intervertebral disc, are not flat as in the lumbar spine. In the sagittal plane, they appear gently curved, tilting greatly downwards and forwards. The anterior inferior border of each vertebral body forms a lip that hangs, like an hook, towards the anterior superior edge of the vertebra below. As a result, the plane of intervertebral disc is not perpendicular but somewhat oblique and supports flexion-extension motion as cardinal movement of these typical cervical segments. The body supplies the strength and support for two-thirds of the vertebral compression load. The upper surface is typically concave from side to side and convex in the antero-posterior direction. On its lower surface, it is convex from side to side and concave in the antero-posterior direction. Also, the upper projection on the lateral superior surface of the vertebra below is called “the uncus”. These bilateral uncinate processes are related intimately with the convex lateral inferior surfaces of the upper vertebral body and form the uncovertebral joints or joints of Luschka. The exact rule of these joints is not known: they would seem to prevent posterior dislocation and limit lateral bending.

The “saddle shape” structure thus described is clearly visible in the sagittal plane, while, by a section taken obliquely through the posterior end of vertebral body along a plane parallel to the plane of the facet joints, the concave superior surface formed by the body and its uncinate processes that receives the convex inferior surface can be

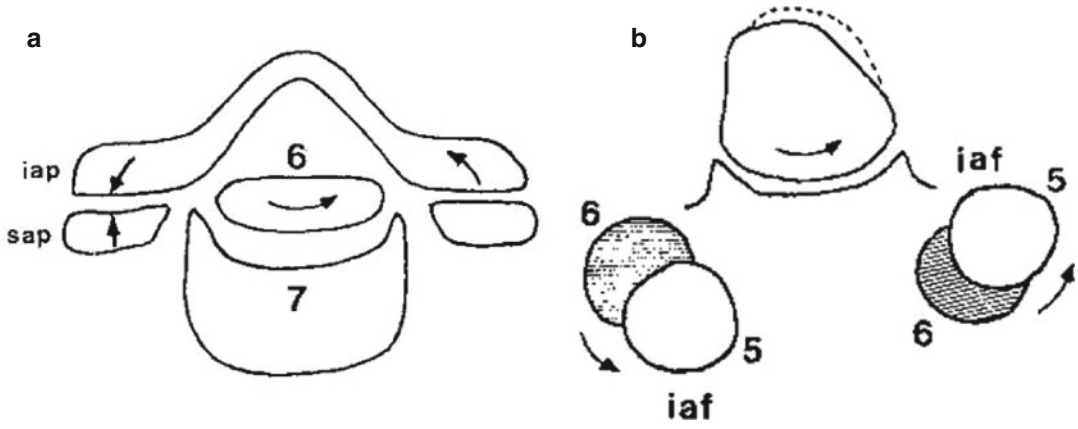


Fig. 2.6 (**a**) axial section of a C6–C7 intervertebral joints along a plane perpendicular to the facets (*Arrow* in center). In this plane, during left C6 vertebral body rotation, the right inferior articular process (*iap*) of C6 immediately impacts into the superior articular (*sap*) process of C7, preventing lateral rotation of C6 (*little arrows on left*); (**b**) axial section of a C5–C6 intervertebral joints along a plane parallel to the facets (*Arrow* in center). In this plane, if the C5 vertebral body rotates, its iap is bilaterally free and can glide across the surface of articular facets of C6 (*little arrows on left and right*) (From Bogduk and Mercer [13], with permission)

assessed. The appearance is that of an ellipsoid joint and suggests that rocking could occur side to side between two adjacent vertebral bodies. But, regarding a section achieved through the uncinate region and facet joints along a plane perpendicular to the latter, it is clear that any attempt of lateral rotation is immediately prevented by the facets. On the contrary, if sections are taken along a plane parallel to that of the facet joints, rocking of the vertebral bodies is not precluded because the facets glide freely upon one another (Fig. 2.6).

These observations indicate that the cervical interbody joints are a saddle joints, meaning that in the sagittal plane the vertebral body is free to rock forwards and backwards around a transverse axis, while in the plane of the facets its rotation is allowed around a perpendicular axis and cradled by the uncinate processes. Motion around an oblique axis is precluded by the orientation of the facets. Since their orientation is about 45°, also the pure axial rotation is 45° in the plane of the facet joints [27]. Horizontal axial rotation is inexorably coupled with lateral flexion and viceversa. If horizontal rotation is attempted, the inferior articular process rises up the slope of the superior facet of the vertebra below and, as a result, a tilt to the side of rotation occurs. A reciprocal combination of events happens when lateral flexion is tested: the inferior process slides backwards down the slope of the superior process and the vertebra rotates to the side of lateral flexion. By CT scanning, some authors [28] tried to estimate the range of axial rotation of the typical cervical vertebrae (Table 2.2). However, this kind of study was conducted with the CT scanning orientated across the conventional horizontal plane, failing to disclose the pure axial rotation. The axis of rotation in the plane of the facet joints passes through the anterior end of the moving vertebral body. During rotation, the anterior edge pivots about the axis without gliding, while the posterior margin is able to swing. The structure of the intervertebral disc supports this kinetics. The disc is the major compressive component of the spine. At low load rates, the disc deforms ad is more flexible, but at higher load it becomes stiff. Degenerative changes

Table 2.2 Mean values and ranges of axial rotation of the typical cervical vertebrae, according to Penning and Wilmink [28]

	ROM (degrees)	
Level	Mean	Range
C2–C3	3	0–10
C3–C4	6.5	3–10
C4–C5	6.8	1–12
C5–C6	6.9	2–12
C6–C7	2.1	2–10

affect its viscoelastic properties and ability to tolerate mechanical stresses. The annulus is well developed and thick anteriorly, but thinner in the region of the uncinate processes. Its tensile properties are related to the orientation of the collagen fibers that converge upwards, towards the anterior portion of the upper vertebral body. This arrangement appears as an inteosseous ligament, disposed like an inverted "V", whose apex points to the axis of rotation so that the vertebra can pivot about its anterior end. The annulus is lacking posteriorly [29] and tapering towards the uncinate processes, with few fibers and about 1 mm thick. It is covered by the posterior longitudinal ligament (see below). In the absence of the posterior annulus, with the progressive formation of posterior transverse discal clefts, the posterior end is free to swing. As it swing, its posterior inferior border can glide up and down the concavity of the uncinate processes, while its inferior facets slip on the superior facets of the vertebra below.

Axial rotation and side bending can be regarded as secondary coupled movements at the typical cervical segments. The primary motion at the lower cervical spine is flexion and extension in the sagittal plane. Flexion is composed by an anterior sagittal rotation and anterior translation to various extent. While, in the past, the slope of the articular facets was postulated as the major determinant of patterns of segmental sagittal motion, more recently the height of the superior articular processes has been shown as the main factor. Infact, regardless of its slope, the taller the superior articular process, the more it impedes anterior translation for any degree of anterior sagittal rotation. In other terms, this height determines the extent of coupling between sagittal rotation and translation [27]. Considering the IAR, it is located close to the intervertebral disc space of the FSU at the lower levels due to the greater height of the superior articular processes. On the contrary, since the articular processes are lower at the upper cervical levels, the IAR lies below more than disc of the segment in question (Fig. 2.7). The first description of the centre of rotation in healthy adults was derived from Penning's measurements [4], obtained by flexion-extension x-ray. With the aid of CT scan, the average centre of rotation for each level was determined [22]. Lysell [30] described the top angle or "arch of motion" from C2 to C7, as being flat at C2 and steep at the lower cervical spine. This means that the motion of the upper segments during flexion-extension is quite horizontal, whereas it is like an arch at the lower segments. The greater distance of the vertebra to the center of rotation in the upper region produces more flat motion, whereas smaller distance provides a sharper top angle. Ultimately, from above downwards the IARs are located progressively higher and closer to the intervertebral disc of their FSU. A critical determinant of this progression is the height of the articular pillars. These are lower at C2–C3 and progressively higher towards C6–C7. The height of the superior articular process at a given level predicts how much sagittal rotation must occur in the segment in relation to a specific and physiological amount of translation. Tall processes prevent an antero-posterior translation higher than 2.7 mm. Abnormal location of the IAR was proposed as a marker of poor quality of cervical motion in presence of pain, headache or previous trauma. The study by Amevo et al [31] on 109 patients with post-traumatic neck pain showed an abnormally located IAR in 77 % of cases and this relationship axis location-pain was highly significant statistically.

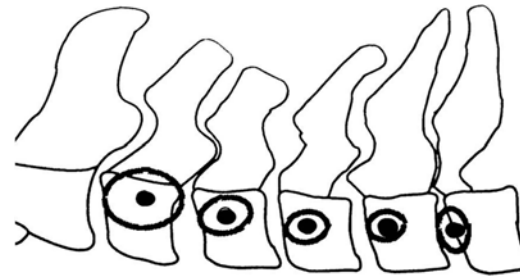


Fig. 2.7 Instantaneous axes of rotation (IAR) during maximal flexion-extension of the cervical spine (C3–C7). Spots indicate the IAR for each level, whereas ovals symbolize the standard deviation (SD)

Generally, flexion is resisted in concert by the posterior longitudinal ligament (PLL), the yellow ligament, the capsules and the posterior ligamentous complex, while extension is principally lim-

ited by the anterior longitudinal ligament (ALL) and the annulus and by impaction of the posterior arches. This spinal architecture introduces the importance of the soft tissues in motion and stability of the cervical spine.

Soft Tissues

Ligaments, discs, fibrous capsules of the zigaphophysial joints and muscles represent the soft tissues of the cervical spine. These soft tissues render the spine compliant in that they allow for movement between vertebrae. They are also responsible for limiting the range of many motion under physiological loads. Ligaments of various types connect the vertebral bodies and the posterior elements and span one or more segments. Ligaments consist of various amounts of collagen and elastina, arranged in an uniaxial manner, so they are able to resist tension forces. At each segmental level, the anulus fibrosus of the intervertebral disc binds the adjacent vertebral bodies. Posteriorly, as see above, in the region of the uncinate processes, the connection is interrupted by transverse clefts of the anulus. The intervertebral discs consist of proteoglycan nucleous designed to sustain compression loads, whereas the collagen fibers of the anulus resist tension, shear and torsion. The rule of the soft tissues in the biomechanics of the human cervical spine can be assesses using mathematical model (e.g. finite element models), investigating the external and internal responses of the spine under loads. As clarified by Yoganandum et al [32] "external responses can be defined as measurable parameters of the spinal structure under an externally applied load" like moment-rotation curve produced by sagittal rotation under flexion-moment loading. In contrast, "internal responses can be defined as intrinsic parameters" like tensile stress of the disc: "Because of the complex nature of spinal architecture, internal responses are not direct measurable quantities in an experiment".

However, the biomechanical roles of the various soft tissues are different and each type must be discussed in terms of individual mechanical, geometrical and material properties.

Ligaments and Joint Capsules

Ligaments are monoaxial structures that resist tensile or distractive forces. The capsular ligaments are an important local stabilizer of the facet joints. Generally, ligaments are more effective when distracted along the direction of the fibers. But, because of their variable and complex orientation, some ligaments are be able to contrast external tensile forces in a wide range of directions. The anterior longitudinal ligament is resistant to an extension bending moment, whereas interspinous and sovraspinous ligaments (posterior complex) are more effective during flexion forces. Posterior longitudinal ligament, which lie close to the IAR, responde with less resistance than anterior and interspinous ligaments. The internal response of the ligaments secondary to loading depends on the severity, magnitude and application of load vector, but also on the individual mechanical properties: for example, ligamentum flavum, which is rich of elastina, is more elastic than the other. To quantify the geometry of the different ligaments of the cervical spine (origin and insertion = length; cross-sectional area), various methods of investigation have been adopted [32]. In summary, for length purposes, the longitudinal ligaments span the mid-height of adjacent vertebrae, ligamentum flavum and interspinous ligaments span the superior and inferior points of attachment of the two vertebrae and joint capsules span from the superior tip of the caudal facet to the inferior tip of the cephalad facet. Maximum cross-sectional area occurs midway between the two spinous processes for interspinous ligaments, mid-disc height for the two longitudinal ligaments and mid-capsule height for joint capsules. The ligaments are deformation sensitive: under axial tensile loading (traumatic force), the load-deformation response is achieved. The typical force-displacement and stiffness displacement responses of a ligament is shown by a non-linear curve which defines neutral, elastic and plastic phases (Fig. 2.8). So, for each ligament, an individual tensile force-deformation, energy and stiffness are calculated [32]. These properties are influenced by age, sex and loading rate [33]. Same biomechanical informa-

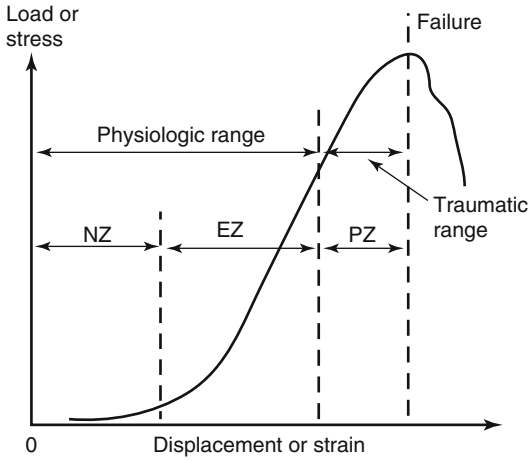


Fig. 2.8 The nonlinear load-displacement curve of the spine can be divided into physiological and traumatic ranges. The first part is the neutral zone (*NZ*) in which the displacement beyond the neutral position is achieved by application of a small force. The second part is the elastic zone (*EZ*) in which more load is required against an internal resistance. The last part, the plastic zone (*PZ*), is the displacement beyond the EZ to failure (From Panjabi et al. [1], with permission)

tions have been reported for stress, strain, stiffness and energy of joint capsules.

Intervertebral Discs

Intervertebral discs, in contrast with the uniaxial response of the ligaments, recognize multiple load vectors. Under any external loading, except tension, discs restrain essentially compressive forces in association with other components. Thus, the fundamental functional mechanical role is to respond to some degree of compressive loading, applied when the weight of the head (approximately three times the weight of the neck) is transmitted to the C2-T1 discs. Like ligaments, the internal response of the disc depends on the magnitude and nature of loading. The eccentrical anatomy of the nucleous polposus contributes to the dissimilar proportions of anterior and posterior anulus internal load-sharing during bending moment, as compression, flexion and tension. Three-dimensional geometrical data of disc nucleous and anulus have been reported in relation to height and cross-sectional area, but studies are in progress to capture intervertebral discs responses in tensile-compressive cycling loading and develop finite element models that may be applied in future [34]. Material properties, such as force-displacement, stiffness and stress-strain, must be achieved in more than one mode because of the multi-modal behavior of the disc, anulus and fibers. Using a single FSU and applying a traumatic compression or tension load, failure of the disc is identified as the point on the load-deflection curve at which an increase of compressive or distractive displacement results in a decrease of the resistive force. The force-displacement is non-linear and the post-traumatic phase indicate discal damage (see Fig. 2.8)

Muscles of Neck and Shoulders

The static and dynamic control of the head and neck is managed by a complex arrangement of about 20 muscles that enclose the cervical spine. The muscles at the upper cervical spine have individual unique structure, enabling lateral bending in C0/C1 and side rotation in C1/C2. Normally, the first 45° of rotation occurs in C1/C2, and then the lower cervical spine becomes involved. On the other hands, the muscles in the lower cervical spine are linear or interwoven, with every muscle activating several segments. This causes the segments of the lower spine to act as one unit. Anatomically, the deeper muscles are related intimately with the cervical osseous and articular elements, performing stabilizing functions, whereas the superficial muscles have no attachments to the cervical vertebrae. The deep musculature has a very high spindle density. The muscle spindles mediates the proprioceptive inputs from the cervical musculature and have an important role in head-eye coordination and postural control. The musculature involved in head and neck movement and stability is presented in Table 2.3.

Table 2.3 Musculature of the head-neck-shoulders system, involved in motion and stability of the cervical spine, according to Tortora and Grabowski [38]

Muscles of the neck, Mm. colli	***Function***
Sternocleidomastoideus	Supports the head
	Extension C0/C1
	Side rotation
Lateral vertebral muscles	Lateral bending
Scalenus anterior	
Scalenus medius	
Scalenus posterior	
Anterior vertebral muscles	Flexion, Lateral bending, Side rotation
Longus colli	
Longus capitis	
Suboccipital muscles 1	Extend, Rotate, Flexion, Side bending
Rectus capitis	
Obliquus capitis	
Muscles of the back, M. dorsi	
Upper trapezius	Elevates the scapula
	Function together with other muscles;
	Seldom as a single unit
Superficial erector spinae muscles	Erect posture,
Ilicostalis cervicis	Lateral bending
Longissimus cervicis	Extension
Longissimus capitis	
Spinalis cervicis	
Spinalis capitis	
Superficial muscles	Rotates the head
Splenius capitis	Rotation and lateral bending
Splenius cervicis	
Deep transverso-spinales muscles	Supports the head
Semispinalis cervicis	Extension of head (C0/C1) and spine
Semispinalis capitis	
Mm. Multifidi	Stabilize individual segments
Mm. rotares cervicis	Lateral bending Side rotation

Normal Global Motion of the Cervical Spine

Data about the segmental motion of each cervical FSU have been reported in detail in vivo (Table 2.4) and *in vitro* (Table 2.5). But, the measurement of global ROM in the cervical spine is a routine part of the clinical examination of patients with neck disorders. The knowledge of normal age and sex-related ROM is the basis to analyze a pathologic motion patterns as well as decreased or increased ROM. In 1992, Dvorak et al. [35] tested 150 healthy asymptomatic volunteers to obtain normal values. Each subject, seated on specially designed chair, was requested to perform active motion, which is followed by passive examination by the physician. Flexion-extension, lateral bending, axial rotation were evaluated. In addition, axial rotations during full flexion and full extension were measured. The volunteers were divided into five groups according to age decades. The overall tendency was for ROM to decrease as age increased: the most dramatic decrease in motion occurred between the group aged 30–39 and 40–49. Axial rotation with cervical spine in full flexion is the only motion that remained the same or increased slightly with age. Substantially, less motion was evident in the active tests and women showed greater ROM but only before age 60. Also, the measurement data for rotation out of maximum flexion suggested that the rotation of the C1–C2 joint did not decrease with age but rather remained constant or increased slightly, perhaps to compensate for the reduced motion of the lower cervical spine. In 1999, Feipel et al. [36] evaluated the normal global motion of the cervical spine by an electrogoniometric study. In 250 asymptomatic volunteers, aged 14–70 year, motion range

Table 2.4 ROM measurements for maximal flexion-extension of each cervical FSU, in degrees (± standard deviation), in normal subjects, according to A [39] and B [40]

	Flexion/extension	
Level	A	B
C0–C1	Not studied	
C1–C2	Not studied	
C2–C3	10 (3)	11 (3.4)
C3–C4	15 (3)	15 (4.0)
C4–C5	19 (4)	17 (4.6)
C5–C6	20 (4)	17 (6.1)
C6–C7	19 (4)	14 (4.7)

Table 2.5 ROM measurements of each cervical FSU, in degrees (±standard deviation), in human cadavers, according to the Multidirectional Flexibility Testing [18]

	C0–C1	C1–C2	C2–C3	C3–C4	C4–C5	C5–C6	C6–C7
Flexion	7.2 (2.5)	12.3 (2)	3.5 (1.3)	4.3 (2.9)	5.3 (3)	5.5 (2.6)	3.7 (2.1)
Extension	20.2 (4.6)	12.1 (6.5)	2.7 (1)	3.4 (2.1)	4.8 (1.9)	4.4 (2.8)	3.4 (1.9)
Axial rotation	9.9 (3.3)	56.7 (4.8)	3.3 (0.8)	5.1 (1.2)	6.8 (1.3)	5.0 (1)	2.9 (0.8)
Side bending	9.1 (1.5)	6.6 (2.3)	8.6 (1.8)	9.0 (1.9)	9.3 (1.7)	6.5 (1.5)	5.4 (1.5)

and patterns between the first thoracic vertebra and the head were analyzed for flexion-extension, lateral bending, rotation in neutral sagittal plane position and in full flexion. Average motion range in the sagittal plane was 122° (Standard Deviation-SD 18°). Flexion was slightly more important than extension. Global bending was 88° (SD 16°), left and right bending being comparable. Homolateral rotation was associated with lateral bending: its extent was approximatively 40 % of the bending range. Global rotation range in neutral sagittal plane position was 144° (SD 20°), without difference between right and left rotations. During rotation in flexed head position, global range was comparable to the one in neutral flexion for values of 134° (SD 24°). Finally, significant reduction of all primary motions with age was recorded, whereas sex had no influence on cervical motion range.

Neutral Zone and Cervical Spine Stability

When a spinal specimen is under a physiological load, the specimen does not return to its initial position. In other terms, a certain residual displacement remains. This displacement, measured from the neutral position, defines the neutral zone (NZ). NZ is the first part of ROM within which displacement of the spine is produced against minimal internal resistance. The NZ is defined by spinal flexibility or laxity. The elastic zone (EZ) is obtained simply as the difference between ROM and NZ. EZ is the part of ROM, measured from the end of the NZ up to the elastic limit, in which displacement is produced against internal resistance. The EZ represents the stiffness of the spine. Panjabi et al [16] and White e Panjabi [37] reported in detail average values of NZ, EZ and ROM for the upper, middle and lower human cadaveric cervical spine and the nonlinear load-displacement curve of an FSU. In summary, with flexion-extension moment loading, coupled translations in the sagittal plane were anteriorly directed for flexion and posteriorly directed for extension in all intersegmental levels. With axial loading, the cervical spine exhibited the largest main rotation at C1–C2 and the largest coupled extension at C0-C1. Coupled lateral bending was present at all levels, in the same direction of the applied torque. Coupled axial rotation was in the same direction as the lateral bending at all intersegmental levels. The NZ proved to be more sensitive than ROM in characterizing spinal instability. Infact, the NZ increased for injuries and fractures, whereas it decreased during muscle actions. An increase of the NZ can exceed the pain-free zone and may disclose the loss of spinal integrity. Post-traumatic failure of the spine occurs when the elastic limit is reached and further forces are applied (see Fig. 2.8).

References

1. Panjabi MM, Yue JJ, Dvorak J, et al. Cervical spine kinematics and clinical instability. The cervical spine. 4th ed. Philadelphia: JB Lippincott; 2005. p. 55–78.
2. Yukawa Y, Kato F, Suda K, et al. Age-related changes in osseous anatomy, alignment, and range of motion of the cervical spine. Part I: radiographic data from over 1200 asymptomatic subjects. Eur Spine J. 2012;21:1492–8.
3. Benzel EC. Biomechanics of spine stabilization. Principles and clinical practice. 1st ed. New York: McGraw-Hill Inc; 1995.
4. Penning L. Functional pathology of the cervical spine. Amsterdam: Experta Medica Foundation; 1968. p. 1–23.
5. Smith TJ, Fernie GR. Functional biomechanics of the cervical spine. Spine. 1991;16:1197–203.

6. Menezes AH, Traynelis VC. Anatomy and biomechanics of normal craniovertebral junction (a) and biomechanics of stabilization (b). Childs Nerv Syst. 2008;24:1091–100.
7. Jofe MH, White AA, Panjabi MM. Clinically relevant kinematics of the cervical spine. The cervical spine. 2nd ed. Philadelphia: JB Lippincott; 1989. p. 57–69.
8. Rhoton Jr AL. The foramen magnum. Neurosurgery. 2000;47:S155–93.
9. Quercioli V. Considerazioni cliniche su di un caso di frattura isolate comminuta simmetrica dello atlante senza lesioni midollari in seguito a caduta sul capo. Il Policlinico. 1908;XV:241–55.
10. White AA, Johnson RM, Panjabi MM, et al. Biomechanical analysis of clinical stability of the cervical spine. Clin Orthop. 1975;109:85–96.
11. Panjabi MM, Dvorak J, Duranceau J, et al. Three-dimensional movements of the upper cervical spine. Spine. 1988;13:726–30.
12. Mercer SR, Bogduk N. Joints of the cervical vertebral column. J Orthop Sports Phys Ther. 2001;31:174–82.
13. Bogduk N, Mercer S. Biomechanics of the cervical spine. Part I: normal kinematics. Clin Biomech (Bristol, Avon). 2000;15:633–48.
14. Ghanayem AJ, Paxinos O. Functional anatomy of joints, ligaments and discs. The cervical spine. 4th ed. Philadelphia: JB Lippincott; 2005. p. 46–54.
15. Penning L. Normal movement in the cervical spine. Am J Roentgenol. 1978;130:317–26.
16. Panjabi MM. The stabilizing system of the spine. Part II: neutral zone and instability hypothesis. J Spinal Disord. 1992;5:390–7.
17. (a) Dvorak J, Panjabi MM, Gerber M et al, CT-functional diagnostics of the rotator instability of the upper cervical spine. Part 1: an experimental study in cadavers. Spine. 1987;12:197–205. (b) Dvorak J, Hayek J, Zehnder R. Part 2: an evaluation on healthy adults and patients with suspected instability. Spine. 1987;12:726–31.
18. Panjabi MM, Crisco JJ, Vasavada A, et al. Mechanical properties of the human cervical spine as shown by three-dimensional load-displacement curve. Spine. 2001;26:2692–700.
19. Mimura M, Moriya H, Watanabe T, et al. Three-dimensional motion analysis of the cervical spine with special reference to the axial rotation. Spine. 1989;14:1135–9.
20. Takasaki H, Hall T, Oshiro S, et al. Normal kinematics of the upper cervical spine during the flexion-rotation test. In vivo measurements using magnetic resonance imaging. Man Ther. 2011;16:167–71.
21. Werne S. The possibilities of movement in the craniovertebral joints. Acta Orthop Scand. 1958;28:165–73.
22. Dvorak J, Panjabi MM, Novotny JE, et al. In vivo flexion/extension of the normal cervical spine. J Orthop Res. 1991;9:828–34.
23. Lind B, Sihlbom H, Nordwall A, et al. Normal ranges of motion of the cervical spine. Arch Phys Med Rehabil. 1989;70:692–5.
24. Frobin W, Leivseth G, Biggemann M, et al. Sagittal plane motion of the cervical spine. A new precision measurement protocol and normal motion data in healthy adults. Clin Biomech (Bristol, Avon). 2002;17:21–31.
25. Penning L. Kinematics of cervical spine injury: a functional radiological hypothesis. Eur Spine J. 1995;4:126–32.
26. Mestdagh H. Morphological aspects and biomechanical properties of the vertebroaxial joint (C2-C3). Acta Morphol Neerl Scand. 1976;14:19–30.
27. Nowitzke A, Westaway M, Bogduk N. Cervical zygapophyseal joints: geometrical parameters and relationship to cervical kinematics. Clin Biomech (Bristol, Avon). 1994;9:342–8.
28. Penning L, Wilmink JT. Rotation of the cervical spine. A CT study in normal subjects. Spine. 1987;12:732–8.
29. Mercer S, Bogduk N. The ligaments and anulus fibrosus of human adult cervical intervertebral discs. Spine. 1999;24:619–26.
30. Lysell E. Motion in the cervical spine: an experimental study on autopsy specimens. Acta Orthop Scand. 1969;123:S41–61.
31. Amevo B, Aprill C, Bogduk N. Abnormal instantaneous axes of rotation in patients with neck pain. Spine. 1992;17:748–56.
32. Yoganandan N, Kumaresan S, Pintar FA. Biomechanics of the cervical spine. Part II: cervical spine soft tissue responses and biomechanical modeling. Clin Biomech (Bristol, Avon). 2001;16:1–27.
33. Pintar FA, Yoganandan N, Voo LM. Effect of age and loading rate on human cervical spine injury threshold. Spine. 1998;23:1957–62.
34. Arun MW, Yoganandan N, Stemper BD, et al. Sensitivity and stability analysis of a nonlinear material model of cervical intervertebral disc under cyclic loads using the finite element method. Biomed Sci Instrum. 2014;50:19–30.
35. Dvorak J, Antinnes JA, Panjabi MM, et al. Age and gender related normal motion of the cervical spine. Spine. 1992;17:S393–8.
36. Feipel V, Rondelet B, Le Pallec J-P, et al. Global motion of the cervical spine: an electrogoniometric study. Clin Biomech (Bristol, Avon). 1999;14:462–70.
37. White AA, Panjabi MM. Clinical biomechanics of the spine. 2nd ed. Philadelphia: JB Lippincott; 1990.
38. Tortora G, Grabowski S. Principles of anatomy and physiology. 9th ed. New York: Wiley; 2000.
39. Dvorak J, Froehlich D, Penning L, et al. Functional radiographic diagnosis of the cervical spine: flexion/extension. Spine. 1988;13:748–55.
40. Amevo B, Worth D, Bogduk N. Instantaneous axes of rotation of the typical cervical motion segments: a study in normal volunteers. Clin Biomech (Bristol, Avon). 1991;6:111–7.

3 Diagnostic Imaging in the Degenerative Diseases of the Cervical Spine

Alessandro Maria Costantini, Antonio Leone, Marco Pileggi, Ronel D'Amico, and Cesare Colosimo

Introduction

Degenerative changes of the cervical spine, both physiological and pathological, proceed jointly with the aging of man and can be easily identified and characterized by modern radiological techniques. The aging of the cervical spine, in particular, involves all its structures (osteo-discal-ligamentous complex); however, the inter-vertebral joints are the earlier and more conspicuously involved targets, being also the most specifically linked to the symptoms determined by the involution process [1]. Imaging can also distinguish degenerative diseases from other causes of radiculo-mielopathy, (i.e. infection or neoplasms).

In this scenario, magnetic resonance imaging certainly represents the best imaging modality in the evaluation of degenerative disease, especially in the cervical segment, where other methods of investigation (radiography, computed tomography) do not have a high diagnostic accuracy because of the peculiar anatomical characteristics of the cervical spine. However, imaging findings must be considered clinically relevant only if correlated to the patient's symptomatology, as degenerative changes of the cervical spine can be found in asymptomatic patients over age 30 years [2]. In fact, imaging findings alone do not justify an aggressive therapy, particularly because some acute soft disk herniations can significantly decrease in size over time with conservative therapy [3]. This chapter is an attempt to provide the clinician with a daily imaging reference in the treatment and management of patients with cervical spine degenerative disease.

Basic Anatomy

Two components anatomically and functionally distinct could be recognized in the cervical spine. The upper cervical spine (or suboccipital spine) consists of the first two cervical vertebrae, atlas and axis, articulating with the occipital bone, forming the craniocervical junction (CCJ). The lower cervical spine (or subaxial cervical spine) extends from the C2-3 to the C7-T1 joints [4].

Cranio-Cervical Junction

The atlas is ring-shaped; it is formed by a thick anterior arch, a thin posterior arch, 2 lateral masses, and 2 transverse processes. In the transverse

A.M. Costantini • A. Leone • M. Pileggi
R. D'Amico • C. Colosimo (✉)
Department of Radiological Sciences,
Radiology/Neuroradiology Institute,
Catholic University of Sacred Heart,
Polyclinic A. Gemelli, School of Medicine,
Largo A. Gemelli 8, 00168 Rome, Italy
e-mail: colosimo@rm.unicatt.it

P.P.M. Menchetti (ed.), *Cervical Spine: Minimally Invasive and Open Surgery*,
DOI 10.1007/978-3-319-21608-9_3

process there is a foramen, through which the vertebral artery passes (transverse foramen). Lateral masses have a superior and an inferior articular facet which form the zygapophyseal joint.

The axis is composed of a vertebral body (which contains the odontoid process), large pedicles, laminae, and transverse processes; the odontoid process has an anterior articular facet that articulates with the anterior arch of the atlas.

The craniocervical junction includes six synovial joints: a pair of atlanto-occipital joints, the anterior and posterior atlanto-odontoid joint and a pair of atlanto-axial lateral joints. The atlanto-occipital joints are established between the occipital condyles and the superior articular facets of the atlas. The atlanto-odontoid joint takes place between the dens and a osteofibrous ring formed by the frontal arc of the atlas and the transverse ligament. The atlanto-axial lateral joints articulate the facet joints of the axis and of the atlas.

The craniocervical junction is held in place by extrinsic and intrinsic ligaments. The extrinsic ligaments include the nuchal ligament, which extends from the external occipital protuberance to the posterior portion of the atlas and of the cervical spinous processes and fibroelastic membranes that replace the anterior longitudinal ligament, intervertebral disks and the flaval ligaments.

The intrinsic ligaments, located within the spinal canal, provide the majority of joint stability. From the dorsal to the ventral side, they include the tectorial membrane, the cruciate ligament and the odontoid ligaments (apical and two alar ligaments). The tectorial membrane connects the back of the axis body to the front of the foramen magnum and it is the cephalic continuation of the posterior longitudinal ligament. The cruciate ligament lies anterior to the tectorial membrane, behind the odontoid process; it is formed by longitudinal fibers, which from the anterior margin of the foramen magnum end behind the body of the axis, and by the transverse ligament, sturdy fibrous tape stretched between the internal surfaces of the atlas masses. A synovial cavity is located between the dens and the transverse ligament. The transverse ligament is the most important ligament for preventing abnormal anterior translation. Odontoid ligament secure the axis dens to the occipital bone through the apical ligament and two alar ligaments, which prevent excessive lateral and rotational motion [5].

Subaxial Cervical Spine

Subaxial cervical spine includes vertebrae C3 to C7. Vertebral bodies are concave on their superior surface and convex inferiorly. On the superior surfaces of the bodies are raised processes or hooks called uncinate processes, each of which articulates with a depression on the inferior endplate of the superior vertebral body (Luschka joints, not considered true articulation) [6]. In most cases the spinous processes of C3-6 are bifid, while the spinous process of C7 is not.

Each vertebra has two superior and two inferior zygapophyseal joints, a disco-somatic joint and two, as we have just mentioned, Luschka joints. The facet joints are diarthrodial synovial joints with fibrous capsules.

The anterior longitudinal ligament (ALL) and the posterior longitudinal ligament (PLL) are found throughout the entire length of the spine; the former is not well developed in the cervical spine and is more closely adherent to the disks than the latter. ALL and PLL are the caudal extension, respectively, of the anterior atlanto-occipital membrane and of the tectorial membrane in the lower cervical spine. The supraspinous ligament, the interspinous ligaments, and the flaval ligaments (posterior ligamentous complex) maintain stability between the vertebral arches. The flaval ligament is the most important: runs from the anterior surface of the cephalic vertebra to the posterior surface of the caudal vertebra and, aided by interspinous ligament, in controlling the excessive flexion and anterior translation. The flaval ligament also connects to and reinforces the facet joint capsules on the ventral aspect.

Intervertebral disks are located between the vertebral bodies between C2 and C7 and are made of four parts: the nucleus pulposus, the

annulus fibrosus and two endplates attached to the superior and inferior vertebral bodies. The disks are thicker anteriorly and, with the physiological process of aging the disk undergoes progressive dehydration and reduction in height.

The foramina progressively decrease in size from C2-3 to C6-7; the spinal nerve, which is the result of the union of the anterior and posterior nerve roots, occupy about one third of the foraminal space. The foramen is bordered anteriorly by the uncovertebral joints, posterolaterally by facet joints, superiorly by the pedicle of the vertebra above, and inferiorly by the pedicle of the lower vertebra.

Technical Approach

Diagnostic workup in the assessment of degenerative cervical spine disease is aimed to identify the pathology of the spinal osteo-discal-ligamentous complex (i.e. spondylosis, hernias, etc.) and the consequently determined alterations of the "content" (spinal cord). We briefly describe the most important imaging modalities (radiography, computed tomography, magnetic resonance imaging) in the evaluation of the effects of degenerative diseases that should be considered preliminary to any therapeutic planning [7].

Radiography

Even if radiography is considered the "first step" technique in the study of degenerative cervical spine examination, nowadays it has undergone critical re-evaluation and its role is currently controversial [8, 9]. In the assessement of brachialgia, radiography can only provide information about bone spinal structure degenerative changes, but it is limited in the evaluation of stenosis of the central canal and disk herniation, the most frequent causes of pain and neurologic symptoms. The only indisputable use of radiography is confined to assessement of the instability, performing a flexion-extension radiograms [10]. However, the functional radiological study itself can't demonstrate the most frequent cause of instability represented by ligament laxity/injury.

Computed Tomography

The introduction of new multidetector computed tomography (CT) scanner has completely changed the accuracy and diagnostic capabilities of CT in the evaluation of degenerative cervical spine disorders. A slice thickness of 0.6–0.7 mm with reconstruction per 1 mm and increases of 0.5–0.6 are recommended parameters for an optimal visualization of degenerative changes. Contrary to radiography, CT is capable to visualize not only the bony structures but also soft tissues features (e.g. disk herniations). However, CT is inadequate in the study of ligaments and bone marrow changes, which are prerogative of MR imaging. Multiplanar and 3D reconstruction may be a useful integration to the axial examination, especially in surgical planning [11]. The use of contrast media is only limited to the differentiation between hernia relapse and granulation tissue, in patients with contraindications to MRI. Finally, the most significant limitations of CT results from its inability to demonstrate spinal cord disease, making MRI the modality of choice in patients with clinical evidence of myelopathy.

Magnetic Resonance Imaging

Cervical spine MR examination should be performed on high-field equipment (≥-1.5 T), using powerful gradient systems and phased-array coils. The T1- and T2-weighted (T1-w and T2-w) images in sagittal and axial planes, which represent the baseline examination, should be completed with 2D-3D GRE T2*-w axial and sagittal images, that optimize the contrast between the bony and the discal/ligamentous structures. However, in some cases, they can be supplemented by more specific sequences and scanning planes to complete the study and optimize the diagnosis (i.e. oblique planes for studying nerve roots course or fat suppressed images in evaluating Modic changes – vide infra). As for CT, the use of contrast media is limited to selected instances, i.e. to evaluate post-surgical hernia relapse and for differential diagnoses of neoplastic and infectious

diseases. Finally, it must be taken into account that MR imaging can directly demonstrate, with high sensitivity, the lesions of spinal cord, nerve roots and meningeal sheaths that are in some cases determined by degenerative changes of the osteodiscal structures.

Basic Findings in the Degenerative Disease

The Disk

Disk degeneration starts early in life and frequently progresses relentlessly. The elderly frequently show disk degeneration of the cervical and lumbar tract.

The pathogenesis of intervertebral disk degeneration is unclear: multiple factors working separately (hereditary factors, age related vascular changes, vertebral endplate changes such as calcification), may lead to a compromise of discal trophism. Mechanical factors as trauma, sports, or working factors may also contribute.

Despite the disk degeneration is due to multifactorial causes, four are the elementary imaging features [12, 13] (Fig. 3.1):

1. Loss of signal intensity of disk (MR imaging)
2. Loss of height (all imaging modalities)
3. Bulging (CT or MR imaging)
4. Herniation (CT or MR imaging)

The radial tear of the annulus that is often strictly associated with the other features, is to be

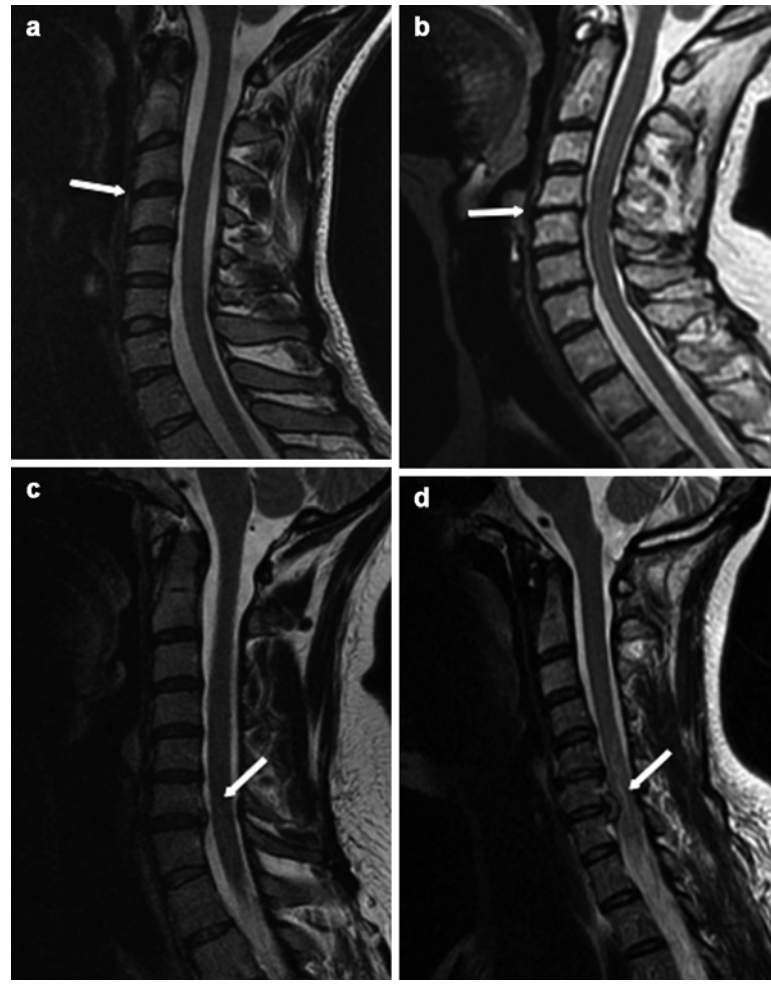


Fig. 3.1 Age-related disk modifications, disk bulging and disk herniation shown on sagittal FSE T2 images. Patient 1 (**a**) Minimal disk dehydration at C3-4 level (*arrow*), as demonstrated by low intensity signal on T2 images. Patient 2 (**b**) With progression of degenerative changes, disk height is reduced and associated with mild spondylotic alteration at C4-5 level (*arrow*). Patient 3 (**c**) Posterior disk bulging at C6-7 level (*arrow*). Patient 4 (**d**) Disk herniation at C6-7 level (*arrow*)

considered the primary failure of the annulus itself [14]. The radial tear involves all layers on the annulus fibrosus and it is well described in MR imaging as high signal intensity tissue in the region of the disk normally characterized by low signal intensity [15].

The disk degeneration processes evolve in a progressively loss of water, with a compromised integrity of the annulus fibrosus.

On MR imaging these signs are well evident on T2-w fast spin echo (FSE) or gradient echo (GRE) images with a loss of normal hyperintensity of signal and an associated loss of height (often a vacuum phenomenon is demonstrated in CT or radiography). Frequently the disk degeneration is associated with an alteration of adjacent intervertebral body endplates (intervertebral osteochondrosis).

Modic [16] distinguishes three progressive grades of alteration adjacent to the endplates on MR imaging (Fig. 3.2), partially corresponding to the sclerosis described in radiographic or CT examination:

- Type I: hypointense on T1-w and hyperintense on T2-w bands which represent the replacement with hematopoietic marrow
- Type II: hyperintense T1-w and iso/hyperintense T2-w bands which represent the replacement by fatty marrow
- Type III: hypointense T1-w and T2-w bands which are characteristic of bone sclerosis.

The endplates bony marrow changes associated with degeneration disks may be however distinguished from the other diseases such as infection and metastases.

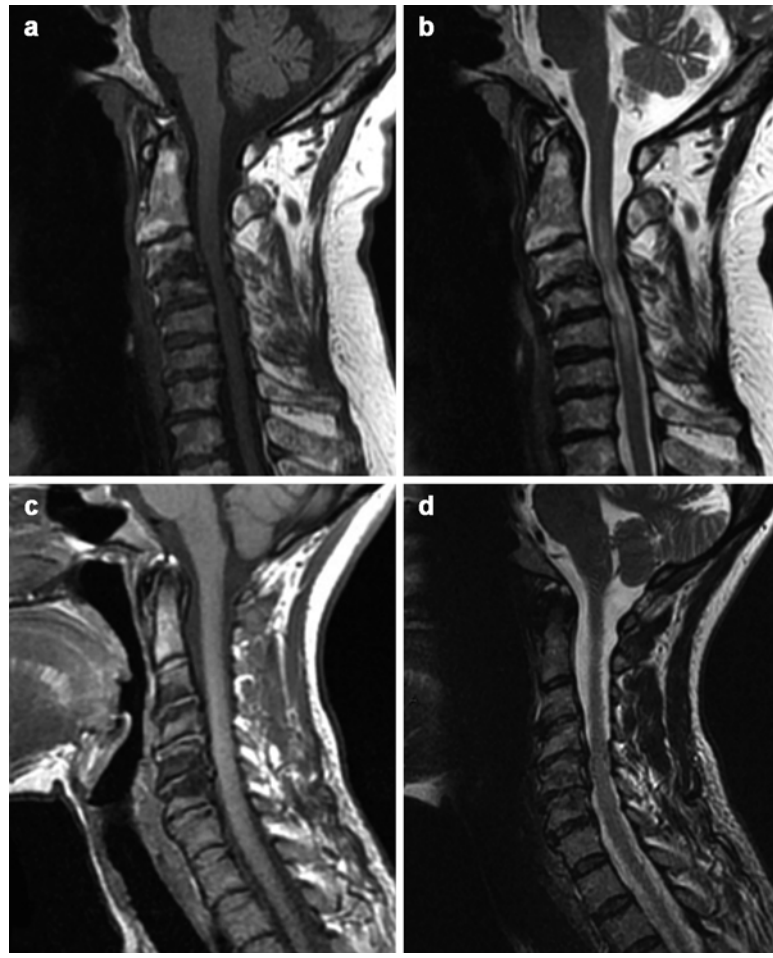


Fig. 3.2 Modic 2–3 alterations on sagittal FSE T1/T2 images. Patient 1: FSE sagittal T1 (**a**), FSE sagittal T2 (**b**). The vertebral endplates at C2-3 level show hyperintensity on both imaging sequences, due to the conversion of normal into yellow fatty marrow (Modic 2). Spondylosis results in spondylotic myelopathy as demonstrated by intrinsic high signal of the compressed spinal cord. Patient 2: FSE sagittal T2 (**c**), FSE sagittal T2 (**d**). The vertebral endplates at C5-6 show hypointensity on both sequences, representing subchondral bony sclerosis (Modic 3)

Spondilosys

Dehydration and fibrosis of the disk mean that static and dynamic mechanical stress can no longer spread through the horizontal plane of the disk, without altering it structurally. The disk becomes the seat of fissures, protrudes out and becomes thinner. Because of the displacement of disk material beyond the margins of the intervertebral disk space, a productive reaction is established, producing fibroblasts, in the adjacent vertebral margins: these phenomena determine spondylosis pathogenesis.

Osteophytes are the most characteristic sign of spondylosis and are more commonly found at levels C5-7; at the beginning they are thin and have a horizontal course to become gradually larger until they weld in the more advanced stages. Uncovertebral joints osteophytes characterize the framework of mono- or bilateral uncoarthrosis: they push into the vertebral foramina and can compress the spinal root and into the intertransverse space, where they take relationship with the vertebral artery [17].

Interapophyseal joints osteophytes that protrude into the foramina will generally occupy the upper part and rarely are able to cause a radiculopathy by themselves. Instead they contribute to cause it in the presence of lateral herniated disk or severe uncoarthrosis. The development of anterior osteophytes in cervical spondylosis is usually modest and asymptomatic. Both radiography and CT can well demonstrate osteophytes. Even in the MR imaging, osteophytes can be well studied with T2*-w sequences that well demonstrate bone structures, distinguishing from the adjacent degenerated disk.

Cervical Facet Arthropathy

The degenerative facet disease or arthropaty is to be considered an osteoarthritis of sinovially lined apophyseal joints. Each apposing facet is composed of a thin uniform layer of dense cortical bone, and an overlying layer of cartilage. The facet joint is lined by synovium.

The degenerative process is not different from other synovial joints. It starts with hypertrophic degenerative inflammatory changes, following by subluxation that may produce gas (vacuum phenomenon). Lately there is a cartilage erosion with narrowed joint space. It is most common in mid lower cervical spine.

Radiologically the early degenerative signs maybe be difficult to demonstrate, while the later changes are well evident in radiography (facet arthrosis, vacuum phenomenon, mushroom caps facet appearance, sclerosis). CT with soft tissue window level well demonstrates the thickening and inflammatory changes of soft tissue better visualized with the injection of contrast media. MR imaging shows a better visualization of the inflammatory changes and the facet effusion (linear T2-w images hyperintensity), but overestimated with the T2*-w images the degree of foraminal and central canal narrowing.

Ligament Degeneration

Cervical ligaments also undergo degenerative changes, represented by the precipitation of calcium salts and the appearance of new bone formation, which compromise their firmness and elasticity. It should also be remembered that it is sufficient the involvement of disks and/or synovial joints to induce ligamentous laxity, consequently alteration that entails the functional spinal unit (FSU). A FSU consists of two adjacent vertebrae, the intervertebral disk and all adjacent ligaments between them.

The calcified depositions and ossification are most frequently found in the flaval ligaments and especially in the anterior and posterior longitudinal ligaments.

Degenerative Cervical Spine Instability

Stability can be defined as the ability of the vertebrae to maintain normal relations between them and to contain their mutual displacements, under

the action of postures and physiological loads. In normal conditions, the geometric characteristics of the vertebrae, a normal intradiscal pressure, the configuration of the facet joints and, above all, a correct ligament tension are able to maintain stable motion segments. When the above conditions are not preserved, the spine becomes unstable.

Despite the efforts of numerous authors to define the spinal instability, there is not a definition shared by all; one of the biggest problems is that the concept has different meanings in various areas of clinical radiology and bioengineering. However, a reasonable definition has been proposed by White and Panjabi [18] that by supporting a biomechanical approach, define instability as a loss of "stiffness" of the motion segment in correspondence of which, under the action of a load, the motion determined abnormal displacement. In biomechanical sense, the "stiffness" is defined as the ratio between the loads applied to the structure and the resulting movement. The instability of the spine may be the consequence of a trauma, of a degenerative disease and various other causes.

This premise is fundamental to allow an interpretation of cervical degenerative instability not as a mere list of topographical radiological signs but as an alteration of the spinal disk-ligamentous complex as a whole. The various degenerative changes must be inserted in well-defined pathological successive phases according to Kirkaldy-Willis [19], which are:

- Phase of functional derangement
- Phase of instability
- Phase of fixity

Phase of Functional Derangement

Degenerative changes in the initial (disk fissures and apophysis' synovitis) determine an interapophyseal joints stress that leads to a modest hypermobility of the vertebrae. Consequently, the hypermobility causes a repeated stress of nerve fibers with the onset of cervical acute pain. Facet joints subluxation can be associated with a disk herniation or a symptomatic synovitis. At this phase the radiography is negative, so in the suspicion of a herniated disk is necessary to perform CT or MR imaging.

Phase of Instability

Going on the functional derangement, degenerative phenomena worsen both on disco-somatic complex (i.e. reduction of disk space, vacuum phenomenon, intervertebral osteochondrosis) and on zygapophyseal joints (sclerosis, "mushroom" deformation of articular pillars, articular effusion). Consequently radiculopathy or myeloradiculopathy may spread out at this phase as a result of disk herniations and also a spondylolisthesis of the vertebra affected (degenerative spondylolisthesis) may result in dynamic narrowing of central canal and/or foraminal stenosis. The radiography, when performed in LL projection in flexion and extension (dynamic study) is able to detect not only the degree of listhesis but also to determine if it is reducible or fixed (Fig. 3.3).

Phase of Fixity

The findings are those of advanced osteoarthritis, with loss of motion, joint deformation and above all an increase in osteoproliferative phenomena (osteophytes and hypertrophy of the articular pillars); these alterations may lead to central canal stenosis. Conventional radiology is able to highlight osteoproliferative changes but not to assess their effects on neurovascular structures, and therefore they should be investigated with CT and MR imaging.

Cranio-Cervical Junction Degenerative Disease

The joint most frequently subject to degenerative changes in the craniocervical junction is the atlanto-odontoid. Atlantoaxial advanced degenerative changes are the main cause of the onset of

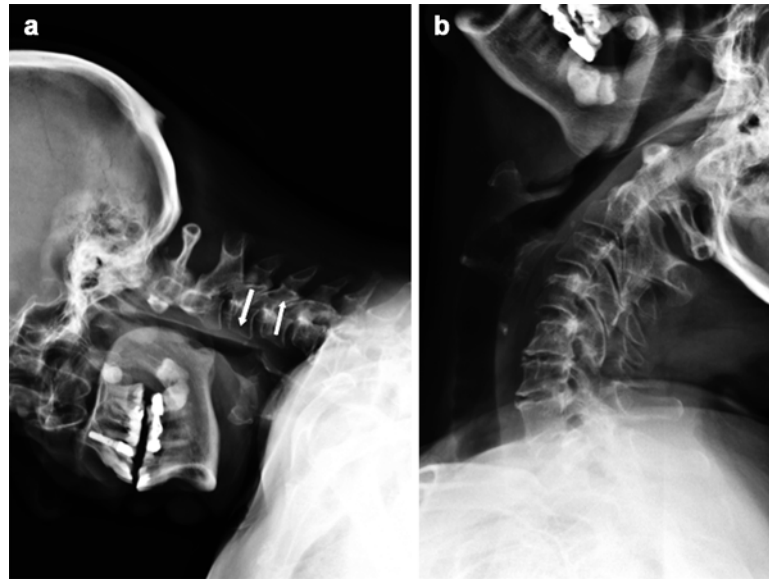


Fig. 3.3 Degenerative instability on flexion/extension radiography. Flexion (**a**) and extension (**b**). Minimal degenerative spondylolisthesis C3-4 evident on the flexion radiogram (*arrows*, "phase of instability" according to Kirkaldy-Willis) with complete reduction on extension radiogram

symptoms (headache), with concomitant reduction in mobility.

Also, it has been suggested that the onset of vertigo can be referred to a strict relation between upper cervical spine afferent fibers and vestibular and oculomotor nuclei [20].

Sometimes degenerative changes can lead to the formation of abundant inflammatory reactive tissue, mainly posteriorly to the odontoid process that could determine an encroach on the ventral surface of the spinal cord (inflammatory pseudotumor).

Imaging

CT and MR axial images, as in the subaxial cervical spine, provide a good evaluation of the spinal canal stenosis which is often associated with the degenerative changes in the cranio-cervical junction; MR imaging is also capable to evaluate the medulla oblongata compression and its lately onset of myelomalacia (characterized by hyperintensity on T2-w images). Moreover, the MR imaging can differentiate hypertrophic pseudotumoral changes of the CCJ (Fig. 3.4). Post-contrast images are useful to exclude/identify inflammatory changes (pannus).

Subaxial Cervical Spine Degenerative Disease

Cervical Disk Herniation

Terminology

The general term of herniated disk means the displacement of disk material beyond the margins of the intervertebral disk space and represents one of the major causes of neck pain. There are not universally accepted terminology and classification to define various pattern of disk herniation; different words are often used to describe the same type of hernia. A purely pathological classification of disk herniations is not suitable in daily radiological practice; i.e., the terms disk prolapse or disk herniation, respectively indicating that a portion of the nucleus pulposus has made its way through a fissure that involves only the innermost fibers of the annulus (prolapse), and the disk material that has gone through the whole annulus fibrosus, but not the posterior longitudinal ligament (disk herniation). However, since these two conditions pathological are not differentiable from each other even with MRI (both can manifest as focal contour deformities of disk), it is better not to make such a distinction. Morphologically we can distinguish protruded

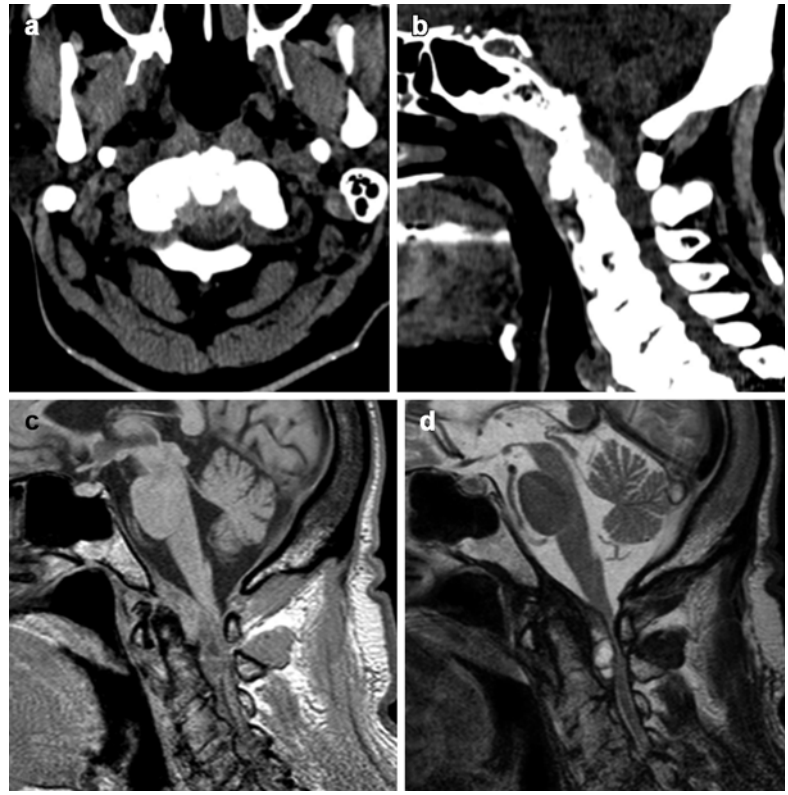


Fig. 3.4 Pseudotumor of the CCJ; CT and MR imaging. CT axial (**a**) and sagittal (**b**) images, sagittal GRE T1 (**c**) and FSE T2 (**d**) images. Abundant retro-odontoid inflammatory tissue at C0-C1 level, resulting in severe spinal cord compression

from extruded hernias: a disk protrusion is a herniated disk in which the distance between the edges of the disk herniation is less than the distance between the edges of the base; conversely, a disk extrusion is a herniated disk in which the distance between the edges of the disk material is greater than the distance at the base [21, 22].

Even if a universally accepted classification is not forthcoming yet, differentiation between the "bulging disk" by "hernia" is necessary.

Bulging Disk (Fig. 3.5)

The "bulging disk" is characterized by wide/diffuse displacement of disk material beyond the normal limits of the intervertebral space, while the herniated disk is instead a focal dislocation. For wide/diffuse dislocation is meant a dislocation that affects more than 50 % (180°) of the circumference of disk, while a dislocation is defined focal when interesting not more than 25 % of the circumference of the disk. It is important to emphasize that the "bulging disk", very common over forty, may be associated with reduction in disk height and does not necessarily represent a pathological condition.

In the presence of a bulging disk, the posterior dislocation of the disk tissue is typically symmetrical and maximum on the median line, but occasionally it is possible to observe also a focal disk displacement on one side. In a relatively narrow spinal canal, the bulging disk can flatten the dural sac surface, but only rarely and in the presence of a marked stenosis, results in a true compression of the spinal cord or nerve roots.

Types of Hernia

A herniated disk can occur in any direction, although those that have clinical relevance occupy the spinal canal or radicular canal and encroach the dural sac and/or nerve roots.

According to the location they are divided as follows (moving from central to lateral):

– "Central" hernia extends into the spinal canal along the midline, compresses and deforms the epidural surface of the dural sac and

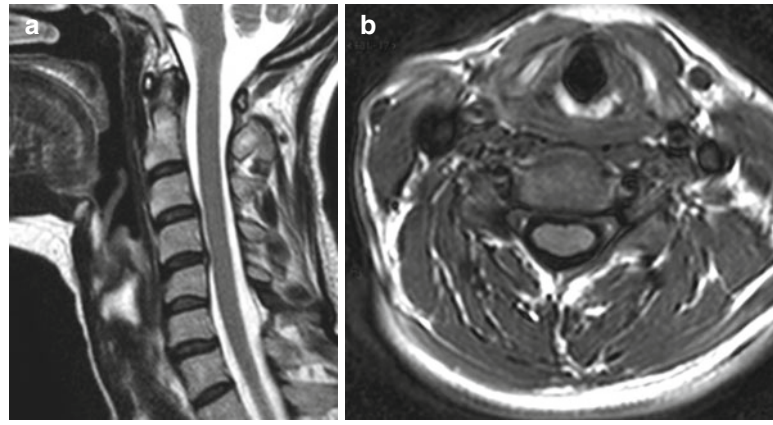


Fig. 3.5 Bulging disk. Sagittal FSE T2 (**a**) and axial FSE T1 (**b**) images. The C4-5 disk presents minimal diffuse bulging of its margins, with minimal effect on the ventral surface of the thecal sac

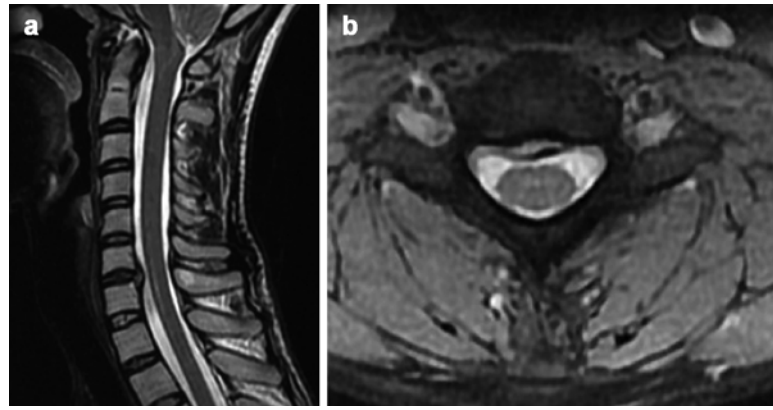


Fig. 3.6 Central disk herniation. Sagittal FSE T2 (**a**) and axial GRE T2 with fat suppression (**b**) images. There is focal C6-7 protrusion/herniation of disk material deforming the ventral surface of the thecal sac on the midline

sometimes, according to its size, is so voluminous as to determine a bilateral radiculopathy and/or myelopathy (Fig. 3.6);
- "Lateral/Paramedian" (Right/Left) hernia: not on the median line, but does not extend into the lateral recess. The herniated material displaces the epidural fat and may occupy the lateral recess, at the origin of the nerve root. It is responsible for a unilateral radiculopathy (Fig. 3.7);
- "Foraminal/extraforaminal" hernia: occupy the radicular (foraminal) canal, or extends beyond the corresponding foramen (foraminal/extraforaminal). Only the foraminal component has clinical relevance as encroaching the nerve root (Fig. 3.8).

By definition the herniated material, which can migrate upward or downward, is always in continuity with the intervertebral disk. The hernia can be more analytically descripted, when the MR imaging is performed, as trans-ligamentous or sub-ligamentous, depending on it has or has not crossed the posterior longitudinal ligament.

When a fragment of disk tissue is identified not in continuity with the disk in the central canal, we use the term of free fragment. This fragment can migrate cranially or caudally and can thus impress a nerve root above or below the level from which it originated.

Although they may have, like all other disk herniations, an acute post-traumatic onset, are generally a result of degenerative processes of intervertebral disks and then associate the reduction in height of the intervertebral space and osteophytes that protrude into the central canal or radicular canals. The evaluation of the relationship between disk tissue hernia and osteophytes is very important; in particular, we must distinguish hernias where the prevailing component

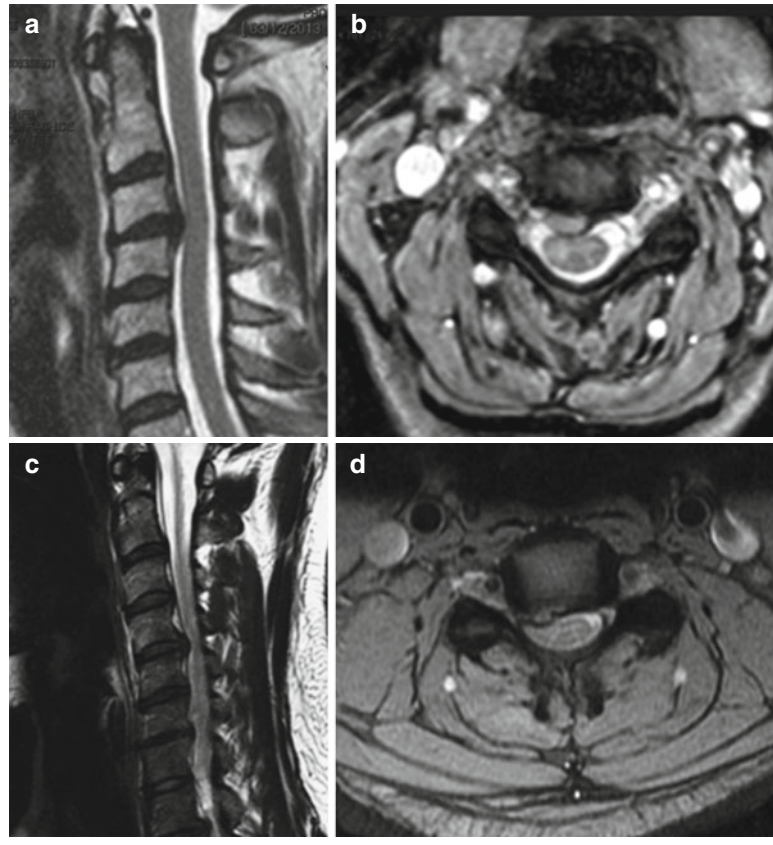


Fig. 3.7 Lateral disk herniations (posterior paramedian/posterolateral). Patient 1: Sagittal FSE T2 (**a**) and axial GRE T2 with fat suppression (**b**) images. The C3-4 paramedian disk herniation results in minimal impingement on the right hemicord. Patient 2: Sagittal FSE T2 (**c**) and axial GRE T2 with fat suppression (**d**) images. The C4-5 posterolateral disk herniation occupies the right lateral recess with compression of the C5 nerve root

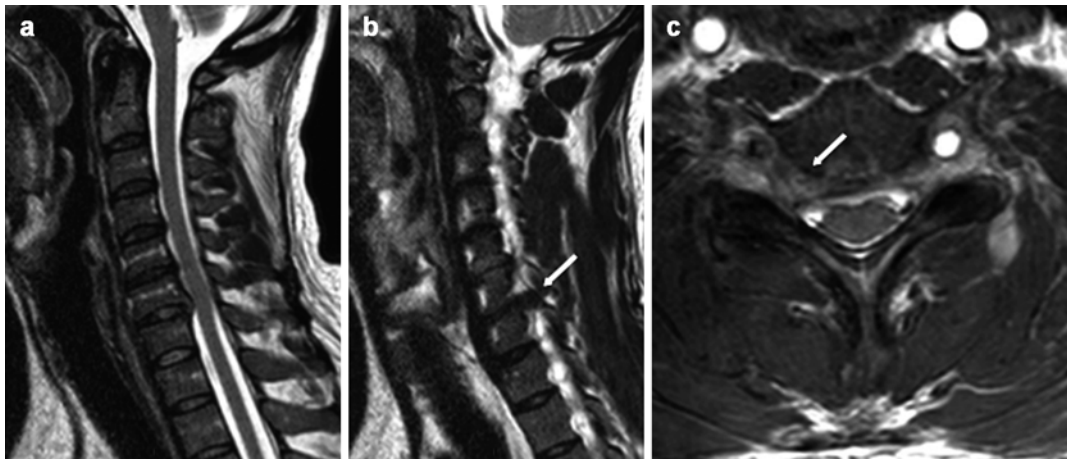


Fig. 3.8 Foraminal C6-7 disk herniation. Sagittal FSE T2 on the midline (**a**), *right* parasagittal FSE T2 (**b**) and axial FSE T2 (**c**). On the midline there is only minimal disk bulging while the large disk herniation (*arrow* in **b** and **c**) completely occupies the right neuroforamen

disk ("soft hernia"), those that are completely contained in a shell bone ("hard hernia"). In the latter, the results of surgery are worse.

Cervical disk herniations are less frequent than lumbar because the cervical vertebrae have to sustained less body weight and because the

uncinate processes play an important containment action. The cervical hernia is more common on the lateral, because in that location, the posterior longitudinal ligament is less tough. Cervical herniations most commonly occur at the C5-6 and C6-7 levels.

Cervical Hernia Imaging

The peculiar anatomy of cervical spine (intervertebral disks are thinner, radicular canals and foramina are less extensive and there is much less epidural fat) should always take into account while performing a CT. CT is typically used to detect the different hernia components ("soft" from "hard" hernias) and in the evaluation of bony structures. The multiplanar oblique reconstructions perpendicular to the major axis of the radicular canals provide, for example, an excellent assessment of the size of the foramina and their possible stenosis due to the presence of uncovertebral osteophytes.

The detection of a small disk herniation can however be difficult for the poor presence of epidural fat or, in patients with short and thick neck, for the superposition of the shoulders and the rib cage. The use of intravenous contrast medium can evidence the conspicuity of disk herniation thanks to the enhancement of epidural veins and that of the associated granulation tissue. Although CT maybe a useful aid in the diagnosis of cervical hernia, post-contrast examination are usually not required to make diagnosis because of the clearcut superiority of MRI. Before a scheduled surgical procedure, however, it may be very important to evaluate the status of the bony walls of the central spinal canal and radicular canal, as shown by CT. In fact, disk herniation is often a contributing cause of the symptoms and may be associated, for example, to the stenosis of a radicular canal secondary to uncovertebral osteophytes, which is better visualized on CT.

MRI is definitely the examination of choice in patients with signs of radiculopathy or myelopathy, caused by disk herniations. The MRI exam should be performed using sagittal and axial SE T1-w images, the corresponding FSE T2-w images, and 2D/3D GRE T2*-w at those levels where there is a suspicion of disk disease. T1-w images provide detailed anatomical information; the disk appears hypointense almost as much as the ligamentous structures and osteophytes. Because of the cerebrospinal fluid (CSF) also presents a low signal intensity and the epidural fat is scarcely evident, there is little contrast between extradural structures and CSF. It is therefore difficult, in axial T1-w images, to differentiate a small herniated disk from an osteophyte. Small herniated cervical disk are certainly easier to detect in 2D/3D T2*-w images, in which the bone is more hypointense, fluids are very hyperintense and therefore it is easier to differentiate the herniated disk from the bone and the adjacent osteophytes. Migrated fragments can sometimes mimics osteophytes, because of their low signal intensity and are better visualized on GRE T2*-w images than on FSE T2-w images. The thinning and low signal of PLL on GRE T2*-w is characteristic of acute disk herniation [23] (Fig. 3.9).

Stenosis

Central canal stenosis is a narrowing of the vertebral canal and/or lateral recesses and/or radicular canal, which can lead to compression of the nerve roots or spinal cord.

Patients with cervical stenosis have insidious symptoms onset, expression of mono- or bilateral radiculopathy or myelopathy (e.g., upper limb paraparesis or dysesthesia).

The neck pain is often associated with but not specific. Early diagnosis is essential, since there is no spontaneous regression of the process and the surgery prevents the progression of the symptoms and of the spinal cord damage.

Using etiological criteria it is possible to distinguish:

- Congenital stenosis (idiopathic, dysplasia, achondroplasia, mucopolysaccharidosis): characterized by short and stubby peduncles, shortness of the interpeduncular and sagittal diameter and hypertrophy and verticalization of the laminae; the central canal appears narrowed, as well as reduced, until the complete absence, appears the epidural fat;

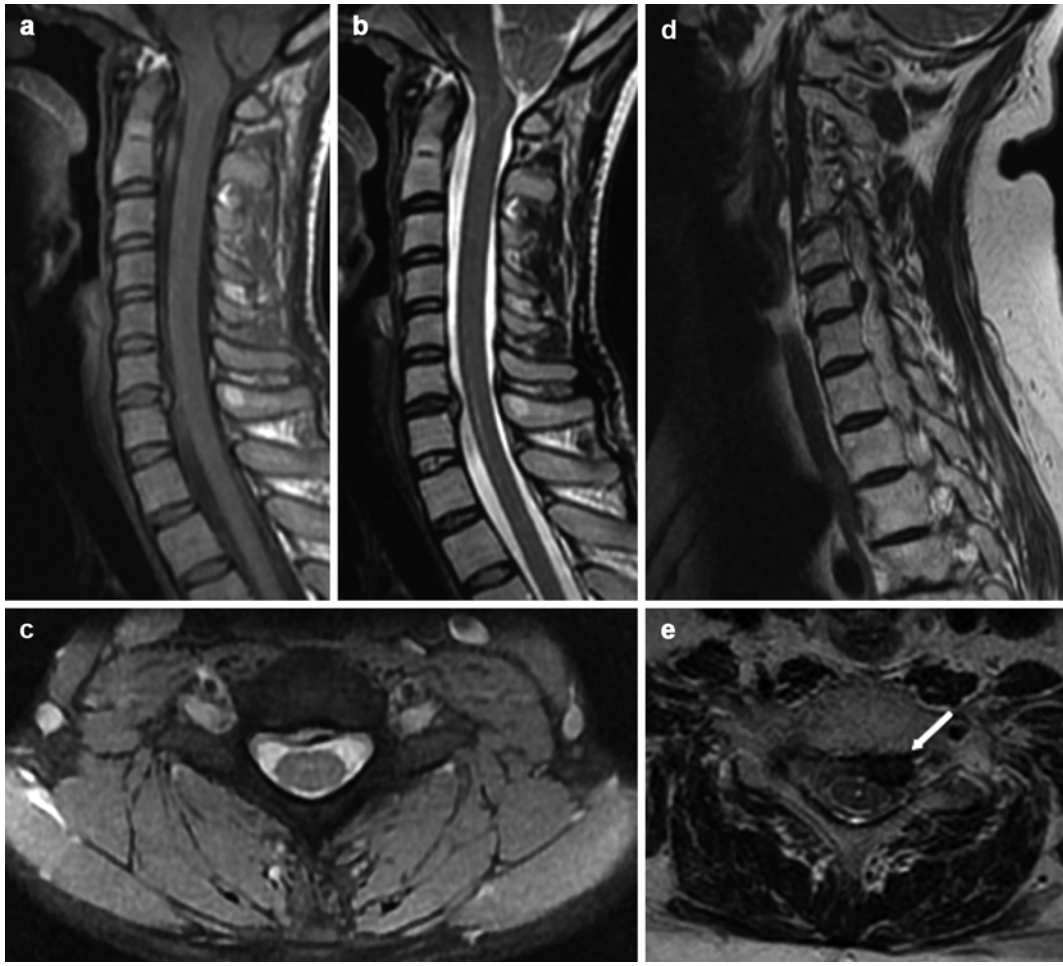


Fig. 3.9 Disk herniations, MR imaging. Patient 1: sagittal FSE T1 (**a**), sagittal FSE T2 (**b**), axial FSE T2 with fat suppression (**c**). Acute disk herniation with high signal intensity at C6-7 level. Patient 2: sagittal FSE T2 (**d**), axial FSE T2 (**e**). Lateral disk herniation with cranially migrated disk fragment (*arrow* in **e**) which shows low signal on T2 images

– Acquired stenosis: can be a result of surgery, traumatic lesions, neoplastic, but more frequently, of degenerative alterations of vertebral bodies (osteophytes), of articular pillars (hypertrophy degenerative osteophytes, subluxation), of intervertebral disks ("bulging", herniated disk), of flaval ligament (hyperplasia, calcification) and/or of posterior longitudinal ligament (ossification). The same reduction in height of the intervertebral space, due to disk degeneration, can determine the shortening and thickening of the intervertebral ligaments resulting in encroach on the dural sac;
– Mixed stenosis: are the most frequent in clinical practice and are derived from the overlap of an acquired form on a condition of congenital stenosis; in this case, a disk protrusion and/or osteophytosis, even modest, may lead to severe nerve root or spinal cord compression.

Using topographic criteria, stenosis may be divided into:

– Central: characterized by a reduction in the size of the central canal that in degenerative forms is supported by the "bulging" disk, hyperplasia and/or calcification of the flaval ligaments, osteophytes and degenerative articular pillars hypertrophy.

– Lateral: include lateral recesses and foraminal stenosis. Lateral recesses stenosis is due to uncinate process hypertrophy, degenerative enlargement of a superior articular facet and/or osteophytosis. Foraminal stenosis is mostly supported by congenital factors (shortness of peduncles), by degenerative pathology of the disk ("bulging") and posterolateral vertebral bodies osteophytosis.

Physiopathology

The spine is to be considered as a dynamic complex constituted by a single functional unit, whose components are interrelated and interdependent. Therefore, it is clear that the physiological and progressive fibrosis of intervertebral disk determines an increased mechanical stress on facet joint and, consequently, a strain of intervertebral disk joint.

The various static and dynamic stresses, especially rotary stress, produce disk and facet joint degeneration, leading to "bulging" and disk height reduction, sclerosis and osteophytes formation with subsequent central canal stenosis, subluxation upward and forward of the superior articular pillars and, eventually, to a lateral recesses and/or foraminal stenosis. The alterations of the articular pillars include sclerosis and hypertrophy, loss of articular cartilage, subchondral cysts, osteophytosis and subluxation resulting in degenerative spondylolisthesis. Degenerative spondylolisthesis leads to a compression of the spinal cord between posterior arch of the vertebra above that slides forward and the upper endplate of the underlying vertebra. Even degenerative changes of the other spinal structures (disk and ligaments) can lead to spinal stenosis. A "bulging" of the annulus fibrosus reduces the sagittal diameter of the central canal, but it can also lead to stenosis of the lateral recesses or foramina; thickening of the flaval ligaments, due to fibrosis, fatty infiltration or calcific deposits, reduces the transverse diameter of the posterior portion of the central canal and also reduces the sagittal diameter displacing forwards the dural sac.

Imaging

Radiography, whether of good technical quality, demonstrates the degenerative changes but it is not able to make an accurate diagnosis. In fact a central bony canal of normal size may be stenotic because of the thickening of the ligamentous components.

Furthermore, measurement of the diameters of the canal is not very reliable, given the considerable individual variability. It is true, however, that at the cervical level there are two semeiological radiographic references that allow assessing the width of the sagittal diameter of the central canal: the first coincides with the ideal line drawn along the posterior wall of the vertebral bodies; the second is the spinolaminar line. This imaginary line joins the points of convergence of the laminae of each vertebral body on the midline. Normally, the spinolaminar line is convex forward and is at least 3–4 mm away from the posterior edge of the articular pillars. If the spinolaminar line is overlapped to the zygapophyseal joints, it is possible to infer that the sagittal diameter of the cervical central canal is reduced.

Another method to assess spinal stenosis is the central canal-to-vertebral body ratio, also called Torg-Pavlov ratio. This is a ratio of the diameter of cervical canal to the width of cervical body. Less than 0.8 on radiography is consistent with cervical stenosis [24]. However, we can consider stenotic a cervical spinal canal with a width less than 13 mm [25]. CT is effective to assess the causes of degenerative spinal stenosis, since it well demonstrates vertebral body and facet joints osteoproliferative processes, degenerative changes of intervertebral disks and calcification of flaval ligaments.

In case of degenerative spondylolisthesis, CT easily identifies subluxation of the zygapophyseal joints, the sign of "double arch" and, in the sagittal multiplanar reconstructions, dural sac impingement. CT also allows easier measurement of the diameter of the central canal, but it is not able to demonstrate the effects of the degenerative injury on the spinal cord. Moreover, in the cervical spine, the low amount of epidural fat and the relatively small size of the spinal canal is insufficient to assess a possible ligamentous hypertrophy.

There is no doubt that MR imaging presents undeniable advantages over CT in the analysis of the relationship between the central canal and the spinal cord. It optimally demonstrates

compressive phenomena on the spinal cord, their extension (on sagittal images) and, above all, the direct effect on the nervous structures (edema, gliosis and myelomalacia). Because of these advantages, especially in the cervical spine, MR imaging represents the preferred imaging modality (Fig. 3.10). The root compression in the foramina is shown, in the sagittal T1-w images, by the dislocation or disappearance of periradicular fat; compression of the dural sac and disk degeneration, however, are more evident in the T2-w images. Using volume 3D GRE techniques, thin sections (1 mm or less) imaging, it is possible to obtain the best evaluation of cervical neural foramen [26]. Although CT can be used to screen for neural foramina narrowing, the MR imaging using axial GRE T2*-w or post-contrast MR imaging usually offers better results. The T2*-w images allow identification of osteophytes and differentiate them from adjacent disk herniation. Furthermore, it clearly demonstrates the ossification of the posterior longitudinal ligament and flaval ligaments hypertrophy due to the intrinsic high contrast that exists between these structures and the adjacent subarachnoid space. If the spinal cord is compressed over a long period, irreversible changes occur with focal areas seen as high intensity signal in the cord on T2-w images [27], namely myelomalacia and gliosis, resulting in a more obvious reduction of the sagittal diameter of the spinal cord (atrophy) with increased evidence of the ventral fissure.

Specific Degenerative Disease

Diffuse Idiopathic Skeletal Hyperostosis Syndrome

The Diffuse Idiopathic Skeletal Hyperostosis or DISH, (also known as Forestier disease, senile ankylosing hyperostosis and asymmetrical skeletal hyperostosis) is a not a so uncommon degenerative disorder in the elderly population, with a reported prevalence in some study of 10 % in patients over 70 years [28, 29]. It is characterized by excessive ossification along the anterior longitudinal ligament of the spine that results in bridging osteophytes. In the '70s, Resnick established specific radiological criteria for the

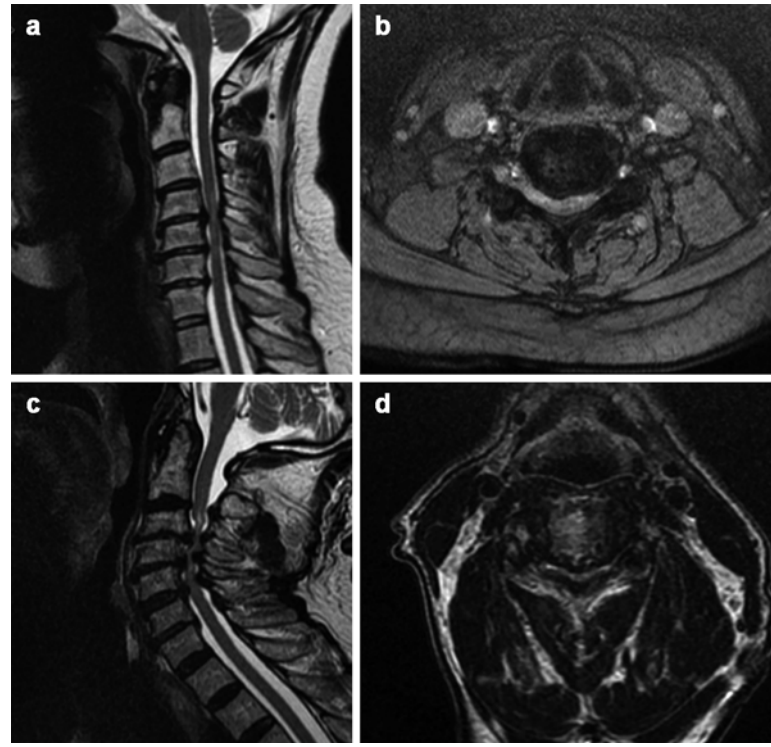


Fig. 3.10 Stenosis of the spinal canal, MR imaging. Patient 1: sagittal FSE T2 (**a**), axial FSE T2 with fat suppression (**b**). Posterior disk herniation associated to mild spondylosis at levels C4-5, C5-6 and C6-7 determine spinal canal stenosis with encroaching the spinal cord that presents intrinsic signal modifications. On axial images the degree of stenosis is better evaluated. Patient 2: sagittal FSE T2 (**c**), axial FSE T2 (**d**). Advanced stages of spondylosis and disk degeneration/herniation. The central canal is almost completely obstructed. Spinal cord is severely compressed with reduction of its sagittal diameter and intrinsic signal modifications

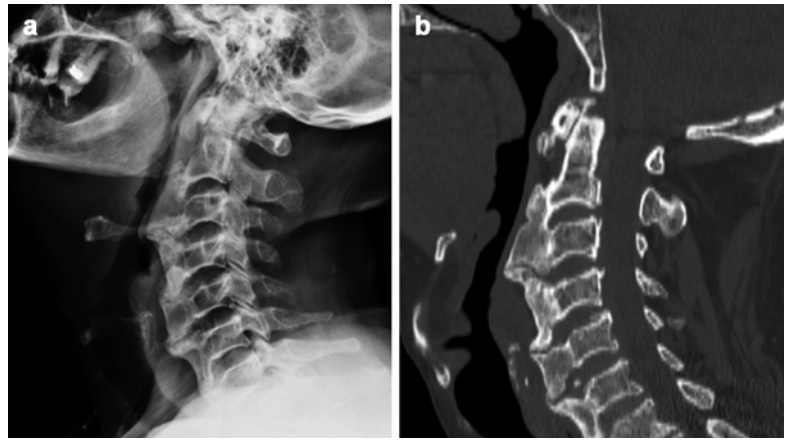


Fig. 3.11 Diffuse Idiopathic Skeletal Hyperostosis Syndrome (DISH), radiography and CT. Lateral radiogram in standing position (**a**) and CT sagittal images (**b**). Diffuse ossification along the ALL with bridging osteophytes from C2 to C7 is well evident, with disk height preserved. The findings are better demonstrate on CT examination, allowing to a more accurate extension of the disease

diagnosis of DISH [30]: (1) presence of flowing calcification and ossification along the anterolateral aspect of at least four contiguous vertebral bodies; (2) relative preservation of intervertebral disk height in the involved vertebral segments without degenerative disk disease; (3) absence of apophyseal joints ankylosis and sacroiliac joint erosion, sclerosis or bony fusion [31]. Extraspinal ossification in DISH may occur at ligamentous attachments and para-articular soft tissues.

DISH is largely asymptomatic and it is usually incidentally detected. The exact etiology of the syndrome in unknown: the DISH could be considered an expression of the ossificans diathesis, typical of the advanced age, that leads to the production of bone tissue at the insertions of tendons and ligaments on the skeletal structures (entheses), both to the ligaments calcification and ossification, and finally to the formation of para-articular osteophytes [1]. The spine is the elective seat of the disease, pointing out that other skeletal areas may be involved.

Imaging

The radiological findings results directly from the histopathologic alterations of the spine. A characteristic aspect of the DISH is that the ossification of the ALL is more pronounced at the level of the disk spaces, creating a "bulky" aspect of the ventral spine profile.

In the first stages of the disease, radiography may show a fine ossification (with a thickness of 2 mm or less); with the progression of the disease, it is possible to observe the development of large syndesmophytes (a syndesmophyte is defined as a bony growth originating within a ligament). The typical site of syndesmophytes formation is the anterior aspects of vertebral body (because of the involvement of ALL).

Radiography is inadequate for evaluating the extent of the compression caused by the large syndesmophytes on trachea, bronchi, or esophagus. In this case, CT of the spine is helpful and especially is aided by coronal and sagittal reconstructions (Fig. 3.11).

CT has a role in the evaluation of complications, such as fracture, spinal canal stenosis secondary to associated ossification of the posterior longitudinal ligament, and pressure effects on the hypopharinx. The only indication in performing an MR imaging is to show/rule out cord compression when DISH is associated with OPLL, as it is observed in a minority of patients [32].

Ossification of the Posterior Longitudinal Ligament

Ossification of the posterior longitudinal ligament (OPLL) is a spine disorder that usually affects individuals between the fifth and seventh decade of life, more frequently males; a higher incidence in the Japanese population has been reported [33]. The disease commonly involves

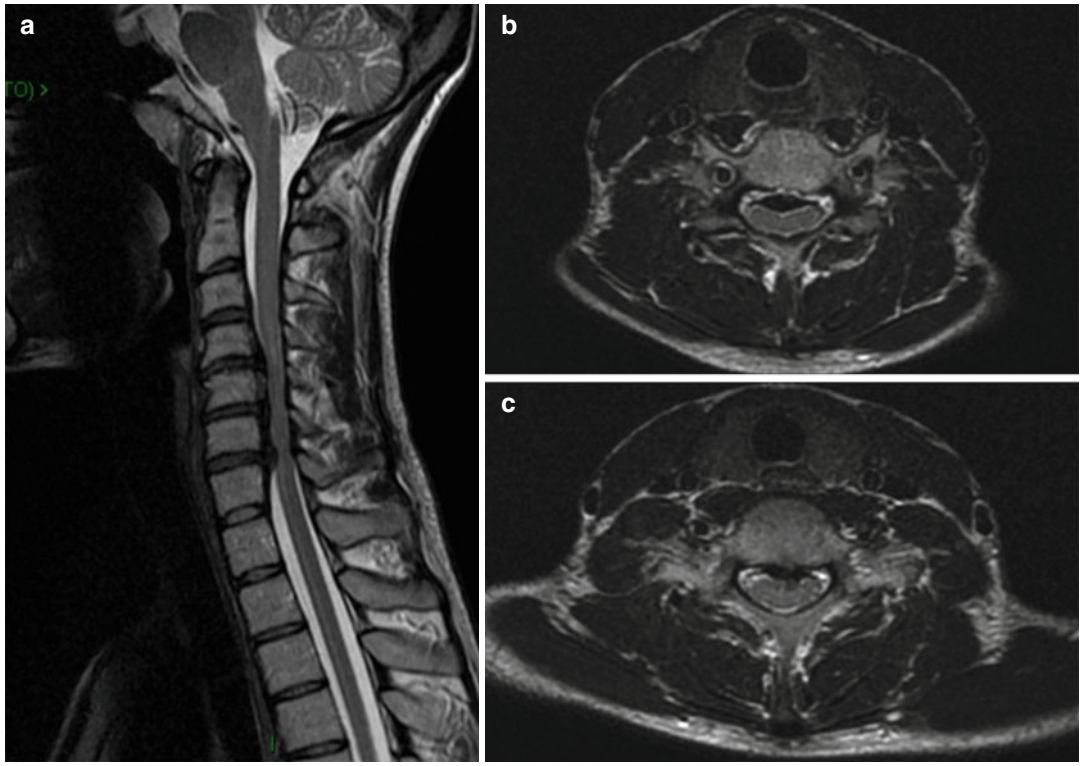


Fig. 3.12 Ossification of Posterior Longitudinal Ligament (OPLL), MR imaging. Sagittal FSE T2 (**a**) and axial FSE T2 (**b**, **c**). Ossification of the posterior longitudinal ligament is observed at C3-C6 levels, in the intermediate tract of cervical spine. The spinal cord shows mild hypertensity at that level (edema/gliosis) due to compression of the thickened ligament

the cervical regions of the spine and is clinically characterized by myeloradiculopathy, even if the OPLL may be often as the symptomatic.

It has been proposed that pathogenesis of OPLL may be related to disk herniation and/or to a diffuse hyperostotic process [34].

Imaging

On radiography, a continuous calcification along the posterior longitudinal ligament is observed, especially on the intermediate tract of the cervical spine (C3-5); the associated disk degeneration and facet ankylosis are often minimal. CT has a higher sensitivity in the assessment of calcification extension; in some cases the axial images can show specific patterns of calcification of the ligament ("upside-down T" and "bowtie"). MR imaging shows the spinal cord damage or lesion that can be associated, particularly in those cases in which the ossification thickness is greater (Fig. 3.12).

In some patients with OPLL it is possibile to detect an extensive calcification of the ALL or other signs of DISH; when it happens, differential diagnosis with inflammatory arthropathy is made possible by observing no facet joint ankylosis and few associated disk degeneration [33].

Destructive SpondyloArthropathy of the Cervical Spine in Long-Term Hemodialyzed Patients

Destructive SpondyloArthropaty (DSA) is radiographically characterized by a notable reduction of the intervertebral disk space associated with erosions and cysts of the adjacent endplates and minimal osteophytosis. Typically, multiple vertebral bodies are involved: the lower part of the cervical spine (C5-7) is the most frequently

affected, though the CCJ may also be involved. Clinically, DSA can lead to medullary compression which requires surgical decompression and stabilization. However, neurological symptoms are rare. The prevalence of DSA is difficult to establish: it varies from 5 to 25.3 % in long-term hemodialyzed patients [35].

The exact pathogenesis of DSA is not well understood: it thought to be the direct consequence of the hemodialysis-related systemic amyloidosis. There are many risk factors associated to the onset of the DSA, such as the duration of renal failure, the age of onset, the duration of hemodialysis, dialysis membranes and the basic clinical condition of the patient but to date the natural history of this syndrome is unclear and no effective treatments are available.

Imaging

The radiographic signs of the syndrome include a severe reduction of the intervertebral disk space associated with erosions and/or cysts of the adjacent endplates and minimal osteophyte formation.

On radiography, in the early stages of the DSA it is possible to detect an enthesopathy, mimicking an early ankylosing spondylitis. As the pathology progresses, an endplate destruction associated with a soft tissue mass is established, very similar to spondylodiscitis signs. These alterations lead to vertebral body collapse, subluxation or listhesis.

The degenerative process, with pseudotumors and bone erosions, can sometimes involve the CCJ, although it is uncommon. A relevant clinical problem is to rule out infections in symptomatic hemodialyzed patients (who present an increased risk of infection) with destructive vertebral lesions. The radiologist should be able to distinguish DSA from spondylodiscitis; if low signal is observed in T2-w and STIR (Short Tau Inversion Recovery) images, DSA is more probable.

Ossification of Flaval Ligaments

It is a degenerative disorder characterized by the ossification of flaval ligaments. The pathogenesis is unclear and probably associated with metabolic disorders (with hydroxyapatite or calcium pyrophosphate deposition in ligament).

Ossification of flaval ligaments appears as a linear thickening of flaval ligament similar to adjacent vertebral marrow ossification. The ossification is typically symmetric and bilateral; it is often diagnosed incidentally during imaging study ordered for other reasons.

Imaging

On radiography, when appreciable, ossification of flaval ligaments appears as a thin calcification anteriorly to lamina.

CT is the best imaging modality for primary diagnosis to show ossification, but it is inadequate for determining the possible spinal cord involvement. On CT, ossification of flaval ligaments appears as a hyperdense thickening within the ligament best shown on axial images with the characteristic V-shape image.

MR imaging may easily detect not only ossification of the ligaments but also the effect indirectly determined on the spinal cord. On T1-w images the ossification of flaval ligaments appears as a hypo- (thinner lesions) to hyperintense (thicker lesions) linear mass within the ligaments. On T2-w images, it appears as a linear hypointensity associated or not with myelomalacia, due to cord compression. On GRE T2*-w images, the flaval ligaments appears as a thickened hypointense band, and it is difficult to estimate the actual degree of canal narrowing due to susceptibility artefact [6].

Calcium PyroPhosphate Deposition Disease

Calcium pyrophosphate deposition disease (CPPD) is a metabolic arthropathy, also known as pseudogout, caused by a proliferation and deposition of calcium pyrophosphate dihydrate in and around joint, especially in articular cartilage and fibrocartilage, with possible involvement of CCJ, namely the peri-odontoid structures. It is characterized by linear disk or ligament calcific deposits. The exact etiology of the syndrome in unclear; it may be associated with hyperparathyroidism, hemochromatosis, gout or hypophosphatasia.

Imaging

Radiography may demonstrate linear calcifications within the disk and it is often associated with calcification of the pubic symphysis or triangular fibrocartilage of the wrist. CT is the best imaging tool for evaluating the calcifications, but the MR imaging, especially on the T2-w images, can evaluate not only the calcifications but also the amount of granulation tissue and fibrosis [6].

References

1. Pistolesi GF. Bergamo Andreis IA: L'imaging diagnostico del rachide. Verona: Ed Libreria Cortina Verona; 1987.
2. Ross J, Neuroimaging Clinics of North America. Philadelphia: WB Sanders; 1995.
3. Maigne JY, Deligne L. Computed tomography follow-up study of 21 cases of nonoperatively treated cervical intervertebral soft disk herniation. Spine. 1994;19:189–91.
4. Milligram MA, Rand N. Cervical spine anatomy. Spine State Art Rev. 2000;14(3):521–32.
5. Johnson R. Anatomy of the cervical spine and its related structures. In: Torg JS, editor. Athletic injuries to the head, neck, and face. 2nd ed. St Louis: Mosby-Year Book; 1991. p. 371–83.
6. Ross JS, Moore KR, Borg B, et al. Diagnostic imaging: spine, 2nd edition. Salt Lake City (Utah): Amirsys; 2010.
7. Colosimo C, Pileggi M, Pedicelli A, Perotti G, Costantini AM. Diagnostic imaging of degenerative spine diseases. Technical approach. In: Minimally invasive surgery of lumbar spine. London/Heidelberg/New York/Dordrecht: Springer; 2014.
8. Fullenlove T, Williams AJ. Comparative roentgen findings in symptomatics and asymptomatics backs. Radiology. 1957;68:572–4.
9. Gehweiler JA, Daffner RH. Low back pain: the controversy of radiologic evaluation. AJR Am J Roentgenol. 1983;140:109–12.
10. Wood KB, Popp CA, Transfeldt EE, Geissele AE. Radiographic evaluation of instability in spondylolisthesis. Spine. 1994;19:1697–703.
11. Rothman SLG, Glenn WV. Multiplanar CT of the spine. Chapters 1–4, p. 1–112, chapters 16– 17, p. 477–504. Baltimore: University Park Press; 1985.
12. Hirsch C, Shajowicz F. Studies on structural changes in the lumbar anulus fibrosus. Acta Orthop Scand. 1952;22:184–231.
13. Yu S, Haughton VM, Sether LA, et al. Criteria for classifying normal and degenerated lumbar intervertebral discs. Radiology. 1989;170:523–6.
14. Virgin WJ. Experimental investigations into the physical properties of the intervertebral disc. J Bone Joint Surg. 1951;33:607–11.
15. Nachemson A. Some mechanicalproperties of the lumbar intevertebral discs. Bull Hosp Joint Dis. 1962;23:130–43.
16. Modic MT, Steinberg PM, et al. Degenerative disc disease assessment of changes in vertebral marrow with imaging. Radiology. 1988;166:193–9.
17. Giunti A, Laus M, Le Radicolopatie Spinali. Aulo Gaggi Editore. Bologna, 1992.
18. Panjabi MM, Krag MH, White AA, Southwick WO. Effects of preload on load displacement curves of the lumbar spine. Orthop Clin North Am. 1977;8:181–92.
19. Kirkaldy-Willis WH. The pathology and pathogenesis of low back pain. In: Kirkaldy-Willis WH, editor. Managing low back pain. New York: Churchill Livingstone; 1983. p. 23–43.
20. Weyreuther M, Heyde CE, Westphal M, Zierski J, Weber U. MRI atlas, orthopedics and neurosurgery, the spine. Heidelberg: Springer-Verlag Berlin; 2007.
21. Kramer J. Intervertebral disc disease. 2nd ed. New York: Thieme; 1992.
22. Wiltse LL, Berger PE, McCulloch JA. A system for reporting the size and location of lesions in the spine. Spine. 1997;22(13):1534–7.
23. Scott Atlas W. Magnetic resonance imaging of the brain and spine, vol. 2. Philadelphia: Lippincott Williams & Wilkins 2009. p. 1491.
24. Kang Y, Lee JW, Koh YH, et al. New MRI grading system for the cervical canal stenosis. AJR Am J Roentgenol. 2011;197(1):W134–40.
25. Yue WM et al. The Torg-Pavlov ratio in cervical spondylotic myelopathy: a comparative study between patients with cervical spondylotic myelopathy and a nonspondylotic, nonmyelopathic population. Spine. 2001;26(16):1760–4.
26. Tsuruda JS, Norman D, Dillon W, et al. Three-dimensional gradient-recalled MR imaging as a screening tool for the diagnosis of cervical radiculopathy. AJNR Am J Neuroradiol. 1989;10:1263–71.
27. Takahashi M, Yasuyuki Y, Yuji S, et al. Chronic cervical cord compression: clinical significance of increased signal intensity on MR images. Radiology. 1989;173:219–24.
28. Julkunen H, Heinonen OP, Knekt P, Maatela J. The epidemiology of hyperostosis of the spine together with its symptoms and related mortality in a general population. Scand J Rheumatol. 1975;4:23–7.
29. Cassim B, Mody GM, Rubin DL. The prevalence of diffuse idiopathic skeletal hyperostosis in African blacks. Br J Rheumatol. 1990;29:131–2.
30. Resnick D, Shaul RS, Robins JM. Diffuse idiopathic skeletal hyperostosis (DISH): Forestier's disease with extraspinal manifestation. Radiology. 1975;115:513–24.
31. Resnick D, Niwayama G. Radiographic and pathological features of spinal involvement in diffuse idiopathic skeletal hyperostosis (DISH). Radiology. 1976; 119:559–68.
32. Cammisa M, De Serio A, Guglielmi G. Diffuse idiopathic skeletal hyperostosis. Eur J Radiol. 1998;27 Suppl 1:S7–11.

33. Resnick D, Guerra Jr J, Robinson CA, Vint VC. Association of diffuse idiopathic skeletal hyperostosis (DISH) and calcification and ossification of the posterior longitudinal ligament. AJR Am J Roentgenol. 1978;131(6):1049–53.
34. Hanakita J, Suwa H, Namure S, et al. The significance of the cervical soft disk herniation in the ossification of the posterior longitudinal ligament. Spine. 1994; 19:412–8.
35. Leone A, Sundaram M, Cerase A, Magnavita N, Tazza L, Marano P. Destructive spondyloarthropathy of the cervical spine in long-term hemodialyzed patients: a five-year clinical radiological prospective study. Skeletal Radiol. 2001;30:431–41. Int Skeletal Soc (ISS).

Pathophysiology of Cervical Pain: Evolution and Treatment

4

Ronald H.M.A. Bartels

Definition of Cervical Pain

Although seemingly obvious, a definition of the region of the neck that is subject of our interest is warranted. The neck extends form the articulations of the occipital condyles with the first cervical vertebra till the articulations of the seventh cervical vertebra and the first thoracic.

Within the neck many structures are present. They can all contribute to cervical pain. Therefore, the differential diagnosis of cervical pain can be exhaustive. A thorough clinical examination before any additional investigations are ordered cannot be over-estimated. In this chapter cervical pain or neck pain will be confined to pain originating from the cervical spine and its contents.

Cervical pain or pain in the neck should also be defined. Pain in the neck (neckpain) can be located in the neck itself, or in combination with irradiating pain into shoulder, arm, digits, breast, shoulderblade (cervical radicular pain) and/or head (cervicogenic headache).

The origins of pain within the cervical spine are manifold: anterior and posterior ligaments, supraspinous ligaments, interspinous fascia and muscle, facet joints, outer fibres of annulus fibrosis, vertebral endplates, dura, and dorsal root ganglions [1, 2]. All these structures can be involved in several pathophysiologic processes like inflammation (also systemic like rheumatoid arthritis), metabolic diseases, trauma, oncologic processes, deformities either congenital or acquired, and degenerative entities. Neck pain can be a symptom of a serious disease warranting medical treatment. Cervical radicular pain can also occur without neck pain. Although they can concur some advocate to distinguish them clearly, since they have different causes, mechanisms and treatments [2]. In this chapter will be focused on the degenerative process as causative mechanism. In clinical practice, neck pain is frequently not distinguished as a separate entity, if it is combined with cervical radicular pain.

Epidemiology

Little is known about incidence and prevalence of cervical radiculopathy. In population-based study the annual average -adjusted incidence rate of cervical radiculopathy was 83.2 per 100,000 population. Men were more affected than women. The highest peak incidence was found in the age group 50–54 years. Involvement of the C7 root was most frequent, followed by C6 [3].

Neck pain is common among adults, but also children [4]. Between 30 and 50 % of an adult

R.H.M.A. Bartels, MD, PhD
Department of Neurosurgery,
Radboud University Medical Center,
Nijmegen, The Netherlands
e-mail: Ronald.Bartels@radboudumc.nl

P.P.M. Menchetti (ed.), *Cervical Spine: Minimally Invasive and Open Surgery*,
DOI 10.1007/978-3-319-21608-9_4

population said that they had suffered from a period of neck pain in the previous year. In most instances the pain did not interfere with work or daily activities [4, 5]. The age – and gender annual cumulative incidence of a new episode of neck pain was 14.6 % in a population-based study. Less than 1 % suffered from disabling neck pain, most were mild [6]. Between 25 % and 75 % of the patients report recurrent neck-pain within 1–5 year after the initial event from which they had recovered [7].

Radiologically, the prevalence of craniocervical osteoarthritis is estimated at 4.8 % with a rise to 5.4 % in the sixth decade and 18.2 % in ninth decade [8, 9]. Head loading activities (e.g. porters at stations) are a risk factor. In a cadaver study of subjects in their seventh till ninth decade at death 42 % showed osteoarthritis-related osteophytes at the median atlantoaxial joint and in 8 % of the occipito-atlantal joint [10]. In 4 % of a population of patients with degenerative spine disease, atlanto-axial osteoarthritis was radiologically present [11].

Pathophysiology

Degeneration of the spine has been subject of investigation for a long time. Excellent reviews have been published [12–14]. The origin of degeneration of the spine starts within the intervertebral disc, and most of the studies were focused on the disc. Mainly attention has been given to degeneration of the lumbar spine. However, the results concerning cellular and matrix changes of the intervertebral disc can also be extrapolated to the cervical spine, since the cervical discs do not differ in composition. It should be emphasized that biomechanical load pattern of the lumbar spine absolutely does not resemble the one of the cervical spine. In the upper cervical spine, osteoarthritis of especially the C1C2 joint can also cause pain. It is evident that the intervertebral disc cannot be responsible for this, and it will be discussed separately. Early in life the vascular supply of the vertebral endplates decreases, and therefore also the nutritional supply of the cells within the disc. The cell density decreases and matrix changes occur. Progressive loss of water content will occur, and an increase in fibrotic tissue. Radial tears appear. In pathologic degeneration disc height will collapse. Osteophytes may occur even in asymptomatic persons. The formation of osteophytes is believed to be an adaptive process to stabilize an unstable segment [12, 13, 15]. Genetic inheritance and loading history can contribute to an advanced aging process and finally degeneration [12]. The influence of these processes on the facet joints at the involved level should be emphasized. These will also show signs of degeneration.

The distinction between normal aging and degeneration is not always clear. Adams defined degeneration of the intervertebral disc as cell-mediated processes that weaken the disc and that are accompanied by structural failure [12].

These processes can lead to extrusion of nucleus pulposis with compression of the spinal cord and/or exiting nerve root at that level. Weakening of the disc can contribute to spondylolisthesis of which a prevalence is reported from 5.2 to 11 % [16, 17]. Also osteophytes can ultimately compress the spinal cord, nerve root and/or dorsal root ganglion. In a population-based study in 21.9 % a disc protrusion is responsible for cervical radicolupathy, in 68.4 % a combination of disc herniation, osteophytes, and spondylolisthesis [3].

Cervical Radicular Pain

The most frequent cause of cervical radicular pain is the disruption of the annulus fibrosis leading to a prolaps of the intervertebral disc or even an overt sequestrated herniated disc. Inflammatory exsudates aggravate the sensory of pain within the dorsal root ganglion. Diseases that only compromise the nerve root cause sensory and motor function loss but no pain, whereas involvement of the dorsal root ganglion produces pain even without these exsudates. This is an argument that the dorsal root ganglion should be involved to produce radicular pain [2]. In case of spondylolisthesis, retrolisthesis contributes to compression of the dorsal root ganglion since it decreases the size of the neuroforamen, whereas anterior listhesis

increases it [18]. Summarizing, pathologic degeneration of a cervical intervertebral disc can lead to herniated intervertebral disc, osteophytes, spondylolisthesis or combinations of these. All of these might become symptomatic.

Impingement of the cervical root can result in neurologic deficit. The patterns of irradiating pain and concomittant neurologic signs and symptoms (radiculopathy) are specific and should be used to define the involved level. These can be found in any neurologic or neurosurgical textbook.

Neck Pain

The pathophysiology of neck pain due to degenerative disease is not well understood. All above mentioned structures within the cervical spine can be involved. None of them causes a specific pain pattern. In some cases even referred pain can occur [2, 14]. For idiopathic neckpain a poor psychological health is a risk factor for developing neck pain [4, 7].

Craniovertebral Osteoarthritis

The pathophysiology of osteoarthritis of the upper cervical segments (C0-C1 and C1-C2) is discussed separately since an intervertebral disc is not involved. Clinically osteoarthritis of C0-C1 is very rare [19]. Radiographically, osteoarthritic changes in the C0-C1-C2 zone were seen in 6.8 % of a group individuals with a mean age of 47.9±8.0 years. Findings at CT were sclerosis of joint margins (2.9 %), ligament calcification (2.9 %), and osteophytes (1.9 %) [8]. The presenting symptom is unremitting unilateral suboccipital pain [19].

Osteoarthritis of C1-C2 is clinically more often encountered although still rare [11]. Due to degeneration of the C1-C2 joint rotatory movement will be restricted, and in a minority disabling pain can occur. This pain can irradiate to the head in the occipital, parietal or even frontal region. Usually unilateral involvement of the joint is responsible for the symptoms [11, 20]. Especially rotating the head is extremely painful [20, 21].

Treatment

Natural Course

Before discussing treatment options it is important to know the natural evolvement of cervical degenerative disease. Degeneration of the cervical disk and eventual degeneration of the facet joints will often not become symptomatic. Narrowing of the canal especially at the disk level is seen with increasing age [22, 23]. One of the explanations of this phenomenon in asymptomatic individuals was that degeneration mainly occurred at the disc level. The relation between age and degeneration of the intervertebral disc was also shown by Matsumoto et al. [24]. In 94 asymptomatic individuals, they found an increasing prevalence with age of various aspects of degeneration of the intervertebral disk, although more than 90 % of the total population had one or more signs of degeneration of the intervertebral disc including anterior compression of the thecal sac in 80.9 %. These findings were confirmed by another study [25]. In this study, the prevalence of cervical disc degeneration was higher in patients with a symptomatic and proven lumbar disc herniation compared to asymptomatic controls. The individuals suffering from lumbar disc herniation did not complain or did not have any signs related to compromise of neurogenic structures within the cervical spine. Overall signs of cervical disc degeneration on the MRI were present in over 80 %. In a cohort of 223 subjects progression of the degenerative findings was found on MRI in 81.1 % during 10 year follow-up of healthy volunteers of whom 34.1 % developed clinical signs in this period [26]. In summary, as we grow older the cervical spine will degenerate chiefly at the level(s) of the intervertebral disc. Very often this process is asymptomatic.

In a minority compression of a nerve root/dorsal root ganglion and/or spinal cord causes pain and/or neurologic deficit. The compression can occur through a herniated cervical disc, spondylarthrotic vertebral spur, degeneration from facet joint, bulging flaval ligament or a combination of these.

The natural course for idiopathic neckpain seems to be mild. In most cases it does not

interfere with daily activities or result in seeking medical attention. Frequently the neck pain is persistent or recurrent [5].

Craniocervical Osteoarthritis

Although the number of reports on surgical treatment of atlanto-axial osteoarthritis steadily rised during the last decennia [20], a description about the natural course was not found. However, considering biomechanical effects of the arthritic changes and the age of the affected people, it can be assumed that symptoms are considered as mild. Somewhat painful restrictions in movement of the neck will in most instances be related to the advanced age.

Conservative Treatment

Cervical Radicular Pain

Cervical radicular pain with or without neurologic deficit is not always an indication for surgical indication. Symptomatic compression of the spinal cord is a more evident indication for surgery, since the recovery of signs and symptoms is completely different than of those due to cervical radiculopathy. In subjects presenting with painful radiculopathy, it has been shown that a cervical herniated disc can regress and that the symptoms resolve or improved [27–29]. It should be stated that the investigated persons did receive non-operative supporting program.

The non-operative treatment of cervical radicular pain with or without neurologic deficit is divers: pain-reducing agents like NSAID's, collar (soft or hard), manual therapy, physiotherapy, steroid injections. It was remarkable that for intervention studies uniform definitions and criteria did not exist [30]. In a recent systematic review it was concluded that regardless of the kind of conservative treatment patients improved [31]. A semi – hard collar was effective in reducing neck – and armpain in the first six weeks after acute onset after cervical radiculopathy. Physiotherapy was also effective in this time period, but because of the extra additional costs not recommended [32].

A reduction of pain can be achieved by percutaneously injection of steroids epidurally. This can be done transforaminally of interlaminarly. The use of steroids is based on the presence of inflammatory chemical substances in case of a herniated intervertebral disc. The effectiveness for interlaminar injections was proven. However, for transforaminal injections the evidence was poor. This in combination with the high risk of complications incuding death justifies a limited use of transforaminal injections [33].

Neck Pain

The causative mechanism of idiopathic neck pain is very . Often it is not possible to distinguish a pain generating structure(s). Therefore, many conservative treatment options exist: education, excercice interventions, medications, manual therapies, physical modalities, acupuncture, laser therapy and magnetic therapy, combined approaches, and workplace interventions. [34]. Active supervised exercises and manual therapy are more effective than no treatment. None of these is more effective compared to each other in the short and/or longterm [34].

Craniocervical Arthritis

In case of painful restriction of neck movements that can be related to degenerative changes in the upper neck, the choice of an usual plethora of conservative management options is possible: nonsteroidal anti-inflammatory drugs, gabapentin, intraarticular injection, bracing, physical therapy, cervical traction, chiropractor manupilations and C2 blocks [19, 20, 35].

Surgery

Cervical Radicular Pain

Surgery is indicated when the patient suffered from intractable pain without sufficient response to pain reducing manoeuvres, persistent pain for 8–12 weeks after a period of conservative treatment, persistent neurological deficit and/or signs and/or symptoms of cervical myelopathy [27]. It was shown that surgery provided better pain relief in the first six months compared to

conservative management. After 1 year a difference between surgical or conservative treatment did not exist anymore [36].

Several surgical options exist. Through an anterior or posterior approach the offending pathology can be treated. Anteriorly a discectomy without or with intervertebral implant can be performed or a micro-foraminotomy. A minimal invasive using laser or coblation option is also a possibility.

Anterior cervical discectomy is a well known procedure. Frequently an intervertebral impant is used after the discectomy. The implant can be iliac crest, cage (also stand alone) or polymethylmethacrylate (PMMA) [37, 38]. For unknown reasons iliac crest with anterior plate (anterior cervical discectomy with fusion; ACDF) is a golden standard. The main reasons for using these kind of intervertebral implants are maintenance of intervertebral disc height, preventing local kyphosis and ultimately fusion (fusion is not the goal for PMMA). Clinically a difference does not exist between the used implants [37]. For unknown reasons ACDF using iliac crest with plate is golden standard. In case of one- or two-level disc disease anterior cervical discectomy alone is as good as ACDF considering pain relief [39, 40]. Complications related to harvesting iliac crest were less when using a cage. However, fusion rates are higher after iliac crest with plate [41]. The clinical relevance of radiological pseudoarthrosis should be questioned. A more recent implant is the cervical disc prosthesis or arthroplasty. The assumption was that maintaining mobility instead of fusion would prevent adjacent disc disease. It is remarkable that adjacent disc disease was never decribed before the introduction of arthroplasty. Since then the number of publications related to adjacent disc disease annually increased [42]. Recently, it was shown that the occurrence of adjacent disc disease was similar after arthroplasty or ACDF [43, 44]. In a randomized controlled trial (RCT) mobility at the adjacent segment was the same after arthroplasty as in ADCF [45]. Finally, adjacent disc disease is a radiological diagnosis with questionable clinical relevance.

After 2 years of follow-up, the clinical results were similar for arthroplasty and ACDF [46]. However, after 4–6 years follow-up of few patients who underwent arthroplasty scored better than ADCF on neckpain but also armpain [44]. Especially the observed difference in armpain is very peculiar since the amount of decompression should be the same for any technique. However, it has been described that in arthroplasty the decompression was wider than in ACDF [47]. In that case two different techniques were compared instead of two kind of implants. Furthermore, most of the RCT's have introduced bias because of financial disclosures of the authors [48].

A micro-foraminotomy is an anterior approach in which the compressing structure is removed through drilling away the uncinate process leaving the disc intact and preserving mobility. In 52–80 % a good or excellent result was achieved [49]. Recurrence can occur [50].

A posterior approach or a dorsal cervical foraminotomy has also a high success rate [51, 52]. The success rate varies between 64 % and 97 % [53]. A disadvantage of this approach is that frequently an indirect compression can be achieved . Especially of anterior located bony spurs indirect decompression is only possible whereas in selected cases an sequestrated disc fragment can also be removed. Furthermore, not every herniated disc can be approached dorsally. Only those that are located laterally from the thecal sac compressing the nerve root are indicated. Any disc protrusion anterior from the thecal sac (spinal cord) is not safely accessible. Using tubular retractors diminished blood loss intraoperatively, stay at the hospital, and postoperative neck pain [54]. Finally, nucleoplasty of Percutaneous Laser Disc Decompression (PLDD) is another percutaneous minimal invasive technique. Energy is delivered within the disc tissue through a laser or ultrasound (coblation). Not every herniated cervical disc is candidate for this treament. The selection is very strict: disc height not less than 50 % estimated on the disc heights of the adjacent discs, no sequestration of the herniated disc, and no accompanying bony spurs [55]. A good result is reported in

83.7 % till 89.1 % [55–58]. PLDD has a better pain reducing effect than conservative treatement [59]. An in vitro study disclosed that less than 1 % of the disc volume was evaporated after decompression by laser with energy and intensity similar to clinical use. Using higher energy and temperature increased the risk on damage of the spinal cord and nerve root. The thermal effect on the noci-receptors was assumed to be causative of the positive effect [60].

Neck Pain

For idiopathic neckpain surgery is not recommended due to its pathophysiology, whereas it can be a serious option for neckpain due to a specific disease (e.g. cancer, infection, inflammatory disease etc.). In a systematic review no firm conclusion could be made on the effectiveness of surgery compared to conservative treatment partly because of the high risk of bias of the included studies [61].

Craniocervical Osteoarthritis

In case of disabling neck pain due to occipito-atlantal degeneration not responding to conservative treatment fusion might be an option. The same holds true for severe atlanto-axial degeneration with concomitant incapacitating pain. The patient should be informed about further restriction of the already restricted flexion and rotation of the head [19, 20, 62]. Occipital neuralgia in combination with atlanto-axial degeneration can resolve immediately after fusion [62]. Fusion can be done by transarticular screws or the method proposed by Harms and Goel for C1-C2 arthrodesis. The occiput should be included in case of occipito-atlantal osteoarthritis.

Authors' Preference of Dealing with Cervical Pain and/or Radiculopathy

If a patient presents with only neck pain, additional investigations will take place after thorough history taking with emphasis on complaints related to neck pand and physical examination. If a specific cause for the neck pain is established, the treatment offered will be according to state of the art concepts of the specific etiology.

However, if a cause is not suspected or found the neck pain is considered as idiopathic. An explanation of the natural course will be given, the advise to exercise and to be active in sports (preferentially avoiding contact sports), and sometimes a referral to a manual therapist will be offered.

In a patient presenting with degenerative cervical radiculopathy within 10 weeks after onset of the complaints and without symptoms of spinal cord involvement, the often beneficial natural course will be explained. The advice to be as active as possible will also be given. If the patient improves, continuation of the management will be encouraged. Otherwise, the option of surgical decompression will be offered. In case of spinal cord involvement surgery in short time will be discussed.

In most instances the author prefers an anterior approach with stand alone cage. However, for recurrent compression (especially seen after arthroplasty) a posterior approach might be an option and also for people who are in daily life dependent upon their voice (e.g. musicians, teachers etc.).

This is algorithm is schematically represented in Fig. 4.1.

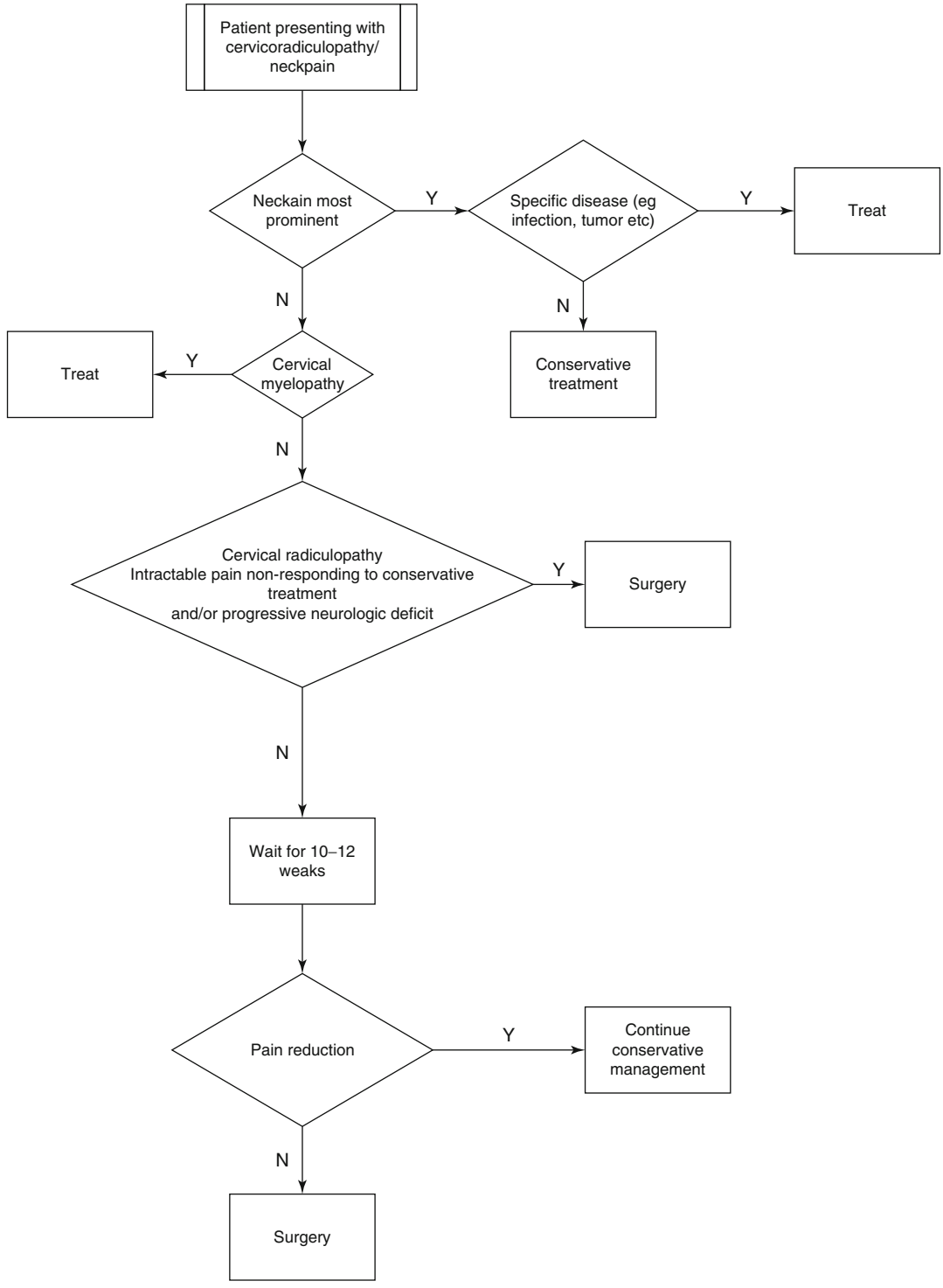


Fig. 4.1 Flow diagram representing algorythm for patients with neck and/or cervival radicular pain

References

1. Kumar R, Berger RJ, Dunsker SB, Keller JT. Innervation of the spinal dura. Myth or reality? Spine. 1996;21: 18–26.
2. Bogduk N. The anatomy and pathophysiology of neck pain. Phys Med Rehabil Clin N Am. 2003;14: 455–72.
3. Radhakrishnan K, Litchy WJ, O'Fallon WM, Kurland LT. Epidemiology of cervical radiculopathy. A population-based study from Rochester, Minnesota, 1976 through 1990. Brain. 1994;117(Pt 2):325–35.
4. Hogg-Johnson S, van der Velde G, Carroll LJ, Holm LW, Cassidy JD, Guzman J, Cote P, Haldeman S, Ammendolia C, Carragee E, Hurwitz E, Nordin M, Peloso P, Bone and Joint Decade 2000-2010 Task Force on Neck Pain and Its Associated Disorders, et al. The burden and determinants of neck pain in the general population: results of the bone and joint decade 2000–2010 task force on neck pain and its associated disorders. Spine. 2008;33:S39–51. doi:10.1097/BRS.0b013e31816454c8.
5. Guzman J, Haldeman S, Carroll LJ, Carragee EJ, Hurwitz EL, Peloso P, Nordin M, Cassidy JD, Holm LW, Cote P, van der Velde G, Hogg-Johnson S, Bone, Joint Decade – Task Force on Neck P, Its Associated D (2008), et al. Clinical practice implications of the bone and joint decade 2000–2010 task force on neck pain and its associated disorders: from concepts and findings to recommendations. Spine. 2008;33:S199–213. doi:10.1097/BRS.0b013e3181644641.
6. Cote P, Cassidy JD, Carroll LJ, Kristman V. The annual incidence and course of neck pain in the general population: a population-based cohort study. Pain. 2004;112:267–73. doi:10.1016/j.pain.2004.09.004.
7. Carroll LJ, Hogg-Johnson S, van der Velde G, Haldeman S, Holm LW, Carragee EJ, Hurwitz EL, Cote P, Nordin M, Peloso PM, Guzman J, Cassidy JD, Bone, Joint Decade – Task Force on Neck P, Its Associated D (2008), et al. Course and prognostic factors for neck pain in the general population: results of the bone and joint decade 2000–2010 task force on neck pain and its associated disorders. Spine. 2008;33:S75–82. doi:10.1097/BRS.0b013e31816445be.
8. Badve SA, Bhojraj S, Nene A, Raut A, Ramakanthan R. Occipito-atlanto-axial osteoarthritis: a cross sectional clinico-radiological prevalence study in high risk and general population. Spine. 2010;35:434–8. doi:10.1097/BRS.0b013e3181b13320.
9. Zapletal J, Hekster RE, Straver JS, Wilmink JT, Hermans J. Relationship between atlanto-odontoid osteoarthritis and idiopathic suboccipital neck pain. Neuroradiology. 1996;38:62–5.
10. Von Ludinghausen M, Prescher A, Kageya I, Yoshimura K. The median atlanto-occipital joint in advanced age. Spine. 2006;31:E430–6. doi:10.1097/01.brs.0000222156.96731.34.
11. Halla JT, Hardin Jr JG. Atlantoaxial (C1-C2) facet joint osteoarthritis: a distinctive clinical syndrome. Arthritis Rheum. 1987;30:577–82.
12. Adams MA, Roughley PJ. What is intervertebral disc degeneration, and what causes it? Spine. 2006;31:2151–61. doi:10.1097/01.brs.0000231761.73859.2c.
13. Galbusera F, van Rijsbergen M, Ito K, Huyghe JM, Brayda-Bruno M, Wilke HJ. Ageing and degenerative changes of the intervertebral disc and their impact on spinal flexibility. Eur Spine J. 2014;23 Suppl 3:324–32. doi:10.1007/s00586-014-3203-4.
14. Rao RD, Currier BL, Albert TJ, Bono CM, Marawar SV, Poelstra KA, Eck JC. Degenerative cervical spondylosis: clinical syndromes, pathogenesis, and management. J Bone Joint Surg Am. 2007;89:1360–78.
15. Kumaresan S, Yoganandan N, Pintar FA, Maiman DJ, Goel VK. Contribution of disc degeneration to osteophyte formation in the cervical spine: a biomechanical investigation. J Orthop Res. 2001;19:977–84. doi:10.1016/S0736-0266(01)00010-9.
16. Park MS, Moon SH, Lee HM, Kim SW, Kim TH, Suh BK, Riew KD. The natural history of degenerative spondylolisthesis of the cervical spine with 2- to 7-year follow-up. Spine. 2013;38:E205–10. doi:10.1097/BRS.0b013e31827de4fd.
17. Dai L. Disc degeneration and cervical instability. Correlation of magnetic resonance imaging with radiography. Spine. 1998;23:1734–8.
18. Ebraheim NA, Liu J, Shafiq Q, Lu J, Pataparla S, Yeasting RA, Woldenberg L. Quantitative analysis of changes in cervical intervertebral foramen size with vertebral translation. Spine. 2006;31:E62–5. doi:10.1097/01.brs.0000199169.92242.70.
19. Yoshihara H, Kepler C, Hasegawa K, Rawlins BA. Surgical treatment for atlantooccipital osteoarthritis: a case report of two patients. Eur Spine J. 2011;20 Suppl 2:S243–7. doi:10.1007/s00586-010-1636-.
20. Elliott RE, Tanweer O, Smith ML, Frempong-Boadu A. Outcomes of fusion for lateral atlantoaxial osteoarthritis: meta-analysis and review of literature. World Neurosurg. 2013;80:e337–46. doi:10.1016/j.wneu.2012.08.018.
21. Schaeren S, Jeanneret B. Atlantoaxial osteoarthritis: case series and review of the literature. Eur Spine J. 2005;14:501–6. doi:10.1007/s00586-004-0856-4.
22. Yukawa Y, Kato F, Suda K, Yamagata M, Ueta T. Age-related changes in osseous anatomy, alignment, and range of motion of the cervical spine. Part I: radiographic data from over 1,200 asymptomatic subjects. Eur Spine J. 2012;21:1492–8. doi:10.1007/s00586-012-2167-5.
23. Kato F, Yukawa Y, Suda K, Yamagata M, Ueta T. Normal morphology, age-related changes and abnormal findings of the cervical spine. Part II: magnetic resonance imaging of over 1,200 asymptomatic subjects. Eur Spine J. 2012;21:1499–507. doi:10.1007/s00586-012-2176-4.
24. Matsumoto M, Okada E, Ichihara D, Watanabe K, Chiba K, Toyama Y, Fujiwara H, Momoshima S, Nishiwaki Y, Hashimoto T, Takahata T. Age-related changes of thoracic and cervical intervertebral discs in asymptomatic subjects. Spine. 2010;35:1359–64. doi:10.1097/BRS.0b013e3181c17067.
25. Okada E, Matsumoto M, Fujiwara H, Toyama Y. Disc degeneration of cervical spine on MRI in patients

with lumbar disc herniation: comparison study with asymptomatic volunteers. Eur Spine J. 2011;20:585–91. doi:10.1007/s00586-010-1644-y.
26. Okada E, Matsumoto M, Ichihara D, Chiba K, Toyama Y, Fujiwara H, Momoshima S, Nishiwaki Y, Hashimoto T, Ogawa J, Watanabe M, Takahata T. Aging of the cervical spine in healthy volunteers: a 10-year longitudinal magnetic resonance imaging study. Spine. 2009;34:706–12. doi:10.1097/BRS.0b013e31819c2003.
27. Vinas FC, Wilner H, Rengachary S. The spontaneous resorption of herniated cervical discs. J Clin Neurosci. 2001;8:542–6. doi:10.1054/jocn.2000.0894.
28. Saal JS, Saal JA, Yurth EF. Nonoperative management of herniated cervical intervertebral disc with radiculopathy. Spine. 1996;21:1877–83.
29. Bush K, Chaudhuri R, Hillier S, Penny J. The pathomorphologic changes that accompany the resolution of cervical radiculopathy. A prospective study with repeat magnetic resonance imaging. Spine. 1997;22:183–6; discussion 187.
30. Thoomes EJ, Scholten-Peeters GG, de Boer AJ, Olsthoorn RA, Verkerk K, Lin C, Verhagen AP. Lack of uniform diagnostic criteria for cervical radiculopathy in conservative intervention studies: a systematic review. Eur Spine J. 2012;21:1459–70. doi:10.1007/s00586-012-2297-9.
31. Thoomes EJ, Scholten-Peeters W, Koes B, Falla D, Verhagen AP. The effectiveness of conservative treatment for patients with cervical radiculopathy: a systematic review. Clin J Pain. 2013;29:1073–86. doi:10.1097/AJP.0b013e31828441fb.
32. Kuijper B, Tans JT, Beelen A, Nollet F, de Visser M. Cervical collar or physiotherapy versus wait and see policy for recent onset cervical radiculopathy: randomised trial. BMJ. 2009;339:b3883. doi:10.1136/bmj.b3883.
33. Manchikanti L, Falco FJ, Diwan S, Hirsch JA, Smith HS. Cervical radicular pain: the role of interlaminar and transforaminal epidural injections. Curr Pain Headache Rep. 2014;18:389. doi:10.1007/s11916-013-0389-9.
34. Hurwitz EL, Carragee EJ, van der Velde G, Carroll LJ, Nordin M, Guzman J, Peloso PM, Holm LW, Cote P, Hogg-Johnson S, Cassidy JD, Haldeman S, Bone, Joint Decade – Task Force on Neck P, Its Associated D (2008), et al. Treatment of neck pain: noninvasive interventions: results of the bone and joint decade 2000–2010 task force on neck pain and its associated disorders. Spine. 2008;33:S123–52. doi:10.1097/BRS.0b013e3181644b1d.
35. Ak H, Ozlem B, Aylin O. Effectiveness of gabapentin in unilateral atlantoaxial osteoarthritis as a cause of painful neck. World Neurosurg. 2014;81:e16–8. doi:10.1016/j.wneu.2013.08.010.
36. Nikolaidis I, Fouyas IP, Sandercock PA, Statham PF. Surgery for cervical radiculopathy or myelopathy. Cochrane Database Syst Rev. 2010;(1):CD001466. doi:10.1002/14651858.CD001466.pub3.
37. Ryken TC, Heary RF, Matz PG, Anderson PA, Groff MW, Holly LT, Kaiser MG, Mummaneni PV, Choudhri TF, Vresilovic EJ, Resnick DK, Joint Section on Disorders of the S, Peripheral Nerves of the American Association of Neurological S, Congress of Neurological S. Techniques for cervical interbody grafting. J Neurosurg Spine. 2009;11:203–20. doi:10.3171/2009.2.SPINE08723.
38. Kwon BK, Vaccaro AR, Grauer JN, Beiner JM. The use of rigid internal fixation in the surgical management of cervical spondylosis. Neurosurgery. 2007;60:S118–29. doi:10.1227/01.NEU.0000249222.57709.59.
39. Jacobs W, Willems PC, van Limbeek J, Bartels R, Pavlov P, Anderson PG, Oner C. Single or double-level anterior interbody fusion techniques for cervical degenerative disc disease. Cochrane Database Syst Rev. 2011;(1):CD004958. doi:10.1002/14651858.CD004958.pub2.
40. van Middelkoop M, Rubinstein SM, Ostelo R, van Tulder MW, Peul W, Koes BW, Verhagen AP. No additional value of fusion techniques on anterior discectomy for neck pain: a systematic review. Pain. 2012;153:2167–73. doi:10.1016/j.pain.2012.04.021.
41. Jacobs W, Willems PC, Kruyt M, van Limbeek J, Anderson PG, Pavlov P, Bartels R, Oner C. Systematic review of anterior interbody fusion techniques for single- and double-level cervical degenerative disc disease. Spine. 2011;36:E950–60. doi:10.1097/BRS.0b013e31821cbba5.
42. Donk RD, Bartels RH. Adjacent disc degeneration in the cervical Spine: personal data and a critical reappraisal of the literature. Internet J Spine Surg. 2012;6(2). doi:http://ispub.com/IJSS/6/2/14092.
43. Jawahar A, Cavanaugh DA, Kerr 3rd EJ, Birdsong EM, Nunley PD. Total disc arthroplasty does not affect the incidence of adjacent segment degeneration in cervical spine: results of 93 patients in three prospective randomized clinical trials. Spine J. 2010;10:1043–8. doi:10.1016/j.spinee.2010.08.014.
44. Ren C, Song Y, Xue Y, Yang X. Mid- to long-term outcomes after cervical disc arthroplasty compared with anterior discectomy and fusion: a systematic review and meta-analysis of randomized controlled trials. Eur Spine J. 2014;23:1115–23. doi:10.1007/s00586-014-3220-3.
45. Sasso RC, Best NM. Cervical kinematics after fusion and Bryan disc arthroplasty. J Spinal Disord Tech. 2008;21:19–22.doi:10.1097/BSD.0b013e3180500778.
46. Bartels RH, Donk R, Verbeek AL. No justification for cervical disk prostheses in clinical practice: a meta-analysis of randomized controlled trials. Neurosurgery. 2010;66:1153–60. doi:10.1227/01.NEU.0000369189.09182.5F; discussion 1160.
47. Riina J, Patel A, Dietz JW, Hoskins JS, Trammell TR, Schwartz DD. Comparison of single-level cervical fusion and a metal-on-metal cervical disc replacement device. Am J Orthop. 2008;37:E71–7.
48. Bartels RH, Delye H, Boogaarts J. Financial disclosures of authors involved in spine research: an underestimated source of bias. Eur Spine J. 2012;21:1229–33. doi:10.1007/s00586-011-2086-x.
49. Matz PG, Holly LT, Groff MW, Vresilovic EJ, Anderson PA, Heary RF, Kaiser MG, Mummaneni

PV, Ryken TC, Choudhri TF, Resnick DK, Joint Section on Disorders of the S, Peripheral Nerves of the American Association of Neurological S, Congress of Neurological S. Indications for anterior cervical decompression for the treatment of cervical degenerative radiculopathy. J Neurosurg Spine. 2009;11:174–82. doi:10.3171/2009.3.SPINE08720.

50. Hacker RJ, Miller CG. Failed anterior cervical foraminotomy. J Neurosurg. 2003;98:126–30.
51. Zeidman SM, Ducker TB. Posterior cervical laminoforaminotomy for radiculopathy: review of 172 cases. Neurosurgery. 1993;33:356–62.
52. Korinth MC, Kruger A, Oertel MF, Gilsbach JM. Posterior foraminotomy or anterior discectomy with polymethyl methacrylate interbody stabilization for cervical soft disc disease: results in 292 patients with monoradiculopathy. Spine. 2006;31:1207–14. doi:10.1097/01.brs.0000217604.02663.59; discussion 1215–206.
53. Heary RF, Ryken TC, Matz PG, Anderson PA, Groff MW, Holly LT, Kaiser MG, Mummaneni PV, Choudhri TF, Vresilovic EJ, Resnick DK, Joint Section on Disorders of the S, Peripheral Nerves of the American Association of Neurological S, Congress of Neurological S. Cervical laminoforaminotomy for the treatment of cervical degenerative radiculopathy. J Neurosurg Spine. 2009;11:198–202. doi:10.3171/2009.2.SPINE08722.
54. Kim KT, Kim YB. Comparison between open procedure and tubular retractor assisted procedure for cervical radiculopathy: results of a randomized controlled study. J Korean Med Sci. 2009;24:649–53. doi:10.3346/jkms.2009.24.4.649.
55. Birnbaum K. Percutaneous cervical disc decompression. Surg Radiol Anat SRA. 2009;31:379–87. doi:10.1007/s00276-009-0462-6.
56. Ahn Y, Lee SH, Shin SW. Percutaneous endoscopic cervical discectomy: clinical outcome and radiographic changes. Photomed Laser Surg. 2005;23:362–8. doi:10.1089/pho.2005.23.362.
57. Lee SH, Ahn Y, Choi WC, Bhanot A, Shin SW. Immediate pain improvement is a useful predictor of long-term favorable outcome after percutaneous laser disc decompression for cervical disc herniation. Photomed Laser Surg. 2006;24:508–13. doi:10.1089/pho.2006.24.508.
58. Li J, Yan DL, Zhang ZH. Percutaneous cervical nucleoplasty in the treatment of cervical disc herniation. Eur Spine J. 2008;17:1664–9. doi:10.1007/s00586-008-0786-7.
59. Cesaroni A, Nardi PV. Plasma disc decompression for contained cervical disc herniation: a randomized, controlled trial. Eur Spine J. 2010;19:477–86. doi:10.1007/s00586-009-1189-0.
60. Schmolke S, Kirsch L, Gosse F, Flamme C, Bohnsack M, Ruhmann O. Risk evaluation of thermal injury to the cervical spine during intradiscal laser application in vitro. Photomed Laser Surg. 2004;22:426–30. doi:10.1089/pho.2004.22.426.
61. van Middelkoop M, Rubinstein SM, Ostelo R, van Tulder MW, Peul W, Koes BW, Verhagen AP. Surgery versus conservative care for neck pain: a systematic review. Eur Spine J. 2013;22:87–95. doi:10.1007/s00586-012-2553.
62. Pakzaban P. Transarticular screw fixation of C1-2 for the treatment of arthropathy-associate occipital neuralgia. J Neurosurg Spine. 2011;14:209–14. doi:10.3171/2010.10.SPINE09815.

Anesthesia and Perioperative Care in Cervical Spine Surgery

5

Chierichini Angelo, Santoprete Stefano, and Frassanito Luciano

Introduction

Cervical spine surgery (CSS) presents several challenges for the anesthesiologist, and the possible complications may be severe; cervical injuries are often permanent and very disabling, as shown by closed claims databases [1].

As for every kind of surgery, a careful preoperative assessment of the physical status of the patient is needed. In particular for the elderly, coexisting diseases and chronic therapies are frequent and often interfere with anesthetics or increase the rate of complications.

However, for CSS several peculiar features deserve special attention. The spine could be stiff or unstable, making the airway management risky and difficult. The surgical field is near the airway, increasing the risks of displacement of the endotracheal tube (ETT) or development of postoperative edema or hematoma which could lead to obstructive complications. The patient positioning, especially for posterior cervical spine surgery (PCSS), always needs a great attention for the smaller details, due to the actual possibility of eyes, nerves and skin injury. Cardiovascular instability could result from preexisting or intraoperative spinal cord injuries (SCI), or be the consequence of wrong positioning or fluid management. Moreover, deliberate or inadvertent hypotension can cause or worsen a SCI, especially when a preoperative cord compression or microvascular impairment (e.g. for diabetes) are present. In order to minimize SCI or root injury an intraoperative neurophysiologic monitoring (IONM) may be adopted, making crucial the choice of a proper anesthetic technique and the close cooperation with the surgeon and the neurophysiologist.

During the postoperative clinical surveillance is mandatory for the early detection of neurological deterioration or airway obstruction. Some adverse events need to be recognized as soon as possible to perform an efficient therapy. The occurrence of a spinal hemorrage could compress the spinal cord, the airway could be rapidly impaired for the possible development of a cervical hematoma or the worsening of pharyngeal edema and/or tongue swelling. The adopted strategy for the postoperative pain control could interfere with the haemostatic mechanism if non-steroideal drugs are administered. Impairment in swallowing function or laryngopharingeal sensitivity could cause an aspiration pneumonia, particularly when postoperative nausea and vomiting (PONV) is present.

C. Angelo (✉) • S. Stefano • F. Luciano
Department of Anesthesiology, Institute of Anesthesiology, Critical Care and Pain Medicine, Catholic University of the Sacred Heart, Largo A. Gemelli, 8., 00168 Rome, Italy
e-mail: angelo.chierichini@rm.unicatt.it; achierichini@gmail.com

P.P.M. Menchetti (ed.), *Cervical Spine: Minimally Invasive and Open Surgery*,
DOI 10.1007/978-3-319-21608-9_5

Anesthetic Management and Prevention of Complications

Preoperative Assessment

The preoperative conditions of the patients scheduled for CSS, and consequently the anesthetic technique chosen, may heavily affect the risks and the outcome of the procedure.

The correct and complete preoperative assessment is a subject too wide to be treated deeply in this chapter. General indications about the most common and important coexisting diseases will be illustrated, underlining some peculiar aspects that need to be evaluated in this kind of surgery.

The most used method for the preoperative risk assessment is the stratification resulting from the American Society of Anesthesiologists Physical Status Classification System (ASA class). ASA could be also used to properly assign the patients to an outpatient protocol, when allowed. As opposed to the past, recent studies show that patients ASA III can be treated as outpatients without significant increase in perioperative complications [2, 3] while ASA IV patients are generally addressed for an inpatient treatment.

However, most authors are now focusing their attention on the single comorbidities and on their grade of stabilization, rather than on the ASA class.

A careful evaluation is needed for patients suffering from diabetes, cardiovascular diseases and/or chronic obstructive pulmonary disease (COPD). Also, patients with already diagnosed or suspected Obstructive Sleep Apnea (OSA) deserve special attentions, in particular if a fast-track treatment is proposed. Untreated or poorly stabilized situations should suggest delaying the surgery or deciding for an inpatient treatment [4].

For diabetic patients, it's greatly advisable to assess the level of control of the disease, based on the history, the number of experienced hospital admission for hypo-hyperglicemia, and so on. It's also important to assess the level of compliance of the patient with his disease. Commonly, a good compliance consists in his ability to perform blood glucose test and to detect the early symptoms of hypoglicemia by himself.

Patients using insulin often take a combined therapy with a basal component (a single dose of long acting insulin) and a postprandial correction with a short acting insulin. Usually, if the patient didn't experience preprandial hypoglicemia in the previous months, it's safe and advisable to administer 75–100 % of basal-dose long acting insulin the morning of surgery. However, the first target is to avoid hypoglicemia, so it's advisable to control blood glucose levels and to be ready to administer 5–10 % glucose solutions i.v. perioperatively when needed.

Oral antidiabetics should not be taken on the day of surgery, and avoided until normal alimentation is resumed.

The preoperative measurement of glicosylated haemoglobin A1c (HbA1c) could help detect patients with poor control of the disease. Levels of HbA1c lower than 7 %, representing the ideal therapeutic target according to the American Diabetes Association Guidelines [5], were found associated with a significantly lower rate of postoperative infections [6]. A recent study showed that poorly controlled diabetic patients had a mean hospital stay 5 days longer than normal stay, while well controlled diabetic patients only 1 day longer [7].

Patients affected by Coronary Artery Disease (CAD) should be carefully investigated, particularly when instability or recent modifications in the appearance of symptoms are present [2]. Adverse cardiac events following CSS are not uncommon (4/1000) but their rate increases significantly in older patients (>65 yo) with greater comorbidities, particularly cardiovascular diseases [8].

Recent works suggest that Congestive Heart Failure (CHF) is actually the most important risk factor for perioperative morbidity and mortality [9]. CHF leading to a NYHA class (New York Heart Association) higher than II, recommends an inpatient treatment.

With few exceptions, there is general agreement to continue chronic medications for cardiac patients until the morning of surgery. Recent reviews suggest a short preoperative suspension for all the antagonists of renin-angiotensin-aldosterone system. These drugs have been involved in increasing the rate of significant hypotension episodes after the induction of anes-

thesia or during neuraxial blocks, and of postoperative developement of acute renal failure [10].

The perioperative continuation of antiplatelet drugs should be carefully considered. While it's commonly accepted, in the presence of a bleeding risk, to suspend the therapy in primary prevention, many reports suggest that the antiplatelet withdrawal during secundary prevention for ischemic diseases may lead to serious complications [11]. When surgery is performed in an area where the development of an hematoma could lead to severe complications (e.g. the anterior region of the neck), or in closed spaces as the spinal canal, the risk of bleeding should be carefully evaluated. When a double antiplatelet therapy is indicated, elective surgery should be postponed. The average increase in bleeding risk in non-cardiac surgery is about 20 % with aspirin or clopidogrel alone [12, 13]. The risk rises up to 50 % over the basic risk when aspirin and clopidogrel are used together [14]. In such particular situations, a multidisciplinary approach involving surgeon, anesthesiologist and cardiologist or neurologist is advisable to customize clinical decisions [15, 16].

COPD is a frequent condition, especially among the older patients, and is often associated with obesity and with an increase in the rate of postoperative bronchopulmonary complications [17]. If general anesthesia or deep sedation are needed for elective surgery, when a severe or poorly compensated COPD is present, with increase in bronchial secretions and clinically relevant bronchial reactivity, a preparation with aerosol therapy and antibiotics is advised. In addition, in the compliant patient smoke banning at least 6–8 weeks before surgery has significantly lowered the rate of bronchopulmonary complications and improved surgical wound healing [18]. If possible, local anesthesia and Monitored Anesthesia Care should be preferred. However, if tracheal intubation is mandatory, the early weaning from invasive ventilation helps prevent complications [19].

In particular in the elderly, smokers and obese patients, OSA is not uncommon and is often underdiagnosed. The frequent association of anatomical abnormalities in the upper airway could advice a careful evaluation for suspected difficult intubation, and the availability of all emergency airway equipment [20]. In the last years, quite simple questionnaires to detect patients with suspected OSA have been proposed, compared with others and validated [21].

Patients with already diagnosed and treated OSA can be managed in OP or DS setting if they are able and skilled in the use of a Continuous Positive Air Pressure (CPAP) device (possibly carrying their own device at the admission to the hospital). Patients with suspected OSA and without comorbidities, with a low risk emerging from clinical evaluation and from the questionnaire results, could be treated in OP or DS setting only if the postoperative pain can easily be controlled without opioids. In patients with high risk for suspected OSA or with comorbidities or when postoperative opioid use is mandatory it seems more prudent to decide in any case for an inpatient treatment [22].

Airway Assessment

As in every kind of surgery, a proper airway evaluation is mandatory before the induction of anesthesia, even if recent surveys show a poor accuracy in the clinical prediction of a difficult direct laryngoscopy (DL) [23].

A simple definition of "difficult airway" could be: a clinical situation in which a meanly skilled anesthesiologist experiences difficulty with facemask ventilation and/or with tracheal intubation [24].

The presence of one or more of the common findings that could hinder an easy direct laryngoscopy or facial mask ventilation must be detected in order to establish a correct behavior (Table 5.1). All other things being equal, a more cautious approach is needed when a patient is scheduled for CSS, mostly if the stability of the spine could be impaired. A collective evaluation with the surgeon regarding the preoperative neurological status, the spine stability and the intervention proposed is surely the best approach to choose the most suitable behavior. Finally, if an awaken intubation is chosen, the psychological compliance of the patients should be appraised, and proper information must be given to the patient.

Table 5.1 Components of the preoperative airway physical examination airway

Examination component	Nonreassuring findings
1. Length of upper incisors	Relatively long
2. Relationship of maxillary and mandibular incisors during normal jaw closure	Prominent "overbite" (maxillary incisors anterior to mandibular incisors)
3. Relationship of maxillary and mandibular incisors during voluntary protrusion of mandible	Patient cannot bring mandibular incisors anterior to (in front of) maxillary incisors
4. Interincisor distance	Less than 3 cm
5. Visibility of uvula	Not visible when tongue is protruded with patient in sitting position (*e.g.*, Mallampati class >2)
6. Shape of palate	Highly arched or very narrow
7. Compliance of mandibular space	Stiff, indurated, occupied by mass, or nonresilient
8. Thyromental distance	Less than three ordinary finger breadths
9. Length of neck	Short
10. Thickness of neck	Thick
11. Range of motion of head and neck	Patient cannot touch tip of chin to chest or cannot extend neck

With permission from Apfelbaum et al. [24]

Thanks to the improvement of electronics and optic fiber technology, many devices have been proposed in the last few years to overcome difficult intubation (Fig. 5.1). These devices have been compared with the classical MacIntosh laryngoscope and also with the fiberoptic bronchoscope or laryngoscope for their efficacy in improving visualization and in reducing neck movements and mechanical stress of cervical spine [25, 26].

Awake fiberoptic intubation can be performed using topic anesthesia with a conscious sedation in order to minimize coughing and neck movements [27]. This is the favorite technique for most practitioners in patients scheduled for general anesthesia with anticipated difficult intubation [28]. However, awake fiberoptic intubation is not without risks. In a closed claims analysis of 12 failed awake intubations, 9 cases (75 %) resulted in death or brain damage either for technical causes or for lack of patient cooperation, or development of airway obstruction for the sedation or edema [29].

Intraoperative Neurological Monitoring

Iatrogenic injury to the spinal cord and peripheral nerves could occur during CSS, caused from wrong positioning, surgical or anesthetic maneu-

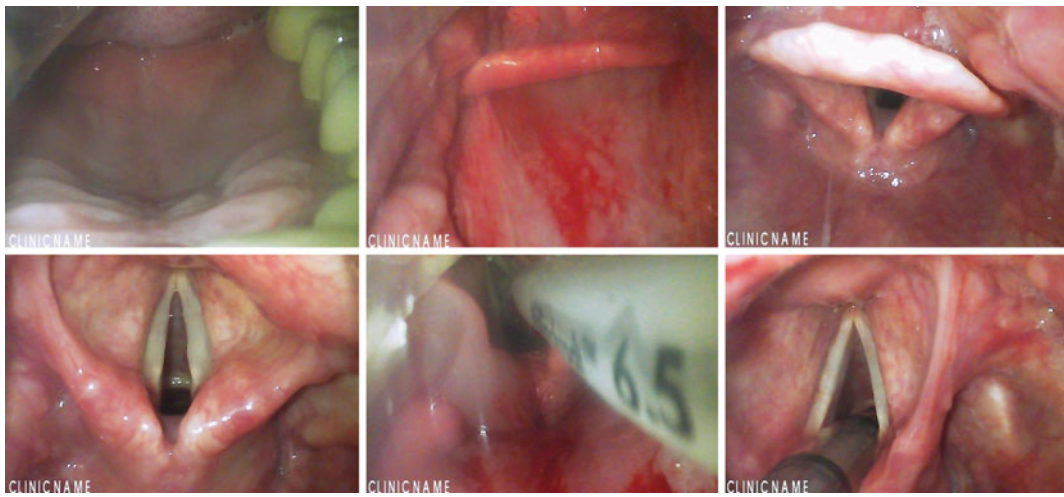


Fig. 5.1 Sequence of images during an endotracheal intubation with a GlideScope ®

vers or poor hemodynamic control. The blood supply to the medulla is granted from the anterior and posterior spinal arteries. The anterior spinal artery feeds approximately the two thirds of the cord mainly in the anterior and central area and the flow is centrifugal. The posterior spinal arteries feed the posterior part of the gray matter of the posterior horns and the more external portion of the anterior-lateral and posterior white matter, and its flow is centripetal. With the exception of the posterior half of the posterior horns, supplied only from the posterior spinal artery, the two systems have a discrete grade of overlapping. Unfortunately, the real efficiency of the interconnections is generally poor and not truly compensatory in case of obstruction of one of the two systems. Moreover, blood supply of the spinal cord is not homogeneous; the cervical tract is more vascularized with a good supply from both anterior and posterior systems, while thoracic and lumbosacral tract have respectively a weaker anterior and posterior flow [30].

In order to early detect neurologic modifications during spinal surgery, various neurophysiologic techniques have been proposed and used. Somatosensory-evoked potentials (SSEPs) were the first to be studied and adopted. The registration of cortical or subcortical potentials after administration of peripheral stimuli and the evaluation of variations in amplitude and latency of the responses, helps in detecting possible functional impairment of the posterior afferent pathways. Typically the stimulating electrode are applied over the median nerve in the arm or over the posterior tibial nerve distally to the knee. The stimulation site is chosen depending of the site of surgery; when CSS is proposed the median nerve is generally used, while for surgery distal to the cervical segment the tibial nerve is stimulated [31].

In most cases, the technique gives indirect information about the functional situation of the anterior regions of medulla.

However, also for the anatomical and functional reasons described above, SSEPs may fail to detect spinal cord injury in the anterior-lateral area involving only the descending motor pathways without impairment of the posterior columns and gray matter.

TcMEPs monitoring was introduced to overcome these false negative responses. The electrical or magnetic stimulation of the precentral motor cortex with the peripheric recording under the surgery level of the muscular response can help assess the integrity of the anterior descending pathways.

Moreover, during CSS, TcMEPs and SSEPs seem to have different patterns of sensitivity: while TcMEPs are more useful to detect hypotension and cord hypoperfusion related injuries, SSEPs may be more helpful in preventing brachial plexus injuries [32].

Literature data highly recommend the continuous recording of both SSEPs and MEPs for the high sensitivity and specificity of the responses they can give when used together, allowing the recovery of situations which could otherwise have a very poor outcome. When pedicle screws are used, the intraoperative EMG is also recommended [33].

Special anesthetic care is needed when monitoring of somatosensory-evoked potentials (SSEPs) and/or motor-evoked potentials (MEPs) is planned, in order to detect intraoperative functional impairment of the spinal pathways. Anesthetic agents can heavily affect the quality of the monitoring, particularly for cortical SSEPs because of cortical direct depression. Moreover, general anesthesia causes a depression of intrinsic spinal cord activity, which is more evident when nitrous oxide or halogenated agents are used. Even if the use of trains of stimuli rather than a single one tends to overcome this poor excitability, the depressive effect is still significant.

Hence, the simultaneous monitoring of a cortical and a subcortical site of SSEPs may help, when necessary, in the interpretation of a decrease in cortical SSEPs amplitude and/or increase in latency, because the subcortical response is far less impaired by the anesthetic effect. Generally the first choice should be a TIVA, because of the impact of inhalational anesthetics on evoked potentials even at low concentrations [34]. Propofol suppresses the activity of the anterior horn cells, but significantly less than halogenated anesthetics [35]. Also intravenous drugs should be chosen carefully: benzodiazepines and

barbiturates produce CMEPs depression at doses less than those affecting the SSEPs and lasting for several minutes. Opioids are an important component of anesthesia for evoked potentials monitoring: they only produce minimal changes in spinal or subcortical SSEP recordings, a mild decrease in amplitude and increase in latency for cortical SSEPs and myogenic responses from MEPs [36].

Recently it has been noted that also remifentanil, when used at higher doses, can affect SSEPs monitoring, acting particularly on the amplitude of signals [37].

Spinal MEPs (stimulating cranially to the level of surgery) or pedicle screw testing during spinal instrumentation (EMG recording) are virtually insensitive to anesthetic agents, while could be hindered by muscle relaxant drugs. However, a controlled degree of neuromuscular blockade with two twitches remaining in the train of four allows an effective monitoring and is preferred in order to avoid excessive movements and facilitate surgery. Many Authors use a continuous infusion of a muscle relaxant agent, generally cis-atracurium, titrated to obtain and maintain the desired pattern of train-of-four.

In any case, due to the complex pattern of interference between anesthesia and intraoperative neurophysiologic monitoring, a continuous exchange of information among all the practitioners involved can improve the interpretation of data and the outcome of the patient [36].

Patient Positioning and Related Complications

Positioning in CSS is potentially challenging. A study on 75 patients undergoing CSS with IONM showed a sudden worsening during positioning of trans cranial MEPs in three cases and both MEPs and SEPs in two cases. Despite the immediate adjustment of the patient's position and the stabilization of an adequate blood pressure, in one case evoked potentials remained depressed during surgery and the patient presented delayed neurological impairment in the postoperative (tetraparesis), but fortunately with a complete recovery after 2 weeks. The other four patients gradually showed improvement of evoked potentials after re-positioning with no neurological deficits at the end of surgery [38].

Neurological impairment, mostly transitorial, is also reported after non-cervical surgery particularly in the elderly patients in which unsuspected cervical stenosis are often present [39]. This always suggests cautious positioning of the head and possibly, in every case of supposed spinal cord compression, a proper maintenance of mean arterial blood pressure that may have potential benefit in improving the blood supply to ischemic areas [30].

Peripheral nerve injury is a rare complication after surgery, generally caused from bad patient positioning with an overall rate ranging from 0.03 to 0.1 % [40]. The complication seems more frequent in patients with some comorbidities such as diabetes mellitus, alcohol addiction and vascular disease, and particularly in the elderly and in the extreme ranges of body mass index. Literature data are poor and missing in randomized trials about the matter; no guidelines are available to help in choosing the correct positioning in any kind of surgery; only some advices have been proposed based on expert opinions, case reports and consensus surveys. The abduction of the arm seems to be more tolerated in the prone rather than in the supine position, though it's advised not to exceed 90° [40]. In the supine position with the arm abducted the ulnar nerve is better protected with the forearm in supine or neutral position; when the arm is tucked at side the forearm should be in neutral position and in any case pressure on the ulnar groove at the elbow and on the radial spiral groove of the humerus must be avoided. Flexion of the elbow may increase the rate of ulnar impairment, while excessive extension beyond the range preoperatively assessed as comfortable may stretch the median nerve. During surgery the position of the upper extremities should be periodically reassessed. Gel or foam padding are advised but they must be used carefully, possibly by experienced staff. A wrong use of padding can even increase rather than decrease the rate of postoperative neuropathy [41].

One of the most devastating complications in non-ocular surgery is the PeriOperative Visual Loss (POVL), in some cases caused from wrong position. POVL is rare if considered in the whole population of surgical patients, ranging from 1:60.000 to 1:125.000, but is more frequent in spine surgery (3.09:10.000); only cardiac surgery has a higher risk of POVL (8.64:10.000). The causes of POVL are mainly two: the Central Retinal Artery Occlusion (CRAO) and the Ischemic Optic nerve Neuropathy (ION). The CRAO leads to the ischemia of the entire retina, while the less severe obstruction of a branch of the artery (BRAO) causes an impaired function only in a sector. Whereas during cardiac surgery the most common mechanism involved is the arterial microembolism, during spine surgery the complication mainly derives from an improper head position, leading to mono or bilateral ocular compression [42]. Recently, an ASA task force has proposed some practical advices for POVL prevention in spine surgery. For the prevention of CRAO and other ocular damage direct pressure on the eye should be avoided, the eyes of prone-positioned patients should be assessed regularly and documented [43]. ION is less rare than CRAO, accounting for about 89 % of cases of POVL after spinal surgery. The mechanisms underlying the development of ION are not completely known, but the pathogenesis seems to be multifactorial [42]. The occurrence of ION seems to be strictly correlated with surgery duration. In a survey of 83 ION after spine surgery, the majority of the cases (94 %) occurred for 6 h anesthetic duration or longer, while only one case was associated with surgery lasting less than 4 h [44]. Other risk factors for ION were detected such as obesity, male sex, Wilson frame use, greater than estimated blood loss, and decreased percent colloid administration. The pathogenesis of ION is not clear. The most popular theory involves the elevation of venous pressure and the development of interstitial edema leading to deformation and obstruction of the vessels feeding the optical nerve. All the factors able to increase the venous pressure in the head or to decrease the oncotic pressure could predispose to ION. Some examples are the prone position with abdominal compression in obese patients or the head position lower than the heart for the former; a significant blood loss with consequent hypoalbuminemia and the scarse administration of colloids for the latter [45].

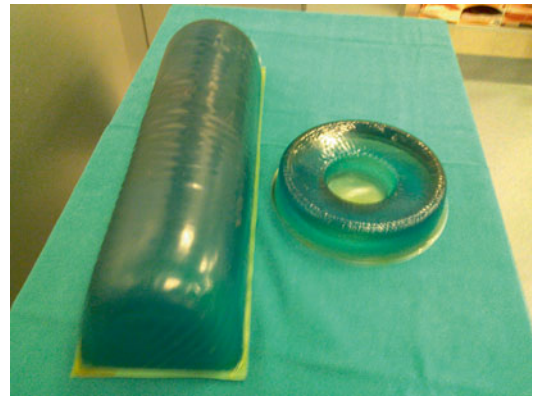


Fig. 5.2 Gel padding devices

Other complications deriving from improper positioning should be prevented using gel or foam-made dedicated devices (Fig. 5.2) or even normal pillows put together with the active contribution of the surgeons, the nurses and the anesthesiologist. The final result must ensure the distribution of the pressures as more as possible over larger extensions of tissues, avoiding excessive and localized compressions, and excessive stretching or flexion of elbows, shoulders and neck. Abdomen compression should be avoided to facilitate intermittent positive pressure ventilation and limit barotrauma. Moreover, the reduction of the intrathoracic mean pressure leads to improvement of venous return and helps in lowering surgical bleeding. This is particularly important in CSS, where a deliberate arterial hypotension must be generally avoided to ensure a proper blood perfusion to the spinal cord. As discussed above, the head and the face should be frequently checked to avoid harmful compressions on the eyes and ears (Figs. 5.3 and 5.4) [46].

Prophylaxis of Surgical Site Infection

Surgical site infection (SSI) is a dreadful and costly complication in spinal surgery. A retrospective

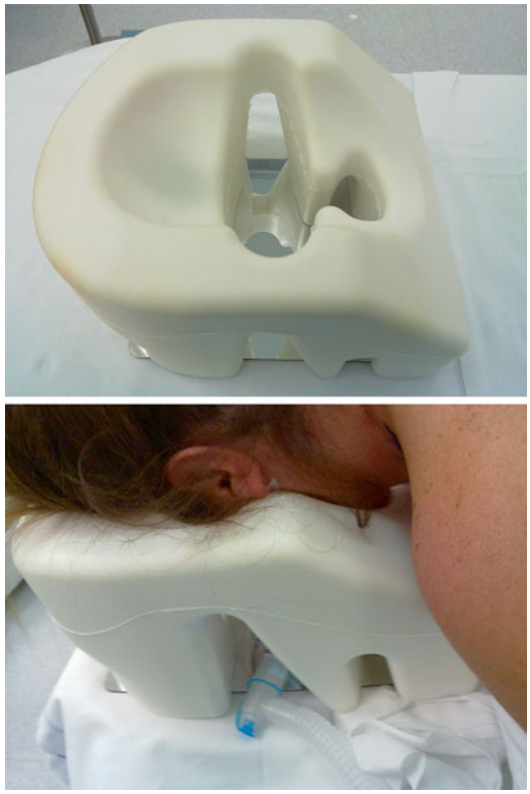


Fig. 5.3 A foam-made headrest for prone positioning, with a mirror for eyes check

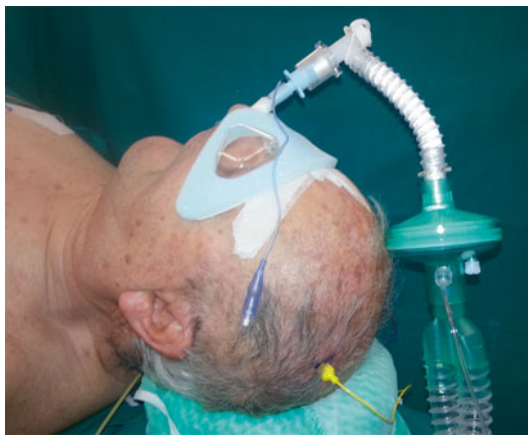


Fig. 5.4 Nasotracheal intubation for ACSS at C3 level. The eyes are protected by an adhesive shell-shaped device

study regarding 90 patients undergoing posterior CSS showed no infections in upper cervical surgery (all infected patients were operated at C3 level or below) while the use of a rigid collar in the postoperative is underlined as an important risk factor for infections of the wound in subaxial cervical surgery [47]. Other known risk factors were investigated, such as smoke with an odds ratio (OR) = 2.10 and perioperative steroids (OR = 3.42), but neither resulted statistically significant. A larger series of 318 patients undergoing posterior cervical decompression, showed an incidence of 1.6 % for SSI needing reoperation (5 cases) with a statistically significant correlation between postoperative infection and the number of levels decompressed [48]. In a retrospective study on 1,615 lumbar spine fusions (1,568 patients), the overall rate of infection in was 2.2 %. Risk factors detected were diabetes (×6), smoke (×2) and positive history of spinal surgery (×3.7). Moreover, risk increased with the number of levels fused [49].

Literature data support the efficacy of perioperative antibiotic prophylaxis in all the orthopedic spinal procedures with or without instrumentation, with a grade A in the strength of recommendation. The standard recommended agent is cefazolin 2 g i.v. for adult patients (3 g in patients weighting over 120 kg, 30 mg/kg for pediatric patients), administered within 60 min before skin incision. Clindamycin or vancomycin should be used as alternative agents in patients with β-lactam allergy. If organizational SSI surveillance shows that gram-negative organisms are associated with infections or if there is risk of gram negative contamination of the surgical site, clindamycin or vancomycin should be used in addition to cefazolin if the patient is not β-lactam allergic, or to aztreonam, gentamicin, or single-dose fluoroquinolone if the patient is β-lactam allergic. In patients who are known to be colonized with methicillin-resistant *Staphylococcus aureus* (MRSA), vancomycin should be added to cefazolin. For agents requiring a slow infusion over 1–2 h, as fluoroquinolones or vancomycin, the administration should begin within 120 min before skin incision. For patients with renal or hepatic impairment, the dose often does not need to be modified when given as a single preoperative administration before surgical incision. In order to maintain an adequate blood and tissue drug concentration, redosing is recommended when the duration of the procedure exceeds two

half-lives of the drug or there is excessive blood loss [50].

Deep Venous Thrombosis and Pulmonary Embolism Prevention

DVT complicates CSS with a mean rate of 0.5 %, with an higher incidence after posterior fixation (1.3 %) than after anterior CSS or posterior decompression (<0.5 %). Despite this low rate of occurrence, the hospital stay increases by 7- to 10-fold over normal when DVT is present, and mortality rates increase by 10- to 50-fold [51]. In a prospective clinical trial in patients undergoing CSS, mechanical prophylaxis with intermittent pneumatic compression (IPC) was equally effective as unfractioned heparin or low molecular weight heparin for the prevention of DVT and PE, but avoided the risk of postoperative hemorrhage [52].

The 9th edition of the Antithrombotic Therapy and Prevention of Thrombosis Guidelines from the American College of Chest Physicians suggests mechanical prophylaxis, preferably with IPC, over no prophylaxis or pharmacological prophylaxis. For patients undergoing spinal surgery at high risk for Venous ThromboEmbolism (VTE), including those with malignant disease or those undergoing surgery with a combined anterior-posterior approach, the guidelines suggest adding pharmacologic prophylaxis to mechanical prophylaxis once adequate hemostasis is established and the risk of bleeding decreases [53].

Postoperative Pain Management

Pain after spine surgery is often more severe than in other surgical settings. Skin incision frequently involves multiple adjacent dermatomes and painful anatomical structures are often involved as periosteum, ligaments, facet joints, muscular fascial tissue. Among the deep somatic structures, periosteum seems to be one of the most painful tissues having the lowest pain threshold nerve fibers [54]. Complex mechanisms of peripheral and central sensitization of pain receptors and spinal cord pathways are also involved in explaining the resistance to treatment and the tendency of the pain to persist even after days. In addition, patients scheduled for spine surgery are often under preoperative chronic pain therapy. In some patients, a large use of opioids in the preoperative creates serious therapeutic challenges in the postoperative, making pain less responsive to incremental doses of opioids [55].

When minimally invasive techniques are adopted, pain could be reduced for the generally small skin incisions and the reduced damage for muscles and deep tissues. However, among the postoperative "side effect" of surgery, pain represents one of the most common causes of hospital re-admission or delayed discharge, especially when an outpatient (OP) or day surgery (DS) treatment is planned. Nowadays, the multimodal approach to pain therapy is considered the best model of treatment, because it allows to reduce the doses of the single drugs used and to minimize the potential side effects. The multimodal or balanced treatment consists in combining opioid and non-opioid analgesics with additive or synergistic actions since the preoperative period [56].

Other techniques can be adopted together with drug therapy to help to decrease postoperative pain. Skin and tissues infiltration with a long acting local anesthetic added with epinephrine before the surgical incision is a common practice. This technique reduces intraoperative bleeding and analgesics requirement, at least in the earlier postoperative period. Continuous postoperative wound infiltration with local anesthetics through microcatheters of various length is also available, but not so widely used, even if the efficacy and the low rate of complications have been demonstrated [57, 58].

Due to the large margin of safety and the very rare complications, acetaminophen deserves a special place in the management of pain after CSS. Acetaminophen alone could efficiently control a moderate pain. When used in combination with other Non-Steroidal Anti-Inflammatory Drugs (NSAIDs) or weak opiates, it significantly reduces the consumption of other

analgesics in the postoperative. The availability of oral and intravenous (iv) preparations makes acetaminophen suitable both for perioperative and for postoperative use, and also allows to continue the support therapy easily after patient discharge [56].

NSAIDs and cyclooxygenase-2 inhibitors (COX-2) lead to increased risk of non-union after spine fusion surgery, but this adverse effect seems limited to prolonged use (>14 days) or high doses. The use of ketorolac at a dose of more than 120 mg/day even for few days or the use of a cumulative dose of more than 300 mg of diclofenac significantly affect the risk of non-union [59]. When used at lower doses and for few days, these drugs surely help in postoperative pain treatment.

Opiates still have an important role in the treatment of moderate-to-severe postoperative pain, but because of the important side-effects, it's advisable to reduce the doses in a multimodal protocol. The association of NSAIDs or celecoxib with a slow-release oxycodone since the preoperative period improved the outcome of spine surgery when compared with intravenous morphine, providing earlier recovery of the bowel function [60]. Patients treated preoperatively with opiates for chronic pain could necessitate large opiates doses in the perioperative period. The use of intraoperative ketamine infusion in these patients has significantly lowered opiates consumption even over 6 weeks after spine surgery, particularly after CSS. The clinical benefit in terms of reduction in opiate-related PONV has been higher for CSS than for lumbar surgery, while the ketamine related side-effects such as disturbing dreams and hallucination were more common after lumbar surgery [61, 62].

The gabapentinoids (gabapentin, pregabalin) have also been used in association with other drugs for multimodal postoperative pain treatment, but their role remains uncertain as some studies failed in demonstrating a reduced opioids consumption. Furthermore, the side effects, such as somnolence and sedation, dizziness and ataxia, could slow the physical and psychological recovery, especially in the elderly [56].

PONV Prevention and Treatment

Postoperative nausea and vomiting heavily affect the grade of satisfaction of the patients and in some cases may increase the risks for other severe complications such as pulmonary aspiration. After ambulatory or 1 day surgery PONV represents, after pain, the second cause of hospital readmission or delayed discharge. Several studies have been dedicated to the problem and guidelines have been established to help physicians in clinical decisions [63].

Preoperative detection of risk factors is crucial to provide a correct PONV prevention for each patient. A simple way to assess the risk of PONV after general anesthesia has been proposed; it's based on the evaluation of four characteristics associated with an increased risk: female gender, history of motion sickness or PONV, non-smoking status, need of postoperative opioids [64]. When none of these conditions are present, no prophylaxis is recommended. Higher risk scores deserve prophylaxis with one or more drugs, and/or the adoption of specific anesthetic techniques. When general anaesthesia is needed, Totally Intra-Venous Anaesthesia (TIVA) is associated with lower PONV incidence than inhalational anaesthesia, especially in the first hours after surgery [65, 66].

If not otherwise contraindicated, the protective effects of adequate preoperative and intraoperative hydration against PONV, drowsiness and dizziness, is generally known [7893018], even if in some kind of surgery it seems less clear [67]. For the same reason, oral intake of clear fluids until 3 h before surgery helps in preventing postoperative nausea and it is considered safe for the risk of inhalation [68].

Dexamethasone is a long acting glucocorticoid with a largely demonstrated activity in reducing PONV [69]. The mechanism of action, probably multifactorial, is still unclear. When administered during anesthesia induction at a dose of 0.05÷0.1 mg/kg, it significantly lowered the rate of PONV in various surgical settings and it's considered safe in terms of side effects [70]. Although many authors suggest that rescue medication should not involve dexamethasone, it has been also associated with a significant reduction

in established PONV when used in addition to ondansetron and droperidol [71].

5-Hydroxytryptamine-3 (5-HT3) receptor antagonists are widely used in the common practice for the prevention of PONV and of the side effects of chemotherapy. Ondansetron is the most famous drug of the family, normally used at a dose of 4 mg at the end of surgery. Palonosetron, a 5-HT3 antagonist with a longer half-life and a higher receptorial affinity, seems very promising especially for the prevention of Post Discharge Nausea and Vomiting (PDNV). Even if more effective and safer than ondansetron (no action on QT interval), the use of palonosetron is still limited [70, 72].

Transdermal scopolamine is effective and the side effects are quite frequent although generally mild and well tolerated [73]. In the elderly, however, the occurrence of confusion or an excessive sedation could be observed, suggesting to remove the patch. The patch is applied the evening before surgery or at least 2 h before the induction of anesthesia, because the onset of the effect is about 2–4 h [74].

Droperidol is very effective in the prevention of PONV with a Number Needed to Treat (NNT) of 5, and highly effective in the prevention of nausea during patient controlled analgesia with opiates (NNT = 3). In the last years, however, the use of droperidol has been greatly limited after the Black Box Warning issued by the Foods and Drugs Administration in the USA in 2001. Droperidol has been associated with adverse cardiac events as prolongation of QT interval and *torsades de pointes*. Despite the fact that several authors suggested a revision of that decision, the warning is still active, restricting the use of droperidol to the treatment of patients who fail to show an acceptable response to other adequate treatments [63, 66, 75].

More recent drugs, the Neurokinin-1 receptor antagonists, appear very interesting for the prevention of PONV. In clinical trials, aprepitant, casopitant and rolapitant showed better results when compared with ondansetron in patients with high risk for PONV, even if the reduction in vomiting is more evident than the reduction of nausea. Rolapitant, for the long half-life, could represent the best choice in the future, especially if it is mandatory to avoid vomiting [70, 76].

Other Complications

Postoperative Airway Compromise

Airway obstruction complicates ACSS with a rate of 1.2÷6.1 %. The situation can rapidly worsen and require emergent reintubation. The obstruction, mainly inspiratory, can cause a pulmonary edema due to the development of a markedly negative intrathoracic pressure. Fortunately, this kind of edema tends to resolve rapidly with the resolution of the obstruction and the oxygenation of the patient [77].

The obstruction is more frequently caused by edema of pharinx, prevertebral tissues and larynx and could eventually be worsened by direct trauma during a difficult intubation. The development of an hematoma in the wound or the involvement of the recurrent laryngeal nerve, with vocal fold palsy are less common. The obstructive events are more frequent when surgery involves more than 3 vertebral bodies or high cervical levels (c2–c4), blood loss is >300 ml, surgery lasts more than 5 h or is performed through a combined anterior plus posterior approach. The incidence is worsened in obese patients and when OSA and other respiratory comorbidities are present [78, 79]. These considerations could help detect the cases that deserve a more cautious clinical monitoring and management. Cases with high risk of postoperative airway obstruction for the characteristics of surgery, especially if other patient-related factors are present, deserve the admission in an intensive care unit (ICU), possibly with the head elevated about 30°, like for an intracranial postoperative [78]. Extubation must be delayed for 24–36 h and performed only after a fiberoptic inspection or a cuff leak test [80].

Dysphagia, Laryngeal Palsy and Aspiration

Early dysphagia is more frequent after ACSS, and is more common when a plate is used and in the elderly [81], but it's not so rare for posterior approaches either. After 2 and 6 weeks from surgery, dysphagia was present respectively in

11 % and 8 % of PCSS cases and 61.5 % and 44 % of ACSS ($p < 0.0001$). No difference among the two surgical approaches was observed after 12 weeks with rates of nearly 12 % [82]. Many different strategies have been proposed in order to reduce the incidence and the lasting of postoperative dysphagia, mostly regarding surgical aspects such as choosing a thinner plate and avoiding plate prominence, limiting the duration of surgery, limiting retraction [83]. In the anesthesiological field, the pressure or the ETT cuff was invoked in worsening an eventual nerve injury due to surgical retraction. In a series of 900 patients who underwent ACSS with plating, Apfelbaum observed a significant reduction in the incidence of temporary vocal fold paresis from 6.4 to 1.7 % ($p = 0.002$), since the systematic adjustment of the pressure of the ETT cuff after the positioning or repositioning of the surgical retractors was adopted. There was no significant difference between the two groups of patients for the rate of permanent palsies [84].

He supposed that the majority of the laryngeal nerve injuries during ACSS could derive from an asymmetric vocal fold compression. The ETT is anchored distally from the cuff and proximally from the tape; when trachea is retracted the tube compress the ipsilateral vocal fold, with possible compression on the endolaryngeal segment of the nerve. The cuff deflation distally disengages the ETT allowing the passive adjustment towards a "neutral" position between the vocal folds, and the release of compression over the ipsilateral nerve.

Many of the factors causing dysphagia and hoarseness are generally involved also in another severe complication after CSS affecting about 0.5 % of all procedures: the aspiration pneumonia. However, even if the anterior approach is more commonly associated with risks of laryngeal nerves and esophagus injury, and neck tissues swelling that could predispose to swallowing disorders, unexpectantly aspiration is more frequent after PCSS (about 1 % vs. 0.4 %). Other risk factors are weight loss, fluid-electrolyte disorders, congestive heart failure, neurological disorders respectively with OR of 8.3, 6.2, 3.1 and 2.1. Moreover, it's more frequent in the elderly (>65 y.o.) and in patients with comorbidities [85]. When aspiration pneumonia occurs, the overall mortality rate in CSS dramatically increases from the basal 0.07–3.44 %.

Particularly in the revision cases of ACSS, surgeons might prefer a contralateral approach to avoid scar and altered anatomy. For these patients, and however in any patient with suspected laryngeal disfunction, a preoperative otorhinolaryngologist consultation is mandatory to prevent the dramatic event of a bilateral laryngeal nerve damage. For patients with monolateral laryngeal paresis surgery must be performed ipsilateral to the preexisting damage, in order to avoid acute airway obstruction and/or severe swallowing impairment with pulmonary complications [83].

Intracranial Complications

A rare complication is the development of an intracranial hemorrage, possibly due to intraoperative and/or postoperative loss of cerebrospinal fluid (CSF) with intracranial hypotension. These rare complications could appear subtly. If they develop during surgery, they can simulate a simple delayed emergence that could be ascribed to persistent anesthetic effect or to cerebral edema due to prolonged prone position. More often the complication appears 10 or more hours postoperatively, with headache, nausea, vomiting; sometimes other symptoms may appear such somnolence, altered consciousness, dysarthria, ataxia, and motor or visual deficits. In a recent review all the eight described cases had intraoperative CSF leakage and postoperative drains with moderate serosanguinous output. Even if the relationship with the complication is not statistically significant it appears very suggestive [86]. This kind of hematomas are more often in the posterior fossa, but sometimes can develop in the supratentorial region [87]. Another rare cause of intracranial hematoma during spine surgery is the possible penetration in the skull of a pin when a Mayfield clamp is adopted for the positioning (Fig. 5.5) [88].

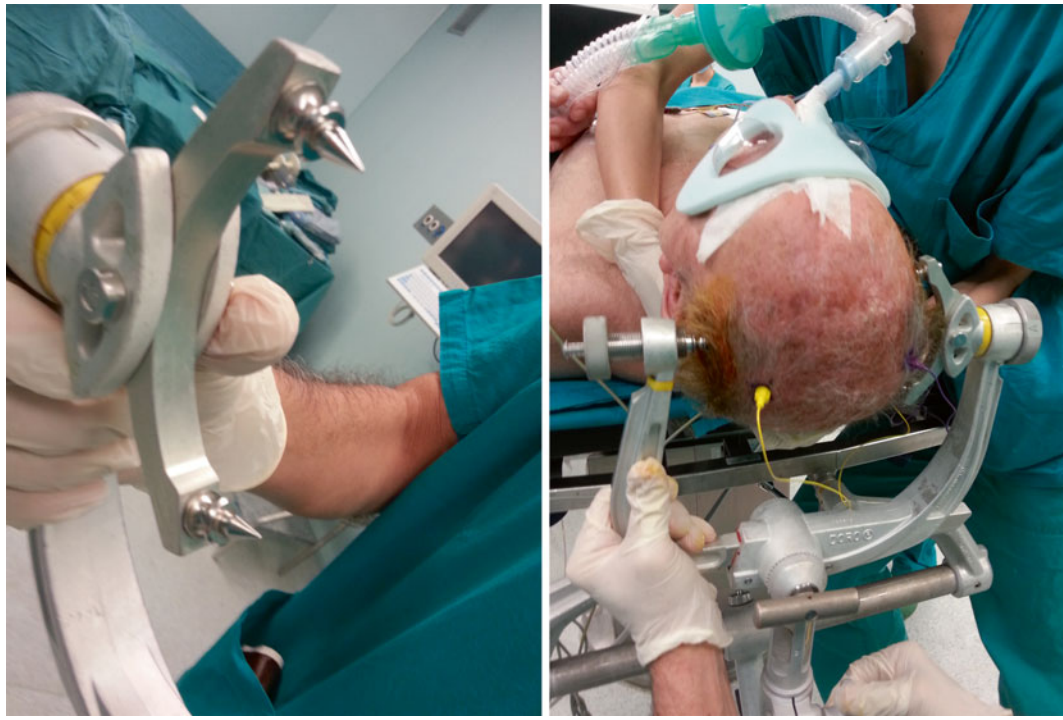


Fig. 5.5 A Mayfield clamp and its positioning

References

1. Hindman BJ, Palecek JP, Posner KL, Traynelis VC, Lee LA, Sawin PD, Tredway TL, Todd MM, Domino KB. Cervical spinal cord, root, and bony spine injuries: a closed claims analysis. Anesthesiology. 2011;114(4): 782–95.
2. Bettelli G. High risk patients in day surgery. Minerva Anestesiol. 2009;75(5):259–68. Epub 2008 Oct 23.
3. Ankichetty S, Chung F. Considerations for patients with obstructive sleep apnea undergoing ambulatory surgery. Curr Opin Anaesthesiol. 2011;24(6):605–11.
4. Bettelli G. Anaesthesia for the elderly outpatient: preoperative assessment and evaluation, anaesthetic technique and postoperative pain management. Curr Opin Anaesthesiol. 2010;23(6):726–31.
5. American Diabetes Association. Executive summary: standards of medical care in diabetes – 2012. Diabetes Care. 2012;35 Suppl 1:S4–10.
6. Joshi GP, Chung F, Vann MA, Ahmad S, Gan TJ, Goulson DT, Merrill DG, Twersky R, Society for Ambulatory Anesthesia. Society for Ambulatory Anesthesia consensus statement on perioperative blood glucose management in diabetic patients undergoing ambulatory surgery. Anesth Analg. 2010;111(6): 1378–87.
7. Guzman JZ, Skovrlj B, Shin J, Hecht AC, Qureshi SA, Iatridis JC, Cho SK. The impact of diabetes mellitus on patients undergoing degenerative cervical spine surgery. Spine (Phila Pa 1976). 2014;39(20): 1656–65.
8. Fineberg SJ, Oglesby M, Patel AA, Singh K. Incidence and mortality of perioperative cardiac events in cervical spine surgery. Spine (Phila Pa 1976). 2013;38(15): 1268–74.
9. Hammill BG, Curtis LH, Bennett-Guerrero E, O'Connor CM, Jollis JG, Schulman KA, Hernandez AF. Impact of heart failure on patients undergoing major noncardiac surgery. Anesthesiology. 2008;108(4):559–67.
10. Auron M, Harte B, Kumar A, Michota F. Renin-angiotensin system antagonists in the perioperative setting: clinical consequences and recommendations for practice. Postgrad Med J. 2011;87(1029):472–81.
11. Biondi-Zoccai GG, Lotrionte M, Agostoni P, Abbate A, Fusaro M, Burzotta F, Testa L, Sheiban I, Sangiorgi G. A systematic review and meta-analysis on the hazards of discontinuing or not adhering to aspirin among 50,279 patients at risk for coronary artery disease. Eur Heart J. 2006;27(22):2667–74. Epub 2006 Oct 19.
12. Burger W, Chemnitius JM, Kneissl GD, Rücker G. Low-dose aspirin for secondary cardiovascular prevention – cardiovascular risks after its perioperative withdrawal versus bleeding risks with its continuation – review and meta-analysis. J Intern Med. 2005; 257(5):399–414.
13. CAPRIE Steering Committee. A randomised, blinded, trial of clopidogrel versus aspirin in patients at risk of

ischaemic events (CAPRIE). CAPRIE Steering Committee. Lancet. 1996;348(9038):1329–39.
14. Chassot PG, Marcucci C, Delabays A, Spahn DR. Perioperative antiplatelet therapy. Am Fam Physician. 2010;82(12):1484–9.
15. Steib A, Hadjiat F, Skibba W, Steib JP, French Spine Surgery Society. Focus on perioperative management of anticoagulants and antiplatelet agents in spine surgery. Orthop Traumatol Surg Res. 2011;97(6 Suppl): S102–6.
16. Fleisher LA, Beckman JA, et al. ACC/AHA 2007 guidelines on perioperative cardiovascular evaluation and care for noncardiac surgery: executive summary: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (Writing Committee to Revise the 2002 Guidelines on Perioperative Cardiovascular Evaluation for Noncardiac Surgery). Anesth Analg. 2008;106(3):685–712.
17. Chung F, Mezei G, Tong D. Pre-existing medical conditions as predictors of adverse events in day-case surgery. Br J Anaesth. 1999;83(2):262–70.
18. Møller AM, Villebro N, Pedersen T, Tønnesen H. Effect of preoperative smoking intervention on postoperative complications: a randomised clinical trial. Lancet. 2002;359(9301):114–7.
19. Spieth PM, Güldner A, de Abreu MG. Chronic obstructive pulmonary disease. Curr Opin Anaesthesiol. 2012;25(1):24–9.
20. Porhomayon J, El-Solh A, Chhangani S, Nader ND. The management of surgical patients with obstructive sleep apnea. Lung. 2011;189(5):359–67.
21. Abrishami A, Khajehdehi A, Chung F. A systematic review of screening questionnaires for obstructive sleep apnea. Can J Anaesth. 2010;57(5):423–38.
22. Joshi GP, Ankichetty SP, Gan TJ, Chung F. Society for Ambulatory Anesthesia consensus statement on preoperative selection of adult patients with obstructive sleep apnea scheduled for ambulatory surgery. Anesth Analg. 2012;115(5):1060–8.
23. Nørskov AK, Rosenstock CV, Wetterslev J, Astrup G, Afshari A, Lundstrøm LH. Diagnostic accuracy of anaesthesiologists' prediction of difficult airway management in daily clinical practice: a cohort study of 188 064 patients registered in the Danish Anaesthesia Database. Anaesthesia. 2015;70(3):272–81.
24. Apfelbaum JL, Hagberg CA, Caplan RA, Blitt CD, Connis RT, Nickinovich DG, Hagberg CA, Caplan RA, Benumof JL, Berry FA, Blitt CD, Bode RH, Cheney FW, Connis RT, Guidry OF, Nickinovich DG, Ovassapian A, American Society of Anesthesiologists Task Force on Management of the Difficult Airway. Practice guidelines for management of the difficult airway: an updated report by the American Society of Anesthesiologists Task Force on Management of the Difficult Airway. Anesthesiology. 2013;118(2):251–70.
25. Cheng WC, Jimmy-Ong, Lee CL, Lan CH, Chen TY, Lai HY. Pentax-airway scope for tracheal intubation breaks through the limitation of neck motion in an ankylosing spondylitis patient wearing halo vest – a case report. Acta Anaesthesiol Taiwan. 2010;48(4):180–1.
26. Brück S, Trautner H, Wolff A, Hain J, Mols G, Pakos P, Roewer N, Lange M. Comparison of the C-MAC(®) and GlideScope(®) videolaryngoscopes in patients with cervical spine disorders and immobilisation. Anaesthesia. 2015;70(2):160–5.
27. Song JW, Kwak YL, Lee JW, Chang CH, Kim HS, Shim YH. The optimal effect site concentration of remifentanil in combination with intravenous midazolam and topical lidocaine for awake fibreoptic nasotracheal intubation in patients undergoing cervical spine surgery. Minerva Anestesiol. 2012;78(5):521–6.
28. Ezri T, Szmuk P, Warters RD, Katz J, Hagberg CA. Difficult airway management practice patterns among anesthesiologists practicing in the United States: have we made any progress? J Clin Anesth. 2003;15(6): 418–22.
29. Peterson GN, Domino KB, Caplan RA, Posner KL, Lee LA, Cheney FW. Management of the difficult airway: a closed claims analysis. Anesthesiology. 2005; 103(1):33–9.
30. Martirosyan NL, Feuerstein JS, Theodore N, Cavalcanti DD, Spetzler RF, Preul MC. Blood supply and vascular reactivity of the spinal cord under normal and pathological conditions. J Neurosurg Spine. 2011;15(3):238–51.
31. Pajewski TN, Arlet V, Phillips LH. Current approach on spinal cord monitoring: the point of view of the neurologist, the anesthesiologist and the spine surgeon. Eur Spine J. 2007;16 Suppl 2:S115–29.
32. Li F, Gorji R, Allott G, Modes K, Lunn R, Yang ZJ. The usefulness of intraoperative neurophysiological monitoring in cervical spine surgery: a retrospective analysis of 200 consecutive patients. J Neurosurg Anesthesiol. 2012;24(3):185–90.
33. Jahangiri FR, Sheryar M, Al Behairy Y. Early detection of pedicle screw-related spinal cord injury by continuous intraoperative neurophysiological monitoring (IONM). Neurodiagn J. 2014;54(4):323–37.
34. Nitzschke R, Hansen-Algenstaedt N, Regelsberger J, Goetz AE, Goepfert MS. Intraoperative electrophysiological monitoring with evoked potentials. Anaesthesist. 2012;61(4):320–35.
35. Stecker MM. A review of intraoperative monitoring for spinal surgery. Surg Neurol Int. 2012;3 Suppl 3:S174–87.
36. Sloan TB, Heyer EJ. Anesthesia for intraoperative neurophysiologic monitoring of the spinal cord. J Clin Neurophysiol. 2002;19(5):430–43.
37. Asouhidou I, Katsaridis V, Vaidis G, Ioannou P, Givissis P, Christodoulou A, Georgiadis G. Somatosensory Evoked Potentials suppression due to remifentanil during spinal operations; a prospective clinical study. Scoliosis. 2010;5:8.
38. Plata Bello J, Pérez-Lorensu PJ, Roldán-Delgado H, Brage L, Rocha V, Hernández-Hernández V, Dóniz A, García-Marín V. Role of multimodal intraoperative neurophysiological monitoring during positioning of patient prior to cervical spine surgery. Clin Neurophysiol. 2014;126(6):1264–70.

39. Kudo T, Sato Y, Kowatari K, Nitobe T, Hirota K. Postoperative transient tetraplegia in two patients caused by cervical spondylotic myelopathy. Anaesthesia. 2011; 66(3):213–6.
40. Kamel I, Barnette R. Positioning patients for spine surgery: avoiding uncommon position-related complications. World J Orthop. 2014;5(4):425–43.
41. American Society of Anesthesiologists Task Force on Prevention of Perioperative Peripheral Neuropathies. Practice advisory for the prevention of perioperative peripheral neuropathies: an updated report by the American Society of Anesthesiologists Task Force on prevention of perioperative peripheral neuropathies. Anesthesiology. 2011;114(4): 741–54.
42. Roth S. Perioperative visual loss: what do we know, what can we do? Br J Anaesth. 2009;103 Suppl 1:i31–40. doi:10.1093/bja/aep295.
43. American Society of Anesthesiologists Task Force on Perioperative Visual Loss. Practice advisory for perioperative visual loss associated with spine surgery: an updated report by the American Society of Anesthesiologists Task Force on Perioperative Visual Loss. Anesthesiology. 2012;116(2):274–85.
44. Lee LA, Roth S, Posner KL, Cheney FW, Caplan RA, Newman NJ, Domino KB. The American Society of Anesthesiologists Postoperative Visual Loss Registry: analysis of 93 spine surgery cases with postoperative visual loss. Anesthesiology. 2006;105(4):652–9; quiz 867–8.
45. Nickels TJ, Manlapaz MR, Farag E. Perioperative visual loss after spine surgery. World J Orthop. 2014;5(2):100–6.
46. St-Arnaud D, Paquin MJ. Safe positioning for neurosurgical patients. AORN J. 2008;87(6):1156–68.
47. Barnes M, Liew S. The incidence of infection after posterior cervical spine surgery: a 10 year review. Global Spine J. 2012;2(1):3–6.
48. Halvorsen CM, Lied B, Harr ME, Rønning P, Sundseth J, Kolstad F, Helseth E. Surgical mortality and complications leading to reoperation in 318 consecutive posterior decompressions for cervical spondylotic myelopathy. Acta Neurol Scand. 2011;123(5):358–65.
49. Schimmel JJ, Horsting PP, de Kleuver M, Wonders G, van Limbeek J. Risk factors for deep surgical site infections after spinal fusion. Eur Spine J. 2010; 19(10):1711–9.
50. Bratzler DW, Dellinger EP, Olsen KM, Perl TM, Auwaerter PG, Bolon MK, Fish DN, Napolitano LM, Sawyer RG, Slain D, Steinberg JP, Weinstein RA, American Society of Health-System Pharmacists (ASHP), Infectious Diseases Society of America (IDSA), Surgical Infection Society (SIS), Society for Healthcare Epidemiology of America (SHEA). Clinical practice guidelines for antimicrobial prophylaxis in surgery. Surg Infect (Larchmt). 2013;14(1):73–156.
51. Oglesby M, Fineberg SJ, Patel AA, Pelton MA, Singh K. The incidence and mortality of thromboembolic events in cervical spine surgery. Spine (Phila Pa 1976). 2013;38(9):E521–7.
52. Epstein NE. Intermittent pneumatic compression stocking prophylaxis against deep venous thrombosis in anterior cervical spinal surgery: a prospective efficacy study in 200 patients and literature review. Spine (Phila Pa 1976). 2005;30(22):2538–43.
53. Gould MK, Garcia DA, Wren SM, Karanicolas PJ, Arcelus JI, Heit JA, Samama CM, American College of Chest Physicians. Prevention of VTE in nonorthopedic surgical patients: antithrombotic therapy and prevention of thrombosis, 9th ed: American College of Chest Physicians Evidence-Based Clinical Practice Guidelines. Chest. 2012;141(2 Suppl):e227S–77.
54. Buvanendran A, Thillainathan V. Preoperative and postoperative anesthetic and analgesic techniques for minimally invasive surgery of the spine. Spine (Phila Pa 1976). 2010;35(26 Suppl):S274–80.
55. Sharma S, Balireddy RK, Vorenkamp KE, Durieux ME. Beyond opioid patient-controlled analgesia: a systematic review of analgesia after major spine surgery. Reg Anesth Pain Med. 2012;37(1):79–98.
56. Elvir-Lazo OL, White PF. The role of multimodal analgesia in pain management after ambulatory surgery. Curr Opin Anaesthesiol. 2010;23(6):697–703.
57. Liu SS, Richman JM, Thirlby RC, Wu CL. Efficacy of continuous wound catheters delivering local anesthetic for postoperative analgesia: a quantitative and qualitative systematic review of randomized controlled trials. J Am Coll Surg. 2006;203(6):914–32.
58. Elder JB, Hoh DJ, Liu CY, Wang MY. Postoperative continuous paravertebral anesthetic infusion for pain control in posterior cervical spine surgery: a case–control study. Neurosurgery. 2010;66(3 Suppl Operative):99–107.
59. Li Q, Zhang Z, Cai Z. High-dose ketorolac affects adult spinal fusion: a meta-analysis of the effect of perioperative nonsteroidal anti-inflammatory drugs on spinal fusion. Spine (Phila Pa 1976). 2011;36(7): E461–8.
60. Blumenthal S, Min K, Marquardt M, Borgeat A. Postoperative intravenous morphine consumption, pain scores, and side effects with perioperative oral controlled-release oxycodone after lumbar discectomy. Anesth Analg. 2007;105(1):233–7.
61. Yamauchi M, Asano M, Watanabe M, Iwasaki S, Furuse S, Namiki A. Continuous low-dose ketamine improves the analgesic effects of fentanyl patient-controlled analgesia after cervical spine surgery. Anesth Analg. 2008;107(3):1041–4.
62. Loftus RW, Yeager MP, Clark JA, Brown JR, Abdu WA, Sengupta DK, Beach ML. Intraoperative ketamine reduces perioperative opiate consumption in opiate-dependent patients with chronic back pain undergoing back surgery. Anesthesiology. 2010;113(3):639–46.
63. Gan TJ, Meyer TA, Apfel CC, Chung F, Davis PJ, Habib AS, Hooper VD, Kovac AL, Kranke P, Myles P, Philip BK, Samsa G, Sessler DI, Temo J, Tramèr MR, Vander Kolk C, Watcha M, Society for Ambulatory Anesthesia. Society for Ambulatory Anesthesia guidelines for the management of postoperative nausea and vomiting. Anesth Analg. 2007;105(6):1615–28.

64. Apfel CC, Läärä E, Koivuranta M, Greim CA, Roewer N. A simplified risk score for predicting postoperative nausea and vomiting: conclusions from cross-validations between two centers. Anesthesiology. 1999; 91(3):693–700.
65. Apfel CC, Kranke P, Katz MH, Goepfert C, Papenfuss T, Rauch S, Heineck R, Greim CA, Roewer N. Volatile anaesthetics may be the main cause of early but not delayed postoperative vomiting: a randomized controlled trial of factorial design. Br J Anaesth. 2002; 88(5):659–68.
66. Kolodzie K, Apfel CC. Nausea and vomiting after office-based anesthesia. Curr Opin Anaesthesiol. 2009;22(4):532–8.
67. Dagher CF, Abboud B, Richa F, Abouzeid H, El-Khoury C, Doumit C, Yaghi C, Yazbeck P. Effect of intravenous crystalloid infusion on postoperative nausea and vomiting after thyroidectomy: a prospective, randomized, controlled study. Eur J Anaesthesiol. 2009;26(3):188–91.
68. White PF, Eng M. Fast-track anesthetic techniques for ambulatory surgery. Curr Opin Anaesthesiol. 2007; 20(6):545–57.
69. Henzi I, Walder B, Tramèr MR. Dexamethasone for the prevention of postoperative nausea and vomiting: a quantitative systematic review. Anesth Analg. 2000;90(1):186–94.
70. Melton MS, Klein SM, Gan TJ. Management of post-discharge nausea and vomiting after ambulatory surgery. Curr Opin Anaesthesiol. 2011;24(6):612–9.
71. Ormel G, Romundstad L, Lambert-Jensen P, Stubhaug A. Dexamethasone has additive effect when combined with ondansetron and droperidol for treatment of established PONV. Acta Anaesthesiol Scand. 2011;55(10):1196–205.
72. Dogan U, Yavas G, Tekinalp M, Yavas C, Ata OY, Ozdemir K. Evaluation of the acute effect of palonosetron on transmural dispersion of myocardial repolarization. Eur Rev Med Pharmacol Sci. 2012;16(4):462–8.
73. Antor MA, Uribe AA, Erminy-Falcon N, Werner JG, Candiotti KA, Pergolizzi JV, Bergese SD. The effect of transdermal scopolamine for the prevention of postoperative nausea and vomiting. Front Pharmacol. 2014;5:55.
74. Apfel CC, Zhang K, George E, Shi S, Jalota L, Hornuss C, Fero KE, Heidrich F, Pergolizzi JV, Cakmakkaya OS, Kranke P. Transdermal scopolamine for the prevention of postoperative nausea and vomiting: a systematic review and meta-analysis. Clin Ther. 2010;32(12):1987–2002.
75. Halloran K, Barash PG. Inside the black box: current policies and concerns with the United States Food and Drug Administration's highest drug safety warning system. Curr Opin Anaesthesiol. 2010;23(3):423–7.
76. Gan TJ, Gu J, Singla N, Chung F, Pearman MH, Bergese SD, Habib AS, Candiotti KA, Mo Y, Huyck S, Creed MR, Cantillon M, Rolapitant Investigation Group. Rolapitant for the prevention of postoperative nausea and vomiting: a prospective, double-blinded, placebo-controlled randomized trial. Anesth Analg. 2011;112(4):804–12.
77. Willms D, Shure D. Pulmonary edema due to upper airway obstruction in adults. Chest. 1988;94(5): 1090–2.
78. Palumbo MA, Aidlen JP, Daniels AH, Bianco A, Caiati JM. Airway compromise due to laryngopharyngeal edema after anterior cervical spine surgery. J Clin Anesth. 2013;25(1):66–72.
79. Anastasian ZH, Gaudet JG, Levitt LC, Mergeche JL, Heyer EJ, Berman MF. Factors that correlate with the decision to delay extubation after multilevel prone spine surgery. J Neurosurg Anesthesiol. 2014;26(2): 167–71.
80. De Bast Y, De Backer D, Moraine JJ, Lemaire M, Vandenborght C, Vincent JL. The cuff leak test to predict failure of tracheal extubation for laryngeal edema. Intensive Care Med. 2002;28(9):1267–72.
81. Zeng JH, Zhong ZM, Chen JT. Early dysphagia complicating anterior cervical spine surgery: incidence and risk factors. Arch Orthop Trauma Surg. 2013; 133(8):1067–71.
82. Radcliff KE, Koyonos L, Clyde C, Sidhu GS, Fickes M, Hilibrand AS, Albert TJ, Vaccaro AR, Rihn JA. What is the incidence of dysphagia after posterior cervical surgery? Spine (Phila Pa 1976). 2013;38(13):1082–8.
83. Anderson KK, Arnold PM. Oropharyngeal Dysphagia after anterior cervical spine surgery: a review. Global Spine J. 2013;3(4):273–86.
84. Apfelbaum RI, Kriskovich MD, Haller JR. On the incidence, cause, and prevention of recurrent laryngeal nerve palsies during anterior cervical spine surgery. Spine (Phila Pa 1976). 2000;25(22):2906–12.
85. Fineberg SJ, Oglesby M, Patel AA, Singh K. Incidence, risk factors, and mortality associated with aspiration in cervical spine surgery. Spine (Phila Pa 1976). 2013;38(19):E1189–95.
86. Kaloostian PE, Kim JE, Bydon A, Sciubba DM, Wolinsky JP, Gokaslan ZL, Witham TF. Intracranial hemorrhage after spine surgery. J Neurosurg Spine. 2013;19(3):370–80.
87. Chen Z, Zhang X, Jiang Y, Wang S. Delayed emergence from anesthesia resulting from bilateral epidural hemorrhages during cervical spine surgery. J Clin Anesth. 2013;25(3):244–5.
88. Lee MJ, Lin EL. The use of the three-pronged Mayfield head clamp resulting in an intracranial epidural hematoma in an adult patient. Eur Spine J. 2010;19 Suppl 2:S187–9.

Cervical PLDD (Percutaneous Laser Discectomy). Ten Years Experience

6

Ralf Klein and Frank Sommer

Introduction

The Percutaneous Laser Disc Decompression/Denervation (PLDD) is a treatment option that has been known for several years. There has, however, been a controversial discussion about its indications and benefits.

The selection of the laser system, the laser settings and parameters, inclusion and exclusion criteria, as well as the effective temperature and the effective temperature distribution in the tissue, have an important influence on the laser radiation in the disc material.

These questions have been raised by several studies in the literature since the introduction of PLDD in 1986.

The aim of this article is to describe the basis, indications, selection of parameters and problems based on our own experience. Furthermore we aim to describe the historical problems which lead to a rather critical view of the PLDD in the literature. In our view these problems have been overcome, and are no longer valid in the present use of PLDD. Dres. Sommer, Schneiderhan et al. have been employing this method since 2001 with great success, and since 2004 for cervical pathologies. Klein has been working on the development and use of laser systems in spine surgery since 1995.

R. Klein (✉)
Department of RadiMed Laser, Radimed GmbH, Bochum, Germany
e-mail: klein@radimed.de

F. Sommer
Department of Spine Unit, Medical Center of Spinal Disorders, Munich/Taufkirchen, Germany

PLDD

PLDD was first described in 1987 by Choy Ascher and colleagues. They were exploring alternative therapies for the chemonucleolysis, which was causing significant side effects [1].

They used a Nd:YAG Laser with a wave length of 1064 nm. The 600 µm laser probe was introduced through a 14G cannula.

The Nd:YAG – often wrongly only referred to as YAG Laser -was the best available model in medical application at that time. The probe could be introduced via fiber optic devices. Furthermore the Nd Yag laser showed the best features for tissue penetration.

Later, several alternative devices were tested (Excimer, Er:YAG, Ho:YAG, Nd:YAG frequency doubled, CO_2 etc, [2–7]). The aim of these experiments was to improve the tissue vaporization and to decrease thermal impairment.

Er:YAG and CO_2 play no role in the clinical application, because no fiber system exists for these wavelengths.

P.P.M. Menchetti (ed.), *Cervical Spine: Minimally Invasive and Open Surgery*,
DOI 10.1007/978-3-319-21608-9_6

Tissue Interaction

The penetration depth is an important parameter for the interaction of light and tissue. It depends solely on the wavelength and the optical properties of the tissue itself. All other laser parameters have no influence on the penetration depth.

Based on the assumption that human disc material contains >70 % of water [8], one could employ the absorption array of water in order to describe basic tissue interactions.

Looking at the most widely used laser systems for PLDD (Nd:YAG 1064 nm) Ho:YAG (2100 nm) and diode laser (980 nm) tissue interactions are significantly different (Fig. 6.1).

Wavelength (nm)	Lasertype	α (cm-1)	L (cm)
980	Diode	0.473	2.11
1064	Nd:YAG	0.144	6.94
2120	Ho:YAG	36.40	0.028

Absorption coefficient of water for the different wavelength, calculated for Ho:YAG [12], Diode and Nd:YAG [13]

The penetration depth given in the table is calculated for water only and is different in the disc material conditionally due to scattering etc. Gangi et al. evaluated the tissue penetration depth for Nd:YAG of nearly 7 mm [14]. Ho:YAG Laser shows a relatively lower penetration depth compared to the Diode Laser, followed by the Nd:YAG Laser.

In addition to the Laser and the tissue type, one has to take more parameters into account in order to understand the tissue interactions (Fig. 6.2).

Laser power, pulse energy, pulse duration, fiber diameter, energy and power density and the duration of the application etc., are important parameters showing a significant influence on the processes taking place in the target tissue [4, 9, 15–17].

Short, high energetic pulses with a high power density lead to tissue disruption and ablation effects. In contrast, longer laser pulses with lower power densities lead to thermal effects.

Ho:YAG Laser have the highest power density and show ablative reactions and lower thermal effects [6]. The disadvantage of the short pulses is the cavitation wave, with possible negative effects on the adjacent tissue [14, 18].

Nd:YAG have a deeper tissue penetration and longer pulse duration, therefore the thermal effects are greater in the tissue [6, 19].

Experiments by Laser und Medizintechnologie GmbH Berlin show [20], that the tissue penetration of the diode laser (980 nm) when compared to the Nd:YAG Laser, is reduced by half. The reason for this is mainly the high water content of the disc material. But the ablation effects of the Ho:YAG are not attained at this power density.

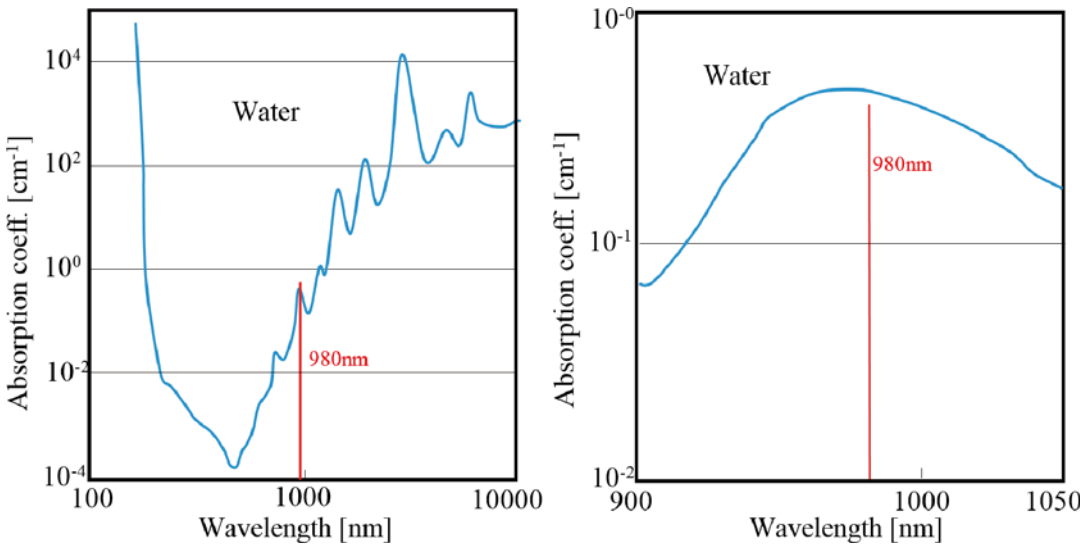


Fig. 6.1 Absorption coefficient of water for the different wavelength according to [9] (Additional Refs. [10, 11])

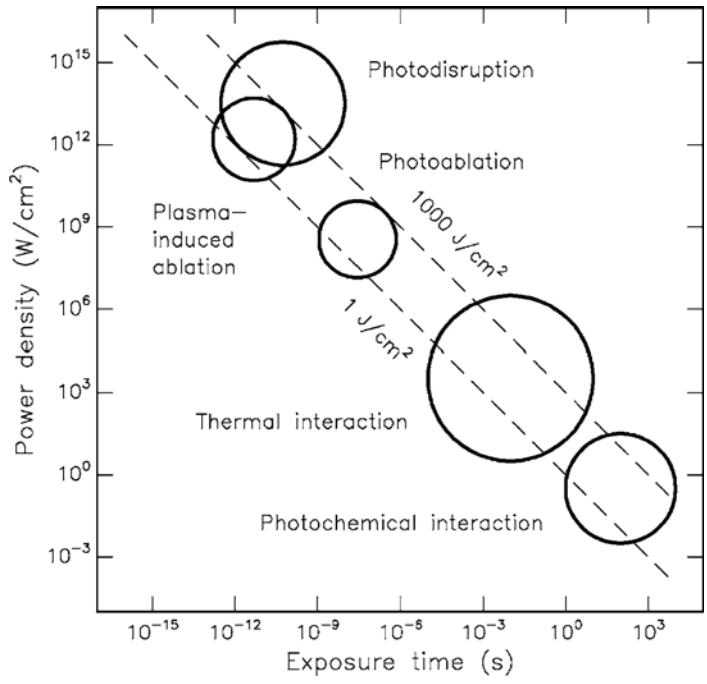


Fig. 6.2 Laser- tissue interaction – *circles* show a rough calculation (With permission from Niemz [15])

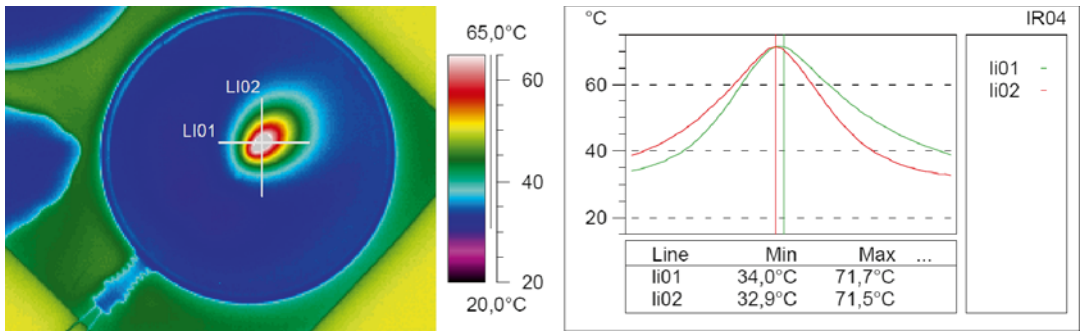


Fig. 6.3 Temperature profile in Agar-Agar for demonstration of the tissue penetration

One has to take into account that carbonization of the fiber tip leads to changed optical properties. Schlangmann et al. examined [21] the carbonization effect of the Nd:YAG Laser. If the fiber tip is carbonized, a direct vaporization of tissue is possible.

Discussions with those who employ it already showed that the hot tip technique is often used by directing the fiber tip to a wooden spatula in order to carbonize the fiber tip.

This technique should avoid a too high penetration depth and possible damage to vascular tissue because of a high absorption of hemoglobin [19, 20].

It is not recommended because it changes the array of the laser probe to an unpredictable amount.

On the contrary a 980 nm Diode laser with a lower tissue penetration should be selected.

The following figures show the thermal properties of a Diode laser in a thin Agar-Agar layer demonstrating the tissue penetration and the heat conduction (Fig. 6.3).

The fibre is symbolized. The cross shows the measuring line of the temperature profile in the diagram.

Parameter: $\lambda = 980$ nm, $P = 7.5$ W, $P_{on} = 750$ ms, $P_{off} = 750$ ms

Mode of Action of the PLDD

Vaporisation

Based on the described tissue interaction between laser radiation and the tissue, one can assume that the tissue will be vaporized leading to a volume reduction [1, 8, 21–24].

The quantitative evaluation of this vaporization effect was done as early as 1995/1996. Buchelt et al. [22] describe a nearly linear relationship between resection rate and applied energy (for the Ho:YAG Lasers), but no significant increase in the ablation rate and maximal power between 10 and 32 W.

Similar results are found by Schlangmann et al. according to ablation rate and applied power [21]. Furthermore, the Ho:YAG and Nd:YAG lasers were compared. The ablation rate was 200 mg (1064 nm, $P_{max}=20$ W, $P_{on}=1$ s, $P_{off}=5$ s, $E=1500$ J).

With the Ho:YAG Laser, Min et al. [8] examined an ablation rate of 1.89 g following the application of 20,000 J.

Shrinkage

In addition to the vaporization effects, tissue shrinkage of collagen takes place by thermal exposure.

In 1995 Siebert in [25], Choy and Altman in [23] and 1999 Hellinger in [26] were able to demonstrate this effect. Several other researchers confirmed tissue shrinkage of disc material [27–29]. Wang et al. showed that a temperature of 75 °C is sufficient, to result in collagen shrinkage. A higher temperature showed no additional effects.

The Diode- and the Nd:YAG Laser seem to be superior to the Ho:YAG, because these two systems show a deeper thermal effect on the tissue and an increased surface where these effects show an influence.

Decompression

The two previously described effects, vaporization and shrinkage of the collagen, lead to a reduction of volume and a lowering of the intradiscal pressure.

Choy considered the disc to be a hydraulic system in which small changes in volume could lead to relatively big changes in the tissue pressure [23].

Hellinger and Stern [30] describe the shrinking effect to be as high as 14 %, employing a Nd:YAG Laser.

According to the property of nucleus pulposus to accumulate water the, shrinking of the disc tissue could create a more permanent effect in relation to its vaporization, because it can be expected, that in course of time the nucleus will cumulate more volume [31].

It is generally accepted that the intradiscal pressure plays an important role in the pathophysiology of pain. During discographies radicular pain can be provoked by an injection of contrast media and an increase of the intradiscal pressure.

In addition to the elevation of the intradiscal pressure and the provocation of pain a radiological examination can be carried out. Discography can be performed in the cervical spine as well as in the rest of the spinal column [7].

Pathological discs show the so-called dicogenic pain, at relatively low intradiscal pressures. (discpain), healthy discs, tolerate higher intradiscal pressures [32]. These conclusions are only correct when the annulus fibrosus is intact. All degenerative changes that lead to a sequestrated disc herniation or a disrupted annulus fibrosus are a contraindication for PLDD.

Denervation

The observation that an increase of the intradiscal pressure can lead to pain, demonstrates that it is possible that the disc in itself can be painful.

Several studies show a neuronal innervation of the disc tissue. Inman et al. were the first to show this in 1947 [33]. These observations are not generally accepted. In the subsequent years several studies were able to demonstrate an innervation of the disc tissue. Most of these studies were performed on lumbar disc material [32, 34], however a few studies could show mechanoreceptors and neuronal tissue in cervical disc material [7, 35].

Annular fissures and micro fractures may lead to a deep penetration of the nerve tissue into the degenerated annulus fibrosus, resulting in increased pain during movements in the motion segment [36].

The laser could lead to a denervation of the disc material and therefore a decreased pain perception.

It is therefore recommended that the laser fiber should not be placed into the center of the disc during a lumbar laser treatment. The probe should be placed at the border of the annulus fibrosus [37, 38].

Because of the different, more anterolateral approach in the treatment of cervical disc pathologies, the posterior part of the disc can be easily reached, but it is recommended avoiding a posterior placement of the probe, in order to prevent damage of neuronal structures. Due to the tissue penetration of the laser radiation, a lesion of neuronal structures cannot be excluded.

Anti Inflammatory Effects

In addition to the innervation of degenerated disc material, biochemical processes like the induction of inflammatory reactions in the disc material can lead to the generation of pain.

Phospholipase A2, Interleukin-1 and nitrogen oxides are found in degenerated disc material. This could lead to the synthesis of the neuropeptide Substance P and to the induction of the pain cascade.

During the laser application a denaturation of these cytokines is assumed [39].

Summary of Action

As opposed to alternative treatment options for discogenic pain like the IDET, PLDD shows more modes of action. PLDD acts not solely anti-inflammatory and via a denervation but results in a shrinkage and volume reduction of the disc material. These effects explain the rapid improvement of pain syndromes that most of the patients describe after PLDD.

Selection of Parameters for Cervical Treatment

In the literature there is a great variety of recommended parameters. Especially the applied energy and the maximal power are inhomogenously reported. Furthermore some peers do not give any information about the selected parameters at all.

Looking especially at cervical laser applications one notices that Hellinger et al. performed as early as 1990 first laser applications for cervical pain syndromes [40] However the cervical treatment amounts to only 7–8 % of all laser applications in the human spine.

In the following years there is no marked increase in the amount of cervical treatments. Choy and Hellinger et al. [41] repost more than 22,615 PLDD treatments of which 1641 were performed on the cervical spine. These numbers refer to their own patients and to a literature review up to 2009. Our own data confirm the previously reported amount of 8 % of cervical treatments.

In the following table some parameters are given for laser treatment in the cervical spine

Laser	P_{max} (W)	$Puls_{on}$ (s)	$Puls_{off}$ (s)	P_{eff} (W)	E_{max} (J)	Year
Nd:YAG	10	1	3	2.5	300	[42] 2004
Nd:YAG	10–12	0.2–1.0	0.5–1.7	2.9–4.4	300–800	[7] 2011
Nd:YAG	10	0.3	1.7	1.5	120–500	[43] 2001
Nd:YAG	15–20	0.3	–	–	350–450	[26] 1999
Nd:YAG	5/10/20	–	–	–	400–700	[44][a] 2004
810 nm	15	1.0	2.0	5	300–1000	[45] 2007
Ho:YAG	12	0.5 J/12 Hz + pause		6	600–800	[46] 2001
Ho:YAG	2.5	0.5 J/5 Hz		2.5	400	[25] 1995
KTP532	12	0.2	0.5	3.4	600–800	[46] 2001
980 nm	**7.5**	**0.7**	**1.0**	**3.1**	**180–200**	**Authors**

[a]In-vitro temperature study

P_{eff} is calculated by the pulse power and the on/off relation

When comparing lumbar laser treatments with cervical laser applications, it becomes evident that for the lumbar treatment, significantly higher parameters were chosen.

Siebert et al. report [47] in in-vitro experiments thermal consequences of the Nd:YAG Lasers employing a power up to 40 W, a pulse duration of 1 s and a total applied power of 1000 J. Min et al. present data of PLDD treatments with Ho:YAG 14 W and a total applied power of up to 20,000 J.

In the early years of lumbar laser application, the parameters differed widely. Due to a vast amount of subsequent in-vivo und in-vitro experiments parameters could be optimized [21, 22, 27, 38, 39, 44, 47–50].

If devices are used which show a longer pulse duration (980 nm Diode laser, Nd:YAG Laser), one could use different pulse duration and pulse pause as well as the pulse power. These observations lead to a continuous decrease in the laser power. At present the recommended parameters for lumbar and cervical laser applications are nearly similar. The only exception is that the applied total power is significantly lower because the total volume of a cervical disc is significantly lower. Therefore 35–50 % of the recommended total power of lumbar applications is employed for cervical treatments [14, 26, 43, 51, 52].

Summarizing the literature it becomes evident that due to the vast amount of possible parameters and the biological properties of the disc material itself a highly complex situation results which makes it impossible to give standard recommendations for the PLDD treatment.

The total applied power is described as the primary parameter in several publications, but it is very important to describe how the total power is archived.

A high pulse power applied for a short amount of time result in the same total power as low pulse power applied for a longer period of time. The resulting tissue interaction however is most likely to be different [31].

In retrospect, however, there is a standardized recommendation of parameters with a certain amount of variation.

Looking at the wavelength the Nd:YAG Laser seems to be superior to the other systems , as well as the Diode laser, which was introduced for clinical applications in the human spine in 1990. A literature review by Chambers et al. [53] in 1995 reveals that 231 patients 90 % were treated by Nd:YAG and the rest of 23 patients were treated with Ho:YAG Laser devices.

Some surgeons still use Ho:YAG Laser systems. Yet looking at the physical parameters, it becomes, in our opinion, self -evident to employ Nd:YAG or diode laser systems.

The primary reason for the Ho:YAG Lasers was the attempt to increase the ablation rate by vaporization of tissue without significant thermal changes in the adjacent tissue. But it was demonstrated that a significant increase of the temperature in some areas is present when employing a Ho:YAG Laser system [54].

Later examinations revealed that a broad thermal effect plays an important role in the treatment of degenerative disc disease (shrinking, anti-inflammatory effects and denervation). Therefore it is recommended to choose a wavelength closer to the near infrared spectrum in order to archive a broader thermal effect.

It is clear that the Ho:YAG shows thermal effects. However, these effects occur as high temperatures at the distal end of the laser fiber without significant thermal penetration into the tissue. Because of the better thermal penetration of lasers, having a wavelength between 980 and 1064 nm, a larger area of disc tissue can be treated.

Reviewing the literature there is no publication concerning the use of the diode laser 980 nm for cervical pathologies. General observations for the intradiscal use of the diode laser can be found by the LMTB Berlin 1995 [20], 1998 Paul and Hellinger in [55] and Grönemeyer, Gervagez et al. since 2000 in [52, 56].

Our group Schneiderhan, Sommer et al. have been employing the 980 nm Laser since 2002 for the PLDD lumbar pathologies, and since 2004 for the cervical treatment. We had reliably good

results in 3978 cases, of which 330 procedures were on the cervical spine.

Necessary Equipment

In order to perform the PLDD in a low complication setting the usual sterile drapes and an appropriate procedure room are necessary. Furthermore, the presence of an anaesthesiologist is mandatory for the cervical PLDD treatment.

Listed is the necessary equipment for the cervical PLDD

- Radiology equipment (Fluroscopy or CT scanner) (alternatively MRI [28, 57] if MRI compatible cannulas are available and the laser fiber is long enough)
- Basic drapes for a sterile work space
- Contrast media for intradiscal application
- Optional single-shot antibiotic treatment (Cephalosporin)
- Diode laser 980 nm, 10 W maximal power (Fig. 6.4)
- Single use laser set – cannula 21G and a laser fiber 360 µm as well as a fixation device. This device is especially important to prevent the laser fiber from sliding back into the cannula where it could lead to a marked increase of the temperature in the cannula with a possible detrimental effect on the adjacent tissue (Fig. 6.5).

Aim, Indications and Contraindications for Cervical PLDD

Aim

Aim of the PLLD treatment is to partially or fully resolve symptoms of degenerative disc disease by employing the above mentioned effects.

Target symptoms are discogenic cervical, cervicocephal and radiating pain syndromes. A resolution of sensory or motor deficit can be archived by the decompression effect of the PLDD.

Inclusion criteria for such a treatment were initiated by Botsford et al. [58–60] in 1993/1995, by revealing data from the radiological examinations especially the CT discography. Grasshoff et al. evaluated in 2001 the correlation between discography and treatment results of the PLDD [61].

Indication

In order to increase the quality of the treatment results, inclusion criteria play an important role. It is recommended that a course of conservative treatment is undertaken, and that the result be unacceptable. In order to archive positive results it is mandatory that the cervical disc can be entered by the cannula. The minimal disc height should be at least 4 mm. Osteophytes should not be present at the ventral border of the disc space. Furthermore calcification, sclerosis of the annu-

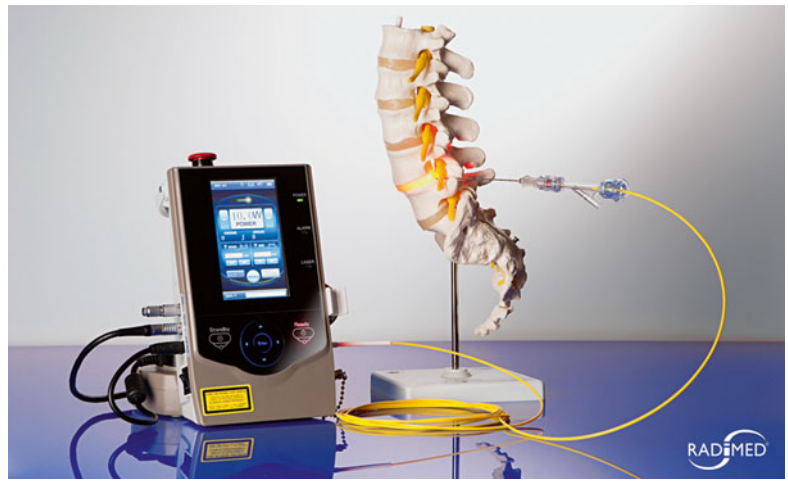


Fig. 6.4 Diode laser 980 nm and laser fiber set, Radimed GmbH

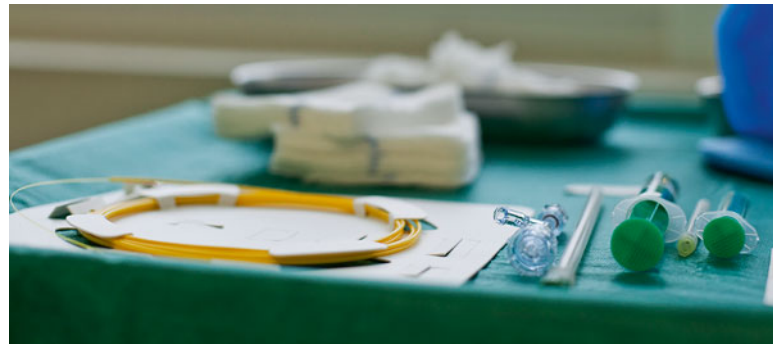


Fig. 6.5 Instruments from left to right – laser fiber, fixation device, cannula 21G

lus fibrosis or the posterior longitudinal ligament should be excluded by a CT scan examination.

A closed annular ring is mandatory for the laser treatment. This is a dislocation grade of III according to Grasshoff et al. [61].

Additional information about the hydration grade of the cervical disc (Black-Disc-Sign) can be archived by MRI examinations. Furthermore, the dislocation grade of the disc can be evaluated non-invasively.

Dislocation grade	Description
Dislocation grade I	Protrusion inside of the annulus fibrosus
Dislocation grade II	Protrusion up to the outer area of the annulus
Dislocation grade III	Covered herniation
Dislocation grade IV	Contained herniation
Dislocation grade V	Sequestrated herniation

Dislocation grade of the disc, according to Kremer et al. [73]

Contraindications

Main contraindications for the PLDD are a dislocation grade of the disc of more than grade III, or a free sequestrated disc herniation. Furthermore, bony spinal canals stenosis cannot be treated by the PLDD.

It is clear that systemic contraindications for surgical treatments like systemic infections, untreated blood clotting diseases are valid for the PLDD. Treatments with anticoagulants limit the treatment with the PLDD. A laser treatment is not indicated after an open surgical intervention was performed or when a spondylodiscitis is present. Due to the fact that the decompression effect occurs over time, patients showing a progressive neurological deficit or a myelopathic deficit cannot be treated sufficiently by PLDD.

Performance

Before the intervention, it is mandatory to inform the patient and archive an informed consent. On the day of the procedure the patient is not allowed food or drink. Sometimes sedatives are administered, as recommended by the anesthesiologist.

Performing this procedure under local anesthesia is not recommended as experience shows that a local anesthesia is not sufficiently effective in the cervical area.

After close consultation with the anesthesiologist, and after establishing the overall physical condition of the patient, intravenous anesthesia or general anesthesia can be chosen. If necessary, all techniques of airway protection can be performed.

According to these precautions a rapid endotracheal intubation is possible in the case of the cervical vessels being accidentally punctured and a hematoma developing. This kind of puncture is unlikely, however, due to the limited movement of the patient in this setting.

An optional single shot antibiotic prophylaxis can be administered. We recommend a cephalosporin 20 min prior to the procedure.

The patient is positioned on his or her back; CT scan or the fluoroscopic device is positioned.

Following the usual antiseptic preparations, the pathological level is identified under radiological guidance.

The sternocleidomastoid muscle is then palpated and laterally advanced in order to move the underlying vessels moderately lateral to the cervical spine.

The skin can then be punctured by the introducing cannula and the cannula will be advanced in an 30° angle medially under radiological guidance (Fig. 6.6).

Repetitive radiological examinations CT scan/Fluoroscopy secure the correct position of the cannula.

When the anterior cervical ligament is reached, the annulus fibrosus is perforated (loss of resistance!); according to the selected target area the cannula is positioned intradiscally (dorsal quadrant right, left or central).

After needle placement, the correct position is evaluated radiologically by CT scan or fluroscopy (ap and lateral view) Furthermore, a discography is performed. With this procedure, the correct needle placement can be documented and a sequestrated disc herniation can be excluded. If an additional level is to be treated, the puncture procedure has to be performed identically (Figs. 6.7 and 6.8).

The 1–2 mm long laser fiber is introduced into the cannula after the removal of the cannula mandrain. The PLDD can be performed without interruption employing the above mentioned parameters. If necessary, an additional level can be treated during the same procedure (Fig. 6.9).

After removal of the laser fiber, a local cephalosporin is intradiscally applied in order to minimize the risk of an infection [62–64]. Then the cannula can be removed and a tape is applied.

Mobilization of the patient is decided according to the recommendation of the anesthesiologist – usually 2 h following the procedure.

Postoperative analgesia is recommended by administration of non-steroidal analgesics for 5 days. Until the patient is fully able to carry out household or professional tasks, a soft collar is recommended, in order to release muscular tension and to moderately immobilize the cervical spine. Detonizing physiotherapy is recommended 14 days after surgery.

Complications

Theoretically a direct puncture of the organs in the cervical region is possible (e.g. carotid artery, jugular vein, esophagus, thyroid, larynx, submandibular gland, symphatic nerve, recurrent laryngeal nerve). The complication varies in the

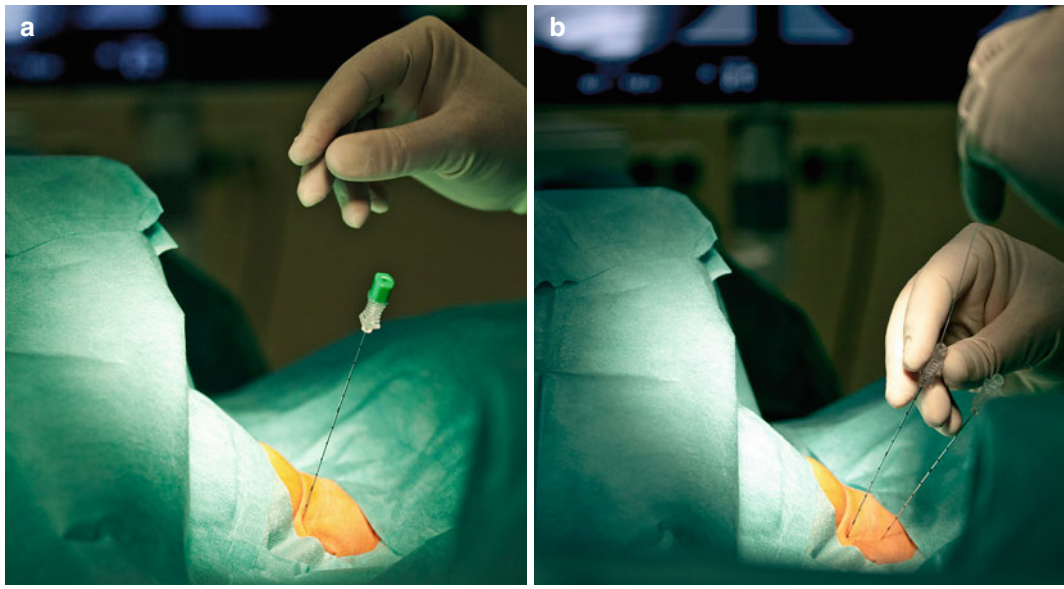


Fig. 6.6 (**a**) Cannula placement (two levels) and (**b**) removal of the mandarin (*right*)

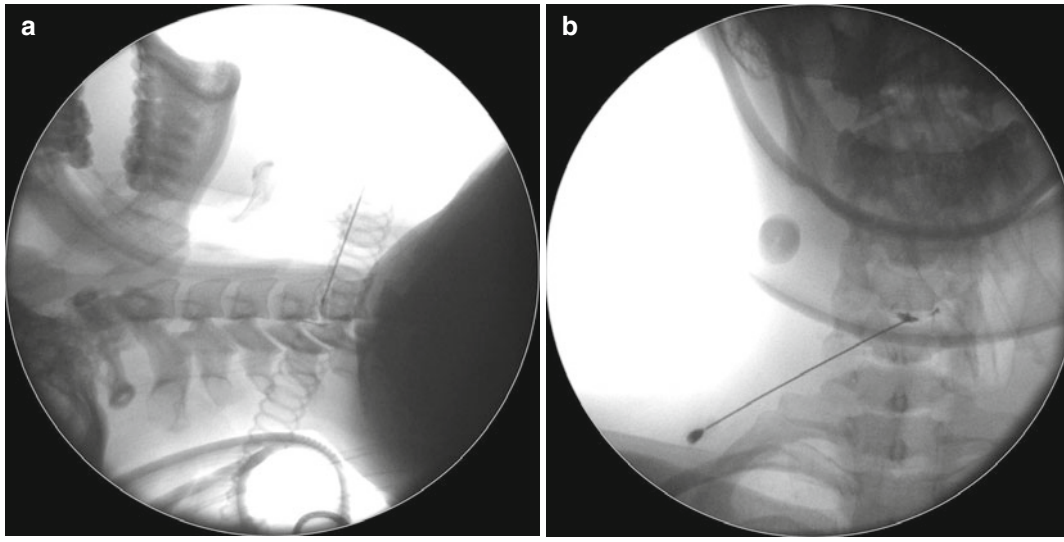


Fig. 6.7 Needle position (**a**) lateral and (**b**) anterior posterior view

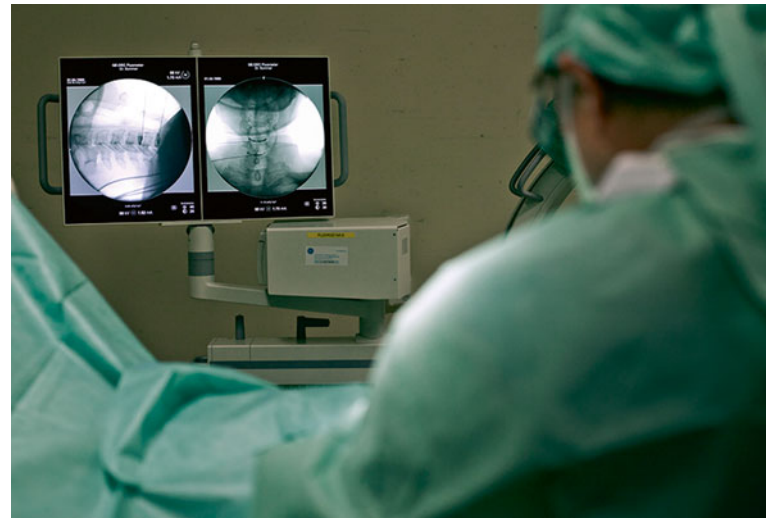


Fig. 6.8 Needle position after placement of a second cannula

literature. However it is significantly lower than following a microsurgical approach. Choy et al. in [65] report a mean complication rate of 1 % in 9 years.

Gangi et al. report [14] a complication rate of 0.6–1 %.

Hellinger provides a good overview in [66] reporting a complication rate of 1 % and an infection rate of 0.5 %.

Recurrent symptoms are reported at a very low rate by Choy and Hellinger et al. in [41] at about. 5 %.

Thermically Induced Complications

The terminally induced alterations of the disc material and its possible complications are a widely discussed.

Siebert et al. [47] conclude on the basis of thermographical examinations that the use of a Nd:YAG laser with the parameters of 20–40 W, single pulse 1 s, pulse after and before 1 s each laser application and a total dose of 600–1000 J lead to no dangerous temperature increases at the end plate of the vertebrae.

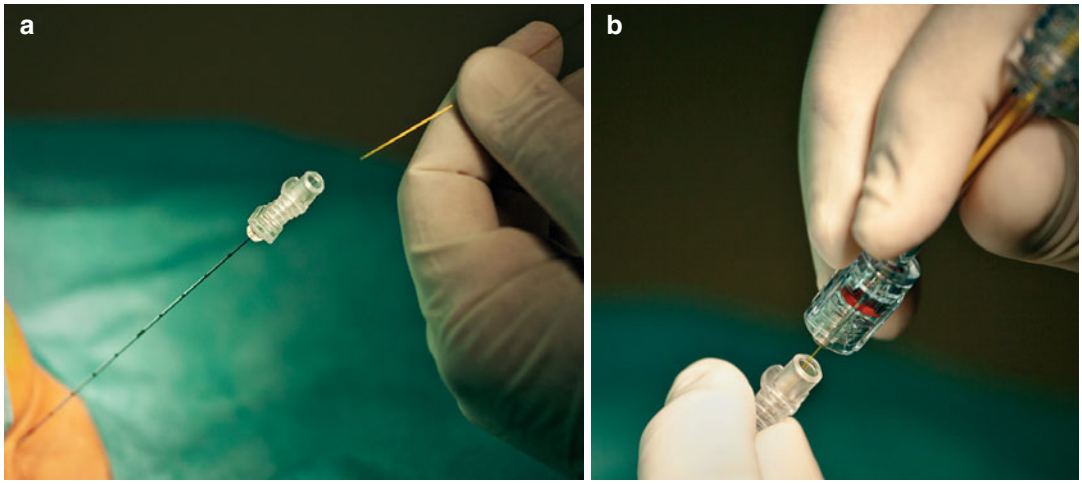


Fig. 6.9 (**a**) Introduction and (**b**) fixation of the laser fiber

Schmolke et al. describe the cervical PLDD in [44] as an effective treatment option which should only be carried out by experienced surgeons because of its possible deleterious effects on the longitudinal posterior ligament.

Turgut et al. describe in [67] possible cartilage lesions due to the applied heat. Koboyashi et al. report thermally induced damage to the nerve root [69].

In order to avoid these heat lesions at the end plates, one has to carefully select the appropriate position of the laser fiber with sufficient distance from them [68, 69]. Furthermore, the fiber tip must be mechanically competent and polished in order to exclude unpredictable scattering of the laser beam.

Discitis

Another typical complication is the thermally induced spondylodiscitis. It can be assumed that there is a correlation between laser parameters like a high pulse rate or the applied [31].

In the studies that mention this complication, a relatively high total energy was applied (e.g. [67, 70]).

However Gangi et al. report in 2009 two cases of aseptic spondylodiscitis with a low applied total amount of energy [14].

When one reviews the literature, however, it becomes clear that this typical complication becomes less frequent over time. In the history of PLDD, the total amount of applied energy diminishes over time. The recent applied energy and the relatively low Parameters do not seem induce this kind of complication. Another important parameter is the optical quality of the target area. If a high degeneration grad is present in the disc space and the water content is low, it is strongly recommended [24] reducing the maximal pulse power, in order to avoid carbonization of the laser fiber tip which could lead to a markedly worsened temperature distribution in the disc space.

Damage of the Endplates

Thermal lesions on the endplates are a frequently reported and discussed complication [66, 67].

In vitro studies results however show that high temperatures which are a prerequisite for such lesions are avoided with the recently applied parameters in cervical PLDD.

It seems that only a malposition of the fiber tip leading to a direct beam onto the endplate can induce such high temperatures at the endplates and induce a lesion in connection with a high applied total amount of energy.

This complication is reported primarily in the older studies and is less frequent in the recent reports (see Turgut et al. [67]).

Infections

Theoretically, infectious complications can occur in the approach area of the cervical spine [14, 71] This complication is most likely to occur by accidental puncture of the esophagus or through the use of reprocessed fiber systems.

Hematoma

One has to differentiate between subcutaneous or cutaneous hematomas and hematomas which occur after puncture of the cervical vessels (e.g. carotid artery, jugular vein …) Subcutaneous and cutaneous hematomas are usually self-limiting and demand no further treatment. However, puncture of one of the larger cervical vessels can lead to a real emergency situation where airway protection is the primary goal.

Some studies show relatively low complication rates. These can be archived by the selection of low laser parameters, strict antiseptic draping and single use laser fibers. We observed the following complication rate in our own patient group.

Cutaneous, subcutaneous hematoma	1.5 %
Hoarseness (<1 week)	2.3 %
Hoarseness (permanent)	0.2 %
No infections were observed	
No thermal induced discitis	

Results, Follow Up

In addition to a neurological/orthopedic examination, we examine the pain level according to the Visual Analog Score (VAS) as well as a modified Prolo Scale.

The Prolo Scale validates the patient satisfaction according to functional and economic parameters.

Our examination intervals are directly before the procedure, 1 week following surgery, 3 months following surgery and 1 year after the procedure. The 1 year follow up is usually performed via a standardized telephone interview.

Prolo scale		
	Functional rating scale	Economic rating scale
1	Pain stronger than before surgery	Invalid
2	Pain as before surgery	No gainful occupation
3	Low level of daily pain	Working but not at premorbid level
4	No pain, but episodic pain	Working at previous level with limitation
5	Complete recovery	Working without any restrictions

Economic and functional rating scale and results

Economicstatus	
E1	Complete invalid
E2	No gainful occupation including ability to do housework or continue retirement activities
E3	Able to work but not at previous occupation
E4	Working at previous occupation part time or limited status
E5	Able to work at previous occupation with no restrictions of any kind

Functional status	
F1	Total incapacity (or worse than before operation)
F2	Mild-to-moderate level of cervical pain and/or brachialgia (or pain same as before operation but able to perform all daily tasks of living)
F3	Low level of pain and able to perform all activities except sports
F4	No pain but patient has had one or more recurrences of cervical pain or brachialgia
F5	Complete recovery, no recurrent episodes of cervical pain, able to perform all previous sport activities

Patient satisfaction according to Prolo scale	
9–10 Points	very good result
7–8 Points	good result
5–6 Points	satisfactory result
2–4 Points	bad result

Patient satisfaction/N = 330				
	Prolo *functional*	Prolo *economic*	Prolo *complete*	VAS
Before operation	2	2.4	4.4	5.9
1 Week after op	–	–	–	3.2
3 Month after	3.8	4.0	7.8	1.9
12 Month after	4.4	4.1	8.5	2.1

Mean results at the 1 year follow up

Due to the successful decompression (330 procedures) of the nerve root following cervical PLLD, 78 % of the patients reported a complete recovery of motor weakness, 18 % of patients showed an incomplete recovery. Sensory deficits recovered fully in 66 % and partially in 18 % of our patients.

Because of persistent symptoms, five patients underwent microsurgery, four patients reported a secondary deterioration after an initial improvement of symptoms. In these patients microsurgical treatment was performed when a sequestrated disc was present.

If the indications and patient selection is performed carefully the results are good. We have observed a recovery of the pain syndromes as well as the resolution of neurological deficits.

Summary

Taking into account that the PLDD is not generally accepted in the treatment of spinal pathologies, several positive studies reveal favorable results in the treatment of discogenic pain syndromes [46, 55, 72]. Therefore the PLDD is, according to the literature, and due to our own results, a treatment option in these patients.

The history, patient selection, indication, as well as the selection of the laser system and the parameters, plays an important role.

Because of the above mentioned physical properties, the 980 nm diode laser seems to the first choice of device.

Complication rate is reported to be as low as <1 %. These findings comply with our own experience.

References

1. Choy DS, Case RB, Fielding W, et al. Percutaneous laser nucleolysis of lumbar disks. N Engl J Med. 1987;317(12):771–2. doi:10.1056/NEJM198709173171217.
2. Choy DS, Altman PA, Case RB, et al. Laser radiation at various wavelengths for decompression of intervertebral disk. Experimental observations on human autopsy specimens. Clin Orthop Relat Res. 1991;(267):245–50.
3. Sherk HH, Black JD, Prodoehl JA, et al. Laser discectomy. Orthopedics. 1993;16(5):573–6.
4. Siebert W, editor. Laser in der Orthopädie. Einsatzmöglichkeiten der Lasertechnik bei operativen und diagnostischen Verfahren am Bewegungsapparat. Stuttgart/New York: Thieme; 1991.
5. Uppal GS, Smith R, Aragon S, et al. In vivo comparison of two infrared laser wavelengths and two delivery systems used for lumbar disc decompression. Contemp Orthop. 1995;30(2):123–6.
6. Lane GJ, Prodoehl JA, Black J, et al. An experimental comparison of CO2, Argon, Nd:YAG and Ho:YAG Laser Ablation of Intervertebral Discs. Spine State Art Rev. 1993;7(1):1–9.
7. DePalma MJ, editor. ISpine. Evidence-based interventional spine care. New York: Demos Medical; 2011.
8. Min K, Leu H, Zweifel K. Quantitative determination of ablation in weight of lumbar intervertebral discs with holmium: YAG laser. Lasers Surg Med. 1996;18(2):187–90. doi:10.1002/(SICI)1096-9101(1996)18:2<187:AID-LSM9>3.0.CO;2-O.
9. Jacques SL. Optical properties of biological tissues: a review. Phys Med Biol. 2013;58(11):R37–61. doi:10.1088/0031-9155/58/11/R37.
10. Palmer KF, Williams D. Optical properties of water in the near infrared. J Opt Soc Am. 1974;(64):1107–10.
11. Chance B, Wang NG, Maris M, et al. Quantitation of tissue optical characteristics and hemoglobin desaturation by time- and frequency-resolved multiwavelength spectrophotometry. Adv Exp Med Biol. 1992;317:297–304.
12. Hale GM, Querry MR. Optical constants of water in the 200-nm to 200µm wavelength region. Appl Opt. 1973;12(3):555–63.
13. Kedenburg S, Vieweg M, Gissibl T, et al. Linear refractive index and absorption measurement of nonlinear optical liquids in the visible and near-infrared spectral region. Opt Mat Express. 2012; 2(11):1588–611.
14. Gangi A, Guth S, Guermazi A, editors. Imaging in percutaneous musculoskeletal interventions. Berlin/London: Springer; 2009.
15. Niemz MH. Laser tissue interactions. Fundamentals and applications; with 33 tables, 40 problems and solutions, 3 ed., 2. print. Berlin [u.a.]: Springer; 2007.
16. Waidelich W, Waidelich R, Hofstetter A, editors. Laser in der Medizin/Laser in Medicine. Berlin/Heidelberg: Springer; 1994.
17. Knappe V, Frank F, Rohde E. Principles of lasers and biophotonic effects. Photomed Laser Surg. 2004;22(5):411–7.
18. Thal R, Danziger MB, Kelly A. Delayed articular cartilage slough: two cases resulting from holmium:YAG laser damage to normal articular cartilage and a review of the literature. Arthroscopy. 1996; 12(1):92–4.
19. Steiner R. Laser-Gewebe-Wechselwirkung. In: Raulin C, Karsai S, editors. Lasertherapie der Haut. Berlin: Springer; 2013. p. 26–39.

20. Berlin LMTB. Comparative study on the use of DIODE lasers and Nd:YAG lasers for medical applications. Berlin: Laser- and Medicine Technology; 1995.
21. Schlangmann BA, Schmolke S, Siebert WE. Temperatur- und Ablationsmessungen bei der Laserbehandlung von Bandscheibengewebe.; Temperature and ablation measurements in laser therapy of intervertebral disc tissue. Orthopade. 1996;25(1):3–9.
22. Buchelt M, Schlangmann B, Schmolke S, et al. High-power Ho:YAG laser ablation of intervertebral discs. Effect on ablation rates and temperature profile. Lasers Surg Med. 1995;(16):179–83.
23. Choy DS, Altman P. Fall of intradiscal pressure with laser ablation. J Clin Laser Med Surg. 1995;13(3):149–51.
24. Vorwerk D, Husemann T, Blazek V, et al. Laserablation des Nucleus pulposus. Optische Eigenschaften von degeneriertem Bandscheibengewebe im Wellenlängenbereich von 200 bis 2200 nm.; ÉALaser ablation of the nucleus pulposus: optical properties of degenerated intervertebral disk tissue in the wavelength range 200 to 2200 nmÉU. RöFo: Fortschritte auf dem Gebiete der Röntgenstrahlen und der Nuklearmedizin. 1989;151(6):725–8.
25. Siebert W. Percutaneous laser discectomy of cervical discs: preliminary clinical results. J Clin Laser Med Surg. 1995;13(3):205–7.
26. Hellinger J. Technical aspects of the percutaneous cervical and lumbar laser- disc-decompression and -nucleotomy. Neurol Res. 1999;21(1):99–102.
27. Wang JC, Kabo JM, Tsou PM, et al. The effect of uniform heating on the biomechanical properties of the intervertebral disc in a porcine model. Spine J. 2005;5(1):64–70. doi:10.1016/j.spinee.2004.10.047.
28. Streitparth F, Hartwig T, Walter T, et al. MR guidance and thermometry of percutaneous laser disc decompression in open MRI. An initial clinical investigation. Eur Radiol. 2013;23.
29. Stephanblome M (1997) Die Kernspintomographie als Untersuchungsmethode von Veränderungen an lumbalen Bandscheiben nach Anwendung der Laservaporisation mit dem Nd:YAG Laser. Eine Kernspintomographische und biomechanische Studie. Dissertation, WWU Münster.
30. Hellinger J, Stern S. 10 Jahre Erfahrung mit der intradiskalen Lasertherapie. Diskogen-Vertebrage Schmerzsyndrome. Erfahrungsbericht über 5000 Patienten. Orthopädie Rheuma. 2002;2002:38–41.
31. Schenk B, Brouwer PA, van Buchem MA. Experimental basis of percutaneous laser disc decompression (PLDD): a review of literature. Lasers Med Sci. 2006;21(4):245–9.
32. Bogduk N, Endres SM. Clinical anatomy of the lumbar spine and sacrum. 4th ed. New York: Elsevier/Churchill Livingstone; 2005.
33. Inman VT, Saunders JBDCM. Anatomicophysiological aspects of injuries to the intervertebral disc. J Bone Joint Surg Am. 1947;29(2):461–75.
34. Freemont AJ, Peacock TE, Goupille P, et al. Nerve ingrowth into diseased intervertebral disc in chronic back pain. Lancet. 1997;350(9072):178–81.
35. Mendel T, Wink CS, Zimny ML. Neural elements in human cervical intervertebral discs. Spine. 1992;17(2):132–5.
36. Kayama S, Konno S, Olmarker K, et al. Incision of the anulus fibrosus induces nerve root morphologic, vascular, and functional changes. An experimental study. Spine. 1996;21(22):2539–43.
37. Zhao XL, Fu ZJ, Xu YG, et al. Treatment of lumbar intervertebral disc herniation using C-arm fluoroscopy guided target percutaneous laser disc decompression. Photomed Laser Surg. 2012;30(2):92–5.
38. Luo DX, Jin XJ, Li GT, et al. The use of targeted percutaneous laser disc decompression under the guidance of puncture-radiating pain leads to better short-term responses in lumbar disc herniation. Eur Rev Med Pharmacol Sci. 2014;18(20):3048–55.
39. Iwatsuki K, Yoshimine T, Sasaki M, et al. The effect of laser irradiation for nucleus pulposus: an experimental study. Neurol Res. 2005;27(3):319–23.
40. Hellinger J. Simultane Lasernukleotomie bei zervikalen und lumbalen Bandscheibenvorfällen. In: Waidelich W, Waidelich R, Hofstetter A, editors. Laser in der Medizin/Laser in Medicine. Berlin/Heidelberg: Springer; 1994. p. 326–31.
41. Choy DS, Hellinger J, Hellinger S, et al. 23rd Anniversary of Percutaneous Laser Disc Decompression (PLDD). Photomed Laser Surg. 2009;27(4):535–8.
42. Choy DSJ, Fejos AS. Cervical disc herniations and percutaneous laser disc decompression: a case report. Photomed Laser Surg. 2004;22(5):423–5. doi:10.1089/pho.2004.22.423.
43. Harada J, Dohi M, Fukuda K, et al. CT-guided percutaneous laser disk decompression (PLDD) for cervical disk hernia. Radiat Med. 2001;19(5):263–6.
44. Schmolke S, Kirsch L, Gossé F, et al. Risk evaluation of thermal injury to the cervical spine during intradiscal laser application in vitro. Photomed Laser Surg. 2004;22(5):426–30.
45. Li K, Qin H, Chen J. Clinical application of percutaneous laser disc decompression in the treatment of cervical disc herniation. Zhongguo xiu fu chong jian wai ke za zhi=Zhongguo xiufu chongjian waike zazhi = Chinese journal of reparative and reconstructive surgery. 2007;21(5):465–7.
46. Knight MT, Goswami A, Patko JT. Cervical percutaneous laser disc decompression: preliminary results of an ongoing prospective outcome study. J Clin Laser Med Surg. 2001;19(1):3–8. doi:10.1089/104454701750066875.
47. Siebert WE, Ksinsik B, Wirth CJ, et al. In-Vitro Untersuchungen zur thermischen Belastung de Bandscheibe bei der Laserablation. In: Siebert W, editor. Laser in der Orthopädie. Einsatzmöglichkeiten der Lasertechnik bei operativen und diagnostischen Verfahren am Bewegungsapparat. Stuttgart/New York: Thieme; 1991. p. 150–3.

48. Ascher P, Holzer P, Sutter B, et al. Nucleus-pulposus-Denaturierung bei Bandscheibenprotrusionen. In: Siebert W, editor. Laser in der Orthopädie. Einsatzmöglichkeiten der Lasertechnik bei operativen und diagnostischen Verfahren am Bewegungsapparat. Stuttgart/New York: Thieme; 1991. p. 169–72.
49. Choi JY, Tanenbaum BS, Milner TE, et al. Thermal, mechanical, optical, and morphologic changes in bovine nucleus pulposus induced by Nd:YAG (lambda = 1.32 microm) laser irradiation. Lasers Surg Med. 2001;28(3):248–54. doi:10.1002/lsm.1046.
50. Sato M, Ishihara M, Kikuchi M, et al. The influence of Ho:YAG laser irradiation on intervertebral disc cells. Lasers Surg Med. 2011;43(9):921–6.
51. Engelke C, Galanski M, Molen AJ van der, et al. Spiral and multislice computed tomography of the body. 332 tables. Stuttgart [u.a.]: Thieme; 2003.
52. Gevargez A, Groenemeyer DW, Czerwinski F. CT-guided percutaneous laser disc decompression with Ceralas D, a diode laser with 980-nm wavelength and 200-microm fiber optics. Eur Radiol. 2000;10(8):1239–41.
53. Chambers RA, Botsford JA, Fanelli E. The PLDD registry. J Clin Laser Med Surg. 1995;13(3):215–9.
54. Anders JO, Pietsch S, Staupendahl G. Kritische Betrachtung der Indikationen des Holmium. YAG- und des Neodym:YAG-Lasers in der orthopädischen Chirurgie anhand einer In- vitro-Studie.; ÉACritical evaluation of indications for the holmium: YAG laser and the neodymium:YAG laser in orthopedic surgery based on an in vitro studyÉU. Biomedizinische Technik. Biomed Eng. 1999;44(4):83–6.
55. Paul M, Hellinger J. Nd:YAG (1064nm) versus Diode (940 nm) PLDN: a prospective randomized blinded study. Spinal Surg Relat Disciplines. 2000:555–8.
56. Grönemeyer DH, Buschkamp H, Braun M, et al. Image-guided percutaneous laser disk decompression for herniated lumbar disks: a 4-year follow-up in 200 patients. J Clin Laser Med Surg. 2003;21(3):131–8.
57. Steiner P, Zweifel K, Botnar R, et al. MR guidance of laser disc decompression. Preliminary in vivo experience. Eur Radiol. 1998;8(4):592–7.
58. Botsford JA. Radiological considerations: percutaneous laser disc decompression. J Clin Laser Med Surg. 1993;11(5):223–31.
59. Botsford JA. Radiological considerations: patient selection for percutaneous laser disc decompression. J Clin Laser Med Surg. 1994;12(5):255–9.
60. Botsford JA. The role of radiology in percutaneous laser disc decompression. J Clin Laser Med Surg. 1995;13(3):173–86.
61. Grasshoff H, Kayser R, Mahlfeld U, et al. Diskographiebefund und Ergebnis der perkutanen Laserdiskusdekompression (PLDD) (Diskography findings and results of percutaneous laser disc decompression (PLDD)). RöFo: Fortschritte auf dem Gebiete der Röntgenstrahlen und der Nuklearmedizin. 2001;173(3):191–4. doi:10.1055/s-2001-11600.
62. Kapoor SG, Huff J, Cohen SP. Systematic review of the incidence of discitis after cervical discography. Spine J. 2010;10(8):739–45. doi:10.1016/j.spinee.2009.12.022.
63. Osti OL, Fraser RD, Vernon-Roberts B. Discitis after discography. The role of prophylactic antibiotics. J Bone Joint Surg. 1990;72(2):271–4.
64. Sharma SK, Jones JO, Zeballos PP, et al. The prevention of discitis during discography. Spine J. 2009;9(11):936–43. doi:10.1016/j.spinee.2009.06.001.
65. Choy DS. Clinical experience and results with 389 PLDD procedures with the Nd:YAG laser, 1986 to 1995. J Clin Laser Med Surg. 1995;13(3):209–13.
66. Hellinger J. Complications of non-endoscopic percutaneous laser disc decompression and nucleotomy with the neodymium: YAG laser 1064 nm. Photomed Laser Surg. 2004;22(5):418–22.
67. Turgut M, Onol B, Kiliniç K, et al. Extensive damage to the end-plates as a complication of laser discectomy. An experimental study using an animal model. Acta Neurochir. 1997;139(5):404–9; discussion 409–10.
68. Ewers E (1997) Percutane Nd:YAG Laservaporisation des Nucleus Pulposus. Ergebnisse einer morphologischen Studie. Dissertation, UGH Essen
69. Kobayashi S, Uchida K, Takeno K, et al. A case of nerve root heat injury induced by percutaneous laser disc decompression performed at an outside institution: technical case report. Neurosurgery. 2007;60(2 Suppl 1):ONSE171-2; discussion ONSE172.
70. Schweitzer ME, Laredo J, editors. New techniques in interventional musculoskeletal radiology. New York: Informa Healthcare; 2007.
71. Farrar MJ, Walker A, Cowling P. Possible salmonella osteomyelitis of spine following laser disc decompression. Eur Spine J. 1998;7(6):509–11.
72. Singh V, Manchikanti L, Calodney AK, et al. Percutaneous lumbar laser disc decompression. An update of current evidence. Pain Physician. 2013;16 (2 Suppl):SE229–60.
73. Kremer J, et al. Bandscheibenbedingte Erkrankungen - Ursachen, Diagnose, Behandlung, Vorbeugung, Begutachtung. 5th ed. Georg Thieme Verlag; 2006.

Endoscopy in Cervical Spine Surgery

7

Joachim M.K. Oertel and Benedikt W. Burkhardt

Introduction

The first evidence of spinal surgery was found in Egyptian mummies 2900 BC [1]. In the antiquity, about 2500 years later, Hippocrates who is considered "The father of spine surgery" collected a valuable heritage of knowledge and methodology about the human body. He was the first who described sciatica and low-back pain. He also proposed a traction procedure and invented devices based on his fundamental principle [2]. Concerning the cervical spine, Aulus Celsus was the first who noted death following injury of the cervical spinal cord [3]. Paulus of Aegina performed the first operative repair of injured spinal cord by removing bony fragments which irritated the spinal cord and caused consecutive paralysis in the seventh century [3]. It took spinal surgery about 1900 years until an endoscope was applied.

J.M.K. Oertel, MD (✉)
Department of Neurosurgery, Faculty of Medicine, Saarland University Medical Center and Saarland University, Kirrbergerstrasse 100, 66421 Homburg-Saar, Germany

Klinik für Neurochirurgie, Universitaet des Saarlandes, Saarbrücken, Germany
e-mail: joachim.oertel@uks.eu

B.W. Burkhardt
Klinik für Neurochirurgie, Universitaet des Saarlandes, Saarbrücken, Germany

In 1983, the first report of an examination technique for intervertebral disc space after nucleotomy via endoscopy/arthroscopy was described by Frost and Hausmann [4]. Since then new surgical technology and techniques for minimally invasive approaches have revolutionized the work of surgeons of all subspecialties. Procedures such as laparoscopic cholecystectomy and orthopedic arthroscopy have proven to decrease surgically related morbidity, shorten postoperative hospital time and improve clinical outcomes [5–7]. In spinal surgery, morbidity is associated with iatrogenic muscle and soft tissue injury due to approach and exposure of the surgical field. Particularly in lumbar spine surgery, the standard open approach leads to iatrogenic injury of the paraspinal muscles which might result in decreased muscle strength and muscle atrophy after extensive muscle retraction [8, 9]. Biomechanical studies have investigated the function of the posterior column and its importance in maintaining lumbar spinal stability [10, 11]. Serial tube dilators and retractors were designed to split the back muscle gently and thus made to minimize retraction and disruption of the paraspinal muscular integrity. Further, other studies demonstrated that the postoperative recovery of CK and CRP levels occurred within 1 week and that the intensity of low back pain was mild [12, 13]. Mayer et al. studied the postoperative muscle architecture on CT scan and its relevance for failed-back syndrome [8]. They found that the

P.P.M. Menchetti (ed.), *Cervical Spine: Minimally Invasive and Open Surgery*,
DOI 10.1007/978-3-319-21608-9_7

integrity of paraspinal muscles might be of utmost importance for the postoperative result. A tubular retraction system provides direct and focal access to the diseased anatomy via a less invasive approach [14, 15]. Surgery can be done by using either an endoscope or using a microscope for visualization. The microendoscopic technique for interlaminar fenestration is considered safe and effective treatment of degenerative lumbar spine diseases and makes this to be seen as an option along with the traditional technique for every spine surgeon [16].

Based on good clinical and experimental results made with the endoscopic technique in lumbar spine surgery, the next step was the application of the microendoscopic technique in cervical spine pathologies. In this chapter, the authors will give a brief review on the development of endoscopy, its application in spinal surgery and different surgical anterior and posterior endoscopic surgical technique to the cervical spine.

Endoscopy

Development of the Endoscope

In 1585, anatomist Julius Aranzi used closed tubes with mirrors to reflect ambient light into the nasal cavity [17]. In 1806, Bozzini created an instrument he named the "Lichtleiter" which was illuminated by candlelight which reflected by an angled mirror into cavities such as of the human body including the urethra, rectum, and female bladder [17, 18]. The evolution of endoscopy went on, and it was Desormeaux who first use the term "endoscopy" in 1853. However, the early endoscopes emitted heat which frequently caused thermal tissue damage and limited their clinical use. In 1879, it was Nitze who developed a minitelescope with a watercooled platinum filament lamp at the tip for internal illumination [19]. A series of lenses inside a metal tube magnified the image down the scope [18, 20, 21]. At this time, the remaining problem was to find a sufficient and inexpensive illumination with a cooling system. A vacuum lamp was followed by an incandescent light bulb. However, neuroendoscopy never prevailed as a surgical technique at that time even though numerous reports demonstrated its potential utility. In the 1950s, reasons for the decline of neuroendoscopy were poor magnification and poor illumination which made safe surgery often difficult and unreliable. Further surgeons seemed daunting because of high morbidity and mortality rates [20, 22].

Harold Hopkins was physicist and contributed major technical advancements in endoscopy to rediscover neuroendoscopy. The fiberscope and the rigid rod-lens endoscope were invented by him. Karl Storz, the founder of Karl Storz Company in Tuttlingen, Germany collaborated with Hopkins and replaced the light source from the tip of the endoscope to an external device (Fig. 7.1) [23]. Today xenon light is used as a so called "cold light" source. Another technical development of Hopkins rigid rod-lens endoscope was the introduction of video cameras for imaging. Direct observing was not necessary any longer because of external monitors and new lighting enabling surgeons to view images on a screen. However, video cameras were very large in the initial phase of endoscopy. Intraoperative maneuvering was challenging, and sterilization in routine practice was lacking. In 1969, charge-coupled devices (CCDs) were invented. Here, image data and light signal are converted into electrical impulses and digital data. They are equipped with miniature cameras which can be attached to the endoscope and fully sterilized [18, 20, 21]. Because of CCDs, engineers were able to develop smaller endoscopic systems with high resolution image quality. Nowadays, image quality is available in high definition (HD) with approximately 2,000,000 pixel which is superior to SD in identifying anatomical structures [24].

For spinal endoscopy, a standard endoscopic system consists of three components:

1. The endoscope which is usually a rod-lens endoscope because of its superior optical quality.
2. The HD-camera which allows excellent image quality and a 16:9 wide screen video monitor.
3. A Xenon light source for cold light transmission.

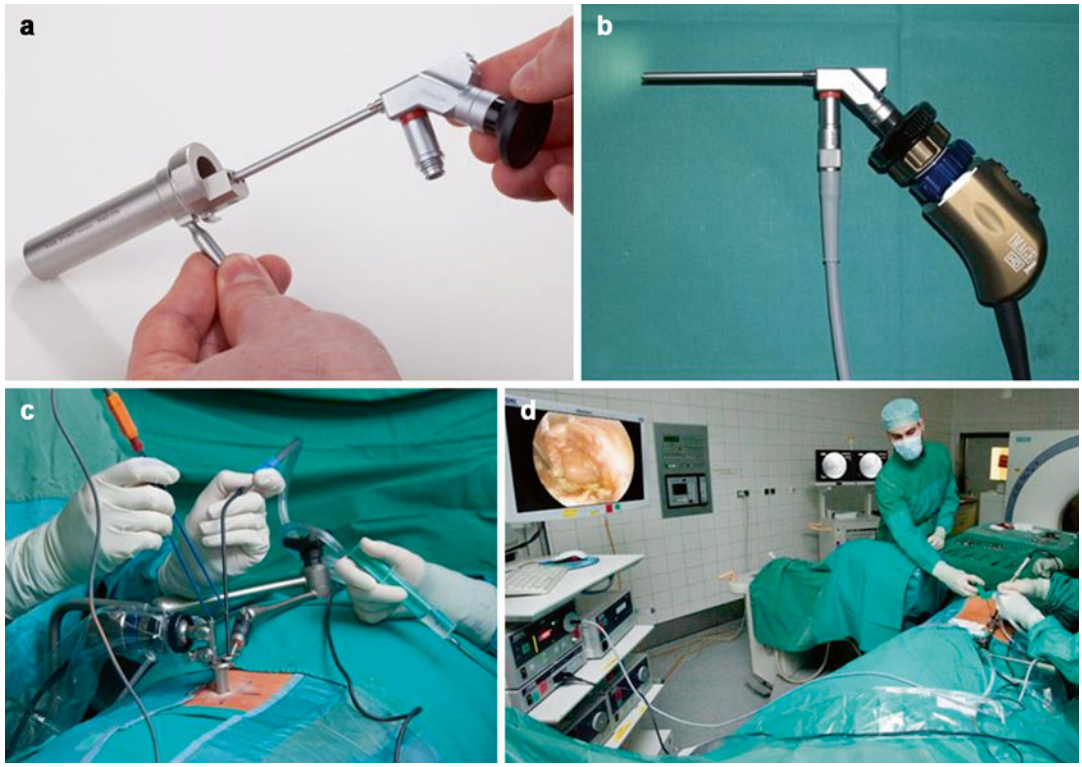


Fig. 7.1 EasyGO-System (Karl Storz Company, Tuttlingen, Germany). (**a**) Working trocar with insertion for rod-lens (EasyGO®-system, Karl Storz Company, Tuttlingen, Germany). (**b**) Rod-lens with light source cable and HD-camera. (**c**) Tubular working trocar with inserted endoscope. (**d**) 16:9 wide screen monitor and cold light transmission Endoscopic Spinal Surgery

Endoscopic spine surgery was first described in 1983. Since then endoscopic visualization and surgical equipment were continuously further developed and redefined. Currently, endoscopy is applied in cervical, thoracic and lumbar spine surgery. First clinical results were reported on lumbar discectomy procedures by Kambin in the early 1990s [25–27]. In 1997, the first tubular retractor system was introduced to the market by Foley. The idea behind was the application of the microsurgical technique for endoscopic lumbar discectomy (MED) via minimally invasive approach. The spine is accessed via serial dilation of the back muscles. This leaves the supporting musculoligamentous structures intact which are located in the midline [28]. The initially poor image quality of telescopes and an associated flat learning curve of the surgeon deterred many spine surgeons from performing endoscopic spine surgery. Further the lack of depth perception and 3D vision reduced the acceptance of the MED technique. As a consequence of this, a new generation, the so called METRx system, was developed. It provided an increased working space and better illumination of the surgical field. Many surgeons didn't want to miss minimally invasive surgery and therefore performed procedures by using the operating microscope or loupes instead. Multiple studies have identified that MED provides the same clinical outcome as microdiscectomy with the advantages of less soft tissue trauma and better aesthetical results [29–31]. Tubular systems became popular soon not only because of good clinical results. The indication for the use of tubular retraction systems in lumbar spine is wide and very similar to conventional open procedures [15, 32]. It is not surprising that microendoscopic techniques were applied to treat pathologies which were traditionally operated on in microsurgical technique.

Anterior and Posterior Approaches and Techniques

Since the introduction of the endoscope to spinal surgery, new endoscopic surgical techniques have been constantly developed. If we look at the cervical spine anterior and posterior approaches have to be subclassified. Further if we talk about endoscopic surgery we have to differentiate these techniques into fullendoscopic and endoscopic assisted surgery. The term fullendoscopic refers to surgical techniques on what the visualization of the surgical field is performed by an endoscope at all time of the tissue manipulation only. The term of endoscopic assisted refers to a technique on what the majority of the procedures is performed without the visualization of the endoscope. The endoscope for example is used sequentially during the procedure to insect a part of the surgical field or to manipulate under endoscopic visualization partially.

In the following session the authors will give a brief review on the common fullendoscopic techniques which are applied anteriorly and posteriorly to the cervical spine.

- Cervical Microendoscopic Discectomy and Fusion
- Anterior Percutaneous Endoscopic Cervical Discectomy
- Endoscopic Posterior Cervical Laminoforaminotomy
- Microendoscopic Cervical Laminoplasty and Laminectomy

Other techniques like endoscopic assisted transoral odontoidectomy, endoscopic transnasal resection of the odontoid or endoscopic posterior fixation are excluded.

Cervical Microendoscopic Discectomy and Fusion

Anterior cervical discectomy and fusion (ACDF) was first described in the 1950s. Since then it became the standard treatment for degenerative cervical disc disease [33–35]. However, ACDF is associated with certain disadvantages such as donor side morbidity in case of bone graft harvesting at iliac crest, graft dislocation, graft subsidence, nonfusion with consecutive pseudarthrosis, esophageal injury, dysphagia, recurrent laryngeal nerve palsy, etc. [36, 37]. Anterior cervical discectomy without fusion (ACD) offers good clinical results but has a higher risk of postoperative segmental kyphosis and postoperative axial pain [38]. In the past decades a variety of different intervertebral implants have been developed to prevent autologous bone harvesting and donor side morbidity. Further minimally invasive techniques were developed to reduce tissue trauma while approaching the spine. It has been proved that minimally invasive techniques for approaches to spinal pathologies preserve healthy tissue and reduce surgical associated morbidity, shorten operative time, decreased complication rates, reduces hospital length of stay, cause less postoperative use of narcotics, enable faster patient recovery and offer lower costs [26, 39]. Depending on the material, minimally invasive techniques can be limited to certain pathologies and indications. The percutaneous endoscopic cervical discectomy as an alternative to ACD is considered to be indicated in cervical disc herniations which have to be soft and contained or noncontained but without sequestration and contained by the posterior ligament [40, 41]. Cervical microendoscopic discectomy and fusion (CMEDF) is an alternative technique for ACDF that reduces the surgical morbidity of conventional surgery but without limited indications for treatment of cervical degenerative pathologies. This chapter will deliver an impression for the endoscopic technique and equipment that is necessary to perform CMEDF and gives a short review about clinical results.

Indications

The CMEDF approach in indicated in the following cervical pathologies and situations [42–44]:

- Central and lateral cervical disc herniations or osteophytes associated with neck injury
- Discogenic radiculopathy
- Discogenic myelopathy
- Spondylotic myelopathy

- Discogenic myeloradiculopathy
- Axial neck pain, lost cervical lordosis, reduced disc space height
- Magnetic resonance image (MRI), computed tomographic (CT) scan or postmyelogram CT-scan that is positive for spinal cord or verve root compressing pathologies consistent with dermatome of clinical symptoms
- Failed improvement of symptoms after conservative treatment for 12 weeks
- Surgery can be performed from mono- to trisegmental pathologies that involves the levels C3–4, C4–5, C5–6, and C6–7

Contraindications

- Compressive pathology located behind the vertebral body (OPLL)
- Severe spinal canal stenosis

Surgical Equipment for CMEDF

The following surgical equipment and instruments are necessary to perform CMEDF:

- Tubular dilators and tubular retractor system (e.g. METRx, Sofamor Danek, Memphis, USA)
- Video digital endoscopy unit with a camera
- Different endoscopes (e.g. 0°-optic and 30°-optic)
- Ordinary endoscopic spine instruments
- 5-mm osteotome
- Cage (e.g. Polyetheretherketone (PEEK))
- Fluoroscopy (C-arm)

Surgical Technique

The CMEDF procedure is performed under general anesthesia with orotracheal intubation. Occasionally the procedure can be performed under local anesthesia in younger patients. Preoperative antibiotics are admitted and dexamethasone might be administered to minimize airway and esophageal edema. The patient is positioned supine with the neck slightly extended. The head might be rigidly affixed via pins in a Mayfield holder. The shoulders are gently tapped down to enhance visualization of the lower cervical spine with intraoperative lateral fluoroscopy. The segment(s) to be operated on can be identified by intraoperative C-arm fluoroscopy. In case of a two- or three-level procedure, a small (18–20 mm) transverse skin incision is recommended to be place at the midpoint of the operative distance. The prevertebral anatomical structures have the characteristics to be movable. Skin incision has to be made deep to the platysma before subplatysmal structures can be dissected by index and the middle finger. The larynx is pushed toward the opposite side with the index and middle fingers while muscle and the carotid was held laterally. Next fingers were slipped inside towards the front of the vertebral body until the anterior cervical spine and edge of the disc is palpated. Optional an artery forceps is placed through the skin incision between both fingers with its blunt tip kept at the vertebral leading edge by creating an access path. Next step the endoscopic tubular dilators were introduced sequentially under fluoroscopic guidance between the carotid artery and the esophagus. A working trocar with an outer diameter of about 18–20 mm is introduced at last and fixed to a mechanical flexible holding arm which is attached to the operating table. After confirming the correct level via lateral C-arm-fluoroscopy the dilators are removed and endoscope system of choice is installed. The anulus fibrosus of the disc is incised by using a microknife before the nucleus pulposus is removed. Osteopytes can be removed by Kerisson punch or diamond drill. Continuous irrigation with saline solution is recommended to remove remaining fragment and to prevent thermal nerve damage in case of drilling. An arterial or any kind of source of bleeding from paraspinal muscular can be controlled by bipolare forceps. Micrograsper, microforcep, dissectors and small curettes are used to remove the rudiment of the disc of the vertebral body. Special curettes are available to dissect the remnant cartilage endplates and enlarge the intervertebral space. Since distraction screws are not placed manual cervical distraction is performed to widen the interbody space by pushing up the head gently and pulling down the arms at the same time. Another technique

for distraction is placing a 5 mm osteotome in the disc followed by its twisting. A cage of choice is placed under fluoroscopic guidance and optional filled with bone graft substitutes. After removal of the tubular retractor, the subcutaneous tissue is closed in standard fashion with a skin adhesive and steristrips the placement of a suctions drain is optional (Fig. 7.2).

Outcome

- CMEDF offers similar functional outcome compared to ACDF
- Odom's criteria 86–91 % of patients report an excellent or good functional recovery
- Significant decrease in arm- and neck pain on visual analog scale (VAS)
- Significant improvement concerning Japanese Orthopaedic Association (JOA) score
- Significant reduction in postoperative analgesic doses, and length of hospital stay
- Low rate of laryngopharyngeal complications

Advantages of CMEDF

- Reduction in the doses of postoperative analgesic
- Reduction in length of hospital stay
- Reduction in laryngopharyngeal complication
- Better aesthetical result

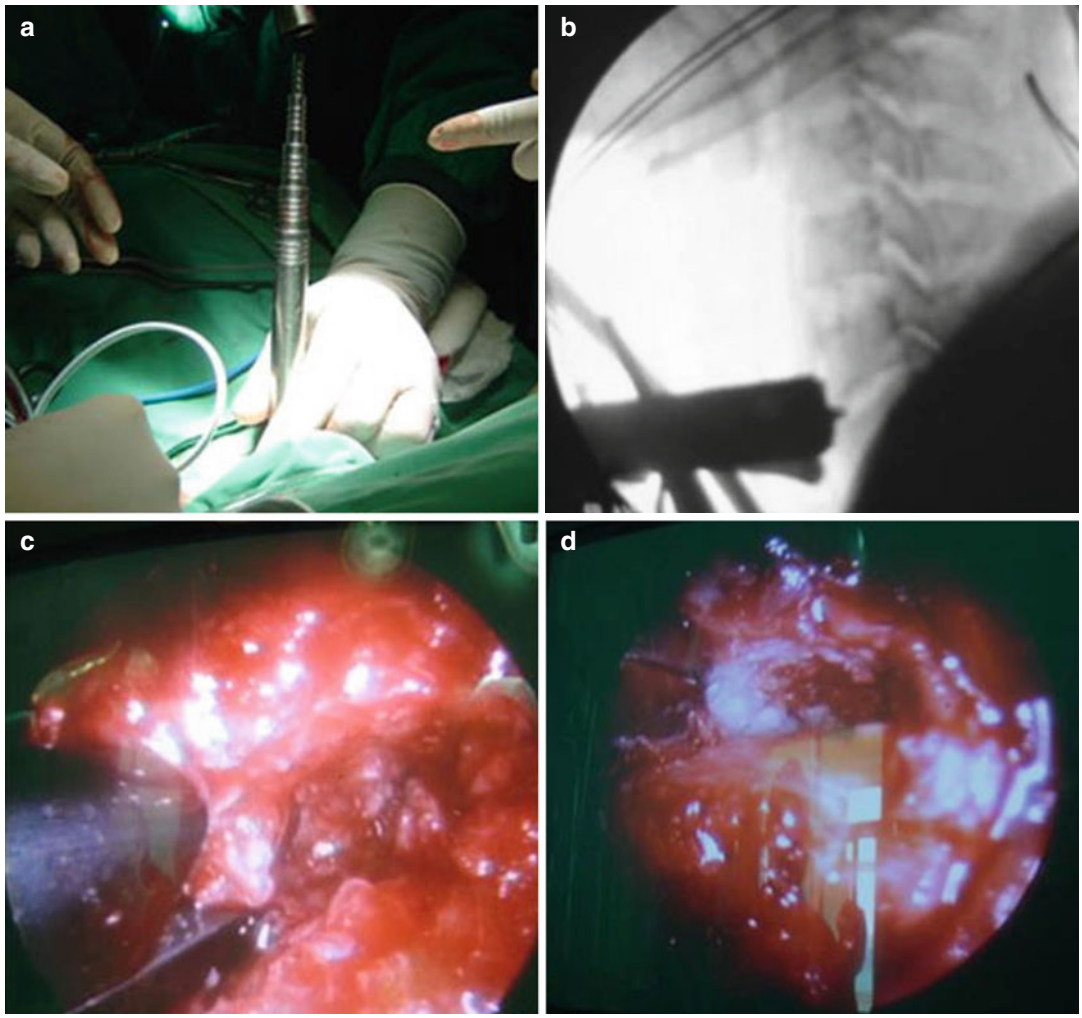


Fig. 7.2 Cervical Microendoscopic Discectomy and Fusion. (**a**) Sequential introduction of endoscopic dilation system between carotid artery and the esophageal. (**b**) Position of working trocar under fluoroscopic control. (**c**) Removal of anterior osteophyte via Kerrison. (**d**) Endoscopic view after implantation of intervertebral cage

- Less retraction and manipulation at the trachea and esophageal

Complications (Access-Related)

- Complications of the traditional open approach are possible
- Vascular injury
- Esophagus
- Trachea
- Thyroid
- Laryngeal nerves

Anterior Percutaneous Endoscopic Cervical Discectomy

The standard treatment for cervical soft disc herniation in spine surgery is anterior cervical discectomy and fusion ACDF. The majority of surgeons perform ACDF because the theory behind it is that fusion prevents segmental instability and kyphosis due to reconstruction of empty disc space by implanting a graft out of an autologous iliac crest, a cage (e.g. PEEK, titan) or disk prosthesis. Surgeons are concerned that cervical alignment would be distorted due to a collapse of the operated segment without fusion which could result in axial neck pain and radicular arm pain in case of a compromised neuroforamen. In the past decades there was less discussion about the imperative of fusion. Little research about the outcome after ACD compared to ACDF although postoperative clinical results seems similar [45, 46]. Since the first description of cervical percutaneous discectomy by Tajima et al. many minimally invasive techniques were developed to treat cervical spine disease [47]. Anterior percutaneous cervical procedures for decompression of the nerval structures can be divided into techniques with endoscopic visualization and nonvisualized techniques. The objective of both techniques is to reduce the nerve compressing volume. Nonvisualized techniques can reduce the volume either via aspiration of the nucleus pulposus [48, 49], via radiofrequency [50, 51], or via radiofrequency [52]. The success of surgery depends on adequate decompression of the nerve root. Therefore the nonvisualized techniques are criticized for their lack of to identify free disc fragments and to assess the status of decompression intraoperatively. The anterior percutaneous endoscopic cervical discectomy (APECD) combines the advantages of minimally invasive approach via a needle and the inspection of the intradiscal space via endoscopic visualization.

Further holmium: Yttrium-Aluminium-Garnet (YAG) laser can be used via this technique for decompressive and thermoannuloplasty. Although a percutaneous cervical stabilization with an expandable holder can be performed via this approach. The idea behind it is to maintain the disc height after decompression. This chapter will deliver an impression for the endoscopic technique and equipment that is necessary to perform APECD and gives a short review about clinical results.

Indications

The APECD approach in indicated in the following cervical pathologies and situations [41, 53–55]:

- Unilateral radiculopathy with sensory disorder, reflex abnormality, motor weakness, arm pain with and intractable neck pain unresponsive to conservative management over 12 weeks
- Magnetic resonance imaging (MRI) computed tomography (CT) that is positive for mediolateral localised monosegmental contained or noncontained soft disc herniation
- Segments C2–3 to C7–Th1;
- Ventral and posterior disc height must be least 4 mm

Contraindication

- Osseous foraminal stenosis
- Intraforaminal disc herniation
- Calcified disc or disc height of less than 4 mm
- Central canal stenosis with broad disc bulging
- Craniocaudal dis sequestering of more than half of the vertebral body
- Evidence of instabilities and / or deformities
- Evidence of myelopathy
- Isolated neck pain
- Foraminal stenosis without disc herniation
- Previous operation at the same segment

Surgical Equipment for APECD

The following surgical equipment and instruments are necessary to perform APECD [40, 41, 55]:

- Endoscopic system (e.g. Karl Storz GmbH & Co KG, Tuttlingen, Germany) Outer diameter 4.0 mm/working length 12 cm/central working channel 1.9 mm
- Video digital endoscopy unit with a camera
- 0° endoscopic optic
- Special endoscopic instruments (microforcep, trepine etc.)
- Discography : Telebrix (Guerbert, France), Contrast agent: Indigo carmine (Korean United Pharma, Seoul, Korea)
- Holm-yttrium aluminium garnet YAG laser (e.g. Trimedyne, Inc., Irvine, CA)
- Fluoroscopy (C-arm)

Surgical Technique

The patient can be operated on under local anesthesia with light sedation so the surgeon can talk to the patient and be aware of any neurological changes. However, if preoperatively there is a sign that the patient may suffer from intraoperative psychological or physical stress because of the introduction of the endoscopic system, general anesthesia can be used as an alternative instead. Preoperative antibiotics are admitted and dexamethasone might be administered to minimize airway and esophageal edema. The patient is placed in a supine position with the neck mildly extended on a radiolucent table. Intraoperatively fluoroscopic guidance (C-arm) the segment of operation is carefully identified in lateral and a.p. X-ray using a radiopaque instrument. Skin incision is marked and with a felt-tipped pen and the skin and subcutaneous tissue were infiltrated with local anesthetic (e.g. 1 % xylocaine, 1 % lidocaine). Generally the approach is at the contralateral side about 2–5 mm paramedian from the midline. The anatomical structures are very mobile due to the compartmentalization and ideal for an anterior percutaneous approach. The goa is to displace the trachea and esophagal medially and the carotid artery and internal jugular vein laterally. First the pulsation of the carotid artery should be felt, then the visceral structures (thyroid, trachea, larynx, and esophageal) can be mobilized to the opposite side with the index finger. The middle finger is then slipped inside towards the cervical spine till the protruding ring of the disc is felt between both plane forefronts of the vertebral bodies. Under continuous fluoroscopy a 18-gauge puncture needle is then carefully inserted in the space between the visceral and vascular compartment into the disc space close to the posterior body line of the posterior part of the disc, trying to preserve the longuscoli muscle. A next step of the surgery a discography (e.g. 10 mL Telebrix and about 0.5 mL of contrast media e.g. indigo carmine is injected to specify the posterior part of the disc) is performed to determine the annular tear, to confirm the presence of soft disc herniation, and to stain the nucleus pulposus into blue in contrast with the neural tissue. Then a guide wire is inserted to replace the puncture needle and is skin incision of 3 mm is made to allow the dilation of the skin and soft tissue via serial progressive dilator (2–5 mm). By this technique soft tissue is prevent from trauma and the approach-related pain is reduced. Finally, the tip of the working cannula is firmly placed to reach the posterior part of the disc. Its correct position sis confirmed via fluoroscopy. The distance between the tip of the working cannula and the end of the posterior longitudinal ligament represent the working depth for the endoscopic instruments. Next the endoscope is inserted into the working cannula. Continuous saline mixed with antibiotics (e.g. cefazolin) is used as irrigation. First endoscopic images of the intradiscal cavity are visible on a monitor. Under endoscopic visualization the herniated disc fragments are removed with microforcep and trephine without injuring the spinal cord. The risk of instability or local kyphosis may be avoided by leaving the anterior fraction of the disc intact while removing the posterior aspect. If necessary the endplate and parts of the posterior edge of the vertebral body are ablated via a Holmium yttrium–aluminum–garnet

(Ho:YAG) laser. Further the laser can be used to shrink the remaining disc herniation and to vaporize abnormal annular structures. A low doses of energy for laser with 2 J and 10 Hz is recommended, therefore YAG-laser is about 0.3–0.5 mm deep. The laser may be useful to create intradiscal cavity for exploration

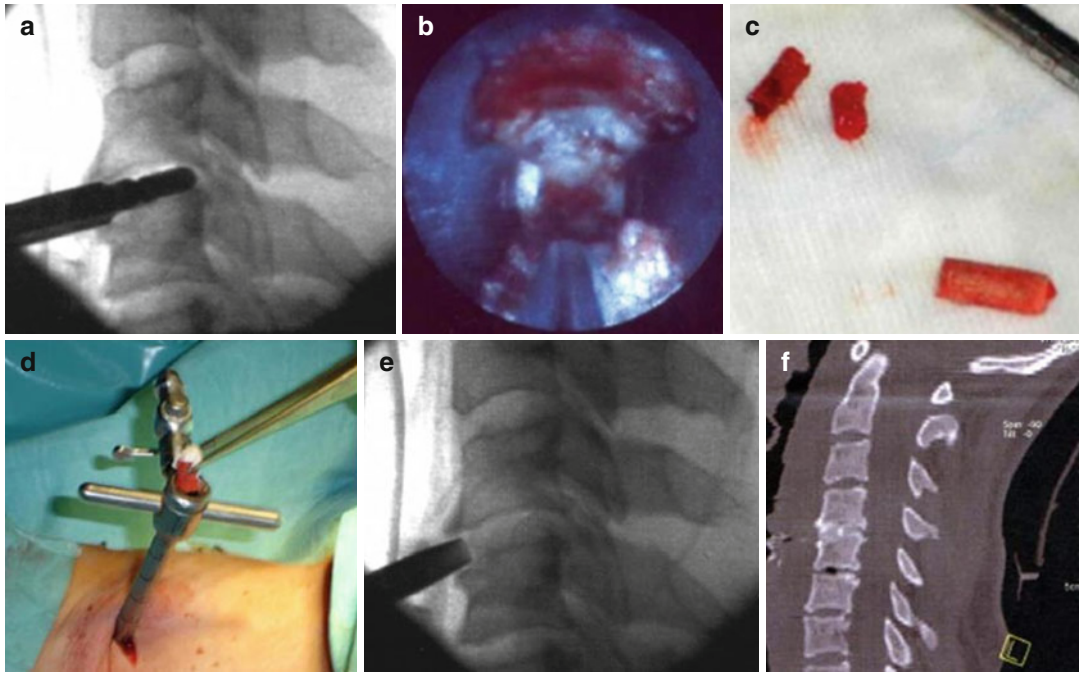


Fig. 7.3 Anterior Percutaneous Endoscopic Cervical Discectomy. (**a**) Fluoroscopic control of trocar and burr placement while preparation of the endplates. (**b**) Endoscopic view of the intervertebral space after preparation. (**c**) Autologous ilia bone graft (dowel shaped). (**d**) Inserting of bone graft in the working trocar. (**e**) Fluoroscopic control of the endoscopic placed bone craft. (**f**) Postoperative CT-scan confirms graft placement and fusion

of adequate decompression. At the end of decompression posterior longitudinal ligament or dura should be clearly visible. Discoplasty of the working cannula surrounding disc tissue may be performed by YAG-laser before removing the working cannula. Position of the laser should be frequently checked via endoscope and fluoroscopy to prevent spinal cord or nerve root injury. Further an expandable holder or autologous iliac bone graft can be introduced for stabilization. The initial diameter of the holder is 3.3 mm while its inserted into the intradiscal cavity. It can be expanded up to 7.0 mm in diameter inside the disc by rotating the expander rotational handle. It is then fixed to the disc. The correct position is controlled under fluoroscopic guidance. If the procedure is performed under local anesthesia the surgeon can interact with the patient and ask whether the preoperative pain has disappeared or was relieved during surgery. The endoscope and working cannula were carefully pulled out. The remaining irrigation and blood is drained before the wound is closed in standard fashion (Fig. 7.3).

Outcome

- MacNab Criteria 83–91 % of patients report an excellent or good functional recovery
- Significant decrease in arm- and neck pain on visual analog scale (VAS)
- Significant improvement concerning Neck Disability Index (NDI)
- Average time before returning to work 10–28 days
- Significantly decrease in disc height
- Postoperative development of segmental kyphosis and instability remains unclear
- About 2 % of patients need additional open surgery

Advantages of APECD

- Outpatient procedure
- As safe as standard open technique

Complications (Access-Related)

- Carotid artery injury (dissection, rupture)
- Jugular vein
- Postoperative temporary headache due to prolonged high irrigation pressure because of epidural venous bleeding
- Decreased disc height
- Discitis
- esophagus,
- Trachea,
- Thyroid and
- Laryngeal nerves

Endoscopic Posterior Cervical Laminoforaminotomy

In 1951 Frykholm first described posterior foraminotomy through partial resection of the medial margin of facet joint to decompress the cervical nerve root in a series of patients with radiculopathy [56]. At that time this new technique was a big step ahead of the established operative techniques for dorsal decompression of the cervical spine like laminectomy with or without chiseling of retrospondylophytes. Conventional posterior approaches have the disadvantage of the detaching the extensor cervical muscles from the laminae and the spinous process. Detaching of the paraspinal muscles can causes a severe trauma and can come along with postoperative complications like axial neck pain, shoulder pain, loss of lordosis or even spinal instability [57, 58]. The posterior cervical laminoforaminotomy technique applied microsurgical principles to the dorsal approach to the cervical spine for the first time. It enables bony decompression of the nerve root in cases of foraminal stenosis or removal of disc fragments with the advantage of far less injuries to the myelon. It does not allow the removal of medioventral nerve compressing lesions. Nonetheless through the development of the anterior approach to the cervical spine (ACDF) by Smith and Robinson and modified by Cloward in 1958 eluded the problem of the myelon being in the way of the pathology [34, 35]. As a consequence the anterior approach became the gold standard in the treatment of degenerative cervical disc disease and cervical stenosis for decades and the posterior approach became obsolete by the time. However, ACDF results in the loss of a motion segment, fusion and approach-related morbidity and graft-related complications. A widespread movement came into the development of new techniques for the treatment of degenerative cervical diseases. Besides alternative to segmental fusion in the anterior approach which mostly centred in artificial disc replacement, the posterior foraminotomy was rediscovered and improved upon [59]. The aim to reduce iatrogenic trauma related to the surgical approach has led to the evaluation of neuroendoscopy in the spinal surgery. Endoscopic lumbar discectomy has been shown to produce comparable results to standard microsurgical discectomy with the advantage of less muscular trauma and thereby less back pain [31]. However till today there is still no consensus about the ideal surgical approach for the treatment of cervical radiculopathy. Depending on the morphologic pathology advantages and disadvantages of both approaches and surgical techniques have to be kept in mind when deciding which approach is ideal. In cases, in which the cause of compression is located posterolaterally, such as intraforaminal cervical herniation, the posterior foraminotomy has showed to be effective and safe [60]. This chapter will deliver an impression of the posterior endoscopic cervical laminoformaminotomy (PECLF) technique and equipment that is necessary to perform PECLF and gives a short review about clinical results.

Indications

The EPCLF approach in indicated in the following cervical pathologies and situation:

- Osseous foraminal stenosis
- Unilateral pathology (mono or bisegmental)
- Nerve root compression and contraindication for anterior approaches (e.g. tracheostomy, cervical radiation therapy prior to surgery)

Contraindication

- Evidence of instabilities and / or deformities
- Discogenic pain resulting in neck pain and nonradicular arm pain

Surgical Equipment for EPCLF

The following surgical equipment and instruments are necessary to perform EPCLF:

- Endoscopic system (e.g. EasyGO- system Karl Storz GmbH & Co KG, Tuttlingen, Germany)
- Video digital endoscopy unit with a camera and data archiving system (e.g. AIDA® compact NEO, Karl Storz GmbH & Co. KG, Tuttlingen, Germany)
- 30° Hopkins® Forward-Oblique telescopes
- Ordinary endoscopic spine instruments
- Fluoroscopy (C-arm)

Surgical Technique

After the induction of general endotracheal anesthesia, the patient is placed in prone position or in sitting position and preoperative antibiotics are admitted. In prone position the head is fixed in a three-point Mayfield headrest. an elevated and slightly inclined. Based on the reduction of blood loss which results in a shorter operative time sitting position is preferred by many surgeons. However, sitting position is discussed controversially, even though the risk of air embolus is negligible due to minimally invasive approach and short operative time. Further the ability to identify the cervicothoracic junction via fluoroscopy is improved in sitting position. In prone position attention should be paid that the surgical field is above the level of the heart if somehow possible to reduce intraoperative bleeding due to dammed epidural blood vessels. The affected segment is identified via lateral fluoroscopy. For ideal identification the shoulders may be pulled down and fixed by using a medical duct tape in prone position. After identification the planned skin incision was marked. The skin incision should not be made to small because of the risk skin ischemia and about 2 cm parallel to the midline. In case of a single level surgery the skin incision is planned in a fashion that the centre of the working sheath points in direct way at the pathology, i.e. neuroforamen of the affected segment. In case of a two level surgery the skin incision is recommended to be made halfway between the two affected segments. The working sheath could be adjusted in his angle towards both facet joints. In the rare case of a three level surgery the skin incision is above the middle segment. By the skin incision the muscle fascia is opened too. Next step of the procedure was the dilation of the muscle with the set of dilators. Beginning with the smallest dilator the vertebral arch was punctured. The tip of each dilator was always in firmly contact to the vertebral arch respectively the facet joint. While holding the dilators in place a particular working sheath was introduced. The whole application of the dilators and the working sheath are done under control of lateral fluoroscopy. After introduction of the working sheath it is connected to the holder and thereby fixed to the surgical table. Depending on the number of segments which has to be operated the working sheath is chosen. For a single level procedure a sheath with an out diameter of 15 mm and a 19 mm for two level procedures are suitable. After connecting the working sheath to the holder the dilators are pulled out and the endoscope can be inserted. The 30° optic points towards the midline and the set up for bimanual surgery is completed. Next step is the removal of the soft tissue and the exposing of the vertebral arch and the facet joint by using a dissector, bipolar forceps and grasper. The lateral part of the vertebral arch is thinned with a diamond drill before the ligamentum flavum is resected. Through this technique the lateral section of the dural sac with its outgoing nerve root are depicted. At this particular moment the endoscope can be turned 180° so that the optic pointed towards the affected neuroforamen. The nerve root is decompressed from medial to lateral towards the neuroforamen by removing the medial half of the facet joint. Heavy bleeding can be caused by dammed epidural veins on the dorsal layer of the nerve. To control the intraoperative bleeding bipolar coagulation in a gently fashion, compression via sponges and cotton, a combination of both or surgical hemostatic agent for haemostasis is recommended. After successful decompression nerve the surgical field was irrigated and the working sheath was carefully pulled out. The wound was closed by fascia-, subcutaneous- and subcuticular sutures (Figs. 7.4 and 7.5).

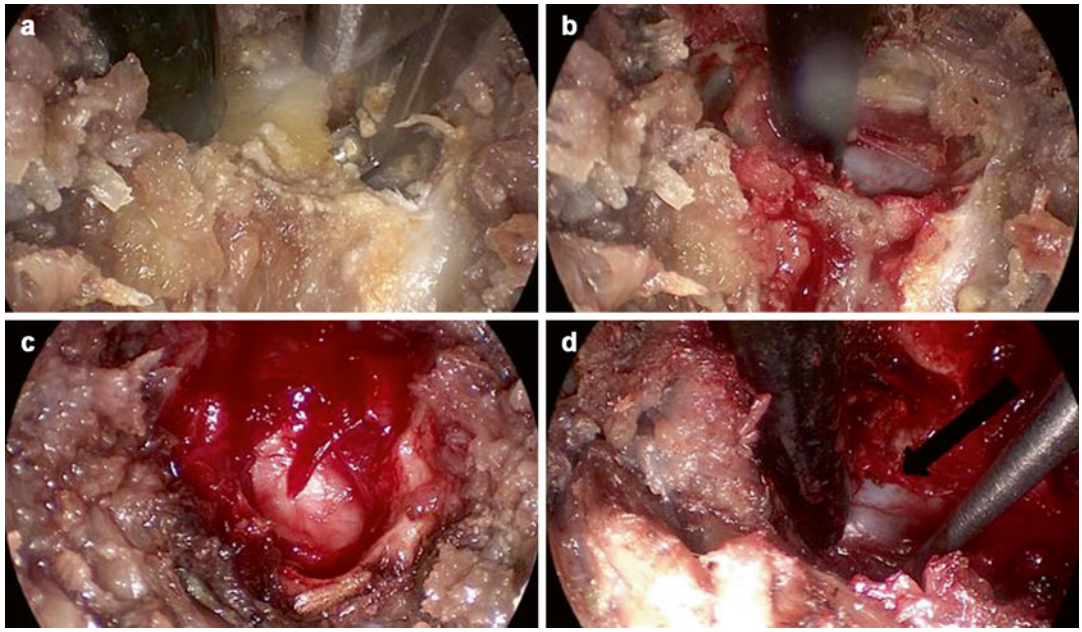


Fig. 7.4 Intraoperative Image of Endoscopic Posterior Cervical Laminoforaminotomy. (**a**) Beginning of the removal of the ligamentum flavum. (**b**) First exposure of the dura after resection of the ligamentum flavum and the bony lamina. (**c**) Foraminotomy and visible dura. (**d**) Decompressed neuroforamen (hook) and exciting nerve root (*arrow*)

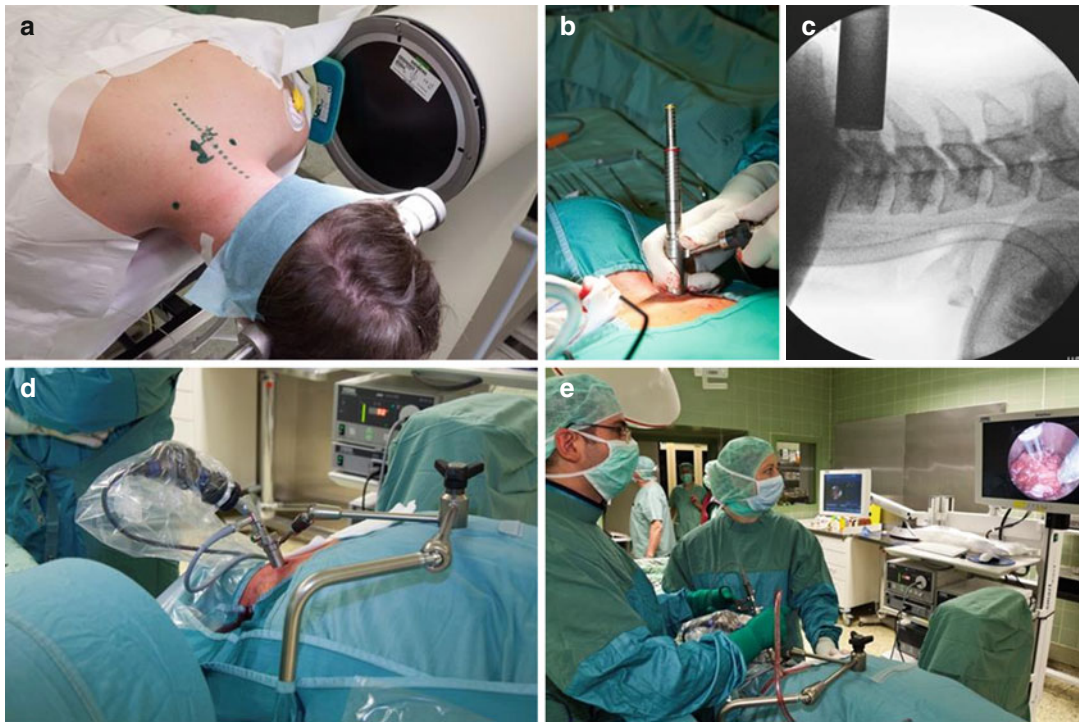


Fig. 7.5 Intraoperative setup for Endoscopic Posterior Cervical Laminoforaminotomy. (**a**) Patient positioning (Prone) with head fixed in a Mayfield clamp. (**b**) Introduction of the dilation system with working trocar which is fixed to the holding arm (EasyGO®-system, Karl Storz Company, Tuttlingen, Germany). (**c**) Fluoroscopic control of trocar positioning (perpendicular to the lamina). (**d**) Fully installed EasyGO®-system (HD-camera). (**e**) Intraoperative set up with 16:9 screen monitor and Video digital endoscopy unit

Outcome

- 97 % of patients report an excellent or good functional recovery [61]
- 92 % of complete resolution in radicular symptoms [62]
- 85 % without pain postoperatively up 100 % 6 weeks post-OP
- Significant improvement concerning Neck Disability Index (NDI)

Advantages of EPCLF

- Outpatient procedure
- Reduced blood loss compared to open technique

Complications (Access-Related)

- Hemostasis, if origin of bleeding is inaccessible
- Contralateral neurogenic thoracic outlet syndrome
- CSF leak management
- Recurrent dis herniation

Microendoscopic Cervical Laminoplasty and Laminectomy

Cervical spondylotic myelopathy (CSM) is the natural result of degenerative compression on the cervical spinal cord. CSM is the most common cervical spinal cord disorder in persons more than 55 years of age. Patients often experience a progressive and stepwise deterioration of neurological function such as gait dystaxia and problems with fine motor skills, dexterity and signs reflecting upper motor neuron disease [63]. Intervention is often controversial discussed, especially when symptoms are absent or minimal [64]. However, surgical intervention is often pursued as symptoms progress but controversy still exists over the optimal choice of surgery for spinal cord decompression [65, 66]. Posterior laminectomy decompression has been described as a treatment for CSM since the 1940s. It requires stripping of the posterior cervical muscular and detachment of supraspinous and interspinous ligamentous structures (posterior tension band) from the bony parts of the cervical vertebra. Patients may experience postoperative neck pain from iatrogenic muscle injury and muscle spasm. Multilevel laminectomies are associated with increased risk of 6–47 % for postlaminectomy kyphosis [57, 67]. Fusion may be required if kyphotic deformity or instability is existing prior to decompression.

Postoperative instability and iatrogenic morbidity has forced spine surgeons to explore more efficacious ways of decompression. Cervical open door laminoplasty allows for adequate posterior decompression of the spinal cord while retaining the posterior elements it was described by Hirabayashi and Satomi first [68]. This technique minimizes the amount of removal of the posterior tension band and, hence, decreases the risk for postoperative instability and kyphosis and therefore the risks of posterior cervical fusion. Multiple techniques for performing a cervical laminoplasty have been described such as expansive "open door," a midline "French Door," En Bloc resection, spinous process splitting, and Z-Plasty [69–72].

The comparative outcomes, however, are still a matter of controversy no definitive literature shows its superiority to laminectomy in conjunction with a posterior cervical fusion. Minimally invasive techniques have been refined constantly. The goal of these techniques is to achieve the comparable clinical outcomes as traditional open surgeries but through smaller incisions and with less muscle dissection and tissue traumatization. Minimized muscle trauma and devascularization favors low rates of wound infections, less blood loss, less postoperative pain, and a shorter hospitalization time [73]. Different techniques for microendoscopic cervical laminoplasty and laminectomy have been reported in the literature. Minamide reported a bilateral decompression technique via a unilateral approach [74]. Yakubi described a technique for a partial laminectomy by performing two paramedian approaches for ipsilateral decompression [75]. Dahdaleh performed single or multilevel hemilaminotomies for treatment of CSM [76]. Recently Oshima reported about a midline approach for interlaminar decompression

The following sections will give a short introduction on these techniques.

Indications

The MECLL approach

Contraindications

- Cervical myelopathy with tumor, trauma,
- Severe ossification of posterior longitudinal ligament (OPLL)
- Rheumatoid arthritis,
- Pyogenic spondylitises,
- Destructive spondylo-arthropathies
- Cervical kyphosis (preoperative)

Surgical Equipment for MECLL

The following surgical equipment and instruments are necessary to perform MECLL:

- Tubular dilators and tubular retractor system (e.g. METRx, Sofamor Danek, Memphis, USA)
- Video digital endoscopy unit with a camera
- Different endoscopes (e.g. 0°-optic and 30°-optic)
- Ordinary endoscopic spine instruments
- Fluoroscopy (C-arm)

Surgical Technique

Microendoscopic Laminoplasty: The procedure is performed in general endotracheal anesthesia. The patient is placed in prone position and the head is fixed in a Mayfield head clamp. The neck is fixed in a neutral position. The fluoroscopic C-arm is recommended to be positioned into the surgical field so that lateral fluoroscopic images can be obtained intraoperatively. The level of interest is marked on the side of the approach. A skin incision of approximately 18 mm in length is made at the spinal level which has to be decompressed. The muscle fascia is split before the tubular dilation system is introduced. The paravertebral cervical muscles are gently dilate before the working channel is then passed over the dilators and connected to the flexible holdingarm mounted to the table side rail. Confirmation of correct working channel position has to be obtained by lateral fluoroscopy before removal of dilators. The tubular retractor is pending perpendicular to the lamina and facet joints, and points parallel to the intervertebral disc space. The endoscope is introduced into the working channel and bipolar cautery is used to remove any residual muscular and soft tissues overlying the lamina and facet joint. After depicting the bony edges of the lamina a small angled dissector is used to confirm inter-lamina space and the medial aspect of the facet joint. First the lamina near to the ligamentum flavum is thinned out whit a high speed diamond drill and then resected with a Kerrison punch. After identifying the attachment of the ligamentum flavum of the superior lamina the drilling and resection is continued by identifying the superior attachment of the inferior lamina. The ligamentum flavum is left intact. The working channel is then turned medially and downward to obtain a contralateral view. Next the basis of spinous process is drilled before laminotomy can be performed. The angled endoscopic view in combination with a turn of the working channel allow for an excellent visualization to the contralateral side. Again the ligamentum flavum is left intact to protect the dura while laminotomy is performed. When all bony structures are removed from the ligamentum flavum the loose ligamentum flavum was inspected. Attention is paid for removing the ligamentum flavum gently without applying to much pressure on the underlying dura or causing a dural tear. Small angled curette or nerve hook are ideal to mobilize it from its attachment. Decompression is finished when dural pulsation is visible. In case of a two-level laminoplasty the working channel can be turned towards adjacent segment either cranially or caudally. For a four-level laminoplasty two separate skin incision are necessary to reach all segments sufficiently. The placement of a drain is optional before wound closure.

Endoscopic Partial Laminectomy: Surgery is performed in general anesthesia and intraoperative set up is the same as described for microendoscopic laminoplasty above. The skin incision starts the inferior part of the superior lamina and continues till the superior part of the inferior lamina thinned out by using a high-speed drill. Resection of the ligamentum flavum by endoscopic hook and Kerrison rongeur is followed. Decompression continues by removing parts of the basis of the spinous process. When the ligamentum flavum was completely removed,

dural pulsation was observed. For decompression of the contralateral side the same approach and technique is performed. However, the spinous process is not resected en bloc to maintain spinal stabilityof approximately 18 mm is marked about 20 mm off the midline. Under fluoroscopic guidance, a K-wire is inserted through the posterior cervical musculature towards the superior lamina at the level of interest. Seeking bony contact at all time is necessary to avoid perforating the interlaminar window and damaging the spinal cord. The best trajectory is slightly inclined from horizontal orientation. After seeking bony contact the first dilator was passed along the K-wire onto the lamina. Once the bone of the lamina is palpated, the K-wire is removed. Sequential dilation of the paraspinal muscle is performed before the working channel is introduced. Dilation of the musculature, introduction and confirming the correct position again is done under fluoroscopic control to ensure a proper working trajectory throughout this process. As described above the working channel is then connected via a flexible arm and affixed to the operating table to maintain correct position. Once the endoscope is inserted the surgeon exposed the bony lamina and the facet joint. The procedure is split in to identical steps. After identifying all the important anatomical structures the partial laminectomy

Endoscopic Interlaminar Decompression through a Midline approach: Surgery is performed in general anesthesia. The skin incision is marked in the midline under fluoroscopic guidance at the level of interest. The nuchal ligament was longitudinal split to expose the tips of the spinous process. After exposure the sequential dilation with a tubular dilation system is performed. The working channel is placed between the two spinous processes. In some cases drilling of the tip of a spinous process may be necessary to create a cavity for the working channel and make position more stable. Once the working trocar is in place the procedure continues by partial resection of the spinous process to gain working space for decompression. First the interspinalis mucles are spread before deep attachment of the semispinalis cervicis and multifidius muscles are coagulated and dissected. After exposure of the bony structures a laminectomy or partial laminectomy with resection of the ligamentum flavum and spinous process may be performed for decompression.

Outcome

- JOA score improved from 10.1 point to 13.6 [74]; 11.6 to 14.1 points [75]
- Nurick score improves from 1.6 to 0.3
- VAS reduction from 46 to 15 mm
- Odoms score 70 % excellent and good results

Advantages of CMEDF

- Minimal blood loss (about 30 cc for one level)
- Maintaining posterior cervical structures

Complications (Access-Related)

- Long surgical time: 106 min for one level laminoplasty / 164 min for partial hemilaminectomy
- Dura tear management

References

1. Perez-Cruet MJ, Balabhadra RSV, Samartzis D, Kim DH. Historical background of minimally invasive spine surgery. In: Kim DH, Fessler RG, Regan JJ, editors. Endoscopic spine surgery and instrumentation. New York: Thieme; 2004. p. 3–18.
2. Marketos SG, Skiadas P. Hippocrates. The father of spine surgery. Spine. 1999;24(13):1381–7. Epub 1999/07/15.
3. Knoeller SM, Seifried C. Historical perspective: history of spinal surgery. Spine. 2000;25(21):2838–43. Epub 2000/11/07.
4. Forst R, Hausmann B. Nucleoscopy – a new examination technique. Arch Orthop Trauma Surg. 1983;101(3):219–21. Epub 1983/01/01.
5. Bosch F, Wehrman U, Saeger HD, Kirch W. Laparoscopic or open conventional cholecystectomy: clinical and economic considerations. Eur J Surg. 2002;168(5):270–7. Epub 2002/10/12.
6. Topcu O, Karakayali F, Kuzu MA, Ozdemir S, Erverdi N, Elhan A, et al. Comparison of long-term quality of life after laparoscopic and open cholecystectomy. Surg Endosc. 2003;17(2):291–5. Epub 2002/10/05.
7. Schwender JD, Foley KT, Holly LT, Transfeldt EE. Minimally invasive posterior surgical approaches to the lumbar spine. In: The spine. 5th ed. Philadelphia: Saunders/Elsevier; 2006.
8. Mayer TG, Vanharanta H, Gatchel RJ, Mooney V, Barnes D, Judge L, et al. Comparison of CT scan muscle measurements and isokinetic trunk strength in

postoperative patients. Spine. 1989;14(1):33–6. Epub 1989/01/01.
9. Sihvonen T, Herno A, Paljarvi L, Airaksinen O, Partanen J, Tapaninaho A. Local denervation atrophy of paraspinal muscles in postoperative failed back syndrome. Spine. 1993;18(5):575–81. Epub 1993/04/01.
10. Adams MA, Hutton WC, Stott JR. The resistance to flexion of the lumbar intervertebral joint. Spine. 1980;5(3):245–53. Epub 1980/05/01.
11. Abumi K, Panjabi MM, Kramer KM, Duranceau J, Oxland T, Crisco JJ. Biomechanical evaluation of lumbar spinal stability after graded facetectomies. Spine. 1990;15(11):1142–7. Epub 1990/11/01.
12. Ikuta K, Arima J, Tanaka T, Oga M, Nakano S, Sasaki K, et al. Short-term results of microendoscopic posterior decompression for lumbar spinal stenosis. Technical note. J Neurosurg Spine. 2005;2(5):624–33. Epub 2005/06/11.
13. Yoshimoto M, Miyakawa T, Takebayashi T, Ida K, Tanimoto K, Kawamura S, et al. Microendoscopy-assisted muscle-preserving interlaminar decompression for lumbar spinal stenosis: clinical results of consecutive 105 cases with more than 3-year follow-up. Spine. 2014;39(5):E318–25. Epub 2013/12/25.
14. Roh SW, Kim DH, Cardoso AC, Fessler RG. Endoscopic foraminotomy using MED system in cadaveric specimens. Spine. 2000;25(2):260–4. Epub 2000/02/24.
15. Guiot BH, Khoo LT, Fessler RG. A minimally invasive technique for decompression of the lumbar spine. Spine. 2002;27(4):432–8. Epub 2002/02/13.
16. Burkhardt BW, Qadeer M, Oertel JMK, Sharif S. Full endoscopic interlaminar lumbar disc surgery: is it the gold standard yet? World Spinal Column J. 2014;5(2): 88–95.
17. Zada G, Liu C, Apuzzo ML. "Through the looking glass": optical physics, issues, and the evolution of neuroendoscopy. World Neurosurg. 2013;79(2 Suppl): S3–13. Epub 2013/02/09.
18. Gow JG. Harold Hopkins and optical systems for urology – an appreciation. Urology. 1998;52(1):152–7. Epub 1998/07/22.
19. Funfack HJ. Development of the urology under Max Nitze. Z Urol. 1953;46(8):497–505. Epub 1953/01/01. Die Entwicklung der Urologie unter Max Nitze.
20. Li KW, Nelson C, Suk I, Jallo GI. Neuroendoscopy: past, present, and future. Neurosurg Focus. 2005; 19(6), E1. Epub 2006/01/10.
21. Prevedello DM, Doglietto F, Jane Jr JA, Jagannathan J, Han J, Laws Jr ER. History of endoscopic skull base surgery: its evolution and current reality. J Neurosurg. 2007;107(1):206–13. Epub 2007/07/21.
22. Grunert P, Gaab MR, Hellwig D, Oertel JM. German neuroendoscopy above the skull base. Neurosurg Focus. 2009;27(3), E7. Epub 2009/09/03.
23. Di Ieva A, Tam M, Tschabitscher M, Cusimano MD. A journey into the technical evolution of neuroendoscopy. World Neurosurg. 2014;82(6):e777–89. Epub 2014/09/17.
24. Philipps M, Oertel J. High-definition imaging in spinal neuroendoscopy. Minim Invasive Neurosurg. 2010;53(3):142–6. Epub 2010/09/03.
25. Kambin P, Cohen LF. Arthroscopic microdiscectomy versus nucleotomy techniques. Clin Sports Med. 1993;12(3):587–98. Epub 1993/07/01.
26. Kambin P, O'Brien E, Zhou L, Schaffer JL. Arthroscopic microdiscectomy and selective fragmentectomy. Clin Orthop Relat Res. 1998;347: 150–67. Epub 1998/04/01.
27. Kambin P. Arthroscopic microdiscectomy of the lumbar spine. Clin Sports Med. 1993;12(1):143–50. Epub 1993/01/01.
28. Foley KT, Smith MM. Microendoscopic discectomy. Technol Neurosurg. 1997;3:301–7.
29. Righesso O, Falavigna A, Avanzi O. Comparison of open discectomy with microendoscopic discectomy in lumbar disc herniations: results of a randomized controlled trial. Neurosurgery. 2007;61(3):545–9; discussion 9. Epub 2007/09/21.
30. Muramatsu K, Hachiya Y, Morita C. Postoperative magnetic resonance imaging of lumbar disc herniation: comparison of microendoscopic discectomy and Love's method. Spine. 2001;26(14):1599–605. Epub 2001/07/20.
31. Oertel JM, Mondorf Y, Gaab MR. A new endoscopic spine system: the first results with "Easy GO". Acta Neurochir. 2009;151(9):1027–33. Epub 2009/07/25.
32. Palmer S, Turner R, Palmer R. Bilateral decompression of lumbar spinal stenosis involving a unilateral approach with microscope and tubular retractor system. J Neurosurg. 2002;97(2 Suppl):213–7. Epub 2002/09/26.
33. Bailey RW, Badgley CE. Stabilization of the cervical spine by anterior fusion. J Bone Joint Surg Am. 1960;42-A:565–94. Epub 1960/06/01.
34. Smith GW, Robinson RA. The treatment of certain cervical-spine disorders by anterior removal of the intervertebral disc and interbody fusion. J Bone Joint Surg Am. 1958;40-A(3):607–24. Epub 1958/06/01.
35. Cloward RB. The anterior approach for removal of ruptured cervical disks. J Neurosurg. 1958;15(6): 602–17. Epub 1958/11/01.
36. Pitzen T, Kranzlein K, Steudel WI, Strowitzki M. Complaints and findings at the iliac crest donor site following anterior cervical fusion. Zentralbl Neurochir. 2004;65(1):7–12. Epub 2004/02/26. Postoperative Beschwerden und Befunde im Bereich der Spanentnahmestelle am Becken bei ventraler zervikaler Fusion.
37. Silber JS, Anderson DG, Daffner SD, Brislin BT, Leland JM, Hilibrand AS, et al. Donor site morbidity after anterior iliac crest bone harvest for single-level anterior cervical discectomy and fusion. Spine. 2003;28(2):134–9. Epub 2003/01/25.
38. Wirth FP, Dowd GC, Sanders HF, Wirth C. Cervical discectomy. A prospective analysis of three operative techniques. Surg Neurol. 2000;53(4):340–6; discussion 6–8. Epub 2000/05/29.
39. Wong AP, Smith ZA, Lall RR, Bresnahan LE, Fessler RG. The microendoscopic decompression of lumbar stenosis: a review of the current literature and clinical results. Minim Invasive Surg. 2012;2012:325095. Epub 2012/08/18.

40. Tzaan WC. Anterior percutaneous endoscopic cervical discectomy for cervical intervertebral disc herniation: outcome, complications, and technique. J Spinal Disord Tech. 2011;24(7):421–31. Epub 2011/03/25.
41. Ahn Y, Lee SH, Shin SW. Percutaneous endoscopic cervical discectomy: clinical outcome and radiographic changes. Photomed Laser Surg. 2005;23(4): 362–8. Epub 2005/09/08.
42. Soliman HM. Cervical microendoscopic discectomy and fusion: does it affect the postoperative course and the complication rate? A blinded randomized controlled trial. Spine. 2013;38(24):2064–70. Epub 2013/09/13.
43. Tan J, Zheng Y, Gong L, Liu X, Li J, Du W. Anterior cervical discectomy and interbody fusion by endoscopic approach: a preliminary report. J Neurosurg Spine. 2008;8(1):17–21. Epub 2008/01/05.
44. Yao N, Wang C, Wang W, Wang L. Full-endoscopic technique for anterior cervical discectomy and interbody fusion: 5-year follow-up results of 67 cases. Eur Spine J. 2011;20(6):899–904. Epub 2010/12/15.
45. Bertalanffy H, Eggert HR. Clinical long-term results of anterior discectomy without fusion for treatment of cervical radiculopathy and myelopathy. A follow-up of 164 cases. Acta Neurochir. 1988;90(3–4):127–35. Epub 1988/01/01.
46. Nandoe Tewarie RD, Bartels RH, Peul WC. Long-term outcome after anterior cervical discectomy without fusion. Eur Spine J. 2007;16(9):1411–6. Epub 2007/01/31.
47. Tajima T, Sakamoto H, Yamakawa H. Diskectomy cervicale percutanee. Revue Med Orthoped. 1989;17: 7–10.
48. Onik G, Helms CA, Ginsburg L, Hoaglund FT, Morris J. Percutaneous lumbar diskectomy using a new aspiration probe. AJR Am J Roentgenol. 1985;144(6): 1137–40. Epub 1985/06/01.
49. Courtheoux F, Theron J. Automated percutaneous nucleotomy in the treatment of cervicobrachial neuralgia due to disc herniation. J Neuroradiol. 1992;19(3):211–6. Epub 1992/09/01.
50. Chao SC, Lee HT, Kao TH, Yang MY, Tsuei YS, Shen CC, et al. Percutaneous pulsed radiofrequency in the treatment of cervical and lumbar radicular pain. Surg Neurol. 2008;70(1):59–65; discussion Epub 2008/01/22.
51. Nardi PV, Cabezas D, Cesaroni A. Percutaneous cervical nucleoplasty using coblation technology. Clinical results in fifty consecutive cases. Acta Neurochir Suppl. 2005;92:73–8. Epub 2005/04/16.
52. Knight MT, Goswami A, Patko JT. Cervical percutaneous laser disc decompression: preliminary results of an ongoing prospective outcome study. J Clin Laser Med Surg. 2001;19(1):3–8. Epub 2001/09/08.
53. Ruetten S, Komp M, Merk H, Godolias G. Full-endoscopic anterior decompression versus conventional anterior decompression and fusion in cervical disc herniations. Int Orthop. 2009;33(6):1677–82. Epub 2008/11/19.
54. Lee SH, Lee JH, Choi WC, Jung B, Mehta R. Anterior minimally invasive approaches for the cervical spine. Orthop Clin North Am. 2007;38(3):327–37; abstract v. Epub 2007/07/17.
55. Lee JH, Lee SH. Clinical and radiographic changes after percutaneous endoscopic cervical discectomy: a long-term follow-up. Photomed Laser Surg. 2014; 32(12):663–8. Epub 2014/11/14.
56. Frykhlom R. Cervical nerve root compression resulting from disc degeneration and root sleeve fibrosis. Acta Chir Scand. 1951;Supplementum(160):1–149.
57. Albert TJ, Vacarro A. Postlaminectomy kyphosis. Spine. 1998;23(24):2738–45. Epub 1999/01/08.
58. Chiba K, Ogawa Y, Ishii K, Takaishi H, Nakamura M, Maruiwa H, et al. Long-term results of expansive open-door laminoplasty for cervical myelopathy – average 14-year follow-up study. Spine. 2006;31(26):2998–3005. Epub 2006/12/19.
59. Herkowitz HN, Kurz LT, Overholt DP. Surgical management of cervical soft disc herniation. A comparison between the anterior and posterior approach. Spine. 1990;15(10):1026–30. Epub 1990/10/01.
60. Williams RW. Microcervical foraminotomy. A surgical alternative for intractable radicular pain. Spine. 1983;8(7):708–16. Epub 1983/10/01.
61. Adamson TE. Microendoscopic posterior cervical laminoforaminotomy for unilateral radiculopathy: results of a new technique in 100 cases. J Neurosurg. 2001;95(1 Suppl):51–7. Epub 2001/07/17.
62. Siddiqui A, Yonemura KS. Posterior cervical mircoendoscopic diskectomy and laminoforaminotomy. In: Kim DH, Fessler RG, Regan JJ, editors. Endoscopic spine surgery and instrumentation. New York: Thieme; 2004. p. 66–73.
63. Klineberg E. Cervical spondylotic myelopathy: a review of the evidence. Orthop Clin North Am. 2010;41(2):193–202. Epub 2010/04/20.
64. Sumi M, Miyamoto H, Suzuki T, Kaneyama S, Kanatani T, Uno K. Prospective cohort study of mild cervical spondylotic myelopathy without surgical treatment. J Neurosurg Spine. 2012;16(1):8–14. Epub 2011/10/11.
65. Ghogawala Z, Martin B, Benzel EC, Dziura J, Magge SN, Abbed KM, et al. Comparative effectiveness of ventral vs dorsal surgery for cervical spondylotic myelopathy. Neurosurgery. 2011;68(3):622–30; discussion 30–1. Epub 2010/12/18.
66. Scheufler KM, Kirsch E. Percutaneous multilevel decompressive laminectomy, foraminotomy, and instrumented fusion for cervical spondylotic radiculopathy and myelopathy: assessment of feasibility and surgical technique. J Neurosurg Spine. 2007;7(5): 514–20. Epub 2007/11/06.
67. McAllister BD, Rebholz BJ, Wang JC. Is posterior fusion necessary with laminectomy in the cervical spine? Surg Neurol Int. 2012;3 Suppl 3:S225–31. Epub 2012/08/21.
68. Hirabayashi K, Satomi K. Operative procedure and results of expansive open-door laminoplasty. Spine. 1988;13(7):870–6. Epub 1988/07/01.

69. Ratliff JK, Cooper PR. Cervical laminoplasty: a critical review. J Neurosurg. 2003;98(3 Suppl):230–8. Epub 2003/04/15.
70. Kihara S, Umebayashi T, Hoshimaru M. Technical improvements and results of open-door expansive laminoplasty with hydroxyapatite implants for cervical myelopathy. Neurosurgery. 2005;57(4 Suppl): 348–56; discussion −56. Epub 2005/10/20.
71. Iwasaki M, Ebara S, Miyamoto S, Wada E, Yonenobu K. Expansive laminoplasty for cervical radiculomyelopathy due to soft disc herniation. Spine. 1996;21(1): 32–8. Epub 1996/01/01.
72. Edwards 2nd CC, Heller JG, Silcox 3rd DH. T-Saw laminoplasty for the management of cervical spondylotic myelopathy: clinical and radiographic outcome. Spine. 2000;25(14):1788–94. Epub 2000/07/11.
73. Fessler RG, O'Toole JE, Eichholz KM, Perez-Cruet MJ. The development of minimally invasive spine surgery. Neurosurg Clin N Am. 2006;17(4): 401–9. Epub 2006/10/03.
74. Minamide A, Yoshida M, Yamada H, Nakagawa Y, Maio K, Kawai M, et al. Clinical outcomes of microendoscopic decompression surgery for cervical myelopathy. Eur Spine J. 2010;19(3):487–93. Epub 2009/12/04.
75. Yabuki S, Kikuchi S. Endoscopic partial laminectomy for cervical myelopathy. J Neurosurg Spine. 2005;2(2):170–4. Epub 2005/03/03.
76. Dahdaleh NS, Wong AP, Smith ZA, Wong RH, Lam SK, Fessler RG. Microendoscopic decompression for cervical spondylotic myelopathy. Neurosurg Focus. 2013;35(1), E8. Epub 2013/07/03.

Anterior Cervical Approach: Decompression and Fusion with Cages

8

Alessandro Landi and Roberto Delfini

Abbreviations

ACCF	Anterior Cervical Corpectomy Fusion
ACDF	Anterior Cervical Discectomy Fusion
ASD	Adjacent Segment Degeneration

Intervertebral disc degeneration and cervical spondylosis are the primum movens of the processes that subsequently lead to cervical spondylodiscoarthosis causing biochemical and morphological modifications of cervical spine. Degenerative changes in the cervical spine, resulting in neck pain and/or cervical myelopathy and radiculopathy are commonly observed conditions in neurosurgical practice.

History

Prior to 1950, cervical spine surgery was performed via a posterior approach. The first ventral cervical spine stabilization with an only fusion was performed by Bailey and Bagley .n 1952. In 1955, Robinson et al. described their operative technique using an interbody graft. In 1958, Cloward's modification of the anterior cervical decompression and interbody fusion (ACDF) procedure was published. Initially, ACDF, was performed using the patient's own iliac crest bone or tibia, fibula and ribs (autograft). However, the use of autologous cancellous bone gave rise to a frequently reported complication, namely acute and chronic pain at the donor site, usually the iliac crest. Graft subsidence was also possible. In fact, graft harvesting complications occurring in traditional fusion procedures favoured the ongoing development of cage technology. Carbon Fiber Cages were introduced in the early 1990s and Brantingan et al. in a very important study, demonstrated that carbon is preferable to other matherials, such as titanium, first because it is radiolucent and, secondly because it also does not induce any kind of bone corrosion or inflammatory reaction. Moreover, in their retrospective study Frati et al. pointed out the advantages offered by the high elasticity of carbon fiber implants, that redistributes load-sharing to the bone graft inside the implant, thus improving the quality of fusion and reducing stress on the adjacent vertebral level. To increase fusion rates and decrease graft complications, some investigators supplement allograft fusion with an anterior cervical plate, a technique initially described by Bohler and Gaudernak, and Caspar for treating cervical trauma

A. Landi, MD, PhD (✉) • R. Delfini, MD, PhD
Division of Neurosurgery, Department of Neurology and Psychiatry, University of Rome "Sapienza", Viale del Policlinico 155, 00185 Rome, Italy
e-mail: dott.alessandro.landi@gmail.com

P.P.M. Menchetti (ed.), *Cervical Spine: Minimally Invasive and Open Surgery*,
DOI 10.1007/978-3-319-21608-9_8

Anterior Cervical Approach

Anterior Cervical Approach: is the standard surgical approach and widely used. The patient is in supine position on the surgical table, with the head in neutral position or slightly rotated towards the contralateral side of the surgical incision, with a little cushion placed under the shoulders, to ensure the maximal extension of the neck. One can identify some anatomic landmarks (Fig. 8.1) pointing out the projection of the cervical vertebrae on the neck.

- Hard palate: atlas arch
- Inferior side of the mandible: C1-C2 space
- Hyoid bone: C3
- Thyroid cartilage: C4-C5 space
- Cricoid cartilage: C5-C6 space
- Carotid tuberculum (Chassignac's tuberculum): lateral margin of C6

Other identifiable landmarks are:

The medial margin of the sternocleidomastoid muscle, from the mastoid process to the sternum

The carotid artery, that can be palpated posteriorly and laterally to the medial margin of the sternocleidomastoid muscle.

After the execution of an intraoperative radiography, the skin incision is performed along a line of the neck (transversal if the level to expose is one, oblique along the margin of the sternocleidomastoid muscle if the levels to expose are at least two). The side chosen is generally the left one to reduce the risk of damage to the recurrent laryngeal nerve, because on the right side this nerve has a more variable anatomical route. After the skin incision, superficial haemostasis is performed, the hypodermis is elevated and the platysma is identified. The fascial sheath over the platysma is dissected with the same orientation of the skin incision and then the platysma is separated longitudinally with a smooth dissection, identifying the medial margin of the sternocleidomastoid muscle covered by the deep cervical fascia; the deep cervical fascia is then incised anteriorly to the anterior margin of the sternocleidomastoid muscle. After that, the sternohyoid and sternothyroid muscles are stretched apart medially so that trachea and oesophagus can be dislocated medially, and the carotid sheath, containing the common carotid artery, the jugular vein and the vagus nerve, is identified. Once the carotid artery has been palpated and well identified, the pretracheal fascia is incised starting from the medial side of the sheath and the sheath is stretched apart with the neurovascular bundle of the neck in lateral and external position together with the sternocleidomastoid muscle [12].

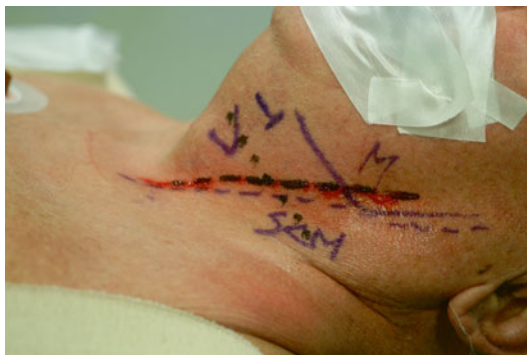


Fig. 8.1 Anatomical landmarks for the anterior prestern-nocleidomastoid – precarotid approach

With a smooth dissection the cervical vertebrae, covered by the prevertebral fascia, are reached, and the longus colli muscles are identified in both sides of the median line. Laterally to the vertebral bodies are located the cervical sympathetic chain ganglia. With the help of an electrocauterium, the longus colli muscle is sectioned in longitudinal direction, and via subperiostium is dissected together with the anterior longitudinal ligament and stretched apart laterally.

The surgeon identifies the intervertebral disc, places a landmark point with a spinal needle and performs an X-Ray to verify that the disc individuated is the right one.

Autostatic retractors are placed to stretch apart the longus colli muscles and a Caspar distracting system is put in place. The distractor takes advantage of his pins inserted into the vertebral bodies do distract the intervertebral space where the surgeon will be working (Fig. 8.2). The disc is

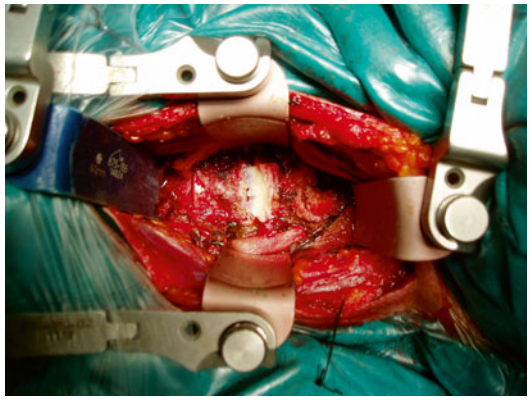


Fig. 8.2 Cervical disk exposed by anterior presternocleidomastoid – precarotid approach

incised with a scalpel and the discectomy is performed from the anterior margin to the posterior one. The fibres of the posterior annulus fibrosus can be detached from the bone, and a cleavage plane with the vertical fibers of the posterior longitudinal ligament can be obtained with the support of a dissector.

At the end of the procedure, a high speed drill can be used to smooth the marginal osteophytes and to cruentate the endplates until one can obtain a bleeding osseous surface where the implant can be inserted. Once a good visualization of the vertebral canal is obtained, the osteophytes located on the posterior margin can be removed and the opening of the intervertebral foramen can be performed to ultimate the decompression. Once this phase is completed, in the intervertebral space can be placed a bony graft, an interbody cage or a disc prosthesis. At the end of the procedure, after a control X-Ray scan, the operatory field is washed with saline solution, an accurate haemostasis is performed and a drainage is placed. In the final phase the platysma muscle is sutured and the superficial planes are sutured.

Complications

The most frequent complications related to the procedure are: damage to the recurrent laryngeal nerve with palsy of the vocal cords (transitory in 11 % of the cases, permanent in 4 % of the cases), damage of sympathetic nerves or of the stellate ganglion (with Horner's syndrome), damage of the vascular structures such as carotid artery or internal jugular vein or, less frequently, of the vertebral artery or of the thoracic duct [1, 2]. Furthermore, trachea, esophagus or pharynx can be accidentally perforated during the surgical procedure or as a late complication due to the mobilization of the implants. This kind of approach can be the cause of early damages to the nervous structures. Dysphagia can be an immediate consequence after the surgical intervention in 60 % of the patients or in 5 % of the patients can be evident after 6 months or more. It can derive from anesthesiological irritative factors (usually remains for 24–72 h) or to a difficult orotracheal intubation, damages to the recurrent laryngeal nerve, to the cervical orthosis or to the protrusion, displacement or rejection of the prosthetic material [10, 11]. Among the late consequences there are: displacement of the implant, pseudoarthrosis, adjacent segment syndrome. The incidence of failed bone fusion with pseudoarthrosis and adjacent segment syndrome is variable between 2 and 20 %; it can be defined as the displacement of 2 or more millimetres between two adjacent vertebral bodies (measured at the distal portion of the spinous processes) in the dynamic flexion and extension X-Rays. This clinical condition can be asymptomatic, associated to chronic pain, recurrence of the preoperative symptoms, alterations of the cervical lordosis with local kyphosis or deformity. If asymptomatic the surgical therapy is not indicated. If symptomatic, a further surgical intervention with a new ACDF with the placement of an anterior plaque, a cervical corpectomy with fusion or a posterior cervical fusion when more than three vertebral bodies are involved.

Personal Experiences

Anterior Cervical Discectomy and Fusion ACDF

Our experience has been published on *European Spine Journal* [13]. It has been the first study to deal with ACDF employing carbon fiber cages with such a long follow-up (77 months, range 54–90

months) and the only one to evaluate the rate of interbody fusion using CT scan. Aim of our study was to demonstrate the high rate of interbody fusion and the low percentile of new adjacent level compression in patients who underwent anterior cervical fusion with carbon fiber cages containing hydroxyapatite. All the patients who had undergone surgical treatment with anterior cervical discectomy and stand-alone cage interbody fusion were included in our study. We used a left anterior retropharyngeal approach. Carbon fiber cages containing hydroxyapatite were implanted in all patients without anterior plating. In our experience, adjacent segment disease was not clinically relevant. We studied our patients by the mean of CT scan with sagittal reconstructed images, that made possible to evaluate the rate of bone fusion. During follow-up, 20 % of the patients included in our study presented AS degeneration, and 10 % of these required a new surgical procedure because of AS disease. The findings evidenced by our experience support the hypothesis of a pathophysiological degeneration of cervical spine by reducing the impact of fusion on adjacent levels. Moreover, the less satisfactory outcome observed in patients over 61 years old, with development of ASD disease, was probably related to the evolution of pathophysiological degeneration of the cervical spine [2].

The ideal cage should correct deformity and provide stability until fusion occurs with no additional morbidity. Carbon fiber cages were introduced almost a decade ago for use as a spacer. They do not induce an inflammatory response, withstand physiological loads and have a modulus of elasticity almost equal to the cortical bone. The Cervical Cages used, are a carbon fiber-reinforced hollow biocompatible polymer implants designed to replace the tricortical bone graft. This cage is radiolucent, which aids in the assessment of bony fusion and have markers to aid in their visualization, radiological assessment, and identification of their position on plain X-ray films. These markers are three intrinsic tantalum beads that serve as radiographic markers. Cervical carbon fiber cages are well documented in their ability to provide structural support while promoting bony fusion. Their radiolucency and biomechanical design properties make them a superior choice among available cages. The potential benefit of enhanced fusion rates and decreased bone donor site morbidity may justify the use of hydroxiapatite with cages. Our experience with carbon fiber cages suggests that these devices represent a valid option for restoring the intervertebral disc space and promoting arthrodesis in cervical disc surgery while their elastic properties minimize the risk of kyphosis, subsidence and adjacent segment disease [2].

In 13 % of the patients, a CT scan documented the non-fusion of the segments: no clinical symptom was related to this condition. In our opinion, pseudoarthrosis is mainly caused by malpositioning of a carbon fiber cage that often rests on the anterior rim of the endplate.

Our study demonstrated that the use of carbon fiber cages containing hydroxyapatite is apparently a safe procedure with a favorable clinical and radiological outcome. The simplicity of the technique and its radiolucency is an advantage during follow-up. In this study, a good fusion rate (87 %) was achieved in accordance with the literature using carbon fiber cages.

Anterior Approach in Multilevel Stenosis

Our experience, published on *International Journal of Clinical Medicine* [9], is based on the evaluation of clinical and radiological effects subsequent to ACCF or ACDF for multilevel cervical spondylosis. The choice between ACDF and ACCF as the best treatment choice in case of multilevel cervical spondylosis is object of numerous studies, but actually remains controversial. It is still an argument of debate that cervical spine compression due to a degenerative process tends to be progressive in time. The results of disc degeneration leads to the reduction of the disc height, hypertrophy and buckling of the ligamentum flavum and PLL, formation of osteophytes, alterations in axial loads with sagittal alignment dysfunction.

The degenerative cascade brings to a progressive canal narrowing, signs and symptoms of myelin dysfunction and radiological finding of cervical instability. Often, even if asymptomatic in initial phase, radiological exams can show the initial degeneration. Sometimes the evolution could be quite progressive

and paucisymptomatic, but sometimes, certain patients may have a precipitous decline with clinical and radiological severe myelopathy [2–7].

Goals of surgical treatment are to decompress the narrowed cervical segment, to arrest the degenerative process, and to restore the physiological biomechanics and the right axial loads [8, 14, 15].

In our opinion, in cases of multilevel stenosis, it is important to consider some radiological preoperative findings, which may lead to the right indication for surgery:

1. Number of involved levels: when three or less levels are involved, anterior compression or kyphosis are present, the anterior approach is preferred. Anterior approach allows direct decompression, interbody space height restore and the possibility to maintain cervical lordosis. Several literature studies have compared multilevel anterior cervical discetomy and fusion (ACDF) with anterior cervical corpectomy and fusion (with mesh cage) (ACCF). Which one is the surgical procedure with best clinical results remains controversial.
2. Radiological and neurological signs: radiological exams as like as standard X-Ray in the antero-posterior and lateral projections and the dynamic flexion and extension projections are of value: sagittal profile, as loss of lordosis, kyphosis development, spinal alignment and bony relationship (e.g. spondylolisthesis), disc space narrowing, bony vertebral structures (vertebral collapse, osteophytes).
3. LLP features (hyperthrophy, ossification, involved levels): in multilevel cervical spondylosis may occur the involvement of the LLP. It can be the responsible for a further reduction of the medullary canal, because of its involvement in the degenerative cascade of spondylodiscoarthosis. LLP modifications occur, in the first phase, with structural modifications caused by local inflammatory processes that lead to an initial ligamentous laxity. LLP then undergoes to a compensatory hypertrophy and subsequent ossification. The involvement of the ligament reflects the number of levels involved in the spondylodiscoarthosis.
4. Vertebral stability: static and dynamic radiographs are useful to determine the range of motion (ROM) of the cervical segment and to value its stability. In case of instability the purpose of the treatment, which depends on the number of levels involved, is to stabilize the segment involved and to promote bone fusion avoiding the development of deformity. It is useful to use the anterior plating for both ACDF or ACCF.
5. Sagittal alignment – kyphosis-lordosis: the more levels involved, greater is the probability of developing cervical instability and consequent greater risk to develops a deformity with secondary loss of the physiological lordosis and consequent kyphosis.

Based on our experience and literature results, multilevel ACDF is preferable when compression involves the intersomatic space, or in the early stages of spondylotic myelopaty, when bone degeneration and spinal cord compression are mainly involving the intervertebral space. ACDF provides good long term results in term of improvement of cervical lordosis in the fused segments. In addition, ACDF restores disc height, promotes posterior ligaments in-buckling correction, maintains a good biomechanical stability during dynamic flexion-extension movements, and maintain a good sagittal alignment (Fig. 8.3). Furthermore, ACDF is less invasive than ACCF in term of blood loss, bone removal, surgical complication (Hoarseness, C5-palsy, dysphagia, dislogment, epidural ematoma, CSF leakage), operation time, length of hospital stay. In contrast, if more than two levels are involved, ACDF can cause pseudoarthrosis or junctional syndrome more likely than ACCF. The pathogenesis and the clinical development of adjacent segment degeneration (ASD) are not completely understood. Probably it is due increased stiffness at the fused level, with concomitant increasing in force and motion at adjacent levels or, as Hilibrand and al. reported, that may reflect the natural history of the underlying cervical spondylosis. Important is the anterior plating, required when preoperative instability is present or when more than two contiguous levels are treated. ACCF is indicate when spinal cord impingement is behind the vertebral body or when two or three vertebral body are involved or when spondylotic myelopaty is advanced (Fig. 8.4). The surface bone fusion is lower than ACDF, so

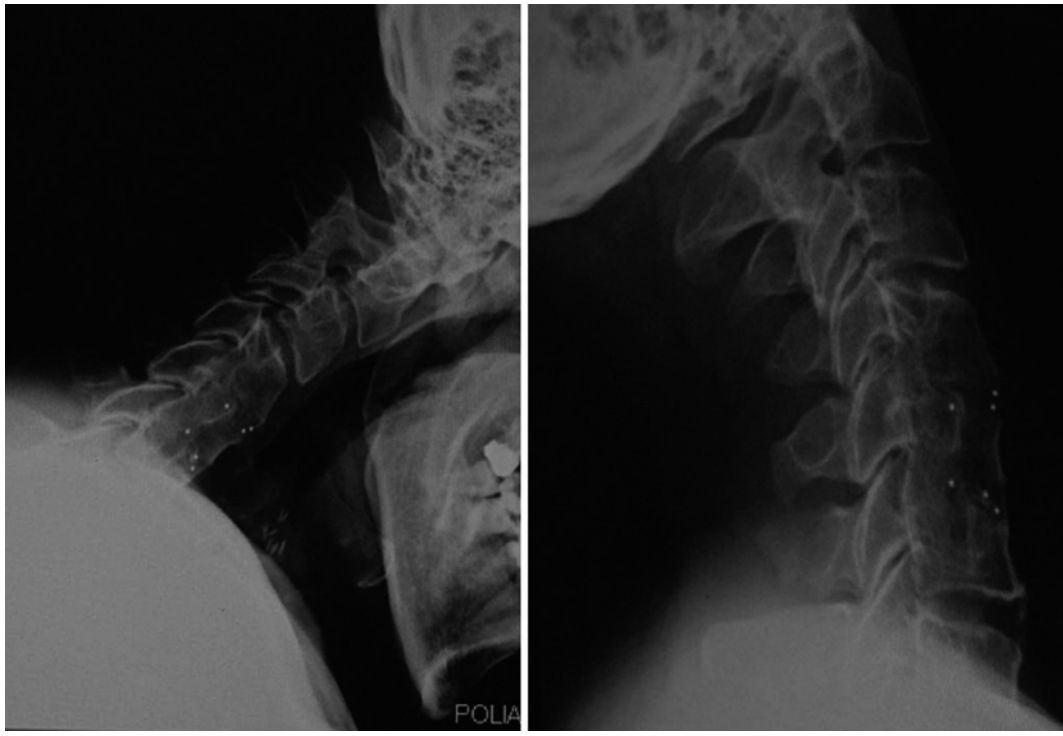


Fig. 8.3 Long term follow-up in two level anterior discectomy and fusion with cages. Dynamic X-rays shows the complete fusion of the segment

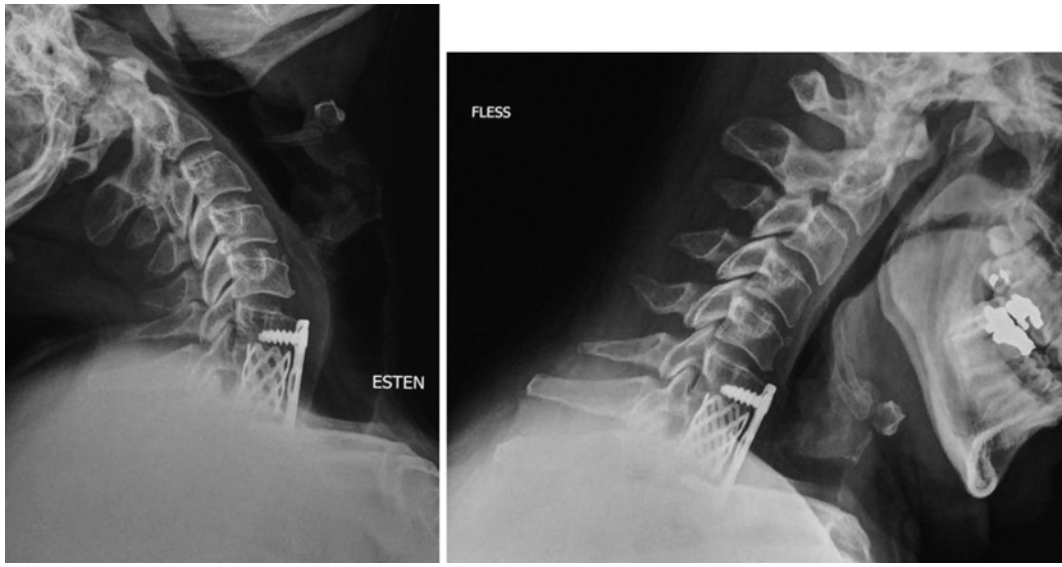


Fig. 8.4 Long term follow-up in anterior corpectomy and fusion with mash and plating. Dynamic X-rays shows the complete fusion of the segment

fusion rate is higher than ACDF if more than 2 or 3 levels are involved. Certainly, it is more invasive than ACDF, it does not restore sagittal alignment and bearing a lesser biomechanical strength of the movements of FE compared to ACDF. In this procedure the anterior plating by placing the screws both to the upper and lower vertebral body and to the graft too is required to avoid any translational movements. Based on our experience, ACDF seem to be more efficacies to correct cervical kyphosis and to restore SA.

Conclusions

The anterior approach is safer, not much traumatic for muscles and familiar to the surgeon. It is recommended when compression involves primarily the anterior horn of spinal cord. The main goal of this procedure is to relieve the compression on the spinal cord and/or the root. Stabilization and fusion in conjunction with decompression are important to hinder the progress of phenomena such as instability and subsequent deformity of the cervical segment, and to restore the height, correct the in-buckling of the ligamentum flavum, reconstruct lordosis, and stabilize the spinal column. The goals of surgical treatment are: to decompress the stenotic cervical segment, to arrest the degenerative process, and to restore the physiological biomechanics and the right axial loads. Even if both ACDF and ACCF can restore lordosis, in multilevel ACDF lordosis can be achieved and maintained easier than in ACCF. This is due to the multiple points of distraction and fixation in addition to the graft and interbody space shaping. Therefore, we conclude that it is necessary to preoperatively study patients to classify degenerative disease and biomechanical features, evaluating the number of levels affected by stenosis, neurological status, the characteristics of the LLP and the stability of the cervical segment. All those are useful parameters to guide the surgeon to choice the best anterior approach for cervical spondylosis.

References

1. Dugoni DE, Mancarella C, Landi A, Tarantino R, Ruggeri AG, Delfini R. Post laminoplasty cervical kyphosis-case report. Int J Surg Case Rep. 2014;5(11):853–7.
2. Hilibrand AS, Carlson GD, Palumbo MA, Jones PK, Bohlman HH. Radiculopathy and myelopathy at segments adjacent to the site of a previous anterior cervical arthrodesis. J Bone Joint Surg. 1999;81A(4):519–28.
3. Hillard VH, Apfelbaum RI. Surgical management of cervical myelopathy: indications and techniques for multilevel cervical discectomy. Spine J. 2006; 6(6 Suppl):S242–51.
4. Hirabayashi K, Watanabe K, Wakano K, et al. Expansive open-door laminoplasty for cervical spinal stenotic myelopathy. Spine. 1983;8:693–9.
5. Ikenaga M, Shikata J, Tanaka C. Long-term results over 10 years of anterior corpectomy and fusion for multilevel cervical myelopathy. Spine. 2006;31:1568–74.
6. Kawakami M, Tamaki T, Iwasaki H, et al. A comparative study of surgical approaches for cervical compressive myelopathy. Clin Orthop Relat Res. 2000;381:129–36.
7. Konya D, Ozgen S, Gercek A, et al. Outcome for combined anterior and posterior surgical approaches for patients with multisegmental cervical spondylotic myelopathy. J Clin Neurosci. 2009;16:404–9.
8. Landi A, Marotta N, Mancarella C, Dugoni DE, Tarantino R, Delfini R. 360° fusion for realignment of high grade cervical kyphosis by one step surgery: case report. World J Clin Cases. 2014;2(7):289–92. ISSN 2307-8960.
9. Landi A, Marotta N, Mancarella C, Morselli C, Tarantino R, Ruggeri AG, Delfini R. Anterior surgery in multilevel stenosis of the lower cervical spine: technical indications and personal experience. 12 years follow-up. Int J Clin Med. 2014;5:157–61.
10. Landi A. Cervical motion preservation surgery: why sometimes failed? A biomechanical point of view. J Spine. 2013;S3:e001. doi:10.4172/2165-7939. S3-e001.
11. Landi A. Elastic resistance of the spine: why does motion preservation surgery almost fail? World J Clin Cases. 2013;1(4):134–9. doi:10.12998/wjcc.v1.i4.134
12. Landi A, Delfini R. Manuale Pratico di Terapia dell'ernia del disco. Ed. Esculapio, Bologna, Italy; 2014.
13. Marotta N, Landi A, Tarantino R, Mancarella C, Ruggeri A, Delfini R. Five-year outcome of stand-alone fusion using carbon cages in cervical disc arthrosis. Eur Spine J. 2011. doi:10.1007/s00586-011-1747-0.
14. Matz PG, Anderson PA, Holly LT, Groff MW, Heary RF, Kaiser MG, Mummaneni PV, et al. The natural history of cervical spondylotic myelopathy. Neurosurg Spine. 2009;11(2):104–11.
15. Hussain M, Nassr A, Natarajan RN, An HS, Andersson GB. Corpectomy versus discectomy for the treatment of multilevel cervical spine pathology: a finite element model analysis. Spine J. 2012;12:401–8.

9 Anterior Cervical Decompression and Fusion with Autologous Bone Graft

Paolo Perrini and Nicola Di Lorenzo

The anterior approach to the cervical spine was conceived and promoted in the early 1950s by the seminal investigations of different pioneers [1, 11, 25]. In 1952, Bailey and Badgely performed an anterior decompression and fusion utilizing an autologous onlay strut bone graft in a patient with a cervical lytic lesion [1]. In 1955, Robinson and Smith reported anterior cervical discectomy and fusion for spondylosis utilizing a tricortical horseshoe-shaped iliac crest graft [25]. Subsequently, Ralph Cloward described his technique for cervical discectomy with removal of ventral osteophytes and fusion using a dowel-shaped iliac crest graft, and popularized the anterior approach for the treatment of degenerative, neoplastic, traumatic and infective pathologies exerting a ventral compression of the spinal cord and/or cervical roots [11]. Since these original descriptions, the progress of available grafting options proposed allograft-, synthetic- and factor/cell-based technologies for bone graft substitutes [4]. However, the autologous bone graft is still considered the gold standard for anterior cervical fusion after anterior cervical discectomy (ACD) or corpectomy because is the only graft with the properties of osteogenesis, osteoinduction and osteoconduction [4, 21]. In addition, the corticocancellous architecture of the autologous bone graft enhances interface activity with bony ingrowth and provides load-bearing capacity, which is extremely relevant in avoiding a kyphotic change across fused segments.

This chapter describes the technical nuances of anterior cervical decompression and fusion with autologous bone graft.

Surgical Techniques

Anesthesia and Positioning

Patients are positioned supine on the operating room table for orotracheal intubation. Awake fiberoptic nasotracheal intubation is required only in selected myelopathic patients in which spinal injury as a result of neck extension during intubation must be avoided. A single dose of intravenous prophylactic antibiotics is administered half an hour before the time of incision. The head is slightly extended without rotation on the radiolucent operating table and a rolled towel is placed under the neck to improve the cervical lordosis. Alternatively, the head is placed on a horseshoe headrest. The

P. Perrini, MD, PhD (✉)
Neurosurgical Department,
Azienda Ospedaliero Universitaria Pisana (AOUP),
Via Paradisa 2, Pisa, Italy
e-mail: p.perrini@ao-pisa.toscana.it

N. Di Lorenzo, MD (✉)
Department of Neurosurgery, University of Florence,
Florence, Italy
e-mail: dilorenzo@unifi.it

P.P.M. Menchetti (ed.), *Cervical Spine: Minimally Invasive and Open Surgery*,
DOI 10.1007/978-3-319-21608-9_9

shoulders are pulled caudally using wide adhesive tape to allow visualization of the lower cervical spine on fluoroscopic images. The knees are slightly flexed to prevent stretch injuries. Electrophysiological monitoring is not necessary in routine cases.

Incision and Soft Tissue Dissection

Diversity of opinions among neurosurgeons exists regarding the effect of approach side on the incidence of recurrent laryngeal nerve (RLN) injury after anterior approach to the cervical spine. Anatomical arguments have been proposed to support one side of approach over the other. Because the left RLN is longer and enters the tracheoesophageal groove at a less steeper angle it has been argued that a left-sided approach would minimize the incidence of RLN palsy [13, 18]. However, several clinical investigations reported that the side of approach has no significant effect on the incidence of RLN injury [3, 6]. In addition, a left-sided approach theoretically places the thoracic duct at risk of injury [17]. It is our practice to operate mostly from the right side for ease of surgery for right-handed surgeon, reserving a left-sided approach in patients with previous left-sided neck surgery and resultant vocal cord dysfunction.

The incision is localized using fluoroscopy. A horizontal skin incision beginning at the midline and extending laterally to the medial border of the sternocleidomastoid muscle is suitable to expose up to two intervertebral discs or one vertebral body (Fig. 9.1). A longitudinal incision following the medial border of the sternocleidomastoid muscle is performed for more extensive procedures. The platysma muscle is sharply divided in line with the incision and a subplatysmal release is performed to relax the wound edges and to facilitate further dissection. Careful dissection and accurate release of fascial planes allow optimal exposure with minimal retraction. The superficial layer of the deep fascia which envelopes the sternocleidomastoid muscle is sharply divided exposing the middle layer of the deep fascia. This layer is incised anterior to the anterior border of the carotid artery, which remains on the lateral side of the surgical field. Transection of the omohyoid muscle that runs obliquely across the field at the level of the C6 vertebral body can be usually avoided through extensive fascial release. At this point the vertebral bodies can be palpated with a finger under the deep cervical fascia also known as alar fascia. The trachea and esophagus, which are contained in the middle layer of the deep fascia, are gently retracted medially whereas the carotid sheath and the sternocleidomastoid muscle remain laterally. The alar fascia is incised to obtain access to the anterior cervical spine. A needle is placed on the anterior anulus of the disc space and a lateral fluoroscopy is obtained for level confirmation. After fluoroscopic confirmation, blunt dissection is used to expose the ventral aspect of vertebral bodies. Identification of the midline is obtained exposing the longus colli muscles bilaterally, which are generally equidistant from the midline. In presence of anterior osteophytes, their removal is necessary for the identification of the midline. The insertions of the longus colli muscles are coagulated and lateral retraction blades are placed bilaterally under their medial edges. When a long segment construct is planned, a second retractor with blunt blades is placed in the craniocaudal direction to enhance the surgical exposure and to protect soft tissues from injury.

Smith-Robinson Technique

The anterior longitudinal ligament and the anulus fibrosus are incised flush from the edges of the vertebral bodies with a No. 11 scalpel (Fig. 9.2). The anterior osteophytes, when present, are removed with a curved osteotome or rongeurs. The anterior longitudinal ligament lying on opposing vertebral bodies is removed to clearly expose the bony surface. Interbody distraction is obtained by placing distracting pins into the midportion of the vertebral bodies above and below the interspace to be treated. After distraction, the disc and the cartilaginous plates are progressively removed with curette. High-speed drill and Kerrison pounch are used to complete the

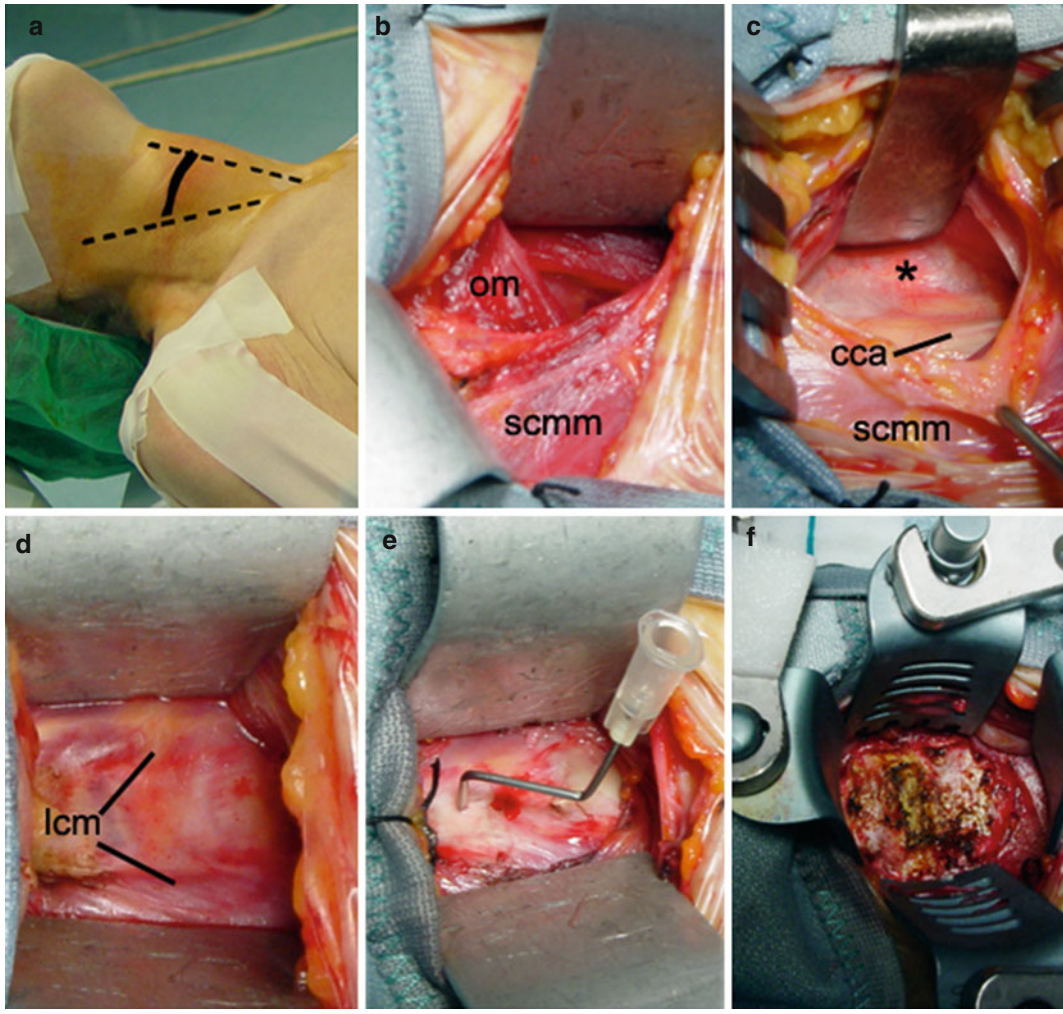


Fig. 9.1 Incision and soft tissue dissection. (**a**) A transverse skin incision extending from the midline to the medial border of the sternocleidomostoid muscle is adequate to expose up to two intervertebral discs or one vertebral body. An oblique incision along the anterior border of the sternocleidomastoid muscle is used in more extensive procedures. (**b**) After incision of the platysma and subplatysma dissection, the superficial layer of the deep cervical fascia is entered with exposure of the sternocleidomastoid muscle. Dissection of the middle layer allows exposure of the omohyoid muscle. (**c**) The carotid artery can be palpated posterior to the sternocleidomastoid muscle. The alar fascia (*asterisk*) covers the longus colli muscles and separates the vertebral bodies from the trachea and esophagus. (**d**) The longus colli muscles are clearly exposed and help to identify the midline. (**e**) A right-angle bent needle is inserted in the disc and a lateral x-ray is obtained to confirm the level. (**f**) The longus colli muscles are dissected and the retractor blades are inserted. The anterior longitudinal ligament and the anulus fibrosus are incised and removed. *cca* common carotid artery, *lcm* longus colli muscle, *om* omohyoid muscle, *scmm* sternocleidomastoid muscle

discectomy and to remove the posterior osteophytes under microscopic view. The posterior longitudinal ligament (PLL) is generally opened widely to expose the dura and to verify complete removal of disc herniation and optimal resection of osteophytes. We use a nerve hook to open laterally the PLL, which is elevated from the dura and progressively resected with kerrison pouch. When foraminal stenosis is present, the medial aspect of the uncovertebral joint is resected using a No. 1 or 2 Kerrison punch. Bleeding from epidural veins in the neural foramen is controlled with small pieces of surgicel and gentle pressure with cottonoid.

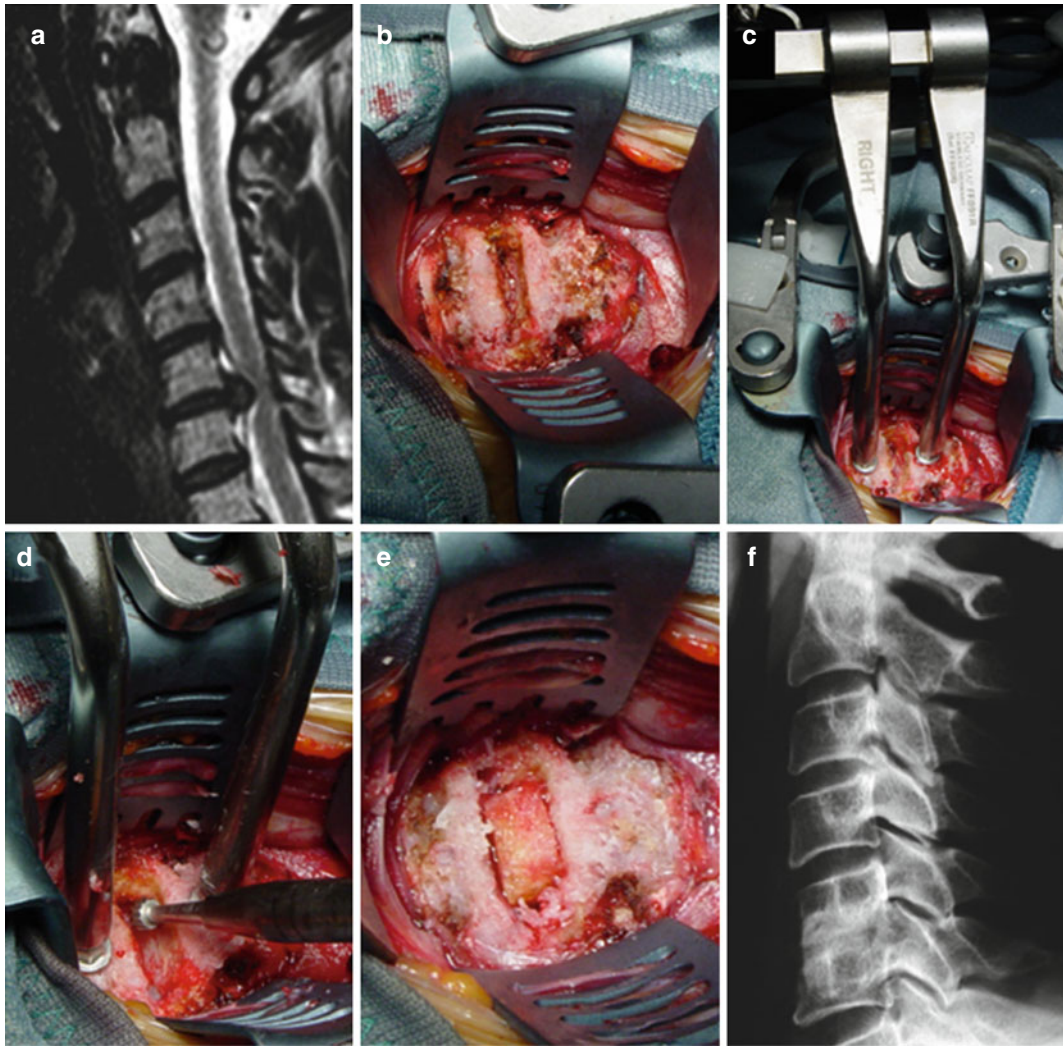


Fig. 9.2 Interbody fusion with Smith-Robinson technique. (**a**) Preoperative midsagittal T2-weighted MRI scan discloses C5-C6 disc herniation with severe compression of the spinal cord. (**b**) After exposure of the cervical spine the anulus fibrosus is incised and the anterior longitudinal ligament is removed at the C5-C6 level. (**c**, **d**) The disc space is opened with Caspar distraction pin device and the discectomy is completed microsurgically. (**e**) After complete removal of soft disc herniation, a tricortical autologous iliac crest graft is tapped into place and the distraction is released. (**f**) Lateral x-ray obtained 6 months after surgery demonstrated solid fusion between C5 and C6

Cloward Technique

This technique increases the space available while the surgeon perform ostheophytes removal and consists of drilling a circular opening in the region of the intervertebral disc, into which a dowel of bone is inserted (Fig. 9.3). After a standard discectomy, measure is taken and the drill depth is determined. The hand-held drill with a guard is applied to the midpoint of the cervical motion segment and drilling of the adjacent vertebral bodies to the desired depth is performed. The guard prevents penetration of the posterior cortical bone, which is removed with high-speed drill and rongeurs. The decompression is completed with microsurgical removal of the PLL, osteophytes and disk herniation, when present. A slightly larger, cylindrical, bicortical autologous

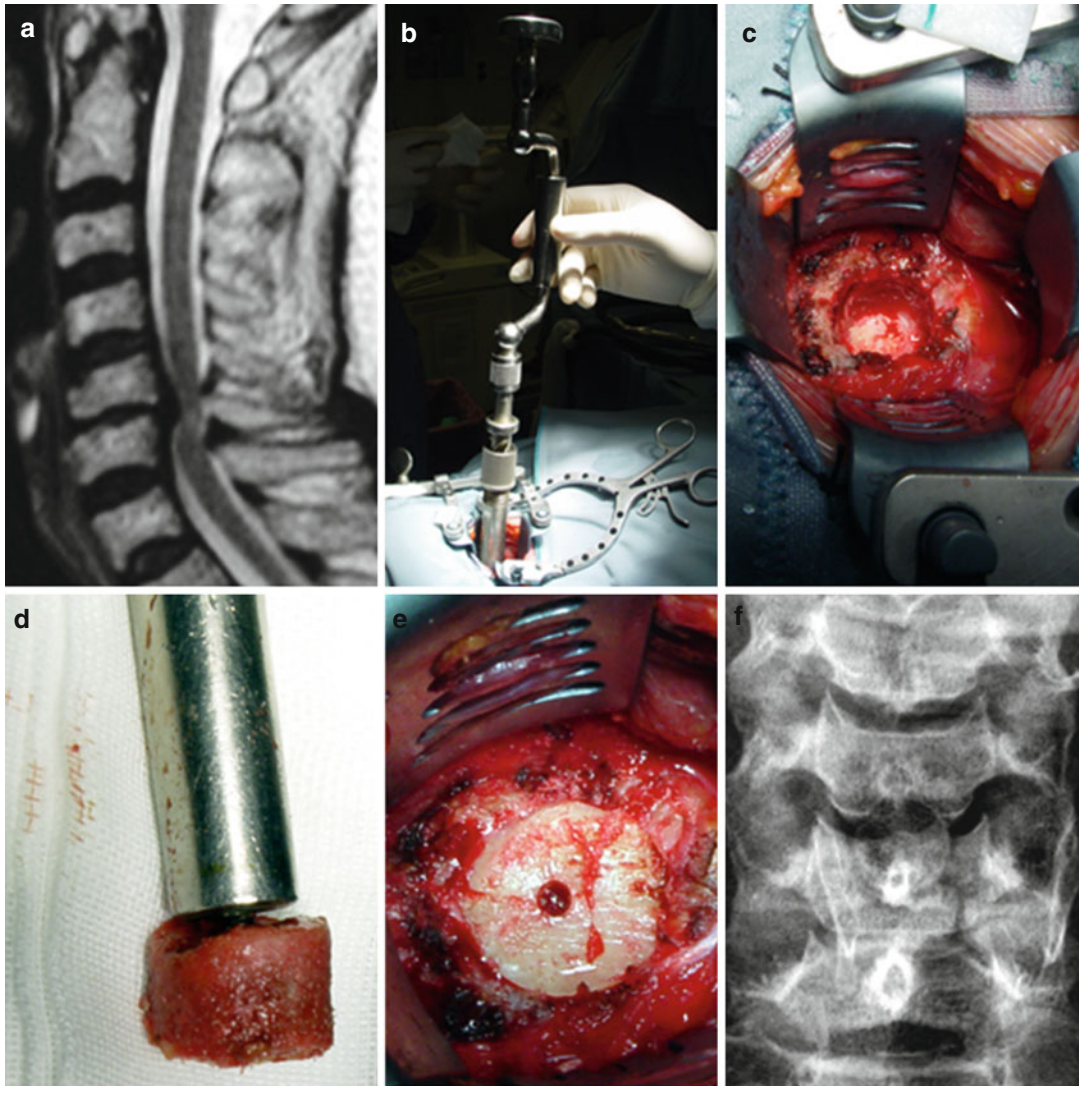


Fig. 9.3 Interbody fusion with Cloward technique. (**a**) Preoperative midsagittal T2-weighted MRI scan discloses C5-C6 spinal cord compression with high signal changes in the spinal cord as a result of herniated disc associated with osteophytes. (**b**) After standard discectomy, a hand-held drill is used to drill the adjacent vertebral bodies. (**c**) The remaining cortical bone is removed microsurgically. (**d**, **e**) A bicortical dowel graft of iliac crest bone is tapped into place. (**f**) Antero-posterior x-ray obtained 6 months after surgery discloses fusion between C5 and C6

dowel graft is harvested from the anterior iliac crest and impacted into the drilled defect. The limitations of this approach consist in the decreased compression strength of the bicortical graft, the extensive exposure of cancellous bone and the impossibility to perform multilevel contiguous fusions [12]. Due to these limitations, the Cloward's technique is nowadays seldom utilized.

Corpectomy

When a corpectomy is planned, the anterior longitudinal ligament over the vertebral body to be resected and over the contiguous portions of the adjacent upper and lower vertebrae is removed (Fig. 9.4). Anterior osteophytes are resected to ensure that the cervical plate will lie flat on the vertebral body. The discetomies above and below

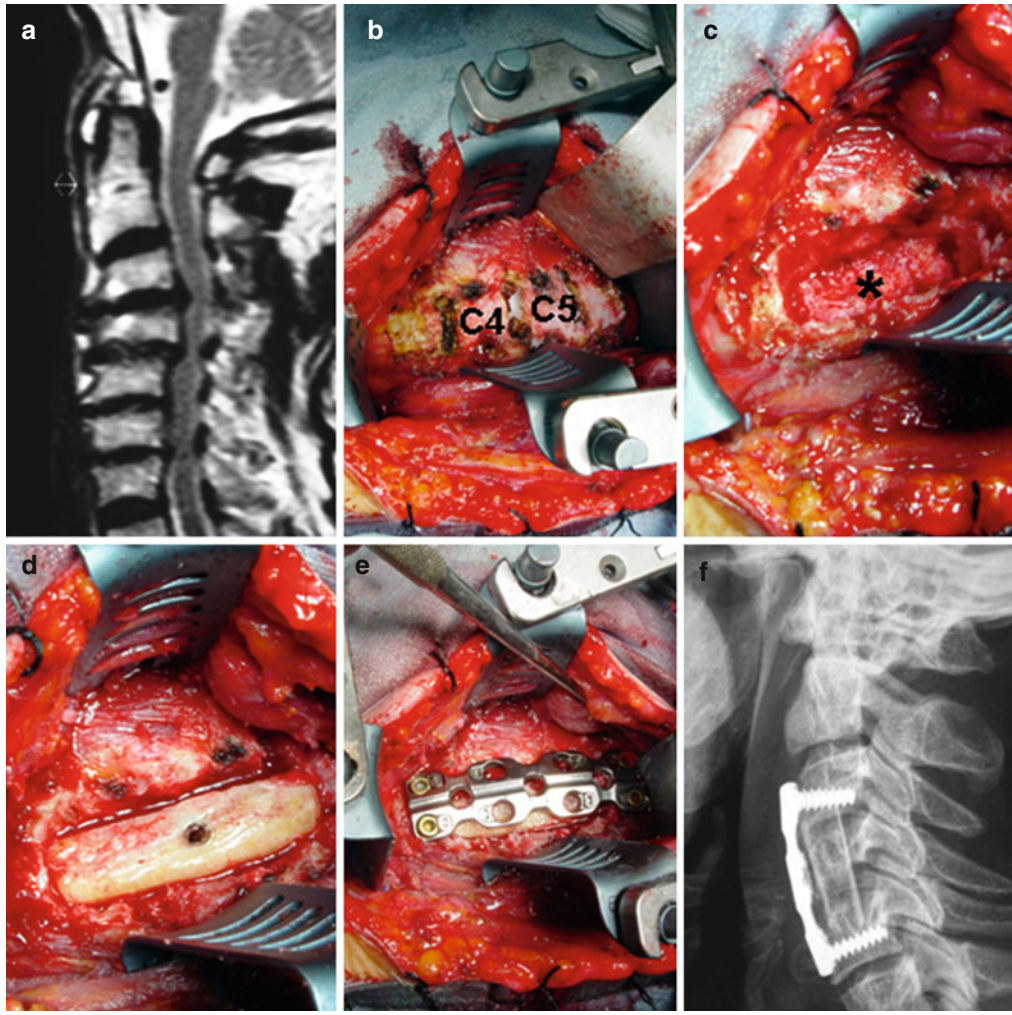


Fig. 9.4 Interbody fusion after corpectomy. (**a**) Preoperative midsagittal T2-weighted MRI scan shows cervical spine stenosis C3-C5 and kyphotic deformity. (**b**, **c**) After wide exposure of midportion of the cervical spine, discectomies are performed above and below the corpectomy site and the vertebral bodies of C4 and C5 are removed using high speed drill. The posterior longitudinal ligament and the osteophytes are resected exposing the decompressed dura (*asterisk*) (**d**, **e**) a tricortical iliac crest graft slightly oversized is tapped into place under distraction and internal fixation is obtained with plate and screws. (**f**) Lateral x-ray obtained 6 months after surgery demonstrates solid fusion and restoration of focal lordosis

the chosen corpectomy site are performed first to evaluate the depth of the spinal canal and to carefully define the limits of bony resection. The majority of the vertebral body is removed under direct visualization to maintain midline orientation and obtain a symmetrical bony decompression. We use a 6-mm cutting burr to rapidly remove the vertebral body to the posterior cortical margin. The location and course of the vertebral arteries is noted on preoperative CT and MRI scans and the distance separating them is measured. Generally, the mean distance separating the medial borders of the transverse foramina is approximately 26–30 mm [22]. According to these findings, we do not extend bony decompression more than 10 mm from the midline to avoid injury of the vertebral artery. Under microscopic view the posterior cortex is removed with a 2-mm Kerrison pouch. The posterior osteophytes are resected with an up-going curette and

Kerrison pouch. A matchstick-type burr is used to resect completely the cartilage from the endplates of edjacent vertebrae while maintaining the bony endplate to prevent graft subsidence. The PLL is entered with a nerve hook, incised and widely removed using kerrison pouch. Bone wax is avoided because it prevents bony fusion.

Bony Reconstruction with Autograft

Autologous bone grafts can be classified according to tissue composition (cortical, corticocancellous, cancellous), anatomic origin (iliac crest, rib, fibula) and blood supply (vascularized, nonvascularized). Autografts such as fibula and tricortical iliac crest graft bear the mechanical compression loads applied to the anterior column of the spine due to their strength from their cortical bone composition [27]. These grafts can be fashioned as tricortical or bicortical struts or dowel according to the technique used. Rib grafts are weak mechanically because provide a limited volume of bone and are characterized by a thin cortex. While autologous rib grafts can be used as source of cancellous bone or can wired to the occiput during an occipitocervical fixation, they are not generally used for bony reconstruction of the cervical spine. Vascularized corticocancellous autograft such as vascularized fibula grafts are used in irradiated and devascularized fusion beds. The main limitation of fibula graft is the mismatch of the densities with that of the vertebral body with resultant penetration of the fibula through the vertebral body, i.e. the "pistoning effect". For bony reconstruction of the cervical spine we use autologous bone graft obtained from the anterior iliac crest. Surgical technique plays a pivotal role to ensure proper bone healing and reducing postoperative complications [29]. The bone graft is harvested after the anterior approach and stored in saline-soaked sponges until used. A short (5 cm) skin incision is made parallel to the anterior iliac crest starting at least 2 cm behind and lateral the anterior superior iliac spine (ASIS) (Fig. 9.5). A limited use of electrocautery is required during superiosteal dissection in order to avoid injuring the ilioinguinal, iliohypogastric and lateral femoral cutaneous nerves, which course along the medial surface of the ileum. Care is taken to cut through the fascia avoiding the muscles. The periosteum of the iliac bone is progressively elevated from the inner and outer bone surfaces with a Cobb periosteal elevator. A bone graft of the measured size is harvested from the ilium using a single-bladed oscillating saw under irrigation for tricortical or, more rarely, bicortical bone. The graft site is measured with caliper and the graft is cut slightly oversized (2–3-mm longer than the rostrocaudal length of the corpectomy). Both ends of the graft are flat-surfaced to increase the surface area for fusion. It is our preference to exert distraction of the cervical spine by having the assistant pull on the angle of the mandible on the long axis of the patient's body. Alternatively, distraction can be obtained by placing distracting pins into the vertebral bodies above and below the corpectomy site. Excessive distraction due to a graft that is to long for the length of the vertebrectomy should be avoided because can lead to postoperative interscapular pain. When the anterior decompression is performed using the Cloward approach, a hand-held drill with a guard is applied on the lateral surface of the ilium at least 2 cm behind the anterior superior iliac spine and a bicortical, cylindrical dowel graft is harvested (Fig. 9.6).

Donor Site Complications

The complication rate after harvesting bi- or tricortical iliac bone ranges from 4 to 39 % [2, 7]. Donor site complications include acute and chronic local pain, nerve injury, infection, hemorrhage, hernia formation and exceptional iliac crest fracture. The most commonly reported complication is acute postoperative pain at the donor site with resultant longer hospital stay. Several evidences suggest that donor site pain is the result of micro- and macro-fractures, hemorrhage and infection that trigger intact nociceptors adjacent to a nerve injury site [2, 9, 10, 14, 20, 23, 31]. A careful standard technique minimizes postoperative pain in most patients [29]. A short skin incision, limited muscle retraction, subperiosteal

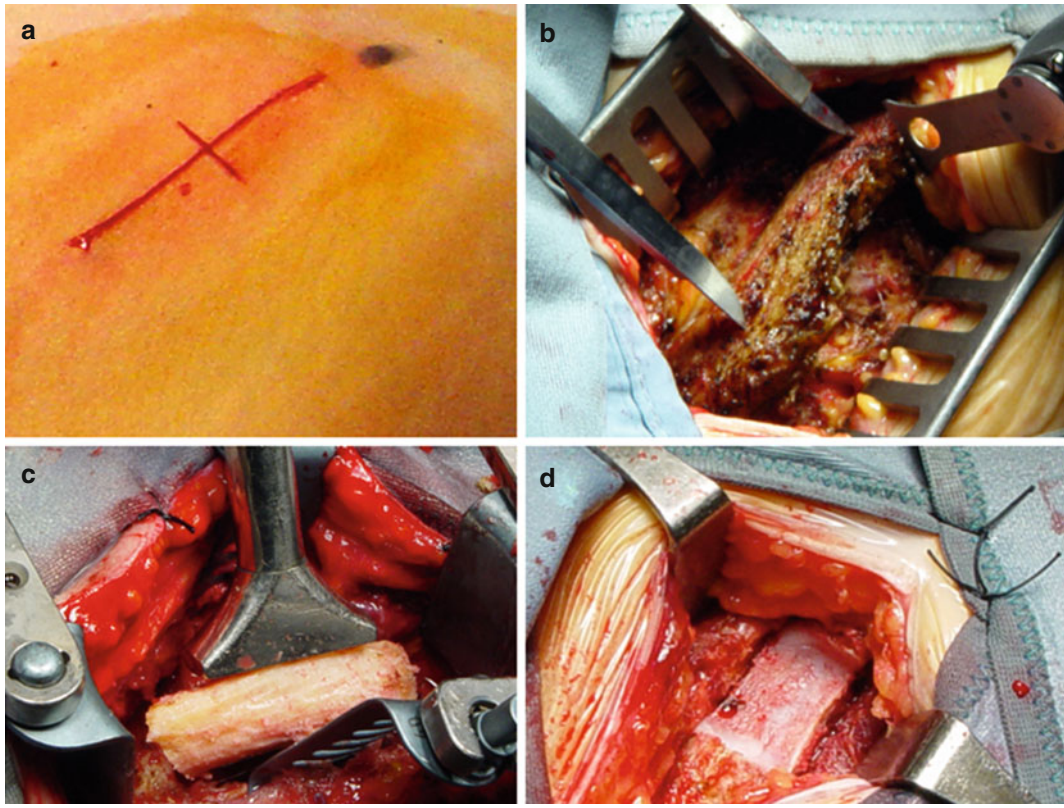


Fig. 9.5 Bone graft-harvesting from the iliac crest. (**a**) A skin incision of approximately 5 cm is made at least 2 cm behind the anterior superior iliac spine. (**b**) After subperioteal dissection, a tricortical bone graft of the measured size is harvested from the ilium using an oscillating saw. (**c**) A pin-headed Cloward impactor is used to place the graft into the corpectomy defect. (**d**) Meticulous hemostasis of the ilium is done with bone wax and the soft tissues are closed in separate layers

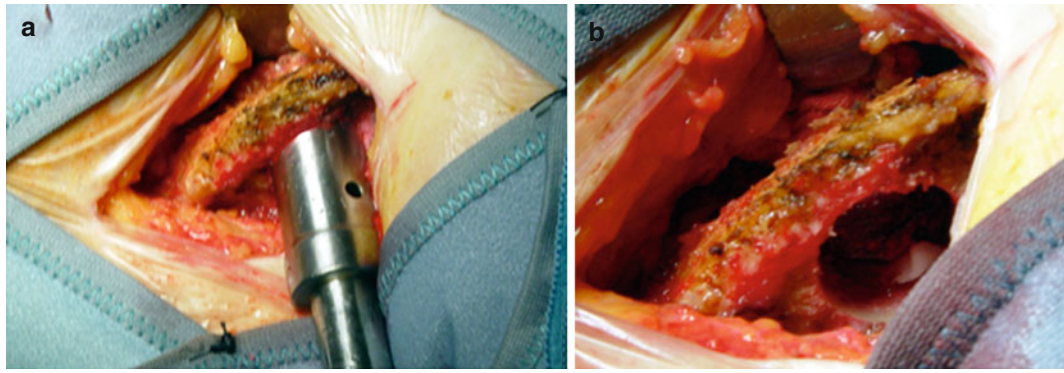


Fig. 9.6 Bone graft harvesting from the iliac crest according to the Cloward technique. (**a**, **b**) A hand-held drill provides a cylindrical, bicortical dowel graft that is impacted into the drilled defect

dissection, and reduced use of electrocautery prevent the injury to the lateral femoral cutaneous nerve, ilioinguinal nerve and lateral cutaneous branch of the subcostal nerve. Performing the most anterior osteotomy at least 2 cm behind the ASIS avoids a stress fracture of the bone remaining

anterior to the harvest site. In addition, some evidences suggest that graft harvesting using single-bladed oscillating saw reduces the risk of stress fracture of the ASIS when compared with the osteotome technique [23, 29]. Finally, careful hemostasis, moderate use of electrocautery and avoidance of muscle stripping help to avoid pain, fluid collection, and cosmetic dissatisfaction [10].

Anterior Instrumentation After Autologous Bone Graft

In single-level discectomy and fusion for degenerative disease, there is no strong support for plate fixation in the literature [28]. In addition, some authors reported no graft extrusions in large series of patients treated with multilevel discectomy and fusion with autograft without supplemental instrumentation [26]. However, recent prospective studies comparing mono- or bisegmental cervical fusion with autograft with and without a plate found that graft quality (height of graft, dislocation and resorption) was significantly better in the plated group [15]. According to the literature, the rate of pseudoarthrosis increases with an increase in the number of segments fused suggesting that fusion over more than two segments is an indication for instrumentation [7].

The critical concerns of graft displacement, graft fracture, pseudoarthrosis, subsidence and kyphotic changes are particularly relevant in cases of corpectomy without plating. Although some authors still recommend uninstrumented corpectomy for cervical spondylotic myelopathy [24, 30] several classic clinical studies reported graft-related complications rates ranging up to 45 % without plating [5, 8, 16, 19, 32]. Yonenobu et al. [32] reported nonunion rates of 5 % and 45 % after one- and three-level corpectomy and autograft without instrumentation, respectively. Internal fixation after cervical corpectomy and autograft provides several advantages including biomechanical improvements, immediate stability and improved fusion rates with acceleration of the fusion process. In fact, when corpectomy is not associated with internal fixation, rotational and translational forces in three dimensions increase complication rates and lower fusion rates. Rigid internal fixation allows immediate stability and fixed bone-to-bone contact under compression, that promotes successful incorporation of the autograft.

References

1. Bailey RW, Badgley CE. Stabilization of the cervical spine by anterior fusion. Am J Orthop. 1960;42-A: 565–94.
2. Banwart JC, Asher MA, Hassanein RS. Iliac crest bone graft harvest donor site morbidity: a statistical evaluation. Spine. 1995;20:1055–60.
3. Baron EM, Soliman AM, Gaughan JP, Simpson L, Young WF. Dysphagia, hoarseness, and unilateral true vocal fold motion impairment following anterior cervical diskectomy and fusion. Ann Otol Rhinol Laryngol. 2003;112:921–6.
4. Beaman FD, Bancroft LW, Peterson JJ, Kransdorf MJ. Bone graft materials and synthetic substitutes. Radiol Clin North Am. 2006;44:451–61.
5. Bernard Jr T, Whitecloud 3rd TS. Cervical spondylotic myelopathy and myeloradiculopathy. Clin Orthop Relat Res. 1987;221:149–60.
6. Beutler WJ, Sweeney CA, Connolly PJ. Recurrent laryngeal nerve injury with anterior cervical spine surgery risk with laterality of surgical approach. Spine. 2001;26:1337–42.
7. Bohlman HH, Sandford EE, Goodfellow DB, Jones PK. Robinson anterior cervical discectomy and arthrodesis for cervical radiculopathy. J Bone Joint Surg Am. 1993;75:1298–307.
8. Boni M, Cherubino P, Denaro V, Benazzo F. Multiple subtotal somatectomy. Technique and evaluation of a series of 39 cases. Spine. 1984;9:358–62.
9. Campbell JN. Nerve lesions and the generation of pain. Muscle Nerve. 2001;24(10):1261–73.
10. Chou D, Storm PB, Campbell JN. Vulnerability of the subcostal nerve to injury during bone graft harvesting from the iliac crest. J Neurosurg Spine. 2004;1(1):87–9.
11. Cloward RB. The anterior approach for removal of ruptured cervical discs. J Neurosurg. 1958;15:601–17.
12. Cornish BL. Complications and limitations of anterior decompression and fusion of the cervical spine (Cloward's technique). Med J Aust. 1972;1:140.
13. Ebraheim NA, Lu J, Skie M, Heck BE, Yeasting RA. Vulnerability of the recurrent laryngeal nerve in the anterior approach to the lower cervical spine. Spine. 1997;22:2664–7.
14. Ebraheim NA, Yang H, Lu J, Biyani A, Yeasting RA. Anterior iliac crest bone graft. Anatomic considerations. Spine. 1997;22(8):847–9.
15. Grob D, Peyer JV, Dvorak J. The use of plate fixation in anterior surgery of the degenerative cervical

spine: a comparative prospective clinical study. Eur Spine J. 2001;10:408–13.
16. Hanai K, Fujiyoshi F, Kamei K. Subtotal vertebrectomy and spinal fusion for cervical spondylotic myelopathy. Spine. 1986;11:310–5.
17. Hart AK, Greinwald Jr JH, Shaffrey CI, Postma GN. Thoracic duct injury during anterior cervical discectomy: a rare complication: case report. J Neurosurg. 1998;88:151–4.
18. Jellish WS, Jensen RL, Anderson DE, Shea JF. Intraoperative electromyographic assessment of recurrent laryngeal nerve stress and pharyngeal injury during anterior cervical spine surgery with Caspar instrumentation. J Neurosurg. 1999;91(2 Suppl):170–4.
19. Kojima T, Waga S, Kubo Y, Kanamaru K, Shimosaka S, Shimizu T. Anterior cervical vertebrectomy and interbody fusion for multilevel spondylosis and ossification of the posterior longitudinal ligament. Neurosurgery. 1989;24:864–72.
20. Kurz LT, Garfin SR, Booth Jr RE. Harvesting autogenous iliac bone grafts. A review of complications and techniques. Spine. 1989;14:1324–31.
21. Ludwig SC, Boden SD. Osteoinductive bone graft substitutes for spinal fusion. Orthop Clin North Am. 1999;30:635–45.
22. Oh SH, Perin NI, Cooper PR. Quantitative three-dimensional anatomy of the subaxial cervical spine: implications for anterior spinal surgery. Neurosurgery. 1996;38:1139–44.
23. Porchet F, Jaques B. Unusual complications at iliac crest bone graft donor site: experience with two cases. Neurosurgery. 1996;39(4):856–9.
24. Rajshekhar V, Arunkumar MJ, Kumar SS. Changes in cervical spine curvature after uninstrumented one- and two-level corpectomy in patients with spondylotic myelopathy. Neurosurgery. 2003;52:799–805.
25. Robinson RA, Smith GW. Anterolateral cervical disc removal and interbody fusion for cervical disc syndrome. Bull Johns Hopkins Hosp. 1955;96:223–4.
26. Russell SM, Benjamin V. The anterior surgical approach to the cervical spine for intervertebral disc disease. Neurosurgery. 2004;54:1144–9.
27. Sandhu HS, Grewal HS, Parantanemi H. Bone grafting for spinal fusion. Orthop Clin North Am. 1999;31(4):685–98.
28. Savolainen S, Rinne J, Hernesniemi J. A prospective randomized study of anterior single-level cervical disc operations with long-term follow-up: surgical fusion is unnecessary. Neurosurgery. 1998;43:51–5.
29. Shamsaldin M, Mouchaty H, Desogus N, Costagliola C, Di Lorenzo N. Evaluation of donor site pain after anterior iliac crest harvesting for cervical fusion: a prospective study on 50 patients. Acta Neurochir (Wien). 2006;148:1071–4.
30. Thakar S, Vedantam A, Rajshekhar V. Correlation between change in graft height and change in segmental angle following central corpectomy for cervical spondylotic myelopathy. J Neurosurg Spine. 2008;9:158–66.
31. Van Den Broecke DG, Schuurman AH, Borg ED, Kon M. Neurotmesis of the lateral femoral cutaneous nerve when coring for iliac crest bone grafts. Plast Reconstr Surg. 1998;102:1163–6.
32. Yonenobu K, Fuji T, Ono K, Okada K, Yamamoto T, Harada N. Choice of surgical treatment for multisegmental cervical spondylotic myelopathy. Spine. 1985;10:710–6.

Posterior Approach to Axis Instability

10

Alberto Maleci, Pier Paolo Maria Menchetti, and Nicola Di Lorenzo

Many pathologies can cause instability of the cranio-vertebral junction (CVJ). Among the most common diseases must be considered thraumatisms, neoplasms, inflammation, but also congenital malformations. Instability of the CVJ is a potentially life-threatening condition and improper treatment can lead to severe neurological deficits as well as continuous, excruciating pain in the neck. Conservative treatments are often disappointing and surgery must always be taken in consideration when approaching instability of the CVJ, being in many cases the only therapy that can provide satisfactory results.

Anterior approaches to the CVJ are usually limited to few and selected cases and posterior approach must be considered the first choice to restore stability of the axial cervical spine.

A. Maleci
Neurosurgery Department,
University of Cagliari, Cagliari, Italy

P.P.M. Menchetti
Minimally Invasive Spinal Surgery Department,
Spine Center, Rome American Hospital, Rome, Italy

Department of Orthopaedics, University of Palermo, Palermo, Italy
e-mail: menchetti@spineislass.org

N. Di Lorenzo (✉)
Neurosurgery Department,
University of Florence, Florence, Italy
e-mail: dilorenzo@unifi.it

History

Posterior sub laminar wiring of C1 and C2 was attempted in 1910 by Mixter and Osgood [24]. Foerster, in 1927, was the first to describe the use a peroneal graft to treat a trauma of the cranio-vertebral region [9]. However, the first widely used surgical technique to restore stability of the C1-C2 segment was posterior fusion with wires and autograft and was developed by Gallie in 1939 [10].

Gallie's technique gained wide appreciation and has been used for many years; in 1978 Brooks and Jenkins [3] proposed a modification of the original technique. The development of the concept of posterior C1-C2 wiring and grafting is represented by clamps between the posterior arch of C1 and C2 laminae. Integrity of the posterior arch of the atlas was necessary and postoperative immobilization was strongly recommended. When the posterior arch of C1 was interrupted the occiput had to be involved in the fusion leading to a complete abolition of rotatory movements and severe limitation of flexo-extension of the head.

In 1987 Magerl and Seeman proposed the union of C2 to C1 by two screws that, passing through the C2 isthmus, were screwed to the C1 lateral masses [22]. The integrity of the posterior arch of C1 was no longer needed and the construct was so stable that also postoperative course did not require firm immobilization. In 1994

P.P.M. Menchetti (ed.), *Cervical Spine: Minimally Invasive and Open Surgery*,
DOI 10.1007/978-3-319-21608-9_10

Goel and Laheri [12] published an original technique where two screws were placed in the lateral masses of C1 and two screws in the isthmus of C2. The screws were connected by plates realizing the stabilization of the C1-C2 segment. Some years later Harms and Melcher [16] proposed a modification of this technique that gained great popularity in the following years. In 2004 Wright [40] proposed a modification of the Harm's technique which avoided the risk of C2 isthmus perforation; the caudal screws were inserted in the laminae and connected to the lateral mass screws.

Conservative Treatment

Pathologies that can be treated by external immobilization are mainly traumatic: fractures of the atlas, fractures of the dens (reducible fractures type 2 and 3 according Anderson and D'Alonzo) [1]. The goal of an external fixation is to maintain an optimal alignment of the axis for a time long enough to provide healing and fusion (usually 3–4 months). The best way to obtain stability of the cranio-vertebral junction by non-surgical techniques is positioning an halo-cast or halo-vest [7, 36], even though a Philadelphia collar has been proposed to treat C2 fractures [29]. The sternal-occipital-mandibular immobilizer (SOMI) –brace has also been used in the past [19]. The most common traumatic lesion of the axis is the C2 fracture type II. Conservative treatment of this type of lesion has been reported by many authors [14], but a high percentage of non-union has also been reported. Unfavourable results are related to many factors, first of all the presentation of fracture. When translation was larger than 6 mm, the non-union rate was as high as 86 % while the results were much better in the cases of dislocation inferior to 4 mm. Another crucial point is the age of the patients: non-union in patients older than 50 [20, 28] is frequently observed. Neurological status is also important; in the presence of progressive neurological deficits or serious impairment of functions as well as in non-cooperative patients, conservative treatment should be avoided. Finally, other lesions involving the cranial and facial bones and thoracic and pulmonary conditions can prevent the correct positioning of a halo vest.

Halo positioning requires insertion of four pins in anterior and posterior position, through the skin and secured to the skull. The direction is vertical, with a 90° angle with the skull, as an angled direction decreases biomechanical resistance [37]. The secure zone for the anterior pins insertion is quite small and is represented by an area of about 10 cm^2 1 cm above the orbital ridge on the external part of the forehead in order to avoid the arterial branch of the superficial temporal artery laterally and the supra-orbitary nerve superiorly and medially.

Non-union is the most common but not the only complication following conservative treatments of cranio-vertebral junction. Cutaneous ulcers are quite common [30], but nerve palsy, particularly of the marginal mandibular nerve (terminal branch of the facial nerve) has also been reported [32]. As far as halo is concerned, loosening of the pins is a common complication [2]. Cutaneous infection can follow the positioning of the pins [11] but infections can involve also bone and intracranial structures [17, 26, 33] and subdural as well as epidural hematoma [23].

Presently conservative treatment should be restricted to axis traumatic lesions with minimal dislocations, in young patients without neurological abnormalities (Fig. 10.1); patients with systemic diseases that carry high operative risk should be treated conservatively as well.

In all other cases surgical treatment should represent the first choice.

Biomechanical Analysis of Surgical Treatments

The goal of the surgical treatment is to provide a stabilization of the unstable segment (i.e. the axial part of the cervical spine) as strong as possible. On the other hand, as every posterior stabilization leads to loss of motion, the ideal treatment should be the most strong and the least invalidating.

Many biomechanical studies have investigated the ability of the different treatments of stabilizing

the C1-C2 segments. According Sim et al. [34], who measured the range of movement and the neutral zone of cadaver specimens after different techniques of stabilization, posterior wiring (PW), transarticular screws (TA) and screws in C1 lateral masses combined with C2 screwing (C1LM-C2 PS) are all able to stabilize an unstable axis in flexion–extension. However, posterior wiring couldn't give enough stability at rotational and lateral bending tests, and were therefore considered insufficient. The three-point reconstruction, using TA and PW provided the best results in all the tests, but also the C1LM-C2PS achieved a sufficient stability in the three planes.

The most recent review has been published by Du et al. in 2015 [6]. The authors found differences in the results of the single papers, but generally TA, C1LM-C2PS provided good

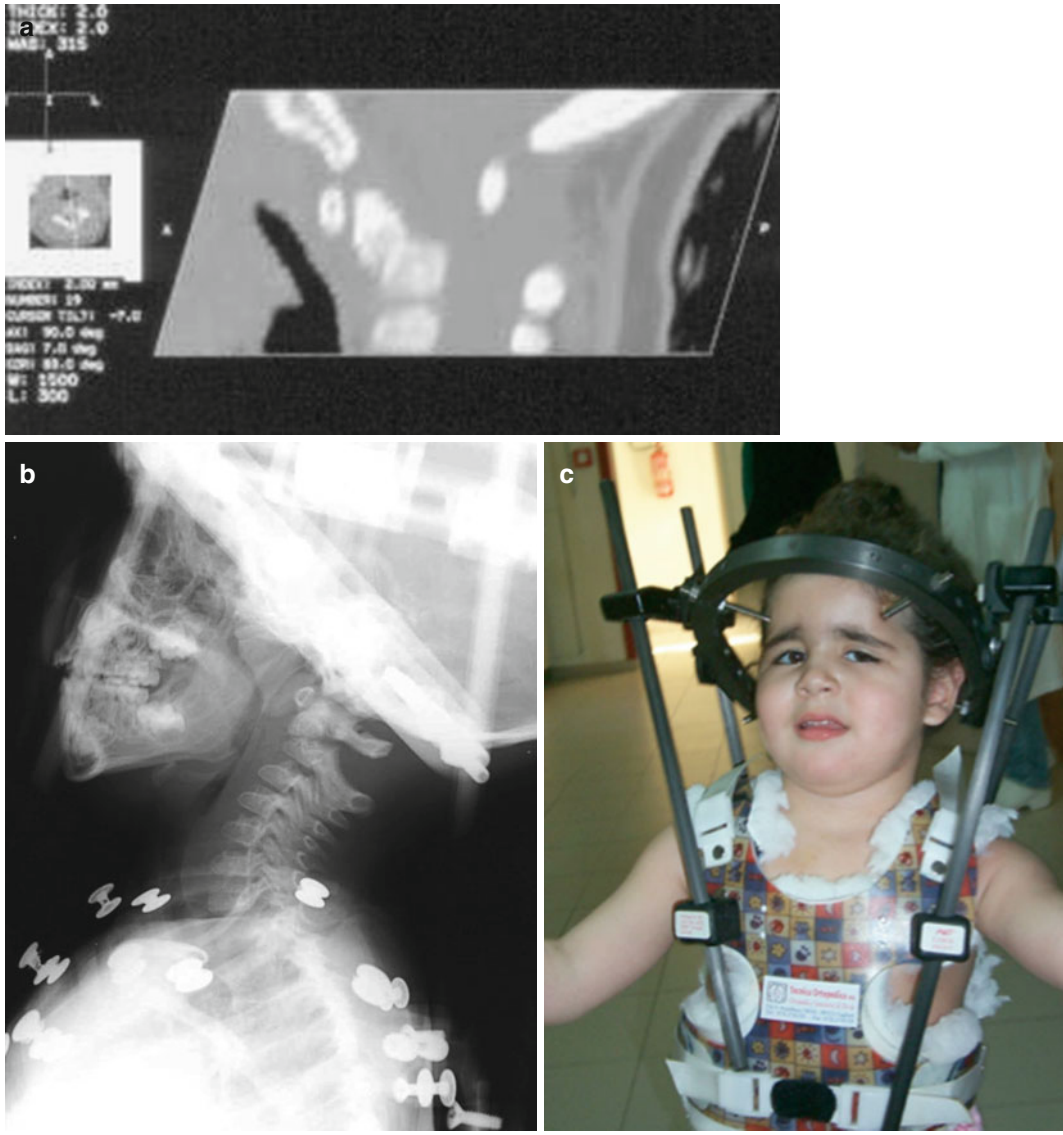


Fig. 10.1 Traumatic subluxation of the dens in a 3 years old girl. (**a**) CT Scan reconstruction. (**b**) Reduction in halo. (**c**) Halo reduction. (**d**) Flexo-extension x-ray after halo removal

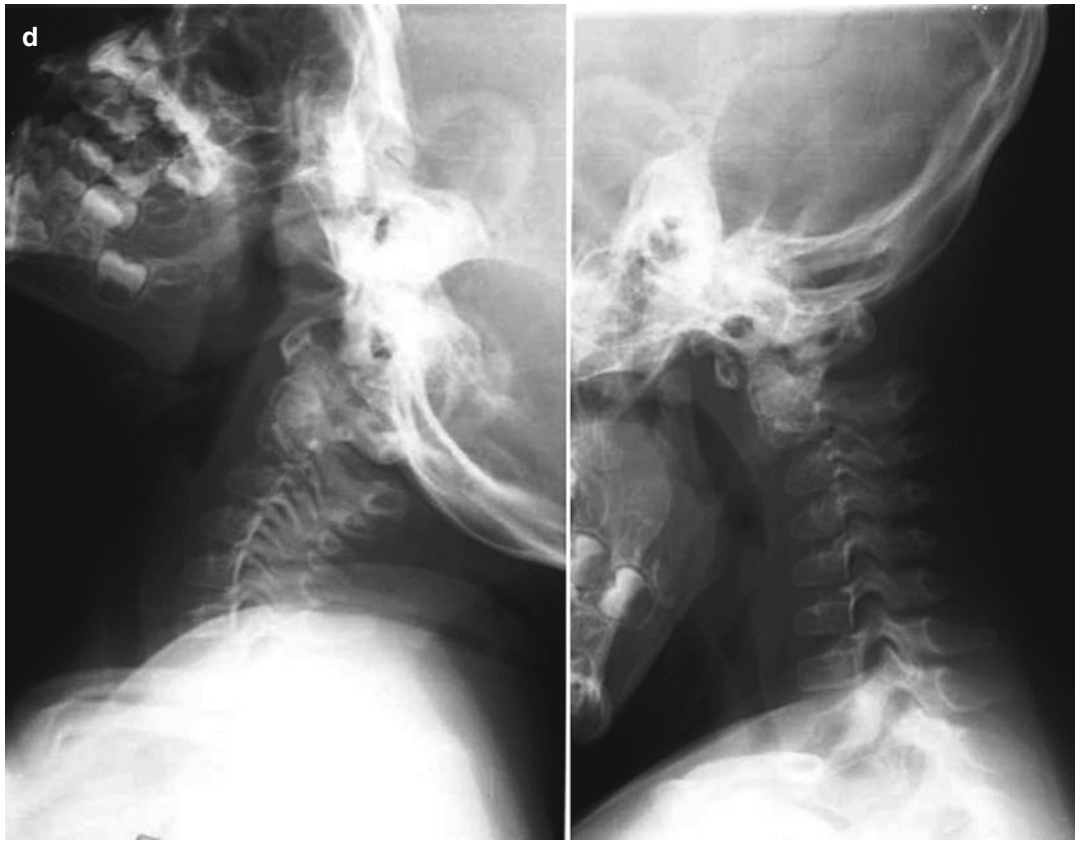


Fig. 10.1 (continued)

stabilization in the three movements tested, while screwing C1 lateral masses and trans laminar C2 (C1LM-C2TL) were less effective in the lateral bending tests.

Posterior Wiring and Clamps

The original Gallie's technique utilized a single bone harvested from the iliac crest and placed on the C2 spinous process and the posterior arch of C1. The stabilization was then obtained by steel wires which passed below the C1 arch and around the C2 spinous process, keeping at the same time the autograft in place. In the Brooks and Jenkins technique two single grafts were used, shaped in order to be positioned between the posterior C1 arch and C2 lamina. The wiring was sublaminar both in C1 and C2. Dickman et al. [4] furtherly modified the original Gallie's technique using a single graft not only leaned on the posterior arch of C1, but wedged underneath the spinous process of C2 and C1. The wires to keep in place the graft and to provide stability passed below the posterior arch of C1 and a notch prepared on the spinous process of C2 in order to increase the stability of the construct.

The results of posterior grafting and wiring were satisfactory in a number of cases. Nevertheless the non-fusion rate was still elevated [5], rotational stability was poor and immobilization for 3–4 months in a halo was mandatory in the postoperative course. Furthermore sublaminar wires carried the risk of nervous injuries and dural tears.

Interlaminar clamps should decrease this risk: the hooks are placed underneath the posterior arch of C1 as well as C2 lamina, and then tightened

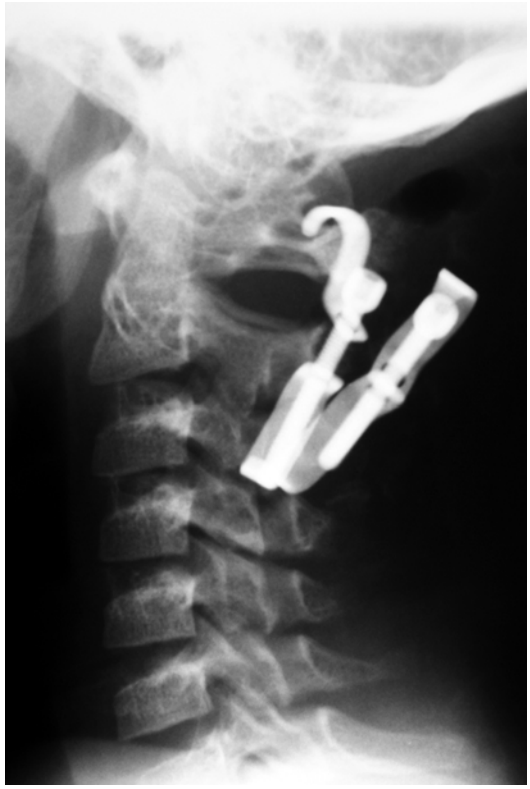


Fig. 10.2 Dislocation of Halifax clamps

by different mechanism [25]; the autograft, harvested by the iliac crest, is compressed between the posterior aspect of C1 and C2. Even though clamps are easier to be positioned than wires, they have good stability only in the flexion and extension movements, while in rotational motion and lateral bending the stability is very poor. Dislocation of the clamps are therefore not uncommon, needing for second surgery (Fig. 10.2). As for all the wiring techniques also clamps require an intact posterior arch of C1.

C1-C2 Trans-articular Screw Technique

This technique, described in 1979 by Magerl [22] gained wide acceptance in the following years, being the most effective technique to stabilize C1-C2 [18], especially if combined with posterior wiring or clamps [31]. This technique can be used also in cases where there is an interruption of the posterior arch of C1 but requires a good alignment of the axis.

The patient is placed in the prone position in a three-points head holder: a horse-shoe head holder can also be used, but, in this case, is more difficult to obtain the optimal alignment of the axis. With an external K-wire the ideal trajectory of the screws is identified before the skin incision [35]. The entry point for the drill, in most cases, lies laterally to the spinous process of T1 or T2. The skin incision is on the midline from C0 to C3 and a careful dissection of the muscles is performed. During this step is important to maintain the midline to avoid bleeding from the muscles which are easily detached from the C1 and C2 posterior aspect, especially in young subjects. There is no need to extend dissection too far laterally, but identification of the C2-C3 joint is mandatory. Two small incisions are then made and two guide tubes are placed along the ideal trajectory from the T2 level up to the C2-C3 joint. The direction is checked with X-rays and the entry point on C2 is identified: it lies just 3 mm medially and superiorly to the center of the C2-C3 joint. After decortication of the dorsal aspect of the joint a guide K-wire is drilled under x-ray control with a sagittal direction toward the anterior C1 tubercle and with a lateral medial inclination of about 0–10°. If it is not possible to obtain a perfect C1-C2 alignment the trajectory should be a little superior to the anterior tubercle. The drilling is stopped 3–4 mm before reaching the anterior tubercle, preventing penetration of the retropharingeal space and a cannulated screw is then screwed on the K-wire. A special attention must be paid to avoid the advance of the K-wire while the screw is positioned. Some systems have also the possibility to connect two hooks, embracing the posterior arch of the atlas, to the screws, creating a very strong stabilization of the axis (Ulrich Company, Ulm, Germany) (Fig. 10.3a, b). Bone autograft or allograft is finally positioned between C1 and C2. If any doubt arises, a small spatula can be inserted in the C1-C2 joint, after dislocation of the C2 nerve root to check the presence of the screw crossing the joint.

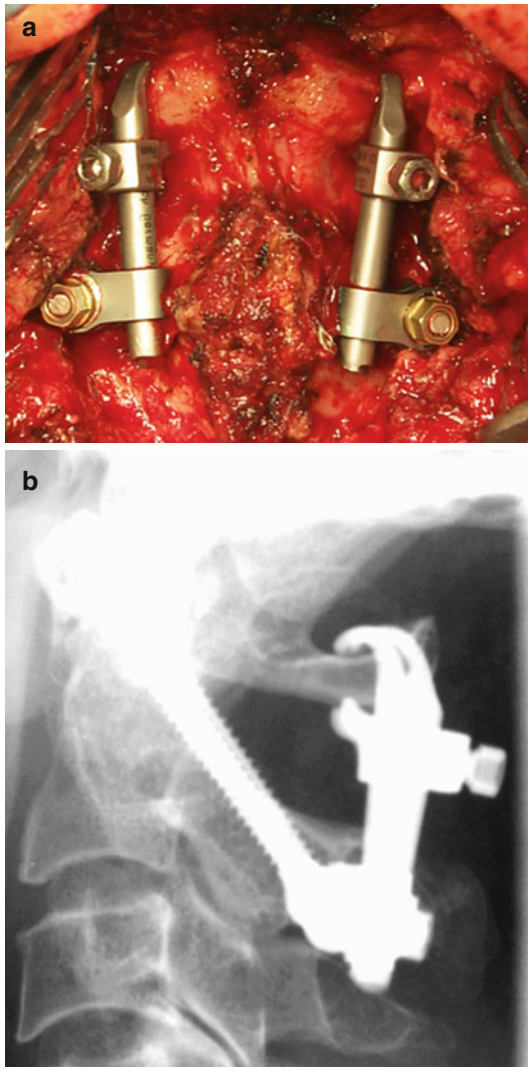


Fig. 10.3 (**a**) Transarticular C1-C2 fixation and C1 posterior arch clamps. Operative field. (**b**) Transarticular C1-C2 fixation and C1 posterior arch clamps. Postoperative X-rays

The main problem of this technique is the risk of lesions to the vertebral artery [39]; a preoperative CT scan with reconstruction should always be performed to investigate the course of vertebral artery. Some studies have shown that anomalies of the vertebral artery anatomy or a large vertebral artery groove are present in more than 20 % of the patients [21, 27]. In these cases there are two options: to change technique or to perform an unilateral transarticular fixation.

C1 Lateral Mass Screws and C2 Pedicle Fixation

This technique was first described by Goel and Leheri in 1994 [11, 13], but gained popularity after its reappraisal by Harms and Melcher [16] some years later. The main advantage of this method is that the integrity of the posterior arch of C1 is not needed and also alignment of the axis is not necessary. With this technique a reduction and alignment of the C1-C2 complex can be obtained also in many cases considered non reducible at the pre-operative studies (Fig. 10.4a–c). At the same time the technique allows good results in terms of primary stability [6] and later fusion [13]. The technique is suitable also in mild cases of basilar invagination: by distraction of C1 and C2 the dens is pulled downward, (or the skull is pushed upward) releasing compression on the ventral aspect of the brain stem, so that transoral decompression can be avoided [15].

The patient is in prone position with the head in a three-point or horse-shoe head holder. The skin incision is from C0 to C3 and the muscle of the neck are detached on the midline, exposing the posterior arch of C1 and C2 on both sides. In comparison with the transarticular technique, the exposition is wider because the lateral mass of the atlas must be fully exposed; some bleeding can rise from the important venous plexus that surrounds the lateral aspect of the spinal cord, the C2 root and the vertebral artery, but it is usually easy to control with gel foam or other haemostatic agents; there is no need to fully expose the vertebral artery. The medial wall of the lateral mass is identified by a smooth dissector and the C2 root is also isolated. The entry point for the C1 screw is in the center of the lateral mass or at the union of the posterior arch with the lateral mass. In order to avoid conflict with the C2 nerve root, a little portion of the inferior aspect of C1 posterior arch can also be removed by drilling or rongeurs. No drilling should be made above the junction of the posterior arch with the lateral mass because this area is too close to the vertebral artery. Under fluoroscopy a hole is drilled with a direction from 0° to 25° medially toward the anterior tubercle. After tapping the hole a screw (3.5 mm) is positioned.

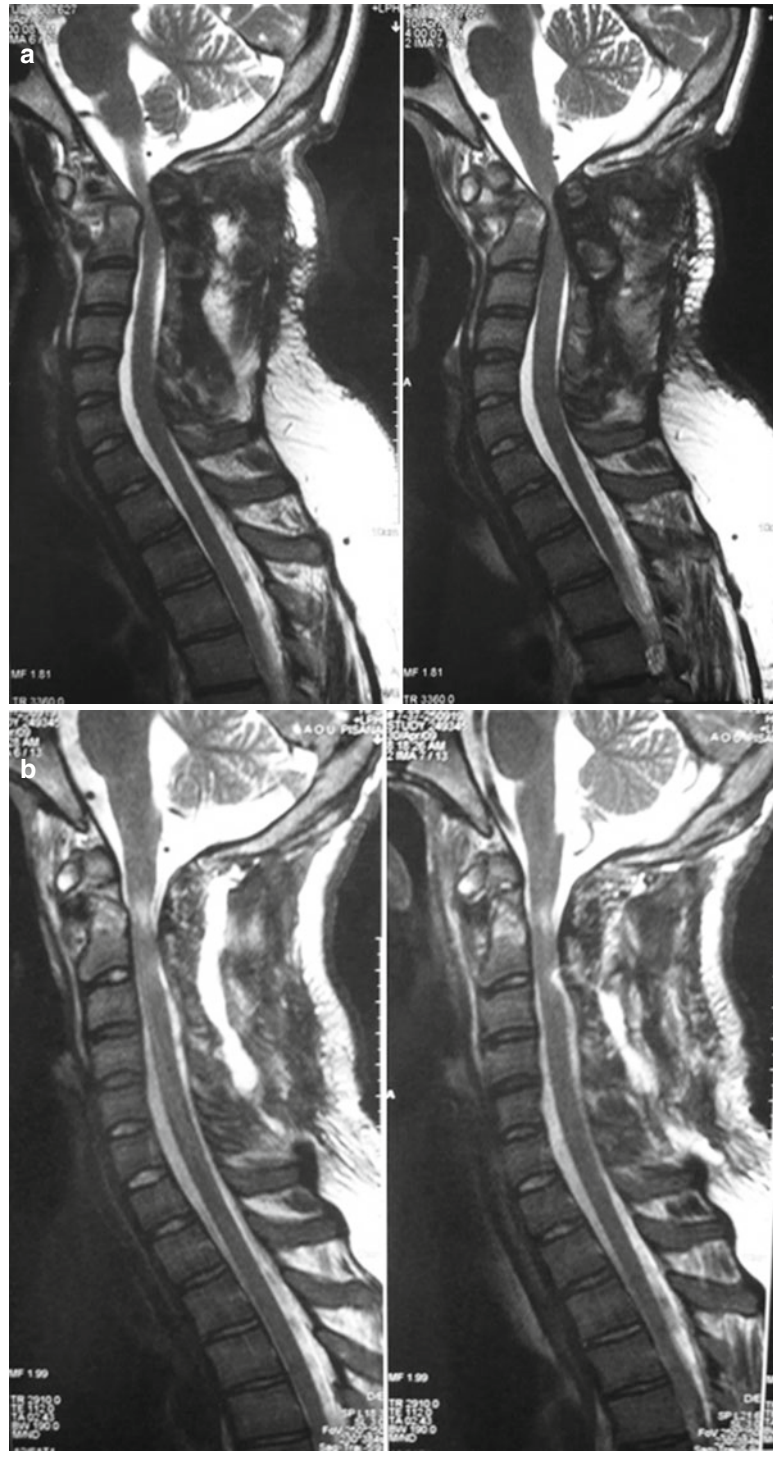
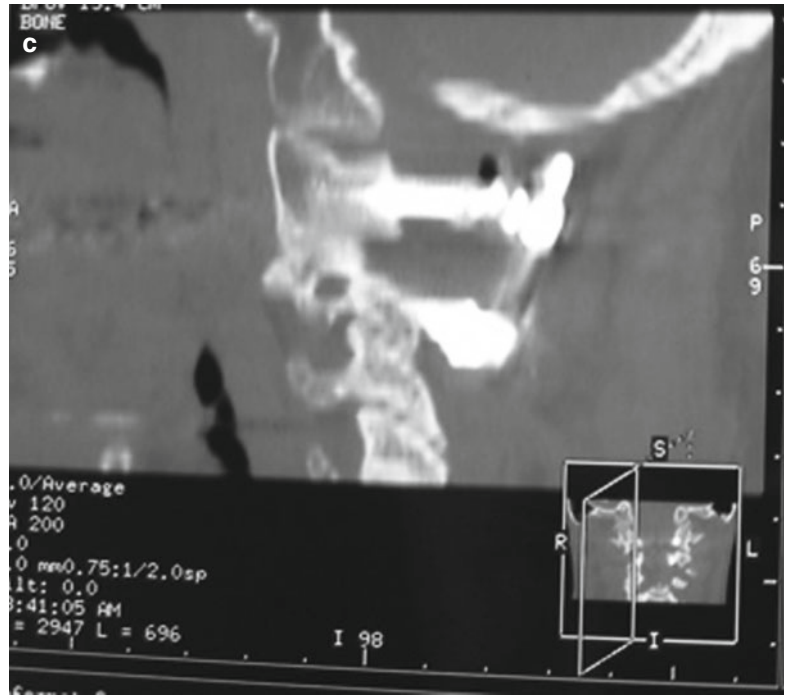


Fig. 10.4 (**a**) Not-reducible os odontoideum in a 21-year old man. Pre-operative MRI. (**b**) The same case following C1-C2 reduction and stabilization according to Goel and Leheri. (**c**) Post-operative CT reconstruction of the same case

Fig. 10.4 (continued)



The entry point of the C2 screw depends on the intention to place the screw in the pedicle or in the pars, knowing that there are not real differences from a biomechanical point of view [8, 34, 38]. Conventionally, the pars of C2 is that portion of the vertebra between the superior and inferior surfaces. The entry point and the direction of the screw are about the same as in the transarticular technique (3 mm medially and 3 mm superiorly to the articular surface of C2 toward the anterior tubercle) with a latero-medial angulation of 15°. The screw is much shorter and the risk of injuries to the vertebral artery is lower. The pedicle of C2 is located anteriorly to the pars and trajectory is a little less angulated (about 20° on a sagittal plane and 15° medially). The entry point of a C2 pedicular screw is very little (about 2 mm) superior and more medial than the entry point for screwing the C2 pars. The C1 and the C2 screws are then connected to bars that allow reduction and stabilize the axis. As in the other techniques bone allograft or autograft are finally inserted between C1 and C2 in order to provide fusion.

Conclusion

Many techniques are available to restore stability of an unstable axis. The choice depends upon the pathology which caused the instability and the severity of damage to bone and ligaments. Posterior wiring and clamps are less demanding from a technical point of view and carry less risks to injuries to the vascular and nervous structures, but give less stability which means the need for postoperative halo or collars and a significant rate of failures. Transarticular screwing of C1-C2 is the best performing technique and should be seen as the gold standard, but carries the risk of life-threatening complications and it is not suitable in all cases. C1 lateral mass and C2 (pars or pedicle) screwing has a wider range of feasibility and is a little less riskful than transarticular screwing. The advantages are balanced by less stability.

Malpositioning of the screws, both when Magerl's technique and Goel's technique are performed, is not uncommon and navigation,

when available, is recommended; nevertheless must be said that clinical complications are exceptional also in case of a mistake in screw positioning [39].

References

1. Anderson LD, D'Alonzo RT. Fractures of the odontoid process of the axis. J Bone Joint Surg Am. 1974;56:1663–74.
2. Botte MJ, Byrne TP, Garfin SR. Use of skin incisions in the application of halo skeletal fixator pins. Clin Orthop. 1989;246:100–1.
3. Brooks AL, Jenkins EB. Atlanto-axial arthrodesis by wedge compression method. J Bone Joint Surg Am. 1978;60:279–84.
4. Dickman CA, Sonntag VK, Papadoupolos SM, Hadley MN. The interior spinous method of posterior atlantoaxial arthrodesis. J Neurosurg. 1991;74:190–8.
5. Dickman CA, Sonntag VK. Posterior C1-C2 transarticular screw fixation for atlantoaxial arthrodesis. Neurosurgery. 1998;43:275–80.
6. Du JY, Aichmair A, Kueper J, Wright T, Lebl DR. Biomechanical analysis of screw constructs for atlantoaxial fixation in cadavers: a systematic review and meta-analysis. J Neurosurg Spine. 2015;22(2):151–61.
7. Dunn ME, Seljesko EL. Experience in the management of odontoid process injuries: an analysis of 128 cases. Neurosurgery. 1986;18(3):306–10.
8. Elliot RE, Tanweer O, Boah A, Smith ML, Frempong-Boadu A. Comparison of safety and stability of C-2 pars and pedicle screws for atlantoaxial fusion: meta-analysis and review of the literature. J Neurosurg Spine. 2012;17(6):577–93.
9. Foerster O. Die Leitungsbahnen des Schmerzge-fuhls und die chirurgische Behandlung der Schmerzzustaude. Berlin: Urban & Schwarzenberg; 1927. p. 266.
10. Gallie WE. Fractures and dislocations of the cervical spine. Am J Surg. 1939;46:495–9.
11. Glaser JA, Whitehill R, Stamp WG, Jane JA. Complications associated with the halo-vest: a review of 245 cases. J Neurosurg. 1986;65:762–9.
12. Goel A, Leheri V. Plate and screw fixation for atlanto-axial subluxation. Acta Neurochir. 1994;129:47–53.
13. Goel A, Desai K, Mazumdar D. Atlantoaxial fixation using plate and screw method: a report of 160 treated patients. Neurosurgery. 2002;51:1351–6.
14. Greene KA, Dickman CA, Marciano FF, et al. Acute axis fracture, analysis of management and outcome in 340 consecutive cases. Spine. 1997;22:1843–52.
15. Guo SL, Zhou DB, Yu XG, Yin YH, Qiao GY. Posterior C1-C2 screw and rod instrument for reduction and fixation of basilar invagination with atlantoaxial dislocation. Eur Spine J. 2014;23(8):1666–72.
16. Harms J, Melcher RP. Posterior C1-C2 fusion with polyaxial screw and rod fixation. Spine. 2001;26:2467–71.
17. Hashimoto Y, Doita M, Hasuda K, Korosue K. Intracerebral pneumocephalus and hemiparesis as a complication of a halo vest in a patient with multiple myeloma. Case report. J Neurosurg. 2004;100(4 Suppl Spine):367–71.
18. Jeanneret B, Magerl F. Primary posterior fusion C1/2 in odontoid fractures: indications, technique and results of transarticular screw fixation. J Spinal Disord. 1992;5(4):464–75.
19. Johnson RM, Hart DL, Simmons EF, Ramsby GR, Southwick WO. Cervical ortosis: a study comparing their effectiveness in restricting cervical motion in normal subjects. J Bone Joint Surg. 1977;59-A:332–9.
20. Lennarson PJ, Mostafavi H, Traynelis VC, et al. Management of type II dens fractures: a case–control study. Spine. 2000;25:1234–7.
21. Madawi AA, Casey AT, Solanki GA, et al. Radiological and anatomical evaluation of the atlantoaxial transarticular screw fixation technique. J Neurosurg. 1997;86:961–8.
22. Magerl F, Seeman P. Stable posterior fusion of the atlas and axis by transarticular screw fixation. In: Kehr P, Weidner A, editors. Cervical spine I. New York: Springer; 1987. p. 322.
23. Medhkour A, Massie L, Horn M. Acute subdural hematoma following halo pin tightening in a patient with bilateral vertebral artery dissection. Neurochirurgie. 2012;58(6):386–90.
24. Mixter SJ, Osgood RB. Traumatic lesions of the atlas and axis. Ann Surg. 1910;51:193–207.
25. Moskovich R, Crockard HA. Atlantoaxial arthrodesis using interlaminar clamps. An improved technique. Spine. 1992;17(3):261–7.
26. Papageloupolos PJ, Sapkas GS, Kateros KT, Papadakis SA, Vlamis JA, Falagas ME. Halo pin penetration and epidural abscess in a patient with a previous cranioplasty: case report and review of the literature. Spine. 2001;26(19):E463–7.
27. Paramore CG, Dickman CA, Sonntag VK. The anatomical suitability of the C1-2 complex for transarticular screw fixation. J Neurosurg. 1996;85:221–4.
28. Patel A, Zakaria R, Al-Mahfoudh R, Clark S, Barrett C, Sarsam Z, Pillay R, Pigott TD, Wilby MJ. Conservative management of type II and III odontoid fractures in the elderly at a regional spine center: a prospective and retrospective color study. Br J Neurosurg. 2014;18:1–5.
29. Polin RS, Szabot T, Bogaev CV, et al. Nonoperative management of type II and III odontoid fractures: the Philadelphia collar versus the halo vest. Neurosurgery. 1996;38:450–6.

30. Powers J. A multidisciplinary approach to occipital pressure ulcers related to cervical collars. J Nurs Care Qual. 1997;12(1):46–52.
31. Richter M, Schmidt R, Claes L, et al. Posterior atlantoaxial fixation: biomechanical in vitro comparison of six different techniques. Spine. 2002;27:1724–32.
32. Rodgers JA, Rodgers WB. Marginal mandibular nerve palsy due to compression by a cervical hard collar. J Orthop Trauma. 1995;9:177–9.
33. Saeed MU, Dacuycuy MA, Kennedy DJ. Halo pin insertion associated brain abscess: case report and review of the literature. Spine. 2007;32(8):E271–4.
34. Sim HB, Lee JW, Park JT, Mindea SA, Lim J, Park J. Biomechanical evaluations of various C1-C2 posterior fixation techniques. Spine. 2011;36(6):E401–7.
35. Solanki GA, Crockard HA. Preoperative determination of safe superior transarticular screw trajectory through the lateral mass. Spine. 1999;24:1477–82.
36. Traynelis VC. Evidence-based management of type II odontoid fractures. Clin Neurosurg. 1997;44:41–9.
37. Triggs KJ, Ballock RT, Lee TQ, Woo SL, Garfin SR. The effect of angled insertion on halo pin fixation. Spine. 1989;14:781–3.
38. Xu R, Bydon M, Macki M, Belkoff SM, Langdale ER, McGovern K, Wolinski K, Gokalsan ZL, Bydon A. Biomechanical impact of C2 pedicle screw length in an atlantoaxial fusion construct. Surg Neurol Int. 2014;5 Suppl 7:S343–6.
39. Wright NM, Lauryssen C. Vertebral artery injury in C1-2 transarticular screw fixation: results of a survey of the AANS/CNS section on disorders of the spine and periphera nerves. J Neurosurg. 1998;88:634–40.
40. Wright NM. Posterior C2 fixation using bilateral, crossing C2 laminar screws: case series and technical note. J Spinal Disord Tech. 2004;17:158–62.

Tissue Sparing Posterior Cervical Indirect Decompression and Fusion in Foraminal Stenosis

11

Kris B. Siemionow, Bruce M. McCormack, and Pier Paolo Maria Menchetti

Background on Cervical Spondylosis

Cervical spondylosis and radicular symptoms are commonly the result of age related degenerative changes that most likely originate at the cervical disc. With aging, the chemical composition of the nucleus pulposus and annulus fibrosis changes and is associated with a progressive loss of the disc's viscoelastic properties. Disc height decreases, the disc bulges posteriorly, and the vertebral bodies drift toward one another. Concurrently, the ligamentum flavum buckles, the facet joint capsules thicken, and osteophytes form contributing to a decrease in size of the central canal and neuroforamina. The end result of the above described changes, often referred to as cervical degenerative disc disease, is spinal stenosis and direct mechanical pressure on the nerve roots or spinal cord. The exact pathogenesis of cervical radicular pain remains unknown, but it is felt to be a result of a combination of direct nerve compression and an inflammatory response [1, 2].

Intrinsic blood vessels of the compressed nerve have been shown to demonstrate increased permeability, which results in nerve root edema. As the edema becomes chronic, fibrosis and scarring ensue contributing to an altered response threshold and increased sensitivity of the nerve root to pain. Pain mediators released from the nerve cell bodies, intervertebral disc, and surrounding tissue play a role in initiating and perpetuating the inflammatory response [3].

Age related degenerative disc changes often lead to painful symptoms, including neck pain, arm pain, shoulder pain, numbness, weakness, and changes in gait. When degenerative changes result in pinched nerves in the cervical spine, the resulting painful condition is commonly referred to as cervical radiculopathy. Globally, the reported annual incidence of cervical radiculopathy is 83.2/100,000 persons [4], while the reported prevalence is believed to be 3.5/1,000 persons [5].

K.B. Siemionow, MD (✉)
Department of Orthopaedic Surgery,
University of Illinois, Chicago, IL, USA
e-mail: Ksiem@myissc.com

B.M. McCormack, MD
Department of Neurosurgery, University of California,
San Francisco, CA, USA
e-mail: bruce@neurospine.org

P.P.M. Menchetti, MD
Minimally Invasive Spinal Surgery Department,
Spine Center, Rome American Hospital,
Rome, Italy

Department of Orthopaedics, University of Palermo,
Palermo, Italy
e-mail: menchetti@spineislass.org

P.P.M. Menchetti (ed.), *Cervical Spine: Minimally Invasive and Open Surgery*,
DOI 10.1007/978-3-319-21608-9_11

Historical Posterior Treatment Options

Posterior cervical foraminotomy has been employed by surgeons for the treatment of radiculopathy since the 1950's [6, 7]. It is typically indicated in patients with unilateral radiculopathy, absent significant neck pain with maintained cervical lordosis [8–10]. Further, it is a desirable option in cases presenting with laterally herniated disc and lateral stenosis [8]. The surgical objective of a foraminotomy is to decompress the nerve roots while maintaining motion at the affected level. A small laminotomy is typically performed to expose the lateral margin of the spinal cord and affected nerve root. This is followed by a foraminal rhizotomy. The technique can be performed using a high speed burr and Kerrison punches.

Early foraminotomies were performed via a midline approach, taking advantage of a subperiosteal laminae dissection to reduce bleeding. The open approach is desirable because of maximum anatomical visualization. The technique has evolved over the past five decades. Fessler and Adamson were among the first to describe clinical outcomes utilizing a microendoscopic approach [8, 11]. This involves establishing tubular access to the affected foramen and visualization of the anatomy via endoscope. By cutting a stab incision 1 cm from midline ipsilateral to the targeted pathology, endoscopic visualization is achieved. The facet is targeted with a small diameter Steinman pin under fluoroscopic guidance. After the skin incision is extended above and below the Steinman pin by a total of 2 cm and the fascia incised, soft tissue is retracted using sequential dilators over which a tubular retractor is placed.

Minimally invasive approaches are desirable because of reduced blood loss, same day surgery and quicker recovery [8, 11, 12]. A meta-analysis of posterior cervical foraminotomies performed by McAnany et al. and a clinical study by Kim et al. showed that a minimally invasive approach did not compromise long-term clinical outcomes. Both the analysis and study reported a significant improvement in pain and return to normal life [13, 14].

Adoption of foraminotomy is suppressed because the procedure can be technically difficult, especially when performed through minimal access incisions [15]. Axial neck pain, and less commonly, instability may ensue because the motion segment is not stabilized [16, 17]. Bilateral foraminotomies are avoided so as not to exacerbate the aforementioned limitation. Foraminotomy, particularly at C4-5, has been associated with motor palsies of the C5 root [18].

It is important to note that the majority of patients with cervical radiculopathy due to degenerative spondylosis that fail medical management are treated with an anterior cervical discectomy and fusion (ACDF) approach. This is driven in part by the prevalence of myelopathy secondary to canal stenosis, which is frequently associated with foraminal stenosis. An anterior approach typically involves removal of the intervertebral disc along with offending osteophytes and reconstruction with a fusion or disc replacement is performed [8, 19]. Total disc replacement (TDR) has been advocated to reduce incidence of adjacent segment disease but with 10+ years follow-up has proven to have more limited clinical indications than originally considered [20, 21]. Both procedures remove disc and bone to decompress the nerve root followed by anterior spinal column reconstruction. ACDF and TDR are safe, but reported complications include implant failure and dislodgement, excessive or incomplete bony healing, spinal deformity, neurologic complications, dysphagia, esophageal injury, and recurrent laryngeal nerve palsy [22–25].

Introduction to Posterior Cervical Tissue Sparing Indirect Decompression and Fusion

By preserving much of the normal osteoligamentous anatomy of the cervical spine, a tissue sparing posterior cervical procedure reduces the risk for post-laminectomy kyphosis, muscle atrophy, and difficulties associated with the post-laminectomy membrane.

Understanding the three-dimensional anatomy of the cervical neural foramen is critical for performing the posterior surgical procedure. As described by Russell and Benjamin, the lateral portion of the cervical spinal canal is covered posteriorly by the

Fig. 11.1 DTRAX Cervical Cage in three configurations

lateral aspects of a superior and inferior lamina [26]. Ventral to the lamina, the ligamentum flavum is attached to two-thirds of the undersurface of the superior lamina, but inferiorly it is attached only to the superior edge of the lower lamina. Laterally, the ligamentum flavum ends 1–2 mm before the medial limit of the neural foramen. The anterior boundary of the cervical neural foramen, from cranial to caudal, is the posterolateral cortical margin of the superior vertebral body, the intervertebral disc covered by the posterior longitudinal ligament (PLL), and a small portion of the postero-lateral cortical margin of the inferior vertebral body. Posteriorly, from cranial to caudal, the neural foramen is bounded by 1–2 mm of the superior facet, followed by the entire ventral surface of the inferior facet. The superior and inferior boundaries of the neural foramen are formed by the superior and inferior vertebral pedicles, respectively.

Removal of the ligamentum flavum in the lateral aspect of the spinal canal exposes the dura. After removal of the medial half of the facet joint, the axilla of the nerve root is seen at its takeoff from the lateral dura/spinal cord. The nerve root in the neural foramen, both covered by connective tissue (root sleeve), are also exposed. A radicular artery is located anteriorly, between the nerve root dura and the root sleeve, and an epidural venous plexus is located circumferentially. The nerve root proper can be seen only after removing the lateral half of the lamina and the medial half of the facet and opening the root sleeve (including the venous plexus); the nerve root is located over the superior and lateral edges of the inferior pedicle.

The motor and sensory roots exit the spinal canal within a common dural sleeve, but in the neural foramen, the dural sleeve divides into an antero-inferior sleeve carrying the motor root, and a postero-superior sleeve housing the sensory root division. At the region of the sensory ganglion, a single dural sleeve covers both the sensory and motor divisions.

DTRAX Spinal System

Tissue sparing indirect decompression and fusion can be performed using instrumentation available on the market. One such system is the DTRAX® Spinal System (Providence Medical Technology, Inc.). The spinal system is composed of specialized instruments that carry out the novel technique and placement of the cervical cage device.

DTRAX Cervical Cages are titanium constructs offered in various footprints and heights. The implants are manufactured from implant grade titanium alloy (6AI-4V Ell Titanium). They are available in three configurations: (1) Cage-T (Taper) with a 7° angle, (2) Cage-B (Bullet) with parallel upper and lower surfaces, and (3) Expandable Cage with an expandable taper washer via advance of a screw (Fig. 11.1). A hollow design in all cages enables packing of bone graft. The teeth on superior and inferior surfaces are designed to resist expulsion. The DTRAX Expandable Cage is not available in the U.S.; it is available in CE approved markets.

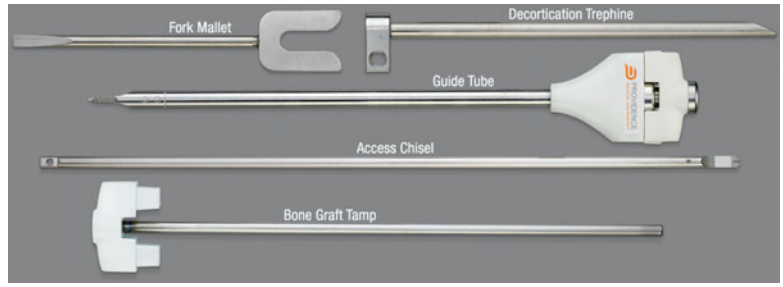


Fig. 11.2 Key instrumentation components of the DTRAX spinal system

The DTRAX Cervical Cage is compatible with a variety of retractors and instrument sets, including DTRAX Spinal System. Figure 11.2 shows many of the key instruments comprising the DTRAX Spinal System; these include:

- Fork Mallet
- Decortication Trephine
- Guide Tube
- Access Chisel
- Bone Graft Tamp

Indications for Use

This surgical technique is indicated for use in skeletally mature patients with cervical spondylosis (C3–C7) and accompanying radicular symptoms at a single level. The level of pathology is confirmed by detailed patient history and radiographic studies. Patients should have received at least 6 weeks of non-operative treatment prior to treatment with the device. The devices are intended to be used with autogenous bone graft and supplemental fixation, such as a bone screw or an anterior plating system.

Contraindications

Contraindications include the following:

Cervical spondylosis, cervical myelopathy, cervical kyphosis; infection; allergy to titanium; pregnancy; Paget's disease; renal osteodystrophy; cancer of the spine; obesity; rheumatoid arthritis; bone absorption, osteopenia, poor bone quality, and/or osteoporosis.

Surgical Technique

Operating Room and Patient Preparation

Confirm the operating table and patient head support are both radiolucent so that these two objects will not interfere with fluoroscopy. Check that there is adequate space at the head of the table to place and position C-Arm(s) and that there is sufficient spacing away from the sterile field. After routine intubation, place the patient in a prone position with patient's head on a foam donut with a slight flexion of the head. Use tape to pull the patient's shoulders inferiorly and secure in place (Fig. 11.3).

C-Arm Preparation

Set up the C-Arm at the side of the table in AP with the arm fully retracted. Find a clear AP view. Advance the C-Arm while rotating the detector back to find the lateral view. A fully retracted C-Arm allows for finding the lateral view by advancing the arm of C-Arm instead of moving the whole machine. Returning to the AP position only requires rotating the detector forward while fully retracting the C-Arm. This C-Arm set up allows clear imaging to be retained while rapidly switching between views.

The use of two C-Arms is recommended for ease of imaging which can improve safety and significantly reduce the time length of the procedure. If a second C-Arm is used, leave the first C-Arm in the lateral position. Rotate the first C-Arm 20–30° so that the arm is under the patient's shoulders. This provides room for the second C-Arm under the patient's neck. Place

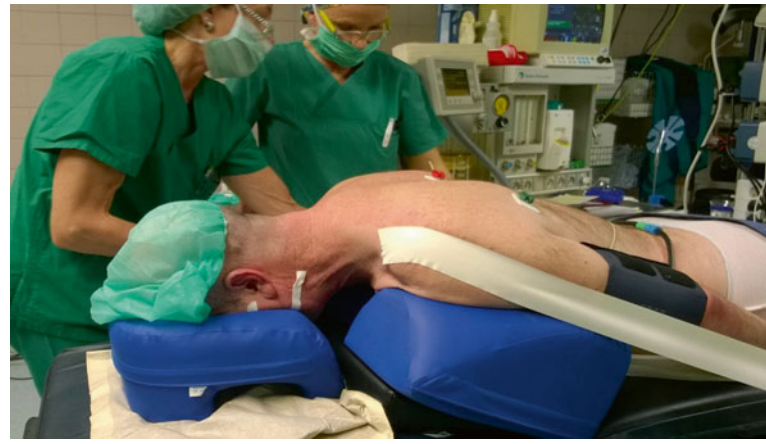


Fig. 11.3 Patient preparation involves prone positioning, head support and pull-down of shoulders

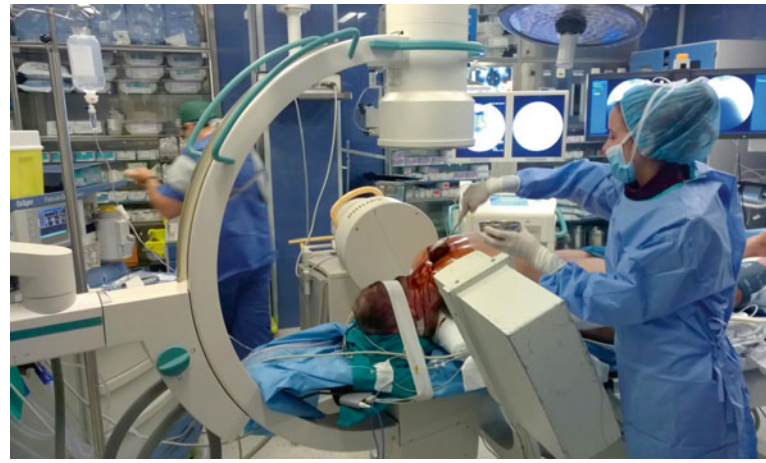


Fig. 11.4 The use of two C-arms for lateral and AP views concurrently is recommended

the second C-Arm at the head of the table and with the arm fully advanced to find the AP view. Finding the AP view with the arm of the second C-Arm fully advanced allows the arm portion to be retracted during the procedure to create working space for tools, then fully advanced to quickly restore AP imaging. On the second C-Arm add approximately 20° caudal/cranial inclination; this adjustment, along with the flexion of the head, allows an en face or near en face view of the target facet joint (Fig. 11.4).

Skin Markings and Sterile Field

Images clearly demonstrating facet joint anatomy are essential for proper preoperative skin markings. Use fluoroscopic guidance to identify surgical border and level to be treated. Identify and mark the medial and lateral borders of the facets using AP view on fluoroscopy, a slender, straight metallic instrument (e.g. K-wire or Steinman pin), and surgical pen (Fig. 11.5). Identify and mark the operative level using the same method (Fig. 11.6). Prepare and drape the patient's posterior neck in a routine sterile fashion. It is recommended the C-Arm(s) remain in place during this portion so that the radiological markers are not lost. Open the kits containing the surgical instruments and implants. Arrange the instruments in the order in which they will be used (Fig. 11.7).

Establish Trajectory and Access the Facet Joint

Use a spinal needle to confirm the trajectory under fluoroscopic guidance (Fig. 11.8a). Due

to the acute angle of the facet joint the trajectory often results in the entry point being located approximately two finger widths below the target level. Reinsert or reposition the spinal needle as needed until the correct trajectory is confirmed. The correct trajectory will match the angle of the facet joint (Fig. 11.8b). Repeat this process for the contralateral side. If desired the needles may be used to administer local anesthesia and/or epinephrine for pain or bleeding control. Remove the first spinal needle while leaving the contralateral needle in place to provide a guidance reference.

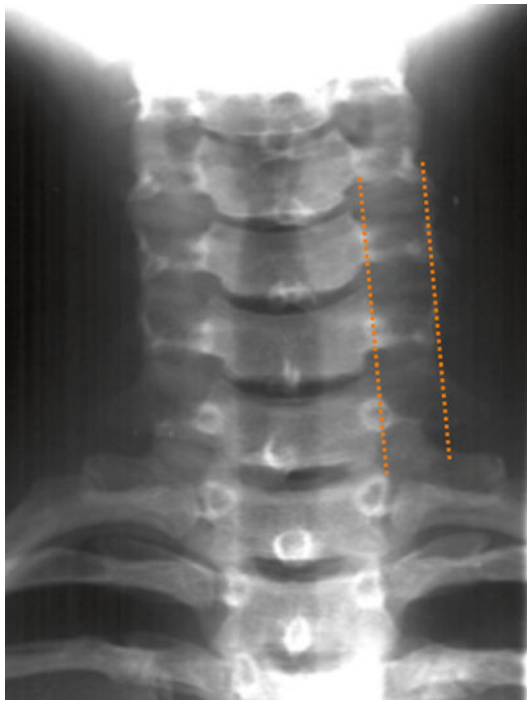


Fig. 11.5 The medial and lateral borders of the facets are identified using AP view

Make initial incision at the midline by the confirmed entry points and carry through the subcutaneous tissue and the fascia. Use a hemostat to spread the fascia and paraspinal muscles laterally. Direct visualization of the surgical site with the naked eye can be achieved. Under AP fluoroscopic guidance, advance the Access Chisel through incision with the chisel blade in the vertical position until bone is reached (Fig. 11.9a). Rotate the Access Chisel 90°. Using control in AP and lateral fluoroscopy, find the superior portion of the facet joint, lower Access Chisel tip to find and cut the capsule of the joint, and advance the Access Chisel into facet joint using hand pressure and/or light malleting (Figs. 11.9b, c).

Decorticate the Lateral Masses and Establish Working Channel

Advance the Decortication Trephine over the Access Chisel until the distal tip contacts bone (Fig. 11.10a, b). Decorticate each lateral mass with 10° rotations of the Decortication Trephine. This action will strip the muscle subperiosteally and create bleeding from the bone. Disengage and

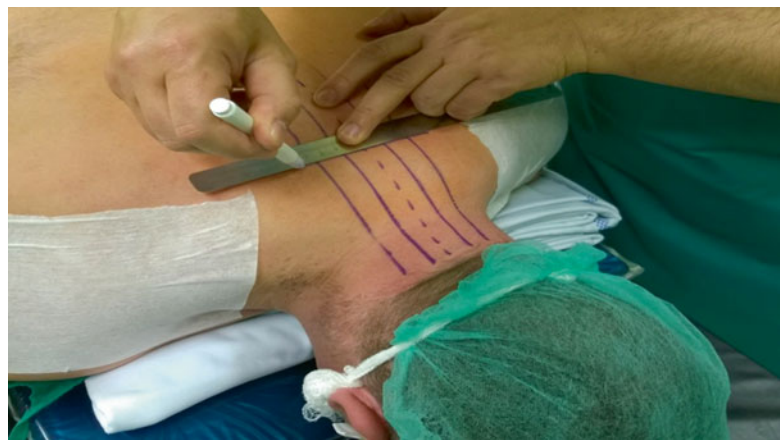


Fig. 11.6 The operative level is identified and marked on the patient

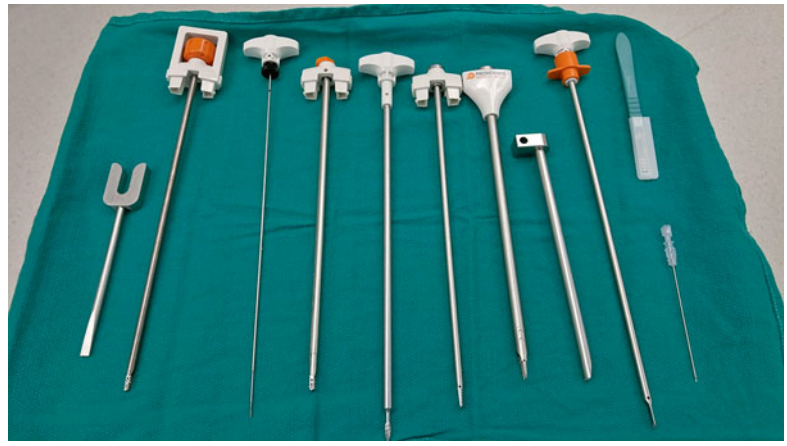


Fig. 11.7 Typical arrangement of instruments for surgery

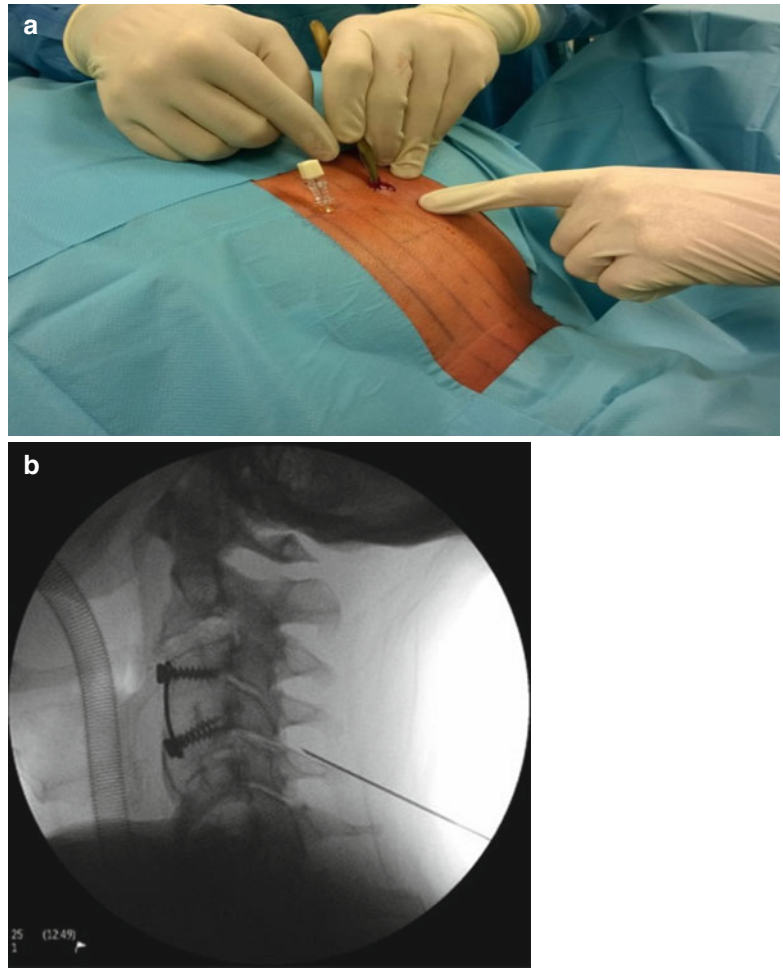


Fig. 11.8 (**a**) The spinal needle confirms trajectory under fluoroscopic guidance. (**b**) The spinal needle is positioned to match the angle of the facet joint

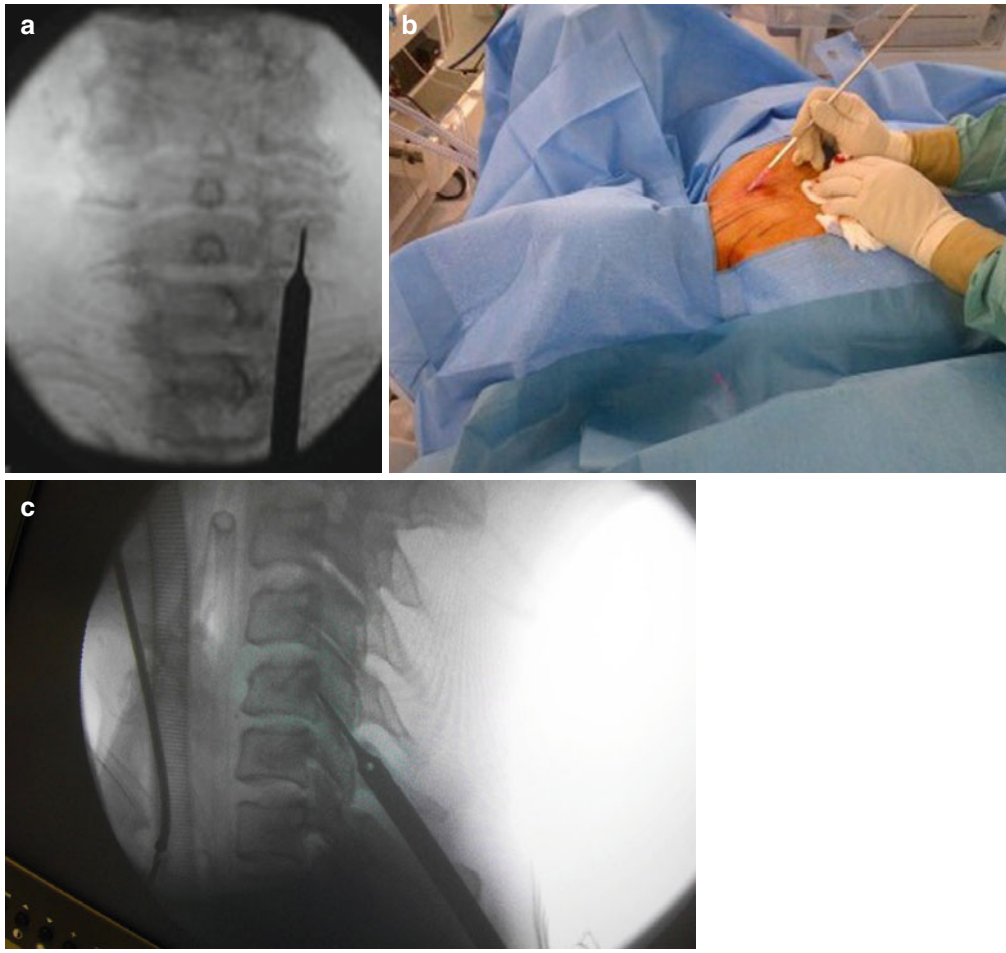


Fig. 11.9 (**a**) The Access Chisel is advanced until bone is reached. (**b**) The Access Chisel tip is lowered to find and cut the capsule of the joint. (**c**) The Access Chisel is advanced into facet joint

retract Decortication Trephine from the lateral mass before rotating to address the inferior lateral mass. Remove Decortication Trephine by retracting it while maintaining position of the Access Chisel. To establish the working channel, place the Guide Tube over the Access Chisel. Use the Fork Mallet to advance the Guide Tube into the facet joint. Verify Guide Tube placement on both lateral and AP views. Proper and final Guide Tube depth is achieved when the markers are at the entry point of the facet joint on lateral view and the Guide Tube is centered between the medial and lateral borders of the facet joint on AP view (Fig. 11.11). Remove the Access Chisel while maintaining position of the Guide Tube in the facet joint.

Decorticate the Facet Joint

Insert the Decortication Rasp through the Guide Tube and advance using the Fork Mallet until the upper handle of the Decortication Rasp locks with the handle of the Guide Tube (Fig. 11.12). Retract the Decortication Rasp by inserting the screwdriver head of the Fork Mallet into the space between handles and turning. This allows controlled removal of the Decortication Rasp while maintaining the position of the Guide Tube in the facet joint. Turn the Decortication Rasp 180° and advance into the joint. Retract as before using the screwdriver head of the Fork Mallet. Remove the Decortication Rasp and clean off bone and cartilage. Reintroduce the Decortication Rasp and repeat these steps to

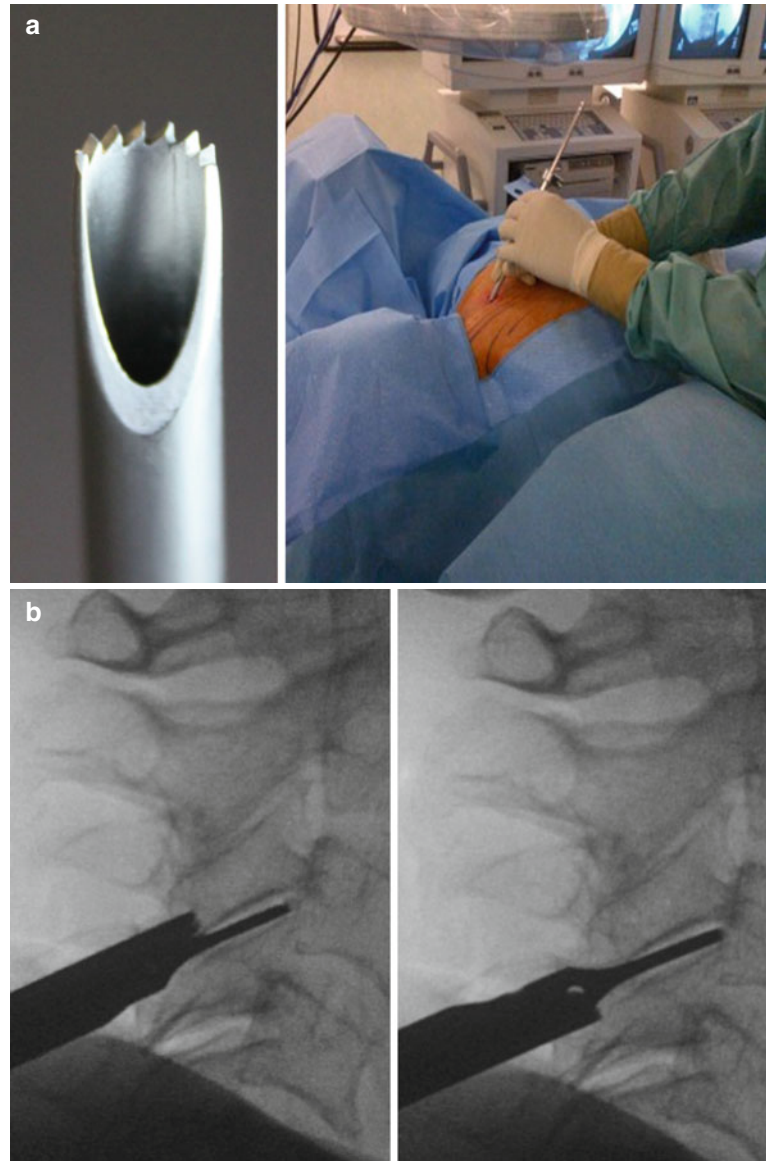


Fig. 11.10 (**a**) Detailed view of the Decortication Trephine, which is advanced over the Access Chisel. (**b**) The Decortication Trephine is advanced over the Access Chisel until the distal tip contacts bone

further decorticate, achieve bleeding of the bone, and remove joint material. Remove the Decortication Rasp one last time while maintaining position of the Guide Tube in the facet joint.

Implant the DTRAX Cervical Cage and Apply Bone Graft Material

Prepare the DTRAX Cervical Cage (Cage) by packing with fusion material. The DTRAX Cervical Cage is preloaded on a delivery instrument. Under AP and lateral fluoroscopic control, advance the DTRAX Cervical Cage Delivery Instrument (Cage Delivery Instrument) into the Guide Tube until its handle locks with the handle of the Guide Tube (Fig. 11.13a). Malleting may be required to fully insert implant and distract target joint. If malleting is needed maintain downward pressure on the Guide Tube to ensure it remains positioned in the facet joint during malleting.

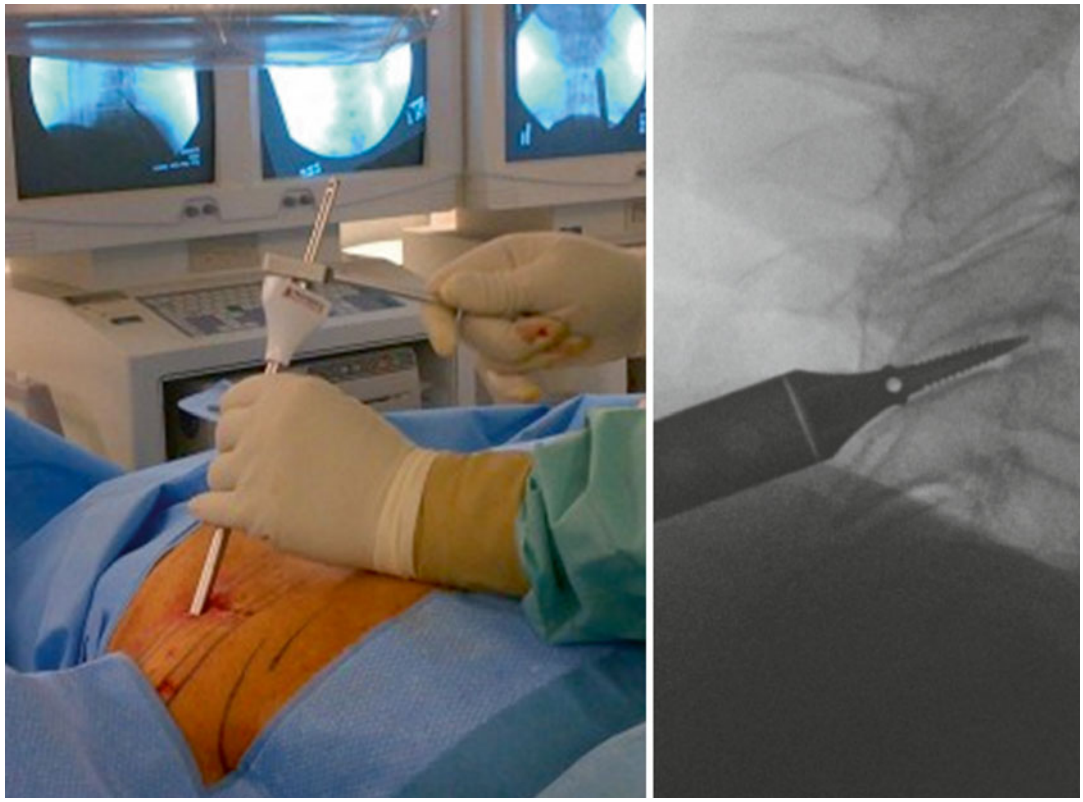


Fig. 11.11 The Guide Tube is advanced into the facet joint using the Fork Mallet

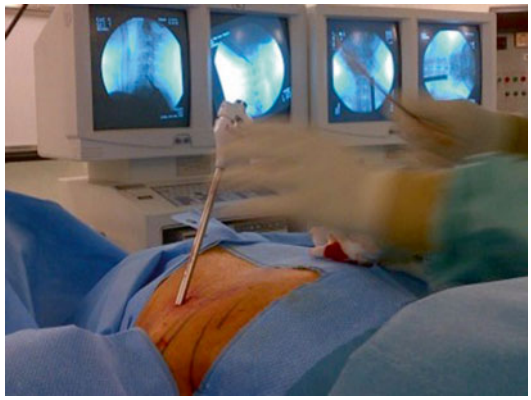


Fig. 11.12 The Decortication Rasp is advanced through the Guide Tube until the upper handle of the Decortication Rasp locks with the handle of the Guide Tube

Use AP & Lateral fluoroscopy to confirm proper placement of the Cage. The Cage should be in the middle of the facet joint, centered between the medial and lateral borders of the facet joint as identified by fluoroscopic views (Fig. 11.13b). Once proper cage position is confirmed, locate the knob on the handle of the Delivery Instrument and turn the knob counter clockwise to release the Cage from the Delivery Instrument. When fully released, the knob will move freely. Remove the Cage Delivery Instrument by inserting the screwdriver head of the Fork Mallet into the space between handles and turning while maintaining position of the Guide Tube. Insert bone graft material such as demineralized bone matrix, into the top of the Guide Tube (Fig. 11.14). Introduce the Bone Graft Tamp into the Guide Tube and advance to push the bone graft material into the prepared bony surfaces, i.e. the decorticated lateral masses. Final control and verification of Cage positioning using AP and lateral fluoroscopy is recommended (Fig. 11.15).

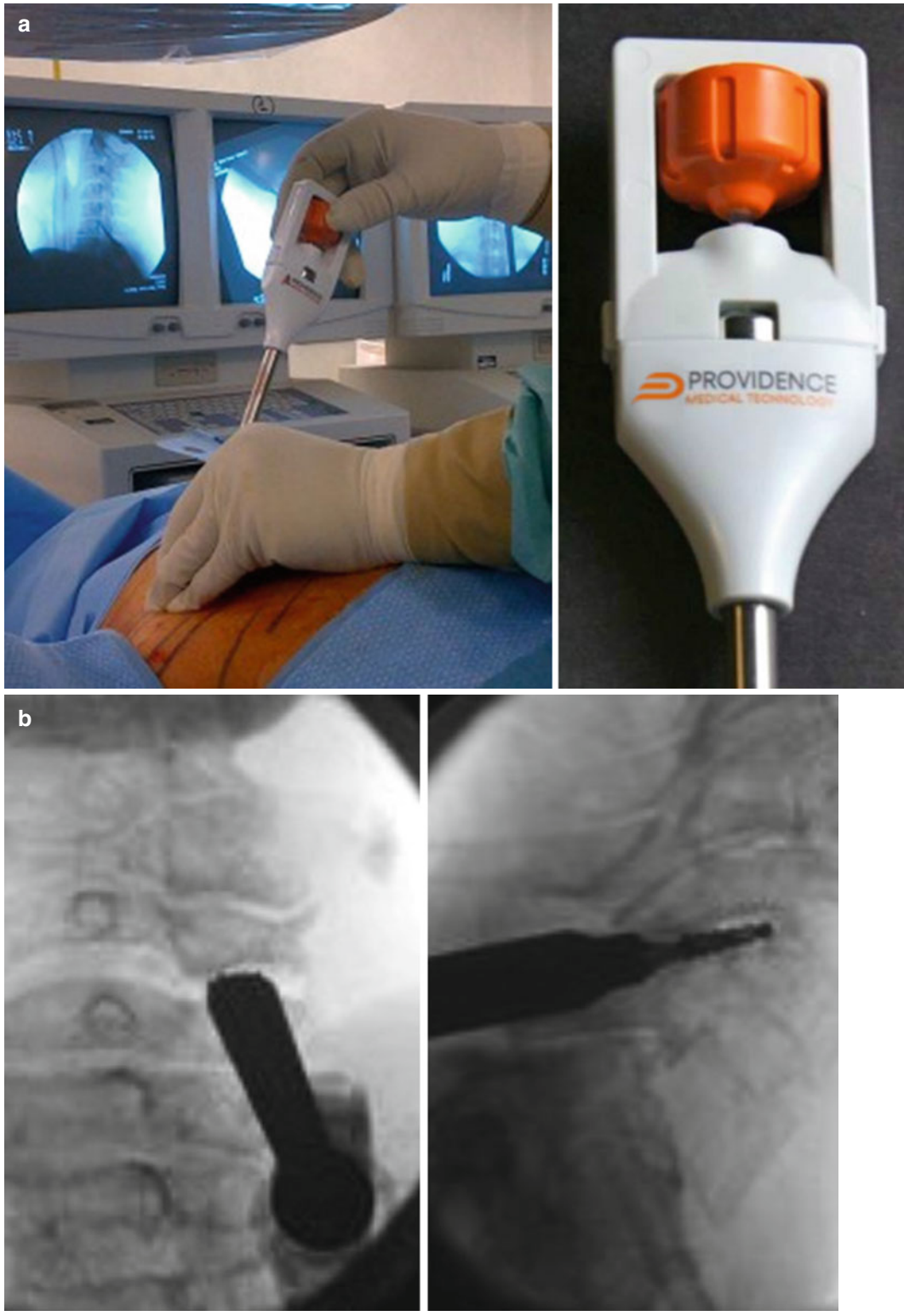


Fig. 11.13 (**a**) The DTRAX Cervical Cage Delivery Instrument is advanced into the Guide Tube until it locks with the handle of the Guide Tube. (**b**) AP & lateral fluoroscopy is used to confirm proper placement of the cage

Sutures, Contralateral Procedure, and Final Patient Preparation

Close the paraspinal muscles, subcutaneous tissues, and skin in layers with sutures. Repeat the full procedure for the contralateral facet joint of the target level. Apply a sterile dressing. Apply external immobilizing collar according to surgeons' post-operative protocol.

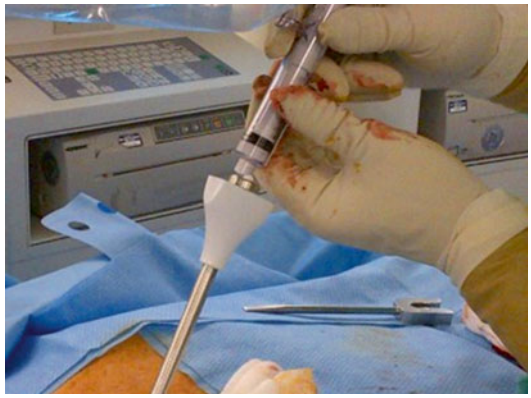


Fig. 11.14 Bone graft material is placed into the top of the Guide Tube

Clinical Evidence for Posterior Cervical Indirect Decompression and Fusion

A prospective, multi-center, single arm clinical study was performed to assess clinical and radiographic outcomes of patients with cervical radiculopathy treated with DTRAX using a tissue sparing indirect decompression and fusion posterior procedure at one level. The patients were followed over a period of 2 years following surgery [27]. The study hypothesis was that indirect root decompression with the DTRAX Expandable Cage would provide clinical relief of radiculopathy in patients with spondylosis with straight or lordotic cervical spines that do not present with symptomatic central canal stenosis necessitating an anterior approach.

Sixty patients were initially enrolled into the study, and 53 of them (88 %) were available at 2-year follow-up. The mean age at the time of surgery was 52.8 years (range: 40–75 years). The treated level was C3–C4 in three patients (5.7 %), C4–C5 in 6 (11.3 %), C5–C6 in 36 (67.9 %) and C6–C7 in 8 patients (15.1 %). A significant decrease was reported in the mean values of Neck Disability Index (NDI) and Visual Analogue

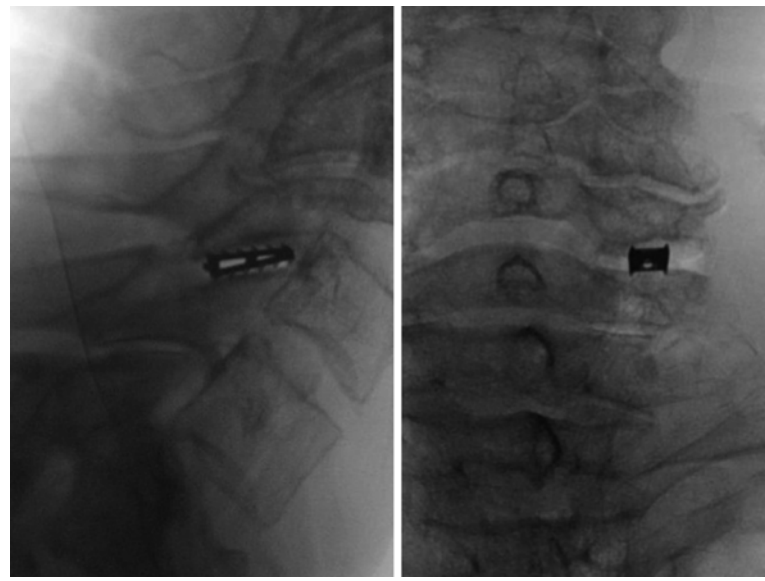


Fig. 11.15 AP and lateral fluoroscopy is used to confirm final cage positioning

Scale (VAS) for the neck and arm pain as well as an increase in SF-12v2 physical and mental scores at each follow-up out to 2 years comparing to the preoperative values. There were no significant differences in clinical outcomes between 1-year and 2-year follow-up.

All patients showed improvement in the NDI when compared to preoperative and this improvement was maintained at 2 years. Of the 53 patients, 2 patients had an increase in arm pain and 2 had an increase in neck and arm pain that was reflected in VAS scores. Three patients had no change in neck pain and one had no change in neck and arm pain scores for VAS.

The most common device-related adverse events were shoulder pain and paresthesia. The most common procedure-related adverse events were postoperative pain, nausea, pain from bone graft harvest site, and shoulder pain. Severe adverse events included shoulder pain, shoulder/elbow weakness, bilateral sciatica, flank pain, mid-back pain, recurrence of neck pain, recurrence of arm pain, and acute exacerbation of osteoarthritis in the knee. No procedure or device-related serious adverse events were noted during the 2-year follow-up. One patient reporting right shoulder pain was noted as a severe adverse event, which was reported as procedure-related. No revision surgeries were reported at the index level or at adjacent levels. Finally, there were no device migrations, expulsions, or breakages at the 2-year follow-up.

The radiographic fusion rate was reported in 52 of 53 patients (98.1 %). Radiographic fusion was defined by less than a 2 mm change in interspinous distance measured on flexion extension radiographs taken at 24 months. The overall change in interspinous distance was 0.78 ± 0.58 mm with a range of 0.04–2.16 mm. Translational motion at the treated level of less than 2 mm were noted for all of the 53 patients. There were no radiographic signs of implant loosening, breakage, migration or screw back-out. CT scans revealed evidence of bridging bone in 93.3 % of patients at 12 months.

Cervical facet distraction implants for indirect decompression for both radiculopathy and myelopathy were previously described by Goel et al. [28]. Goel and colleagues used an open approach to the posterior cervical spine followed by placement of metallic dowels to treat single and multilevel spondylotic disease; they reported excellent results in 25 patients (70 %) with 6-month minimum follow-up. The radiographic fusion rate at 2 years (98.1 %) with this tissue sparing posterior procedure is comparable to fusion rates reported after ACDF [29]. Clinical results suggest that this posterior procedure is able to achieve indirect neural decompression without the need for directly decompressing the involved nerve root. A cadaveric study by Tan and colleagues supports the concept of posterior indirect decompression; they demonstrated an average increase in foraminal area of 18.4 % following placement of an interfacet spacer [30]. Furthermore, Leasure and Buckley recently reported that the rate of indirect foraminal effective distraction from DTRAX was maintained in flexed, extended, and axially rotated postures [31]. Indirect foraminal decompression affords potential advantages, specifically eliminating risks associated with neural manipulation and iatrogenic direct neural injury.

Biomechanical Evidence for Posterior Cervical Indirect Decompression and Fusion

Until recently, the ability of the DTRAX Expandable Cage to effectively decompress the cervical foramen had yet to be proven. The efficacy of this device depends on many factors, including decreased range of motion at the instrumented level, distraction of the affected foramen, and maintenance of its deployment position during repeated bending motion and loading. Ideally the device should perform favorably during each scenario as a stand-alone fixation device and potentially also as part of an anterior-posterior fixation construct.

The previously mentioned study by Leasure and Buckley was conducted to evaluate the

biomechanical efficacy of the DTRAX cervical cage in vitro [31]. Three aspects of device performance were addressed, including acute stabilization, neuroforaminal distraction, and migration of the implant over time due to repeated loading. Stand-alone cervical cage and the cage supplemented with anterior plating were tested. The results of this study indicate that a stand-alone cage substantially increases intervertebral stability, does not loosen within the cervical facet joint during repeated bending loads, and maintains decompression of the cervical nerve roots through extension.

Additionally, the cervical cage successfully increased the neuroforaminal space in 83 % of Leasure and Buckley's observations. Foraminal area was increased by the cage during flexion, extension, axial rotation, lateral bending, and when left in the neutral position. The cage produced bilateral area increases or unilateral area increases with no adverse effects on the contralateral foramen in a majority of the observations. Flexion, extension, and axial rotation all produced successful area increases of the foramen at a rate above 75 %. These results are expected considering flexion motion results in distraction of the foramen even in the intact state. Successful increases in area of the foramen during extension supports the effect of DTRAX's ability to maintain area increases when a decrease would be expected. Lateral bending produced a higher success rate in the cage's ability to open the foramen contralateral to the direction of bending while 50 % of observations were successful in the foramen ipsilateral to the direction of the bend.

Application of circular, metallic, posterior cervical implants and allograft spacers was reported by both Goel et al. and Tan et al., respectively. Neither of the authors reported the effects of the spacers on range of motion and there was no biomechanical testing performed [28, 30]. The authors reported that distraction of the cervical facets can lead to immediate stabilization-fixation of the spinal segment and increase in space for the spinal cord and nerve roots. Goel and Shah noted that stabilization at the fulcrum of cervical spinal movements provided a ground for segmental spinal arthrodesis. They concluded that immediate postoperative improvement and lasting recovery from symptoms suggest the validity of the procedure.

Although bilateral placement of DTRAX implants has been shown to result in a decrease of range of motion at the index level [31], no biomechanical studies have evaluated the biomechanical effects of the implant with the use of an anterior cervical plate construct. This investigation is currently underway by Avinash Patwardhan, Ph.D. and Leonard Voronov, M.D., Ph.D. at the Musculoskeletal Biomechanics Laboratory at Loyola University-Chicago and the Edward Hines Jr VA Hospital.

Conclusion

Current surgical treatment options for cervical radiculopathy remain largely invasive with considerable comorbidities, suggesting a need for less invasive approaches for select patients where conservative management has failed. This chapter introduces a novel, tissue sparing approach for effective treatment of cervical radiculopathy evidenced by clinical outcomes, radiography, and biomechanical analysis. The surgical technique and implant described here present a less invasive option that is successful in achieving indirect decompression of the nerve root and cervical fusion, ultimately providing a clinically significant improvement in patient pain and disability scores.

References

1. Chabot MC, Montgomery DM. The pathophysiology of axial and radicular neck pain. Semin Spine Surg. 1995;7:2–8.
2. Cooper RG, Freemont AJ, Hoyland JA, Jenkins JP, West CG, Illingworth KJ, Jayson MI. Herniated intervertebral disc-associated periradicular fibrosis and vascular abnormalities occur without inflammatory cell infiltration. Spine. 1995;20:591–8.
3. Siemionow K, Klimczak A, Brzezicki G, Siemionow M, McLain RF. The effects of inflammation on glial fibrillary acidic protein expression in satellite cells of the dorsal root ganglion. Spine (Phila Pa 1976). 2009;34(16):1631–7.
4. Radhakrishnan K, Litchy W, O'Fallon W, et al. Epidemiology of cervical radiculopathy. A population-

based study from Rochester, Minnesota, 1976 through 1990. Brain J Neurol. 1994;117(Pt 2):325–35.
5. Salemi G, Savettiere G, Meneghini F, et al. Prevalence of cervical spondylotic radiculopathy: a door-to-door survey in a Sicilian municipality. Acta Neurol Scan. 1996;93(2–3):184–8.
6. Scoville WB, Whitcomb BB. Lateral rupture of cervical intervertebral discs. Postgrad Med. 1966;39:174–80.
7. Frykholm R. Cervical nerve root compression resulting from disc degeneration and root sleeve fibrosis. Acta Chir Scand. 1951;160:1–149.
8. Fessler RG, Khoo LT. Minimally invasive cervical microednoscopic foraminotomy: an initial clinical experience. Neurosurgery. 2002;51 Suppl 2:37–45.
9. Herkowitz H, Kruz L, Overholt D. Surgical management of cervical soft disc herniation: a comparison between the anterior and posterior approach. Spine. 1990;15:1026–30.
10. Russel S, Benjamin V. Posterior surgical approach to the cervical neural foramen for intervertebral disc disease. Neurosurgery. 2004;54:662–6.
11. Adamson TE. Microendoscopic posterior cervical laminoforaminotomy for unilateral radiculopathy: results of a new technique in 100 cases. J Neurosurg. 2001;95(1 Suppl):51–7.
12. Coric D, Adamson T. Minimally invasive cervical microendoscopic laminoforaminotomy. Neurosurg Focus. 2008;25(2):E2.
13. McAnany S, Kim J, Overley S, et al. A meta-analysis of cervical foraminotomy: open versus minimally invasive techniques. Spine J. 2015;15(5):849–56.
14. Kim KT, Kim YB. Comparison between open procedure and tubular retractor assisted procedure for cervical radiculopathy: results of a randomized controlled study. J Korean Med Sci. 2009;24(4):649–53.
15. Ruetten S, Komp M, Merk H, Godolias G. Full-endoscopic cervical posterior foraminotomy for the operation of lateral disc herniations using 5.9-mm endoscopes: a prospective, randomized, controlled study. Spine (Phila Pa 1976). 2008;33:940–8.
16. Chang JC, Park HK, Choi SK. Posterior cervical inclinatory foraminotomy for spondylotic radiculopathy preliminary. J Korean Neurosurg Soc. 2011;49: 308–13.
17. Fehlings MG, Gray RJ, Editorial. Posterior cervical foraminotomy for the treatment of cervical radiculopathy. J Neurosurg Spine. 2009;10:343–6.
18. Choi KC, Ahn Y, Kang BU, Ahn ST, Lee SH. Motor palsy after posterior cervical foraminotomy: anatomical consideration. World Neurosurg. 2013;79(2):405.e1–4.
19. Grochulla F. Anterior cervical discectomy and fusion. In: Vieweg U, Grochulla F, editors. Manual of spine surgery. Berlin/Heidelberg: Springer; 2012. p. 127–33.
20. Bertagnoli R, Duggal N, Pickett GE, Wigfield CC, Gill SS, Karg A, et al. Cervical total disc replacement. Part two: clinical results. Orthop Clin North Am. 2005;36:355–62.
21. Zechmeister I, Winkler R, Mad P. Artificial total disc replacement versus fusion for the cervical spine: a systematic review. Eur Spine J. 2011;20:177–84.
22. Fountas KN, Kapsalaki EZ, Nikolakakos LG, Smisson HF, Johnston KW, Grigorian AA, et al. Anterior cervical discectomy and fusion associated complications. Spine (Phila Pa 1976). 2007;32:2310–7.
23. Heary RF, Benzel EC, Vaicys C. Single and multiple-single interbody fusion techniques. In: Benzel EC, editor. Spine surgery: techniques, complication avoidance, and management. Philadelphia: Elsevier; 2005. p. 351–62.
24. Riley III LH, Vaccaro AR, Dettori JR, Hashimoto R Post-operative dysphagia in anterior cervical spine surgery. Spine (Phila Pa 1976). 2010;35(9 Suppl)): S76–85.
25. Wenger M, Markwalder TM. Bryan total disc arthroplasty: a replacement disc for cervical disc disease. Med Devices (Auckl). 2010;3:11–24.
26. Russell SM, Benjamin V. Posterior surgical approach to the cervical neural foramen for intervertebral disc disease. Neurosurgery. 2004;54(3):662–5; discussion 665–6.
27. Siemionow, K, Phillips, P, Youssef J, Tyrakowski M, McCormack B. Clinical and radiographic results of indirect decompression and posterior cervical fusion for single level cervical radiculopathy using an expandable implant with 2-year follow up. In: Cervical Spine Research Society annual meeting, Orlando, 4–6 December 2014.
28. Goel A, Shah A. Facetal distraction as treatment for single- and multilevel cervical spondylotic radiculopathy and myelopathy: a preliminary report. J Neurosurg Spine. 2011;14(6):689–96.
29. Fraser J, Härtl R. Anterior approaches to fusion of the cervical spine: a metaanalysis of fusion rates. J Neurosurg Spine. 2007;6(4):298–303.
30. Tan L, Gerard C, Anderson P, Traynelis V. Effect of machined interfacet allograft spacers on cervical foraminal height and area. J Neurosurg Spine. 2014;20(2): 178–82.
31. Leasure J, Buckley J. Biomechanical evaluation of an interfact joint decompression and stabilization system. J Biomech Eng. 2014;136(7):171010.

Lateral Mass Screw Fixation of the Subaxial Cervical Spine

12

Francesco Cacciola and Nicola Di Lorenzo

Background

Efficient instrumented fusion of the cervical spine by means of screw and plate or screw and rod fixation represents a multifaceted and peculiar challenge to the spinal surgeon.

This is determined by a series of conditions that characterize this anatomical segment. On the one hand the cervical spine is the most mobile segment of the spinal column and exposed to a high risk of acceleration trauma, such as in whiplash injuries, as it serves as a carrying pillar for the relatively heavy skull and its contents. On the other hand it is the most delicate segment of the vertebral column with thin bony structures, especially in the posterior segments, and only a relatively small surrounding support structure given by the neck muscles when compared to the remaining spinal sections.

This peculiarity of the cervical spine, where high ranges of movement and potentially high acceleration forces on all three spatial planes encounter a delicate musculoskeletal structure, make a sound fixation in case of congenital or destructive destabilization absolutely mandatory. Being able to perform a 360° cervical spine fusion is therefore of paramount importance for the spinal surgeon who wishes to engage in treating complex cervical spine pathology. Posterior instrumented fixation with lateral mass screws has opened up the path for complex cervical spine surgery delivering the first technique to integrate from the posterior aspect the already further developed anterior approaches being both versatile and biomechanically sound.

Introduction

Lateral mass screw (LMS) fixation of the subaxial cervical spine has gained increasing diffusion in the spinal surgical community over the last two decades, thus integrating the anterior approaches already established for a longer time.

The first description of Roy-Camille using a technique of screw and plate fixation in the posterior cervical spine comes almost exactly 20 years after Orozco Delclos and Llovet Tapies describe an anterior cervical plate in 1970 and this, in turn, comes 15 years after the first description of Smith-Robertson's anterior cervical discectomy and fusion in 1955 [1–3].

It should, however, not be forgotten that the first approaches of fixation of the cervical spine involve the posterior aspect and date as far back as 1891 when Dr. Berthold Earnest Hadra first

F. Cacciola
Department of Neurosurgery, University of Siena, Siena, Italy

N. Di Lorenzo (✉)
Department of Neurosurgery, University of Florence, Florence, Italy
e-mail: dilorenzo@unifi.it

P.P.M. Menchetti (ed.), *Cervical Spine: Minimally Invasive and Open Surgery*,
DOI 10.1007/978-3-319-21608-9_12

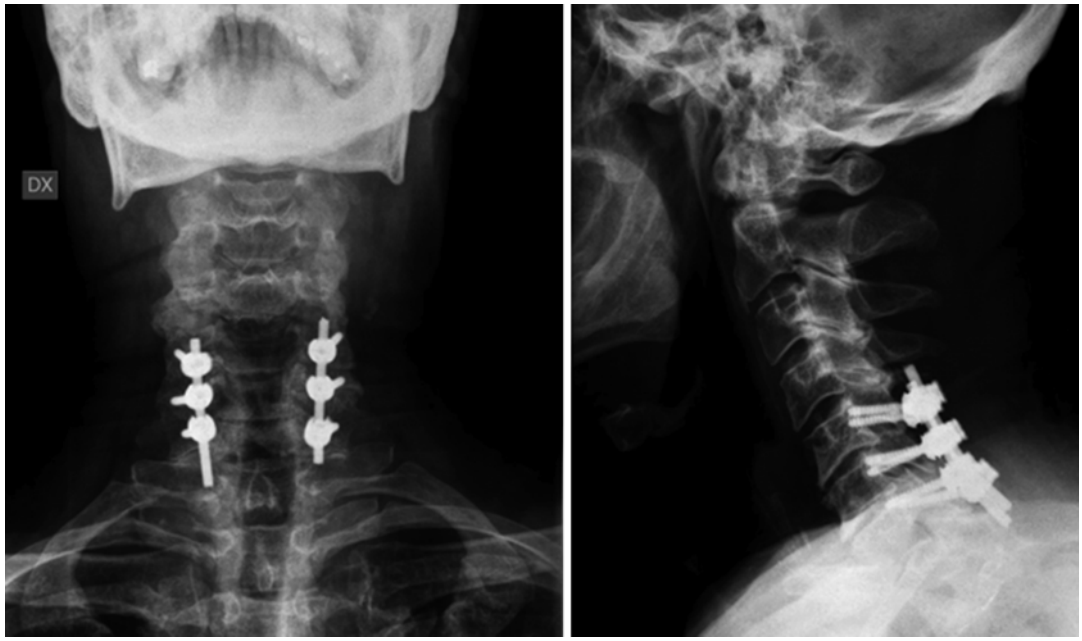


Fig. 12.1 Postoperative cervical spine x-rays in the anteroposterior and lateral projections of a C5–7 LMS fixation

described a wire fixation technique using the spinous processes as anchoring points [4]. During the years the techniques of wiring and placement of hooks evolved having, however, the need for the presence of the posterior elements as a limiting factor in those settings where fixation is needed to integrate a posterior decompression. The absence of spinous processes and laminae makes wiring and hook techniques unfeasible.

With the advent of LMS and plate fixation the presence of the laminae and spinous processes was no longer needed making it therefore a very versatile tool in posterior cervical spine surgery and with the technical improvement of the hardware the possibilities of even complex correction surgeries have clearly evolved (Figs. 12.1 and 12.2).

We will now carry on to describe the surgical technique of the main LMS fixation procedures.

Surgical Techniques

Four techniques of LMS fixation have been more diffusely described and compared.

The original Roy-Camille procedure was modified by Magerl, Anderson and An. While all

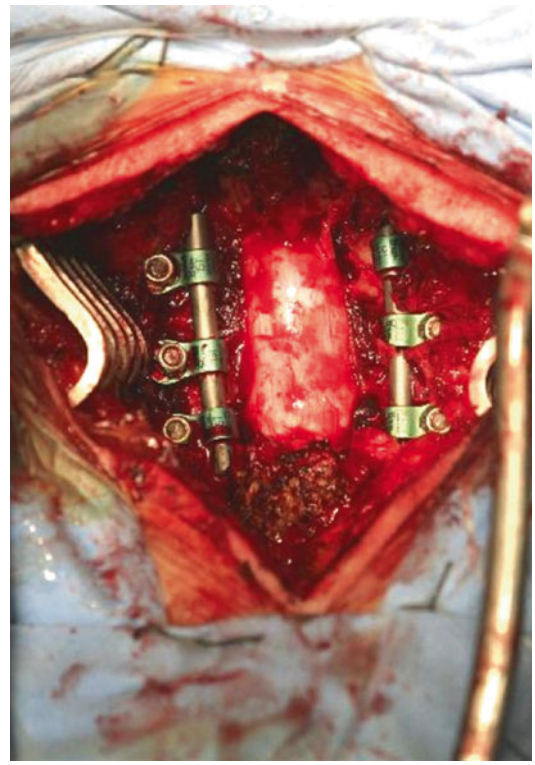


Fig. 12.2 Intraoperative photograph of a three level LMS fixation of the subaxial spine. Note the wide decompression and dural exposure with removal of all posterior elements

four techniques are conceptually the same, involving the placement of a screw in the width of the lateral mass, they differ in the entrance point for screw insertion and in the orientation of screw trajectory.

This is due to the attempt of the various authors to find the ideal combination of maximum screw purchase and minimum risk of injury to the exiting cervical nerve root and the vertebral artery in the transverse process of the cervical vertebra.

Approach to the Posterior Cervical Spine

While the initial exposure of the posterior aspect of the cervical spine is not specific to LMS instrumentation procedures it is worth underlining some peculiar steps from skin incision to muscle dissection that will facilitate the entire procedure.

In approaches to the posterior cervical spine, especially if only a single level fixation is contemplated, it is worth it to plan the skin incision with lateral fluoroscopic control. Particular attention should be paid not only to the rostrocaudal extension of the incision but also to the orientation of the deepening of the incision as muscle dissection proceedes. This will help minimizing the extent of muscle dissection, bleeding and injury to the zygoapophyseal joint capsules not involved in the fusion. Contrarily to pedicle screw insertion techniques, LMS insertion requires a diverging screw trajectory, thus not requiring extensive muscle dissection rostrally and caudally to the instrumented levels for appropriate muscle retraction.

If instrumentation is confined to subaxial levels, attention should be paid not to dissect the rectii capitis and oblique muscles off the posterior aspect of C2 to avoid unnecessary destabilization of the craniocervical junction.

Holding to the midline after incision of the fascia and meticulous dissection of the paraspinal muscles off the spinous processes and laminae can help avoid excessive bleeding often encountered in the posterior cervical spine due to large paraspinal venous plexuses.

Finally, a clean dissection of the levels to be instrumented is mandatory to correctly identify the surgical landmarks which essentially consist in the midpoint of the lateral mass on its posterior aspect. Inferior, superior and lateral confines of the lateral mass to be instrumented should thus be clearly identified.

Once the midpoint of the lateral mass is identified, the four techniques proceed according to their specific indications.

Roy-Camille

The entry point for screw positioning is exactly in the center of the posterior surface of the lateral mass. On the sagittal plane the trajectory is obtained by aiming anteriorly with an inclination perpendicular to the posterior surface and on the axial plane by aiming laterally at 10° degrees (Fig. 12.3).

Magerl

The entry point is 2 mm medial and 2 mm superior to the center of the posterior facet of the lateral mass. On the sagittal plane the trajectory is oriented cephalad at an angle so as to parallel the joint space and on the axial plane it goes laterally at an angle of 25–30° (Fig. 12.4). In this technique, given that the cephalad orientation on the sagittal plane parallels the facet joint, this landmark can be used in two ways to help guiding screw insertion: a thin straight dissector can be inserted into the joint space between two levels that need to be instrumented, thus guiding orientation, or lateral fluoroscopy can be used to plan the trajectoy, paralleling the cephalad and caudad facet joints.

An

The entry point is two mm medial to the midpoint of the lateral mass at the same height. On the sagittal plane the trajectory is oriented 15° cephalad and on the axial plane 30° laterally (Fig. 12.5).

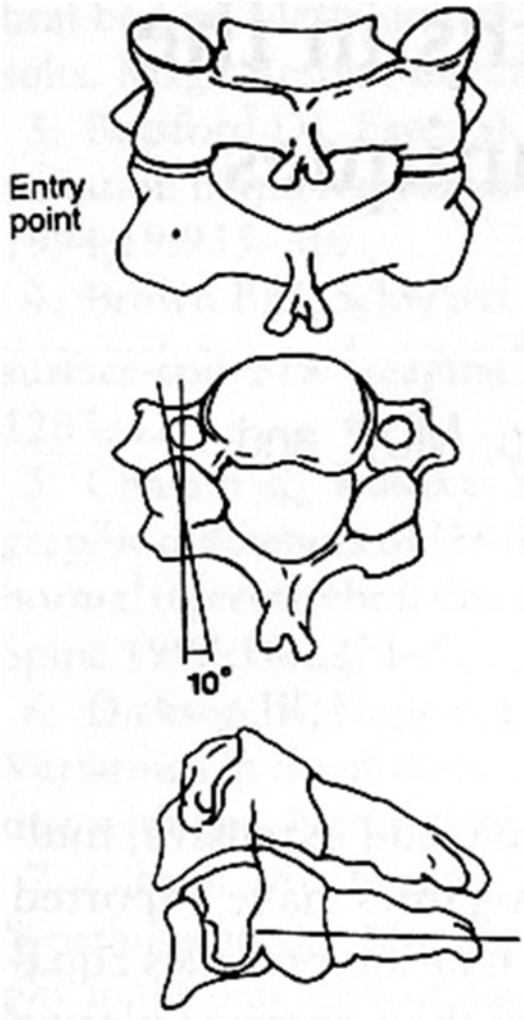


Fig. 12.3 Schematic drawing of cervical vertebrae depicting on top a view from behind. Note the entry point at the center of the dorsal aspect of the lateral mass (Ebraheim et al. [5]. Reprinted with permission)

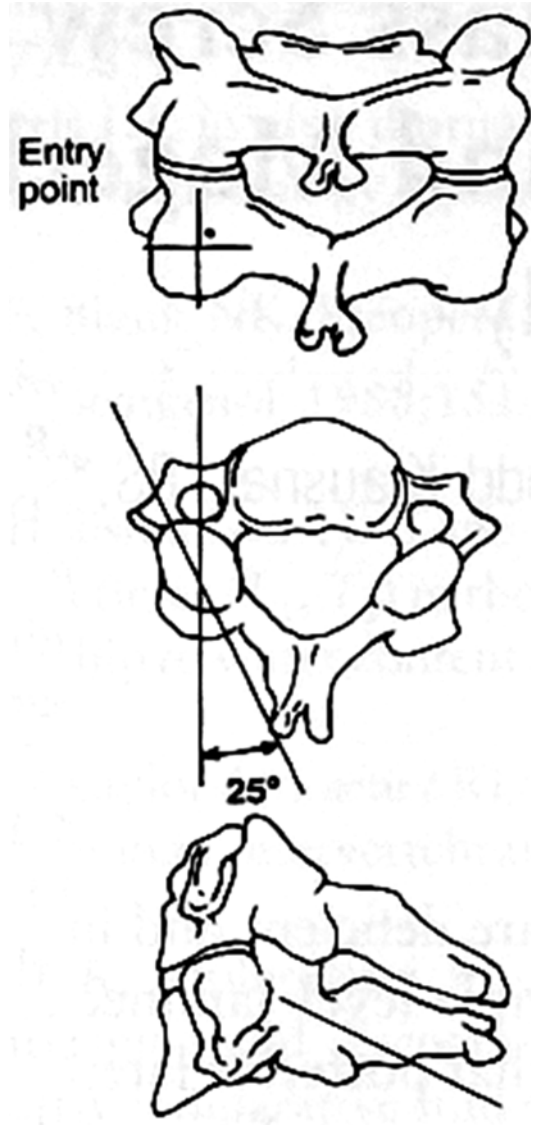


Fig. 12.4 Schematic drawing of the Magerl technique. Note that the entry point is slightly medial and cranial with respect to the center point (Ebraheim et al. [5]. Reprinted with permission)

Anderson

The entry point is again two mm medial to the midpoint of the lateral mass at the same height. On the sagittal plane the trajectory is oriented 30–40° cephaladly and on the axial plane 10° laterally (Fig. 12.6).

Once the trajectories have been made according to one or the other technique, as far as screw diameter and length are concerned, nowadays most manufacturers have a cervical instrumentation kit in their program and standard screw diameter is 3.5 mm with a rod of the same measure. In terms of screw length, as we will see in the next section, bicortical purchase should be obtained in order to achieve the highest biomechanical resistance of the implant. Average screw length, based on anatomical studies, is around 15 mm from dorsal to ventral cortex but this is just an indicative value.

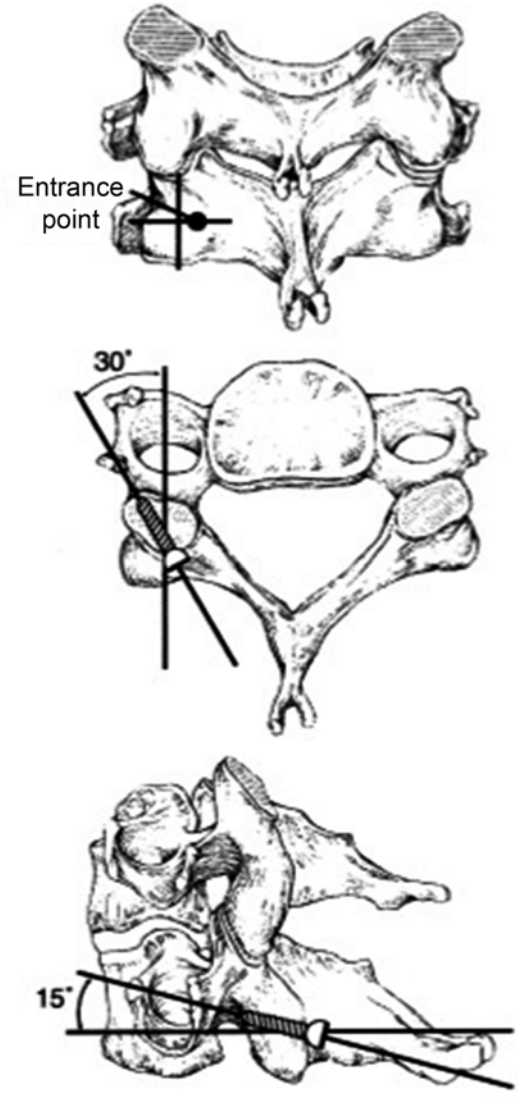


Fig. 12.5 Schematic drawing of the An technique. The entry point is slightly medial and at the same level of the center point (Xu et al. [8]. Reprinted with permission)

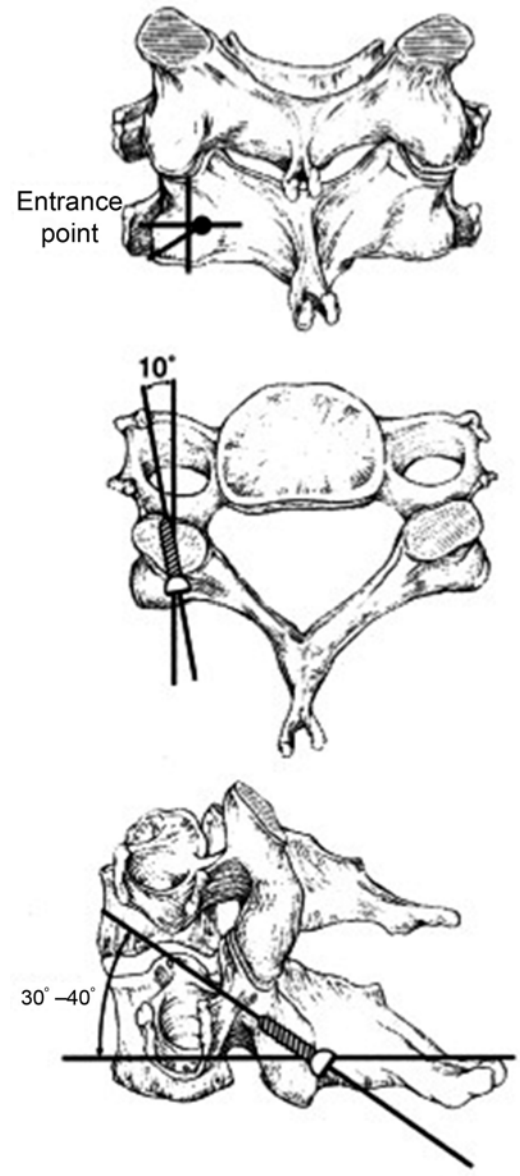


Fig. 12.6 Schematic drawing of the Anderson technique. The entry point is the same as for the An technique (Xu et al. [8]. Reprinted with permission)

Actual screw length is case specific and the authors suggest the use of a fine tip ball probe to explore the screw hole once probed. With some experience it can be quite reliably felt when the ball tip exits the breached ventral cortex and the position of the probe is then held just at that point while a small Mosquito clamp is attached to the probe flush with the dorsal cortex. Once retracted the distance between the Mosquito and the ball tip is then measured and this quite reliably gives an indication for the actual screw length. Some manufacturers offer specific depth gauges in their instrument kits to perform these measurements.

In any case it is important not to overpenetrate the ventral cortex too much as we will see in the next section.

Comparison of the Four Techniques

Among the four techniques illustrated, the Magerl technique seems to have gained the widest diffusion in the literature describing case series. This is most likely due to the fact that the cephalad orientation on the sagittal plane is indicated as having to be parallel to the joint spaces. This obviously furnishes the surgeon with a precise landmark, at least on this plane, that can be reliably identified either by insertion of a dissector into the joint space or by fluoroscopy as outlined above (Fig. 12.7).

While identification of the inclination on the sagittal plane is quite straightforward also in the Roy-Camille technique, where it should be oriented perpendicularly to the posterior plane of the lateral mass, on the axial plane the inclination of 25–30° in Magerl's technique probably gives surgeons more confidence in knowing to avoid transverse foramen breaching and thus potential vertebral artery injury with respect to the 10° divergence in the Roy-Camille technique even though this inclination was obviously designed to avoid the vertebral artery just as reliably.

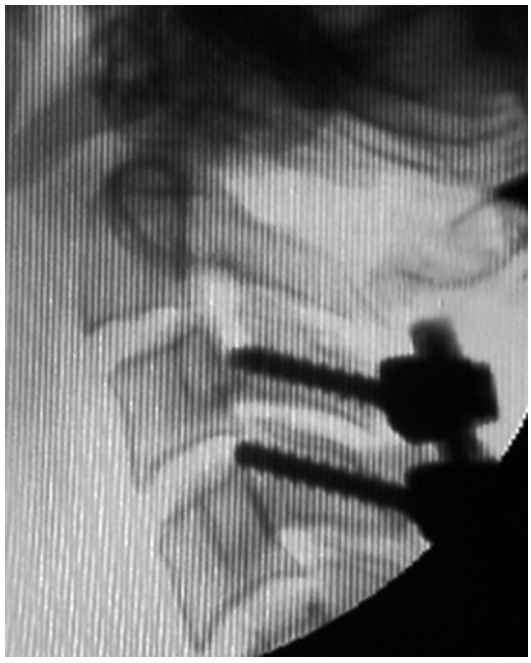


Fig. 12.7 Intraoperative fluoroscopic image of the cervical spine in the lateral projection. LMS fixation of C3-4 according to the Magerl technique. Note the trajectories of the screws parallel to the joint space

Vertebral artery injury does, in fact, not appear to be a concern in the literature, as we will see further ahead, and comparative anatomical studies that compare the safety of LMS techniques have looked at which technique represents the highest risk for nerve root injury.

Ebraheim et al. [5] have carried out an anatomical study comparing the Magerl and Roy-Camille techniques in order to identify maximum screw length and related hazard of injury to the exiting nerve root. In their paper they make the premise that bicortical purchase of the screws yields higher biomechanical stability, as stated in previous studies, and thus examined the location of the nerve root with respect to the screw tip once this has exited the distal cortex. Considering that anatomically, the spinal nerve exiting from the intervertebral foramen courses in an anterolateral and inferior direction and is situated directly in the front of the medial portion of the superior facet and the posterior ridge of the transverse process, they made the following observations: The cervical specimens from their study showed that the spinal nerve lies directly in front of the Roy-Camille screw's trajectory in all specimens. The spinal nerve will therefore be penetrated if the screw is too long, even though the screw's entrance point and trajectory are correct. The mean distance between the ventral or distal cortex of the lateral mass and the spinal nerve along the screw path measured 1.2–2.3 mm.

With the Magerl technique only in 21 % of specimens the nerve root was located in front of the screw's trajectory, although most were located just below the screw's path. Risk of nerve root injury with Magerl's technique was highest in the lower cervical levels.

They therefore conclude suggesting that ideally penetration of the ventral cortex for bicortical purchase should not be higher than 1 mm as this would represent the safety zone in all instances.

Xu et al. [6], of the same group, one year later published another study comparing Magerl's technique with the An and the Anderson technique. In this study, which again is a cadaveric

study, they placed 20 mm screws to overpenetrate the lateral mass on purpose in order to create a nerve root conflict. They then dissected the specimens and established the screw-nerve relationship in particular to the dorsal and ventral ramus.

In their series the overall percentage of nerve violation was significantly higher with the Magerl (95 %) and Anderson (90 %) techniques than with the An (60 %) technique ($P > 0.05$). The largest percentages of nerve violation for the Magerl, Anderson, and An screws were found at the dorsal ramus (50 %), the bifurcation of the ventral dorsal ramus (45 %), and the ventral ramus (55 %), respectively.

They conclude that the results of this study indicate that the potential risk of nerve root violation is higher with the Magerl and Anderson techniques than with the An technique.

While such studies are certainly highly important in order to establish in particular the amount of risk every single technique carries, it has to be kept in mind that they are performed with the use of measuring devices on a cadaver and that the in-vivo conditions generally entail the surgeon estimating the inclination based on his or her experience. Under such conditions a difference of 10° inclination in an angle can easily occur making it thus difficult to effectively differentiate between the techniques and to know whether the intended angulation is effectively being applied.

Pal et al. [7] have carried out a study starting from the assumption that estimation of the angle of inclination during LMS positioning remains arbitrary and would appear to be very much operator dependant.

The aim of their study was to assess how accurately the lateral trajectory angle of 30° is achieved by visual estimation amongst experienced surgeons in a tertiary spinal unit and to determine the likelihood of neurovascular injury during the procedure. They chose an anatomical 'sawbone' model of the cervical spine with simulated lordosis. The senior author marked the entry points. Five spinal consultants and five senior spinal fellows were asked to insert 1.6-mm K wires into the lateral masses of C3 to C6 bilaterally at 30° to the mid- sagittal plane using the marked entry points. The lateral angulation in the transverse plane was measured using a custom protractor and documented for each surgeon at each level and side.

The overall mean angle of insertion was 25.15 (range 20.4–34.8). The overall SD was 4.78.

They concluded that a moderate but notable variability in trajectory placement exists between surgeons during insertion of cervical lateral mass screws. Freehand estimation of 30° appears therefore to not be consistently achieved between surgeons and levels and in patients with gross degenerative or deformed cervical spine anatomy, this may increase the risk of neurovascular injury.

The same group, in a paper of Bayley et al. [8], suggest the use of the ipsilateral lamina as a guidance for determination of the axial angle of insertion. They performed a CT based measuring study to determine whether alignment of the LMS trajectory parallel to the ipsilateral cervical lamina reliably avoids vertebral artery violation in the sub-axial cervical spine. They placed a virtual trajectory through the lateral mass parallel to the ipsilateral lamina and found that in all cases this would avoid vertebral artery injury while delivering a precise landmark that can thus help in determining axial inclination. Limitations of this technique are, however, that the length of lateral mass available for bony purchase ranges from 5 to 7 mm and could in some cases not encounter sufficient bone stock at the C3 and C7 level as, for example, in female patients.

Safety of LMS Techniques

Even though the potential hazards of vertebral artery or nerve root injury in LMS positioning would appear quite obvious, given the vicinity of these structures to the screw path traversing and exiting the lateral mass, the literature available shows quite consistently that it is a safe procedure with small complication rates.

Kim et al. [9] report in a prospective study on the evaluation of 1256 lateral mass screws positioned in 178 consecutive patients at their institution. Their technique, that appears to be a combination of Magerl's and An's in terms of

entry point and inclinations, and is executed "freehand", with only an initial lateral radiograph for level determination, they describe an incidence of foramen transversarium (FT) violation of 0.876 % with, however, no case of vertebral artery injury. FT violation was most common at C6 (6/11 violations). Mean divergent angle in cases of FT violation was 15.0° and was significantly smaller than that of safe cases. They report no violation of an intervertebral foramen and an incidence of facet violation of 1.433 %.

Coe et al. [10] have conducted a systematic literature review to describe the safety profile and effectiveness of LMS fixation. They found twenty articles (two retrospective comparative studies and eighteen case series) that satisfied the inclusion and exclusion criteria.

Both of the comparative studies involved comparison of lateral mass screw fixation with wiring and indicated that the risk of complications was comparable between treatments (range, 0–7.1 % compared with 0–6.3 %, respectively). In one study, the fusion rate reported in the screw fixation group (100 %) was similar to that in the wiring group (97 %). Complication risks following lateral mass screw fixation were low across the 18 case series. Nerve root injury attributed to screw placement occurred in 1.0 % (95 % confidence interval, 0.3–1.6 %) of patients. No cases of vertebral artery injury were reported. Instrumentation complications such as screw or rod pullout, screw or plate breakage, and screw loosening occurred in <1 % of the screws inserted. Fusion was achieved in 97.0 % of patients across nine case series.

They conclude that the risks of complications were low and the fusion rate was high when LMS fixation was used in patients undergoing posterior cervical subaxial fusion.

Conclusions

LMS fixation has changed the face of surgery in the cervical spine. While similar to wiring techniques in terms of complication and fusion rates it is, however, certainly more versatile and thus efficient. This is due to the fact that no posterior elements are needed, therefore enabling the surgeon to associate it with wide compressions or to employ it in case of revision surgeries where a decompression had already been performed [11]. Furthermore, the screw and tulip setup of modern systems delivers the possibility to associate subaxial cervical fixations easily with craniocervical fixations or dorsal fixations via appropriate transition rods or domino connectors due to the modularity that this technique permits with the appropriate systems.

References

1. Roy-Camille R, Saillant G, Mazel C. Internal fixation of the unstable cervical spine by a posterior osteosynthesis with plates and screws. In: Cervical Spine Research Society, editor. The cervical spine. 2nd ed. Philadelphia: JB Lippincott; 1989. p. 90–403.
2. Orozco Delclos R, Llovet Tapies J. Osteosintesis en las fracturas de raquis cervical. Nota de tecnica. Rev Ortop Traumatol. 1970;14:285–8.
3. Robinson RA, Smith GW. Anterolateral cervical disc removal and interbody fusion for cervical disc syndrome. Bull Johns Hopkins Hosp. 1955;96:223–4.
4. Omeis I, DeMattia JA, Hillard VH, Murali R, Das K. History of instrumentation for stabilization of the subaxial cervical spine. Neurosurg Focus. 2004;16(1):1–6.
5. Ebraheim NA, Klausner T, Xu R, Yeasting RA. Safe lateral mass screw lengths in the Roy-Camille and Magerl techniques. Spine. 1998;23(16):1739–42.
6. Xu R, Haman SP, Ebraheim NA, Yeasting RA. The anatomic relation of lateral mass screws to the spinal nerves a comparison of the Magerl, Anderson, and An techniques. Spine. 1999;24(19):2057–61.
7. Pal D, Bayley E, Magaji SA, Boszczyk BM. Freehand determination of the trajectory angle for cervical lateral mass screws: how accurate is it? Eur Spine J. 2011;20:972–6.
8. Bayley E, Zia Z, Kerslake R, Klezl Z, Boszczyk BM. Lamina-guided lateral mass screw placement in the sub-axial cervical spine. Eur Spine J. 2010;19:660–4.
9. Kim HS, Suk KS, Moon SH, Lee HM, Kang KC, Lee SH, Kim JS. Safety evaluation of freehand lateral mass screw fixation in the subaxial cervical spine. Evaluation of 1256 screws. Spine. 2014;40(1):2–5.
10. Coe JD, Vaccaro A, Dailey AT, Skolasky Jr RL, Sasso RC, Ludwig SC, Brodt ED, Dettori JR. Lateral mass screw fixation in the cervical spine a systematic literature review. J Bone Joint Surg Am. 2013;95:2136–43.
11. Song M, Zhang Z, Lu M, Zong J, Dong C, Ma K, Wang S. Four lateral mass screw fixation techniques in lower cervical spine following laminectomy: a finite element analysis study of stress distribution. BioMed Eng Online. 2014;13:115.

Role of Materials in Cervical Spine Fusion

13

Carlo Doria and Massimiliano Gallo

Introduction

Spondylosis is the most common cause of neural dysfunction in the cervical spine. The degenerative changes of ageing typically herniated disc, osteophyte formation and hypertrophied ligament may compress the spinal cord to present symptomatically as neck pain, radiculopathy, myelopathy or radiculo-myelopathy [1]. Anterior cervical discectomy or multilevel somatectomies with fusion are common surgical procedures for patients suffering pain and/or neurological deficits and unresponsive to conservative management [2].

Several authors, including Smith-Robinson [3], Cloward [4], Bailey and Badgley [5], and Simmons and Bhalla [6], have described various methods of anterior cervical fusion. These methods were developed in the 1950s and 1960s and serve as the historical foundation for modern reconstruction techniques. Robinson et al. described the use of a horseshoeshaped tricortical graft removed from the anterior iliac crest; in their technique, the bony endplates are preserved during discectomy and the tricortical graft is impacted into the disc space. Cloward described a technique using a cylindrical drill to create a round hole centered at the disc; fusion was achieved by impacting a slightly oversized cylindrical dowel of bone into the hole. Simmons et al. described the use of a keystoneshaped graft for anterior cervical fusion; the keystone graft was developed to increase graft stability and provide a larger surface area of cancellous bone to enhance bony fusion. Bailey and Badgley described a method of anterior fusion of the cervical spine using a strut of iliac crest bone placed into a trough prepared in the cervical vertebra.

The success of these procedures relie on a thorough decompression and development of a solid osseous fusion [7–9]. For single level discectomy with autogenous bone fusion, anterior cervical discectomy and fusion can achieve a 92–100 % fusion rate [10] and 70–90 % neurologic and symptomatic improvement [11, 12]. However, in multilevel discectomies or somatectomies, the success rate declines as the number of levels increase [13]. In cervical degenerative diseases, the literature supports a consistent rate of 10–12 % non-fusion (pseudoarthrosis) for single level anterior discectomy and autogenous bone fusion, 20–27 % for 2-level, and approximately 30–56 % for 3-level fusions [14, 15]. Non-fusion accounts for 80 % of spinal surgery failures [16]. Graft collapse with autogenous bone is also reported in 20–30 % of multilevel fusion [17]. Even with solid fusion, kyphosis of spinal curve

C. Doria • M. Gallo (✉)
Orthopaedic Department, University of Sassari, Sassari, Italy
e-mail: cdoria@uniss.it; massimilianogallo5@gmail.com

P.P.M. Menchetti (ed.), *Cervical Spine: Minimally Invasive and Open Surgery*,
DOI 10.1007/978-3-319-21608-9_13

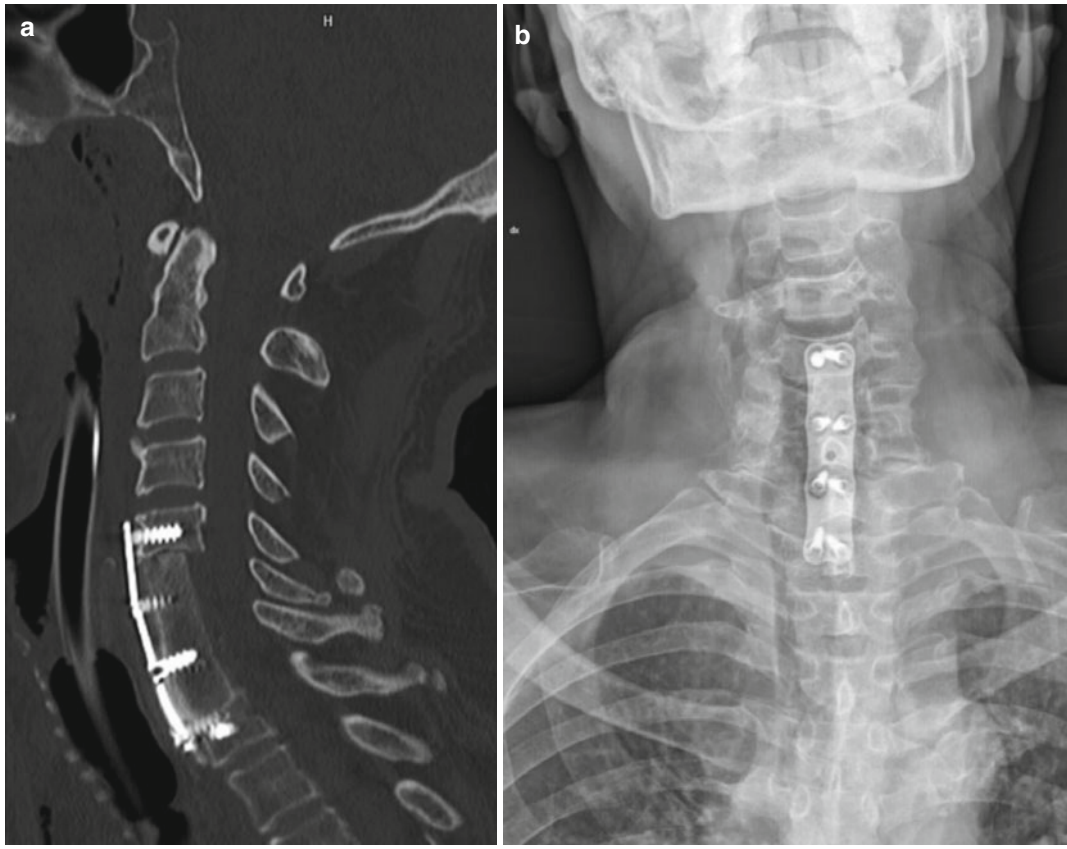


Fig. 13.1 CT scan sagittal view showing C6-C7 somatectomies and tri-cortical iliac strut graft and anterior plating (**a**). Postoperative posteroanterior X-ray view of the same patient (**b**)

often develops in multilevel discectomies with autogenous iliac crest graft fusion [18, 19]. Cervical plate fixation may decrease the micromovement of the cervical spine, enhance the fusion rate, and correct spinal curve to physiologic lordosis (Fig. 13.1a, b) [20]. Plate complication rate varied from 2.2 to 24 % and included screw pullout and breakage [21, 22], injury of laryngeal nerve [23], injury of esophagus, injury of spinal cord or root, injury of vertebral artery, and wound infection [24, 25].

Bone graft in anterior cervical surgery is used to achieve several goals. Structural grafts are used to reconstruct anterior column defects and restore the load-bearing capacity of the cervical spine. Bone grafts may be shaped to restore the normal lordotic posture of the cervical segment. Bone graft also performs a biologic role in promoting a bony fusion, which spans the spinal defect and achieves long-term stability. To be successful, bone grafts must be able to fulfill successfully the dual role of providing structural support and achieving a solid fusion [26].

Various materials have been used for interbody grafts in anterior cervical fusion [27]. To supplement the bone graft, a number of fusion devices have been developed over the past decades for stand-alone use or in conjunction with anterior or posterior instrumentation (Fig. 13.2a, b).

Cervical Spinal Devices

The objective of these spinal devices is to immobilize the unstable degenerated motion segment so that bony fusion can occur. Currently three types of spinal fusion devices are available:

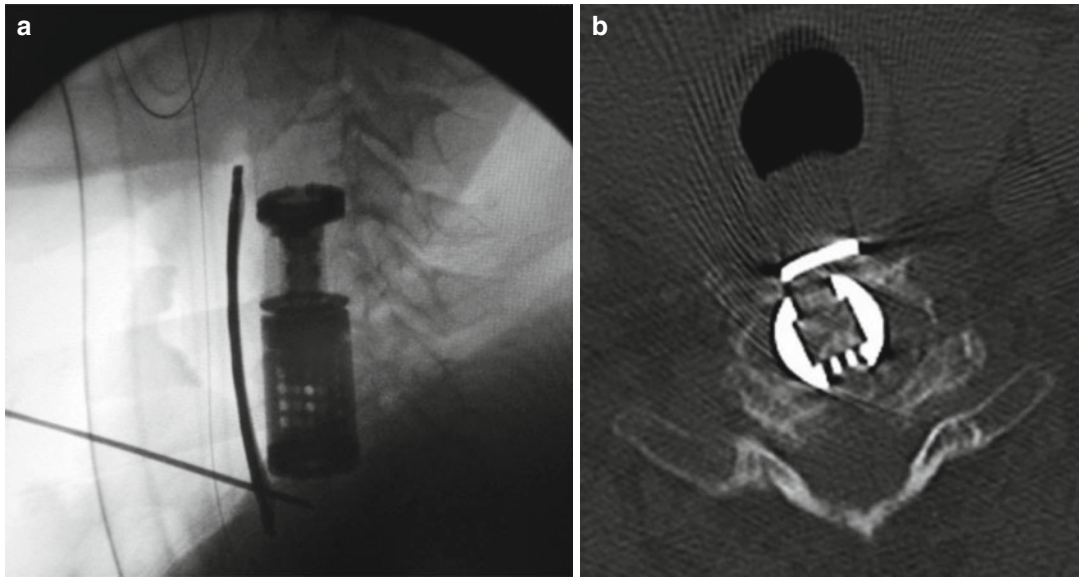


Fig. 13.2 Intraoperative X-ray image showing anterior plating after multilevel somatectomies and positioning of expandable vertebral bodies substitute (**a**). CT scan axial view showing mature bony trabeculae inside the expandable device of the same patient (**b**)

Fig. 13.3 Intraoperative picture showing expandable vertebral bodies substitute inserted into the corpectomy defects

horizontal cylinders, vertical rings and open box cages (Fig. 13.3). We evaluated different fusion material devices: carbon fiber, polyetheretherketone (PEEK) and titanium [14, 28, 29].

Carbon fiber implants seem to present better osteointegration in comparison to metallic materials. The elasticity of carbon fiber implants, almost equal to that of cortical bone, reduces the so-called phenomenon of "stress protection." In other words, it allows distribution of the physiologic load to the bone graft inside the implant, thus stimulating bone formation and improving the quality of fusion [30, 31] with less involvement of stress the adjacent vertebral segments. The advantages are obvious: radiolucency to assess fusion, a more compatible modulus of elasticity compared to titanium, and the ability for precision design and mass production. Potential drawbacks include fracture as a standalone device without anterior plating or a reactive inflammatory response to carbon [32]. Carbon debris does not seem to be problematic with the interbody space, as it is not exposed to a synovial joint. Carbon can fracture with loading, so it remains unclear as to the requirement of an additional anterior osteosynthetic support structure, such as a plate [33].

PEEK is a semi-crystalline polyaromatic linear polymer having a good combination of strength, stiffness, toughness and environmental resistance. PEEK cages are biologically inert and have high versatility and out-standing mechanical properties, including high strength in all

directional planes, elasticity close to that of bone, impact and fatigue resistance [34]. In addition, PEEK is radiolucent, allowing a better radiographic assessment of bone fusion than titanium; the position of the cage can be assessed by radiopaque lines incorporated within the cage. Even if the data are still limited, PEEK cages seem to be MRI and CT compatible and cause no relevant artifacts that would reduce the clarity of imaging. Moreover, PEEK cages do not induce a corrosive reaction to contiguous vertebral bodies and show excellent properties at pull-out and mechanical compression tests [35]. Bone grows in response to applied stress and will be reabsorbed if a mechanical stimulus is lacking. Thus, stress shielding due to a high elastic mismatch between implant and bone can detrimentally influence bone growth, resulting in cortical thinning. In accordance with Williams et al. [36], these phenomena can be avoided by using cages made by pure PEEK possessing an elastic modulus close to that of bone grafting material.

The list of titanium benefits is lengthy. This makes it incredibly useful for a number of different industries, including the automotive, aerospace and architectural worlds. But because titanium resists corrosion, is biocompatible and has an innate ability to join with human bone, it has become a staple of the medical field, as well. From surgical titanium instruments to orthopedic rods, cages, mesh, pins and plates, medical titanium has truly become the fundamental material used in medicine. Titanium Ti 6Al–4 V and Ti 6Al–4 V ELI, alloys made of 6 % Aluminum and 4 % Vanadium, are the most common types of titanium used in medicine. Benefits of medical titanium are: strong, lightweight, corrosion resistant, cost-efficient, non-toxic, biocompatible (non-toxic and not rejected by the body), long-lasting, non-ferromagnetic, osseointegrated (the joining of bone with artificial implant), long range availability, flexibility and elasticity rivals that of human bone. Two of the greatest benefits of titanium are its high strength-to-weight ratio and its corrosion resistance. Couple this with its non-toxic state and its ability to fight all corrosion from bodily fluids and it's no wonder titanium has become the metal of choice within the field of medicine.

Use of different devices (cages, mesh, plates) can help to get a primary mechanical stability of the segment operated but the fusion processes, which can't ignore the stability worth the evolution in non-union, have as main actor bone graft whether autologous, eterologous, synthetic bone graft substitute or factor and cell–based approaches for bone graft substitutes.

Bone Grafts

Autograft

Cortico-cancellous bone harvested from the iliac crest is widely used for the cervical spine (Fig. 13.4). A systematic review of the literature reported autograft to have a mean arthrodesis rate of 77 % [26]. In one-level non-instrumented procedures, autograft fusion rates are a reported 83–99 % [37], but decreases with number of levels fused [38]. Autograft experiences relatively few incidences of graft complication, such as graft collapse or migration, and is biocompatible, poses no risk of disease transmission and is non-immunogenic [39]. For these reasons, autograft remains the standard of care for cervical spinal fusion. Unfortunately, the stipulation of a second

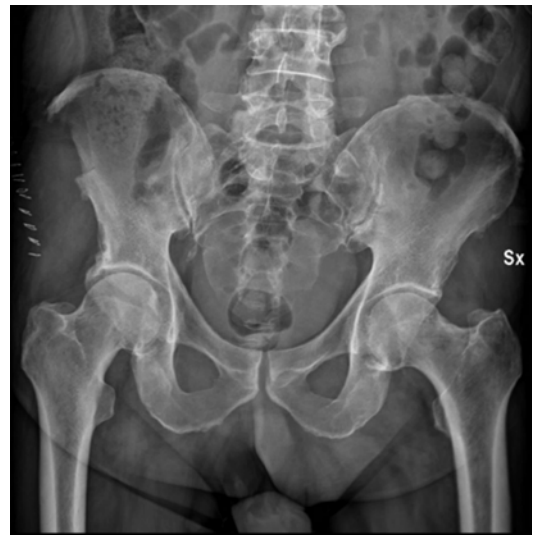


Fig. 13.4 Posteroanterior X-ray of pelvis after the harvest of tri-cortical iliac strut graft on the right side

surgical site not only increases operative time and blood loss but introduces significant donor site morbidity. Although the risk of harvest site morbidity has been suggested to be overstated, it is generally accepted within the literature to be of significant concern [40]. A retrospective study of one-level anterior cervical fusion found 26.1 % of patients suffered persistent pain and 15.7 % experienced numbness at the harvest site [41].

Functional assessment revealed impairment in ambulation (12.7 %) and other daily activities. Many other complications have been observed including infection, hematoma, bruising, pelvic fracture, periotoneal perforation, hernia, gait, ureteral injury, reoperation and poor cosmesis [42, 43]. Rawlinson reported 31 % of patients felt donor site pain caused them to remain in hospital longer than if they had not had that procedure [44]. Finally, there are inherent limitations with supply and occasionally, autograft quality. Some authors have investigated the harvest of autograft from alternative locations, such as the fibula [45], cervical vertebrae [46], clavicle [47], and the manubrium [48], so as to retain the advantages of autograft whilst circumventing its associated morbidity, to varying success. Others have explored the effectiveness of iliac crest reconstruction using synthetic materials in alleviating postoperative pain, with mixed results [49, 50].

Allograft

Allograft is the most commonly used non-autogenous grafting material in spinal surgery, and 35 % of all bone transplantations involve the use of human allograft tissues [51]. Mineralized allograft is primarily osteoconductive, with weak osteoinductive capacity and no osteogenic potential because graft cells do not survive processing and transplantation. Allograft used for orthopedic applications is fresh frozen, freeze-dried, or demineralized. The method of preparation has significant effects on graft strength, immunogenicity, capacity for incorporation, and potential for disease transmission. Fresh-frozen allografts retain much of their original mechanical strength, while freeze-drying can reduce graft strength up to 50 % [52]. The freezing process also reduces immunogenicity of allografts [53]. The effect of immunogenicity in compromising graft incorporation may be significant [54–56]. Transmission of disease from donor to recipient is a problem with human allografts. The principle pathogens involved are human immunodeficiency virus (HIV) and hepatitis viruses B and C. The risk of disease transmission is determined by the rigor of screening procedures for donors and tissue, and the only cases of disease transmission in musculoskeletal allografts from the method of graft preparation to date have involved frozen, unprocessed grafts [57]. Tissue processing techniques include high pressure lavage to clear out marrow elements and donor cells and chemical treatments to eliminate viruses and reduce immunogenicity of the graft. The combination of donor screening, tissue testing, and tissue processing reduces the risk of viral transmission to less than one event per million grafts [58]. Allograft is available in many preparations. However, the majority are composed of primarily cancellous or cortical bone. Cortical allografts provide significant mechanical stability and structural support, while cancellous bone lends little mechanical stabilization on implantation but has a faster rate of incorporation. Cancellous allograft and particulate allograft preparations (cancellous or cortical) incorporate with new bone forming on the surfaces of trabeculae, with a large surface area available for new bone formation [54, 59]. In contrast, cortical incorporation occurs slowly via a process of periosteal new bone formation around the allograft as an external callus derived from the host bone [60]. Particulate and structural grafts demonstrate significant differences in the histology of incorporation. Particulate grafts demonstrate more rapid and complete revascularization than structural grafts. Particulate bone remodels completely with time, while cortical bone remains a mixture of necrotic and viable bone. The process of creeping substitution is also differs significantly between these forms of allograft, with new bone formation occurring appositionally followed by resorption in cancellous bone, which process is reversed in cortical allografts [61]. These differences in biologic

capacity between graft types lead to significant differences in optimal clinical applications. The use of bone allografts in the spine has been reviewed previously by the senior author [62]. Structural cortical allografts are most useful in interbody arthrodesis of the lumbar and cervical spine, with low rates of graft tricortical allograft may be as effective as iliac crest in promoting anterior arthrodesis of the spine [63]. Crushed cortical or cancellous allograft may be useful as an autograft extender in posterior spinal fusion. In thoracolumbar deformity, cancellous allograft with instrumentation may give satisfactory results in the pediatric population but yields inferior results in adults. The conclusion from the senior author's experience is that successful use of allograft bone in the spine is dependent on the type of allograft bone used, the anatomic site of fusion, and patient age. A review of other clinical applications of allograft compared with autogenous bone in spinal surgery is useful. In cervical spine, the use of allograft vs autograft has been debated since the first anterior discectomies and interbody fusions. Smith and Robinson used autogenous iliac crest graft and reported radiographic union in 18/21 patients [64]. Concurrently, Cloward reported resorption of only 3/46 grafts using his dowel technique with fresh-frozen allograft [4]. More recent reviews demonstrated similar fusion rates using autogenous and allogenous grafts in single level cervical surgery but significant differences in multilevel cervical fusions [65, 66]. In posterolateral arthrodesis of the lumbar spine, differences in function between allograft and autograft are more significant. In a prospective comparison of autograft and allograft preparations in posterolateral arthrodesis of the spine, differences in fusion mass were radiographically clearly apparent, reliable arthrodesis being achieved with autograft, followed by mixed autograft and allograft, and frozen allograft, and the least reliable graft material was freeze-dried allograft [67]. Similarly, a prospective evaluation of mineralized and demineralized allograft mixed with autogenous bone radiographically demonstrated fusion inferior to that from posterolateral arthrodesis with iliac autograft [68].

Synthetic Bone Graft Substitutes

There are four characteristics that an ideal bone graft material should exhibit which include [69]:

I. osteointegration, the ability to chemically bond to the surface of bone without an intervening layer of fibrous tissue;
II. osteoconduction, the ability to support the growth of bone over its surface.;
III. osteoinduction, the ability to induce differentiation of pluripotential stem cells from surrounding tissue to an osteoblastic phenotype; and
IV. osteogenesis, the formation of new bone by osteoblastic cells present within the graft material.

Only autogenous bone graft satisfies all of these requirements. Allograft is osteointegrative and osteoconductive and may exhibit osteoinductive potential, but it is not osteogenic because it contains no live cellular component. Synthetic bone graft substitutes currently possess only osteointegrative and osteoconductive properties. Ideally synthetic bone graft substitutes should be biocompatible, show minimal fibrotic reaction, undergo remodelling and support new bone formation. From a mechanical point of view synthetic bone graft substitutes should have a similar strength to that of the cortical/cancellous bone being replaced. This needs to be matched with a similar modulus of elasticity to that of bone in an attempt to prevent stress shielding as well as maintaining adequate toughness to prevent fatigue fracture under cyclic loading. Synthetic materials that demonstrate some of these properties are composed of either calcium, silicon or aluminium [70].

Calcium Phosphate

The calcium phosphate family of synthetic bone grafts has both osteointegrative and osteoconductive properties. Osteointegration results from the formation of a layer of HA shortly after

implantation. The Ca^{2+} and PO_4^{2-} ions required to establish this layer are derived from the implant and surrounding bone. The pathways of both Ca^{2+} and PO_4^{2-} ions have been traced in serum and urine without any significant elevation in serum levels from which it can be concluded they are handled as part of the normal body ion pool. They have an excellent record of biocompatibility with no reports of systemic toxicity or foreign body reactions [71].

Beta Tricalcium Phosphate

Beta tricalcium phosphate (βTCP) was one of the earliest calcium phosphate compounds to be used as a bone graft substitute. In 1920 Albee and Morrison reported that the rate of bone union was increased when βTCP was injected into the gap of a segmental bone defect [72]. Beta tricalcium phosphate is available in porous or solid form as either granules or blocks. Structurally porous βTCP has a compressive strength and tensile strength similar to cancellous bone [73]. Like other calcium phosphate preparations it has been found to be brittle and weak under tension and shear, but resistant to compressive loads [74].

Typically it has been used in its granular porous form. Porous granules tend to migrate less than solid granules due to earlier fixation by fibrovascular ingrowth [75]. Beta tricalcium phosphate undergoes reabsorption via dissolution and fragmentation over a 6–18-month period. Unfortunately the replacement of βTCP by bone does not occur in an equitable way. That is, there is always less bone volume produced than the volume of βTCP reabsorbed [76]. For this reason the clinical use of βTCP has been as an adjunctive with other less reabsorbable bone graft substitutes or as an expander for autogenous bone graft.

Hydroxyapatite (HA)

The chemico-physical characteristics of the HA graft allow to induce a rapid and complete interbody fusion but also restore the physiological lordosis and maintain the intervertebral and foraminal height [77]. The HA ceramics are composed of hydroxylized calcium phosphate and are chemically identical to natural HA of bone. The process of mixing these materials leads to porous ceramics with high osteoconductive properties. The graft can be invaded by newly formed bone that grows directly into the pores [78]. Unlike other synthetic grafts, however, there is no interposition of fibrous tissue between implant and bone [73]. In experimental studies and, in particular, those in which electron microscopy observations are made, the authors have demonstrated the bioactive properties of HA grafts and their apparent ability to be directly bonded to bone, reproducing the natural bone-cementing mechanism [79].

Unlike autografts and allografts, HA is not amenable to absorption by the host cells. Resorption of HA is very limited in both cell and solution-mediated processes, in contrast to tricalcium phosphate compounds, which are rapidly resorbed [80]. Preliminary clinical results were published in 1986 by Koyama and Handa [81] and then by Senter et al. [82] in 1989 and by Böker et al. [83] in 1993. These studies report the use of the HA graft combined with plate placement and demonstrated that this graft material is very effective in inducing cervical interbody fusion. The first step of fusion was always a remodeling of the bone–graft interface. Progressively, a bone bridge appeared around the graft, mainly posteriorly, and enlarged until total incorporation of the graft occurred.

Coralline Hydroxyapatite

Coralline-derived hydroxyapatite is manufactured from the Porites and Goniopora species of sea coral by the hydrothermal chemical conversion of calcium carbonate to hydroxyapatite [84]. These two products have porous microstructures similar to human cortical and cancellous bone [85]. Zdeblick et al. [86] reported the results of cervical interbody fusion in a dog model using coralline-

derived hydroxyapatite. In the non-instrumented group, fewer than half the grafts incorporated, 14 % extruded, and 29 % collapsed. Extrusion was eliminated, and the fusion rate increased to 71 % with non-rigid anterior plating. However, graft collapse was reduced to only 24 %. In a retrospective study Thalgott et al. [87] reported the results of cervical interbody fusion in 26 patients using the same implants associated with rigid anterior cervical plating. At the 2-year follow-up assessment, there was an average of 75.8 % reduction in pain, and 100 % of the grafts were reported as incorporated on radiograph evaluation. Thalgott et al. concluded that coralline-derived hydroxyapatite is a promising material for bone replacement in the cervical spine and suggested that future studies should compare this new material with autograft in prospective randomized trials. In a prospective randomized trial McConnell et al. [88] demonstrated a high rate of radiographic fragmentation, collapse, and loss of alignment of the coralline-derived hydroxyapatite that appears structurally inferior to iliac crest bone for cervical interbody fusion.

Bioactive Glasses

Bioactive glass composites are currently being trialled for vertebral body prosthesis [89]. Bioactive glasses are hard, solid materials consisting of calcium, phosphorus, and silicondioxide (silicate, the main component). By varying the proportions of sodium oxide, calcium oxide, and silicon dioxide, all range of forms can be produced from soluble to non-resorbable. They possess both osteointegrative and osteoconductive properties. A mechanically strong bond between bioactive glass and bone forms eventually through hydroxyapatite crystals similar to that of bone [90]. They have significantly greater mechanical strength when compared to calcium phosphate preparations, such as ceramic-hydroxyapatite. Bioactive glass blocks resist drilling and shaping, however, and they may fracture in the process. As a consequence they are difficult to fix to the skeleton. They have been successfully used as a bone graft expander [91, 92].

"Bioactive-ceramics", a new variation, are stronger than bioactive glass with improved mechanical properties. However, both are relatively brittle and prone to fracture with cyclic loading. To improve the fracture toughness, of bioactive glasses and bioactive ceramics, two methods have been employed. Incorporation of stainless steel fibres into bioglass increased bending strength, and incorporation of ceramic particles (zirconia) into apatite-wollastonite glass ceramic increased bending strength and toughness [93].

Factor and Cell–based Approaches for Bone Graft Substitutes

Emerging adjuvant therapies have allowed surgeons the option of composite bone grafts. The addition of an osteoinductive and/or osteogenic substance provides theoretical benefits when combined with an osteoconductive substrate. The most potent and promising of these adjuvants are the highly osteoinductive bone morphogenetic proteins (BMPs), discovered by Urist in 1965 following his observation of bone growth from animal demineralized bone matrix. Human BMPs may now be produced through recombinant techniques and produced on a large scale. Of interest in the cervical spine is the recombinant human BMP-2 (rhBMP-2) which has been the focus of a number of human clinical studies. Less expensive alternatives include bone marrow aspirate (BMA) taken from the iliac crest and platelet rich plasma (PRP) [94].

Bone Morphogenetic Proteins (BMPs)

BMPs have shown considerable promise in the human lumbar spine [95] and in animal models of anterior cervical fusion [96]. Recently, a number of clinical studies have focused on its appropriateness in the human cervical spine, with consistently reported fusion rates of 100 % [97]. Baskin et al. conducted the first prospective randomized controlled trial for anterior cervical interbody fusion, comparing recombinant human

BMP-2 with iliac crest autograft, both placed within a fibula allograft and supplemented with anterior plating [98]. All 33 patients from both groups were fused by 6 months. At 24 months, the rhBMP-2 group had significantly better improvement in neck ($P < 0.03$) and arm ($P < 0.03$) pain than autograft, had no complications attributable to rhBMP, and had avoided statistically significant pain ($P < 0.007$) from the harvest site at 6 weeks. Boakye et al. in a retrospective review of 23 patients with one- to three-level procedures similarly found 1.05 mg/level of rhBMP-2 in PEEK cages induced solid fusion with good clinical outcomes and no significant morbidity [99]. However ectopic bone formation was observed to occur in three patients who were early on in the series and had received twice that amount. However, many authors have elucidated the need for caution when using rhBMPs in the cervical area. Smucker et al. performed a multivariate analysis and found patients receiving rhBMP-2 to have a 10.1-fold increase in risk for swelling complication compared to those that did not receive rhBMP-2 [100]. In a retrospective review of 151 patients undergoing anterior cervical fusion using rhBMP-2 with plating, Shields et al. found 23.2 % had suffered complications including hematoma, swelling, dysphagia, and increased hospital stay [101]. The authors noted their three-and-a-halffold dose of bone morphogenetic protein (2.1 mg BMP/level) compared to Baskin et al. (0.6 mg/level) as a possible reason, perhaps causing an excessive inflammatory response in the initial phase of bone healing. Tumialan et al. noted a decrease in dysphagia with a dosage reduction from 2.1 mg/level down to 0.7 mg/level, and from multilevel compared to single-level procedures [102]. In a prospective non-randomized study Buttermann compared BMP-2 with allograft against iliac crest autograft in anterior cervical discectomy with fusion. Using 0.9 mg BMP/level he found that although both groups demonstrated similar clinical improvements, 50 % of the BMP group suffered dysphagia caused by neck swelling compared to 14 % autograft. In a letter, Dickerman et al. reported clinical success with a dose of 1.05 mg/level insulated by a DBM putty and delivered in PEEK cages, as these measures provide containment of the BMPs [103]. In a study that contained rhBMP-2 using thrombin glue and bioabsorbable spacers, no graft-related complications occurred [104]. Vaidya et al. reviewed the cases of 22 patients who received 1 mg rhBMP-2/level contained in polyetheretherketone (PEEK) cages and 24 patients who received allograft spacer with demineralized bone matrix. BMP performed well radiographically with probable fusion in 100 % of patients at 12 months. Allograft attained similar results. BMP had statistically significant dysphagia associated with anterior swelling, with severity observed to be dose-dependent. Compared to allograft, the BMP procedure was three times more expensive, and so was ceased [105]. In another study by the same lead author, rhBMP-2 with allograft for cervical fusion was ceased despite 100 % fusion, due to a 33 % incidence of graft subsidence [106]. Costs associated with the implementation of BMP for anterior cervical fusion may be prohibitive, however it remains to be seen how cost-effective they are compared to autograft and other alternatives long-term [107]. Further investigation is required in determining the optimal dose and delivery method of BMP for anterior cervical fusion, whether a measurable clinical advantage is produced, and if so, in whom these procedures should be performed.

Bone Marrow Aspirate (BMA)

BMA has been used as part of a composite graft in conjunction with an osteoconductive scaffold held within a mechanical structure for anterior cervical fusion. BM aspiration from the iliac crest causes minimal morbidity while providing osteogenic potential [108]. Due to the scarcity of osteoprogenitor content, selective-retention or culture-expanded cell technology may be employed to maximise osteogenecity, although these add to costs [109]. Khoueir et al. reported on the use of BMA soaked in collagen-hydroxyapatite matrix inside fibula allograft for instrumented multilevel anterior cervical fusion. A total of 81.7 % of patients demonstrated

clinical improvement and 96.8 % had radiographic fusion, with no graft-related complications. Several limitations of this study prevent direct comparison to autograft, however it does suggest BMA to be a safe, potentially efficacious and cheaper alternative to BMP [110].

Platelet Rich Plasma (PRP)

The supplementation of platelet concentrate in grafting is purported to benefit bone healing through provision of osteopromotive growth factors and an osteoconductive fibrin clot meshwork [111]. Feiz-Erfan et al. conducted a double-blinded randomized trial for anterior cervical fusion using instrumented allograft with or without platelet-gel concentrate. Platelet-gel showed no evidence of promoting early fusion and achieved no significant difference in arthrodesis rates at 12 months [112].

Conclusion

There are several acceptable and promising material options for anterior cervical spine fusion. Although many studies have investigated the effectiveness of these substrates, currently, no option is conclusively superior to strut iliac bone autograft combined with rigid anterior plate fixation. Autograft remains the standard of care for anterior cervical spine fusion, allowing a good stability with higher incidence of radiographic fusion rate, near to 100 % and excellent clinical outcomes. For this reason the autograft technique is still considered the gold standard between a high number of materials and techniques in cervical spine fusion. Moreover, the use of autograft avoid the risk of infection, disease transmission, and histocompatibility differences associated with allograft. Allograft is somewhat substandard in comparison to autograft due to increased graft complication and reduced fusion rates, but it's still an acceptable option especially when combined with plating.

Other bone graft substitutes may offer a viable alternative, in fact the use of alternative devices avoids the harvest of strut iliac tri-cortical graft without complications at the bone donor site. Titanium may offer a satisfactory alternative, with good fusion rates and low rate of complications. Ceramics achieve acceptable fusion rates and clinical outcomes at a reasonable price and is thus another acceptable alternative to autograft. Bone morphogenetic proteins (BMPs) are an unrefined graft technology with developing guidelines on dosage and delivery. Although BMPs demonstrate impressive osteoinductive properties, they are currently hindered by significant cost constraints and complications. Other composite bone grafts present theoretical benefits however no consistent algorithm has been proposed.

References

1. Whitecloud 3rd TS. Modern alternatives and techniques for one-level discectomy and fusion. Clin Orthop Relat Res. 1999;359:67–76.
2. Wigfield CC, Nelson RJ. Non-autologous interbody fusion materials in cervical spine surgery: how strong is the evidence to justify their use? Spine. 2001;26:687–94.
3. Robinson RA, et al. The results of anterior interbody fusion of the cervical spine. J Bone Joint Surg Am. 1962;44:1569–87.
4. Cloward RB. The anterior approach for ruptured cervical discs. J Neurosurg. 1958;15:602–17.
5. Bailey RW, Badgley CE. Stabilization of the cervical spine by anterior fusion. J Bone Joint Surg Am. 1960;42:565–94.
6. Simmons EH, Bhalla SK. Anterior cervical discectomy and fusion: a clinical and biomechanical study with eight years follow-up. J Bone Joint Surg Br. 1969;51:225–37.
7. Bohlman HH, et al. Robinson anterior cervical discectomy and arthrodesis for cervical radiculopathy: long-term follow-up of one hundred and twenty-two patients. J Bone Joint Surg. 1993;75:1298–307.
8. Bose B. Anterior cervical instrumentation enhances fusion rates in multilevel reconstruction in smokers. J Spinal Disord. 2001;14:3–9.
9. Bose B. Anterior cervical fusion using Caspar plating. Analysis of results and review of the literature. Surg Neurol. 1998;49:25–31.
10. Kaiser MG, et al. Anterior cervical plating enhances arthrodesis after discectomy and fusion with cortical allograft. Neurosurgery. 2002;25:229–35.
11. Sampath P, et al. Outcome of patients treated for cervical myelopathy: a prospective, multicenter study with independent clinical review. Spine. 2000;25:670–6.

12. Sampath P, et al. Outcome in patients with cervical radiculopathy: prospective, multicenter study with independent clinical review. Spine. 1999;24:591–7.
13. Emery SE, et al. Three-level anterior cervical discectomy and fusion. Spine. 1997;22:2622–5.
14. Zdeblick TA, Ducker TB. The use of freeze-dried allograft bone for anterior cervical fusions. Spine. 1991;16:726–9.
15. Zdeblick T, et al. Anterior cervical discectomy, fusion, and plating. Spine. 1991;18:1974–83.
16. Schneeberger AG, et al. Anterior cervical interbody fusion with plate fixation for chronic sponylotic radiculopathy: a 2- to 8-year follow-up. J Spinal Disord. 1999;12:215–20.
17. Katsuura A, et al. Anterior cervical plate used in degenerative disease can maintain lordosis. J Spinal Disord. 1996;9:470–6.
18. Shapiro S. Banked fibula and the locking anterior cervical plate in anterior cervical fusions following cervical discectomy. J Neurosurg. 1996;84:161–5.
19. Shapiro S, et al. Cadaveric fibula, locking plate, and allogenic bone matrix for anterior cervical fusion after cervical discectomy for radiculopathy or myelopathy. J Neurosurg (Spine 1). 2001;95:43–50.
20. Coric D, et al. Revision of anterior cervical pseudoarthrosis with anterior allograft fusion and plating. J Neurosurg. 1997;86:969–74.
21. Kostuik JP, et al. Anterior cervical plate fixation with the titanium hollow screw plate system. Spine. 1993;18:1273–8.
22. Profeta G, et al. Preliminary experience with anterior cervical microdiscectomy and interbody titanium cage fusion (Novus CT-T1) in patients with cervical disc disease. Surg Neurol. 2000;53:417–26.
23. Eleraky M, et al. Cervical corpectomy: report of 185 cases and review of literature. J Neurosurg (Spine 1). 1999;90:35–41.
24. Geyer T, Foy MA. Oral extrusion of a screw after anterior cervical spine plating. Spine. 2001;26:1814–6.
25. Hanci M, et al. Esophageal perforation subsequent to anterior cervical spine screw/plate fixation. Paraplegia. 1995;33:606–9.
26. Anderson DG, Albert TJ. Bone grafting, implants, and plating options for anterior cervical fusions. Orthop Clin North Am. 2002;33:317–28.
27. Malloy KM, Hilibrand AS. Autograft versus allograft in degenerative cervical disease. Clin Orthop Relat Res. 2002;394:27–38.
28. Zdeblick TA, Phillips FM. Interbody cage devices. Spine. 2003;28:S2–7, Review.
29. Romner B, et al. Modified Robinson-Smith procedure for the treatment of cervical radiculopathy. Acta Neurol Scand. 1994;90:197–200.
30. Adams D, Williams DF. The response of bone to carbon–carbon composites. Biomaterials. 1984;5:59–64.
31. Brandwood A, et al. Phagocytosis of carbon particles by macrophages in vitro. Biomaterials. 1992;13:646–8.
32. Tullberg T. Failure of a carbon fiber implant. A case report. Spine. 1998;23:1804–6.
33. Podoshin L, et al. Long-term histologic study of a new carbon–carbon ossicular replacement prosthesis. Am J Otol. 1988;9:366–75.
34. Cho DY, et al. Treatment of multilevel cervicalfusion with cages. Surg Neurol. 2004;62:378–85.
35. Cho D, et al. Preliminary experience using a polyetheretherketone (PEEK) cage in the treatment of cervical disc disease. Neurosurgery. 2002;51:1–8.
36. Williams A, et al. Potential of Polyetheretherketone and Carbon-fiber-reinforced PEEK in medical application. J Mater Sci Lett. 1987;6:188–90.
37. Wright IP, Eisenstein SM. Anterior cervical discectomy and fusion without instrumentation. Spine. 2007;32:772–4.
38. Fernyhough JC, et al. Fusion rates in multilevel cervical spondylosis comparing allograft fibula with autograft fibula in 126 patients. Spine. 1991;16:S561–4.
39. Bishop RC, et al. Anterior cervical interbody fusion using autogeneic and allogeneic bone graft substrate: a prospective comparative analysis. J Neurosurg. 1996;85:206–10.
40. Samartzis D, et al. Is autograft the gold standard in achieving radiographic fusion in one-level anterior cervical discectomy and fusion with rigid anterior plate fixation. Spine. 2005;30:1756–61.
41. Silber JS, et al. Donor site morbidity after anterior iliac crest bone harvest for single-level anterior cervical discectomy and fusion. Spine. 2003;28:134–9.
42. Schnee CL, et al. Analysis of harvest morbidity and radiographic outcome using autograft for anterior cervical fusion. Spine. 1997;22:2222–7.
43. Seiler 3rd JG, Johnson J. Iliac crest autogenous bone grafting: donor site complications. J South Orthop Assoc. 2000;9:91–7.
44. Rawlinson JN. Morbidity after anterior cervical decompression and fusion. The influence of the donor site on recovery, and the results of a trial of surgibone compared to autologous bone. Acta Neurochir (Wien). 1994;131:106–18.
45. Epstein NE, Hollingsworth R. Does donor site reconstruction following anterior cervical surgery diminish postoperative pain? J Spinal Disord Tech. 2003;16:20–6.
46. McGuire RA, St JK. Comparison of anterior cervical fusions using autogenous bone graft obtained from the cervical vertebrae to the modified Smith-Robinson technique. J Spinal Disord. 1994;7:499–503.
47. Tubbs RS, et al. Use of the clavicle in anterior cervical discectomy/corpectomy fusion procedures: cadaveric feasibility study. Childs Nerv Syst. 2008;24:337–41.
48. Peelle MW, et al. A novel source of cancellous autograft for ACDF surgery: the manubrium. J Spinal Disord Tech. 2007;20:36–41.
49. Bojescul JA, et al. Backfill for iliac-crest donor sites: a prospective, randomized study of coralline hydroxyapatite. Am J Orthop. 2005;34:377–82.
50. Resnick DK. Reconstruction of anterior iliac crest after bone graft harvest decreases pain: a randomized,

controlled clinical trial. Neurosurgery. 2005;57: 526–9.
51. Hamer AJ, et al. Biomechanical properties of cortical allograft bone using a new method of bone strength measurement: a comparison of fresh, fresh-frozen, and irradiated bone. J Bone Joint Surg Br. 1996;78:363–8.
52. Sandhu HS, et al. Bone grafting for spine fusion. Orthop Clin North Am. 1999;30:685–98.
53. Stevenson S, et al. Factors affecting bone graft incorporation. Clin Orthop. 1996;324:66–74.
54. Stevenson S, Horowitz M. The response to bone allografts. J Bone Joint Surg Am. 1992;74:939–50.
55. Stevenson S, et al. The fate of cancellous and cortical bone after transplantation of fresh and frozen tissue-antigen-matched and mismatched osteochondral allografts in dogs. J Bone Joint Surg Am. 1991;73:1143–56.
56. Strong DM, et al. Immunologic responses in human recipients of osseous and osteochondral allografts. Clin Orthop. 1996;326:107–14.
57. Tomford WW. Transmission of disease through transplantation of musculoskeletal allografts. J Bone Joint Surg Am. 1995;77:1742–54.
58. Asselmeier MA, et al. A review of allograft processing and sterilization techniques and their role in transmission of the human immunodeficiency virus. Am J Sports Med. 1993;21:170–5.
59. Bauer TW, Muschler GF. Bone graft materials. An overview of the basic science. Clin Orthop. 2000; 371:10–27.
60. Enneking WF, Mindell ER. Observations on massive retrieved human allografts. J Bone Joint Surg Am. 1991;73:1123–42.
61. Burchardt H. The biology of bone graft repair. Clin Orthop. 1983;174:28–42.
62. Butterman GR, et al. The use of bone allografts in the spine. Clin Orthop. 1996;324:75–85.
63. Buttermann GR, et al. Revision of failed lumbar fusions. A comparison of anterior autograft and allograft. Spine. 1997;22:2748–55.
64. Smith G, Robinson RA. The treatment of certain cervical spine disorders by anterior removal of the intervertebral disc and interbody fusion. J Bone Joint Surg Am. 1958;40:607–24.
65. Hanley EN, et al. The use of allograft bone in cervical spine surgery. Semin Spine Surg. 1989;1:262–70.
66. Zdeblick TA. A prospective randomized study of lumbar fusion: preliminary results. Spine. 1993;18:983–91.
67. An HS, et al. Prospective comparison of autograft vs allograft for adult posterolateral lumbar spine fusion: differences among freezedried, frozen, and mixed grafts. J Spinal Disord. 1995;8:131–5.
68. Jorgenson SS, et al. A prospective analysis of autograft versus allograft in posterolateral lumbar fusion in the same patient. A minimum of 1-year follow-up in 144 patients. Spine. 1994;19:2048–53.
69. Constantino PD, Freidman CD. Synthetic bone graft substitutes. Otolaryngol Clin North Am. 1994;27: 1037–73.
70. Cypher T, Grossman JP. Biological principles of bone graft healing. J Foot Ankle Surg. 1996;35:413–7.
71. Hollinger JO, Battistone GC. Biodegradable bone repair materials. Clin Orthop. 1986;207:290–305.
72. Albee FH, Morrison HF. Studies in bone growth, triple calcium phosphate as a stimulus to osteogenesis. Ann Surg. 1920;71:32–6.
73. Jarcho M. Calcium phosphate ceramics as hard tissue prosthetics. Clin Orthop. 1981;157:259–78.
74. Geesink RGT, De Groot K. Bonding of bone to apatite coated implants. J Bone Joint Surg Br. 1988;70: "17–22.
75. Byrd HS, Hobar PC. Augmentation of craniofacial skeleton with porous hyroxyapatite granules. Reconstr Surg. 1993;91:15–22.
76. Hollinger JO, Brekke J. Role of bone substitutes. Clin Orthop. 1996;324:55–65.
77. Bizette C, et al. Résultats d'arthrodèses intersomatiques cervicales par greffons coralliens. Neurochirurgie. 1999;45:4–14.
78. Cook SD, et al. In vivo evaluation of anterior cervical fusions with hydroxylapatite graft material. Spine. 1994;19:1856–66.
79. Eggli PS, et al. Porous hydroxyapatite and tricalcium phosphate cylinders with two different pore size ranges implanted in the cancellous bone of rabbits. A comparative histomorphometric and histologic study of bony ingrowth and implant substitution. Clin Orthop. 1988;232:127–38.
80. Kim P, et al. Bisegmental cervical interbody fusion using hydroxyapatite implants: surgical results and long-term observation in 70 cases. J Neurosurg. 1998;88:21–7.
81. Koyama T, Handa J. Porous hydroxyapatite ceramics for use in neurosurgical practice. Surg Neurol. 1986;25:71–3.
82. Senter HJ, et al. Anterior cervical discectomy with hydroxyapatite fusion. Neurosurgery. 1989;25:39–43.
83. Böker DK, et al. Anterior cervical discectomy and vertebral interbody fusion with hydroxyapatite ceramic. Preliminary results. Acta Neurochir. 1993; 121:191–5.
84. Roy DM, Linnehan SK. Hydroxyapatite formed from coral skeletal carbonate by hydrothermal exchange. Nature. 1974;247:220–8.
85. Holmes R, et al. A coralline hydroxyapatite bone graft substitute. Clin Orthop. 1984;188:252–62.
86. Zdeblick TA, et al. Anterior cervical discectomy and fusion using a porous hydroxyapatite bone graft substitute. Spine. 1994;19:2348–57.
87. Thalgott JS, et al. Anterior interbody fusion of the cervical spine with coralline hydroxyapatite. Spine. 1999;24:1295–9.
88. Wittenberg RH, et al. Compressive strength of autologous and allogenous bone grafts for thoracolumbar and cervical spine fusion. Spine. 1990;15:1073–8.
89. Schulte M, et al. Vertebral body replacement with a bioglass–polyurethane composite in spine metastases: Clinical, radiological and biomechanical results. Eur Spine J. 2000;9:437–44.

90. Gross V, Brandes J. The ultrastructure of the interface between a glass ceramic and bone. J Biomed Mater Res. 1981;15:291–305.
91. Kinnunen I, et al. Reconstruction of orbital floor fractures using bioactive glass. J Craniomaxillofac Surg. 2000;28:229–34.
92. Peltola M, et al. Experimental follow-up model for clinical frontal sinus obliteration with bioactive glass. Acta Otolaryngol Suppl. 2000;543:167–9.
93. Cao W, Hench LL. Bioactive materials. Ceramics Int. 1996;22:493–507.
94. Urist MR. Bone: formation by autoinduction. Science. 1965;150:893–9.
95. Boden SD, et al. The use of rhBMP-2 in interbody fusion cages. Definitive evidence of osteoinduction in humans: a preliminary report. Spine. 2000;25:376–81.
96. Burkus JK, et al. Is INFUSE bone graft superior to autograft bone? An integrated analysis of clinical trials using the LT-CAGE lumbar tapered fusion device. J Spinal Disord Tech. 2003;16:113–22.
97. Zdeblick TA, et al. Cervical interbody fusion cages. An animal model with and without bone morphogenetic protein. Spine. 1998;23:758–65.
98. Baskin DS, et al. A prospective, randomized, controlled cervical fusion study using recombinant human bone morphogenetic protein-2 with the CORNERSTONE-SR allograft ring and the ATLANTIS anterior cervical plate. Spine. 2003;28:1219–24.
99. Boakye M, et al. Anterior cervical discectomy and fusion involving a polyetheretherketone spacer and bone morphogenetic protein. J Neurosurg Spine. 2005;2:521–5.
100. Smucker JD, et al. Increased swelling complications associated with off-label usage of rhBMP-2 in the anterior cervical spine. Spine. 2006;31:2813–9.
101. Shields LBE, et al. Adverse effects associated with high-dose recombinant human bone morphogenetic protein-2 use in anterior cervical spine fusion. Spine. 2006;31:542–7.
102. Tumialan LM, et al. The safety and efficacy of anterior cervical discectomy and fusion with polyetheretherketone spacer and recombinant human bone morphogenetic protein-2: a review of 200 patients. J Neurosurg Spine. 2008;8:529–35.
103. Dickerman RD, et al. rh-BMP-2 can be used safely in the cervical spine: dose and containment are the keys! Spine J Off J N Am Spine Soc. 2007;7:508–9 comment.
104. Lanman TH, Hopkins TJ. Early findings in a pilot study of anterior cervical interbody fusion in which recombinant human bone morphogenetic protein-2 was used with poly (Llactide-co-D, L-lactide) bioabsorbable implants. Neurosurg Focus. 2004; 16, E6.
105. Vaidya R, et al. Complications of anterior cervical discectomy and fusion using recombinant human bone morphogenetic protein-2. Eur Spine J. 2007;16: 1257–65.
106. Vaidya R, et al. Interbody fusion with allograft and rhBMP-2 leads to consistent fusion but early subsidence. J Bone Joint Surg Br. 2007;89:342–5.
107. Buttermann GR. Prospective nonrandomized comparison of an allograft with bone morphogenic protein versus an iliaccrest autograft in anterior cervical discectomy and fusion. Spine J Off J N Am Spine Soc. 2008;8:426–35.
108. Papavero L, et al. A composite bone graft substitute for anterior cervical fusion. Spine. 2002;27: 1037–43.
109. Muschler GF et al. Selective retention of bone marrow-derived cells to enhance spinal fusion. Clin Orthop Relat Res. 2005;432:242–51.
110. Khoueir P, et al. Multilevel anterior cervical fusion using a collagen-hydroxyapatite matrix with iliac crest bone marrow aspirate: an 18-month follow-up study. Neurosurgery. 2007;61:963–71.
111. Attawia M et al. Toward an International Tissue Engineering Curriculum: The Drexel Initiative (2002). In: Laurencin CT, editor. Bone graft substitutes. West Conshohocken: ASTM International; 2003. p. 126–41.
112. Feiz-Erfan I, et al. Effect of autologous platelet gel on early and late graft fusion in anterior cervical spine surgery. J Neurosurg Spine. 2007;7:496–502.

14 Biomechanical Engineering in Choice of Different Stiffness Material

Stefan Freudiger

Introduction

It is generally believed that the modulus of elasticity is a major criterion to anticipate the success of an implant material. Often, this elasticity is only partially addressed, since the geometrical data are omitted. For axial and bending stiffness the cross section's area and area moment of inertia must also be taken into consideration. An additional criterion in respect to the bony anchorage of vertebral cages is being presented, which is the induced lateral strain $\varepsilon_q = \nu \cdot \varepsilon$. This strain must be sufficiently similar in order to prevent detrimental micromotion. A unique and ideal material stiffness out of the available biomaterials cannot be formulated. But a set of additional criteria for a successful bony anchorage can be listed, such as friction behavior at the interface or material with a potential for stimulating bone ingrowth. The evaluation of stiffness cannot avoid the necessity to carry out numerical analysis, experimental tests with preferably human specimen or careful clinical observations.

Natural Vertebral Endplate

The natural vertebral endplate is an extraordinary structure. It incorporates a thin shell made of compact bone over an elastic foundation made of cancellous bone [1, 2] (Fig. 14.1). The shell is connected to the walls of the vertebral body. The vertebral endplate is comparable to the tibial plateau. The shell together with the elastic foundation is capable to carry high compressive loads and impacts [3]. These compressive loads are optimally distributed, as these loads are applied through the nucleus pulposus with hydrostatic properties (i.e. uniform pressure load). Across the vertebral body the loads are further transferred by the trabeculae, the scaffold of the cancellous bone.

Vagueness exists over the load sharing between the endplate and the cancellous bone underneath. According to White and Panjabi [4] the endplate may contribute 45–75 %. An own rough estimate may yield as follows: The

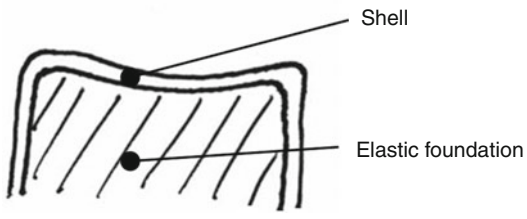


Fig. 14.1 Vertebral plateau

S. Freudiger
Department of Biomedical engineering,
Ingenieurbüro Flugwesen und Biomechanik IFB AG,
Kalchackerstr. 108, Bremgarten CH-3047, Germany
e-mail: stefan.freudiger@ifbag.ch
http://www.ifbag.ch

P.P.M. Menchetti (ed.), *Cervical Spine: Minimally Invasive and Open Surgery*,
DOI 10.1007/978-3-319-21608-9_14

compression strength of a cervical vertebra is in the range of 1585 N [4]. Assuming an endplate surface of 291 mm^2 (inferior endplate average of [5]) multiplied with the cancellous bone strength of 2.37 N/mm^2 [6] yields on overall strength of 690 N, thus leaving an endplate contribution of 56 %. This becomes important whenever the endplate is resected or damaged in order to accommodate a disc prosthesis or a cage.

Natural Vertebral Disc

The characteristic of the vertebral disc is the compressibility and extendibility of the annulus fibrosus due to the diagonal arrangement of its fibers. Consequently the annulus fibrosus is capable to transfer rotational loads while allowing lateral bending as well as flexion and extension movements. Simultaneously it acts as the seal of the nucleus pulposus providing uniform pressure at arbitrary inclination angles (Fig. 14.2).

Surgical Treatments

Whenever a natural discs has undergone severe degeneration with loss of normal performance it will normally be removed partially or entirely. As replacement two procedures are generally used. One procedure intends to preserve motion whereas the other procedure intends to achieve the fusion with the adjacent vertebrae [7, 8].

(a) Implantation of a prosthetic disc
Two types of disc prostheses are distinguished. Disc prostheses which move along a geometrical hard sliding core (Fig. 14.3) and disc prostheses which move as a result of the elasticity of an elastomeric core (Fig. 14.4).

(b) Fusion of the segment
The fusion of two adjacent vertebral bodies is often assisted by the insertion of a body to maintain height. Such body can be autologous bone, a cage or a combination of both (Fig. 14.5).

Great care must be given to the load transfer from the implant to the vertebra. As soon as the natural endplate is resected or otherwise damaged, the maximum loading capacity may be reduced up to its half. The implant, whether it is a disc prosthesis or a cage, should cover as much

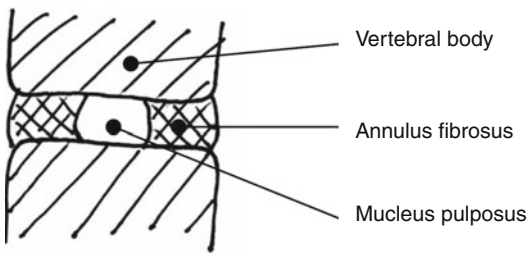


Fig. 14.2 Vertebral disc

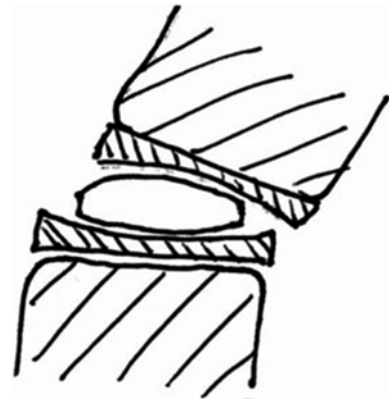


Fig. 14.3 Prosthetic disc with sliding core

Fig. 14.4 Prosthetic disc with elastomer core

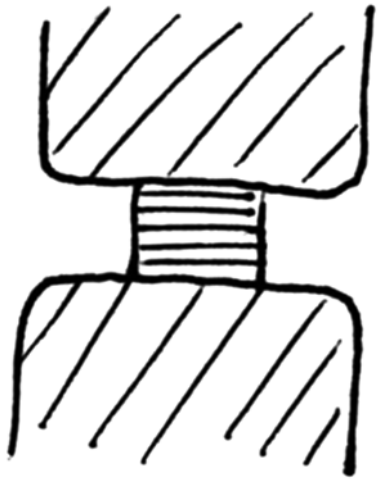


Fig. 14.5 Intersomatic body

surface of the vertebra as possible. If the contact area would be lower, strong bone adherence with consecutive bone remodeling [9] would be required.

Prosthetic Discs

Prosthetic discs are to be divided into two different concepts.

The first concept includes prosthetic discs with a sliding core (Fig. 14.3) (also called "ball and socket") mostly made of *UHMWPE* (ultra high molecular weight polyethylene) and two endplates made of titanium alloy. One endplate is sliding over the other imposing an ICR (instantaneous center of rotation) when the adjacent vertebrae undergoes flexion and extension movements. This ICR is often far from the natural ICR. This concept is further subject to wear of the polyethylene core against the metal endplates. This concept does not provide axial elasticity along the vertebral column axis, since the sliding core is too stiff, in comparison with the natural intervertebral disc.

The second concept includes prosthetic discs with an elastomeric core (Fig. 14.4) (also called "silent bloc"). The materials used shall mimic a vertebral disc and have therefore a pronounced elasticity. The mostly used material is the PCU (polycarbonateurethane) (e.g. *Bionate*®) possibly blended with silicone (e.g. *Carbosil*®). The elastomer core does not impose any cinematic constraints. It allows motion according to it's elasticity in the specific loading axis. The elastomer core is able to absorb axial loads and to provide axial elasticity along the vertebral column axis.

Cages

A basic feature of an implant material is the stiffness and a basic characteristic of the stiffness is the elastic modulus (also called Young's modulus) (denoted as E). But when comparing stiffness from one body to another, the modulus of elasticity is only half of the truth. For comparing stiffness, beside the material constant, also a geometrical parameter needs to be considered, which depends on the type of loading. For axial load (Fig. 14.6) the geometrical parameter is the cross section area (denoted as A) and for bending (Fig. 14.7) the geometrical parameter is the cross section area moment of inertia (denoted as I). Consequently the axial stiffness is given by E·A and the bending stiffness is given by E·I.

If in the axial direction the body has a constant cross section (i.e. prismatic) and if the area of contact on the supporting structure corresponds to the cross section, then the area may be dropped from the equation. In all other cases, the areal parameters need to be taken into consideration.

Typical materials used for cages are *PEEK* (polyetherehterketone), *Titanium*, *carbon fiber composites*, *PMMA* (polymethylmetacrylate) and *TCP* (tricalciumphosphate) as a filler material.

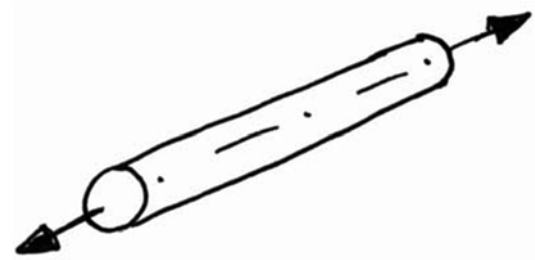


Fig. 14.6 Axial load

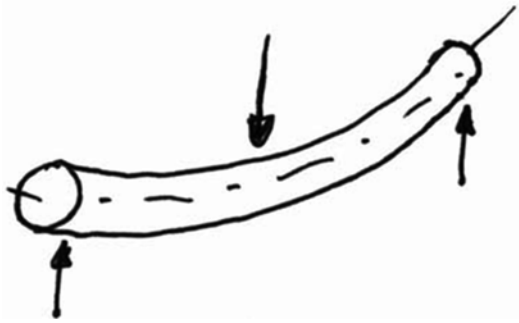


Fig. 14.7 Bending load

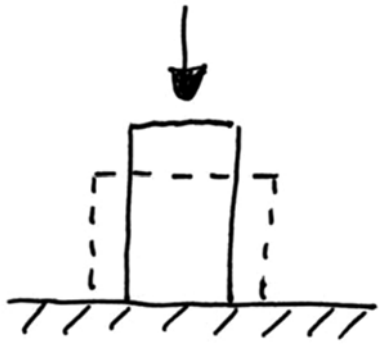


Fig. 14.8 Lateral strain

The cage typically has a frontal contact with the bone and is subject to compression loads. As a consequence the cage is principally exposed to lateral strain (Fig. 14.8), which in the worst circumstances may produce micromotion against the bone, if the interface shear characteristics do not comply with each other. Furthermore, the vertebral endplate would only be loaded on a limited surface, where the endplate itself is being surrounded by compact bone along its periphery; both limiting lateral strain.

Lateral strain (denoted by ε_q) is given by the longitudinal strain (denoted by ε) multiplied with Poisson's ratio (denoted by ν) [6] where the longitudinal strain ε equals the stress (which is the force divided by the surface, denoted by σ) divided by the modulus of elasticity (E). If the force and the surface are the same for the cage and the bone, the lateral strain becomes proportional to the quotient of the Poisson's ratio and the modulus of elasticity or $\varepsilon_q \approx \nu/E$.

Cages must cover a sufficiently large area of the (resected) vertebral body, since the strength contribution of the natural shell is being sacrificed. Cages need to achieve a good bone adherence for successfully transmit the expected loads. If the cage surface is not sufficiently osseoinductive it will need to undergo a surface treatment with an adequate coating.

Comparison of Materials

The considered materials are biomaterials with a proven biocompatibility which must have demonstrated compliance with the relevant international standards (e.g. ISO 10993).

For overview, the mechanical properties of the materials of interest are listed in Table 14.1.

Data are order of magnitudes for reference. Especially polymer characteristics may vary with strain rate, body temperature and environment.

For illustration, the initial stiffness ($E = \sigma / \varepsilon$) of the materials of interest are plotted in Fig. 14.9. The curves are highly idealized. Other slopes using other databases are possible. The TCP curve had to undergo a coordinate transformation for comparison. For ease of illustration, tensile and compressive data are shown in the same quadrant.

However, UHMWPE, Bionate® and Carbosil® are not expected to be used in direct contact with bone. They are rather used as core material for disc prostheses.

TCP is also not expected to be used as standalone cage, because of its resorbable behavior. TCP is rather be used to fill voids in hollow cages to accelerate bone-ingrowth.

Results/Conclusion

An elasticity of an implant closer to bone is often considered as an advantage for biomechanical perspectives. Mostly the elasticity is only considered by looking at the modulus of elasticity of the material used. But in order to properly evaluate the elasticity of an implant (or

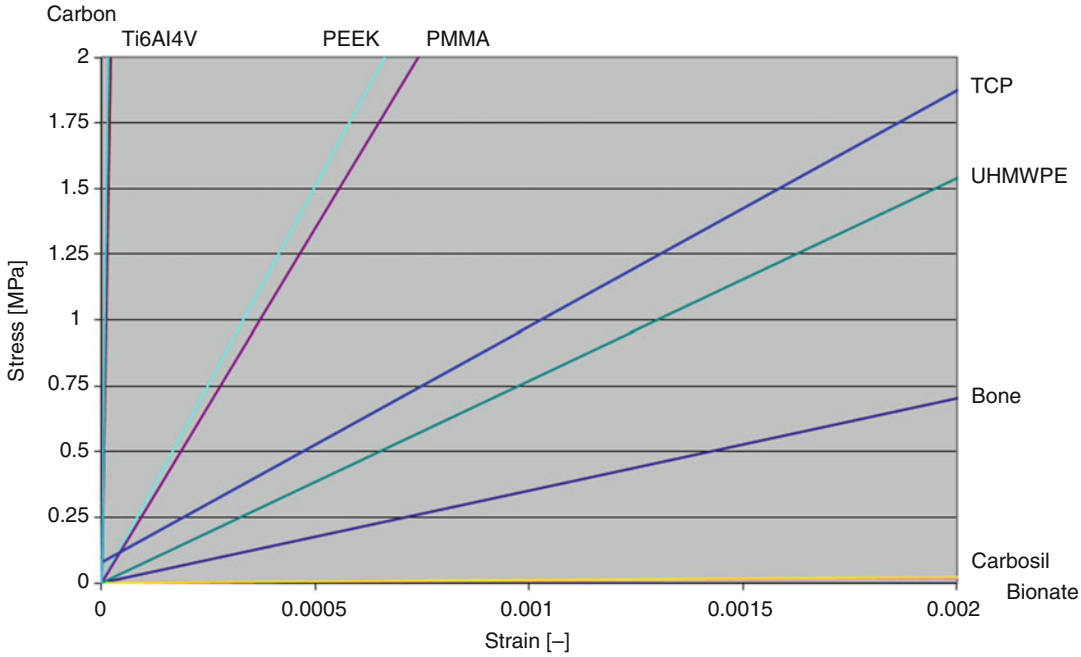


Fig. 14.9 Stress/strain plot of specific biomaterials

Table 14.1 Overview of biomaterials of interest

Material	Strength [MPa]	Mod. of elast.[a] [MPa]	Ultim. strain [%]	Poisson ratio	Lat. strain[b] [%]	Refs.	Note
Cancellous bone	2.37 (c)	352.00	1.19	.20	.057	[6, 10]	
PEEK	107.00 (t)	2,853.00	20.00	.36	.013	[11]	
Ti6Al4V	950.00 (t)	113,800.00	14.00	.34	.000	[12]	
Carbon fiber	1,315.00 (t)	235,000.00	0.56	See note	.000	[13]	1
Bionate® 80A	46.61 (t)	8.74	531.00	.50[c]	5.721	[14]	2
Carbosil® 80A	35.03 (t)	9.70	473.00	.50[c]	5.155	[15]	2
TCP	21.13 (c)	1,198.00	2.24	.28	.023	[16]	
PMMA	100.00 (c)	2,700.00	5.10	.40	.015	var.	
UHMWPE	21.00 (t)	770.00	350.00	.42[c]	.055	var.	

(c) Measured in compression
(t) Measured in tension
[a]Secant modulus (first distinctive segment – idealized)
[b]Lateral strain with unit stress
[c]Ex: http://ocw.mit.edu/courses/materials-science-and-engineering/3-11-mechanics-of-materials-fall-1999/modules/props.pdf
Notes:
1. Mechanical properties of carbon fiber implants depend also on the orientation of the fiber in the composite and the axis of loading. Exact fiber orientations within spinal cages are not disclosed (Data shown are averages of Ref. [13])
2. Bionate® and Carbosil® are also available in other grades. Exact grades used in the prosthetic discs are not disclosed

its stiffness, as the inverse) other parameters need to be looked at. For comparing axial stiffness, bending stiffness or induced lateral strain, the cross section's area, the cross section's area moment of inertia or the Poisson's ratio must also be taken into consideration.

According to Polikeit et al. [17] the density of the vertebra's cancellous bone would be of higher importance for the stabilization of a functional spinal unit than the cage material.

Elasticity or stiffness numbers are not the only parameter for determining the success of an implant. The interface with the bone should have sufficient primary stability to allow bone to adhere to. Friction of the interface may contribute to this characteristics. The material should ideally stimulate bone ingrowth. Numerical analysis, experimental tests with preferably human specimen and careful clinical observations are further prerequisites to end-up with an appropriate material choice.

® Bionate and Carbosil are trademarks of DSM PTG

References

1. Yang H, et al. Micromechanics of the human vertebral body for forward flexion. J Biomech. 2012;45(12): 2142–8.
2. Ferguson S, Steffen T. Biomechanics of the aging spine. Eur Spine J. 2003;12 Suppl 2:S97–103.
3. Currey J. The mechanical adaptations of bones. Princeton: Princeton University Press; 1984.
4. White AA, Panjabi MM. Clinical biomechanics of the spine. Philadelphia: J.B. Lippincott Company; 1990.
5. Thaler M, et al. Footprint mismatch in total cervical disc arthroplasty. Eur Spine J. 2013;22:759–65.
6. Banse X, Sims TJ, Bailey AJ. Mechanical properties of adult vertebral cancellous bone: correlation with collagen intermolecular cross-links. J Bone Miner Res. 2002;17(9):1621–8.
7. Grob D. A comparison of outcomes of cervical disc arthroplasty and fusion in everyday clinical practice: surgical and methodological aspects. Eur Spine J. 2010;19:297–306.
8. Nabhan A. Assessment of adjacent-segment mobility after cervical disc replacement versus fusion: RCT with 1 year's results. Eur Spine J. 2011;20:934–41.
9. Wolff J. Das Gesetz der Transformation der Knochen. Hirschwald; Berlin; 1892. Translated by Maquet P, Furlong R. The Law of Bone Remodelling. Springer: Berlin/Heidelberg; 1986.
10. Carter DR, et al. Relationships between loading history and femoral cancellous bone architecture. J Biomechanics. 1989;22(3):231–44.
11. Kurtz SM, Devine JN. PEEK biomaterials in trauma, orthopedic and spinal implants. J Biomaterials. 2007; 28(32):4845–69.
12. http://www.aerospacemetals.com/titanium-ti-6al-4v-ams-4911.html
13. Petersen RC. Bisphenil-polymer/carbon-fiber-reinforced composite compared to titanium alloy bone implant. Int J Polym Sci. 2011;2011, Article ID 168924, 11 pages.
14. Datasheet Bionate® (2009) by DSM PTG, 2810 7th Street, Berkeley, CA 94710
15. Datasheet Carbosil® (2009) by DSM PTG, 2810 7th Street, Berkeley, CA 94710
16. Martínez-Vázquez FJ, et al. Improving the compressive strength of bioceramic robocast scaffolds by polymer infiltration. Acta Biomater. 2010;6:4361–8.
17. Polikeit A, et al. Factors influencing stresses in the lumbar spine after the insertion of intervertebral cages: finite element analysis. Eur Spine J. 2003;12: 413–20.

HA-TCP Augmented Cage-Role on Fusion in Cervical Spine

15

Giles G. Dubois and A. Lerch

Introduction

Medical application is one of the most exciting and rewarding research areas of the materials science. Examples from our daily life are sutures, catheters, heart valves, pacemakers, breast implants, fracture fixation plates, nails and screws in orthopedics, dental filling materials, orthodontic wires, as well as total joint replacement prostheses. During the past decades, both an ageing population and a democratization of high-risk sports have led to a surge of bone-related diseases and bone fractures, which must be treated through implants. In order to be accepted by the living body, all implantable items must be prepared from a special class of materials, called biomedical materials or biomaterials in short.

All solid materials are generally categorized as four major groups: metals, polymers ceramics and composites thereof. Similarly, all biomaterials are also divided into the same major types: biometals, biopolymers, bioceramics and biocomposites. All of them play very important roles in both replacement and regeneration of the human tissues.

G.G. Dubois, MD (✉) • A. Lerch, PhD
Service de Neurochirurgie, Clinique de l'Union,
Bld de Ratalens, St Jean 31240, France
e-mail: gilles.dubois@clinique-union.fr

Calcium orthophosphate-based bioceramics and biomaterials are found in a variety of different applications throughout the body, covering all areas of the skeleton: dental implants, percutaneous devices and use in periodontal treatment, healing of bone defects, fracture treatment, total joint replacement (bone augmentation), orthopedics, cranio-maxillofacial reconstruction, otolaryngology, ophthalmology and spinal surgery [1–5].

History

Man's attempts to repair the human body with the use of implant materials were recorded in the early medical writings of the Hindu, Egyptian and Greek civilizations. The earliest successful implants were in the skeletal system. In early times, a selection of the materials was based on their availability and an ingenuity of the individual making and applying the prosthetic [6]. Some example biomaterials seem in museum exhibits from archaeological findings are animal or human (from corpses) bones and teeth, shells, corals, ivory (elephant tusk), wood, as well as some metals (gold or silver). For instance, the Etruscans learned to substitute missing teeth with bridges made from artificial teeth carved from the bones of oxen, while in ancient Phoenicia loose teeth were bound together with gold wires for tying artificial ones to neighboring teeth. In the

P.P.M. Menchetti (ed.), *Cervical Spine: Minimally Invasive and Open Surgery*,
DOI 10.1007/978-3-319-21608-9_15

17th century, a piece of dog skull was successfully transplanted into the damaged skull of a Dutch duke. The Chinese recorded the first use of dental amalgam to repair decayed teeth in the year 659 AD, while pre-Columbian civilizations used gold sheets to heal cranial cavities following trepanation [7]. Furthermore, in 1970, Amadeo Bobbio discovered Mayan skulls, some of them more than ~ 4000 years old, in which missing teeth had been replaced by nacre substitutes [8]. Unfortunately, due to the practice of cremation in many societies, little is known about prehistoric materials used to replace bone lost to accident or disease.

Plaster of Paris was the first widely tested artificial bioceramics in history. In the past many implantations failed due to infections, and furthermore the infections tended to be exacerbated in the presence of implants, since they provided a region inaccessible to the body's immunologically competent cells. The use of biomaterials did not become practical until the advent of an aseptic surgical technique developed by Dr. J. Lister in the 1860s. Furthermore, there was a lack of knowledge about a toxicity of the selected materials. In this frame, application of calcium orthophosphates appears to be logical due to their similarity with the mineral phases of bones and teeth [9–13]. Calcium orthophosphates families are not toxic and do not cause cell death in the surrounding tissues. According to available literature, the first attempt to use them (it was TCP) as an artificial material to repair surgically created defects in rabbits was performed in 1920 [14]. Although this may be the first scientific study on use of a calcium orthophosphate for bone defects repair, it remains unclear whether the calcium orthophosphate was a precipitated or a ceramic material and whether it was in a powder or granular form. The second clinical report was only published 30 years later [15]. More than 20 years afterwards, the first dental application of a calcium orthophosphate (erroneously described as TCP) in surgically created periodontal defects [16] and the use of dense HA cylinders for immediate tooth root replacement [17] were reported. According to the available databases, the first paper with the term "bioceramics" in the abstract was published in 1971 [18], while with that in the title were published in 1972 [19, 20]. However, application of the ceramic materials as prostheses had been known prior to that time [21–24]. Further historical details might be found in literature [25, 26]. The first international symposium on bioceramics was held in Kyoto, Japan on April 26, 1988.

Commercialization of the dental and surgical applications of calcium orthophosphate (mainly, HA) bioceramics occurred in the 1980s, largely due to the pioneering efforts by Jarcho [27–30] in the USA, de Groot [31–33] in Europe and Aoki [34–46] in Japan. Shortly afterwards HA has become a bioceramic of reference in the field of calcium orthophosphates for biomedical applications. Preparation and biomedical applications of apatites derived from sea corals (coralline HA) [38–40] and bovine bone [41] have been reported at the same time [42].

General Knowledge and Definitions

A number of definitions have been developed for the term "biomaterials". For example, by the end of the 20th century, the consensus developed by the experts was the following: biomaterials were defined as synthetic or natural materials to be used to replace parts of a living system or to function in intimate contact with living tissues [47]. However, in September 2009, a more advanced definition was introduced: "A biomaterial is a substance that has been engineered to take a form which, alone or as part of a complex system, is used to direct, by control of interactions with components of living systems, the course of any therapeutic or diagnostic procedure, in human or veterinary medicine" [6]. The definition alterations were accompanied by a shift in both the conceptual ideas and the expectations of biological performance, which mutually changed in time [7].

In general, the biomaterials discipline is founded in the knowledge of the synergistic interaction of material science, biology, chemistry, medicine and mechanical science and it requires the input of comprehension from all these areas so that potential implants perform

adequately in a living body and interrupt normal body functions as little as possible [8]. As biomaterials deal with all aspects of the material synthesis and processing, the knowledge in chemistry, material science and engineering is essential. On the other hand, as clinical implantology is the main purposes of biomaterials, biomedical sciences become the key part of the research. These include cell and molecular biology, histology, anatomy and physiology. The final aim is to achieve the correct biological interaction of the artificial grafts with living tissues of a host. In order to achieve the goals, several stages have to be performed, such as: material synthesis, design and manufacturing of prostheses, followed by various types of tests. Furthermore, any potential biomaterial must also pass all regulatory requirements before its clinical application [9].

Chemical Composition and Preparation

Hydroxyapatite (HA)

Hydroxyapatite (HA) is part of the apatite family of apatite that are compounds whose main feature is their ability to accept a large number of substitutions and ionic gaps. The stoichiometric apatites are generally represented by the chemical formula:

$$Me_{10}\left(XO_4\right)_6 Y_2$$

Where Me is a divalent metal, XO_4 a trivalent anion and Y a monovalent anion. Stoichiometric hydroxyapatite is therefore represented by the formula $Ca_{10}(PO_4)_6(OH)_2$. The stoichiometric HA is characterized by its Ca/P ratio of 1.67. Its infrared spectroscopic analysis shows characteristic bands allocated to OH^- ions and phosphate group; and its X-ray diffraction diagram of X corresponds to a hexagonal structure (P63/m group) with the lattice parameters: a = 0.9422 nm and c = 0.688 nm [48].

The mesh contains ten calcium atoms and six PO_4^{3-} tetrahedra and two hydroxyl groups. The assembly of PO_4^{3-} ions in the form of honeycomb which constitutes the backbone of the network and provides a great stability to the structure of hydroxyapatite. There in the house of the mesh type two tunnel, one with a diameter of about 2.5 Å and the other between 3 Å and 4.5A. These tunnels confer hydroxyapatite ion exchange properties and acceptor small molecules (O_2, H_2O, glycine …).

The synthesis of hydroxyapatite can be done in two ways, either by precipitation in an aqueous medium in the presence of ammonia to adjust pH or by thermal reaction at high temperature.

β -tricalcium phosphate (β-TCP)

β -tricalcium phosphate has the chemical formula $Ca_3(PO_4)_2$. It is characterized by a Ca / P ratio of 1.5. It is rhombohedral structure (R3c group) and has the lattice parameters a = b = 1.0439 nm and c = 3.7375 (for multiple hexagonal mesh).

Its preparation is made by sintering at high temperature deficient apatite calcium Ca/P ratio of 1.5 or by solid-solid reaction at high temperatures. Sintering temperatures are usually between 1000 and 1250 ° C [49].

There is another way of implementing the TCP wet. The principle is to obtain a precipitate poorly crystallized using a phosphate source and a source of calcium while controlling the temperature and pH. The whole is then calcined at high temperature.

Forming and Shaping

In order to fabricate bioceramics in progressively complex shapes, scientists are investigating the use of both old and new manufacturing techniques. These techniques range from an adaptation of the age-old pottery techniques to the newest manufacturing methods for high-temperature ceramic parts for airplane engines. Namely, reverse engineering [50, 51] and rapid prototyping [52–54] technologies have revolutionized a generation of physical models, allowing the engineers to efficiently and accurately produce physical models and

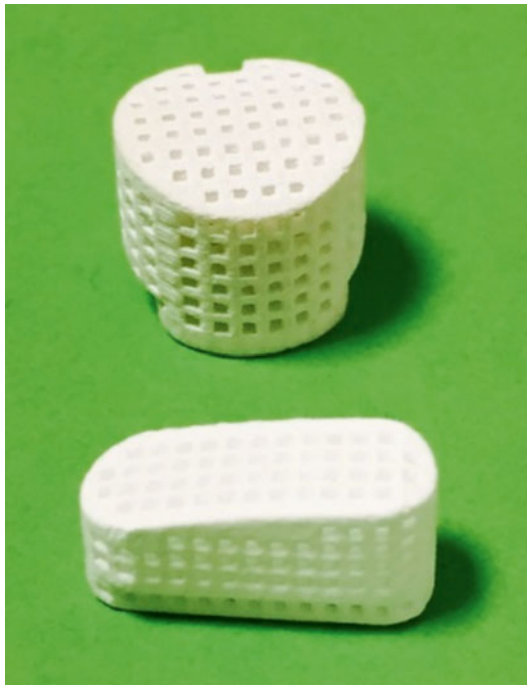


Fig. 15.1 Example of calcium phosphate ceramic obtains by rapid prototype technique

customized implants with high levels of geometric intricacy. Combined with the computer-aided design and manufacturing (CAD/CAM), complex physical objects of the anatomical structure can be fabricated in a variety of shapes and sizes. In a typical application, an image of a bone defect in a patient can be taken and used to develop a three-dimensional (3D) CAD computer model [55–58]. Then a computer can reduce the model to slices or layers. Afterwards, 3D objects and coatings are constructed layer-by-layer using rapid prototyping techniques. A custom-made implant of actual dimensions would reduce the time it takes to perform the medical implantation procedure and subsequently lower the risk to the patient. Another advantage of a pre-fabricated, exact-fitting implant is that it can be used more effectively and applied directly to the damaged site rather than a replacement, which is formulated during surgery from a paste or granular material (Fig. 15.1).

In addition to the aforementioned modern techniques, classical forming and shaping approaches are still widely used. The selection of the desired technique depends greatly on the ultimate application of the bioceramic device, e.g., whether it is for a hard-tissue replacement or an integration of the device within the surrounding tissues. In general, three types of the processing technologies might be used:

- Employment of a lubricant and a liquid binder with ceramic powders for shaping by impregnation of polymeric foam and subsequent firing;
- Application of self-setting and self-hardening properties of water-wet molded powders with or without porogen agent;
- Materials are melted to form a liquid and are shaped during cooling and solidification.

Sintering and Firing

A sintering (or firing) procedure appears to be of a great importance to manufacture bulk bioceramics with the required mechanical properties. Usually, this stage is carried out according to controlled temperature programs of electric furnaces in air. The firing step can include temporary holds at intermediate temperatures to burn out organic binders [59]. The heating rate, sintering temperature and holding time depend on the starting materials. For example, in the case of HA, these values are in the ranges of 0.5–3 °C/min, 1000–1250 °C and 2–5 h, respectively [60]. In the majority cases, sintering allows a structure to retain its shape. However, this process might be accompanied by a considerable degree of shrinkage, which must be accommodated in the fabrication process.

In general, sintering occurs only when the driving force is sufficiently high, while the latter relates to the decrease in surface and interfacial energies of the system by matter (molecules, atoms or ions) transport, which can proceed by solid, liquid or gaseous phase diffusion. Namely, when solids are heated to high temperatures, their constituents are driven to move to fill up pores and open channels between the grains of powders, as well as to compensate for the surface energy differences among their convex and concave sur-

faces (matter moves from convex to concave). At the initial stages, bottlenecks are formed and grow among the particles. Existing vacancies tend to flow away from the surfaces of sharply curved necks; this is an equivalent of a material flow towards the necks, which grow as the voids shrink. Small contact areas among the particles expand and, at the same time, a density of the compact increases and the total void volume decreases. As the pores and open channels are closed during a heat treatment, the particles become tightly bonded together and density, strength and fatigue resistance of the sintered object improve greatly. Grain-boundary diffusion was identified as the dominant mechanism for densification. Furthermore, strong chemical bonds are formed among the particles and loosely compacted green bodies are hardened to denser materials.

In the case of calcium orthophosphates, the earliest paper on their sintering was published in 1971 [61]. Since then, numerous papers on this subject were published and several specific processes were found to occur during calcium orthophosphate sintering. Firstly, moisture, carbonates and all other volatile chemicals remaining from the synthesis stage, such as ammonia, nitrates and any organic compounds, are removed as gaseous products. Secondly, unless powders are sintered, the removal of these gases facilitates production of denser ceramics with subsequent shrinkage of the samples. Thirdly, all chemical changes are accompanied by a concurrent increase in crystal size and a decrease in the specific surface area. Fourthly, a chemical decomposition of all acidic orthophosphates and their transformation into other phosphates (e.g., $2HPO_4^{2-} \rightarrow P_2O_7^{4-} + H_2O\uparrow$) takes place. Besides, sintering causes toughening, densification, partial dehydroxylation (in the case of HA) [32], grain growth, as well as it increases the mechanical strength.

Bone Substitute Characteristics

For their use in clinical, bone substitutes must meet certain criteria. These characteristics define the efficiency of filling material.

Biocompatibility

The biocompatibility of substitute employees is very important. These materials and their degradation products must not, in fact, present cytotoxicity or be accompanied by a strong inflammatory reaction.

By their nature, calcium phosphate materials and their degradation products (calcium phosphate) are perfectly assimilated by the body and even participate in bone regeneration. Either in vitro or in vivo, most of these materials exhibit a very good biocompatibility. The implantation of HA ceramic, of β-TCP or BCP in animals is accompanied by a good bone apposition to the surface of the materials, without the presence of inflammatory response [62]. In rare cases, excessive dissolution of materials is accompanied by cytotoxicity and consequently a lack of efficacy. Such observations have been made for ceramic of α-TCP [63].

Osteoconduction

The osteoconduction is currently defined as the ability of a material to permit bone growth when in contact or near a bone [62]. The material must be able to accommodate the osteoblast precursors that migrate from the bone marrow and ensure their proliferation and differentiation into osteoblasts.

Calcium phosphate ceramics have very good osteoconductive properties and their capacity is determined by characteristics including their chemical composition and macroporosity. Implantation in BCP ceramic dog femurs (HA / β-TCP: 60/40) shows an earlier osseointegration and a quantity of new bone than all time of the study compared to samples HA (similar porosity) [64].

Wilson et al. [65] have also studied in combination the effects of composition and the macroporosity of the osteoconductive potential of calcium phosphate ceramics. They compared bone formation after implantation in the lumbar spine of samples goat β-TCP, HA and BCP (HA / β-TCP: 80/20) which were sintered at different temperatures, and therefore having different

macropores. They then classified the samples to their potential osteoconductive: BCP sintered at low and medium temperature (rough and smooth) = β-TCP > HA sintered at low temperature > PCO sintered at high temperature (rough and smooth) > HA sintered high temperature. In view of the results, they indicate that the parameter that determines the potential bioactivity would osteoconductive ceramics related to their dissolution rate.

In their study, Habibovic et al. [66] have obtained comparable results after implantation site in orthotopic various calcium phosphates: HA, carbonated apatite ceramics and BCP lacking macropores induce little bone formation while it is very important for BCP macroporous samples.

Bioactivity

Bioactive materials have the unique property to create a direct contact with the bone without fibrous cap formation thereby increasing their potential for integration. This ability is the ability for these biomaterials to precipitate to their surface a nanocrystalline apatite similar to bone mineral, in contact with biological fluids [67]. The formation of the apatite phase is done in several steps: (1) existence of a supersaturated environment in calcium and phosphate ions; (2) precipitation in the material surface of a nanocrystalline carbonated apatite; (3) organization and incorporation of this phase with the organic matrix of the newly formed bone. The first step is carried out naturally and biological fluids in contact with an implant are supersaturated with respect to apatite nanocrystalline likely to form. It is considered that the ionic product is close to the serum phosphate solubility product octacalcium (OCP) [68]. The second step depends on the surface nucleating properties, it is particularly important for hydroxyapatite and other calcium phosphates may promote the epitaxial growth of apatite crystals. However, the ability of a surface to promote the germination of an apatite phase may be enhanced by the release of inorganic ions of the biomaterial itself.

Two other ions may contribute to this effect, phosphates and OH^- ions by their effect on the local pH, and some biomaterials also use these properties. The third step is more complex and involves many physicochemical and biological parameters. Among the physical-chemical parameters, it should be mentioned the speed of crystal growth, the inhibition of growth and germination by proteins or ions (Mg, carbonates, pyrophosphates, citrates …), the distribution of these groups to the mineralization front.

The biological parameters concern, including adhesion, proliferation, differentiation and mineralization of osteoblasts, which depend strongly on the surface of the biomaterial and certain mineral ions in solution (particularly calcium and phosphate). As bone mineral, apatite nanocrystalline new formed phase is very reactive and it has significant capacity ion exchange and adsorption of proteins. It has also been suggested that proteins from surrounding fluids may be co-precipitated and thus included in this apatite layer during its formation. The materials of bioactivity was shown for the first time by Hench et al. [69] who noticed the formation of the apatite layer on their bioglass.

The presence of nucleation sites and an increase of the supersaturation of calcium and / or phosphate on the surface of the material are two mechanisms to induce the formation of the apatite similar to bone mineral [70]. Most ceramics based calcium phosphates are bioactive in varying degrees. The macroporosity of these materials appears to play an important role in this phenomenon, this macroporosity increases the surface area of the samples and therefore the number of nucleation sites. It has, on the other hand, been suggested that it may allow to obtain a micro environment for ion supersaturation and calcium phosphate [70].

Biodegradation

Shortly after implantation, a healing process is initiated by compositional changes of the surrounding bio-fluids and adsorption of biomolecules. Following this, various types of cells reach

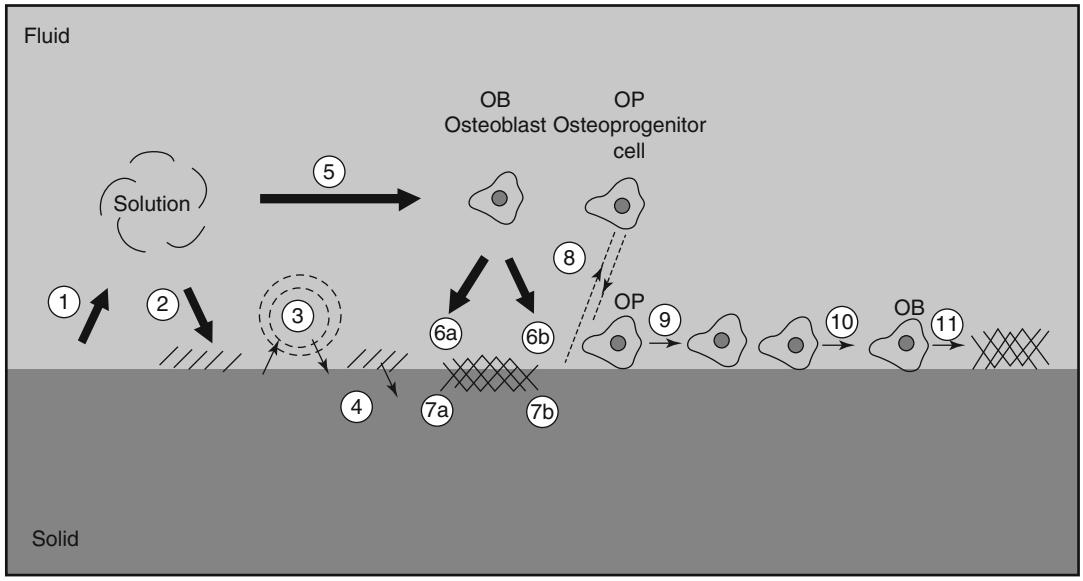


Fig. 15.2 A schematic diagram representing the events, which take place at the interface between bioceramics and the surrounding biological environment: (*1*) dissolution of bioceramics; (*2*) precipitation from solution onto bioceramics; (*3*) ion exchange and structural rearrangement at the bioceramic/tissue interface; (*4*) interdiffusion from the surface boundary layer into the bioceramics; (*5*) solution-mediated effects on cellular activity; (*6*) deposition of either the mineral phase (*a*) or the organic phase (*b*) without integration into the bioceramic surface; (*7*) deposition with integration into the bioceramics; (*8*) chemotaxis to the bioceramic surface; (*9*) cell attachment and proliferation; (*10*) cell differentiation; (*11*) extracellular matrix formation. All phenomena, collectively, lead to the gradual incorporation of a bioceramic implant into developing bone tissue (Reprinted with permission from Ducheyne and Qiu [23])

the bioceramic surface and the adsorbed layer dictates the ways the cells respond. Further, a biodegradation of the implanted bioceramics begins. This process can occur by either physicochemical dissolution with a possibility of phase transformations or cellular activity (so called, bioresorption). More likely, a combination of both processes takes place in vivo. Since the existing calcium orthophosphates are differentiated by Ca/P ratio, basicity/acidity and solubility their degradation kinetics and mechanism depend on the chosen type of calcium orthophosphate [71, 72]. Since dissolution is a physical chemistry process, it is controlled by some factors, such as solubility, surface area to volume ratio, local acidity, fluid convection and temperature.

With a few exceptions, dissolution rates of calcium orthophosphates are inversely proportional to the Ca/P ratio (except of TTCP), phase purity and crystalline size, as well as it is directly related to both the porosity and the surface area. Bioresorption is a biological process mediated by cells (mainly, osteoclasts and, in a lesser extent, macrophages). It depends on the response of cells to their environment. Osteoclasts attach firmly to the implant and dissolve calcium orthophosphates by secreting an enzyme carbonic anhydrase or any other acid, leading to a local pH drop to ~4–5 [73]. In any case, in vivo biodegradation of calcium orthophosphates is a complicated combination of various non-equilibrium processes, occurring simultaneously and/or in competition with each other (Fig. 15.2).

The experimental results demonstrated that both the dissolution kinetics and in vivo biodegradation of biologically relevant calcium orthophosphates proceed in the following decreasing order: β-TCP > bovine bone apatite (unsintered) > bovine bone apatite (sintered) > coralline HA > HA. In the case of biphasic (HA + TCP), triphasic and multiphasic calcium orthophosphates, the biodegradation kinetics depends on the HA/TCP ratio: the higher the ratio, the lower the degradation rate. Similarly, in vivo

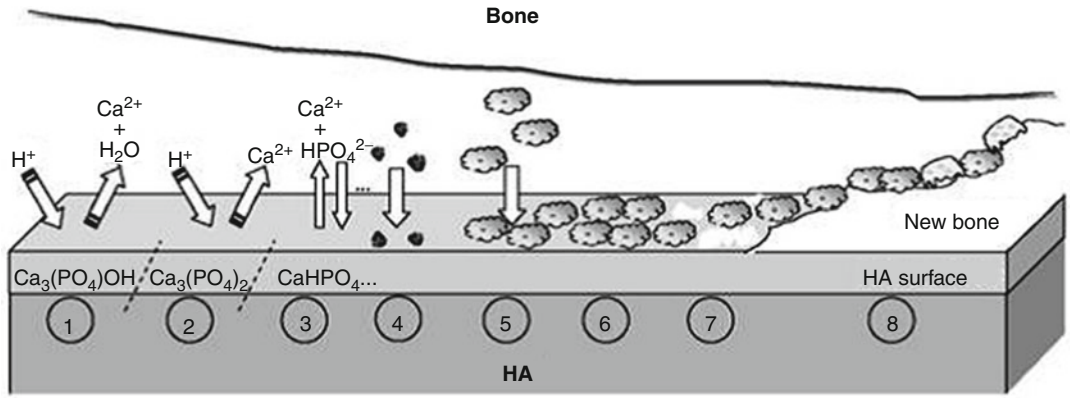


Fig. 15.3 A schematic diagram representing the phenomena that occur on HA surface after implantation: *1* beginning of the implant procedure, where a solubilization of the HA surface starts; *2* continuation of the solubilization of the HA surface; *3* the equilibrium between the physiological solutions and the modified surface of HA has been achieved (changes in the surface composition of HA does not mean that a new phase of DCPA or DCPD forms on the surface); *4* adsorption of proteins and/or other bioorganic compounds; *5* cell adhesion; *6* cell proliferation; *7* beginning of a new bone formation; *8* new bone has been formed (Reprinted with permission from Bertazzo et al. [74])

degradation rate of biphasic TCP (α-TCP + β-TCP) bioceramics appeared to be lower than that of α-TCP and higher than that of β-TCP bioceramics, respectively (Fig. 15.3).

Strength

Bone substitutes may be subject to large mechanical forces similar to those that the bone has to support. It is therefore important that these materials have good mechanical properties in order to avoid erosion or fracture in the establishment during the surgery or at the time of loading.

The mechanical strength of bone substitutes depends mainly on their composition, their method of production and morphology.

Dense hydroxyapatite has a high tensile strength or compression with higher or similar values to that of cortical bone. Its tensile strength is between 79 and 106 MPa against 69–110 MPa for cortical bone [75] and its compressive strength up to 400 MPa against 100–200 MPa for the cortical bone [76].

However, the necessary presence of interconnected pores in the materials decreases drastically their mechanical properties. The values obtained, which vary depending on the type of calcium phosphate ceramic studied, varies between 1 MPa for an average porosity of 70 % and 10 MPa for a porosity of 50 %.

Porosity

The morphology of bone substitutes is a major parameter that determines their effectiveness.

It is indeed necessary that the material contains interconnected pores. It has been shown that two porosities ranges must be present to ensure good bone reconstruction:

A Macroporosity

Macroporosity generally corresponds to pores of diameter greater than 100 μm, and typically between 300 and 600 μm. The presence of these macropores provides invasion of the material by the cells as well as the establishment of the vasculature for a contribution of biological fluids for the survival and cell differentiation. A minimum porosity of 40–70 μm is essential to the invasion of blood vessels and bone formation. Klenke et al. [77] showed that the size of the macropores was directly correlated to the amount of bone and the number of vessels formed after implantation BCP ceramics on rat skulls. The values obtained were significantly higher porosities for ranges greater than 140 μm and with increasing pore size.

A Microporosity

The presence of mesopores of diameter less than 10 μm - commonly called micropores in biomaterials - also plays an important role in the reconstruction efficiency of these materials, particularly their osteoconductive properties. It has been suggested that these micropores were likely to play a role at several levels: increase the surface area of the materials, creating a microenvironment within the pores, increasing roughness, increased resorbability. These various parameters associated with the reactivity of the material, may thus have an influence on the bioactivity of the material or its adsorption capacity [78].

Clinical Use

It is clear from the above analysis that the tricalcium phosphate ceramics with Hydroxyapatite provide an excellent channel to perform interbody grafts referred obtaining fusion. The mechanical properties of these ceramics are poorly resistant materials to compression and in case of direct trauma, which can be prone to breakage phenomena. For this reason and because of their high standards of biocompatibility, osteoconduction, bioactivity and biodegradation that make it a particularly attractive alternative. Must protect the ceramic undue strain while putting it in contact with the bone surface to which it is desired to fusion. For this reason, we turned to the use of cages polyetheretherketone (PEEK), which are filled with ceramic ensuring immediate stabilization and that endures over time, for osseointegration. We use this type of cage since 2003 and their current presentations RSF (ready-set-fuse) since 2007, he is ready to install cage, sterile, single package, presented on a disposable cage holder (KG BONE KASIOS Biomaterials).

Technical

The technique uses a channel pre sterno-mastoid cleido classic type ROBINSON Smith by lateral anterior left approach centered on the floor to be treated under image control intensifier and the operating microscope. The horizontal incision in the folds of the 4 cm long neck, allows the dissection of the aero-digestive elements repressed inwards while the vessel elements are pushed apart until they reach the front side of the disc level concerned. Then put in place a retractor Caspar to achieve adequate distraction. Under the operating microscope, pathological discectomy disc is full, osteophytes are removed with strawberry or Kerrison forceps to the posterior longitudinal ligament is resected. Decompression may be complete; should allow good visualization of the dura and the departure of the roots. It is then strictly dissect the most central part of the endplates above and below while leaving a corolla device that will be used to support the cage peak to limit or avoid any phenomenon of collapse (subsidence). For this reason, the choice of the height of the cage is crucial, it is performed under control amp slight detraction so that self-locking by simply tension neck muscles, provides a self definitely complete stabilization preventing any mobilization cage. Furthermore, the contact area between the plate and the substitute must be discreetly sharpened to facilitate the fastest possible exchange between the cells and the patient's blood and bone substitute ready to be colonized. The height of the implant is also determined by the height of the adjacent discs.

Clinical Series: Indications

Our personal experience is about more than 200 cases and we have taken for this article, the most distant event. Clinical series beginning in 2003 and 2007 in its current format with the use of cages peek responsible substitute, called cages anatomical given their retantifs profiles and the presence of striated surfaces that allow immediate attachment to the endplates and prevents any possible cringe to the pharyngolaryngeal space. We distinguish two main types of indications, the soft disc herniation responsible for cervical brachial neuralgia refractory to medical treatment for more than 3 months with positive signs EMG to suggest a

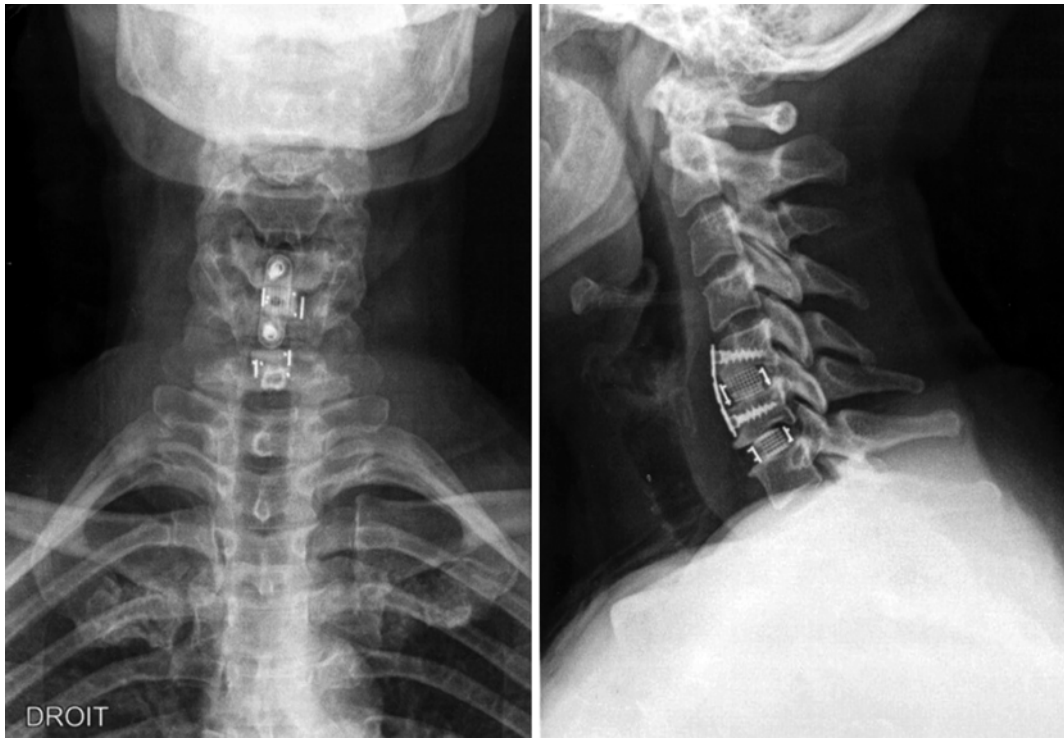


Fig. 15.4 Three months control of a double stabilization by cage with plate on 5/6 for re-lordosis and stand-alone on 6/7

confrontation with the clinic, rigorously root issue in compression phenomenon. As part of the treatment for herniated disc, we perform a remote installation of KGBONE cage without associated plate; as well as for the treatment of cervical-brachial neuralgia by uncarthrosis.

Our resort to the use of a plate located on the anterior aspect of the vertebral bodies in front of the space not filled cage is used only when wide bone resection, in case of change of slope trays, secondary to the release or when it is necessary to induce re-segmental lordosis. We then use the Wedge types of cages and protect the implant by the establishment of a bone plate. The procedure can be one or two floors, the plate protecting only the space that the angle has been modified and / or release imposed a modification of the anatomical profile of the vertebral plates (Fig. 15.4).

We are then in the treatment of cervico-arthrosis myelopathy second major indication or damage post-traumatic disc.

Analysis of Results

The purpose of this review is to analyze only the complications of surgical technique, performed according to the principles of minimally invasive surgery, or in connection with the hardware or RSF cages.

One hundred records were reviewed.

The average follow-up was 6 years with extremes ranging from 48 to 96 months.

- Regarding the surgical technique: no recovery for the stage in question; no hematoma or infection; three transient dysphagia less than 10 days; three dysphonia by recurrent laryngeal nerve paresis in three already operated for two patients in the cervical spine for the third of the thyroid. The three cases have recovered with speech therapy.
- No postoperative cervical collar; physiotherapy isometry the first three weeks and then possibly dynamic.

– About hardware: no recovery for the surgery floor
  No breakage substitute or cage
  No mobilization of equipment.
– Concerning fusion: it is confirmed by the presence of an osseous bridge between the two endplates. Typically the bone bridge is faster visible back of the cage; Then an earlier bridge is frequently observed; loss of lucency substitute on lateral radiographs confirmed bone colonization.

In case of doubt the dynamic views and scan with reconstructions can be concluded the merger or nonunion.

In our review, - 8 cases were syntheses, all fusion (100 % fusion with plate). - 92 cases received a single cage, 2 cases showed no melting criterion control to a year. A recovery was proposed with osteosynthesis which was refused. The fusion rate at one year was 97.8 % in this series. This is in agreement with the literature and the results published by RJ Mobbs [79].

One these two non-fusion patients also presented impaction of the cage. This phenomenon was found in two other cases that have merged but with impaction of the cage in the adjacent plates give an overall rate of subsidence 3.26 %. This rate is lower than in the literature, probably related to the surgical technique, our preparation of plates being very frugal, strictly maintaining a central "corolla" peripheral support for the cage.

Conclusion

Cages PEEK containing a dicalcium phosphate with hydroxyapatite ceramic is a reliable alternative to autograft in cervical surgery by anterior approach for the treatment of cervico neuralgia by herniated or uncarthrose and cervico-arthrosis myelopathy one, two or three floors. They provide an excellent fusion rate.

This is a simple, fast, reliable, decreasing the risk of infection. Ceramics realize real interbody fusions.

References

1. Vallet-Regí M. Ceramics for medical applications. J Chem Soc Dalton Trans. 2001;2:97–108.
2. Dorozhkin SV. Calcium orthophosphates in dentistry. J Mater Sci Mater Med. 2013;24:1335–63.
3. US Bone Grafts Market to Reach US$2.3 billion by 2017, according to new report by Global Industry Analysts, Inc. Available online: http://www.prweb.com/releases/bone_grafts/standard_bone_allografts/prweb8953883.htm. Accessed 3 Sept 2013.
4. Dorozhkin SV. Calcium orthophosphates: applications in nature, biology, and medicine. Pan Stanford: 8 Temasek Boulevard, Singapore; 2012. p. 850.
5. Oktar FN, Kesenci K, Pişkin E. Characterization of processed tooth hydroxyapatite for potential biomedical implant applications. Artif Cells Blood Substit Immobil Biotechnol. 1999;27:367–79.
6. Williams DF. On the nature of biomaterials. Biomaterials. 2009;30:5897–909.
7. Bongio M, van den Beucken JJJP, Leeuwenburgh SCG, Jansen JA. Development of bone substitute materials: from 'biocompatible' to 'instructive'. J Mater Chem. 2010;20:8747–59.
8. Mann S, editor. Biomimetic materials chemistry. Oxford: Wiley-VCH; 1996. p. 400.
9. Vallet-Regí M. Bioceramics: where do we come from and which are the future expectations. Key Eng Mater. 2008;377:1–18.
10. Jandt KD. Evolutions, revolutions and trends in biomaterials science—a perspective. Adv Eng Mater. 2007;9:1035–50.
11. Meyers MA, Chen PY, Lin AYM, Seki Y. Biological materials: structure and mechanical properties. Progr Mater Sci. 2008;53:1–206.
12. Ceramics. Available online: http://en.wikipedia.org/wiki/Ceramics. Accessed 14 Aug 2013.
13. Hench LL. Bioceramics: from concept to clinic. J Am Ceram Soc. 1991;74:1487–510.
14. Cao W, Hench LL. Bioactive materials. Ceram Int. 1996;22:493–507.
15. Hench LL. Bioceramics. J Am Ceram Soc. 1998; 81:1705–28.
16. Hench LL, Day DE, Höland W, Rheinberger VM. Glass and medicine. Int J Appl Glass Sci. 2010; 1:104–17.
17. Pinchuk ND, Ivanchenko LA. Making calcium phosphate biomaterials. Powder Metall Metal Ceram. 2003;42:357–71.
18. Heimann RB. Materials science of crystalline bioceramics: a review of basic properties and applications. CMU J. 2002;1:23–46.
19. Tomoda K, Ariizumi H, Nakaji T, Makino K. Hydroxyapatite particles as drug carriers for proteins. Colloids Surf B. 2010;76:226–35.
20. Zamoume O, Thibault S, Regnié G, Mecherri MO, Fiallo M, Sharrock P. Macroporous calcium phosphate ceramic implants for sustained drug delivery. Mater Sci Eng C. 2011;31:1352–6.
21. Bose S, Tarafder S. Calcium phosphate ceramic systems in growth factor and drug delivery for bone tissue engineering: a review. Acta Biomater. 2012;8:1401–21.
22. Arcos D, Vallet-Regí M. Bioceramics for drug delivery. Acta Mater. 2013;61:890–911.

23. Ducheyne P, Qiu Q. Bioactive ceramics: the effect of surface reactivity on bone formation and bone cell function. Biomaterials. 1999;20:2287–303.
24. Dorozhkin SV. Calcium orthophosphates and human beings. A historical perspective from the 1770s until 1940. Biomatter. 2012;2:53–70.
25. Dorozhkin SV. A detailed history of calcium orthophosphates from 1770s till 1950. Mater Sci Eng C. 2013;33:3085–110.
26. Vallet-Regí M, González-Calbet JM. Calcium phosphates as substitution of bone tissues. Progr Solid State Chem. 2004;32:1–31.
27. Taş AC, Korkusuz F, Timuçin M, Akkaş N. An investigation of the chemical synthesis and high-temperature sintering behaviour of calcium hydroxyapatite (HA) and tricalcium phosphate (TCP) bioceramics. J Mater Sci Mater Med. 1997;8:91–6.
28. Layrolle P, Ito A, Tateishi T. Sol-gel synthesis of amorphous calcium phosphate and sintering into microporous hydroxyapatite bioceramics. J Am Ceram Soc. 1998;81:1421–8.
29. Engin NO, Tas AC. Manufacture of macroporous calcium hydroxyapatite bioceramics. J Eur Ceram Soc. 1999;19:2569–72.
30. Ahn ES, Gleason NJ, Nakahira A, Ying JY. Nanostructure processing of hydroxyapatite-based bioceramics. Nano Lett. 2001;1:149–53.
31. Khalil KA, Kim SW, Dharmaraj N, Kim KW, Kim HY. Novel mechanism to improve toughness of the hydroxyapatite bioceramics using high-frequency induction heat sintering. J Mater Process Technol. 2007;187–188:417–20.
32. Laasri S, Taha M, Laghzizil A, Hlil EK, Chevalier J. The affect of densification and dehydroxylation on the mechanical properties of stoichiometric hydroxyapatite bioceramics. Mater Res Bull. 2010;45:1433–7.
33. Kitamura M, Ohtsuki C, Ogata S, Kamitakahara M, Tanihara M. Microstructure and bioresorbable properties of α-TCP ceramic porous body fabricated by direct casting method. Mater Trans. 2004;45:983–8.
34. Kawagoe D, Ioku K, Fujimori H, Goto S. Transparent β-tricalcium phosphate ceramics prepared by spark plasma sintering. J Ceram Soc Jpn. 2004;112:462–3.
35. Wang CX, Zhou X, Wang M. Influence of sintering temperatures on hardness and Young's modulus of tricalcium phosphate bioceramic by nanoindentation technique. Mater Charact. 2004;52:301–7.
36. Ioku K, Kawachi G, Nakahara K, Ishida EH, Minagi H, Okuda T, Yonezawa I, Kurosawa H, Ikeda T. Porous granules of β-tricalcium phosphate composed of rod-shaped particles. Key Eng Mater. 2006;309–311:1059–62.
37. Kamitakahara M, Ohtsuki C, Miyazaki T. Review paper: behavior of ceramic biomaterials derived from tricalcium phosphate in physiological condition. J Biomater Appl. 2008;23:197–212.
38. Vorndran E, Klarner M, Klammert U, Grover LM, Patel S, Barralet JE, Gbureck U. 3D powder printing of β-tricalcium phosphate ceramics using different strategies. Adv Eng Mater. 2008;10:B67–71.
39. Descamps M, Duhoo T, Monchau F, Lu J, Hardouin P, Hornez JC, Leriche A. Manufacture of macroporous β-tricalcium phosphate bioceramics. J Eur Ceram Soc. 2008;28:149–57.
40. Liu Y, Kim JH, Young D, Kim S, Nishimoto SK, Yang Y. Novel template-casting technique for fabricating β-tricalcium phosphate scaffolds with high interconnectivity and mechanical strength and in vitro cell responses. J Biomed Mater Res A. 2010;92:997–1006.
41. Carrodeguas RG, de Aza S. α-tricalcium phosphate: synthesis, properties and biomedical applications. Acta Biomater. 2011;7:3536–46.
42. Zhang Y, Kong D, Feng X. Fabrication and properties of porous β-tricalcium phosphate ceramics prepared using a double slip-casting method using slips with different viscosities. Ceram Int. 2012;38:2991–6.
43. Tancret F, Bouler JM, Chamousset J, Minois LM. Modelling the mechanical properties of microporous and macroporous biphasic calcium phosphate bioceramics. J Eur Ceram Soc. 2006;26:3647–56.
44. Bouler JM, Trecant M, Delecrin J, Royer J, Passuti N, Daculsi G. Macroporous biphasic calcium phosphate ceramics: influence of five synthesis parameters on compressive strength. J Biomed Mater Res. 1996;32:603–9.
45. Gauthier O, Bouler JM, Aguado E, Pilet P, Daculsi G. Macroporous biphasic calcium phosphate ceramics: influence of macropore diameter and macroporosity percentage on bone ingrowth. Biomaterials. 1998;19:133–9.
46. Daculsi G. Biphasic calcium phosphate concept applied to artificial bone, implant coating and injectable bone substitute. Biomaterials. 1998;19:1473–8.
47. Williams DF. The williams dictionary of biomaterials. Liverpool: Liverpool University Press; 1999. p. 368.
48. LeGeros RZ. Properties of osteoconductive biomaterials: calcium phosphates. Clin Orthop Relat Res. 2000;395:81–98.
49. Rey C, Combes C, Drouet C, Somrani S. Tricalcium phosphate-based ceramics. In: Kokubo T, editor. Bioceramics and their clinical applications. Cambridge: Woodhead Publishing in Materials; 2008. p. 326–66.
50. Ahato I. Reverse engineering the ceramic art of algae. Science. 1999;286:1059–61.
51. Popişter F, Popescu D, Hurgoiu D. A new method for using reverse engineering in case of ceramic tiles. Qual Access Success. 2012;13:409–12.
52. Yang S, Leong KF, Du Z, Chua CK. The design of scaffolds for use in tissue engineering. Part II. Rapid prototyping techniques. Tissue Eng. 2002;8:1–11.
53. Yeong WY, Chua CK, Leong KF, Chandrasekaran M. Rapid prototyping in tissue engineering: challenges and potential. Trends Biotechnol. 2004;22:643–52.
54. Hieu LC, Zlatov N, Sloten JV, Bohez E, Khanh L, Binh PH, Oris P, Toshev Y. Medical rapid prototyping applications and methods. Assem Autom. 2005;25:284–92.

55. Eufinger H, Wehniöller M, Machtens E, Heuser L, Harders A, Kruse D. Reconstruction of craniofacial bone defects with individual alloplastic implants based on CAD/CAM-manipulated CT-data. J Cranio Maxillofac Surg. 1995;23:175–81.
56. Klein M, Glatzer C. Individual CAD/CAM fabricated glass-bioceramic implants in reconstructive surgery of the bony orbital floor. Plast Reconstruct Surg. 2006;117:565–70.
57. Yin L, Song XF, Song YL, Huang T, Li J. An overview of in vitro abrasive finishing & CAD/CAM of bioceramics in restorative dentistry. Int J Mach Tools Manuf. 2006;46:1013–26.
58. Li J, Hsu Y, Luo E, Khadka A, Hu J. Computer-aided design and manufacturing and rapid prototyped nanoscale hydroxyapatite/polyamide (n-HA/PA) construction for condylar defect caused by mandibular angle ostectomy. Aesthet Plast Surg. 2011;35: 636–40.
59. Kokubo T, editor. Bioceramics and their clinical applications. Cambridge: Woodhead Publishing; 2008. p. 784.
60. Oktar FN, Genc Y, Goller G, Erkmen EZ, Ozyegin LS, Toykan D, Demirkiran H, Haybat H. Sintering of synthetic hydroxyapatite compacts. Key Eng Mater. 2004;2087–2090:264–8.
61. Monroe EA, Votava W, Bass DB, McMullen J. New calcium phosphate ceramic material for bone and tooth implants. J Dent Res. 1971;50:860–1.
62. Jarcho M. Calcium phosphate ceramics as hard tissue prosthetics. Clin Orthop Relat Res. 1981;157: 259–78.
63. Yuan H, De Bruijn JD, Li Y, Feng J, Yang Z, De Groot K, Zhang X. Bone formation induced by calcium phosphate ceramics in soft tissue of dogs: a comparative study between porous alpha-TCP and beta-TCP. J Mater Sci Mater Med. 2001;12(1):7–13.
64. Yuan H, van Blitterswijk CA, de Groot K, de Bruijn JD. Cross-species comparison of ectopic bone formation in biphasic calcium phosphate (BCP) and hydroxyapatite (HA) scaffolds. Tissue Eng. 2006; 12(6):1607–15.
65. Wilson CE, Kruyt MC, de Bruijn JD, van Blitterswijk CA, Oner FC, Verbout AJ, Dhert WJ. A new in vivo screening model for posterior spinal bone formation: comparison of ten calcium phosphate ceramic material treatments. Biomaterials. 2006;27(3): 302–14.
66. Habibovic P, Yuan H, van der Valk CM, Meijer G, van Blitterswijk CA, de Groot K. 3D microenvironment as essential element for osteoinduction by biomaterials. Biomaterials. 2005;26(17):3565–75.
67. Takadama H, Kokubo T. vitro evaluation of bone bioactivity. In: Kokubo T, editor. Bioceramics and their clinical applications. Cambridge: Woodhead Publishing in Materials; 2008. p. 165–82.
68. Eidelman N, Chow LC, Brown WE. Calcium phosphate saturation levels in ultrafiltered serum. Calcif Tissue Int. 1987;40(2):71–8.
69. Hench LL, Splinter RJ, Allen WC, Greenlee TK. Bonding mechanisms at the interface of ceramic prosthetic materials. J Biomed Mater Res. 1972;2:177–41.
70. Duan YR, Zhang ZR, Wang CY, Chen JY, Zhang XD. Dynamic study of calcium phosphate formation on porous HA/TCP ceramics. J Mater Sci Mater Med. 2004;15(11):1205–11.
71. Lu J, Descamps M, Dejou J, Koubi G, Hardouin P, Lemaitre J, Proust JP. The biodegradation mechanism of calcium phosphate biomaterials in bone. J Biomed Mater Res. 2002;63:408–12.
72. Wang H, Lee JK, Moursi A, Lannutti JJ. Ca/P ratio effects on the degradation of hydroxyapatite in vitro. J Biomed Mater Res A. 2003;67:599–608.
73. Teitelbaum SL. Bone resorption by osteoclasts. Science. 2000;289:1504–8.
74. Bertazzo S, Zambuzzi WF, Campos DDP, Ogeda TL, Ferreira CV, Bertran CA. Colloids Surf B. 2010;78: 177–84.
75. LeGeros RZ. Properties of osteoconductive biomaterials: calcium phosphates. Clin Orthop Relat Res. 2002;395:81–98.
76. Rezwan K, Chen QZ, Blaker JJ, Boccaccini AR. Biodegradable and bioactive porous polymer/inorganic composite scaffolds for bone tissue engineering. Biomaterials. 2006;27(18):3413–31.
77. Klenke FM, Liu Y, Yuan H, Hunziker EB, Siebenrock KA, Hofstetter W. Impact of pore size on the vascularization and osseointegration of ceramic bone substitutes in vivo. J Biomed Mater Res A. 2008;85(3): 777–86.
78. Zhu XD, Fan HS, Xiao YM, Li DX, Zhang HJ, Luxbacher T, Zhang X D. Effect of surface structure on protein adsorption to biphasic calcium-phosphate ceramics in vitro and in vivo. Acta Biomater. 2009;5(4):1311–18.
79. Mobbs RJ, Chau AM, Durmush D. Biphasic calcium phosphate contained within a polyetheretherketone cage with and without plating for anterior cervical discectomy and fusion. Orthop surg. 2012;4(3): 156–65.

Cervical Disc Arthroplasty

16

Luigi Aurelio Nasto and Carlo Logroscino

Introduction

The cervical spine consists of seven vertebral bodies with intervening discs. The discs and the unique configuration of the posterior zygoapophyseal joints allow a full 3D positioning of the head in the space, while the vertebral bodies provide a protective passage for the spinal cord and vertebral arteries. Degenerative changes in intervertebral discs due to aging or trauma can alter significantly the biomechanics of the cervical spine and lead to compression of nerve roots or spinal cord. For many years, the only available treatment option for cervical degenerative disc disease has been either discectomy (*anterior cervical discectomy*, ACD) or discectomy and fusion (*anterior cervical discectomy and fusion,* ACDF). In recent years cervical disc arthroplasty (or *cervical total disc replacement,*TDR) has emerged as a viable alternative to fusion and the development of new artificial disc devices has been an area of intense research. The aim of this chapter is to present the current state of this technique, including the results of the best available outcome studies of the most common devices.

Anterior cervical discectomy and fusion (ACDF) surgery was pioneered by Cloward and Smith - Robinson in early 1950s. Following the early encouraging results, the new technique rapidly spread out and became the gold standard in treatment of cervical spondylosis and disc degeneration. Numerous recent studies have reported good to excellent results in 70–90 % of patients, and a fusion rate of 89 % in single level operation [1]. However, despite being a successful and widely used procedure some important drawbacks of this technique have become apparent as more fusions are performed every year throughout the world.

Adjacent segment degeneration is defined as the radiographic appearance of degenerative changes at a level above or below a fused segment. The reported incidence of this phenomenon varies greatly in literature, and it is a matter of intense debate among spinal surgeons. It is worth noting that a clear difference exists in the meaning of the terms *adjacent segment degeneration (ASDeg)* and *adjacent segment disease (ASDis)*.

L.A. Nasto, MD
Department of Orthopaedics and Traumatology, Catholic University of Rome, "A. Gemelli" University Hospital, l.go Agostino Gemelli 8, Rome 00168, Italy

The Centre for Spinal Studies and Surgery, Queen's Medical Centre, Nottingham University Hospitals NHS Trust, Derby Road, NG7 2UH Nottingham, United Kingdom

C. Logroscino, MD (✉)
Department of Orthopaedics and Traumatology, Catholic University of Rome, "A. Gemelli" University Hospital, l.go Agostino Gemelli 8, Rome 00168, Italy
e-mail: studio@carlologroscino.it

P.P.M. Menchetti (ed.), *Cervical Spine: Minimally Invasive and Open Surgery*,
DOI 10.1007/978-3-319-21608-9_16

Adjacent segment disease is defined as adjacent segment degeneration with clinical symptoms (pain or neurologic disorders or both), whilst *adjacent segment degeneration (ASDeg)* only refers to the presence of radiographic degenerative changes in the absence of clinical symptoms. This distinction is not always clear in literature, and often leads to unclear estimates of the real extent of the phenomenon.

In 1999, Hilibrand et al. [2] reported on the long-term outcome of 374 patients after single and multiple-level ACDF surgery and observed a constant yearly incidence of ASDis of 2.9 % (range, 0.0–4.8 % per year) during the first 10-years after the operation. The Kaplan-Meier survivorship analysis developed by the authors suggested that 13.6 % of patients with ACDF will develop ASDis within the first 5 years after surgery and that 25.6 % will have new disease within 10 years after the index procedure. Although the actual reported figures of 11.7 % prevalence of ASDis at 5 years and 19.2 % prevalence at 10 years are slightly lower, they provide a good overview of the real extent of the problem. Other authors [3, 4] have confirmed these findings reporting an incidence of ASDis of 25 % at 5–10 years after surgery. On the other hand, reported incidence of ASDeg is much higher as shown by many studies available in literature. In 2004, Goffin et al. [5] studied the long-term outcome of 108 patients after ACDF surgery and observed a 92 % rate of ASDeg at 5 years after surgery. More recently, Matsumoto et al. [6] conducted a prospective 10-year follow-up study on 64 patients who underwent ACDF and 201 asymptomatic volunteers and found progression of degenerative changes to be significantly more frequent in the ACDF group.

Although reported data suggest a strong correlation between ACDF surgery and higher risk of ASDis, this is most likely a multifactorial process. The incidence of degenerative changes in the cervical spine increases with aging. In a seminal study which is both beautiful in its simplicity and informative in its results, Boden et al. [7] studied the prevalence of degenerative changes in the cervical spine of 68 asymptomatic volunteers and found that abnormalities were present in 14 % of the subjects less than 40 years old and in 28 % of those who were older than 40. In a different study on cervical disc herniation and radiculopathy, Henderson et al. [8] noted new radiculopathy at a different level in 9 % of 846 patients after postero-lateral foraminotomy without fusion at an average of 3 years after surgery. This study is frequently cited by authors who believe that ASDeg/ASDis is part of the normal aging process of the cervical spine and the higher incidence observed in patients treated with ACDF is to be related to an intrinsic genetic predisposition of these patients.

Other factors are also important in determining the risk of ASDeg. As shown by Nassr and co-workers [9] the insertion of a marking needle during surgery in a disc at the wrong level determined a 3-fold increase of the risk of disc degeneration at that level. Similarly, placement of an anterior plate within 5 mm from the adjacent segment has been shown to be a significant risk factor for adjacent level ossification and degeneration [10, 11]. On the other hand, intrinsic mechanical factors are also involved in the degeneration process. According to Hilibrand et al. [2] the relative risk of ASDis is 3.2 times higher at the C3-C4 and C4-C5 levels than C2-C3 level and 4.9 times higher at C5-C6 and C6-C7 interspaces. Biomechanical analyses have shown an increase of intradiscal pressure (stress) at the levels adjacent to a previous fusion and led to the concept that levels adjacent to a fusion have to compensate for the loss of motion in the fused segment [12]. Finally, more recent studies have also focused their attention of the effects of spine sagittal alignment on the incidence of ASDeg and ultimately ASDis. Many studies have shown a direct correlation between postoperative spinopelvic parameters (i.e. mismatch between lumbar lordosis and pelvic incidence) and higher risk of degenerative changes at adjacent levels to a lumbar fusion [13–15]. The effects of sagittal balance on ASDeg have been much less studied in the cervical spine, but it is reasonable to think that similar relationships can be identified between cervical sagittal imbalance and incidence of ASDeg [16].

The aim of cervical disc arthroplasty is to preserve segmental motion after removing local pathology that is deemed to be the cause of patient's symptoms. The typical candidate for cervical disc replacement is the young active adult with single level soft disc herniation and intact zygapophyseal joints. Motion preservation at the index level avoids stress raise at the adjacent levels and prevents later adjacent segment degeneration/disease (ASDeg/ASDis). By not achieving fusion, cervical disc replacement also avoids the morbidity of bone graft harvest and typical complications of ACDF surgery, such as pseudoarthrosis, issues caused by anterior cervical plating, and prolonged cervical spine immobilization.

History and Implant Design

Some basic understanding of the history of TDR is of pivotal importance in interpreting present clinical results and evaluating future devices. Many new implants have been developed in recent years, reflecting an increased interest on non-fusion technologies by industry and clinicians. However, over the last 40 years, three fundamental designs have emerged in TDR [17]. These three design philosophies have led to the development of three different prosthetic devices: the PRESTIGE (Medtronic, Inc.), the BRYAN (Medtronic, Inc.), and the ProDisc-C (Synthes-Spine, Inc.). These three implants will be discussed here and will serve as base knowledge to evaluate other available implants.

Early attempts at developing an artificial substitute of the intervertebral disc with stainless steel balls are credited to Ulf Fernstrom and date back to 1960s. However, the early clinical follow-up of the new technique showed unacceptably high rates of implant migration (88 %) and subsidence and led many surgeons to direct their interest towards fusion procedures [18]. Twenty years later, in 1989, B.H. Cummins at the Frenchay Hospital in Bristol, UK, developed the first model of a modern cervical disc arthroplasty. This new device consisted of two pieces of 316 L stainless steel with a metal-on-metal ball-and-socket design. The anchoring system consisted of two anterior screws that fixed the device to the vertebral body. Unfortunately, early implants were plagued by high incidence of screws pullout, dysphagia and implant mobilization [19].

A second-generation device was developed from the original Cummins prosthesis with the name of Frenchay artificial disc in 1998. The anterior profile of the device, the locking screw system and the articulating surface were all completely redesigned and following acquisition by Medtronic, Inc., renamed PRESTIGE I Disc. Several redesigns of the implants have led to the fourth-generation system, PRESTIGE ST, and more recently to the fifth-generation PRESTIGE LP (low profile) disc. Although the metal-on-metal design has not been modified, the articulating mechanism of the PRESTIGE ST has been changed into a coupled, semiconstrained system. The newer PRESTIGE LP model is made of a titanium-ceramic composite and incorporates two endplate rails for extra fixation strength in the vertebral body (Fig. 16.1).

The BRYAN cervical disc (Medtronic, Inc.) was designed by the American neurosurgeon Vincent Bryan from Seattle in 1990s. The concept and design of the BRYAN disc is completely different from the Bristol/PRODISC series. This device consists of two titanium alloy endplates articulating with a polyurethane core. The two titanium endplates are fixed to the bone by a porous titanium layer and stability is achieved through a tight fit of the prosthesis in the milled cavity (Fig. 16.2). The implant has been extensively tested in Europe and received US FDA approval in May 2009.

The third alternative to metal-on-metal implants is represented by the ProDisc-C device (Synthes, Inc.) which has recently obtained the approval for use in the United States. The ProDisc-C system was developed by Dr. Thierry Marnay in France and consists of two cobalt-chrome-molybdenum (CCM) endplates with an UHMWPE articulating surface. It is a ball-and-socket constrained prosthesis and has a central keel for extra fixation in the vertebral body.

Fig. 16.1 *Left*, PRESTIGE® ST cervical disc prosthesis; *Right*, PRESTIGE® LP prosthesis (Image provided by Medtronic, Inc)

Fig. 16.2 BRYAN® Cervical Disc prosthesis (the BRYAN® Cervical Disc incorporates technology developed by Gary K. Michelson, MD. Image provided by Medtronic, Inc)

Other devices have recently joined the market of cervical TDR. Kineflex-C disc (Spinal Motion, Inc.) and CerviCore disc (Stryker Spine, Inc.) are metal-on-metal implants, whilst PCM (CerviTech, Inc.), DISCOVER (DePuy Spine, Inc.), and the MOBI-C (LDR, Inc.) are metal-on-UHMWPE implants.

Indications for Use and Contraindications

The rationale of considering TDR rather than a standard fusion procedure (i.e. ACDF) lies in the aim of preserving motion of the treated segment and preventing adjacent-segment degeneration. The typical candidate patient for TDR is the young active adult patient with single level symptomatic disc disease (i.e. radiculopathy) from C3 to T1 with intact posterior facet joints. General contraindications are marked reduction of the disc space with loss of motion at that level, zygapophyseal joint osteoarthritis, significant deformity in the sagittal and coronal plane, clear segmental instability, and infection. Other relative contraindications include rheumatoid arthritis, renal failure, osteoporosis, cancer, and preoperative corticosteroid use [20].

Evaluation of sagittal alignment, presence of zygapophyseal joint osteoarthritis and instability is of paramount importance and should be undertaken as routine preoperative assessment in every patient. Standard X-ray films (i.e. AP and lateral view) of the cervical spine and flexion-extension studies are usually sufficient in clarifying the extent of residual movement at the index level

Table 16.1 List of commonly accepted indications and contraindications to cervical total disc replacement

Indications for cervical TDR	*Relative* indications for cervical TDR	Contraindications for cervical TDR
Radiculopathy caused by soft disc herniation	Radiculopathy caused by hard disc herniation	Osteoarthritis of the zygapophyseal joints
	Myelopathy caused by disc herniation	Sagittal malalignment of the cervical spine
	Radiculopathy caused by foraminal osteophytes	Segmental instability
		Infection
		Previous posterior surgery
		Ossification of the Posterior Longitudinal Legament (OPLL)

and the presence of osteoarthritic changes in the posterior joints.

The role of TDR in patients with axial neck pain has not been clarified yet and therefore disc pathology with no neurological symptoms should not be considered an indication for TDR. European and US trails have enrolled patients with cervical radiculopathy due to disc herniation (soft or hard), foraminal osteophytes as well as cervical myelopathy. In our clinical experience the presence of a hard disc herniation should be considered a relative contraindication to TDR due to frequent need of a more extensive disruption of the endplate for a satisfactory clearance of the canal. In both European and North American trials, there has been a strong prevalence of patients enrolled with radiculopathy (77–93 %) rather than cervical stenosis/myelopathy. The role of TDR in cervical myelopathy has been recently investigated by different authors. Sekhon and coworkers [21] from Australia reported on 11 patients with single level myelopathy treated with TDR and average follow-up of 18 months. Although significant improvement was reported in clinical outcome measures, two complications were noted. One patient developed heterotopic ossification, and another patient developed progression of myelopathic compression due to postoperative oedema. Moreover, worsening of sagittal alignment of the cervical spine was noted in three patients. On the other hand, other authors have reported their positive experience of TDR in myelopathic patients. Fay et al. [22] reported on the results of a comparative study of TDR in 151 consecutive patients with cervical radiculopathy and cervical myelopathy. At the average follow-up of 36 months, no differences were identified in the two groups in terms of clinical and radiographic outcomes. However in our opinion cervical TDR should be avoided in patients with cervical myelopathy. Complete clearance of the spinal canal and wide decompression of the spinal cord are top priorities in cervical myelopathy surgery and the achievement of a solid and stable fusion if the best single guarantee for a long term success of the decompression.

A summary of the most common indications and contraindications for cervical TDR is shown in Table16.1. Although a thorough discussion on the indications of TDR is not possible due to the recent introduction into clinical practice of this technique, indications and contraindications listed in the table are widely accepted by most authors.

Clinical Studies

BRYAN Disc

The BRYAN disc has the longest clinical and radiological follow-up among cervical TDR devices. The first multicentre study on this device was published in 2002 by Goffin and co-worker as part of a European prospective multicentre trial [23]. The study enrolled 60 patients with cervical radiculopathy or focal myelopathy non responsive to at least 6-weeks of conservative

treatment. Exclusion criteria were the presence of sole axial neck pain, malalignment of the cervical spine, previous neck surgery and cervical instability. Only single level implants were used for this study and clinical success rates at 6 months and 1 year were 86 and 90 %. Because of the lack of a control group, the authors assumed from the literature a target level of success rate of 85 % for ACDF surgery. The number of patient lost at follow-up was significant with only 30 patients available at the 1-year follow-up. No complications directly related to the implant were detected. However, three patients underwent revision operation for prevertebral hematoma drainage, posterior foraminotomy for residual compression, and posterior laminectomy for residual myelopathy.

In a second study, Goffin and colleagues [24] expanded their original study with a second group of patients treated with two levels TDR. The study reported the results for 103 patients in the single-level group and 43 patients in the two-level group at 2 years follow-up. Success rates for the single-level group were 90, 86, and 90 % at 6 months, 1 and 2 years follow-up respectively. Patients in the two-level group had success rates of 82 % at 6 months, and 96 % at 1 year. No device failure or subsidence was reported in this second study and an average postoperative range of motion of 7.9° per level in flexion-extension was recorded. Movement was maintained in 87.8 % of the single-level patients and 85.7 % of two-level patients. Four complications were reported including one case of prevertebral hematoma, one case of epidural hematoma, one case of pharyngeal and oesophageal injury, and one case of residual nerve root compression.

Although enrolment criteria for the European study included patients with focal myelopathy, the actual number of patients with myelopathy enrolled in the study was minimal. In a separate study, Sekhon et al. [21] reported the results of BRYAN disc in treatment of 11 patients with cervical myelopathy with average follow-up from 1 to 17 months. No complications were reported and improvement of Nurick grade of 0.72 points and NDI scale of 51.4 points was noted. In contrast to these observations, Lafuente et al. reported on clinical results of 37 patients with cervical radiculopathy and 9 patients with cervical myelopathy. Analysis of the results showed that radiculopathy patients were doing better than myelopathy patients. Moreover, patients with myelopathy were also more likely to experience residual symptoms [25].

The first extensive report on North American experience with the BRYAN disc has been published by Sasso and co-workers in 2007 and 2008 [26, 27]. The authors conducted a prospective, three-center, randomized trial on 115 patients randomized in a 1:1 ratio to disc replacement and ACDF and plate surgery. Inclusion criteria were similar to the European studies and included patients with cervical radiculopathy and focal myelopathy due to single-level disc degeneration with symptoms non responsive to conservative treatment. Follow-up was 2 years for 99 patients. The authors reported a longer operative time for the arthroplasty group (1.7 h vs 1.1 h) but a significantly lower NDI for the disc replacement group at 12 and 24 months (11 vs 20, $p = .005$). Analysis of arm pain at 1 and 2 years also favoured the arthroplasty group with significantly lower VAS scores (14 vs 28, $p = .014$). The reported average range of motion per level in the disc replacement group was 7.9° in flexion-extension at 24 months, whilst it was 0.6° in the fusion group. No complications related to the implants were noted, as well as no heterotopic ossifications. Six patients underwent additional operations during the follow-up period, four patients in the control group and 2 patients in the BRYAN group. Four patients (2 in the control group and 2 in the BRYAN group) underwent a new ACDF surgery for adjacent segment degeneration.

The most recent and comprehensive study on BRYAN disc has been published by Heller and colleagues in 2009 [28]. This was part of the US IDE trial for FDA approval of the device and consisted of a prospective, randomized, controlled trial on 463 patients with minimum follow-up of 24 months. Inclusion criteria and outcomes measures were similar to the studies published by Sasso and co-workers [26, 27]. A total of 242 patients were enrolled in the BRYAN group and 221 patients in the control group (ACDF with

plating). Fusion occurred in 94.1 % of the ACDF patients at the final follow-up. Although both groups showed improvement of the outcome measures, analysis of the data favoured the BRYAN group in several outcomes, including NDI, neck pain and return to work. Overall success rate was 82.6 % for the disc replacement group and 72.9 % for the ACDF group at 2 years. Complications occurred in 75 patients (31.0 %) of the disc replacement group and 61 (27.6 %) of the fusion group. Almost all complication were related to general medical conditions, secondary procedures were needed in only 6 patients for the BRYAN group (1 revision, 3 removals of the implant, and 2 re-operations) and in 8 patients for the fusion group (3 removals, 1 re-operation, and 4 supplemental fixations). Total revision rate for the BRYAN group was 2.9 and 3.2 % for the ACDF group. The average range of motion at 24 months for the arthroplasty group was 8.1°.

ProDisc-C

The ProDisc-C implant has received the US FDA approval for use in single-level disc arthroplasty due to the good results reported by the IDE study by Murray and colleagues [29]. An earlier study by Bertagnoli et al. [30] reported on the results of 27 patients treated with single-level ProDisc-C implantation at 1 year follow-up. Patients experienced sustained improvement of their symptoms at 1 year follow-up with decrease of NDI and VAS scores. No device complications were reported.

The actual FDA approval study was published in 2009 [29]. It was a prospective, multicenter, randomized controlled trail conducted on patients with single-level pathology. A 1:1 randomization scheme was adopted, 106 patients were randomized into the ACDF group and 103 patients in the arthroplasty group. VAS, NDI, and SF-36 scores were recorded at 3, 6, 12, 18, and 24 months after surgery. Clinical outcome measures significantly improved in both groups after surgery and results were maintained at final follow-up. Arthroplasty group maintained range of motion at the index level in 84.4 %. Overall, the ProDisc-C group showed results equivalent or slightly superior to the ACDF group although there was a statistically significant difference in the complication rates. In the fusion group, 8.5 % of the patients needed re-operation, revision, or supplemental fixation compared with 1.8 % of the ProDisc-C group ($p = .033$).

PRESTIGE Disc

The Cummins/Bristol device was the precursor of the PRESTIGE series of disc arthroplasty. The Cummins disc was developed to address the problem of disc degeneration in patients with previous fusions or with Klippel-Feil syndrome. The first study on this device enrolled 20 patients and showed, at 5 years, significant clinical improvement and preservation of the movement in 88.9 % of the patients. Unfortunately, a high rate of complications was reported, including screw loosening, mobilization of the implant, dysphagia and transient hemiparesis.

The PRESTIGE I and II discs were developed as an evolution of the original Cummins disc. Clinical results of the PRESTIGE I disc were published by Wigfield and coworkers in 2002. A total of 15 patients were enrolled in a prospective non randomized trial. Inclusion criteria encompassed patients with cervical radiculopathy or single level myelopathy secondary to cervical disc herniation or foraminal osteophytes. No significant complications were reported by the authors and all patients showed preservation of motion at the index level at 2 years after surgery. Mean flexion-extension ROM was 6.5° and mean antero-posterior translation was 2 mm. Clinical improvement was documented by ODI, NDI, and SF-36 but no valuable statistical analysis was undertaken because of the small number of patients. The PRESTIGE II implant was studied by Porchet and Metcalf on 55 patients. Standard clinical and radiographic evaluation was undertaken by the authors and the results showed a substantial overlap between the artificial disc and the ACDF surgery group.

The best available data on clinical safety and efficacy of the PRESTIGE ST disc has been

published in 2007 by Mummaneni and colleagues. Data from this report have also served as the basis for the current FDA approval of this device in the United States. The study consisted in a prospective 1:1 randomized trial with patients undergoing either single level disc arthroplasty or single level ACDF. A total of 541 patients were enrolled, 276 patients in the PRESTIGE ST group and 265 patients in the ACDF group. The study showed a two-point greater improvement of NDI in the investigational group at 12 and 24 months. Improvement in SF-36 questionnaire scores was higher in the arthroplasty group at 12 and 24 months, as well as the VAS score. The rate of revision surgery was lower for the interventional group (5 revision surgeries) vs the fusion group (23 revision surgeries). No device failures or complications were reported, the average motion preservation at 2 years was 7°. The PRESTIGE LP disc arthroplasty has received FDA approval for use in patients in July 2014.

In a recent meta-analysis, McAfee and colleagues have summarized best available evidences about the use of cervical total disc replacement in clinical practice. The authors looked at the reported results of four prospective randomized controlled FDA IDE trials using BRYAN, PRESTIGE, ProDisc-C, and PCM implants. Data from 1226 patients at 24 months were available for the analysis. Results showed an overall success rate of 70.8 % in the ACDF patients and 77.6 % in the arthroplasty group ($p = 0.007$), thus favouring this last treatment. The analysis of all clinical subcomponents (i.e. neck disability index, neurological status, and survivorship) also favoured arthroplasty over ACDF surgery at 24 months. Survivorship ranged from 90.9 % in the PRESTIGE group to 98.1 % in the ProDisc-C group. Survivorship was achieved by 96.6 % of the cervical arthroplasty group on average and by 93.4 % of the ACDF patients. Some criticism has been raised regarding the poor results of the ACDF surgery (70.8 % overall success rate) in the reported FDA IDE trials. As pointed out by the authors of the study a common perception of a much higher success rate in fusion patients undermines confidence in the results of these trials. FDA criteria for definition of *success* are much more stringent than what has been traditionally reported in observational studies on ACDF surgery. This may account for the lower than expected results of the control fusion groups; taken together these data suggest that cervical disc arthroplasty is at least as clinically successful as fusion at 24 months [31].

Complications

Cervical disc replacement surgery shares with standard anterior cervical fusion surgery the same risks related to surgical approach. In a recent retrospective review by Fountas et al. of 1015 cases of primary one, two, and three level ACDF and plating, reported mortality was 0.1 %; 9.5 % of the patients suffered from postoperative dysphagia, 3.1 % had recurrent laryngeal nerve palsy, 2.4 % prevertebral hematoma, 0.5 % had dural perforation, 0.1 % hardware failure, and 0.1 % wound infection [32]. Access related complications for cervical arthroplasty are in the same range. In the two European studies on BRYAN disc, 0.97 % of patients (1 out of 103) required evacuation of prevertebral hematoma, and 2.91 % (3 out of 103) required additional surgery to decompress the neural canal. Dural tear was noted in 2.33 % of patients, and one patient required oesophageal tear repair [23, 24]. Analysis of complications in one FDA IDE trail showed more general medical complications in patients who underwent total disc replacement than the fusion group. Dysphonia/dysphagia was noted in 10 % of patients in the arthroplasty group, and 2.8 % of patients developed wound infection [28].

Heterotopic ossifications (HO) and anterior ankylosis is a known and dreaded complication of cervical disc replacement surgery. Leung and colleagues reported an incidence of 17.8 % (16 patients) of HO in a multicentre study on BRYAN disc arthroplasty [33]. Similarly, Mehren et al. reported an incidence of moderate (grade III) HO of 10.4 % at 4 years after surgery in a case series of 54 patients treated with ProDisc-C, whereas 7 cases (9.1 %) had spontaneous fusion of the

treated segment at 1 year after surgery [34]. Other studies have reported similar figures in the range of 11–44 % with concomitant adjacent segment degeneration [35, 36]. Identified risk factors for heterotopic ossifications are pre-existing spondylosis, male gender and increased age [33]. Nevertheless, the aetiology of this complication of TDR remains unknown. Some authors speculate that the extensive dissection of the longus colli muscle could be a contributing factor, while others think that extensive endplate milling should be taken into account. Non-steroidal anti-inflammatory drugs (NSAIDs) have been shown to be effective in preventing HO in hip arthroplasty and similarly some authors have advised their use for prevention of this complication in cervical TDR as well. Standard protocol requires administration of NSAIDs for 2 weeks after surgery although this practice is still not supported by any evidence [28, 37].

The aim of cervical arthroplasty is to preserve movement at the index level and avoid mechanical overloading of adjacent segments. Sagittal alignment of the spine is of paramount importance in determining load distribution on discs and posterior joints. Multiple studies have reported post-operative kyphosis as an adverse event of cervical TDR [38, 39]. Troyanovich and co-workers have shown that adjacent segments to a kyphotic level develop compensating hyperlordosis and accelerated degeneration [40]. Kyphosis may be caused by preoperative loss of physiological lordosis of the cervical spine but also by asymmetric milling of the endplates, wrong insertion angle of the implant, or undersizing of the prosthesis [41].

Implant subsidence and/or migration have been also reported by some authors. Goffin and colleagues reported a total of 4 implant complications (3 cases of subsidence and 1 case of implant migration) in a series of 146 patients. Implant failures were related to an improper milling of the endplates and implant positioning [24]. General advice is to avoid TDR in osteoporotic patients because of the increased risk of implant subsidence and supposedly stress shielding effect of the implant on adjacent bone. The largest available and possible implant footprint should also be used in each patient in order to increase the load sharing area of the implant. It is important to notice that no cases of posterior migration and neurological compromise due to cervical arthroplasty have been reported so far to our knowledge. On the other hand some keeled implants carry the risk of vertebral body fracture during implant insertion. Datta and co-workers reported a case of C6 vertebral body fracture during insertion of a keeled implant [42]. Similarly Shim and colleagues described a case of an avulsion fracture [43]. A specific disadvantage of keeled implants is the bone defect created in the vertebral body and the need of extra bone graft in case of revision of the implant. Although no specific reports have been published in literature, the decreased bone stock may be a problem if a salvage fusion is needed.

"Aseptic loosening" or failure of a total joint arthroplasty is a very well-known phenomenon of polymer-bearing implants in general orthopaedics. Failure of the implants in these cases is related to the local inflammatory response induced by the wear debris released by the prosthesis. Macrophages and inflammatory cells incorporate wear debris and release inflammatory cytokines which induce a progressive bone resorption and eventually mechanical failure of the implant. The amount and type of local response varies with the size, shape, amount and surface chemical reactivity of the released particles [44]. There is some concern that this effect may lead to aseptic loosening and chronic inflammatory reaction in cervical TDR as well. Cavanaugh and co-workers reported a case where a revision of TDR was performed and a local chronic inflammatory reaction was noted, the patient also developed a delayed hypersensitivity reaction to metal ions [45]. More recently, Guyer and colleagues reported on 4 cases of early failure of metal-on-metal TDR presenting with worsening pain and/or radicular symptoms. There were 3 cases of lumbar TDR and 1 case of cervical TDR, all patients underwent posterior decompression and anterior removal of the implant. In the cervical case the authors observed the presence of a gray-tinged soft-tissue surrounding the implant suggestive of metallosis

[46]. Goffin also reported on a similar case with a BRYAN prosthesis where a chronic inflammatory reaction led to osteolysis and loosening of the implant. Lebl et al. recently published a case series of 30 ProDisc-C implants removed and analysed using light stero-microscopy, scanning electron microscopy and x-ray. Posterior endplate-endplate impingement was present in 80 % of the implants. Although no backside wear was observed, third-body wear occurred in 23 % of the implants [47].

Anderson published two seminal studies on *in vitro* behaviour of the BRYAN prosthesis [48, 49]. The authors showed that wear debris by this implant is produced at a rate of 1.2 mg/1 million cycles with decrease of implant height of 0.02 mm/1 million cycles. The average size of debris particle was 3.9 μm, larger than the particles observed with hip and knee arthroplasty (1–1.8 μm). In a second study the same authors confirmed the linear relationship between the number of cycles and loss of prosthesis height. Observed wearing of the BRYAN polymeric nucleus was uniform and particulate diameter was on average 3.89 μm. The authors also tested the same device in an animal model of goats sacrificed at 3, 6, and 12 months after implantation of the artificial disc. A trend of increased local inflammatory reaction was noted with later sacrifices in the prosthesis group, however the amount of inflammatory reaction and local debris was higher in the control group treated with fusion and anterior plating. As clinical experience of cervical TDR expands over time, more studies will be needed to fully assess the long-term risks of wear debris released by the implants.

Biomechanics

The main aim of cervical TDR is maintenance of segmental motion at the index level and avoidance of adjacent segment degeneration. Several studies have shown that segments adjacent to a fusion develop increased compensatory movement and higher intradiscal pressure [12, 50, 51]. These changes are thought to be the basis of increased incidence of ASDeg/ASDis after fusion. Therefore, the most important aim of cervical TDR is to restore the physiological segmental motion of the treated level. Each cervical motion segment consists of three joints, the disc in the front and the two zygapophyseal joints in the back. Ligaments provide extra stability to the motion segment and help prevent extreme motions. The normal cervical spine exhibits flexion-extension movement as well as some anterior translation. The centre of motion is mobile during flexion-extension in order to accommodate for the anterior and posterior translation. Motion constraints also change with flexion-extension. In flexion, load is applied to the disc and posterior joints "unlock" reducing their constraining effects. In extension, load is applied on the posterior joints which also "lock" and limit the amount of possible movement. Therefore, from a mechanical point of view, it is extremely important to achieve a correct balance between posterior joints and intervertebral disc.

In vivo and *in vitro* studies have confirmed these ideas on the motion of the cervical spine. TDR has been shown to maintain index-level sagittal motion, translation, coupled motion in lateral bending with rotation, disc-space height, and centre of rotation, as compared with preoperative or intact states [52, 53]. However, biomechanical studies have shown some important differences in the design of the implants that can significantly affect the *in vivo* biomechanical behaviour of the prostheses. DiAngelo and colleagues compared motion of two different implants on human cadaveric cervical spines. The PRESTIGE disc was chosen as a typical semiconstrained implant, whilst the ProDisc-C implant was chosen as typical constrained implant. Results of the study were in support of a semiconstrained implant because of a better restoration of normal kinematics in all movements, most importantly the anterior translation movement of the normal cervical spine [50, 54].

Sasso and colleagues have also studied the long-term outcome in terms of motion preservation in a cohort of prospectively enrolled patients [55]. Longest follow-up available for the study was at 24 months. Data showed that motion is preserved at 24 months in the prosthesis group.

Average flexion-extension was 7.95° and postero-anterior translation 0.36 mm. Interestingly, the authors reported no statistically significant difference with regard to adjacent segment motion in the investigational group vs the fusion group. In contrast with these findings, Chang and colleagues have shown a net and significant decrease of adjacent segment motion in patients treated with two cervical TDR (PRESTIGE and Prodisc-C), whilst increased motion was observed in the ACDF control group [56].

Cost Analysis

A great deal of discussion in the cervical arthroplasty field revolves around the increased costs of this procedure and the short and long-term technological and economical impact of widespread usage of this new technique. Average cost of a single-level cervical total disc replacement implant is about $4000 in the US, whilst the cost for a cervical interbody cage and anterior plate is $2500 [57]. The target market of disc arthroplasty technologies is huge. In US only, a total of 450,000 cervical and lumbar fusion procedures are performed every year and conservative estimations are that 47.9 % of these patients would be good candidates for a motion preservation procedure. The estimated yearly revenue from this segment of the market was $2.18 billion dollars in 2010 [57].

Early cost-analysis studies have only focused on the simple comparison of raw costs of ACDF surgery vs cervical disc replacement surgery. Increased costs were justified by a supposedly decreased number of adjacent-segment operations and earlier return to work and active life. Interest in motion preservation technologies has increased in recent years, and more in depth analyses of costs have been published. Qureshi and co-workers conducted a cost-effectiveness analysis comparing single-level disc arthroplasty vs ACDF surgery. The authors assumed an average failure rate (pseudoarthrosis or hardware failure) of ACDF at 1 year of 5 %, and incidence of ASDis of 3 %. Failure rate of disc arthroplasty at 1 year was assumed in the range of 0–2 %. Costs of the two procedures were estimated using the 2010 Medicare database. Supported by a recent meta-analysis of 4 randomized trials on disc arthroplasty vs ACDF the authors also assigned a utility value to TDR of 0.9 (scale 0–1) as compared to ACDF which was assigned a slightly lower value, 0.8. According to the authors disc replacement surgery generated a total lifetime cost of $11,987, whilst ACDF lifetime cost was $16,823. Cervical disc replacement resulted in a generation of 3.94 QALY, whereas ACDF resulted in 1.92 [58]. A similar analysis by Warren and colleagues showed an average cost for ACDF of $16,162 and TDR of $13,171. QALY increase at 2 years was better for ACDF than TDR using NDI results (0.37 vs 0.27), but better for the disc replacement group when comparing SF-36 results (0.47 vs 0.32) [59].

Although real cost estimation is extremely difficult and varies greatly in different health care systems and settings, the more recently published studies are more positive about the clinical utility of cervical arthroplasty. However, although figures seem to support the use of cervical arthroplasty in clinical practice, it must be kept in mind that these studies are based on some fundamental assumptions. Sensitivity analysis by Qureshi and co-workers showed that TDR is a cost-effective strategy once survival time of the prosthesis approaches 11 years. A survival time of the prosthesis less than 9.75 years means that ACDF is a better and more convenient strategy [58]. At the present time, the longest term clinical data on disc arthroplasty available in literature are at 6 years follow-up [31]. These observations call for more long-term studies of clinical efficacy of cervical disc arthroplasty.

Conclusions

Cervical disc arthroplasty has progressed over the last three decades from a merely hypothesis to a clinical reality. Although it is still far from being a commonly accepted standard for treatment of cervical disc herniation and related conditions, the concept of artificial substitution of cervical discs has been adopted by many spinal surgeons and centres throughout the world. Early failures and complications

have fostered more research in cervical spine biomechanics and design of better implants. Biomechanical studies have also confirmed that disc replacement decreases the amount of stress posed on adjacent motion segments and on this observation is based the promise of this technique of reducing the incidence of adjacent segment degeneration and disease. Finally, wear analysis seems to confirm the safety of the implants with regard to tissue reaction and aseptic mobilization at least at medium-term follow-up. Available short and medium-term clinical studies show that cervical arthroplasty offers similar, and in some cases, better results than the commonly accepted "golden standard" of fusion. This has been confirmed by short and medium-term studies reporting survivorship rates for cervical arthroplasty superior to ACDF surgery. Nevertheless only long-term studies can fully validate this hypothesis and prove clinical utility of cervical TDR. As interest for non-fusion technologies from spinal surgeons, industry, and patients increases, cervical total disc replacement will remain an active and fruitful area of research of spinal surgery in the years to come.

References

1. Bohlman HH, et al. Robinson anterior cervical discectomy and arthrodesis for cervical radiculopathy. Long-term follow-up of one hundred and twenty-two patients. J Bone Joint Surg Am. 1993;75(9): 1298–307.
2. Hilibrand AS, et al. Radiculopathy and myelopathy at segments adjacent to the site of a previous anterior cervical arthrodesis. J Bone Joint Surg Am. 1999;81(4):519–28.
3. Baba H, et al. Late radiographic findings after anterior cervical fusion for spondylotic myeloradiculopathy. Spine (Phila Pa 1976). 1993;18(15):2167–73.
4. Gore DR, Sepic SB. Anterior cervical fusion for degenerated or protruded discs. A review of one hundred forty-six patients. Spine (Phila Pa 1976). 1984;9(7):667–71.
5. Goffin J, et al. Long-term follow-up after interbody fusion of the cervical spine. J Spinal Disord Tech. 2004;17(2):79–85.
6. Matsumoto M, et al. Anterior cervical decompression and fusion accelerates adjacent segment degeneration: comparison with asymptomatic volunteers in a ten-year magnetic resonance imaging follow-up study. Spine (Phila Pa 1976). 2010;35(1):36–43.
7. Boden SD, et al. Abnormal magnetic-resonance scans of the cervical spine in asymptomatic subjects. A prospective investigation. J Bone Joint Surg Am. 1990;72(8):1178–84.
8. Henderson CM, et al. Posterior-lateral foraminotomy as an exclusive operative technique for cervical radiculopathy: a review of 846 consecutively operated cases. Neurosurgery. 1983;13(5):504–12.
9. Nassr A, et al. Does incorrect level needle localization during anterior cervical discectomy and fusion lead to accelerated disc degeneration? Spine (Phila Pa 1976). 2009;34(2):189–92.
10. Kim HJ, et al. The risk of adjacent-level ossification development after surgery in the cervical spine: are there factors that affect the risk? a systematic review. Spine (Phila Pa 1976). 2012;37(22 Suppl):S65–74.
11. Park JB, Cho YS, Riew KD. Development of adjacent-level ossification in patients with an anterior cervical plate. J Bone Joint Surg Am. 2005;87(3):558–63.
12. Dmitriev AE, et al. Adjacent level intradiscal pressure and segmental kinematics following a cervical total disc arthroplasty: an in vitro human cadaveric model. Spine (Phila Pa 1976). 2005;30(10):1165–72.
13. Park JY, et al. New prognostic factors for adjacent-segment degeneration after one-stage 360 degrees fixation for spondylolytic spondylolisthesis: special reference to the usefulness of pelvic incidence angle. J Neurosurg Spine. 2007;7(2):139–44.
14. Sudo H, et al. Biomechanical study on the effect of five different lumbar reconstruction techniques on adjacent-level intradiscal pressure and lamina strain. J Neurosurg Spine. 2006;5(2):150–5.
15. Barrey C, et al. Sagittal balance of the pelvis-spine complex and lumbar degenerative diseases. A comparative study about 85 cases. Eur Spine J. 2007;16(9):1459–67.
16. Ozer E, et al. Kyphosis one level above the cervical disc disease: is the kyphosis cause or effect? J Spinal Disord Tech. 2007;20(1):14–9.
17. Baaj AA, et al. History of cervical disc arthroplasty. Neurosurg Focus. 2009;27(3):E10.
18. Fernstrom U. Arthroplasty with intercorporal endoprothesis in herniated disc and in painful disc. Acta Chir Scand Suppl. 1966;357:154–9.
19. Cummins BH, Robertson JT, Gill SS. Surgical experience with an implanted artificial cervical joint. J Neurosurg. 1998;88(6):943–8.
20. Duggal N, et al. Early clinical and biomechanical results following cervical arthroplasty. Neurosurg Focus. 2004;17(3):E9.
21. Sekhon LH. Cervical arthroplasty in the management of spondylotic myelopathy: 18-month results. Neurosurg Focus. 2004;17(3):E8.
22. Fay LY, et al. Arthroplasty for cervical spondylotic myelopathy: similar results to patients with only radiculopathy at 3 years' follow-up. J Neurosurg Spine. 2014;21(3):400–10.

23. Goffin J, et al. Preliminary clinical experience with the Bryan Cervical Disc Prosthesis. Neurosurgery. 2002;51(3):840–5; discussion 845–7.
24. Goffin J, et al. Intermediate follow-up after treatment of degenerative disc disease with the Bryan Cervical Disc Prosthesis: single-level and bi-level. Spine (Phila Pa 1976). 2003;28(24):2673–8.
25. Lafuente J, et al. The Bryan cervical disc prosthesis as an alternative to arthrodesis in the treatment of cervical spondylosis: 46 consecutive cases. J Bone Joint Surg Br. 2005;87(4):508–12.
26. Sasso RC, et al. Artificial disc versus fusion: a prospective, randomized study with 2-year follow-up on 99 patients. Spine (Phila Pa 1976). 2007;32(26):2933–40; discussion 2941–2.
27. Sasso RC, Foulk DM, Hahn M. Prospective, randomized trial of metal-on-metal artificial lumbar disc replacement: initial results for treatment of discogenic pain. Spine (Phila Pa 1976). 2008;33(2):123–31.
28. Heller JG, et al. Comparison of BRYAN cervical disc arthroplasty with anterior cervical decompression and fusion: clinical and radiographic results of a randomized, controlled, clinical trial. Spine (Phila Pa 1976). 2009;34(2):101–7.
29. Murrey D, et al. Results of the prospective, randomized, controlled multicenter Food and Drug Administration investigational device exemption study of the ProDisc-C total disc replacement versus anterior discectomy and fusion for the treatment of 1-level symptomatic cervical disc disease. Spine J. 2009;9(4):275–86.
30. Bertagnoli R, et al. Early results after ProDisc-C cervical disc replacement. J Neurosurg Spine. 2005;2(4):403–10.
31. McAfee PC, et al. A meta-analysis of comparative outcomes following cervical arthroplasty or anterior cervical fusion: results from 4 prospective multicenter randomized clinical trials and up to 1226 patients. Spine (Phila Pa 1976). 2012;37(11):943–52.
32. Fountas KN, et al. Anterior cervical discectomy and fusion associated complications. Spine (Phila Pa 1976). 2007;32(21):2310–7.
33. Leung C, et al. Clinical significance of heterotopic ossification in cervical disc replacement: a prospective multicenter clinical trial. Neurosurgery. 2005;57(4):759–63; discussion 759–63.
34. Mehren C, et al. Heterotopic ossification in total cervical artificial disc replacement. Spine (Phila Pa 1976). 2006;31(24):2802–6.
35. Suchomel P, et al. Clinical results and development of heterotopic ossification in total cervical disc replacement during a 4-year follow-up. Eur Spine J. 2010;19(2):307–15.
36. Yi S, et al. Radiologically documented adjacent-segment degeneration after cervical arthroplasty: characteristics and review of cases. Surg Neurol. 2009;72(4):325–9; discussion 329.
37. Chen J, et al. Prevalence of heterotopic ossification after cervical total disc arthroplasty: a meta-analysis. Eur Spine J. 2012;21(4):674–80.
38. Johnson JP, et al. Sagittal alignment and the Bryan cervical artificial disc. Neurosurg Focus. 2004; 17(6):E14.
39. Pickett GE, et al. Effects of a cervical disc prosthesis on segmental and cervical spine alignment. Neurosurg Focus. 2004;17(3):E5.
40. Troyanovich SJ, et al. Does anterior plating maintain cervical lordosis versus conventional fusion techniques? a retrospective analysis of patients receiving single-level fusions. J Spinal Disord Tech. 2002;15(1):69–74.
41. Xu JX, et al. Effect of modified techniques in Bryan cervical disc arthroplasty. Spine (Phila Pa 1976). 2009;34(10):1012–7.
42. Datta JC, et al. Sagittal split fractures in multilevel cervical arthroplasty using a keeled prosthesis. J Spinal Disord Tech. 2007;20(1):89–92.
43. Shim CS, Shin HD, Lee SH. Posterior avulsion fracture at adjacent vertebral body during cervical disc replacement with ProDisc-C: a case report. J Spinal Disord Tech. 2007;20(6):468–72.
44. Goodman SB, et al. Cellular profile and cytokine production at prosthetic interfaces. Study of tissues retrieved from revised hip and knee replacements. J Bone Joint Surg Br. 1998;80(3):531–9.
45. Cavanaugh DA, et al. Delayed hyper-reactivity to metal ions after cervical disc arthroplasty: a case report and literature review. Spine (Phila Pa 1976). 2009;34(7):E262–5.
46. Guyer RD, et al. Early failure of metal-on-metal artificial disc prostheses associated with lymphocytic reaction: diagnosis and treatment experience in four cases. Spine (Phila Pa 1976). 2011;36(7):E492–7.
47. Lebl DR, et al. In vivo functional performance of failed Prodisc-L devices: retrieval analysis of lumbar total disc replacements. Spine (Phila Pa 1976). 2012;37(19):E1209–17.
48. Anderson PA, et al. Wear analysis of the Bryan Cervical Disc prosthesis. Spine (Phila Pa 1976). 2003;28(20):S186–94.
49. Anderson PA, et al. The Bryan Cervical Disc: wear properties and early clinical results. Spine J. 2004;4(6 Suppl):303S–9.
50. DiAngelo DJ, et al. Biomechanical testing of an artificial cervical joint and an anterior cervical plate. J Spinal Disord Tech. 2003;16(4):314–23.
51. Wigfield CC, et al. Internal stress distribution in cervical intervertebral discs: the influence of an artificial cervical joint and simulated anterior interbody fusion. J Spinal Disord Tech. 2003;16(5):441–9.
52. Pickett GE, Rouleau JP, Duggal N. Kinematic analysis of the cervical spine following implantation of an artificial cervical disc. Spine (Phila Pa 1976). 2005;30(17):1949–54.
53. Puttlitz CM, et al. Intervertebral disc replacement maintains cervical spine kinetics. Spine (Phila Pa 1976). 2004;29(24):2809–14.
54. DiAngelo DJ, et al. In vitro biomechanics of cervical disc arthroplasty with the ProDisc-C total disc implant. Neurosurg Focus. 2004;17(3):E7.

55. Sasso RC, et al. Motion analysis of bryan cervical disc arthroplasty versus anterior discectomy and fusion: results from a prospective, randomized, multicenter, clinical trial. J Spinal Disord Tech. 2008;21(6):393–9.
56. Chang UK, et al. Range of motion change after cervical arthroplasty with ProDisc-C and prestige artificial discs compared with anterior cervical discectomy and fusion. J Neurosurg Spine. 2007;7(1):40–6.
57. Singh K, Vaccaro AR, Albert TJ. Assessing the potential impact of total disc arthroplasty on surgeon practice patterns in North America. Spine J. 2004; 4(6 Suppl):195S–201.
58. Qureshi SA, et al. Cost-effectiveness analysis: comparing single-level cervical disc replacement and single-level anterior cervical discectomy and fusion: clinical article. J Neurosurg Spine. 2013;19(5): 546–54.
59. Warren D, et al. Cost-utility analysis of anterior cervical discectomy and fusion versus cervical disc arthroplasty. Evid Based Spine Care J. 2011;2(3):57–8.

Odontoid Screw Fixation

17

Francesco Cacciola and Nicola Di Lorenzo

Introduction

Odontoid fractures are among the most common fractures of the spine in general. They account for approximately 20 % of all cervical fractures, with Anderson and D'Alonzo type II fractures comprising around 2/3–3/4 of dens fractures [1–4].

Type II fractures are furthermore the most common spinal fractures in the elderly and thus in a population where decision making and treatment, whether invasive or not, and in case of surgery what type, represent certainly an exquisite challenge for the spinal surgeon [3].

A Pubmed search with the simple search terms "odontoid" AND "fractures" yields as many as 60 papers only for the year 2014 which reflects the interest that continues to surround the topic. The ideal management of these often complex entities through the different age groups is yet all but clear.

In this chapter we want to lay out the technical steps necessary for a sound odontoid screw fixation procedure.

Ever since the description of the surgical technique as early as 1980 by Nakanishi and in 1982 by Bohler, reporting his 8 years experience, some refinements and interpretations have been made on the topic, but essentially the fundamental steps of the operation have remained the same [5, 6].

In addition to the technical description we also attempt to delineate some basic facts that should help guide the surgeon in the decision making process such as fracture type, timing of surgery and age of the patient.

Indications for Odontoid Screw Fixation

In appropriately selected young patients the success rates of direct odontoid osteosynthesis via an anterior screw can be as high as 90 % in terms of good functional outcome [7–10].

This can furthermore be accomplished with relatively little risk and in this section we will highlight some fundamental points that need to be evaluated and included in the decision making process when it comes to choice of treatment (Table 17.1).

Fracture Type

Fracture type and the amount of displacement are important factors in selecting a patient for surgery.

F. Cacciola
Department of Neurosurgery, University of Siena, Siena, Italy

N. Di Lorenzo (✉)
Department of Neurosurgery, University of Florence, Florence, Italy
e-mail: dilorenzo@unifi.it

P.P.M. Menchetti (ed.), *Cervical Spine: Minimally Invasive and Open Surgery*,
DOI 10.1007/978-3-319-21608-9_17

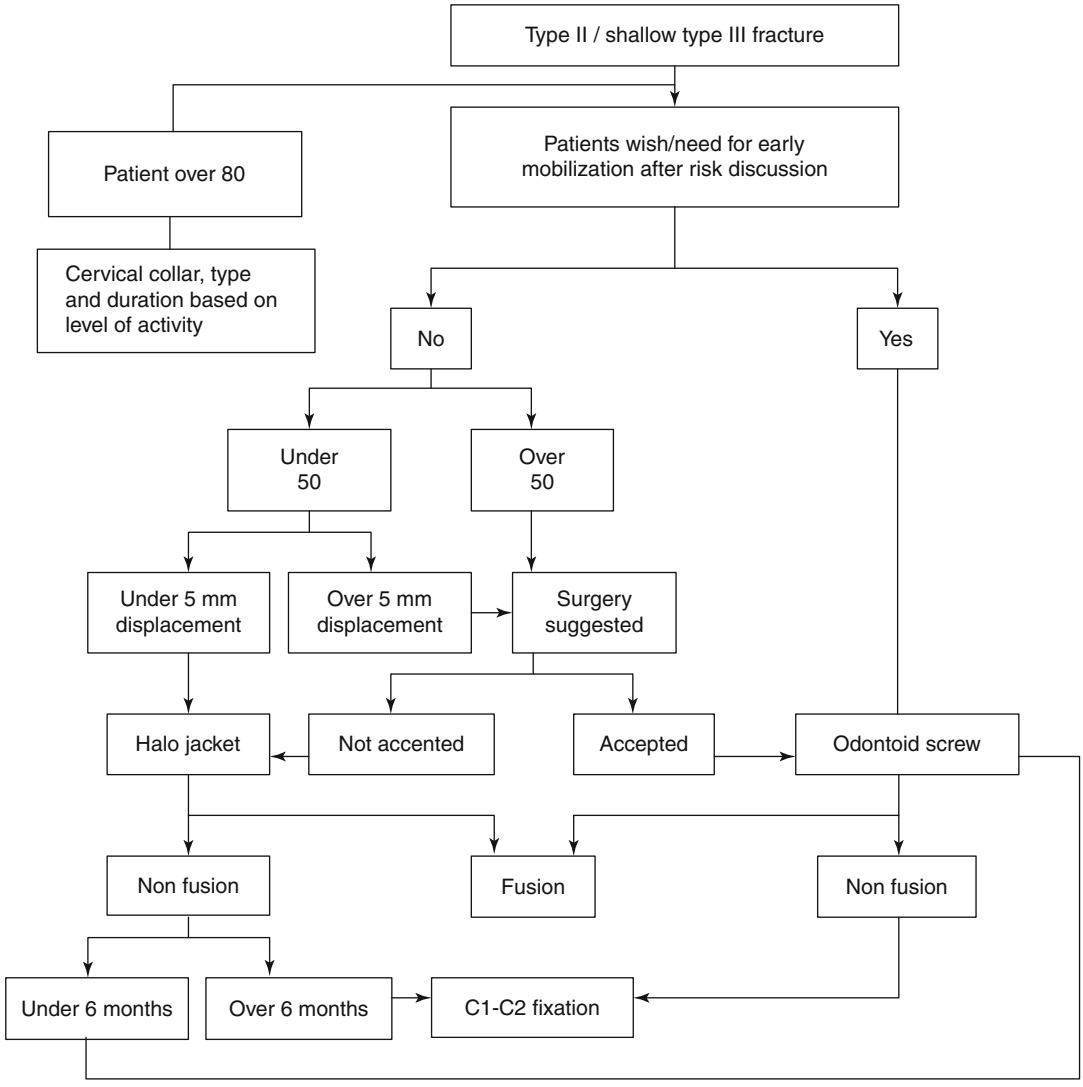


Table 17.1 Flow chart suggesting a decision making process based both upon author preference and available evidence from the literature

Type II and "shallow" or rostral type III fractures according to the classification of Anderson and D'Alonzo are an indication for odontoid screw fixation [4]. Apfelbaum et al. have suggested a subclassification of type II fractures in three types according to the orientation of the fracture line in one of their series. According to this subclassification horizontal as well as oblique antero-superiorly oriented fracture lines on the sagittal plane predict higher fusion rates than oblique antero-inferiorly oriented fracture lines. This subdivision has however not been reported in series by other authors and given that the overall fusion rate in the oblique antero-inferior group is still 75 % this information is probably not indispensable, but can be of help in difficult decisions [11].

In addition to the above criteria the axis needs to be carefully examined for additional fractures or fracture lines extending into the body, as this could have negative repercussions on screw purchase. The same goes for the fractured dens fragment.

Type IIA fractures (comminution of the dens) might not warrant sufficient screw purchase, which is particularly important at the cortical tip of the dens that needs to be engaged by the screw [8–12].

As far as the amount of displacement is concerned the literature shows that values over 4–6 mm seem to represent a threshold beyond which the risk of non-fusion gets significantly and probably inacceptably high with conservative treatment [13–15].

Finally, an MRI scan of the area to check for integrity of the transverse ligament is indicated even though not indispensable, if not available, in our opinion due to the relatively low association of ligamentous rupture in association with an odontoid fracture. However, due to the diffuse availability of the imaging technique and its routine use in spinal trauma in many centres, particular attention to the state of the transverse ligament should be paid. In case of a clear rupture this would represent a contraindication to odontoid screw fixation.

Timing of Surgery

The general rule "The earlier you fuse, the better" surely also applies to this type of procedure. Evidence from the literature seems to suggest that there are no differences in fusion rates during the first 6 months, whilst after 18 months fusion rates drop clearly. This information is based on a series published by Apfelbaum et al. and has initially led to a division of the patients in "early" and "late". The fact that there is essentially no information on patients who had a fracture between 6 and 18 months is due to the lack of such patients in that study and to our knowledge no other study has examined this thereafter [10–12, 16–18].

Knowing, however, that it apparently does not make a difference whether a patient undergoes fusion immediately or after 6 months is surely valuable information, as it gives ample time to first try conservative treatment in those patients where deemed appropriate and still have the time to offer surgery should that treatment fail.

Age

Even though again a matter of controversy in the literature with a vast amount of related articles, there is a certain prevalence towards the opinion that age influences the outcome of odontoid screw fixation [11–29]. The younger the patients, the more likely it is that fusion may be obtained by external immobilization. Sherk et al have reported a series of 35 children (under 7 years), in whom only one failed to fuse after halo immobilization [27]. The more age advances, however, the more the fusion rate seems to correlate inversely and Lennarson et al. have even shown in one of their studies that the nonunion rate in patients over 50 years is 21 times higher than in those that are younger [18].

Even if one tends to not believe in the inverse relationship between age and fusion rate in conservative management, the important message surely seems to be that older patients do at least as well as younger patients with surgery and this can be an important piece of information when tailoring a specific treatment plan. In older patients the compliance with external immobilization like a Halo Jacket and the resulting overall movement restriction, can have significant negative repercussions on outcome and the patients general health.

We therefore tend to favour surgery in older patients, that is patients over age 50, taking only unfitness for general anesthaesia or severe osteopenia as contraindications.

A third age group we consider in selecting treatment is the geriatric population with patients over 75–80 years of age. In this age group pseudoarthrosis rate has been described to be as high as 85 % [30].

Recent papers based on the AOSpine North America Geriatric Odontoid Fracture Study showed an increase in mortality of non surgically treated patients at one year but non significant difference between the surgical and conservative groups after that. As the patients in this study were not randomized, the difference in the first year likely reflects the poorer general conditions of those that were not operated and could be the result of a selection bias. Other weak points of

this study are that neurological status in the patients groups was not accounted for. Furthermore, a group of patients out of the same study that was followed after conservative treatment showed a "union rate", whether fibrous or bony, of as high as 75 %. The remaining 25 % eventually developed "non union" following which around 2/3 underwent surgery. It is however not clear how this non union reflected itself clinically, in particular with regards to the neurological status. The only conclusion that is drawn is that operated patients demonstrated a significant benefit on the Neck Disability Index (NDI) and the SF-36 version 2 Bodily Pain dimension. Again, this difference could reflect the difference in the general conditions of the two groups and thus be a selection bias [30, 31].

In our eyes this study failed to show convincing elements to favour surgery in the geriatric population and if anything showed an increased incidence of dysphagia and permanent feeding tube placements in the surgical group.

In addition there are papers that describe series of patients, even though small, followed after conservative treatment who did not develop any complications, as well as our own experience which seems to reproduce these findings, and this makes us withhold from surgery in the geriatric population, that is over 75–80 of age, unless the patient is in particularly good general conditions and most of all still very active [32, 33].

We tend to treat these patients with a cervical collar choosing the type, either rigid or soft, and the duration of treatment based on the level of activity of the patient, as well as on the range of movement of the fracture on dynamic x-rays.

Surgical Technique

The following is a description of the operative technique used in odontoid screw fixation outlining the most significant general steps that need to be followed. Various manufacturers offer different systems to carry out this operation and some specific steps might thus differ according to the specific system. It is not our intent to specifically describe the use of any of these systems but outline the important points that are necessary for a smooth and successful performance of the operation.

Patient Positioning and Setup

The patient is under general anesthaesia with endoscopic endotracheal intubation. This can be accomplished either via the nose or the mouth making sure that a non armoured tube is used. The patient is then positioned neutrally supine on the operating table. The head can either be secured in a three pin fixation device, rest on a horseshoe or directly on the operating table with a towel roll under the neck. What is essentially important is that the head remains immobile throughout the procedure.

Once the patient is thus positioned, two C-arm image intensifiers are brought in and centred on the C1-C2 complex, with one obtaining a lateral view and the other one obtaining an anteroposterior view (Fig 17.1).

In case of dislocated fractures, the patients head is now gently manipulated under lateral fluoroscopy in an attempt to reduce the fracture as much as possible, and the head is finally secured in the desired position. In repositioning the fracture direct manipulation by pressure on the pharynx through the mouth can be of help. The two C-arms will remain in position during the entire procedure, as frequent imaging is crucial during the various steps. In order to obtain a good anteroposterior view it is often helpful to obtain open mouth views by inserting a radiolucent mouth opener or bite-blocks in the patient's mouth.

Once all these steps are accomplished, the C-arms are both in a position to obtain good views, the patients head in the correct position to obtain as much fracture reduction as possible and the head well secured, the patient and the equipment are draped in the usual fashion.

Approach to the Lower Edge of the Axis and the Screw Insertion Site

The approach to the anterior cervical spine is identical to a standard approach to the subaxial spine for an anterior cervical discectomy. A horizontal

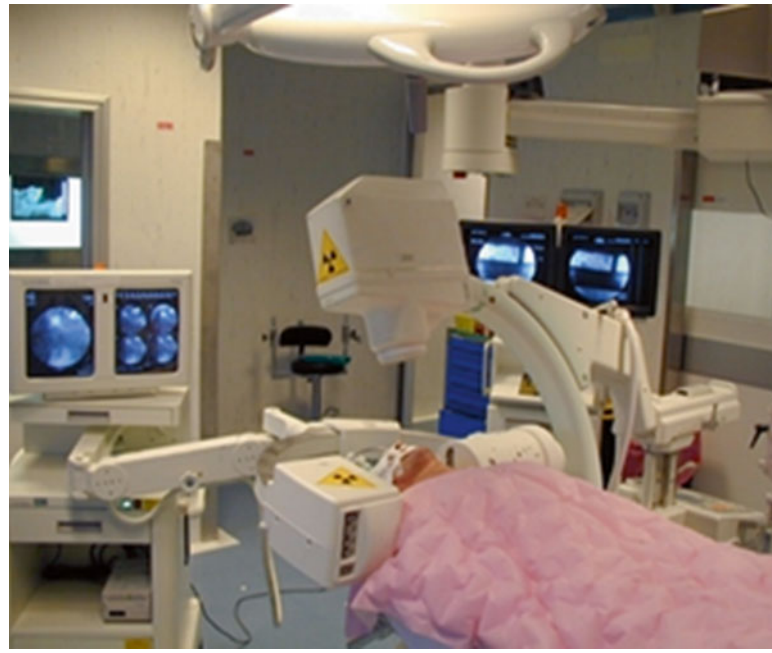


Fig. 17.1 Intraoperative photograph showing patient positioning for operation. Note the biplanar flouroscopy left in place throughout the entire procedure

skin incision is made roughly at the level of C5, extending from the midline to slightly beyond the medial border of the sternocleidomastoid, usually on the right side of the patient or according to surgeon preference (Fig. 17.2).

After division of the platysma, the fascia of the sternocleidomastoid is sharply incised along its medial border. Blunt dissection along natural planes and medial to the carotid sheath leads down to the anterior plane of the cervical spine. At this stage both longus colli muscles are partially lifted up from the vertebral plane and a self retaining blade retractor firmly positioned underneath them. Up to this stage the approach is identical to an anterior discectomy.

Once the lateral retractors are inserted the vertebral plane is followed rostrally until the inferior border of C2 is palpated. At this stage the craniocaudal self retaining retractor blades are inserted.

Under fluoroscopic control a K-wire is now inserted through the incision and advanced to the anteroinferior border of C2 and impacted with a mallet (Fig 17.2). On the anteroposterior plane the K-wire should sit in the centre of the odontoid process, whilst on the lateral view, it should already be angulated in a way that its projection will go through the major axis of the dens and penetrate its posterior half. The central position on the anteroposterior view is due to the fact that we prefer the insertion of a single screw, as it seems to emerge both from our experience and the literature that insertion of two screws offers no advantage.

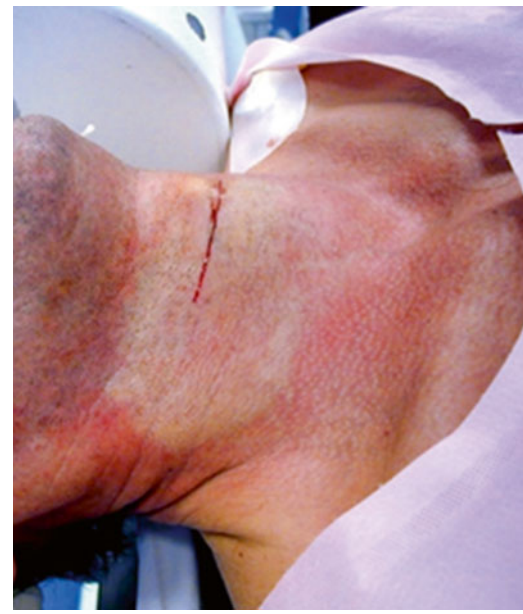


Fig. 17.2 Intraoperative photograph showing the localization of the skin incision identical to a standard anterior approach to the mid-cervical spine

Once the K-wire is in place it can be used to slide a cannulated drill guide over it and anchor it on the cervical spine. With some systems the K-wire is actually fully advanced through the whole length of C2 with a drill, thus creating the trajectory for the screw. Other systems replace the K-wire once the drill guide is in place and use a drill bit of 2 mm to actually drill the screw trajectory (Fig 17.3). Continuous fluoroscopic control is mandatory.

What is important at this stage, non dependent on whether a K-wire or a drill bit is used to create the screw hole and canal, is to measure the depth of penetration into C2 and the dens, as this will determine the screw length that needs to be inserted. The various systems have various devices and means of accomplishing that.

Once the screw hole is thus created and the depth of penetration measured, insertion of the actual screw can follow.

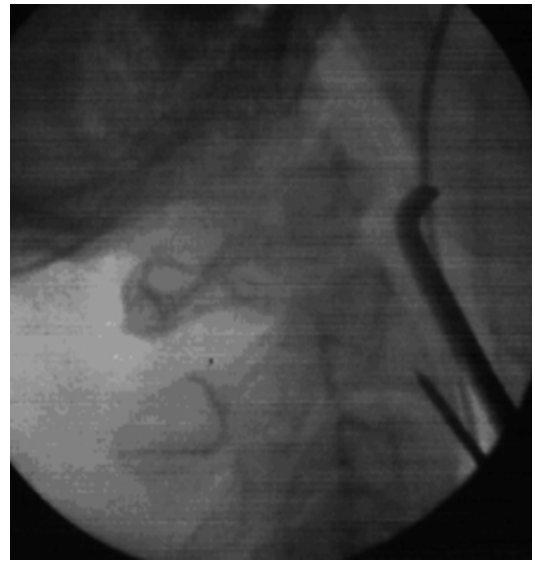


Fig. 17.3 Intraoperative lateral image intensifier x-ray showing the K-wire impacted in the axis on its anteroinferior level already projecting in the desired direction. Note also the blade of the self-retaining retractor (Apfelbaum System, Aesculap)

Screw Insertion

Screw diameter should be 4.5 mm single or double 3.5 mm as this was shown to have biomechanical advantages over 3.5 mm single [34].

As far as screw design is concerned, there are essentially two types of screws: lag screws and fully threaded screws (Fig 17.4). In our view, lag screws are indicated in the majority of cases as due to their conformity they deliver the possibility to reduce and compress a fracture fragment, as once the screw head is engaged against the inferior border of C2 the threaded part will continue to deliver the fragment downwards upon turning with the whole of the screw, however, not changing position anymore. The only scenario where lag screws may be contraindicated is an anteroinferior oblique fracture line of the dens, as the compression can lead to malalignment of the fracture (Fig. 17.5).

When using lag screws the exact measurement of the needed screw length prior to insertion becomes particularly important.

At the stage of screw insertion there is only one more important point to be observed and that is to make sure that the screw engages and traverses the cortex of the fractured dens fragment.

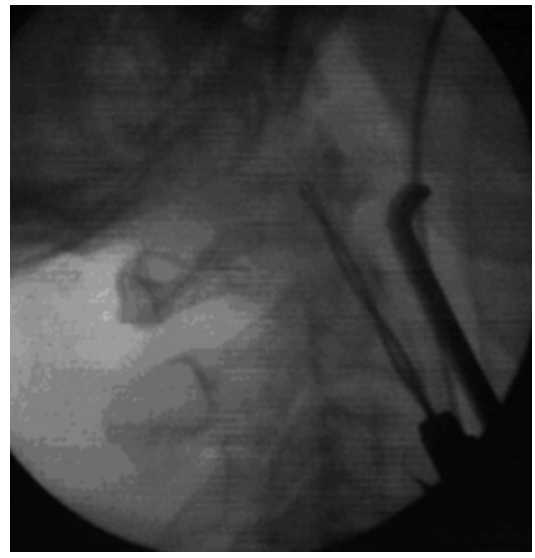


Fig. 17.4 Intraoperative lateral image intensifier x-ray. After insertion of the drill guide over the K-wire, the latter is withdrawn and the screw canal drilled with a 2 mm drill bit. Note the anchoring spike of the drill guide in the body of C3 (Apfelbaum System, Aesculap)

A protrusion of the screw a couple of millimeters beyond the dens cortex is safe and mandatory for good purchase and to avoid later screw pullout.

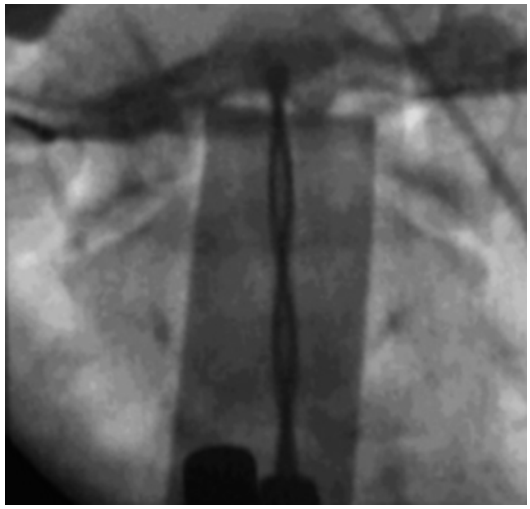


Fig. 17.5 Intraoperative lateral image intensifier x-ray of the same situation as in Fig. 17.4, only in the anteroposterior view. The drill bit is in a central position, has traversed the fracture line and almost reached the tip of the dens. Note the radiolucent retractor blade, which is the same as in the previous figures

Again, this obviously needs to be closely monitored on fluoroscopy.

Postoperative Care

The issue of whether or not to suggest a postoperative cervical collar is not resolved. In a fracture fixed with a lag screw of the correct length, that has appropriately traversed the dens cortex and offers good purchase in a good quality bone, a collar is most likely superfluous, whereas poor quality bone and less good purchase in a non compliant patient would probably warrant immobilization in a rigid cervical collar for 6–8 weeks. Again, the final decision is probably most appropriately based upon the inclusion of specific patient features and needs.

Conclusion

Odontoid screw fixation can be a very efficient and rewarding procedure for both the patient and the surgeon. Correct patient selection is an important step in this procedure and appropriate corroboration of the guideline recommendations with the particular features and needs of the single patient can lead to a 90 % success rate with a minimal need for patient immobilization.

The surgical technique is straightforward and as long as all the single steps are correctly performed and good fluoroscopic visualization is guaranteed throughout the entire procedure, the risk of any surgery related complication is almost nil.

As a matter of fact in our experience as well as in the literature, apart from the possibility of retraction related problems associated with the standard anterior approach to the cervical spine, no morbidity or mortality directly related to the procedure of odontoid screw fixation have been reported [2–15, 14–19, 21–26].

References

1. Smith HE, Kerr SM, Fehlings MG, et al. Trends in epidemiology and management of type II odontoid fractures: 20-year experience at a model system spine injury tertiary referral center. J Spinal Disord Tech. 2010;23:501–5.
2. Ryan MD, Henderson JJ. The epidemiology of fractures and fracture-dislocations of the cervical spine. Injury. 1992;23:38–40.
3. Golob Jr JE, Claridge JA, Yowler CJ, et al. Isolated cervical spine fractures in the elderly: a deadly injury. J Trauma. 2008;64:311–5.
4. Anderson LD, D'Alonzo RT. Fractures of the odontoid process of the axis. J Bone Joint Surg Am. 1974;56:1663–74.
5. Nakanishi T. Internal fixation of the odontoid fracture. Cent Jpn J Orthop Traumatic Surg. 1980;23:399–406.
6. Bohler J. Anterior stabilization for acute fractures and non-unions of the dens. J Bone Joint Surg Am. 1982;64:18–27.
7. Aebi M, Etter C, Coscia M. Fractures of the odontoid process. Treatment with anterior screw fixation. Spine. 1989;14:1065–70.
8. Dunn ME, Seljeskog EL. Experience in the management of odontoid process injuries: an analysis of 128 cases. Neurosurgery. 1986;18:306–10.
9. Montesano PX, Anderson PA, Schlehr F, et al. Odontoid fractures treated by anterior odontoid screw fixation. Spine. 1991;16 Suppl 3:33–7.
10. Greene KA, Dickman CA, Marciano FF, et al. Acute axis fractures. Analysis of management and outcome in 340 consecutive cases. Spine. 1997;22(16):1843–52.
11. Apfelbaum RI, Lonser RR, Veres R, et al. Direct anterior screw fixation for recent and remote odontoid fractures. J Neurosurg. 2000;93 Suppl 2:227–36.

12. Fountas KN, Eftychia ZK, Karampelas I, et al. Results of long-term follow up in patients undergoing anterior screw fixation for type II and rostral type III odontoid fractures. Spine. 2005;30(6):661–9.
13. Apuzzo ML, Heiden JS, Weiss MH, et al. Acute fractures of the odontoid process. An analysis of 45 cases. J Neurosurg. 1978;48:85–91.
14. Hadley MN, Dickman CA, Browner CM, et al. Acute axis fractures: a review of 229. J Neurosurg. 1989;71: 642–7.
15. Maak TG, Grauer JN. The contemporary treatment of odontoid injuries. Spine. 2006;31(11 Suppl):S53–60.
16. Geisler FH, Cheng C, Poka A, et al. Anterior screw fixation of posteriorly displaced type II odontoid fractures. Neurosurgery. 1989;25:30–8.
17. Julien TD, Frankel B, Traynelis VC, et al. Evidence-based analysis of odontoid fracture management. Neurosurg Focus. 2000;8(6):e1.
18. Lennarson PJ, Mostafavi H, Traynelis VC, et al. Management of type II dens fractures: a case–control study. Spine. 2000;25(10):1234–7.
19. Pitzen T, Caspar W, Steudel WI, et al. Dens fracture in elderly patients and surgical management. Aktuelle Traumatol. 1994;24:56–9.
20. Pepin JW, Bourne RB, Hawkins RJ. Odontoid fractures with special reference to the elderly patient. Clin Orthop. 1985;193:178–83.
21. Hanigan WC, Powell FC, Elwood PW, et al. Odontoid fractures in elderly patients. J Neurosurg. 1993; 78:32–5.
22. Andersson S, Rodrigues M, Olerud C. Odontoid fractures: high complication rate associated with anterior screw fixation in the elderly. Eur Spine J. 2000;9: 56–60.
23. Jenkins JD, Coric D, Branch CL. A clinical comparison of one- and two-screw odontoid fixation. J Neurosurg. 1998;89(3):366–70.
24. Harrop JS, Przybylski GJ, Vaccaro AR, et al. Efficacy of anterior odontoid screw fixation in elderly patients with Type II odontoid fractures. Neurosurg Focus. 2000;8(6):e6.
25. Kuntz 4th C, Mirza SK, Jarell AD, et al. Type II odontoid fractures in the elderly: early failure of nonsurgical treatment. Neurosurg Focus. 2000;8(6):e7.
26. Börm W, Kast E, Richter HP, et al. Anterior screw fixation in type II odontoid fractures: is there a difference in outcome between age groups? Neurosurgery. 2003;52(5):1089–92.
27. Sherk HH, Nicholson JT, Chung SM. Fractures of the odontoid process in young children. J Bone Joint Surg Am. 1978;60:921–4.
28. Mandabach M, Ruge JR, Hahn YS, et al. Pediatric axis fractures: early halo immobilization, management and outcome. Pediatr Neurosurg. 1993;19:225–32.
29. Odent T, Langlais J, Glorion C, et al. Fractures of the odontoid process: a report of 15 cases in children younger than 6 years. J Pediatr Orthop. 1999;19: 51–4.
30. Smith JS, Kepler CK, Kopjar B, et al. Effect of type II odontoid fracture nonunion on outcome among elderly patients treated without surgery. Spine. 2013;38:2240–6.
31. Chapman J, Smith JS, Kopjar B, et al. The AOSpine North America geriatric odontoid fracture mortality study. Spine. 2013;38:1098–104.
32. Hart R, Saterbak A, Rapp T, et al. Nonoperative management of dens fracture non-union in elderly patients without myelopathy. Spine. 2000;25:1339–43.
33. Ryan MD, Taylor TK. Odontoid fractures in the elderly. J Spinal Disord. 1993;6:397–401.
34. McBride AD, Mukherjee DP, Kruse RN, et al. Anterior screw fixation of type II odontoid fractures. A biomechanical study. Spine. 1995;20:1855–9.

Injuries of the Middle and Lower Cervical Spine

18

Riccardo Ciarpaglini, Paolo Fornaciari, and Gianluca Maestretti

Epidemiology

Traumatic spinal fractures have a reported incidence rate of 19–88 per 100,000 persons per year and cervical spine fractures represent up to 20–30 % of all spine fractures [1]. Within cervical fractures only 10–20 % result in spinal cord injuries [1].

Demographic risk factors associated with cervical spine injuries are age more than 65 years, male sex and white ethnicity [2].

Among patients who underwent blunt cervical spine injury approximately two thirds of fractures and three fourth of dislocation concern the subaxial spine (from C3 to C7) [3].

The most frequent level of lesions are C5 and C6 [4]. Nonetheless fracture of C7 are reported in 19.08 % of cases [5]. This must reinforce the need of a clear radiology assessment of the cervico-thoracic junction [6].

The reasons of the relatively height incidence of cervical lesions are biomechanics and peculiar anatomy of the cervical spine [7]. The relation between the spinal canal and the spinal cord diameter are quite unfavourable and the leverages are strong because of the weight of the head [7]. The lower cervical lesions have a different and more complex distribution than other spinal segments with involvement of facet joints and disco-ligamentary structures.

Anatomy

The characteristic anatomy of the cervical spine, necessary to its specific mobility, exposes itself to a higher risk of traumatic injuries compared to thoracolumbar spine.

Cervical vertebral bodies are smaller and the canal relatively wider than in the lower segments of the column. The canal of the lower cervical spine is clearly narrower than in the upper cervical spine [7].

Vertebral bodies are cuboidal with triangular shaped foramen.

The articular surfaces of the zigoapophysialis joints present a 45° craniocaudal inclination and are oriented on the frontal plane in contrast to the toracolumbar spine.

The transverse processes are formed from an anterior and a posterior Tuberculum enclosing the transverse Foramen. From the 3rd vertebra the transverse processes present a concave depression for spinal nerves [8].

The vertebral artery runs through the transverse processes between C3 and C6 while in C7 is occupied from an accessory vein [7].

R. Ciarpaglini, MD (✉) • P. Fornaciari, MD
G. Maestretti, MD
Spinal Unit, Department of Orthopedics Surgery, Fribourg Cantonal Hospital, Fribourg, Switzerland
e-mail: ciarpa@hotmail.com

P.P.M. Menchetti (ed.), *Cervical Spine: Minimally Invasive and Open Surgery*,
DOI 10.1007/978-3-319-21608-9_18

The spinous processes from C3 to C6 are bifid. C2 and C7 spinous processes are prominent and easily palpated under the skin as landmarks.

Except C7, all the other spinous processes are directed caudally and posteriorly serving as attachment for muscles [9].

Most of the rotation range of motion of the head is related to the atlantooccipital joint while the middle-lower cervical spine is mainly responsible for flexion-extension.

The mean flexo-extension mobility of each segment is 12° (ranging 8–17°) with a maximum between C5-C6. The lateral inclination is in the lower cervical spine between 4° and 11° for each segment with a maximum in C4/C5. The rotation takes place for 50 % in the atlantoaxial junction while around 8–12° of rotation are possible in each segment of the lower cervical spine [7].

The ligamentous structures are decisive in biomechanical stability of the cervical spine. They can be divided in anterior and posterior ligamentary complex.

Posterior ligamentary complex is composed by: Ligamentum nuchae formed from a funicular part (ligamentum suprasinosus dorsal) and a lamellar portion (between the funicular and the processi spinosi); the posterior longitudinal ligament is a thick ligament more resistant than the anterior one which get broader and thicker from cranial to caudal; the intertrasversal ligaments are thin and fibrous bands from one processus trasversus to the other; the ligamentum flavum runs between the adjacent laminae; the capsular ligaments wrap the joints in a perpendicular relation to the articular plane.

The annulus fibrosus is well fixed with the anterior and posterior longitudinal ligament as also to the cartilaginous plate.

The anterior complex consists of the longitudinal anterior ligament which is well fixed to the annulus and at the anterior edge of the vertebral body [7].

The anterior ligamentary complex is composed by the anterior longitudinal ligament which connect the anterior border of the vertebral bodies of the whole spine.

The capsule of the zygapophysialis joints origins from the edges of the articular processes and are related to the ligamentum flavum. In cervical segments capsules are looser than in other segments and leave a major range of motion. In almost all the joints we can found the meniscoid synovial folds which present many vessels and connective tissue adapting articular incongruences.

Each upper plate of the cervical vertebral body (C3-C7) presents a sagittal oriented process called uncinated processes. They come in contact with the semilunate lower plate of the upper vertebral body in an uncovertabral joint favouring the lateral stability of the cervical spine [7].

Compartmentalisation and neurovascular contents surrounding the cervical spine are unique but their description is not purpose of this chapter. We outline the most important surgical anatomy of the neck territories.

The skin on the dorsal portion of the neck is thick with direct connection to the fascia. It explains why scars are usually quite thick in this region.

The skin on the anterior part of the neck is thin because of loose subcutaneous tissue and the superficial fascia remains unconnected to the deep cervical fascia of the neck.

Posteriorly there are three layers of muscles. The most superficial consists of the trapezius, which takes origin from the superior nuchal line and from the spinous processes and attaches on the spina scapulae. Its function is to lift the upperlimb. Laterally in the superficial layer lies the sternocleidomasteoid muscle. The intermediate layer is composed by the splenius capitis, a flat and relatively large muscle (its insertions are the spinous process of C7, lower half of the ligamentum nuchae, the upper 3 thoracic spinous processes and the occipital bone). The deep layer presents three sub-layers: superficial, middle and deep. The superficial consists of the semispinalis capitis. The middle portion consists of the semispinalis cervicis. The deepest portion is filled from multifidus, short and long rotator muscles.

Also in the anterior part of the neck we can recognize three muscular layers separated by connective structures (Fig. 18.1). The most superficial is the investing layer of deep cervical fascia. The fascia is like a collar around the neck and

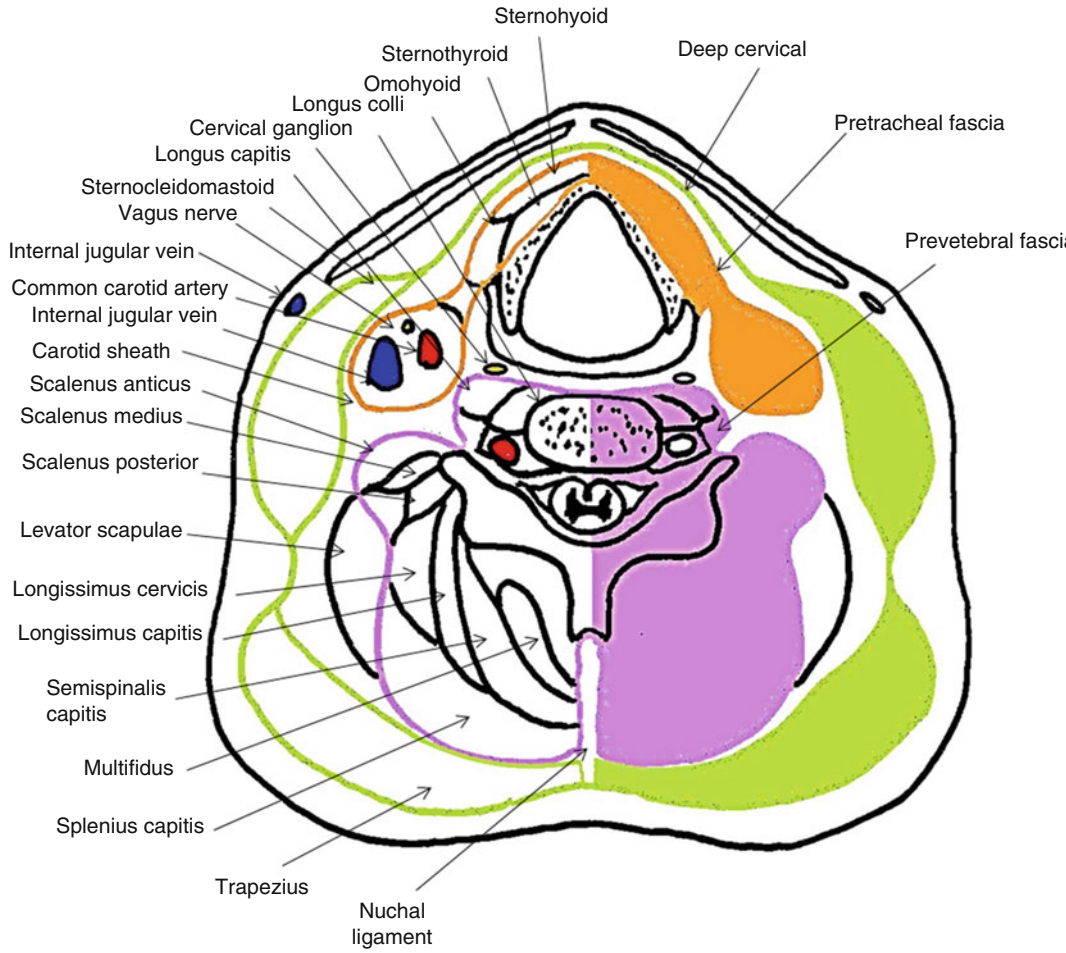


Fig. 18.1 Drawing of cross-section at C5 level. Deep cervical fascia is marked in green, pretrachreal fascia with carotid sheath in orange (neurovascular bundle is contained in it) and prevertebral fascia in violet

encloses the trapezium and the sternocleidomastoid muscles. The only structure over it is the platysma, which is a mimic muscle. The second layer is represented from the pretracheal fascia, which is a layer between two sliding surfaces. The strap muscles are invested from it and run from hyoid bone into the chest. The pretracheal fascia encloses the common carotid artery, the internal jugular vein and the vagus nerve (neurovascular bundle). Two important arteries run through the fascia towards the midline, the superior and the inferior thyroid vessels. The superior laryngeal nerve runs with the superior thyroid vessels. The deepest layer is the prevertebral fascia, a thick membrane that lies in front of the prevertebral muscles (Fig. 18.2). It presents important relations with the sympathetic trunk. Under the fascia lie the longus colli, which has an important surgical meaning as reference and protection for nerve [9].

The superior laryngeal nerve divides itself near the Ganglion inferius of the vagus nerve, at the level of the hyoid bone, in an internal and external branch. The external branch innervates the thyreopharyngeal and cricopharyngeal part of the inferior pharyngeal constrictor muscles and the cricothyroideal muscle. Some of its fibers breaks through the Membrana cricothyroidea and innervate the mucosa of the anterior commissure of the larynx. The internal branch runs with the superior laryngeal artery through the Membrana thyroidea and runs under the mucosa of the

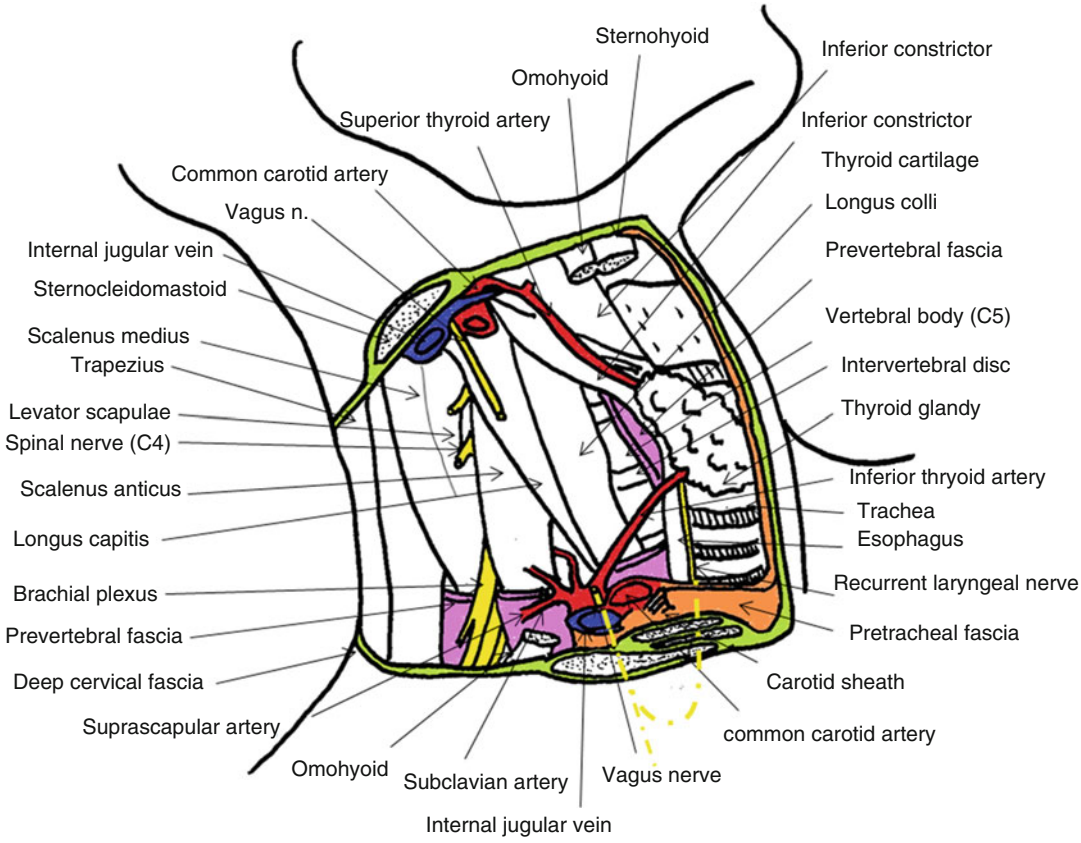


Fig. 18.2 Drawing of the antero-lateral cervical anatomy. Inferior constrictor and esophagus are retracted medially. The cranial carotid sheath and surrounding pretracheal fascia are removed. The prevertebral fascia overrides the scalenus muscles and the longus colli. The nervus vagus is sectioned. The *dashed* and *dotted line* shows the vagus nerve which runs in the thoracic cavity and gives the recurrent laryngeal nerve

Recessus piriformis (Plica nervi laryngei). It innervates the mucosa of the inlet of the larynx, the atrium of the larynx and the posterior part of the Plica vocalis. In the Recessus piriformis the internal branch of the superior laryngeal nerve forms an anastomose with the inferior laryngeal nerve (Galen-Anastomose).

Inferior laryngeal nerves are end-branches of the N. laryngei recurrenti. They are asymmetric, with the left one which descends the carotid sheath into the thorax.

The inferior laryngeal nerve is located in a trough between Trachea and Esophagus cranially and reaches the larynx between the inferior horn of the thyroid cartilage and the posterior cricoarythenoid muscle. Here the nerve gives a posterior and an anterior branch. The posterior branch innervates the posterior cricothyroideal muscles as the transversal and the oblique arytenoideal muscles. The anterior branch innervates the thyreoarytenoideal and lateral cricoarytenoideal muscles. The inferior laryngeal nerve is responsible of sensitivity of the infraglotteal cavity of the upper trachea, esophagus and hypopharynx.

It curves around the aortic arch and return up between esophagus and trachea. The right one turns around the subclavian artery.

Lesions of the nervus laryngeus superior leads to a paralysis of the cricothyroid muscles and hypoestesy of major part of the internal laryngeal space. The tension of the vocal folds is decreased and the protection reflex (cough reflex, and close of the glottis) are impaired.

Lesions of the inferior laryngeal nerve (n. laryngeus recurrens) are called recurrent paralysis. Symptoms of the paralysis of the muscles innervated from the nerve are individually different. In general the main symptom is "whispering". In case of monolateral lesion, is the vocal fold in a paramedian position. In case of bilateral lesion the patient will become dyspnoic [10].

Classification

Main purposes of a classification system of traumatic cervical spine lesions are giving a scale related to the gravity of the injury which is easy to communicate, offering treatment options and providing outcome. Unfortunately any classification meets all the expectation and doesn't exist till now a widely accepted system [11].

In our opinion three main criteria have to be considered:

- Biomechanics of the accident (compression, distraction, translation/rotation)
- Neurological status (radicular, medullary, mieloradicular)
- Stability of the lesion (White and Panjabi, columns theory, MRI)

Biomechanics

Compression Lesions

They represent the most common injuries. The mechanism is flexion and axial loading or a combination of both. Pure compression fractures involve only the anterior column. The involved part can be the vertebral body or the endplate. Occasionally fractures of the posterior elements are possible such as displaced or undisplaced facet fractures and/or lateral mass fracture. These lesions can be associated to osteopenia and osteoporosis, pathologic fracture and loss of normal cervical lordosis.

Particular morphologies of such fractures are represented from:

- Burst fractures: the predominant component is the axial compression and only in a less measure flexion. In this fracture the anterior and middle columns are involved and fragments are often present in the canal. Concomitant spinal cord injuries are quite frequent [4, 12].
- Teardrop fractures: the anterior inferior vertebral body is interrupted with the presence of a free fragment. The predominant mechanism is hyperflexion. The concomitant presence and the degree of an axial loading can contribute to transform this lesion in a burst fracture. Neurological lesions are possible [4, 12].

Distraction Lesions

The main aspect of these lesions is the disruption of the anatomical vertical axis. During an extension the anterior longitudinal ligament, the vertebral bodies and the intervertebral discs counteract the forces while during the flexion the solely bony and capsuloligamentous constraints of the facet articulation counteract the forces. The fact that these strong constraints are knocked informs us of the great degree of injury as well the higher instability represented from these injuries than a mere compression injury [12]. Common dynamic of the injury are falls or vehicular injuries [4]. Ligamentous disruption is quite common in this kind of injury. They can affect the facet joints (subluxation or luxation) and the disc space (widening; "fish mouth" anterior deformity). If concomitant axial load is present, posterior elements can be broken or spinal cord injury can occur [12]. The standard radiology after the accident can show only paravertebral soft tissue abnormalities because at the injury force arrest the column can be spontaneously returned to an "anatomical" rest situation [4]. MRI can be decisive to evaluate the injury pattern of distraction [12]. Among the posterior elements, the facet complex seems to be the most important for the stability [13]. At the MRI, signal of abnormality of the spinal cord after distraction lesion are quite common [4].

Translation/Rotation Lesions

The main characteristic is the horizontal displacement of a vertebral body on plain AP X-Rays. The usual degree of translation and rotation defined as pathologic are respectively 3.5 mm and $\geq 11°$ [14].

These pattern of injury are characterized from: bilateral pedicle fractures, bilateral facet fractures/dislocations, fracture separation of the lateral mass ("floating fractures") [15]. Anterior and posterior complex can be both injured. An MRI study is usually indicated [12].

Two specific cases deserve a more accurate description because are combinations of the previous three mechanism of injury:

Unilateral facet dislocation

The dynamic is a combined flexion and rotation. The facet on the opposite side of the rotation is displaced anteriorly with locking in front of the facet below. Two adjacent segments show a different projection, with one that is projected laterally and the other on an oblique plane. On the anteroposterior view a brisk misalignment of the spinous processes can be observed. CT or MRI can give more informations (Fig. 18.3). Spinal cord injuries can be associated. In these injuries a radicular symptoms can present in the clinical pattern [4].

Bilateral facet dislocation

The dynamic is an abrupt hyperflexion and anterior translation with posterior longitudinal ligament insufficiency, which permit a forward dislocation of the facets. In this case a spinal cord injury is more frequent than in the unilateral. Usually the dislocation of the vertebral body is higher than 25 %. They are always highly instable lesions and traction weight must be monitored with radiographically for the risk of over distraction [4].

Neurological Status

Radicular, medullary or mielo-radicular syndromes can be objectivated.

There are different types of incomplete injury syndromes.

Anterior cord syndrome: usually due to traumatic anterior flexion of the cervical spine with direct injury of the spinal cord or indirectly with impairment of the blood supply from the anterior spinal artery. There is motor function impairment and a temperature and pain sensation deficit below the lesion, while proprioception and touch as well vibration sensation are intact.

Posterior cord syndrome: is a very rare condition and is caused from the direct trauma or loss of blood supply from the posterior spinal artery in a hyperextension of the spine. It results in loss of proprioception and epicritic sensation below the injured level.

Hemicord syndrome (Brown–Séquard syndrome): is a hemisection of the spinal cord. Precise hemisection are rare and the most of these kind of lesions are caused by penetrating wound (knife or gunshots). The ipsliateral side of the injury presents a loss of motor function, light touch, vibration and proprioception. The controlateral side has a loss of pain, temperature and gross touch below the lesion level. Usually the controlateral deficit starts few dermatomes below the section (spinotalamic tract doesn't cross immediately but ascend between two and four levels before to decussate).

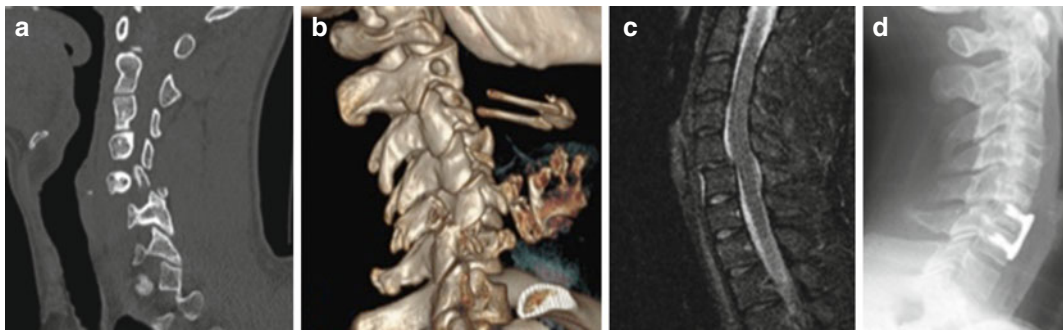


Fig. 18.3 Radiologic assessment of an unilateral facet joint fracture/luxation with anterior and rotatory shift on the preoperative CT (**a**, **b**) and MRI (**c**). On the right (**d**) the postoperative lateral X-Ray control after anterior microdiscectomy, open reduction using axial traction and plating

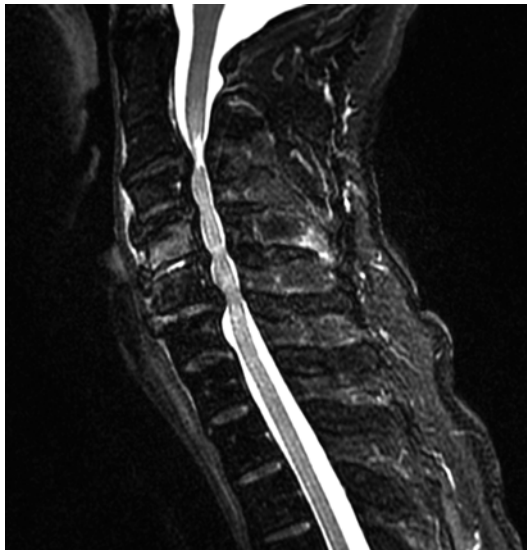


Fig. 18.4 Sagittal T2 MRI image of a cervical injury associated to spinal cord lesion with preexistent spinal canal stenosis

Central cord syndrome: represents a form of spinal cord injury with impairment of the arms and hands function and only to a lesser extent in the legs. Some clinicians refer to that like a reversed plegia. Cervical and thoracic segments can be affected. The condition is caused mainly by hemorrhage, ischemia or necrosis. Trauma can cause prolonged ischemia of the spinal cord tissue. The corticospinal fibers committed to the leg are spared because of the external anatomical location. The condition can also emerge in a second time after spinal shock because of prolonged swelling around the vertebrae. The syndrome may be permanent or transient (Fig. 18.4).

Neurological Impairment Scales

The first popular clinical scale to segregate the posttraumatic neurological status was introduced internationally by Frankel in the seventies.

It was organized in five categories were i.e. no function (A), sensory only (B), some sensory and motor preservation (C), useful motor function (D), and normal (E) [16].

Acute spinal cord injury – Frankel Classification grading system

Grade A	Complete neurological injury – no motor or sensory function clinically detected below the level of the injury.
Grade B	Preserved sensation only – no motor function clinically detected below the level of the injury; sensory function remains below the level of the injury but may include only partial function (sacral sparing qualifies as preserved sensation).
Grade C	Preserved motor non-functional – some motor function observed below the level of the injury, but is of no practical use to the patient.
Grade D	Preserved motor function – useful motor function below the level of the injury; patient can move lower limbs and walk with or without aid, but does not have a normal gait or strength in all motor groups.
Grade E	Normal motor – no clinically detected abnormality in motor or sensory function with normal sphincter function; abnormal reflexes and subjective sensory abnormalities may be present.

The successor of the Frankel scale was the American Spinal Injury Association impairment scale introduced the first time in the 1982 [17]. The ASIA impairment scale categorizes motor and sensory impairment in individuals with SCI.

ASIA impairment scale

A = Complete	No sensory or motor function is preserved in the sacral segments S4-5
B = Sensory Incomplete.	Sensory but not motor function is preserved below the neurological level and includes the sacral segments S4-5 (light touch or pin prick at S4-5 or deep anal pressure) AND no motor function is preserved more than three levels below the motor level on either side of the body.
C = Motor Incomplete	Motor function is preserved below the neurological level[a], and more than half of key muscle functions below the neurological level of injury (NLI) have a muscle grade less than 3 (Grades 0–2).
D = Motor Incomplete.	Motor function is preserved below the neurological level[a], and at least half (half or more) of key muscle functions below the NLI have a muscle grade > 3.

E = Normal	If sensation and motor function as tested with the ISNCSCI are graded as normal in all segments, and the patient had prior deficits, then the AIS grade is E. Someone without an initial SCI does not receive an AIS grade.

[a]For an individual to receive a grade of C or D, i.e. motor incomplete status, they must have either (1) voluntary anal sphincter contraction or (2) sacral sensory sparing with sparing of motor function more than three levels below the motor level for that side of the body. The International Standards at this time allows even non-key muscle function more than 3 levels below the motor level to be used in determining motor incomplete status (AIS B versus C).
NOTE: When assessing the extent of motor sparing below the level for distinguishing between AIS B and C, the motor level on each side is used; whereas to differentiate between AIS C and D (based on proportion of key muscle functions with strength grade 3 or greater) the neurological level of injury is used.

Stability

Columns Theory

Holdsworth introduced the new concept of two columns [18]. The anterior column is composed of the anterior longitudinal ligament, vertebral body, intervertebral disk and posterior longitudinal ligament. The posterior column is made up of all the ligamentous and bony structures behind the posterior longitudinal ligament. This concept has been decisively to understand injury pattern mainly in flexion and extension mechanism. The improvement offered from the Denis' concept of three columns represented a breakthrough to define the condition of vertebral column stability [19]. The concept was initially applied to the thoracolumbar column but can be helpfully extended to the cervical spine for the understanding of its biomechanics.

To the middle column take part the posterior third of the vertebral body, the annulus fibrosus and the posterior longitudinal ligament. The posterior column consists of posterior neural arch, spinous process, articular processes and their capsules.

Radiographic Instability Criteria

Normal kinematics is facilitated from two fundamental structures: discoligamentous complex and the articulating facet joints.

Most of the criteria of spinal instability were studied and introduced from White and Panjabi and it is not purpose of this book chapter to analyse them.

Beside the kinking image in lateral acquisition the presence of a sagittal displacement of two vertebral bodies gets a clear meaning of instability. The dislocation occurs in flexion and disappears in reclination. A step of more than 3.5 mm is referred from White and Panjabi as a severe instability where the neurological structures are put at risk [20, 14]. Daffner proposed as rule of thumb 2 mm to define a normal finding [21].

According to White and Panjabi a segmental kyphosis of more than 11° is defined as pathologic [20, 14]. The pathological substrate of a segmental kyphosis is fragmentation of vertebral body or discoligamentary disruption.

Concerning subluxation of the facetary joint, White and Panjabi give 50 % of overlapping as limit between stable and unstable lesion.

Increased intervertebral disc space, increased shadow of the connective prevertabtral tissue (normal values: 10 mm C1; 4 mm C3-C4; 15 mm C6) and interspinous widening are others signs of radiologic instability [7].

Diagnosis

Physical exam of the patient has a central role for the evaluation of the patient before the radiogram. The sensitivity of the spontaneous pain and palpatory pain was reported to be respectively of 86 and 79 % [22]. Clinical exams and neurological exams with indicative signs for cervical column lesion was found have a sensitivity of 93 %.

A standardized process to reach the correct diagnosis is not defined. We recommend:

- Direct or third person history outline
- Thoroughly patients examination.
- Acquiring of three standard radiographs: anteroposterior, lateral and transoral.

- Swimming acquisition if the cervicothoracal passage is not well visualized.
- Oblique acquisition to clarify different questions about articular processes or small vertebral joints as the foramina intervertabralia
- Computer tomography is necessary if a bone injury is already visualized or just suspected
- The magnetic resonance in every case of neurological lesion, or incongruence between the clinical findings and radiological finding.

Conventional radiography is the basis for the diagnostic of lesion of vertebral column.

Daffner proposed a systematic evaluation of plain radiogram with the ABCD rule. "A" for alignment and anatomy abnormalities; "B" for bony integrity abnormalities; "C" for cartilage (joint) space abnormalities and "S" for soft tissue abnormalities [23].

Most of these signs are combined or associated and are not to be found as isolated finding.

Is not always possible to do immediately the dens view because the patient has to be compliant.

The proper AP view is made with rays inclined 20° cranially and with centered cricoid.

The proper lateral view shows always the 7th cervical vertebral body, the intervertebral disc between C7 and T1 and the endplate of T1 [24, 25]. If necessary is necessary to pull on the patient's arms to avoid overlap of the images.

The anteroposterior and lateral views play a main role in the diagnoses, which help us to understand the stability and not to prove instability. The instability is clarified individually for each patient with all necessary and available diagnostical studies (see chapter "Radiologic assessment").

Patients presenting consciousness impairment, intoxications, neck pain or midline tenderness or severe associated injuries should undergo a complete radiologic assessment of the cervical spine.

The role of functional radiological studies is debated and with the wide spreading of CT and MR techniques the importance of such study is very limited.

In case of symptomatic patient with suspect radiography the indication for a CT to clarify the possible skeletal lesion should be posed. In presence of radiographic instability criteria or neurological deficit an MR investigation is justified.

CT is the tomographic methods of choice in acute spinal injury [26] and should precede supplemental studies (MRI, functional radiograms and digital subtraction angiography).

The sensitivity of the CT study is considerably higher than radiographs (e.g., 98 % versus 52 %) [27].

MRI is always more popular for the study also in acute setting thanks to the reduction in the time of scanning and processing and the availability of devices for traction compatible with magnetic field.

The MRI study can discover ligamentous disruptions not visualized with other imaging techniques.

In some cases also vascular dysfunction can be visualized with MRI, albeit DSA and angio-CT remain investigations of choice to clarify these situations. Indications and timing of the MRI study remain anyway a topic of debate [28]. Commonly, MRI is administered sub acutely as help to surgical planning.

With the MRI we can achieve adjunctive information which are not recognized with other imaging systems. For example many hyperintense signals which are defined as "indeterminant" can be signs for instable injuries. When MR sequences detect changes of signal in the facet capsules, interspinous ligament and disc space a pathologic process is objectivized but the clinical meaning remains not unknown [12]. Also injuries of the neck muscles or perivertebral hematoma are detected with high sensibility with the MRT.

Of all the severe injuries of the vertebral column 80–90 % has no neurological deficit. Anyway exists an absolute indication for use of MRI in acute neurological imparment [29].

Treatment

The optimal management of cervical spine injuries is still a matter of debate and the choice of treatment has to consider multiple variables such as clinical patient conditions, stability of the lesion and presence of deformity [30].

Conservative Treatment

A conservative management is the treatment of choice in case of stable, non-displaced cervical injuries without neurological deficit. The Philadelphia collar is the most used rigid system of external stabilization for the intermediate and lower cervical spine (Fig. 18.5). It allows a good stiffness in flexo-extension maneuvers even if it limits only partially the axial rotation. In case of association of a lesion on the craniocervical junction between C0 and C2 a more rigid rotation stabilization device such as a halovest has to be considered while in case of lesion on the cervicothoracic junction the stability may be assured by a rigid collar with thoracic prolongation. The duration of the cervical external immobilization can vary according to the severity of the lesion but in general doesn't last before 8 weeks of treatment.

Surgical Treatment

The main goals of the surgical treatment of traumatic cervical injuries are to decompress the neurological structures, to restore the vertebral alignment and to guarantee the stability of the injured spine. In case of lesions provoking an anterior or posterior displacement of vertebral structures with consequent neurological impairment, the surgical treatment is for sure to be preferred. In case of incomplete spinal cord lesion, the surgical stabilization should take place in the first 8 h while in case of complete spinal cord lesion the surgical treatment window is 72 h [30]. When distinguishing between complete or incomplete lesion is not possible, an early stabilization is to be preferred to avoid secondary dislocations. It is worldwide accepted that a prompt operative treatment provide less complication and reduce the time of intensive care [31].

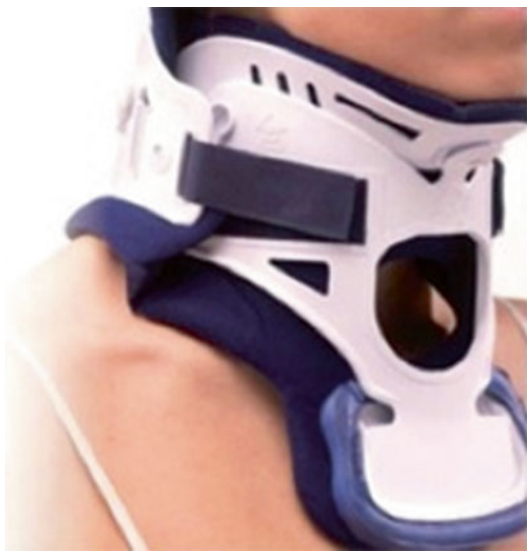


Fig. 18.5 Image of a rigid cervical collar type Philadelphia

In case of acute spinal cord injury Methylprednisolone sodium succinate has been shown to improve neurologic outcome up to 1 year post-injury if administered within 8 h of injury and in dose regimen of: 30 mg/kg over 15 min, with maintenance infusion of 5,4 mg/kg per hour infused for 23 h [32].

Nevertheless quite often the initial radiologic assessment shows minimal dislocation without neurological symptoms. In these situations the severity of the injury can be assessed with complementary diagnostic exams such as MRI which can provide further informations concerning the integrity of the discoligamentary structures. The superiority of surgical over the conservative treatment in these situations is still not proved [33, 34]. Anyway the operative treatment allows a reduction of hospitalization and rehabilitation time [35–37]. Moreover the diffusion and standardization of surgical procedure have contributed to the tendency to privilege the surgical option.

The treatment decision has to be tailored on the patient case by case.

Cervical Axial Traction

In case of vertebral disallignment the restoration of the physiologic cervical lordosis is an independent parameter of good clinical result in term of axial pain. It is well known that the reduction of post-traumatic cervical misalignment can be very challenging and the utilization of cervical axial traction is still very useful either in non-operative close reduction of facet luxation and fractures or

in preoperative and intraoperative open reduction maneuvers. The weight that has to be applied for axial traction through a head holder (such as Garden-Wells) depends on the level of the lesion and on the entity of the displacement [7].

Surgical Approaches

Two main surgical approach can be used to treat a lesion of the intermediate and lower cervical spine: the anterior approach has the advantage to allow good restoration of the cervical lordosis and it is in general preferred when a high comminution of the vertebral body imply a vertebrectomy, the posterior approach allows instead a good surgical decompression but can exitate in a kyphotic cervical disbalance. Familiarity of the surgeon with the technique and available equipment plays a role in the choice. On the patient's side the anterior approach presents the risk of temporary dysphagia or hoarse voice, neck scar, and injury to visceral structures (esophagus) on the contrary the posterior approaches expose to local wound infection and paraspinal muscle damage. Indeed the anterior approach can be preferred to avoid the prone position in traumatized patient; disc herniations can be directly removed and restore of segmental lordosis is possible [38–41]. The criticism of the anterior approach for cervical subaxial trauma is its biomechanical inferiority when compared with posterior fixation [42, 43].

Generally burst and compression fracture with dorsal herniation or dorsal fragments dislocation of vertebral body are treated by an anterior fixation [44] while unstable translation and rotation lesions are usually treated from posterior or from combined anterior and posterior approaches [45]. In chronic dislocations posterior approach is generally preferred.

Anterior Approach to the Cervical Spine

In 1950 three independent authorships developed this access: Bailey and Badgley [46], Robinson and Smith [47] and Cloward [48] which allowed a good exposition of discs, vertebral bodies and uncovertebral joints from C3 to Th1, representing an elegant solution to treat cervical pathologies.

The split of the stilohyoid muscle and of the posterior belly of the digastric muscle allows to reach C2. Distally the Th2 and Th3 vertebral bodies can be reached with sternotomic prolongation approach.

(i) *Position of the patient*
- Supine on radiolucent operating table with neutral position of the head.
- Extension of the neck is improved with a small sandbag between the shoulder
- If motor evoked potential (MEP) and somatosensory evoked potential (SSEP) monitoring is available the head can be extended and distraction applied (after halter traction or taping of the chin) and turned away of the operative side to enlarge the operative field. Inhaling narcotics should be adapted to the neuromonitoring devices.

(ii) *Reference points*

Several reference points are available in the anterior approach, making easier to determine the incision level:
- Lower border of the mandible: C2-3
- Hyoid bone: C3
- Thyroid cartilage: C4-5
- Cricoid cartilage: C6
- Carotid tubercle (large tubercle adjacent to the carotid pulse on the anterior part of the transverse process of C6): C6

  Sternocleidomastoid muscle origins from the mastoid process and attach to the sternum and clavicle. Turning the head controlaterally makes its relief more prominent.

  Carotid artery pulse can be touched on the medial edge of the sternocleidomastoid muscle with gently pressure posterior and laterally.

(iii) *Incision*

Once chose the level a transverse skin crease incision is performed. The incision is usually oblique mediolaterally to the posterior border of the sternocleidomastoid muscle.

The platysma can be incised without innervation problems (supplied by facial nerve, VII cranial nerve).

In the deeper layer there is a internervous plane between the medial strap muscles of the neck (segmental innervation from C1, C2 and C3) and the sternocleidomastoid muscle (spinal accessory nerve, XI cranial nerve).

(iv) *Superficial surgical dissection*

- Anterior neck superficial structures are well vascularized and bleeding can create problem by dissection. Adrenalin injection can temporarily reduce the bleeding.
- The fascia of platysma is incised in line with the skin.
- The platysma is blunt dissected with the fingers parallel to the fiber direction, or cut with the Metzenbaum scissors.
- Incise the fascia anterior and medial to the sternocleidomastoid muscle.
- If the omohyoid muscle (that runs oblique in the operative field) cannot retract medially it must be cut in the midtendon.
- Retract medially the sternohyoid and sternothyroid strap muscles protecting trachea and esophagus.
- The carotid sheath (enclosing carotid artery, vein and vagus nerve) is identified
- Cut the pretracheal fascia between the carotid sheath and the midline structures.
- The superior and inferior thyroid arteries connect the carotid sheath with the midline and limit the upper exposure to C3-C4. If it is necessary they can be ligated.

(v) *Deep Surgical Dissection*

- Once opened the pretracheal fascia to access the cervical column is necessary a longitudinally section on the midline of the longus colli muscle.
- Strip off the longus colli muscle subperiosteally with the anterior longitudinal ligament from the anterior portion of the vertebral body and retract it to the right and to the left.
- The anterior longitudinal ligament is visualized as a gleaming with structures.
- Lateral to the longus colli lies the sympathetic chain lies.
- Place a radiopaque marker in the appropriate vertebral body and take a lateral image with the radioscopy to control the position.
- Insert the retractors under the longus colli muscles and wide them protecting trachea esophagus and recurrent laryngeal nerve.

(vi) *Specific surgical risks*

The recurrent laryngeal nerve can be injured during the deep surgical dissection. The longus colli muscle protect it. The recurrent laryngeal nerve and its anatomical course are of great importance for anterior cervical approach. Using this approach the major parts of surgeons prefer to use, when possible, the left side for an anatomical reason. The right recurrent laryngeal nerve is more vulnerable because it crosses the subclavian artery form lateral to medial to reach the midline trachea still in the lower part of the neck with higher risk for injuries. On the left side the nerve crosses under the aortic arch with lower risk of intraoperative lesion. If right approach is chosen the nerve should be visualized during the dissection, particularly below C5; reference for the nerve is the inferior thyroid artery (Fig. 18.3).

Sympathetic nerves and stellate ganglion can be injured with following Horner's syndrome. To protect it the stripping of the longus colli muscles must be subperiosteal and limited laterally before the transverse processes.

Carotid sheath must be protected from the sternocleidomastoid muscle. For retraction is suggested to use only round and hand-held retractors.

Vertebral artery is protected in the transverse foramina and shouldn't be exposed during the operation. Laceration occurs in 0.5 % of the cases; more frequently with decompression involving hemicorpectomy and corpectomy.

Inferior thyroid artery can be inadvertly cutted or retracted underneath the carotid sheath.

Injuries of trachea and esophagus can occur by using retractors or after screw displacement.

Spinal cord and nerve roots damage are possible in every anterior spinal cord surgery (rate of neurologic complication 0.28 %) and somatosensory evoked potentials monitoring reduce its incidence [49].

Microdiscectomy

This phase imply the use of the microscope or at list of magnifying loops.

- Lateral radiograph is obtained after positioning a radiopaque needle to control the level.
- Preparing of the longus colli muscle to visualize the vertebral body.
- When osteophytes are present they must be excised with rongeurs to avoid malposition of the interbody graft. Now is the anterior vertebral margin visible.
- Cut a rectangular window in the anterior disc
- Remove anterior disc material with a pituitary rongeur.
- Remove the cartilage from the upper and lower endplates with a curette.
- Remove posterior disc material with a pituitary rongeur without violating the posterior longitudinal ligament.
- Wide the intervertebral disc space with positioning and twisting a Cobb elevator. With this device mobilize the vertebral body. Distraction can be obtained position in a distractor (Cloward distractor or Caspar distractor)
- The enlargement of the disc space must have at least 6 mm height.
- Frequently small fragments of disc extrude through posterior longitudinal ligament. In this case with a curette they can be removed. Sounding with micronerve hook can be useful to probe the defects. If the fragments are in the posterolateral margin of the vertebra adjacent to the foramen can be useful the use of burr to offer direct visualization.
- If the bulge-mass of an osteophyte is important it can be removed under direct vision with the burr.
- The cartilage of the endplates must be removed with a curette
- Insertion of auto or allograft (usually the graft is 13–15 mm deep and 6–8 mm high)
- Distraction of the prepared disc
- Insertion and countersunk of the graft till 2 mm behind the anterior vertebral margin with impactor. Fragmented graft shouldn't be used
- Release of the traction and test of the graft stability
- Control with lateral radiography graft placement
- Drainage and closing of the platysma and skin

Cervical Vertebral Corpectomy

- Accurately exposure of the vertebral body to be excised is decisive.
- Excision of anterior longitudinal ligament and upper and lower disc to the chosen vertebral body is necessary to expose it and to orientation to the depth of the posterior longitudinal ligament.
- After incision the disc material is removed with a curette and pituitary rongeurs.
- If the vertebral bodies are still intact an intervertebral spreader can be used.
- Visualize well the uncovertebral joint as this mark the lateral limit of the disc and are reference points for the corpectomy.
- Remove the anterior cortex of the vertebral body with rongeurs followed by burr of the rest of the body but leaving intact the posterior wall.
- The posterior wall must be gently burr with diamond-point and then the debries and remained osteophytes withdrawn with curette.
- The posterior longitudinal ligament if still intact should be preserved as useful middle to create tension band after the graft/cage insertion.
- Width of the decompression is decisive for the result of the operation. The width in the posterior portion of the vertebral body should be 16 mm to ensure decompression. A "trumpet-shaped" burr can be also an alternative to get decompression exactly in forn of the spinal cord.
- Now can be increased the traction to correct the deformity and implant the bone graft/cage.

- Prepare holes with burr central in the endplates to receive the graft.
- Measure the distance with malleable probe or calipers.
- Tricortical T-shaped iliac crest strut graft/cage is collected and positioned with the tricortical part dorsally.
- Reduce the traction and test the graft/cage stability with a clamp.
- Eliminate the traction and control extension and flexion of the head. Fragmented and instable grafts must be changed.
- Smooth the anterior face of the graft/cage to avoid esophageal lesions.
- Radioscopic control of the graft/cage position.

Anterior Plating

Realignment, fixation and compression provide better union following fractures.

Anterior plate fixation was developed from Böhler in 1967 [50].

The titanium cervical spine locking plate was introduced by Morscher providing good stability without bicortical screw purchase [51]. This plate uses an expansion screw.

All the instability of the anterior column can be well addressed with anterior surgery.

Plating provide as in other body segments rigid internal fixation and optimal condition for the bone graft healing.

- Obtain good mobilization of the longus colli.
- Decompression and bone grafting /cage implantation
- Remove osteophytes to permit application of the plate.
- Before to applicat the plate remove all distractors and traction.
- It is decisive the correct contour of the bone graft and cancellous grafting to fill the gaps before the plate implantation.
- Determine the size of the plate with fluoroscopy.
- Bend the plate to keep lordosis alignment and compress the bone graft (temporarily stabilization of the plate is get with plate holder and pin use).
- Position of the plate on the cervical spine
- Drill holes measuring 3.5 mm with depth of 14 mm.
- Place the drill thoroughly in the center to avoid eccentric screw placement.
- Tap and insert screws of 4 mm.
- Two screws are placed above and below the graft.
- Don't overtight the screws.
- Insert the screws which expand the head of the plate screws.
- Additional screw through the central holes to fix the bone graft can be used.

Posterior Approach to the Cervical Spine

In traumatology of the cervical columns this approach permits:

- Enlargement of spinal canal (laminectomy or laminoplasty)
- Posterior cervical spine fusion
- Nerve root exploration
- Treatment of facet joint dislocations
- Excision of foraminal disc herniation

(i) *Position*:
- Prone
- Shave up the inferior margin of the occiput.
- The flexion of the head in "chin-tucked and slightly forward-flexed" position opens the interpinous and interlaminar spaces
- Fix the patient with brace and tong (Mayfield) to permit airway intubation and control of the position during operation.
- A reverse Terndelemburg of 30° is preferable to reduce venous bleeding and facilitate exposure.
- Knees are flexed to prevent distal displacement of the patient.
- Tape down the shoulders to obtain best radioscopy visualization.

- Upright seated position is possible with special braces but has higher risk of air emboli.
- The use of microscope is, depending on availability an advantage to perform the operation.

(ii) *Reference points*

Spinous processes are the most prominent and useful landmarks.

C2, C7 (vertebra prominens) and Th1 have wide and large spinous process.

The spinous process of C2 is origin of many muscular attachments and should be spared from eventual excision.

(iii) *Incision*

- Straight incision in the midline of the neck
- Natural internervous plane exists between the two hemisomes muscles which are innervated by the right and left posterior rami of the spinal nerves.

(iv) *Superficial surgical dissection*

- Proceed with the dissection up to the spinous processes through the nuchal ligament (position of third occipital nerve).
- Cauterize the subcutaneous bleeding coming from venous plexus.
- Subperiosteally stripping of the paraspinal muscles bilaterally with help of the Cobb elevator or cautery.
- Lateralize the dissection to reveal the lamina or the articular facets.
- Place the self-retaining retractors

(v) Deep Surgical Dissection

- Visualize the ligametum flavum between the laminae.
- Excise it from the inferior lamina
- With a spatula cut from the midline mediolateral the two ligaments separating them from the underlying dura.
- Perform laminectomy (partial or complete) with high-speed tool and then with Kerrison rongeur according to the necessary exposure of the subjacent dura often covered from epidural fat.
- With blunt instruments visualize the disc space, the posterior portion of the vertebral body and eventually bony, disc fragments.
- Cauterize with attention not to injury the spinal root the bleeding coming from the numerous epidural veins.

(vi) *Specific surgical risks*

- Nerve root and spinal cord: expose as much as necessary to avoid abruptly retraction on the nervous structures. Aggressive retracting causes postoperative adhesions. If necessary remove partially the facet joint to expose the nerve root.
- Posterior primary rami of the cervical nerve roots: innervation is usually so abundant that also denervation has not clinical consequence.
- Venous plexus in the cervical canal: abundant and easily bleeding during operation. Bipolar cauterization is almost always necessary.
- Segmental blood supply of the muscles: usually active contraction of the muscle cause hemorrhage arrest. Cauterization can always be used without risks of significantly devascularization. If nutrient foramina of the spinous processes bleed bone wax can be used.
- Vertebral artery: well protected in the canal established from the transverse foramina. If the process is destroyed as result of the trauma pay attention in the lateral dissection.

(vii) *Pitfalls*

- Spina bifida
- Previous posterior cervical surgery

(viii) *Posterior cervical laminoplasty*

The original description comes from Hirabayashi [52]; two possible variations do exist: unilateral "open-door" and bilateral "French-door".

- spinous processes from C3 to C7 can be removed.
- With the burr 2 bony troughs are made medially to the lateral masses or in the lamina-facet junction.
- In the "open-door" technique the hinge side is burr only monocortical. If the

burring is bicortical the laminoplasty is transformed in a laminectomy and a salvage plate may be necessary.
- The opening side is burr bicortically and removed.

The use of microscope is currently standard use.

- Excision of the ligamentum flavum from the C2-C3 and C7-T1 interspaces are excised with the Kerrison. The flavectomy is performed at the caudal and rostral levels of the lamnoplasty.

Dural adhesions on the opening are freed with curettes and 2 mm Kerrison.
- Opening of the hinge side using small forward-angled curettes or skin hooks.
- Gently opening to allow slow migration of root and spinal cord.
- Accommodate a bone grafts of 6–8-mm.
- Plates for laminoplasty are applied in sequence. Usually the lateral mass is 8 mm and the laminar screw is 6 mm.

After plating the mobilization postoperatively can be immediate.

Tension sutures to the paraspinal musculature and the facet joint capsule represent an alternative to plating.

(ix) *Postoperative management*
- Optional soft cervical collar can be used to start active exercises.
- Physical therapy is begun 6 weeks postoperatively.

(x) *Complications*
- Closure of laminoplasty door.
- Neck pain.
- Nerve root palsies. Most of the patient have recovering after 6 months.
- Postoperative cervical kyphosis.

Lateral Mass Screw Fixation

In case of severe osteopenia/osteoporosis supplementary pedicle screw fixation and/or posterior wiring could be necessary.

If the screw penetration is too deep (bicortical drilling) nerve root can be injured.

Injury of vertebral artery is extremely rare but if screw penetration is too deep and pulsatile bleeding occurs hemostasis, thrombogenic agents and bone wax should be applied and postoperative angiography should be required.

Avoiding extreme flexion or extension of the head allows to prevent the fusion in deformed position. Also lateral alignment must be careful to avoid loss of horizontal gaze.

Is extremely important individuate the center of lateral mass to perform correct screw implantation. Accurate preparation of the approach is crucial to get good visualization. The procedure must be controlled regularly at the fluoroscopy.

- Define entry point 1 mm medially to the center of the lateral mass. The point direction is 25°–30° laterally and 10°–15° cranially.
- Drill with drill guide (2.4 mm drill bit). Increase the drill depth 2 mm. Confirm the screw length with the depth gauge. If spinous processes disturb drilling is possible to trim them. Proper direction of the drill is mandatory to strive avoiding injury of the facet joint, nerve root and vertebral artery.
- Tapping is made with tap size of the outer screw diameter. Bicortical insertion of the screw (choose length 2 mm smaller of the screw to avoid nerve root irritation).
- Adapt the rod with the cutter and bender. Countouring must be made stepwise to obtain the proper shaping. Additional stability is reached with cross connectors between parallel rods. Titanium rods can undergo fatigue after multiple contour correction.
- Place the nut in the polyaxial screw head. Tight the screws gently and systematically to avoid screw torque. Then tight the nut with torque driver and antitorque device.

Soft collar, or rarely hard collar, are indicated in postoperative period.

Wound infection must be controlled early because it can require implant removal and external immobilization.

Failure of bony fusion may necessitate hardware revision.

Pedicle Screw Fixation

First report of this technique applied to the segment from C3 to C6 by Abumi et al. for traumatic

injury of the cervical spine [53]. Superior stability of this system compared to other internal fixation was experimentally demonstrated [54]. The technique allows the reconstruction of the sagittal alignment without requiring stabilization to the lamina. Trauma patients can benefit of this procedure at the same time of an adequate decompression. The risks linked the procedure are anyway higher than the stabilization on the lateral masses. For this reason a thoroughly knowledge of the anatomy is essential to avoid severe complication.

(i) *Indications*

- In the traumatology the posterior surgical cervical pedicle screw fixation find application in cases of posterior elements injuries or in anterior and posterior injuries without severe impairment of the anterior column.
- Post-traumatic kyphosis
- Salvage of pseudoarthrosis of anterior fusion
- Fusion-level alongation in case of adjacent segment degeneration in postfusion surgery (anterior or posterior).

An accurate selection of the patient is necessary to achieve good results. General and specific contraindication have to be thoroughly excluded before surgery:

- Infection disorders
- Osteoporosis
- Major anomalies
- Disrupted pedicles by trauma, rheumatoid arthritis, injuries.
- Small pedicles
- Unilateral obstruction of vertebral artery (contralateral at risk).

According to this contraindications a CT assessment is an essential preoperative tool. The MRI must be administered in all case of evidence or suspect of anatomic variations.

(ii) *Specific Anatomy*

From the studies of Karaikovic et al. we know that screw of 3.5 mm of diameter can be applied, except in case of anatomical variations [55].

Reinhold et al showed that the average overall angle between the sagittal and the longitudinal pedicle is of 46° varying from 30° to 62 (smaller in C7 and bigger in C4). Extremely large angle are at risk for the spinal cord and the vertebral artery [56].

Moreover a solid cortical bone in the pedicles, with difficulties in the screw implantation is to be expected in 0.9 % in C2, in 2.8 % in C3 and C4 and in 3.8 % in C5 [55]. The lateral cortex of the pedicle is always the thinnest with important consequences in the screw insertion.

(iii) *Specific Exposure*

The skin incision is quite long. It is important to visualize completely the superior lamina and discover completely lateral masses.

(iv) *Procedure*

- A little spatula can be inserted in the canal next to the medial cortex of the pedicle to define the direction. Once the spatula is positioned an angle of 15–25° lateral to the spatula direction has to be pointed. From C3 to C7 the insert point is slight lateral to the center of the mass and near to the inferior margin of the articular process of the upper vertebra (individual anatomical variations are possible). Another reference of the screw insertion point are the lateral vertebral notch. Each vertebra presents a notch on the lateral aspect of the articular mass. It is approximately at the level of the pedicle. The notch is located slight above the pedicles in C2, at the level of the pedicle from C3 to C6 and below the pedicle at C7. The entry point is located always 2–4 mm medially to the notch. The sagittal inclination can be difficult; the screw can be inserted at a smaller angle than the angle of anatomical axis. A good compromise is to insert the screw with angles from 25 to 45° in the sagittal plane. Fluoroscopic control can help in any moment of the procedure.
- The funneling procedure of the entry point is a useful option to get more freedom in the direction of the screw. It can be made with a curette or a burr.

- Afterward can be inserted a pedicle probe and tapping is performed. Insertion of the screw under C-arm control. The thick medial cortex of the pedicle works like a guide by inserting the screw. In the cervical spine the neurocentral junction is quite hard to pass and can be helpful the use of a Kirschner wire or a diamond burr to cross this point (avoid drilling for the risk of injuries). The screw axes is parallel to the upper endplate from C5 to C7 and slight cranially directed from C2 to C4.
- Diameter of the screw can go from 3.5 to 4.5 mm. The expected length of the screw is usually between 20 and 24 mm.
- Use of Computer-assisted screw placement is possible even if the effectiveness is still controversial.
- Fixation of screws with a rod or a plate. In general when more than 2 segments must be fixated is better to choose the rods. Before the fixation anyway an adequate decompression is compelling because the alignment change can narrow the canal. The bone chips obtained from the spinous processes should be reposed.
- Thanks the strength of the pedicle screw, appropriate sagittal alignment and kyphotic correction can be achieved with good results. However sharp correction of the kyphosis (or sometimes of scoliosis) can cause spine shortening and/or neural foramina stenosis. In case of preexistent neuronal foramina degeneration and stenosis a prophylactic foraminal decompression must be performed.

(v) *Complications*

Risks related to the insertion of pedicular screws are always possible with damage of neural and vascular elements. Later neurologic deficits in series of 227 cases of cervical pedicle screw fixation was seen in 2.6 %. Correlation with correction angle of kyphosis was described [57].

The posterior approach is biomechanically more robust, particularly when used to stabilize primarily posterior injuries [42, 43]. There have been concerns, however, regarding the rate of wound infection and the possibility to neutralize the development of segmental kyphosis as the injured disc collapses and settles [45].

Prognosis

The neurological status after trauma is a decisive prognostic factor in cervical spine lesions.

The reference score to evaluate the post-traumatic neurological status is the ASIA-Score [58] (see chapter "Classification; Neurological status"). It is not the aim of this book chapter to deeply describe neurorehabilitation techniques after a spinal lesion but just to offer an overview on this subject.

The rehabilitation process is psychosocial and economic costly and intricate [59].

Statistically are more frequent incomplete injuries with partial connections present across the injury level, providing a substrate of plasticity [60] affording some degree of functional recovery.

After the flaccid phase due to spinal shock period, flaccidity is replaced from spasticity [61].

Acute and Subacute Rehabilitation

After a trauma responsible of a complete or incomplete neurologic damage, the patient is usually hospitalized between 6 and 12 weeks. At this stage the rehabilitation program starts as prevention of long term complications. The main goal of rehabilitation in this period is the strengthening to permit sitting up in the bed, using a wheelchair and dressing [61].

The most common acute complications are spastic deformities. Within 1 year 66 % of the patient with post-traumatic spinal cord injuries develop spasticity.

Passive exercises against spasticity is a basic type of rehabilitation [61]. The movement can be done from a robot or a physical therapists. Most of the human movements are organized around reflex circuit disrupted by the trauma, which coordinate different joints together. Passive exercises

can normalize some of these circuits and can activate cell growth, proliferation, protein synthesis and stimulate neurotrophic factors [62].

Control of the joint position is mandatory (pillows, sandbags as well orthotics and splints). Position in bed should change regularly every 2–3 h. Prone position must be adopted sometimes to avoid flexion contractures of the hip. Cleanliness of the skin is useful to prevent decubitus complications. Fixation and supporting upper body is obtained with the use of corsets.

Concerning active exercises, the most used strategy is to perform repetitive movements where the patient ambulates, with help of parallel bars or therapist. Repetitive active movement favors cortical remapping and corticospinal drive [63, 64].

If truncal mobility is present isometric active and active-assisted exercises should be performed. It can prevent pulmonary function decline. Also breathing exercises should be performed during the acute phase to preserve the lung capacity [61].

Orthesis and Mobilization Devices

In the acute phase of complete paraplegia, the strengthening of the upper extremities is pivotal to permit using of electric bicycles, crutches, and to allow transfer from the bed [65].

Wheelchair is the most important device for the patient with spinal cervical injury. It permits to patients to maintain a social life and an individual adaptation is very important [61].

Incomplete spinal injured patients have in some cases still the potentiality to walk. Usually the level corresponding a functional ambulation is T12.

In patient upright standing can be used a locked knee joint walking device. Standing has advantages of reducing deep vein thrombosis and spasticity, bladder and bowel function reactivation, decubitus prevention and osteoporosis [66].

Devices like crutches and walkers are useful to help patients with pelvic control in the chronic stage of ambulation. Light weight of the devices is expensive but crucial in the efficiency.

If the quadriceps strength is normal the orthesis associated to elbow crutches are sufficient to walk without wheelchair.

Hip guidance orthesis (parawalker) can permit ambulation in patient with complete injury of C8-T12.

Chronic Rehabilitation

The independent mobilization is the priority in complete and incomplete paraplegic patients. Usually an injury of T10 level permits an ambulation compatible to physiotherapy exercises. The injury of T11-L2 is correlated to domestic ambulation. With lower level of injury is normally possible an ambulation related to social life.

The patient must be maintain the best physical form possible (reduce excess weight, increase muscle mass and increase aerobic capacity) to allow a more effective mobilization.

In the chronic phase of neurorehabilitation the social integration and the patient independency must be supported [61].

The house must be adapted (door, electric switches height, insulation and heat, door handles, carpets, bath tubs, kitchen apparatus height etc.) to the daily living of patients.

Depression develops in one third of patients after 6 months. The most common cause of death in patient with spinal cervical injury less than 55 years old is suicide. In case of depression or psychotic behavior a psychological support is needed.

Restore the role and occupation of the patient in the society is the most important factor for psychological healthy of the patient. Occupational therapy is an important part of the rehabilitation process [61].

Electrical Stimulation

The functional neuromuscular stimulation is based on stimulating nerve fibers of intact denervated muscles [67].

It has been proved that electrical stimulation increases neurotransmitter expression [68],

reactivates spinal reflex actions [69], affects properties of the spinal pattern generator [70].

A study demonstrates that not only motoric stimulation has positive effect on the recovery of patients but also the stimulation of the sensory pattern [71].

Electrical stimulation works directly on the pathophysiology and the neural plasticity of spinal injuries. The goal of electrical stimulation is to recreate functional movement patterns and make them useful in the daily life [72–74].

Across individual exist different patterns of muscle activation for the same movement. These differences are higher after the injury. So predefined stimulation algorithms are limited in the effectiveness and strike with the problem of higher muscle fatigue.

With "early application" of neuromuscular electrical stimulation, within 2 weeks from the injury, the patient can benefit of an accelerate recovery following spinal injuries. Nevertheless timing of rehabilitation techniques plays an important role in the obtained results.

References

1. Holly LT, Kelly DF, Counelis GJ, Blinman T, McArthur DL, Cryer HG. Cervical spine trauma associated with moderate and severe head injury: incidence, risk factors, and injury characteristics. J Neurosurg. 2002;96(3 Suppl):285–91.
2. Lowery DW, Wald MM, Browne BJ, Tigges S, Hoffman JR, Mower WR, Group N. Epidemiology of cervical spine injury victims. Ann Emerg Med. 2001;38(1):12–6. doi:10.1067/mem.2001.116149.
3. Kwon BK, Vaccaro AR, Grauer JN, Fisher CG, Dvorak MF. Subaxial cervical spine trauma. J Am Acad Orthop Surg. 2006;14(2):78–89.
4. Vollmer DG, Eichler ME, Jenkins III AL. Assessment of the cervical spine after trauma. In: Youmans neurological surgery. 6th ed. Philadelphia: Saunders/Elsevier; 2011.
5. Goldberg W, Mueller C, Panacek E, Tigges S, Hoffman JR, Mower WR, Group N. Distribution and patterns of blunt traumatic cervical spine injury. Ann Emerg Med. 2001;38(1):17–21. doi:10.1067/mem.2001.116150.
6. Spielmann RP, Meenen NM, Maas R, Bittrich A. Radiological diagnosis of cervical trauma at the level C7/T1. Arch Orthop Trauma Surg. 1989;108(2):122–4.
7. Blauth MT, Harald T. Untere Halswirbelsäule. Tscherne Unfallchirurgie Wirbelsäule. Berlin etc: Springer; 1998.
8. Schünke M, Ross LM, Lamperti ED, Schulte E, Schumacher U, Rude Jr J, Voll M, Wesker K, Taub E, Telger T. Thieme atlas of anatomy. Stuttgart/New York: Thieme; 2006.
9. Hoppenfeld S, DeBoer P, Buckley R, R2 Library (Online service). Surgical exposures in orthopaedics the anatomic approach. Philadelphia: Wolters Kluwer/Lippincott Williams & Wilkins Health; 2009.
10. Zilles K, Tillmann B. Anatomie. Heidelberg: Springer-Lehrbuch; 2010.
11. Moore TA, Vaccaro AR, Anderson PA. Classification of lower cervical spine injuries. Spine. 2006;31(11 Suppl):S37–43. doi:10.1097/01.brs.0000217942.93428.f7; discussion S61.
12. Vaccaro AR, Hulbert RJ, Patel AA, Fisher C, Dvorak M, Lehman Jr RA, Anderson P, Harrop J, Oner FC, Arnold P, Fehlings M, Hedlund R, Madrazo I, Rechtine G, Aarabi B, Shainline M, Spine Trauma Study G. The subaxial cervical spine injury classification system: a novel approach to recognize the importance of morphology, neurology, and integrity of the disco-ligamentous complex. Spine. 2007;32(21):2365–74. doi:10.1097/BRS.0b013e3181557b92.
13. Pitzen T, Lane C, Goertzen D, Dvorak M, Fisher C, Barbier D, Steudel WI, Oxland T. Anterior cervical plate fixation: biomechanical effectiveness as a function of posterior element injury. J Neurosurg. 2003;99(1 Suppl):84–90.
14. White AA, Panjabi MM. Clinical biomechanics of the spine. 2nd ed. Philadelphia: Lippincott; 1990.
15. Bono CM, Vaccaro AR, Fehlings M, Fisher C, Dvorak M, Ludwig S, Harrop J. Measurement techniques for lower cervical spine injuries: consensus statement of the Spine Trauma Study Group. Spine. 2006;31(5):603–9. doi:10.1097/01.brs.0000201273.39058.dd.
16. Frankel HL, Hancock DO, Hyslop G, Melzak J, Michaelis LS, Ungar GH, Vernon JD, Walsh JJ. The value of postural reduction in the initial management of closed injuries of the spine with paraplegia and tetraplegia. I. Paraplegia. 1969;7(3):179–92. doi:10.1038/sc.1969.30.
17. Waring 3rd WP, Biering-Sorensen F, Burns S, Donovan W, Graves D, Jha A, Jones L, Kirshblum S, Marino R, Mulcahey MJ, Reeves R, Scelza WM, Schmidt-Read M, Stein A. 2009 review and revisions of the international standards for the neurological classification of spinal cord injury. J Spinal Cord Med. 2010;33(4):346–52.
18. Holdsworth F. Fractures, dislocations, and fracture-dislocations of the spine. J Bone Joint Surg Am. 1970;52(8):1534–51.
19. Denis F. The three column spine and its significance in the classification of acute thoracolumbar spinal injuries. Spine. 1983;8(8):817–31.
20. White 3rd AA, Panjabi MM. Update on the evaluation of instability of the lower cervical spine. Instr Course Lect. 1987;36:513–20.
21. Daffner RH, Deeb ZL, Goldberg AL, Kandabarow A, Rothfus WE. The radiologic assessment of post-traumatic vertebral stability. Skeletal Radiol. 1990;19(2):103–8.

22. Roberge RJ, Wears RC. Evaluation of neck discomfort, neck tenderness, and neurologic deficits as indicators for radiography in blunt trauma victims. J Emerg Med. 1992;10(5):539–44.
23. Daffner RH. Evaluation of cervical vertebral injuries. Semin Roentgenol. 1992;27(4):239–53.
24. Rizzolo SJ, Vaccaro AR, Cotler JM. Cervical spine trauma. Spine. 1994;19(20):2288–98.
25. Mace SE. Emergency evaluation of cervical spine injuries: CT versus plain radiographs. Ann Emerg Med. 1985;14(10):973–5.
26. Keene JS, Goletz TH, Lilleas F, Alter AJ, Sackett JF. Diagnosis of vertebral fractures. A comparison of conventional radiography, conventional tomography, and computed axial tomography. J Bone Joint Surg Am. 1982;64(4):586–94.
27. Holmes JF, Akkinepalli R. Computed tomography versus plain radiography to screen for cervical spine injury: a meta-analysis. J Trauma. 2005;58(5):902–5.
28. Friedman D, Flanders A, Thomas C, Millar W. Vertebral artery injury after acute cervical spine trauma: rate of occurrence as detected by MR angiography and assessment of clinical consequences. AJR Am J Roentgenol. 1995;164(2):443–7. doi:10.2214/ajr.164.2.7839986; discussion 448–49.
29. Kaye JJ, Nance Jr EP. Thoracic and lumbar spine trauma. Radiol Clin North Am. 1990;28(2):361–77.
30. Glaser JA, Jaworski BA, Cuddy BG, Albert TJ, Hollowell JP, McLain RF, Bozzette SA. Variation in surgical opinion regarding management of selected cervical spine injuries. A preliminary study. Spine. 1998;23(9):975–82; discussion 983.
31. Wuermser LA, Ho CH, Chiodo AE, Priebe MM, Kirshblum SC, Scelza WM. Spinal cord injury medicine. 2. Acute care management of traumatic and nontraumatic injury. Arch Phys Med Rehabil. 2007;88(3 Suppl 1):S55–61. doi:10.1016/j.apmr.2006.12.002.
32. Bracken MB. Steroids for acute spinal cord injury. Cochrane Database Syst Rev. 2012;1:CD001046. doi:10.1002/14651858.CD001046.pub2.
33. Ducker TB, Russo GL, Bellegarrique R, Lucas JT. Complete sensorimotor paralysis after cord injury: mortality, recovery, and therapeutic implications. J Trauma. 1979;19(11):837–40.
34. Murphy KP, Opitz JL, Cabanela ME, Ebersold MJ. Cervical fractures and spinal cord injury: outcome of surgical and nonsurgical management. Mayo Clin Proc. 1990;65(7):949–59.
35. Caroli GC, Parisini P, Laguardia AM, Ranocchi R, Salfi C. Reduction and early surgical stabilization of fractures and fracture-luxations in cervical vertebral and spinal cord injuries. Minerva Anestesiol. 1989;55(3):99–102.
36. Gambardella G, Staropoli C, Toscano S, Tomasello F. Early stabilization in severe cervical vertebral and spinal cord injuries. Minerva Anestesiol. 1989;55(3):95–7.
37. Levi L, Wolf A, Rigamonti D, Ragheb J, Mirvis S, Robinson WL. Anterior decompression in cervical spine trauma: does the timing of surgery affect the outcome? Neurosurgery. 1991;29(2):216–22.
38. Aebi M, Zuber K, Marchesi D. Treatment of cervical spine injuries with anterior plating. Indications, techniques, and results. Spine. 1991;16(3 Suppl):S38–45.
39. Goffin J, Plets C, Van den Bergh R. Anterior cervical fusion and osteosynthetic stabilization according to Caspar: a prospective study of 41 patients with fractures and/or dislocations of the cervical spine. Neurosurgery. 1989;25(6):865–71.
40. Razack N, Green BA, Levi AD. The management of traumatic cervical bilateral facet fracture-dislocations with unicortical anterior plates. J Spinal Disord. 2000;13(5):374–81.
41. Lifeso RM, Colucci MA. Anterior fusion for rotationally unstable cervical spine fractures. Spine. 2000;25(16):2028–34.
42. Do Koh Y, Lim TH, Won You J, Eck J, An HS. A biomechanical comparison of modern anterior and posterior plate fixation of the cervical spine. Spine. 2001;26(1):15–21.
43. Ianuzzi A, Zambrano I, Tataria J, Ameerally A, Agulnick M, Goodwin JS, Stephen M, Khalsa PS. Biomechanical evaluation of surgical constructs for stabilization of cervical teardrop fractures. Spine J. 2006;6(5):514–23. doi:10.1016/j.spinee.2005.12.001.
44. Toh E, Nomura T, Watanabe M, Mochida J. Surgical treatment for injuries of the middle and lower cervical spine. Int Orthop. 2006;30(1):54–8. doi:10.1007/s00264-005-0016-4.
45. Dvorak MF, Fisher CG, Fehlings MG, Rampersaud YR, Oner FC, Aarabi B, Vaccaro AR. The surgical approach to subaxial cervical spine injuries: an evidence-based algorithm based on the SLIC classification system. Spine. 2007;32(23):2620–9. doi:10.1097/BRS.0b013e318158ce16.
46. Bailey RW, Badgley CE. Stabilization of the cervical spine by anterior fusion. J Bone Joint Surg Am. 1960;42-A:565–94.
47. Smith GW, Robinson RA. The treatment of certain cervical-spine disorders by anterior removal of the intervertebral disc and interbody fusion. J Bone Joint Surg Am. 1958;40-A(3):607–24.
48. Cloward RB. The anterior approach for removal of ruptured cervical disks. J Neurosurg. 1958;15(6):602–17. doi:10.3171/jns.1958.15.6.0602.
49. Flynn TB. Neurologic complications of anterior cervical interbody fusion. Spine. 1982;7(6):536–9.
50. Bohler J. [Immediate and early treatment of traumatic paraplegias]. Z Orthop Ihre Grenzgeb. 1967;103(4):512–29.
51. Morscher E, Sutter F, Jenny H, Olerud S. Anterior plating of the cervical spine with the hollow screw-plate system of titanium. Chirurg. 1986;57(11):702–7.
52. Hirabayashi K, Watanabe K, Wakano K, Suzuki N, Satomi K, Ishii Y. Expansive open-door laminoplasty for cervical spinal stenotic myelopathy. Spine. 1983;8(7):693–9.
53. Abumi K, Itoh H, Taneichi H, Kaneda K. Transpedicular screw fixation for traumatic lesions of the middle and lower cervical spine: description of the techniques and preliminary report. J Spinal Disord. 1994;7(1):19–28.

54. Kotani Y, Cunningham BW, Abumi K, McAfee PC. Biomechanical analysis of cervical stabilization systems. An assessment of transpedicular screw fixation in the cervical spine. Spine. 1994;19(22): 2529–39.
55. Karaikovic EE, Daubs MD, Madsen RW, Gaines Jr RW. Morphologic characteristics of human cervical pedicles. Spine. 1997;22(5):493–500.
56. Reinhold M, Magerl F, Rieger M, Blauth M. Cervical pedicle screw placement: feasibility and accuracy of two new insertion techniques based on morphometric data. Eur Spine J. 2007;16(1):47–56. doi:10.1007/s00586-006-0104-1.
57. Hojo Y, Ito M, Abumi K, Kotani Y, Sudo H, Takahata M, Minami A. A late neurological complication following posterior correction surgery of severe cervical kyphosis. Eur Spine J. 2011;20(6):890–8. doi:10.1007/s00586-010-1590-8.
58. Maynard Jr FM, Bracken MB, Creasey G, Ditunno Jr JF, Donovan WH, Ducker TB, Garber SL, Marino RJ, Stover SL, Tator CH, Waters RL, Wilberger JE, Young W. International standards for neurological and functional classification of spinal cord injury. American spinal injury association. Spinal Cord. 1997; 35(5):266–74.
59. Pickett GE, Campos-Benitez M, Keller JL, Duggal N. Epidemiology of traumatic spinal cord injury in Canada. Spine. 2006;31(7):799–805. doi:10.1097/01.brs.0000207258.80129.03.
60. Munce SE, Wodchis WP, Guilcher SJ, Couris CM, Verrier M, Fung K, Craven BC, Jaglal SB. Direct costs of adult traumatic spinal cord injury in Ontario. Spinal Cord. 2013;51(1):64–9. doi:10.1038/sc.2012.81.
61. Nas K, Yazmalar L, Sah V, Aydin A, Ones K. Rehabilitation of spinal cord injuries. World J Orthop. 2015;6(1):8–16. doi:10.5312/wjo.v6.i1.8.
62. Dupont-Versteegden EE, Houle JD, Dennis RA, Zhang J, Knox M, Wagoner G, Peterson CA. Exercise-induced gene expression in soleus muscle is dependent on time after spinal cord injury in rats. Muscle Nerve. 2004;29(1):73–81. doi:10.1002/mus.10511.
63. Norton JA, Gorassini MA. Changes in cortically related intermuscular coherence accompanying improvements in locomotor skills in incomplete spinal cord injury. J Neurophysiol. 2006;95(4):2580–9. doi:10.1152/jn.01289.2005.
64. Thomas SL, Gorassini MA. Increases in corticospinal tract function by treadmill training after incomplete spinal cord injury. J Neurophysiol. 2005;94(4): 2844–55. doi:10.1152/jn.00532.2005.
65. Jacobs PL, Nash MS. Exercise recommendations for individuals with spinal cord injury. Sports Med. 2004;34(11):727–51.
66. Guest RS, Klose KJ, Needham-Shropshire BM, Jacobs PL. Evaluation of a training program for persons with SCI paraplegia using the Parastep 1 ambulation system: part 4. Effect on physical self-concept and depression. Arch Phys Med Rehabil. 1997; 78(8):804–7.
67. Hillen BK, Abbas JJ, Jung R. Accelerating locomotor recovery after incomplete spinal injury. Ann N Y Acad Sci. 2013;1279:164–74. doi:10.1111/nyas.12061.
68. Knikou M, Conway BA. Effects of electrically induced muscle contraction on flexion reflex in human spinal cord injury. Spinal Cord. 2005;43(11):640–8. doi:10.1038/sj.sc.3101772.
69. Al-Majed AA, Tam SL, Gordon T. Electrical stimulation accelerates and enhances expression of regeneration-associated genes in regenerating rat femoral motoneurons. Cell Mol Neurobiol. 2004;24(3): 379–402.
70. Lavrov I, Gerasimenko YP, Ichiyama RM, Courtine G, Zhong H, Roy RR, Edgerton VR. Plasticity of spinal cord reflexes after a complete transection in adult rats: relationship to stepping ability. J Neurophysiol. 2006;96(4):1699–710. doi:10.1152/jn.00325.2006.
71. Dobkin BH. Do electrically stimulated sensory inputs and movements lead to long-term plasticity and rehabilitation gains? Curr Opin Neurol. 2003;16(6):685–91. doi:10.1097/01.wco.0000102622.38669.ac.
72. Kim SJ, Fairchild MD, Iarkov Yarkov A, Abbas JJ, Jung R. Adaptive control of movement for neuromuscular stimulation-assisted therapy in a rodent model. IEEE Trans Biomed Eng. 2009;56(2):452–61. doi:10.1109/TBME.2008.2008193.
73. Jung R, Belanger A, Kanchiku T, Fairchild M, Abbas JJ. Neuromuscular stimulation therapy after incomplete spinal cord injury promotes recovery of interlimb coordination during locomotion. J Neural Eng. 2009;6(5):055010. doi:10.1088/1741-2560/6/5/055010.
74. Fairchild MD, Kim SJ, Iarkov A, Abbas JJ, Jung R. Repetetive hindlimb movement using intermittent adaptive neuromuscular electrical stimulation in an incomplete spinal cord injury rodent model. Exp Neurol. 2010;223(2):623–33. doi:10.1016/j.expneurol.2010.02.011.

Neck Pain Rehabilitation

19

Daniele Castelli, Dalila Scaturro,
Antonio Sanfilippo, and Giulia Letizia Mauro

Definition

Neck pain is par excellence one of the most common disorders of the musculoskeletal system, second only to low back pain. It constitutes 40 % of all backache. The International Association for the Study of Pain (IASP) defines pain of cervical origin coming from an area between the nuchal line and another imagi-nary line that passes through the lower end of the spinous process of the first thoracic vertebra and the sagittal plans tangent to the side edges of the neck. This definition considers therefore posterior pain which in turn can be divided into high pain, up to C3, and lower pain, down from C4. Also, as all diseases, it can be divided into acute and chronic neck pain, merely according to the time of onset: it lasts more than 3 months in the first case and for longer in the second case. The painful perception depends on the nociceptive elicitation of the major structures innervated in the neck region, such as cervical muscles, ligaments, facet joints and nerve roots.

The pain may radiate to the upper limbs if there is a nerve root compression, with an annual incidence of 83 per 100,000 individuals, aged between 13 and 91 years, in the US [1]. Clearly the distribution of pain depends on the affected nerve root.

Epidemiology

Despite being a predominantly benign pathology, it has a significant effect in terms of economic and social costs, due to the significant number of days of absence from work. However in 10 % of cases it tends to become chronic. It affects 30–50 % of the general population every year. It reaches its peak in middle age and women are the most affected [1].

It is estimated that its prevalence is of 12.1–71.5 % in the general population and 27.1–48.8 % in workers, while the annual prevalence of disability is of 1.7–11.5 % [2].

Functional Anatomy

To understand the importance of this pathology it is necessary to know in detail the cervical spine from the viewpoint of functional anatomy. Cervical spine performs three important functions: it acts as a support for the head, it enables the movements of the head and provides protection to the spinal cord and the vertebral arteries flowing inside. It consists of two anatomically and functionally distinct parts:

– The upper cervical spine, formed by the first two vertebrae (atlas and axis) that are articulated through a three-axis hinge that allows three degrees of freedom; it coordinates in

C. Daniele • D. Scaturro • A. Sanfilippo • G.L. Mauro (✉)
Dipartimento delle discipline chirurgiche,
Oncologiche e stomatologiche,
University of Palermo, Palermo, Italy
e-mail: giulia.letiziamauro@unipa.it

The original version of this chapter was revised.
An erratum to this chapter can be found at DOI 10.1007/978-3-319-21608-9_20.

P.P.M. Menchetti (ed.), *Cervical Spine: Minimally Invasive and Open Surgery*,
DOI 10.1007/978-3-319-21608-9_19

space the position of the head and allows the alignment of the sense organs.
– The lower cervical spine, that runs from the bottom plate of the axis to the top of the first dorsal vertebra, and allows movements of flexion-extension and mixed rotation-tilt.

These two traits functionally complement and allow the execution of the classical movements of the head: rotation, tilt and flexion-extension. The posture of the head keeps the eyes parallel to the horizon, influences the TMJ static/dynamic occlusal scheme and body scheme, in order to maintain balance.

Etiology

Except for post traumatic events, such as whiplash, the etiology of cervical pain is still misunderstood, or otherwise attributable to different triggers [3]. However, it is possible to identify risk factors and with them the possible causes.

It can be fully considered a multifactorial disease.

We distinguish non-modifiable and modifiable risk factors. Among the first we consider: the age, gender (women are more affected) and genetic factors. While the latter are: smoking (active and passive), physical activity, poor posture, high demands at work, a repetitive or precision work, low social esteem [4].

In most cases the etiologic mechanism is attributed to a dysfunctional source ("nonspecific" or "common" neck pain), in which coexist inflammatory, muscular, neurological, mechanical and postural components [5].

It may be related to:

– A specific organic problem (cervical uncarthrosis, zygapophyseal arthrosis, facet joint syndrome, disc degeneration, spinal canal stenosis, myofascial syndrome, rheumatic diseases, cancer, etc)
– Psycho-social, "not organic" problems
– Post-trauma, work, sports … [6]

Many authors agree that neck pain can be defined as a clinical syndrome that occurs due to imbalance between load conditions, load capacity and, especially, adaptation. A weakness of the cranio-cervical flexor muscles and a forward head posture, usually associated, seem to be the basis of the functional aspects of this disease. Also, hyperlordosis of the upper cervical trait and increased kyphosis of the lower trait result in the increase of load on the transition area between the two curves [7].

Classification

The most common classification defines four grades of neck pain:

– Grade I : absence of signs of major diseases and without interference in everyday activities.
– Grade II: absence of signs of major diseases, but with interference in daily activities (<10 %).
– Grade III: neck pain with signs/symptoms of radicular pain. Requires specific tests and treatments.
– Grade IV: neck pain with signs of major diseases (instability or infection). It requires tests and an urgent treatment.

Clinical Evaluation

Being a multifactorial disease, clinical evaluation of neck pain plays a primary role in the diagnosis, treatment and prognosis.

A comprehensive history is a very important moment of the clinical investigation that can direct you to a diagnostic hypothesis and especially allows you to suspect other diseases that have symptoms such as neck pain ("Red flags").

Next stop is the inspection, that begins with the patient's entry in ambulatory. It will assess the posture of the head, shoulders and upper limbs. It continues while the patient undresses and during all his natural movements. Are to be assessed, also, the presence of any scars, blisters, etc.

Then we begin palpating bones in a supine position, so that the deeper muscles are released and the bony prominences more attainable. In the front, you can pal-pate the hyoid bone, thyroid cartilage, the first cricoid ring and the carotid tubercle. In the rear the occiput, the inion, the superior nuchal line, the mastoid process, the spinous processes of the cervical and, moving sideways to 3 cm, the facet joints. Palpation of the soft tissues also identifies two zones: front and rear. In the first we will find the sternocleidomastoid muscles, the lymphatic chain, thyroid, parathyroid, the carotid pulse and supraclavicular fossa. In the second: the trapezius muscles, occipital nerves and the superior nuchal ligament.

Then you can evaluate the articulation. The range of motion of the cervical spine allows six degrees of freedom: flexion, extension, left and right rotation and tilt. This range of motion allows the head and neck large movements. About 50 % of the flexion and extension occurs between occiput and C1, the remaining 50 % is distributed evenly among the other vertebrae; mind 50 % of the rotations occur between C1 and C2, the other 50 % involves the breaking 5 cervical vertebrae. You will first consider active motility and then passive motility. For the cervical spine more than for any other district, the neurological examination takes a very important role for the presence of the brachial plexus. It consists of two phases: the evaluation of muscle strength of the intrinsic muscles of the cervical spine and peripheral neurological examination of the upper limbs (muscle strength, sensitivity and tendon reflexes). Clinical evaluation can be completed with the execution of some provocative tests such as: Spurling's Neck Compression Test, Shoulder Abduction (Relief) Test, Neck Distraction Test, Lhermitte's Sign, Hoffmann's Sign and Adson's Test and Valsalva Maneuver.

A very important step to monitor the effectiveness of treatment and the course of the disease is the administration of district specific rating scales, as the Neck Pain, Cervical Radiculopathy, Neckache Scale, and so on.

In recent years, however, the World Health Organization is trying to guide the framing of the patient towards a bio-psycho-social vision that considers all aspects related to the health of the individual in order to achieve therapeutic interventions that go to improve quality of life of the person. This system has been identified in the ICF (International Classification of Functioning Disability and Health), around which you can build the evaluation/diagnostic process, pharmaceutical, rehabilitation and subsequent outcomes.

Red Flags

In line with the 2011 SIMFER diagnostic and therapeutic recommendations for back pain, in order to exclude a serious cervical disease, specific research is necessary to evaluate alarm signals (red flags), in reference to the criteria for specialized medical differential diagnosis and forensic medical responsibility for good clinical practice.

The red lights are the following: (tab)

- Age less than <20 years or >50 years
- Signs of systemic disease
- Incessant pain at rest
- Altered state of consciousness
- Language disorders
- Symptoms or signs of alteration of the central nervous system
- Ligamental weakness
- Sudden onset of acute neck pain or headache with unusual characteristics
- Suspected carotid dissection
- Suspected neoplasia
- Suspected discitis, osteomyelitis and tuberculosis
- Surgical outcomes
- Structural deformities with progressive pain

Diagnostic Imaging

Studies of diagnostic imaging should be targeted to the confirmation of a clinical suspicion and not used routinely. The execution of the radiograph

of the cervical spine in standard projections is recommended if symptoms persists for more than a month and on suspicion of a specific diseases. The MRI or CT are justified only in cases of documented neurological compression, together with an EMG/ENG (herniated discs, spinal stenosis), or if a serious condition is suspected (myelopathy, discitis, fractures) [8].

Therapy

Medical Therapy

The 2011 SIMFER guidelines of the diagnostic and therapeutic recommendations for neck pain recommend the use of paracetamol/NSAID/Steroids for the reduction in the short term of the painful symptoms related to the gradient of the symptoms. However, two systematic reviews show no evidence in the use of analgesics, NSAIDs, muscle relaxants and antidepressants for the acute and chronic neck pain.

Rehabilitation Treatment

The primary objective of rehabilitation treatment, since it is not possible a etiological therapy, will be aimed at the reduction or resolution of pain, the global and segmental joint recovery, and especially the restoration of skills decreased from cervical disease. In literature there are numerous studies that describe multiple interventions, however due to the poor methodological quality and diversity of patient samples is not possible to identify a standard treatment. The treatment involves the integration of drug therapy in combination with an individual rehabilitation program, tailor made for each patient depending on the intensity of symptoms and the general clinical condition.

Specifically, it will be in pursuit of shortterm goals (pain control, initial joint recovery if there is limitation), medium term (full recovery of ROM, resolution of muscle contractures, reinforcement of the stabilizing muscles of the head) and long term (taking proper posture and prevention of relapse).

The program, however, will make use of several techniques such as: global postural reeducation by Souchard, that arises from the assumptions of Mezieres and the techniques of McKenzie.

The first technique is based on the clear distinction between behavior and role of the static muscle and dynamic muscles.

The cardinal principle of the method is that static muscles are exercised in a eccentric way and the dynamic muscles in a concentric way. As a consequence, a shortening of the static muscles will lead to a retraction and an excessive resistance to elongation, while the dynamic ones can be freely shortened (contracted).

Going beyond the limits of the Mezieres method, Souchard also places a focus on the diaphragm (respiratory muscle) and the phrenic nerve that supports it, as well as its synergistic action with the posterior back muscles chain and the ileopsoas muscle.

Souchard believes that muscular chains can be summarized in two larger groups: anterior and posterior.

The choice of the used postures is done after a careful functional evaluation of the dynamic and static muscles, and an examination of retractions. Souchard identifies mainly two morphological pattern. The first is called the anterior, in which patients have a forward position of the head, dorsal kyphosis, lumbar hyperlordosis, anteversion of the pelvis, femur internally rotated and valgus knees, heel and foot valgus.

The second is named posterior. In this category patients may present mainly the following characteristics: short neck, flat back, lumbar hypolordosis and subsequent diaphragmatic problems, retroverso pelvis, varus knees, heel and foot varus.

The McKenzie method, developed by a physiotherapist from New Zealand, is based on maintaining correct posture and how to perform specific exercises to treat some forms of back pain, mainly mechanical (related to the maintenance of posture or execution of movements harmful) . The treatment according to McKen-zie tip on the involvement and active participation of the patient for the resolution of the symptoms and above provides the means to prevent recurrence.

The method aims to provide the patient with a program of self-treatment for pain management and prevention of recurrence (Fig. 19.1).

Therapeutic Exercise

The scientific literature supports the effectiveness of therapeutic exercise for acute neck pain. Rehabilitation treatment involves strengthening and stretching of the stabilizing muscles of the cervical spine and shoulder girdle, improved mobility and proprioception, always respecting the pain threshold [9].

In case of chronic neck pain, isometric strengthening exercises have been proven effective, with results maintained even in 3 years.

The dosage of the specific exercise depends on the local load capacity, while, for nonspecific exercises, individual general load capacity must be taken into account, and in particular the presence of comorbidity. According to the clinical presentation, exercises may be directed to the upper cervical spine, the lower spine and the cervicothoracic transition.

The final phase of the treatment will be "gesture-specific", i.e. the patient will mimic work gestures movements, or sport movements, in order to allow the full reintegration of the person in its activities.

Manual Therapy

The therapeutic exercise seems to have a synergistic effect in combination with manual therapy enough to be strongly recommended in the guidelines [10]. Manual therapy through its two different techniques allows the separate treatment of the soft tissues and the joints. The first one is performed on the muscles, tendons and ligaments designed to restore the elasticity of the structure and the resolution of the pain of myofascial origin.

The second one uses mobilization with and without impulse. Mobilizations are carried out by applying different parameters of intensity and time, respecting the range of motion allowed. Depending on the direction of the movement it can be divided into direct, if the mobilization is carried out towards the barrier of restriction, or indirect, if it takes place in the opposite direction. The technique is also called primary, when it involves only the articulation to mobilize, and secondary if it takes place through the mobilization of other joints.

Physical Therapy

The application of physical therapy in the reduction of acute and chronic neck pain consists mainly in magnetic therapy, analgesic

Fig. 19.1 Manual treatment of the patient

electrotherapy, ultrasound and laser therapy in its various forms.

A single randomized trial demonstrated a modest short-term efficacy of magnetic therapy in the treatment of acute and chronic non-specific neck pain [11].

TENS and ultrasound instead, lacking of systematic reviews, are recommended in combination with exercise therapy and other methods of physical therapy in chronic neck pain [12, 13].

Laser therapy is recommended for the reduction of neck pain in the short term in both acute and chronic phases [14].

References

1. Hoy DG, Protani M, de R, Buchbinder R. The epidemiology of neck pain. Best Pract Res Clin Reumatol. 2010;24(6):783–92.
2. Carroll LJ, Holm LW, Hogg-Johnson S, Côté P, Cassidy JD, Haldeman S, Nordin M, Hurwitz EL, Carragee EJ, van der Velde G, Peloso PM, Guzman J. Task Force on Neck Pain and Its Associated Disorders. Bone and Joint Decade 2000-2010. Spine (Phila Pa 1976). 2008 Feb 15;33(4 Suppl):S83-92. doi: 10.1097/BRS.0b013e3181643eb8. Review.
3. Van der Donk J, Schouten JS, Passchier J, van Romunde LK, Valkenburg HA. The associations of neck pain with radiological abnormalities of the cervical spine and personality traits in a general population. J Rheumatol. 1991;18(12):1884–9.
4. Korhonen T, Ketola R, Toivonen R, Luukkonen R, Häkkänen M, Viikari-Juntura E. Work related and individual predictors for incident neck pain among office employees working with video display units. Occup Environ Med. 2003;60(7):475–82.
5. Recommendations diagnostic-therapeutic SIMFER for cervical, 2011
6. Guzman J1, Hurwitz EL, Carroll LJ, Haldeman S, Côté P, Carragee EJ, Peloso PM, van der Velde G, Holm LW, Hogg-Johnson S, Nordin M, Cassidy JD A new conceptual model of neck pain: linking onset, course, and care: the Bone and Joint Decade 2000-2010. Task Force on Neck Pain and Its Associated Disorders. J Manipulative Physiol Ther. 2009;32 (2 Suppl):S17-28. doi: 10.1016/j.jmpt.2008.11.007
7. Panjabi MM, Cholewicki J, Nibu K, Grauer JN, Babat LB, Dvorak J. Mechanism of whiplash injury. Clin Biomech (Bristol, Avon). 1998;13(4-5):239–249.
8. Slipman CW, Plastaras C, Patel R, et al. Provocative cervical discography symptom mapping. Spine (Phila Pa). 2005;5:381–8.
9. Ylinen JJ, Savolainen S, Airaksinen O, Kautiainen H, Salo P, Häkkinen A. Decreased strength and mobility in patients after anterior cervical diskectomy compared with healthy subjects. Arch Phys Med Rehabil. 2003;84(7):1043–7.
10. Bronfort G, Haas M, Evans RL, Bouter LM. Efficacy of spinal manipulation and mobilization for low back pain and neck pain: a systematic review and best evidence synthesis. Spine J. 2004;4(3):335–56. Review.
11. Kroeling P, Gross A, Goldsmith CH, et al., Cervical overview group. Electrotherapy for neck disorder. Cochrane Database Syst Rev. 2005;(2):CD004251.
12. Chiu TT, Hui-Chan CW, Chein G. A randomized clinical trial of TENS and exercise for patients with chronic neck pain. Clin Rehabil. 2005;19(8):850–60.
13. Majlesi J, Unalan H. High PPower pain threshold ultrasound technique in the treatment of myofascial trigger point: a randomized, double blind, case control study. Arch Phys Med Rehabil. 2004;85(5):833–6.
14. Ozdemir F, Birtane M, Kokino S. The clinical efficacy of low power laser therapy on pain and function in cervical osteoarthritis. Clin Rheumatol. 2001;20: 181–4.

Erratum To:

Neck Pain Rehabilitation

Castelli Daniele, Dalila Scaturro, Antonio Sanfilippo, and Giulia Letizia Mauro

P. P. M. Menchetti (ed.), *Cervical Spine,* DOI 10.1007/978-3-319-21608-9_19,

DOI 10.1007/978-3-319-21608-9_20

The original version of the book contained errors which have been corrected. The corrections are given below:

"Author name Castelli Daniele is incorrectly captured in this chapter, it should be Daniele Castelli."

The updated original online version for this chapter can be found at DOI…http://dx.doi.org/ 10.1007/978-3-319-21608-9_19

Index

P.P.M. Menchetti (ed.), *Cervical Spine: Minimally Invasive and Open Surgery*,
DOI 10.1007/978-3-319-21608-9