

# Contents

## List of contributors

xiii

## Editor bios

xvii

## The sine qua non encyclopedia for spinal cord neurotrauma, spine trauma, and neurorehabilitation

xix

## Preface

xxi

## Acknowledgments

xxiii

## Introduction

xxv

## 1. Anatomy

LAUREEN D. HACHEM, ALI MOGHADDAMJOU, AND MICHAEL G. FEHLINGS

Spinal column 1

Spinal nerves 4

Gray matter: nuclei and rexed lamina 5

White matter tracts 7

Vascular supply 9

Autonomic nervous system 10

Conclusion 11

References 11

## 2. Epidemiology

THORSTEN JENTZSCH, ANOUSHKA SINGH, AND MICHAEL G. FEHLINGS

Overview 13

History 14

Pediatrics 15

Resources 16

Prevalence 17

Incidence 18

Costs 19

Clinical 20

Etiology 22

Gender and age 24

Organized systems of care 25

Rehospitalizations 26

Neurological recovery 26

Survival 28

Acknowledgments 28

References 28

## 3. Classification systems: spine trauma

ARIANA A. REYES, SRIKANTH N. DIVI,  
THOMAS J. LEE, DHRUV GOYAL, AND  
ALEXANDER R. VACCARO

Introduction 37

Cervical spine trauma classification systems 37

Upper cervical spine (occiput to C2) 38

Thoracolumbar classification systems 46

Sacral classification systems 49

Summary 55

Acknowledgment 55

References 55

## 4. Classification systems: SCI

SUKHVINDER KALSI-RYAN AND  
GITA GHOLAMREZAEI

Introduction 63

Classification systems 64

Summary 70

References 70

## 5. Outcome measures

JETAN H. BADHIWALA, CHRISTOPHER D. WITIW,  
HETSHREE JOSHI, OMAR KHAN, AND  
SUKHVINDER KALSI-RYAN

Introduction 75

Imaging outcomes 76

Clinically determined outcome measures 76

Electrophysiological outcomes	81
Patient-reported outcome measures	82
Conclusions	84
References	86

## 6. Imaging: spine trauma

PARTHIK D. PATEL, MICHAEL MARKOWITZ, SRIKANTH N. DIVI,  
GREGORY D. SCHROEDER, AND ALEXANDER R. VACCARO

Introduction	89
Cervical spine imaging indications	89
Patients who warrant imaging	89
Plain radiography (X-ray)	90
Computed tomography	92
Magnetic resonance imaging for the injured spinal column	93
Cervical spine clearance	95
Magnetic resonance imaging for spinal cord injury	96
Noteworthy cases	99
Imaging evaluation of vertebral artery injury	100
Summary	101
References	101

## 7. Advanced imaging for spinal cord injury

MUHAMMAD ALI AKBAR, ALLAN R. MARTIN, DARIO PFYFFER,  
DAVID W. CADOTTE, SHEKAR KURPAD, PATRICK FREUND,  
AND MICHAEL G. FEHLINGS

Introduction	105
Conventional magnetic resonance imaging	107
Quantitative magnetic resonance imaging	111
Clinical applications	117
Conclusion and future directions	119
References	120

## 8. Intraoperative imaging and image guidance

DAIPAYAN GUHA, ADAM A. DMYTRIW, JAMES D. GUEST, AND  
VICTOR X.D. YANG

Evolution of computer-assisted navigation	125
Registration, imaging, and actuation techniques in spinal computer-assisted navigation	132
Intraoperative ultrasound	140
References	143

## 9. Upper cervical spine and spinal cord injuries

ERIK HAYMAN, ROD J. OSKOUIAN, AND JENS R. CHAPMAN

Diagnostic considerations	149
Anatomy and injury classification	152

Upper cervical spine injury	155
Spinal cord injury in upper cervical spine injury	156
Prognosis after upper cervical spinal cord injury	157
Management of upper cervical spinal cord injury	158
Conclusion	164
References	164

## 10. Spine trauma management issues: C-spine

JARED T. WILCOX, MINA AZIZ, RAKAN BOKHARI,  
SOLON SCHUR, LIOR ELKAIM, MICHAEL H. WEBER,  
AND CARLO SANTAGUIDA

Preoperative management	167
Operative management	176
Future considerations	183
Acknowledgments	185
References	185

## 11. Spine trauma management issues: thoracic and lumbar

DAVID BEN-ISRAEL AND W. BRADLEY JACOBS

List of abbreviations	191
Introduction	191
Clinical evaluation	191
General management considerations	192
Specific management considerations by fracture subtype	194
Special considerations	202
Conclusion	204
References	204

## 12. Spine trauma: sacral fractures

CARLO BELLABARBA, HAITAO ZHOU, AND  
RICHARD J. BRANSFORD

Introduction	211
Anatomy	211
Epidemiology	215
Classification	215
Evaluation	222
Treatment	225
Complications	236
Special considerations	240
Outcomes	241
Summary	241
References	242

### 13. Spine trauma management issues: polytrauma

JEREMIE LAROUCHE AND FRANK LYONS

Take home points 247

Introduction 247

Conflicting priorities 248

Spine clearance 248

Primary versus secondary spinal cord injury in the setting of polytrauma 249

Cord perfusion and coagulopathy 250

Timing of fixation 250

Case examples 253

References 255

### 14. Spine trauma in the elderly — management issues and treatment goals

MARK J. LAMBRECHTS, CHRISTINA L. GOLDSTEIN, AND JAMIE R.F. WILSON

Pathophysiology 259

Traumatic spinal cord injury 260

Central cord syndrome 262

Medical considerations in the geriatric spinal cord injured patient 262

Multimodality analgesia regimen 263

Cost-effectiveness of surgery in SCI 264

Vertebral compression fractures 264

Diffuse idiopathic skeletal hyperostosis 267

Conclusions 267

References 268

### 15. Spine Trauma: Areas of controversy and Emerging Concepts

JOSEPH H. MCMORDIE, JAMIE R.F. WILSON, F. CUMHUR ONER, ALEXANDER R. VACCARO, AND MICHAEL G. FEHLINGS

Introduction 271

Management of AO Spine A3/A4 fractures: operative versus nonoperative 271

MIS versus open surgery for fractures without deformity 275

Operative management of type 2 odontoid fractures in the elderly 277

Timing of surgery for central cord syndrome 279

Role of MRI in decision-making for spine fractures 281

Conclusion 283

References 284

### 16. Traumatic central cord injury

JETAN H. BADHIWALA, LAUREEN D. HACHEM, BIZHAN AARABI, BRIAN K. KWON, AND MICHAEL G. FEHLINGS

Introduction 289

Diagnosis and definition 290

Epidemiology 291

Pathophysiology 291

Clinical course 293

Management 294

Conclusion 299

References 299

### 17. Management and pathophysiology

JAMES HONG, NOAH POULIN, BRIAN K. KWON, AND MICHAEL G. FEHLINGS

Epidemiology 303

Clinical management of spinal cord injury—standard of care in North America 304

Pathophysiology of spinal cord injury 308

References 312

### 18. SCI management: role and timing of surgical intervention

PAULA VALERIE TER WENGEL, FAN JIANG, JEFFERSON R. WILSON, AND MICHAEL G. FEHLINGS

Introduction 319

Natural history 319

The nature of surgical decompression for spinal cord injury 320

Timing of surgical decompression in cervical spinal cord injury 321

Timing of decompression in the “central cord” pattern of cervical incomplete tetraplegia 324

Timing of decompression in thoracic and thoracolumbar spinal cord injury 326

Timing in cauda equina injury 327

Current guidelines 329

Knowledge gaps surgical timing and recommendation for future research 329

References 330

## 19. Intensive care and drugs after spinal cord injury

ANTON FOMENKO, ALWYN GOMEZ, AND GREGORY W.J. HAWRYLUK

Introduction 335

Initial management 335

Timing of surgical decompression 339

Hemodynamic targets after SCI 339

Spinal cord perfusion pressure monitoring 340

Pharmacologic management of SCI 341

Extraspinal complications of SCI 344

References 344

Further reading 347

## 20. SCI management: rehabilitation

JULIO C. FURLAN AND B. CATHARINE CRAVEN

Introduction 349

Overview of the rehabilitation principles 350

Restoration of motor and sensory function 351

Minimizing secondary health conditions 359

Knowledge gaps and research opportunities 363

References 363

## 21. Economic impact of traumatic spinal cord injury

JULIO C. FURLAN, BRIAN C.F. CHAN, VIVIEN K.Y. CHAN, AND MICHAEL G. FEHLINGS

Introduction 371

Economic burden of diseases 374

Current knowledge on cost-effective opportunities 375

Knowledge gaps and research opportunities 381

References 382

## 22. Complications and adverse events following traumatic spinal cord injury

ZAID SALAHEEN, NADER HEJRATI, IAN H.Y. WONG, FAN JIANG, AND MICHAEL G. FEHLINGS

Introduction 385

Incidence and prevalence of complications in tSCI 385

Spectrum of complications in traumatic spinal cord injury 387

Impact of complications on neurological and functional recoveries 392

Mortality following traumatic spinal cord injury 393

The role of prediction models in evaluating patients' risk for complications 394

Conclusion 395

References 395

## 23. Neurochemical biomarkers of acute spinal cord injury

ANDREA J. MOTHE, STEVEN CASHA, AND BRIAN K. KWON

Introduction 401

Promising neurochemical biomarkers of acute SCI 403

References 409

## 24. Clinical trials: pharmacological approaches to enhance neural repair and regeneration after spinal cord injury

ARMAAN K. MALHOTRA, LAUREEN D. HACHEM, JETAN H. BADHIWALA, MARK R.N. KOTTER, AND MICHAEL G. FEHLINGS

Introduction 411

Completed clinical trials 413

Drugs under active clinical investigation 429

Drugs entering clinical trials 433

Conclusion 434

References 435

## 25. Clinical trials: cellular regenerative approaches

NAYaab PUNJANI, VJURA SENTHILNATHAN, CHRISTOPHER S. AHUJA, AND MICHAEL G. FEHLINGS

Introduction 441

Conclusion 456

References 467

## 26. Clinical trials: noncellular regenerative approaches

VJURA SENTHILNATHAN, NAYaab PUNJANI, NARIHITO NAGOSHI, CHRISTOPHER S. AHUJA, AND MICHAEL G. FEHLINGS

Introduction 473

Conclusion 496

References 496

**27. Clinical trials: rehabilitation approaches**

NEWTON CHO, PAUL A. KOLJONEN, AND ANTHONY S. BURNS

Background 501

Rehabilitative approaches to improve function after SCI 502

Conclusions 515

References 515

**28. Neuroprotective strategies: translational perspectives**

JAMES HONG, NOAH POULIN, AND MICHAEL G. FEHLINGS

Introduction 523

Excitotoxicity 523

Immunological modulation 525

Blood–spinal cord barrier maintenance 527

Other 529

Combinatorial strategies 530

References 531

**29. Translational perspective: neuroregenerative strategies and therapeutics for traumatic spinal cord injury**

ANDREA J. SANTAMARIA, PEDRO M. SARAIVA, JUAN P. SOLANO, AND JAMES D. GUEST

Introduction 537

Biologic therapeutics 539

Extrinsic determinants of neuronal regeneration 539

Intrinsic determinants of neuronal regeneration: the conditioning lesion paradigm 546

Cellular and acellular (biomaterial) transplant interventions 550

Summary 559

Conclusions 560

References 560

**30. Emerging concepts in the clinical management of SCI for the future**

LAUREEN D. HACHEM, JETAN H. BADHIWALA, FAN JIANG, BRIAN K. KWON, MARK R.N. KOTTER, JEFFERSON R. WILSON, ALEXANDER R. VACCARO, F. CUMHUR ONER, AND MICHAEL G. FEHLINGS

Introduction 575

Time is spine 576

Measures of spinal cord physiology 576

Integration of imaging data into predictive and prognostic models 577

Minimally invasive treatment modalities 578

Redefining clinical heterogeneity 578

Aging and frailty 579

A personalized approach to SCI management 580

Regenerative medicine 582

Interrogating neural circuitry to understand disease states 582

Application of brain–computer interfaces 582

Conclusion 583

References 583

**31. Translational research in spinal cord injury – What is in the future?**

NADER HEJRATI, WILLIAM BRETT MCINTYRE, KATARZYNA PIECZONKA, SOPHIE OSTMEIER, CHRISTOPHER AHUJA, BRIAN K. KWON, ALEXANDER R. VACCARO, F. CUMHUR ONER, AND MICHAEL G. FEHLINGS

Introduction 587

Epidemiologic changes 588

Clinical considerations 589

Personalized approaches 591

Future perspectives in neuromodulation 597

Future perspectives related to artificial intelligence 598

Conclusion 598

References 599

Index 603