Surgery of Spinal Tumors

With 1879 Figures and 105 Tables
Dedications

For my wonderful wife Ulrike and our son Lukas, whose continuing love and understanding provided so much support for me throughout this project.

Jörg Klekamp

To my beloved family.

Madjid Samii

This book is dedicated to all patients suffering from spinal tumors. Their courage and enthusiasm to withstand progressive immobility or even life-threatening situations has been a tremendous inspiration for us.

Jörg Klekamp
Madjid Samii
The request from Professor Jörg Klekamp for me to write the foreword for this monograph was an appealing challenge. Prior to the era of microneurosurgery, I was firmly involved in the surgery of spinal lesions, and achieved surgical removal of spinal arteriovenous malformations (AVMs) on 12 patients in the years between 1960 and 1965. Microneurosurgical techniques were introduced in Zurich in 1962, and since then I have applied these techniques to the exploration of the various spinal lesions: 182 herniated discs, 78 spinal cord AVMs, and 263 spinal tumors (46 epidural, 94 extramedullary, and 123 intramedullary tumors). These have been published in a preliminary paper only, for I was unable to accomplish completion of the planned Volume V in my Microneurosurgery series within an adequate time frame. I therefore admire the achievement of Klekamp and Samii, who present to us a most comprehensive work.

This monograph is outstanding in many aspects, providing an overview of the clinical experiences gained in a single neurological institution over a period of 25 years between 1978 and 2003, consisting of 1081 spinal tumors treated in 868 patients, with 973 operations (intramedullary tumors in 198 patients, extramedullary tumors in 446 patients, and epidural tumors in 329 patients). The entire cohort of patients was explored surgically by applying microsurgical techniques. The history of spinal surgery, spinal anatomy, neuroradiology, clinical neurophysiology, surgical approaches, and surgical techniques in the treatment of intramedullary, extramedullary, and epidural tumors in cervical, thoracic, and lumbosacral areas, postoperative results and outcome, complications, morbidity, recurrences, survival, and adjuvant therapies are all meticulously analyzed and thoroughly documented in numerous informative statistical tables and in educative pictures. In addition, multivariate analyses were performed to determine the factors predicting surgical results or outcome. For each factor, a β-value is given, which indicates its predictive power compared to others.

Three distinct time periods can be traced throughout the approximately 120-year history of spinal surgery.

1. The Previsualization Period (1880–1920). A precise neurologic examination of the patient revealed a reliable topographic diagnosis of a spinal lesion. Extramedullary tumors were successfully removed by Macewen (1883, 1884), Horsley (1887), Thornburn (1888), Abbe (1889), Chipault (1894), and Starr (1895). The surgery of intramedullary tumors, however, was pioneered by von Eiselsberg (1907), Fedor Krause (1908), Braun (1910), Röpke (1911), and Charles Elsberg (1914). Cushing had explored an intramedullary tumor in 1905, but did not remove it.
Klekamp and Samii emphasize the impact of the paper by Horsley, as he passionately recommended surgery on patients with spinal tumors, because the alternative, “conservative treatment” was associated with a very high mortality rate. The worldwide highly respected pioneer of spinal tumor surgery was Charles Elsberg. In 1925 and 1941, Elsberg published his series of cases (168 with extramedullary tumors, 73 with epidural tumors, and 19 with intramedullary tumors), wherein he recorded remarkably reduced mortality rates.

2. The Myelography Period (1921–1975). The introduction of myelography (1921) by Sicard and Forestier was a welcome and reliable diagnostic advance, for it displayed the precise localization of the lesions. The publication of Guidetti and Fortuna (1967) reflects the positive impact of myelography technology on spinal surgery. They collected in the literature published prior to 1965, 473 operated cases of intramedullary tumors: 119 ependymomas, 125 astrocytomas, 11 oligodendroglomas, 59 glioblastomas, 113 lipomas, 29 hemangioblastomas, and 17 melanomas. In addition to the effectiveness of myelography for topographic diagnosis, another innovation became essential for the successful treatment of spinal tumors, namely the introduction of the first generation of bipolar coagulation tools by James Greenwood. In 1941, 1942, 1952, and 1953 Dr. Greenwood successfully operated on four patients with spinal cord lesions, none of whom suffered either pre- or postoperative neurological deficits. Previous to Dr. Greenwood’s success, there had been a great reluctance to attempt surgery on an intramedullary tumor, especially on a patient having no, or only discrete neurological deficits.

3. The introduction of selective spinal angiography by M. Djindjian (1970), and noninvasive neurovisualization technology (computed tomography in 1970 and magnetic resonance imaging in 1985). These innovations signified very relevant breakthroughs in achieving precise topographic and differential diagnoses of spinal lesions, as well as delineating their vascularization pattern. This knowledge is of great benefit when evaluating the location of the lesion, and when devising a plan for surgical exploration.

Many developments and innovations followed that represented enhancing factors for the continually evolving microsurgical techniques; for example, the introduction of the operating microscope, the development of greatly improved bipolar coagulation technology by L. Malis, with specifically modeled bipolar coagulation forceps and bipolar coagulation balls, cavitation ultrasound surgical aspirator suction technology, and intraoperative monitoring. In addition, intense laboratory training, the experiences of the surgeon, and a certain talent are components that contribute to expertise, and these elements are substantiated by Klekamp and Samii.

Analysis of the operative results of the authors, as well as evaluation of the experiences of other authors in this field, strongly indicate the great importance of operating on patients with spinal lesions in an early phase, when they present with no or minor neurologic deficits. The more severe the preoperative neurologic condition of the patient, the less the injured cord will recover. Further advances in neurovisualization technology with diffusion and perfusion modalities promise to differentiate accurately the neuroplastic lesion from demyelinating, degenerative, vascular, or infection diseases.
The generally observed postoperative course is characterized by transient worsening of neurologic symptoms for a few days or even months before functional recovery occurs. There are reasonable hopes that the research activities of molecular biologists will offer effective treatment for faster recovery of the operated spinal cord patient.

This monumental work of Klekamp and Samii represents an impressive document recounting their neurosurgical endeavors in the last quarter of the 20th century. The meticulous statistical analyses will be of great value as a reliable source of reference. This unique monograph will undoubtedly be of great interest to neurosurgeons, neurologists, neuroradiologists, neuromolecular biologists, neurophysiotherapists, and occupational therapists alike.

Little Rock, July 2006

M.G. Yaşargil
Spinal tumors are rare and potentially devastating lesions that threaten the patient’s mobility or even life. Despite their rarity, every neurosurgeon in clinical practice has to deal with them regularly. With modern imaging, microsurgical techniques, and improved understanding of spinal biomechanics and modern instrumentation systems, the fate of complete paraplegia can be avoided if therapy is instituted in time. Whereas intramedullary and extramedullary tumors are the domain of the neurosurgeon, extradural tumors are treated by neurosurgeons and orthopedic surgeons alike.

The aim of this book is to give an overview about the clinical experience gained in a single neurosurgical institution over a period of 25 years. This series consists of 1081 spinal tumors treated in 868 patients who underwent 973 operations between 1978 and 2003 (Table 1). Thus, this entire series consists of patients undergoing surgery with microsurgical techniques. The great majority of them were diagnosed using modern imaging techniques such as computerized tomography and magnetic resonance imaging. We do not claim to cover every aspect or every pathology of spinal tumors, but rather concentrate on what we have seen, found, learned, and achieved during this time. The results presented here represent this entire period. The treatment recommendations and descriptions of surgical techniques are based on these experiences and our ongoing analyses, and reflect our current state of the art. We hope that this book will aid neurosurgeons and spine surgeons in counseling and treating patients with spinal tumors.

Table 1. Data of 1081 spinal tumors treated in 868 patients with 973 operations between 1978 and 2003

<table>
<thead>
<tr>
<th>Type of tumor</th>
<th>Number of patients</th>
<th>Number of tumors</th>
<th>Number of operations</th>
<th>No surgery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intramedullary</td>
<td>182</td>
<td>199</td>
<td>198</td>
<td>9</td>
</tr>
<tr>
<td>Extramedullary</td>
<td>406</td>
<td>553</td>
<td>446</td>
<td>20</td>
</tr>
<tr>
<td>– Intradural</td>
<td>349</td>
<td>466</td>
<td>385</td>
<td>18</td>
</tr>
<tr>
<td>– Intra-extradural</td>
<td>57</td>
<td>87</td>
<td>61</td>
<td>2</td>
</tr>
<tr>
<td>Epidural</td>
<td>280</td>
<td>329</td>
<td>329</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>868</td>
<td>1081</td>
<td>973</td>
<td>33</td>
</tr>
</tbody>
</table>

Each chapter of this book has been written in such a way that it can be read as a separate section. First, we would like to outline how patients were evaluated and what statistical methods were employed.

Patients were examined on outpatient visits and during their hospital stay before and after surgery. Each pre- and postoperative neurological symptom was documented and analyzed individually according to a scoring system.

Preface
In addition, their overall clinical condition was evaluated according to the Karnofsky score. These parameters were used to describe the preoperative condition and the short-term clinical course after surgery. To describe the preoperative course, we asked for the first clinical symptom the patient had noticed and which symptom was the major complaint at the time of surgery (i.e., the main symptom).

Table 2. Neurological scoring system

<table>
<thead>
<tr>
<th>Score</th>
<th>Sensory disturbance, pain, dyesthesias</th>
<th>Motor weakness</th>
<th>Gait ataxia</th>
<th>Sphincter function</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>No symptom</td>
<td>Full power</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>4</td>
<td>Present, not significant</td>
<td>Movement against resistance</td>
<td>Unsteady, no aid</td>
<td>Slight disturbance, no catheter</td>
</tr>
<tr>
<td>3</td>
<td>Significant, function not restricted</td>
<td>Movement against gravity</td>
<td>Mobile with aid</td>
<td>Residual, no catheter</td>
</tr>
<tr>
<td>2</td>
<td>Some restriction of function</td>
<td>Movement without gravity</td>
<td>Few steps with aid</td>
<td>Rarely incontinent</td>
</tr>
<tr>
<td>1</td>
<td>Severe restriction of function</td>
<td>Contraction without movement</td>
<td>Standing with aid</td>
<td>Often catheter</td>
</tr>
<tr>
<td>0</td>
<td>Incapacitated function</td>
<td>Plegia</td>
<td>Plegia</td>
<td>Permanent catheter</td>
</tr>
</tbody>
</table>

Success of treatment for spinal tumors can be analyzed in several ways. Could the tumor be completely removed? Did the patient improve clinically? Did the patient deteriorate clinically during follow-up? Did the tumor recur? How long did the patient survive? For each section of the book we used the same data acquisition and statistical methods.

Long-term results were analyzed by calculating recurrence rates according to survival statistics, because this method allows us to account for varying follow-up times and gives a much more realistic picture regarding long-term postoperative results. Two types of recurrences were distinguished: (1) whenever a patient developed progressive neurological symptoms after surgery, this was defined as a clinical recurrence; (2) whenever a tumor recurred or a tumor remnant progressed on neuroradiological imaging, this was called a tumor recurrence.

To determine the factors predicting surgical results or outcome, multivariate analyses were performed. For each factor, a β-value is given, which indicates its predictive power compared to others.

Most, but not all of the case illustrations show pathologies treated within the study period between 1978 and 2003. The intraoperative photographs, in particular, are intended to demonstrate our current way of treatment rather than to present examples of how we used to operate on them.

The overwhelming majority of operations were performed with the patient in the prone position. As far as intraoperative photos are concerned, all are oriented according to the surgeon’s view. If the semisitting position was used, this is mentioned in the figure legend.

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Jörg Klekamp and Madjid Samii
References


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Contents

1 History
1.1 Surgical Approaches .................................. 1
1.2 Tumor Removal ........................................ 2
1.3 Diagnostic Imaging ..................................... 3
1.4 Spinal Reconstruction and Fusion .................... 3
1.5 Modern Advances ...................................... 4
References ................................................. 5

2 Anatomy
2.1 Cervical Spine .......................................... 7
2.2 Thoracic Spine .......................................... 10
2.3 Lumbar Spine and Sacrum ............................. 12
2.4 Spinal Biomechanics .................................. 14
2.5 Spinal Meninges ......................................... 14
2.6 Spinal Cord and Nerve Roots ......................... 15
References ................................................. 18

3 Intramedullary Tumors
3.1 History and Diagnosis ................................. 20
3.2 Neuroradiology ......................................... 21
3.3 Surgery ................................................. 40
3.3.1 Exposure ............................................ 41
3.3.2 Tumor Removal .................................... 42
3.3.3 Closure .............................................. 82
3.3.4 Adjuvant Therapy .................................. 82
3.4 Postoperative Results and Outcome .................... 84
3.4.1 Tumor Resection .................................... 84
3.4.2 Clinical Results .................................... 85
3.4.3 Syringomyelia ....................................... 88
3.4.4 Complications ....................................... 89
3.4.5 Morbidity, Recurrences, and Survival .......... 92
3.5 Specific Entities ......................................... 97
3.5.1 Ependymomas ....................................... 97
3.5.2 Astrocytomas ....................................... 103
3.5.3 Angioblastomas ..................................... 112
3.5.4 Hamartomas ......................................... 114

4 Extramedullary Tumors
4.1 History and Diagnosis ................................. 144
4.2 Neuroradiology ......................................... 145
4.3 Surgery ................................................. 167
4.3.1 Exposure ............................................ 167
4.3.2 Closure .............................................. 240
4.3.3 Adjuvant Therapy .................................. 240
4.4 Postoperative Results and Outcome ..................... 240
4.4.1 Tumor Resection .................................... 240
4.4.2 Clinical Results .................................... 241
4.4.3 Complications ....................................... 244
4.4.4 Morbidity, Recurrences, and Survival .......... 245
4.5 Specific Entities ......................................... 248
4.5.1 Meningiomas ........................................ 248
4.5.2 Nerve Sheath Tumors ............................... 260
4.5.3 Arachnoid Cysts .................................... 275
4.5.4 Hamartomas ......................................... 286
4.5.5 Ependymomas of the Filum Terminale ............ 300
4.5.6 Metastases ........................................... 303
4.5.7 Angioblastomas ..................................... 305
4.5.8 Cavernomas .......................................... 305
4.5.9 Sarcomas .............................................. 306
4.5.10 Hemangiopericytomas ............................ 306
4.5.11 Exophytic Astrocytomas ......................... 306
4.5.12 Tumors with Subarachnoid Seeding ............. 306

4.6 Management of Recurrent Extramedullary Tumors ....... 311
4.7 Conclusions ............................................. 312
References ................................................. 312
Chapter 1

Contents

1.1 Surgical Approaches 1
1.2 Tumor Removal 2
1.3 Diagnostic Imaging 3
1.4 Spinal Reconstruction and Fusion 3
1.5 Modern Advances 4

References 5

History

Today, surgery of spinal tumors is a very gratifying part of neurosurgery. With modern imaging techniques the diagnosis has become quite simple. Tumors can now be detected early, and with modern microsurgical techniques the neurological function of the spinal cord can almost always be preserved and often even improved. This is the result of a long period of development that started way before Victor Horsley’s first operation of a spinal meningioma in 1887.

1.1 Surgical Approaches
Claudius Galen, born in the year 129 in Pergamon in Turkey, was probably the first anatomist to note the segmental representation of the spinal cord. He performed experiments and dissections on dogs to better understand the human anatomy and the consequences of spinal cord injuries. This was 1800 years before Darwin’s evolution theory. Examining victims of gladiator fights, he observed specific neurological deficits according to the level of the spinal cord and was able to specify the spinal level of injury according to his clinical examination [10].

First attempts on spinal surgery were undertaken by the French army surgeon Ambroise Paré as early as 1549 for patients with spinal dislocations. He diagnosed the level of injury by palpation and crepitation, excised bony splinters compressing the cord, and applied traction for spinal dislocations with the aid of a wooden frame [35]. However, throughout the middle ages and well into the 19th century, spinal surgery was met with great scepticism. Most physicians considered injuries and tumors of the spine and spinal canal as untreatable. For instance, Nicolaus Petreius Tulpius described a patient with spina bifida aperta in 1641, who presented with a cystic mass attached to the underlying spinal cord by a small pedicle. The pedicle was ligated, the cystic mass became necrotic, and the patient died [18]. At that time, spina bifida was thought to be related to osteomyelitis of the spine. Associated cysts were considered to be connected to the urinary bladder [18]. The first attempt to close a spina bifida with a musculoskeletal flap can be attributed to Bayer in 1892 [18].

Systematic spinal surgery started in the 19th century with attempts at spinal cord decompression by performing laminectomies. The first description dates back to 1814 and was performed on a 26-year-old patient with a thoracic injury and complete paraplegia after falling from the roof of a house. The surgeon was unable to reduce the associated dislocation, and the patient demonstrated no recovery of function and died soon thereafter [24]. Obviously, this experience did not help to make spinal surgery more acceptable in the neurological community. The major problems at the time were inadequate anesthesia and pain control, leading to intraoperative shock and infections.

The first patient to survive a laminectomy was operated in 1828. This patient had fallen from a horse and suffered a complete paralysis of both legs. Some improvement of his sensory function was observed postoperatively [48]. Until 1840, just 12 spinal surgery patients were described in the literature. This number rose to 29 by 1867 [36]. A first systematic description of the surgical technique for laminectomy was given by Chipault in 1894 [5]. Further modifications and technical improvements were reported subsequently. To limit blood loss, Krause introduced what he called a laminitome. This was a kind of a strong biting forceps, which worked its way through bone by cutting and compressing the lamina [30]. By 1894, Menard
described the technique of costotransversectomy for treatment of Pott’s disease [37]. The first description of a hemilaminectomy was provided by Bonomo in 1902 [4]. Several surgeons preferred to operate on patients in the right lateral position so that the part of the spine that was targeted could be elevated with cushions. In that way, cardiac function was considered to be more easily managed [29, 43].

Surgical approaches to the spine from the anterior direction were developed considerably later. Early attempts by Albee [2] and Hibbs [25] were associated with considerable mortality rates. They were performed for patients with Pott’s disease, and the lack of antimicrobial drugs meant that postoperative infections were the major problem. Ito et al. [28] developed the extraperitoneal approach to the lumbar spine in 1934. A series of transthoracic decompressions with somewhat acceptable morbidity and mortality figures was finally published by Hodgson and Stock in 1956 [26] at a time with better anesthesia, diagnostic techniques, and operating skills, and when antibiotics were being developed in increasing numbers.

### 1.2 Tumor Removal

So, with the technique of laminectomy, the standard approach to spinal lesions was available in the second half of the 19th century. The first spinal tumor operation is widely attributed to Victor Horsley, who described the removal of a spinal meningioma, performed on June 9th in 1887 [20]. However, Lecat operated on a spinal tumor as early as 1753 [32]. Macwen reported on two patients in whom he had removed fibrous neoplasms of the dura in 1883 and 1884, respectively [33, 34]. As he was not a neurosurgeon, however, not much credit was given to these successful operations. Furthermore, the two patients were victims of Pott’s disease with spinal deformities, suggesting that granulation tissue rather than true neoplasms were probably removed [44]. Horsley himself listed in his paper 58 patients with spinal tumors from the literature, of which 2 had been operated on previously to his own operation. Horsley’s operation did not go smoothly. He opened the spine of this 42-year-old man at the wrong level at first and only after one of his assistants, Charles Ballance, who had studied the anatomy of the spinal cord and its roots carefully, had pointed out that due to the descending course of spinal nerve roots the lesion may be located higher than the clinical evaluation would predict, did Horsley extend the exposure cranially finding the meningioma at last. Postoperatively, the patient made a very gratifying recovery with preservation of his neurological functions. However, he suffered from a cerebrospinal fluid fistula for 6 weeks before it subsided spontaneously. Fortunately, no infection had developed. The patient was able to work 16 h a day 1 year after the operation, and finally died 20 ears later from causes unrelated to his spinal meningioma [42].

Horsley’s paper had a tremendous impact on the medical community. He passionately recommended operating on patients with spinal tumors, as the alternative – conservative treatment – was associated with a very high mortality: 74% of patients with unoperated extradural tumors and 83% of patients with unoperated intradural tumors died due to respiratory failure, pneumonia, urinary septicemia, or decubitus ulcer, to mention the commonest causes of death. Horsley was convinced that surgery could prevent grave complications and death for a significant number of patients even given the prevailing enormous diagnostic and technical restraints. His paper was so stimulating that Starr could report on 19 spinal tumor operations as early as 1895, adding three cases of his own [49]. Eleven of these, however, died from postoperative complications. With increasing experience, however, mortality figures could be reduced. Even attempts on intraoperative functional studies were undertaken at that time and probably started with Abbe, who performed motor root stimulations during operations [1].

Whereas the first removals of extradural tumors can be attributed to Thorburn in 1888 [52] and Abbe in 1889 [1], surgery on intramedullary tumors started in the early 20th century. Cushing had exposed an intramedullary tumor by a myelotomy, but thought the lesion to be inoperable. Despite that, the patient recovered well from his procedure [8]. The first intramedullary tumor removal was successfully undertaken in 1907 by Freiherr von Eiselsberg in Vienna, with recovery of function after transient aggravation of his preoperative deficits [13].

The first series of spinal tumors was presented by Fedor Krause in 1908 [29]. He reported on 25 operated patients. Eight died from postoperative complications. In his former publication 2 years earlier, 6 of his first 11 patients had died [40]. In other words, he was able to improve operative mortality from 55% to 14% within a very short time. Listed among his spinal tumors were two enchondromas. These have to be considered the first operations on spinal disc prolapses, which he mistook for neoplasms [30]. Harvey Cushing concentrated on cranial surgery, but he did perform a considerable number of operations on spinal

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2. [Hibbs, 1889](#).
3. [Ito et al., 1934](#).
4. [Hodgson and Stock](#).
5. [Macwen](#).
6. [Lecat, 1753](#).
7. [Horsley](#).
8. [Cushing](#).
9. [Krause](#).
10. [Abbe](#).
11. [Thorburn](#).
12. [Freiherr von Eiselsberg](#).
13. [Fedora](#).
tumors as well. Between 1912 and 1932, he treated 60 cases of spinal tumors: 23 meningiomas, 4 neurofibromas, 8 sarcomas, 3 ependymomas, and 4 astrocytomas to mention the intradural tumors [6].

The pioneer of spinal tumor surgery, however, is Charles A. Elsberg. His first major publication on his clinical work with intramedullary and extramedullary tumors was published in 1925; this book remains a landmark publication [15]. His results on 54 extramedullary, 13 intramedullary, and 14 epidural tumors compare favorably even with the first series published in the microsurgical era. He described the concept of a two-stage operation for the removal of intramedullary tumors, which he had discovered by accident. In a patient with the assumed diagnosis of an extramedullary tumor, he had injured the pia mater upon opening the dura. Unexpectedly, he observed that the intramedullary tumor extruded out of the cord almost by itself. The cord was reexposed in a second operation, performed after the patient had recovered from the first. At that time, the tumor had exposed itself almost completely out of the cord, so that he was able to resect it completely with a good functional result [17, 14]. However, this technique was used only a few times. In the second edition of his book in 1941, he summarized his work and presented his experience on the basis of 168 extramedullary, 73 epidural, and 19 intramedullary tumors. He had achieved complete resections for 150 extramedullary, 63 epidural, and 7 intramedullary tumors. His mortality rates were 5%, 7%, and 16% for extramedullary, epidural, and intramedullary tumors, respectively [16].

1.3 Diagnostic Imaging

The first endeavors on spinal cord surgery were performed without any imaging of the lesions. Radiological signs of a spinal tumor, such as a widening of the spinal canal or erosion of bony elements, were rarely encountered [7, 30, 39, 40, 45]. Neurologists determined the spinal level of the suspected tumor clinically and the surgeon had to do the operation to confirm the diagnosis and to remove the tumor. The major differential diagnostic sign was an increased intensity of neurological deficits without an ascending spinal level [50]. Only if the preoperative assumptions and clinical evaluations were correct could the patient expect to profit from surgery. In von Eiselsberg and Ranzi’s series of 17 patients operated for suspected tumors, 5 patients underwent surgery without a tumor being discovered [13]. This illustrates the enormous diagnostic difficulties faced during that time. The commonest misdiagnosis was a circumscribed area of arachnoiditis [30].

Therefore, further imaging techniques were needed desperately. Dandy introduced air myelography in 1919. He injected air into the lumbar area and measured the time until the air could be detected intracranially [9]. Obviously, this was a very unprecise way of diagnosing a spinal tumor. The major neuroradiological breakthrough was the discovery of myelography with contrast material injected into the subarachnoid space by Sicard and Forestier [47]. It was a discovery by accident. Originally, the contrast material was aimed for the epidural space because they considered an intrathecal injection to be harmful. However, the intradural injection did not cause any apparent problems in this patient and a diagnostic method was born that gained immediate acceptance worldwide. A few years later, Peiper described the technique of myelography systematically and provided criteria for the differential diagnosis of myelographic findings [41].

1.4 Spinal Reconstruction and Fusion

With the introduction of approaches to the spine and increasing surgical attempts to treat spinal tumors as well as spinal trauma and degenerative disorders, little concern existed for spinal stability among neurosurgeons – not to mention for the side effects of surgery on spinal stability. First attempts to reconstruct the vertebral column were met with great scepticism by many respected neurosurgeons because reconstruction and stabilization meant longer surgery, a risk of insufficient vascularization of the reinserted laminae, and a higher risk of infection at a time without sufficient anesthetic techniques and antibiotics [29, 30, 40, 50].

As early as 1889, Dawbarn performed an H-type opening with lateral transection over the transverse processes and a horizontal transection connecting the two. In this way he could reflect two flaps of soft tissue together with bony elements cranially and caudally [11]. Urban and Bickham used U-shaped incisions for the same purpose [3, 53]. Röpke described a similar technique to thin out the lamina with a chisel, transecting it in the midline and then retracting both lamina halves together with attached soft tissues laterally [43]. With closure of the soft tissues, these authors approximated the lamina sufficiently to allow fusion.

Spinal stabilization was first developed to treat patients with Pott’s disease. Hadra used wiring of the
spinal processes to prevent kyphotic deformities [21]. In 1910, Lange suggested steel bars for fusion of a spondylitic spine [31]. Albee, Hibbs, and Ito used bone grafts to achieve bony fusion [2, 25, 28]. However, it was not until the advent of better anesthetic techniques and antibiotic treatment, as well as a better understanding of spinal biomechanics, that stabilization techniques for the spine finally became practical. A major step was the pioneering work of Sir Frank Holdsworth, who classified spinal fractures according to the mechanism into pure flexion, flexion-rotation, extension, and compression fractures. He also introduced a two-column model of spinal stability [27]. This work provided an important background for the development of the first successful spinal instrumentation system for posterior spinal fusion by Paul Harrington in the 1960s [22, 23]. The first ventral instrumentation system was introduced soon thereafter by Dwyer et al. in 1969 [12].

1.5 Modern Advances

With good anesthetic techniques, antibiotic treatment, and reasonable diagnostic imaging established, the next major advance was the introduction of the operative microscope in the 1960s. Before the introduction of microsurgery, surgeons were most of all concerned for the patients’ survival after spinal cord surgery. With the advent of the operative microscope, it became possible to preserve the patients’ neurological function with increasing frequency. In 1975, Yasargil and De Preux published the first paper on a series of microsurgically removed intramedullary angioblastomas with excellent clinical outcomes [54]. This paper was followed by a congress report on 37 intramedullary tumors undergoing microsurgical removal. Of these, 24 had been resected completely (11 of 12 angioblastomas, 8 of 11 ependymomas, and 1 of 4 astrocytomas), of which 13 demonstrated postoperative improvement, while 6 remained unchanged and just 5 were neurologically worse. Apart from the operative microscope, he emphasized the bipolar coagulation technique as the second major technical advance for treatment of these patients, the correlation between preoperative neurological status and postoperative functional results, and recommended surgical removal before serious neurological deficits were present. Each step for microsurgical resection as outlined in this paper describes the state-of-the-art technique up to today [55]. In a later publication he advised against laminectomies to remove intra- or extramedullary tumors to avoid problems of postoperative spinal instability. He had used osteoplastic laminotomies – cutting laminæ with an oscillating saw, removal in one bloc and reinsertion with sutures – since 1973 for extensive tumors and advocated partial hemilaminectomies for smaller tumors – a technique he developed in 1980 [56]. Apart from concerns regarding spinal stability after resection of intradural tumors, he also applied a telescoping screw for reconstruction of the T11 and T12 vertebrae after resection of a giant-cell tumor, which can be considered the prototype for the expandable cages employed today [46].

A large number of publications have since dealt with intramedullary tumors. By comparison, little has been published on extramedullary tumors. The largest series on extramedullary tumors with a detailed analysis of the literature was published by Nittner in 1976. He analyzed 4885 patients [38].

With the introduction of magnetic resonance imaging in the 1980s, the diagnosis of spinal tumors has finally become much easier and more reliable. Patients can now be discovered before severe neurological deficits are present. This enables surgeons even to improve neurological symptoms in patients with intramedullary tumors. A recent monograph on a large series of intramedullary tumors presenting the current therapeutic standard was published by Fischer and Brotchi in 1996 [19].

Whereas intradural spinal tumors are the domain of neurosurgeons, different concepts were followed for the management of epidural tumors by neurosurgeons and orthopedic surgeons. Initially, neurosurgeons focused solely on neurological function and performed surgery with the intention of decompressing the spinal cord and nerve roots. They had little concern for spinal stability. For instance, the potentially devastating long-term effects of laminectomies were overlooked by most neurosurgeons for decades. On the other hand, orthopedic surgeons tended to concentrate only on the biomechanical problems associated with tumors. Achievement of stability was the foremost goal.

Today, surgical approaches that respect the integrity of the intervertebral joints and spinal stability are available for any part of the spine. If the tumor has caused spinal instability or tumor removal has to compromise stability, a variety of fusion techniques are available for each segment of the vertebral column from any angle. In this respect, patients and neurosurgeons have profited a great deal from the work of orthopedic and trauma surgeons [51]. In fact, there still is a large field for interdisciplinary research and clinical work to improve even further the management of patients with spinal tumors.
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This chapter provides some anatomical information to help the reader to understand the pathophysiology of tumors of the spine and spinal cord as well as to guide surgeons to particular configurations and important aspects for planning and performing surgery in the safest and least traumatic manner.

2.1 Cervical Spine

The cervical spine consists of two “special” vertebrae – the atlas and axis – connecting the spine with the cranium in a complex set of joints and ligaments, and five “ordinary” vertebrae in a slightly lordotic curve (Figs. 2.1–2.3). In young adults, the average length of the cervical spine measures 12.5 cm from the lower border of C7 to the tip of the dens axis. In retroflexion, the average length is 11.5 cm, compared to 12.69 cm in anteflexion [9, 10]. This needs to be considered for correct intraoperative localization of intradural tumors; radiological examinations are performed in a different neck position than the operative one!

The atlas is formed like a ring with small lateral masses, which articulate with the occipital condyles of the cranium above and the lateral masses of the axis underneath. A fifth joint provides the rotation of the head and is formed between the atlas and the dens axis (i.e., the odontoid process). The axis articulates with the lateral masses of C1 above and supports the dens axis in the midline (Figs. 2.2 and 2.3). The remaining vertebral bodies are rectangular in shape, with a slight depression of the superior surface, giving rise to bony edges on either side (i.e., the uncinate processes). Thus, the intervertebral discs rest on a cup-like surface of the lower vertebra, whereas the lower surface of a cervical vertebra (i.e., the upper surface of the intervertebral space) is flat (Fig. 2.2).

The posterior elements of the second to seventh vertebra form the neural arches consisting of pedicles, the lamina, and spinous processes. The short pedicles connect the vertebral body with the facet joints, which are formed by articular processes above and below. These processes are named according to their orientation: the articular of the inferior vertebra projecting upward is called the superior articular process, and vice versa for articular process from the superior vertebra facing downward (Fig. 2.1). In axial sections through the facet joints, the posterior facet belongs to the superior neural arch representing the inferior articular process and vice versa for the anterior facet (Fig. 2.3). A neuroforamen is formed by pedicles above and below the vertebral body and uncinate process medially, the transverse process laterally, and the articular processes posteriorly. The cervical foraminae are oriented about 30º anterolaterally. The neural arches project posteriorly to meet at the base of the spinous process. On cross section, they are ovoid in shape, with a flattened anterior surface. The spinous processes point downward in the midline (Fig. 2.1).

There is no spinous process at C1, but there are particularly large processes at C2 and C7. The average anterior–posterior diameter of the bony spinal canal measures 18–20 mm at C1 and C2, and 15–17 mm between C3 and C7. The thecal sac measures 10–14 mm throughout the cervical spine, and the spinal cord 6–9 mm. In other words, the spinal cord normally occupies about 40–50% of the spinal canal.

As far as ligamentous structures are concerned, the atlantoaxial ligaments, anterior and posterior longitudinal ligaments, the yellow ligament, the interspinous ligament, and the supraspinous ligament should
be mentioned. The medial atlantoaxial joint is stabilized by a complex set of ligaments. The most important of these is the cruciform ligament, which lies immediately behind the dens in the coronal plane (Fig. 2.3). The vertical and horizontal arms of this ligament explain its name. The horizontal arms form the so-called transverse ligament between the lateral masses of C1 and the posterior surface of the dens to hold it firmly against the anterior arch of C1 (Fig. 2.1). The vertical arms run between the anterior rim of the foramen magnum and the body of C2. The dens is linked to the skull base by the apical ligament extending from its tip to the anterior foramen magnum and the alar ligaments laterally toward the occipital condyles. The vertebral bodies are connected by anterior and posterior longitudinal ligaments from C1 right down to the sacrum along their anterior and posterior surfaces, respectively. The anterior longitudinal ligament ends in the anterior atlantooccipital membrane at the level of the foramen magnum. The posterior longitudinal ligament is connected with the posterior foramen magnum via the tectorial membrane (Fig. 2.1). The posterior vertebral elements are stabilized by yellow, interspinous, and supraspinous ligaments. The yellow ligament links the vertebral laminae and, thus, forms the posterior border of the spinal canal in the interlaminar space and is connected to the posterior atlantooccipital membrane cranially. The interspinous ligament serves as an important posterior anchor and runs between spinous processes, whereas the supraspinous ligament extends between the tips of the spinous processes (Fig. 2.1).

The vascular anatomy consists of the vertebral arteries and a venous plexus. This plexus runs along the posterior surface of the vertebral bodies mainly in the midline, where it elevates the posterior longitudinal
ligament. The vertebral arteries arise from the subclavian arteries in 90% of patients. In rare instances, the left vertebral artery may arise from the aortic arch. Other unusual origins such as the inferior thyroid and the common carotid artery have been described. The arteries travel anterolaterally of the neuroforaminae between C6 and C1 through foraminae in the transverse processes. However, the vertebral artery may enter the spine at other levels such as C3, C4, C5, and C7 [10]. In about 89% of cases the artery arises in a straight line through these transverse foraminae.

However, medial loops at C4, C5, and C6 may occur in rare cases [10]. Above C2, the artery turns posteriorly and superiorly, traverses the transverse foramen of C1 and continues medially along the superior margin of the atlas in a sulcus to form a loop toward the dura of the foramen magnum. In some cases, a foramen is formed in this area (i.e., the arcuate foramen). The vertebral artery is surrounded by a venous plexus, which is particularly prominent between C2 and its intracranial section (Figs. 2.1–2.3).

Fig. 2.2. a Anterior coronal T1-weighted MRI scan of the craniocervical junction and upper cervical spine: D Dens axis, UP uncinate process. b Coronal T1-weighted MRI scan of the craniocervical junction and upper cervical spine in the midline. c Posterior coronal T1-weighted MRI scan of the craniocervical junction and upper cervical spine. OB Occipital bone, IOM inferior oblique muscle, MM multifidus muscle, SM semispinal muscle.
2.2 Thoracic Spine

The 12 thoracic vertebral bodies are rectangularly shaped with flat superior and inferior surfaces. The neural foraminae exit almost laterally. From top to bottom, the height of the bodies gradually increases. The intervertebral discs appear flatter than their cervical and lumbar counterparts. The pedicles of the thoracic vertebrae extend from the superior half of the vertebral body. The neuroforaminae are directed laterally. The laminae form an almost circular spinal canal of constant width throughout the thoracic spine. As this part of the spine forms a slight kyphosis, the thecal sac and spinal cord seem slightly displaced anteriorly in the upper thoracic canal (Figs. 2.4 and 2.5). The major difference in the bony anatomy of the thoracic spine is the articulation with the ribs. The heads of ribs 2–10 articulate with their posterior surfaces to the posterolateral aspects of vertebral bodies. Half of the joint surface is on the superior and half on the inferior body. Ribs 1, 11, and 12 articulate only...
Further, the tubercles of ribs 1–10 articulate on their posterior surfaces with the transverse processes of the same-numbered vertebral body.

As far as the vascular anatomy is concerned, the external venous plexus around the vertebral bodies is of particular importance in the thoracic and lumbar spine. Changes in intrathoracic and intra-abdominal pressure are transferred to the epidural internal venous plexus through anastomoses and affect the cerebrospinal fluid (CSF) pressure in the thoracic and lumbar spine. Furthermore, interconnections exist between the external venous plexus and the azygos venous system. This connection provides a parallel drainage system that bypasses the superior and inferior vena cava.

**Fig. 2.4.** a Sagittal T2-weighted MRI scan of the thoracic spine in the midline. b Paramedian sagittal T2-weighted MRI scan of the thoracic spine

**Fig. 2.5.** Axial T2-weighted MRI scan of the midthoracic spine
2.3 Lumbar Spine and Sacrum

Similarly to the thoracic vertebrae, the five lumbar vertebral bodies are rectangular in shape, with flat superior and inferior surfaces. The pedicles project posterolaterally. The neural foraminae exit almost laterally. The posterior border of each foramen is formed by the articular processes. These processes are comparably long and form the facet joints, which are oriented in the coronal plane. The lumbar laminae form an oval spinal canal in the upper lumbar spine. In the lower part, the shape becomes more triangular, with bony recesses anterolaterally; these are formed by indentations of the superior articular processes of the facet joints (Figs. 2.6 and 2.7). The sacrum is composed of four or five fused vertebrae that form a triangle. It articulates laterally with the iliac bones (Fig. 2.8).

Fig. 2.6. a Sagittal T2-weighted MRI scan of the lumbar spine in the midline. CE Cauda equina. b Paramedian sagittal T2-weighted MRI scan of the lumbar spine. EV Epidural vein, PI pars interarticularis

Fig. 2.7. a Axial T2-weighted MRI scan of the lumbar spine at Th12/L1. b Axial T2-weighted MRI scan of the lumbar spine at L3. c Axial T2-weighted MRI scan of the lumbar spine at L3/4. d Axial T2-weighted MRI scan of the lumbar spine at the pedicle level of L5. AVP Anterior epidural venous plexus. e Axial T2-weighted MRI scan of the lumbar spine at foraminal level of L5. f Axial T2-weighted MRI scan of the lumbar spine at L5/S1
2.3 Lumbar Spine and Sacrum

(a) T12/L1, AR, Conus, ped, Dura, Epidural Fat, Lamina T12

(b) L3 Root, SAP L4, IAP L3, Lamina L3

(c) L3/4, SAP L4, IAP L3, Epidural Fat, Lamina L3

(d) L5, AVP, Pedicle, L5 Root, Dura, Lamina L3

(e) L5/S1, Pedicle S1, SAP S1, IAP L5, Dura, Lamina L5
Lumbar nerve root sleeves lie anterolateral to the thecal sac at the level of the pedicle, and continue into the upper half of the neuroforamen. The epidural fat of the spinal canal contains a venous plexus and connective tissue. This plexus communicates with the external venous plexus surrounding vertebral body and posterior elements. Individual veins may accompany the nerve root on its way through the neuroforamen, and are positioned in the lower part of the foramen (Fig. 2.7). The thecal sac extends approximately to S2 (Fig. 2.8).

2.4 Spinal Biomechanics

The line of the center of gravity of the erect human body lies anterior to the vertebral column. As a consequence, axial loads to the body in the upright position result in a combination of spinal axial compression and bending movements. A simple biomechanical concept of the spine is as two columns, an anterior column and a posterior column [6].

The anterior column provides the weight-bearing part of the spine. About 80% of the axial load is absorbed by this column, whereas the remaining 20% is spread to posterior elements as a shearing force. Vertebral bodies and intervertebral discs are constructed to withstand these weight-bearing forces, whereas the annulus fibrosus of the disc absorbs torque and shear movements. Thus, the anterior column acts like a distraction device.

The posterior column, on the other hand, consists of laminae and facet joints, which work as a chain of articulators. The remaining 20% of the axial load is absorbed mainly by the facet joints. This articulation chain is controlled by ligaments and muscles, which compress the posterior elements like a tension band. In other words, the posterior column serves as a compression device.

The posterior compressing forces of the muscles provide a balance between the anterior column and posterior articulation chain. Movements are possible due to deformations of the intervertebral discs and the facet joints. Ligaments limit the amount of motion possible within each segment. The stability of the spine requires intact anterior and posterior elements. Neoplasms of the spine, which destroy parts of the anterior and/or posterior column structures, will tend to cause kyphotic deformities, because the weight-bearing capability of the anterior and/or the compressive action of the posterior column is compromised. For restoration of stability, anterior reconstructions require distraction, whereas posterior devices have to apply compression. In each individual case, anterior and posterior elements have to be analyzed carefully to select the appropriate reconstruction: anterior, posterior, or a combined approach [4].

2.5 Spinal Meninges

The dura mater is about 0.8 mm thick and consists of collagen and elastic fibers. At the foramen magnum, the dura mater of the head and the external periost merge into the spinal dura mater. Here, the dura mater consists of three layers: (1) the innermost layer of the spinal dura is in continuity with the inner dural layer of the skull, (2) the middle spinal layer continues to form the external dural layer of the skull, and (3) the outer layer transgresses into the periost of the skull (Fig. 2.1) [10]. A complex set of fiber bundles inside the dura allows head movements without displacing the dural sac out of the midline of the spinal canal.

The arachnoid membrane is the outer wall of the CSF space. It is watertight, loosely attached to the dura [13], and ensheathes the spinal nerves toward the root sleeves, where it fuses with the dura. In the subarachnoid space, numerous strands run between the arachnoid membrane and cord surface, mainly in the posterior, and to a lesser degree in the anterior subarachnoid space. These septations have been described to be derived from an intermediate, fenestrated leptomeningeal layer, which is attached to the inner surface of the arachnoid membrane and surrounds nerve roots and blood vessels on the cord surface as a fenestrated layer (Fig. 2.9) [13]. Posteriorly, a septum
runs in longitudinal direction between the pia mater and the arachnoid membrane. It separates the posterior subarachnoid space into a left and right half (Figs. 2.3, 2.5, and 2.9) [8]. Toward the cervical area, it becomes more and more fenestrated and tapers off toward the cisterna magna. Similar fenestrations are evident toward the conus medullaris. The insertion of the septum at the spinal cord surface follows the course of the midline dorsal vein. In other words, pulling the arachnoid membrane may apply tension to the midline septum, and hence to this attached vein! Further septations have been described more laterally along the posterior roots from the dorsal root entry zone toward the arachnoid membrane, into the root sleeve, mainly in the lower cervical and thoracic spine. The anterior subarachnoid space does not demonstrate any such septations. Thus, anterior roots do not display such enveloping arachnoid membranes. The posterior septations may ease the dissection of large extramedullary tumors off the spinal cord, as they may provide a nice dissection plane [12].

The denticulate ligament is a transverse plate of fibers originating from the pia mater and running to the inner surface of the dura, usually inserting about 1.5–2 mm dorsal to the dural nerve root sleeve. It courses alongside the spinal cord on either side between the anterior and posterior roots (Figs. 2.3 and 2.5) [10].

The pia mater ensheathes the spinal cord. It contains fiber bundles, forming a complex support system for the spinal cord together with its extensions – the denticulate ligaments – and the dura mater. It holds the spinal cord in the center of the dural sac and protects it from undue extension as a result of spine movements [10]. The pia mater is not permeable to water and provides a barrier between the subarachnoid space and perivascular spaces of the cord [13].

Several observations, however, suggest that the extracellular space of the spinal cord and subarachnoid space should be considered as two compartments of the same fluid space that require free communication between each other. According to Rennels et al. [15], CSF enters the extracellular space of the central nervous system along the perivascular spaces of arteries, whereas extracellular fluid leaves it along the perivascular spaces of veins toward the subarachnoid space. This exchange depends on normal arterial and venous blood flow and can be abolished by interfering with the arterial blood supply. Studies with contrast medium injected into the subarachnoid space support this concept [3, 7, 11]. The required communication between the subarachnoid space and the perivascular spaces was demonstrated along posterior root entry zones, where Cloyd and Low [1] demonstrated the existence of fenestrations in the pia mater.

2.6 Spinal Cord and Nerve Roots

The spinal cord is about 45.9 cm long in males and 41.5 cm in females [10]. In the cervical and lumbar regions, the spinal cord is enlarged in its transverse diameter. The cervical enlargement between C4 and C7 is most pronounced at C5/6 (Fig. 2.1). According to magnetic resonance imaging measurements, the cervical cord varies in length corresponding to neck movements between 12.69 cm in anteflexion and 11.5 cm in retroflexion [9]. The lumbar enlargement is located approximately at the level of Th12, depending on the conus position (Fig. 2.6). The conus medullaris ends normally at about L1 and is surrounded by the nerve roots of the cauda equina. Caudally to the conus, the filum terminale is located in the center of the dural sac (Fig. 2.6).

The spinal cord contains white matter, which consists of axons, myelin-forming oligodendroglial cells, and fibrous astrocytes, and gray matter, which consists of neuronal cells, dendrites, neuroglial processes, oligodendroglia, and astrocytes. White matter is less vascularized than gray matter. The axons are organized in tracts with major motor or sensory functions. Most of these tracts are myelinated and either interconnect different spinal levels with each other or...
Fig. 2.10. Horizontal section through the fifth to sixth cervical segment of the spinal cord: 1 marginal cells, 2 substantia gelatinosa, 3 nucleus proprius, 4 reticular process, 5 substantia intermedia, 6 lateral motoneurons, 7 medial motoneurons, 8 posterior root, 9 fasciculus gracilis, 10 fasciculus cuneatus, 11 fasciculus dorsolateralis, 12 posterior spinocerebellar tract, 13 lateral pyramidal tract, 14 anterior spinocerebellar tract, 15 fasciculus anterolateralis, 16 anterior pyramidal tract, 17 fasciculus longitudinalis medialis, 18 anterior root. Reprinted with permission from Nieuwenhuys et al. (1978) [14]

Fig. 2.11. Horizontal section through the fifth thoracic segment of the spinal cord: 1 marginal cells, 2 substantia gelatinosa, 3 nucleus proprius, 4 nucleus intermediolateralis, 5 nucleus thoracicus, 6 substantia intermedia, 7 motoneurons, 8 fasciculus gracilis, 9 fasciculus cuneatus, 10 fasciculus dorsolateralis, 11 posterior spinocerebellar tract, 12 lateral pyramidal tract, 13 anterior spinocerebellar tract, 14 fasciculus anterolateralis, 15 central canal, 16 commissura alba, 17 anterior root, 18 fasciculus longitudinalis medialis, 19 anterior pyramidal tract. Reprinted with permission from Nieuwenhuys et al. (1978) [14]

Fig. 2.12. Horizontal section through the fifth lumbar segment of the spinal cord: 1 marginal cells, 2 substantia gelatinosa, 3 nucleus proprius, 4 processus reticularis, 5 substantia intermedia, 6 nucleus cornu commissuralis, 7 motoneurons, 8 funiculus posterior, 9 posterior root, 10 fasciculus dorsolateralis, 11 funiculus posterolateralis, 12 funiculus anterolateralis, 13 funiculus anterior, 14 anterior root. Reprinted with permission from Nieuwenhuys et al. (1978) [14]
contain long descending or ascending fibers. The posterior midline tracts (i.e., the lateral fasciculus cuneatus and medial fasciculus gracilis) carry sensory information from the upper and lower part of the body, respectively, to the brain. Fibers enter these columns from posterior nerve roots. Thus, axons from lower segments of the body gradually become placed more medially the higher the spinal level. Between these two fascicles, a small intermediate sulcus may be detectable on the posterior surface. The lateral segments of white matter contain the spinocerebellar, lateral spinothalamic, and lateral corticospinal tracts. The anterior spinothalamic and anterior corticospinal tracts are found anteriorly (Figs. 2.10–2.12).

The gray matter of the spinal cord forms an H-shaped structure in the axial plane and varies in size according to the spinal level. It is greatest in the cervical and lumbar cord and considerably smaller in the thoracic cord due to the larger numbers of neurons required for motor function of upper and lower extremities, respectively. In the center of the cord and white matter lies the central canal, which is lined by ependymal cells. This canal is surrounded by fiber tracts of the anterior and posterior commissures. The gray matter is organized in the posterior and anterior horn on either side. The posterior horn contains sensory neurons organized in layers. In the cervical region, the posterior horn also contains the spinal nucleus of the trigeminal nerve. Thus, upper cervical pathologies may cause sensory dysfunctions in the face. The ventral horns, on the other side, contain motoneurons and interneurons. Of particular importance is the nucleus of the phrenic nerve, which is located between C3 and C6. Operations at these levels may cause phrenic dysfunctions and, thus, respiratory functions should be monitored carefully after operations at this level (Figs. 2.10–2.12).

Blood is supplied through the radicular arteries, which branch off the vertebral, aortic intercostal, and lumbar arteries and run along the anterior surface of the roots. They form the anterior and the paired posterior spinal arteries. In the cervical area, the anterior spinal artery is derived from paired branches of the distal vertebral arteries. The rest of the vascular supply to anterior and posterior spinal arteries is extremely variable. In most cases, there are two or three radicular branches to the cervical cord. Between one and six anterior radicular arteries connect to the anterior spinal artery in the cervical region, while none to eight posterior radicular arteries may supply the paired posterior spinal arteries [16]. In other words, sacrificing a radicular artery in the cervical region may be considered safe for most patients, but it may cause serious deficits in a patient with a low number of radicular arteries in the cervical area. A watershed region between the upper and lower spinal cord supplies is at about Th4. A regular lower major artery (i.e., the arteria radicularis magna or artery of Adamkiewicz) enters from the left side in 75% of patients, mostly (85% of cases) between Th9 and L2 and less often (in 15% of cases) between Th5 and Th8, to supply the anterior spinal artery [2]. Further radicular arteries supplying the anterior spinal artery may be encountered more often on the left side [5]. The anterior spinal artery courses along the anterior median sulcus. Anastomoses to the posterior spinal arteries exist, which are located on the dorsolateral surface of the cord. Branches of the anterior spinal artery penetrate the cord to supply the anterior white matter, ventral horns of the gray matter, base of the posterior horns, and the lateral columns. Distances between these central spinal arteries are larger in the thoracic cord compared to the conus area, where they are shortest, and the cervical cord. Arteries within the spinal cord are considered as end-arteries, as no anastomoses are detectable. Branches of the posterior spinal arteries supply the remaining posterior parts of the cord [16].

Veins run in a longitudinal direction on the cord surface and continue along the nerve roots toward the epidural venous plexus. About one-third to one-half of all roots carry radicular veins [16].

As far as vegetative functions of spinal nerves are concerned, sympathetic afferent and sympathetic efferent fibers can be distinguished. Neurons of the intermediolateral and intermediomedial nuclei of the thoracic and upper lumbar cord send out efferent fibers, which terminate either in the ganglia of the sympathetic trunk on the same level, in adjacent ganglia, or further cranially in cervical ganglia [10].

Little is known about sympathetic afferent fibers, which mediate vasoconstriction upon a cold stimulus to the skin. Even after complete transection of the cord, a cold stimulus to a lower extremity can still trigger vasoconstriction in the upper extremity via the sympathetic trunk. As far as efferent, vasoconstrictor fibers are concerned, those for the neck and head exit through the roots of C8–Th3, those for the upper extremities at Th3–Th6, and those for the lower extremities at Th4–L3. Vasodilator control is exerted through purely spinal reflex mechanisms and cannot be mediated across a level of cord transection. Its spinal representation is thought to correspond to the sensory distribution [10].

Sweat secretion is controlled by thermoregulatory centers of the brainstem, and efferent fibers leave the