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Hua Chen
Editors

Orthopaedic Trauma Surgery

Volume 3: Axial Skeleton Fractures and Nonunion

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ISBN 978-981-16-0218-4 ISBN 978-981-16-0219-1 (eBook)
https://doi.org/10.1007/978-981-16-0219-1

Jointly published with Military Science Publishing House
The print edition is not for sale in China (Mainland). Customers from China (Mainland) please order the print book from: Military Science Publishing House.

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Foreword

In the last 50 years, the methodology of treating fractures has undergone a series of changes. The Association for the Study of Internal Fixation (AO), shortly after its establishment in 1980, proposed the treatment principle emphasizing mechanical stability and focusing on anatomical reduction, rigid internal fixation, surrounding soft tissue protection, and early functional exercise. Gradually, this concept evolved into one emphasizing a biological internal fixation that better protects the blood supply of bone and soft tissues at the fracture site. The change has prompted the invention of new types of implants, including locking compression plates and interlocking intramedullary nails, and the development of new technologies, including minimally invasive plate osteosynthesis. These advances, in combination with high-quality intraoperative imaging technologies, such as X-ray and CT, have raised fracture care to a new level.

The Chinese PLA General Hospital is a top-tier comprehensive hospital. Its Department of Orthopaedics has been established in 1953. In 1977, the Orthopaedic Trauma Center was formed. It has obtained prominent medical and scientific achievements in the field of orthopaedic trauma treatment. Great thanks to the contributions of our respected seniors, such as Prof. Shibi Lu, Prof. Shengxiu Zhu, Prof. Boxun Zhang, and Prof. Yan Wang. Prof. Peifu Tang, as the editor-in-chief of this book, chairman of the department of orthopaedic surgery, and director of the Orthopaedic Trauma Group of the Orthopaedics Division of the Chinese Medical Association, has been a good friend of mine for many years. Under his leadership, the Department of Orthopaedic Trauma of the Chinese PLA General Hospital has made brilliant achievements in clinical and scientific research. I am delighted to see that the books have summarized years of experience at the 301 Orthopaedic Hospital of the Chinese PLA General Hospital in fracture care in a book, which will surely benefit the development of orthopaedic trauma care in China.

The following distinguishing features of this book stand out to me.

First, this book is a valuable guide for clinicians. By introducing the conceptual evolution of internal fracture fixation approaches in recent years, the book increases the awareness and willingness of readers to utilize new technologies. Considering that orthopaedic trauma medicine covers a wide range of injuries with diverse mechanisms and complex conditions, the book emphasizes the importance of treatment timing and individualized optimal treatment strategies in clinical decision-making and presents practicable approaches for reference.

Second, the book has a well-organized, easy-to-read structure with concise, bulleted text, full-colour illustrations, and intraoperative photographs. Each chapter follows a similar format, starting with applied anatomy and then combining it with the biomechanics and functional characteristics of the fractured body part to describe the anatomical structure and clinical issues such as injury mechanisms, treatments, and healing. This unique format is an attractive feature of the book. In addition, the book maintains a focus on clear, step-by-step depictions and descriptions of surgical procedures for each surgical technique, consistent with the working habits of clinicians. Another feature of the book is the combination of illustrations/photographs and text. On many occasions, intraoperative photographs, schematic diagram(s), and intraoperative X-ray or CT images are jointly used. The schematic diagrams help readers understand the mechanisms underlying the surgical approach and fracture reduction and fixation, the intraoperative photographs supply readers with an intuitive visual impression of the intraoperative scene, and the intraoperative radiographs and CT images offer a reference for reduction and fixation.

Third, this book provides tips and cautions based on the experience obtained over the years by the Department of Orthopaedic Trauma of the Chinese PLA General Hospital. In the sections introducing the surgical procedures in particular, the experience and lessons, which have not been easy to explain clearly in previous books, are unreservedly presented in detail through illustrations and text, which offers a surgeon's-eye view of the relevant scenarios and helps readers grasp the "gold content" of the book.

I have known Prof. Peifu Tang for more than 15 years. He is a rising star in the young generation of orthopaedic traumatologists in China. With his intelligence and diligence, he has become a good model for the young generation of orthopaedic trauma surgeons. Hard work will certainly yield fruitful results. I sincerely applaud the publication of this book and hope that Prof. Peifu Tang will continue to publish more work in orthopaedic trauma.

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Ying-ze Zhang

Preface

In recent years, with the economic growth and subsequent rapid development of the construction and transportation industry, the incidence of orthopaedic trauma has shown a prominent increasing trend. Moreover, with the advancement of medicine, the expectations of patients regarding treatment outcomes have also increased. Surgery is an important treatment method for orthopaedic trauma, which is attracting an increasing amount of attention.

In response to these trends, the Department of Orthopaedics of the Chinese PLA General Hospital was established in 1953, upgraded to a grade one Orthopaedic Trauma Center in 1977. The Department has been developed along the path initiated by a group of well-known researchers, including Prof. Jingyun Chen, Prof. Zhikang Wu, Academician Shibi Lu, Prof. Shengxiu Zhu, Prof. Boxun Zhang, Prof. Jifang Wang, and Prof. Yan Wang. They emphasize clinical and scientific research and have earned five first-class and two second-class awards of the National Science and Technology Progress Award. This book, *Orthopaedic Trauma Surgery*, is a summary of our valuable experience in fracture treatment gained over the previous 60 years.

We systematically searched for relevant information in China and other countries and compiled case reports and imaging data from the Department of Orthopaedics of the PLA General Hospital accumulated over the years, writing this book, which has three volumes and 29 chapters that, respectively, introduce upper extremity fractures and dislocations, lower extremity fractures and dislocations, and axial skeleton fractures and non-union.

The book adopts the principle of guiding surgery by anatomy, fixation by biomechanics, and clinical procedures by functional recovery. In each chapter, the applied anatomy of the fracture site is first introduced. This section confers prominence to the relationship between the anatomical structure and surgery and emphasizes the structure that must be protected and repaired during surgery. In addition, the biomechanical characteristics of the fracture site are described, so that the appropriate fixation method can be selected according to the characteristics of the mechanical environment. In most chapters on periarticular fractures, the book also describes in detail how the joints fulfil their function, which is often the core of clinical decision-making, with the hope that the reader can understand the how and the why.

The book adopts the outline-style format instead of the traditional paragraph-by-paragraph discussion to supply readers with the extracted essence in a more succinct manner, which improves the logical flow and concision and thereby improves the readability of the book. In addition, using more than 3000 illustrations and photos, many of which were obtained from our clinical practice, the book discusses the injury mechanisms and the classification and assessment of extremity and axial skeleton fractures, with a focus on typical and new surgical methods developed in recent years. These illustrations and photos provide the reader with a good reference for learning surgical techniques and skills. Hopefully, this design will make the book useful for orthopaedic surgeons at all levels in China.

Many professors and associate professors with rich clinical experience in the Department of Orthopaedic Trauma of the PLA General Hospital have contributed to this book. We would like to thank Dr. Zhe Zhao for his painstaking efforts in the preparation of this book. He has contributed a tremendous amount of work in the structural design, content compilation, case selection, and figure design. Thanks are extended to Dr. Hua Chen for his work in the structural design of this book, which laid the foundation for this book. We also thank Prof. Boxun Zhang and Prof. Yutian Liang for their meticulous review of the manuscript.

During the preparation of this book, we have done our best to keep abreast of the latest surgical advances in fracture treatment and striven to deliver accurate and informative content. However, due to the rapid development of new concepts and instruments for the treatment of orthopaedic trauma, and time and knowledge source limitations, inevitably there might be deficiencies in this book, and we welcome the reader to point them out and help us to improve the content of the book.

Beijing, China Peifu Tang

Contents

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Cervical Spine Fractures and Dislocations

1

Zhe Zhao, Lihai Zhang, Yong Sun, and Gaoxiang Xu

1.1 Basic Theory and Concepts

1.1.1 Overview

- Cervical spine injuries refer to fractures and dislocations of the section from the atlanto-occipital joint to C7, including the upper (C1–2) and lower (C3–7) cervical spine.
- The major causes of cervical spine injuries are high-energy violence, mostly consisting of transportation accidents (45%) and falls from a high place (20%) (Koval and Zuckerman 2006).
- Fractures of the atlas, axis, and lower cervical spine account for 7%, 12%, and 75% of all cervical spine fractures, respectively (Zhang 2012).
- Approximately 40% of cervical spine fractures are associated with nerve injury. Lower cervical spine injuries are more likely associated with spinal cord damage than upper cervical spine injuries (Koval and Zuckerman 2006).

1.1.2 Applied Anatomy

- The cervical spine has a natural lordosis of 25° (Fig. 1.1), and the perpendicular line of C7 passes S1.
- The upper cervical spine consists of the atlas and the axis with unique shapes, and the lower cervical spine consists of C3–7, which have similar structures.
- The range of motion of the upper and lower cervical spine in neck movements:
  - The vertebral segments constituting the cervical spine vary in range of motion on the three planes during neck movements; correspondingly, arthrodesis of different segments leads to varying degrees of loss of range of motion (Table 1.1).
  - Arthrodesis involving fewer segments retains a larger motion range.
- The atlas (C1; Fig. 1.2):
  - The atlas has a unique shape as its vertebral body has evolved into the odontoid process.
  - Lateral mass:

    It is one of the major contributors to head movements.

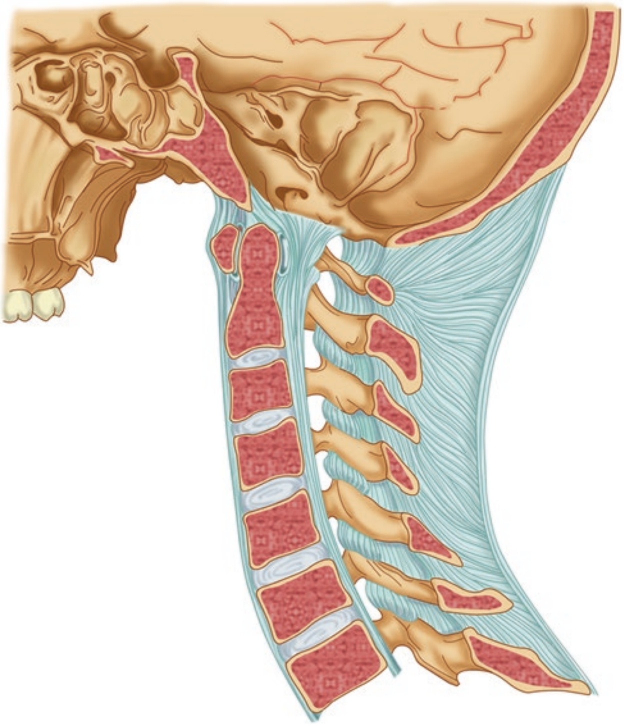

Fig. 1.1 The cervical spine has a physiological lordosis of approximately 25°

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P. Tang, H. Chen (eds.), *Orthopaedic Trauma Surgery*, https://doi.org/10.1007/978-981-16-0219-1_1

Table 1.1 Ranges of motions of different joints and regions of the cervical spine in three planes

Joint or Region	Flexion and Extension (Sagittal Plane, Degrees)	Axial Rotation (Horizontal Plane, Degrees)	Lateral Flexion (Frontal Plane, Degrees)
Atlanto-occipital joint	Flexion: 5 Extension: 10 Total: 15	Negligible	About 5
Atlanto-axial joint complex	Flexion: 5 Extension: 10 Total: 15	35-40	Negligible
Intracervical region (C2-C7)	Flexion: 35-40 Extension: 55-60 Total: 90-100	30-35	30-35
Total across craniocervical region	Flexion: 35-40 Extension: 55-60 Total: 90-100	65-75	35-40

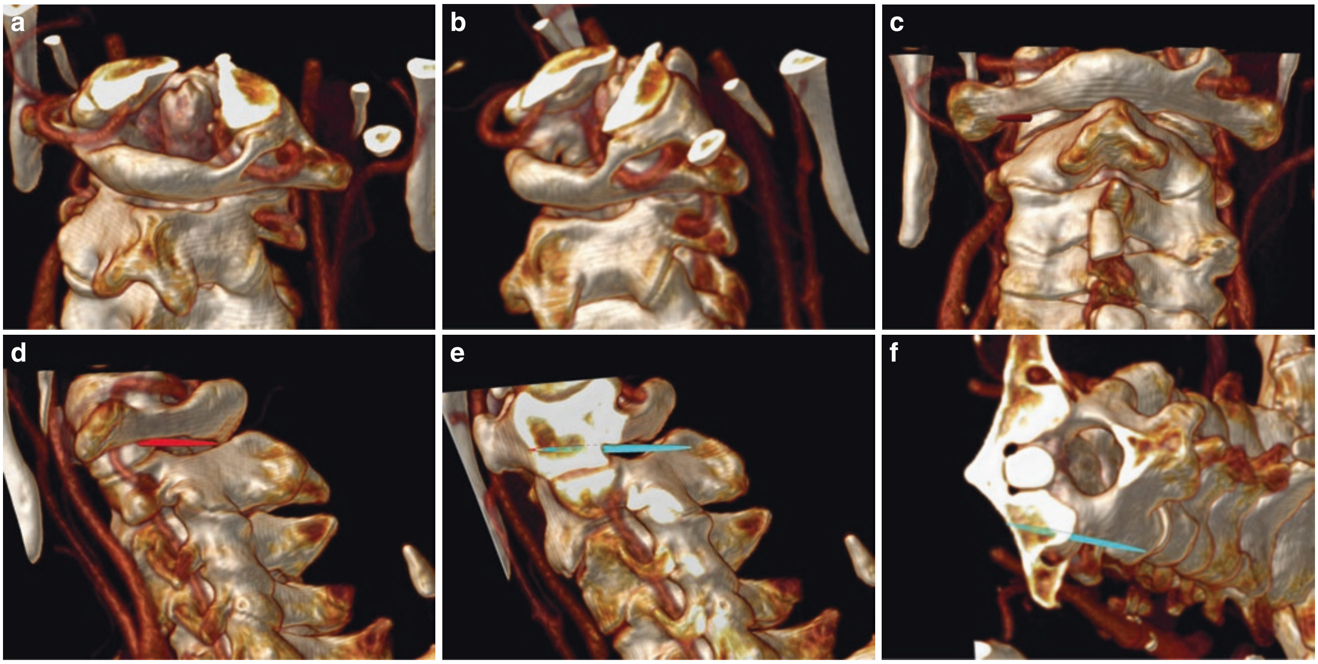


Fig. 1.2 (**a**, **b**) The vertebral artery runs through a bony arch structure in the vertebral artery groove of C1 in a portion of patients. Under such a circumstance, it is important to identify anatomical structures carefully, and non-vigilant screw placement might damage the vertebral artery. (**c**, **d**) The entry point of the C1 lateral mass screw (red bar) is located below the posterior vertebral lamina and on the perpendicular line passing the center of the C1/2 joint. (**e**) The near-sagittal plane of the C1 lateral mass along the direction of the guide wire: the screw placement should be inclined 10° to 20° towards the head side and parallel to the C1 ring. (**f**) The near-cross-section of the C1 lateral mass along the direction of the guide wire: Both sides of the screw converge at an angle of 10° to avoid the lateral vertebral artery

It is located between the anterior and posterior arches, with both the top and bottom surface being articular facets, the spinal canal at its medial side, and the vertebral artery at its lateral side.

The entry point of the lateral mass screw is located below the posterior vertebral lamina and on the perpendicular line passing the center of the C1/2 joint.

The lateral mass screw is placed along the direction inclining to the head by 10–20°, which positions the screw parallel to the ring of C1, and a convergence angle of 10° to avoid damaging the vertebral artery.

- The vertebral artery groove is at the junction of the posterior arch and lateral mass. However, the vertebral artery runs through a bony arch structure in the vertebral artery groove of C1 in a portion of patients. Under such a circumstance, it is important to identify anatomical structures and properly determine the screw entry point; otherwise, non-vigilant screw placement might damage the vertebral artery (Young et al. 2005).
- The atlantoaxial intervertebral venous plexus:

  The venous plexus is behind the atlantoaxial joint, and as a result, the venous wall might be easily damaged during tissue separation.

The entry point of the C1 lateral mass screw should be at a higher rather than lower level. The venous plexus and C2 dorsal root ganglion are gently pulled aside using a nerve stripper for screw placement (Goel and Laheri 1994; Harms and Melcher 2001).

- The axis (C2):
  - The odontoid process is the vestige of the vertebral body of the atlas.
  - Vertebral pedicle:

    The upper and lower edges of the vertebral pedicle of the axis are the superior and inferior articular processes, respectively; the spinal canal and the vertebral artery are located on the medial and lateral sides of vertebral pedicle, respectively.

    The entry point of the pedicle screw is at the midpoint of the perpendicular bisector of the superior articular process of C2.

    The pedicle screw is placed along a direction inclining to the head by 25° and has a convergence angle of 25–35° to avoid damaging the vertebral artery (Borne et al. 1984) (Fig. 1.3).
- Distinct structure of the atlantoaxial ligaments (Fig. 1.4):
  - The surrounding ligaments and other soft-tissue structures play a pivotal role in stabilizing the occipital bone, atlas, and axis, as the bony interconnection among the latter three lacks internal stability.
  - Anteriorly, the anterior atlanto-occipital membrane, which is an extension of the anterior longitudinal ligament, connects the anterior rim of the foramen magnum and the anterior arch of the atlas.
  - Posteriorly, the posterior atlanto-occipital membrane, which shares the same origin as the ligamentum flavum, connects the posterior rim of the foramen magnum and the posterior arch of the atlas.
  - The atlantoaxial ligament consists of three layers:

    The superficial layer is the tectorial membrane, which originates from the ventral side of the foramen magnum and ends at the dorsal side of the odontoid process, is the major ligament stabilizing the atlanto-occipital joint.

    The middle layer includes the cruciate ligament (the transverse ligament of the atlas), which originates from the two inner tubercles of the anterior arch of the atlas, pulls the odontoid process towards the anterior arch of the atlas to prevent the odontoid process from moving backward, and enhances the ability of the cervical spine to rotate.

    The deep layer includes the alar ligament and the apical odontoid ligament. The alar ligament is attached to the tubercles on the two sides of the foramen magnum, additionally stabilizing the atlanto-occipital joint, whereas the apical odontoid ligament contributes little to the stability of the joint.
- C3–C7 vertebrae have a similar structure (Fig. 1.5).
  - The transverse foramen:

    The transverse foramen, which is a unique structure in the cervical vertebrae, includes the ventral and dorsal parts. The ventral part has the same origin as the corresponding rib and is therefore called the costal process. The round blunt end of the costal

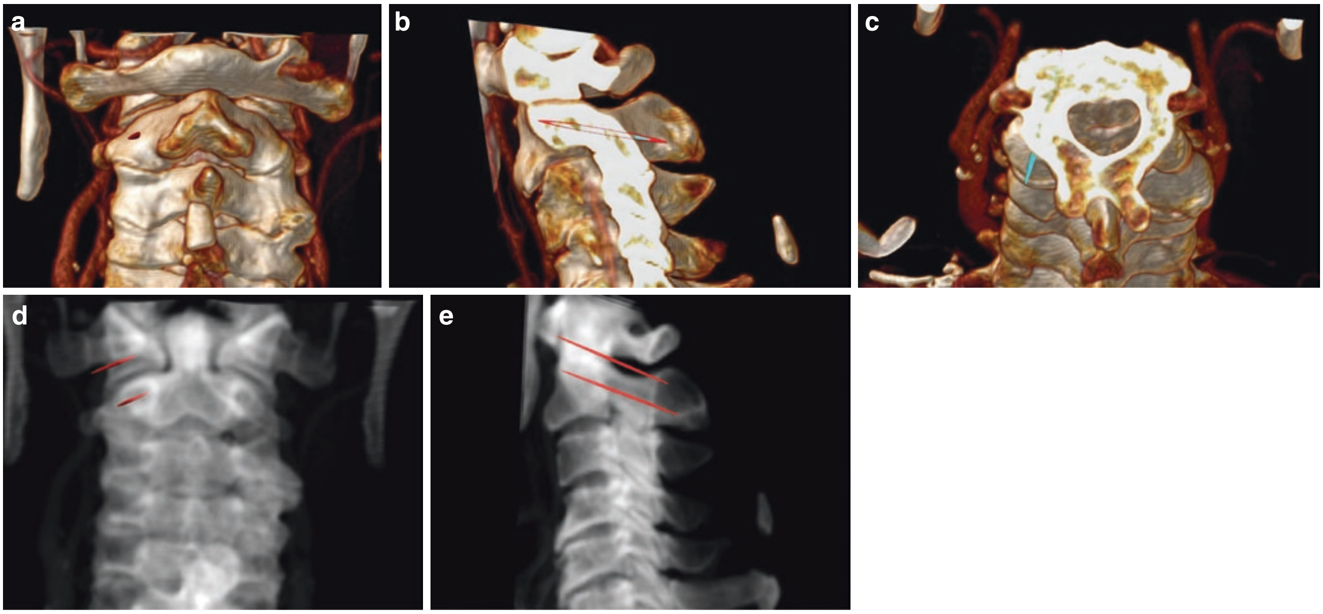


Fig. 1.3 (**a**) The entry point of the pedicle screw is located at the midpoint of the perpendicular bisector of the superior articular process of C2. (**b**) The near-sagittal plane of the C2 pedicle along the direction of the guide wire: The pedicle screw should be tilted towards the head side by 25°. (**c**) The near-cross-section of C2 along the direction of the guide wire: The screws at both sides converge at an angle of 25–35° to avoid damaging the vertebral artery. (**d**, **e**) Reconstructed X-ray CT image showing the guide wire positions

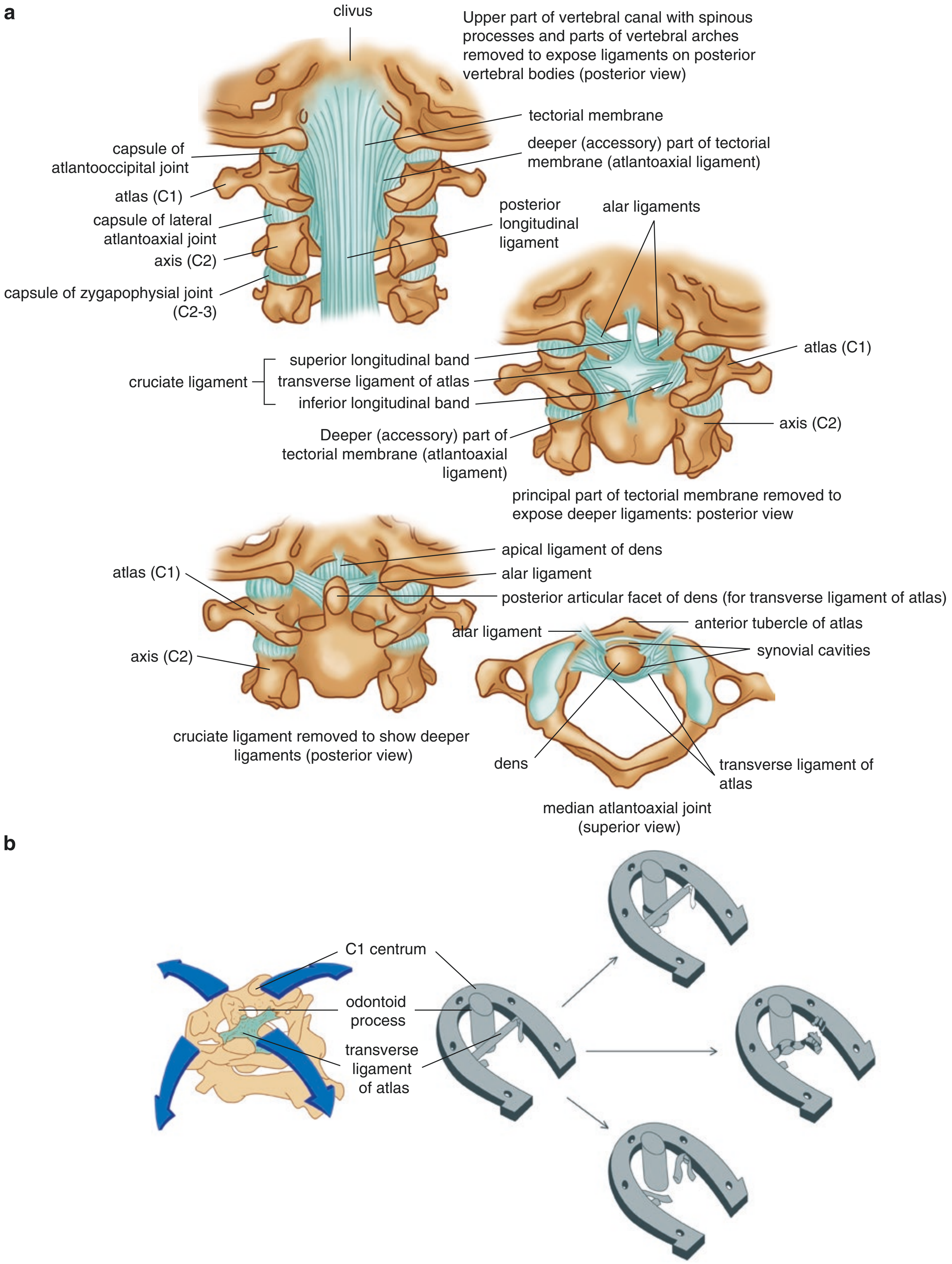


Fig. 1.4 (**a**) The atlantoaxial ligament: The superficial layer is the tectorial membrane, which originates from the ventral side of the foramen magnum and ends at the dorsal side of the odontoid process. The middle layer includes the cruciate ligament (the transverse ligament of the atlas), which originates from the two inner tubercles on the dorsal side of the anterior arch of the atlas. The deep layer includes the alar ligament and the apical odontoid ligament. (**b**) The relationship between the atlas and the axis can be simplified in the following model: the atlas is the horseshoe, the odontoid process is the wooden pole, and the transverse ligament is the cloth belt. There are three basic types of damage, a break of the wood pole (i.e., an odontoid process fracture), a break at the junction of the cloth belt and the horseshoe (i.e., the avulsion of the transverse ligament), and a break of the cloth belt (i.e., a transverse ligament rupture)

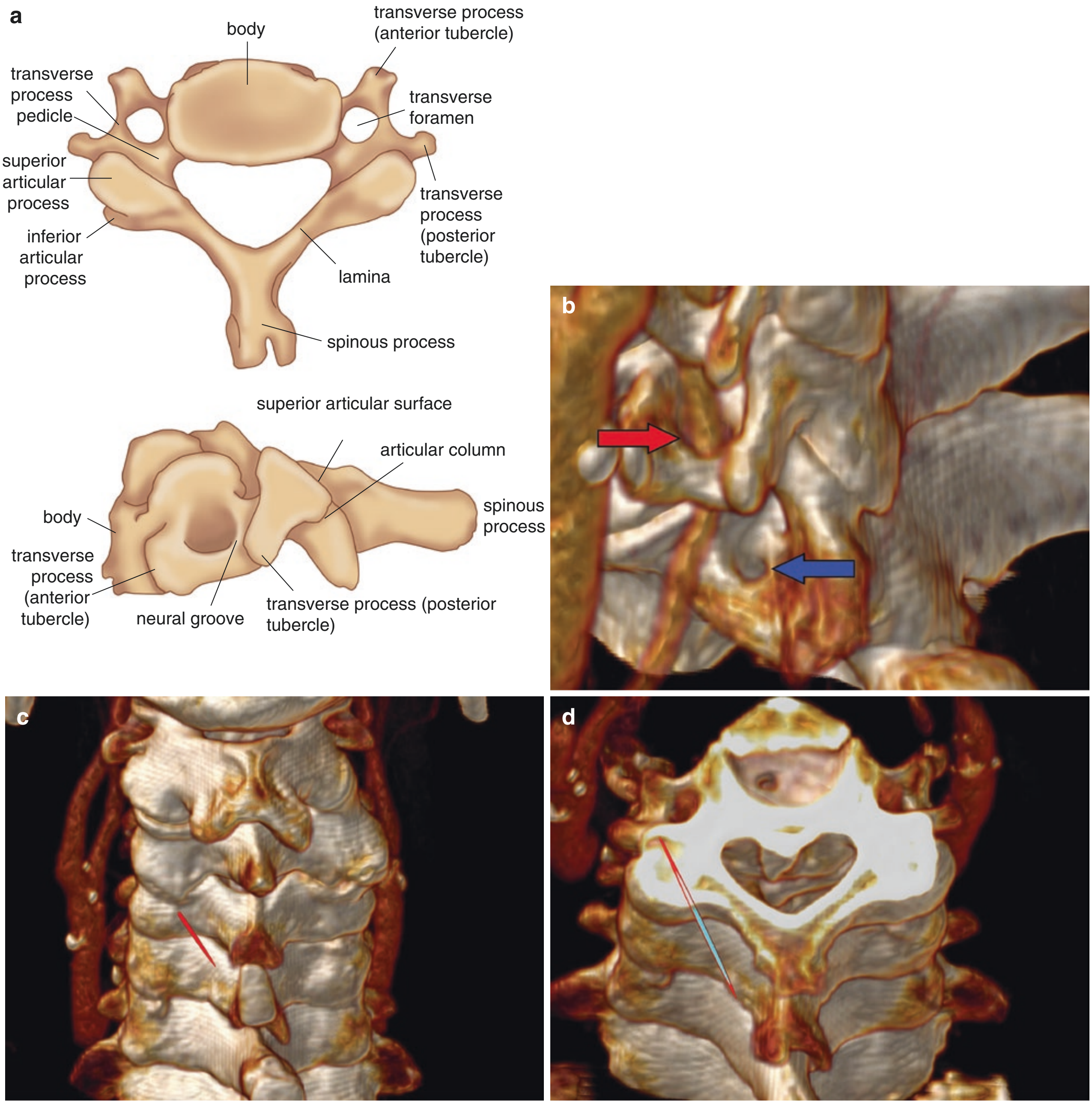


Fig. 1.5 (**a**) Schematic diagrams of AP and lateral views of a lower cervical vertebra, showing the structure of the transverse foramen. (**b**) The transverse foramina of the sixth and seventh cervical vertebra: The red arrow indicates the vertebral artery passing through the transverse foramen of the sixth cervical vertebra; the blue arrow indicates the transverse foramen of the seventh cervical vertebra without any vertebral artery passage. (**c–g**): The fourth cervical vertebra is used as an example to display the method for lateral mass screw placement in the lower cervical spine: (**c**) The entry point of the lateral mass screw is 2 mm medial to the center of the rectangular area that is lateral to the junction of the vertebral lamina and lateral mass and between the superior and inferior articular facets. (**d**) The near-cross-section of C2 along the direction of the guide wire: The screw is inclined laterally 20°–25° to avoid damaging the vertebral artery. (**e**) The near-sagittal plane of the C4 lateral mass along the direction of the guide wire: The screw is inclined to the head side 30–40°. (**f**, **g**) Reconstructed X-ray CT image showing the guide wire positions. (**h–j**) The seventh cervical vertebra is used as an example to show the method for pedicle screw placement of the lower cervical spine: (**h**) The entry point of the pedicle screw is lateral to the midpoint of the lateral mass and close to the lower edge of the inferior articular process of the above vertebral body. (**i**) The cross-section of the C7 vertebral body along the direction of the guide wire showing that the pedicle screw should be placed at a convergence angle from 25° to 45°. (**j**) Reconstructed X-ray CT image showing the guide wire positions

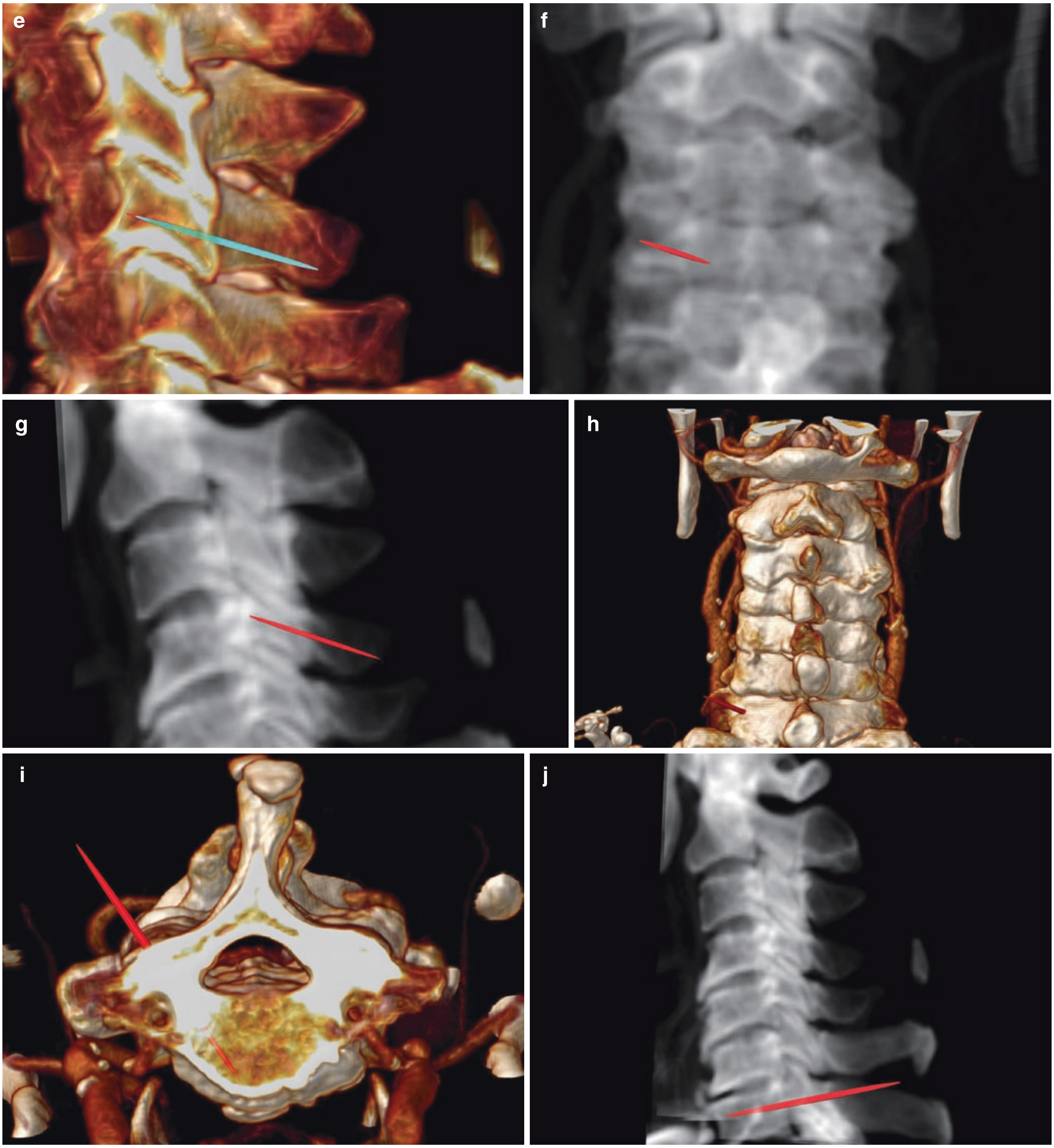


Fig. 1.5 (continued)

process is the anterior tubercle of the transverse process.

The dorsal part is the actual transverse process, and its relatively flat end forms the posterior tubercle of the transverse process.

The vertebral artery travels between the anterior and posterior tubercles, and the costotransverse bar is located at its lateral aspect.

Generally, no vertebral artery travels in the transverse foramen of C7.

- The lateral mass:

  The lateral mass is an enlarged bony structure between the superior and inferior articular processes. Because the vertebral artery travels in the transverse foramen, it is difficult to place a pedicle screw; instead, the lateral mass screw technique is safer and thus often used to secure the lower cervical spine.

  The Magerl technique is often used for lateral mass screw placement (Heller et al. 1991; Xu et al. 1998), which is briefly described as follows:

  - The entry point of the lateral mass screw is 2 mm medial to the center of the rectangular area that is lateral to the junction of the vertebral lamina and lateral mass and between the superior and inferior articular facets.
  - The lateral mass screw should be placed in the direction pointing to the head side at a 30–40° angle and biased laterally by 20–25°.

- The vertebral pedicle:

  Because no vertebral artery travels in the transverse foramen of C7, it is safer to place a pedicle screw via the vertebral pedicle of C7 than via that of C3–6.

  The pedicle screw entry point is slightly lateral to the center of the lateral mass and close to the lower rim of the inferior articular process of the above vertebra.

  The pedicle screw should be placed at a convergence angle of 25–45°.

1.1.3 Mechanism of Injury

- Direct violent force: Cervical spine fractures are rarely caused by direct violence.
- Indirect violent force: This is relatively common. The violent force applied on the head, foot, and hip is longitudinally transmitted to a particular cervical spinal segment and causes a vertebral fracture and dislocation. There are five types of forces according to the direction acted on by the force:
  - Vertical compressive forces: An axial violent force parallel to the spine acts on the vertebra. A representative is the C1 Jefferson fracture (Bozkus et al. 2001; Jefferson 1920).
  - Compressive hyperflexion forces: The violence acts on the flexed spine and causes a compression of the vertebra, which might even be associated with dislocation or interlocking of the facet joints.
  - Compressive hyperextension forces: The violence acts on the backward extended spine and damages the anterior longitudinal ligament and posterior osteoligamentous complexes.
  - Compressive lateral shear forces: A force acting on the side of the vertebra causes unilateral injuries of the vertebra and facet joints.
  - Compressive rotary forces: A violence acting on the rotated spine causes a spine fracture, which is often accompanied by other types of injuries, as described above.

1.1.4 Fracture Classification

- Classification of upper cervical spine injuries
  - Levine classification of atlas fractures (Levine and Edwards 1985) (Fig. 1.6).

    Type I: Isolated fractures of the protuberant components of the atlas.

    Type II: A single fracture of the posterior arch, which is stable and usually a compressive hyperextension injury.

    Type III: A single fracture of the anterior arch, which is stable and usually a compressive hyperflexion injury.

    Type IV: A lateral mass fracture of the atlas. The fracture line often crosses the lateral mass joint from anterior to posterior. The open-mouth view can demonstrate whether the bilateral atlantoaxial complexes are separated and asymmetric.

    Type V: Atlas burst fractures. Typically, the patients have two fracture sites in the anterior arch, two in the posterior arch, and probably a lateral mass facture. A finding of bilateral lateral displacements larger than 6.9 mm might suggest that the transverse ligament is ruptured and that both the atlas and axis are unstable.
  - Classification of axis fractures: The Anderson classification is the most commonly used method for odontoid fractures (Grauer et al. 2005) (Fig. 1.7).

    Type I: Avulsion fractures of the odontoid tip, which is the attachment point of the alar ligament.

Fig. 1.6 Levine classification of atlas fractures. (**a**) Transverse process fracture. (**b**) Posterior arch fracture. (**c**) Anterior arch fracture. (**d**) Comminuted or lateral mass fracture. (**e**) Burst fracture

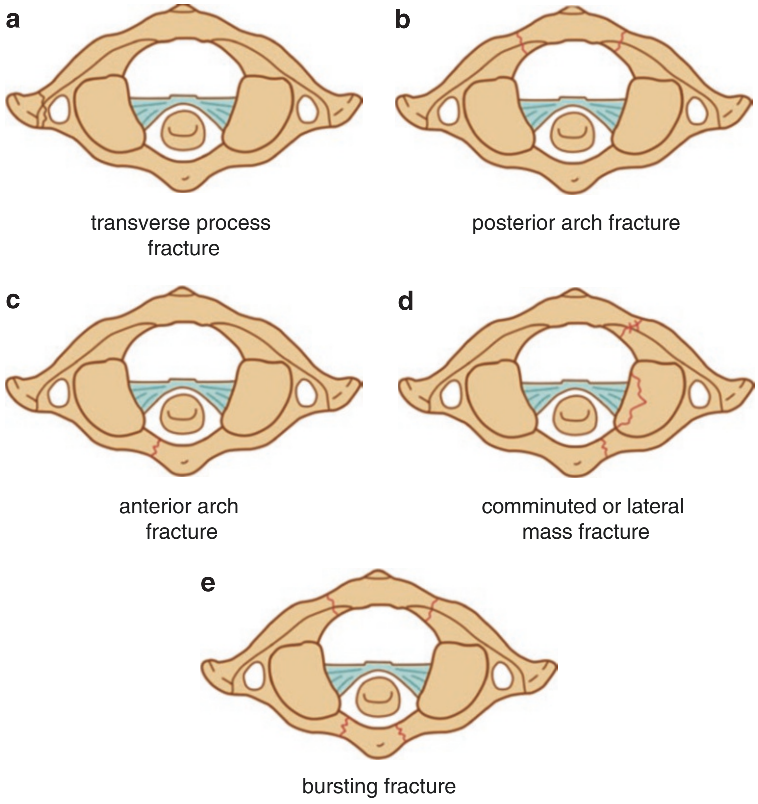
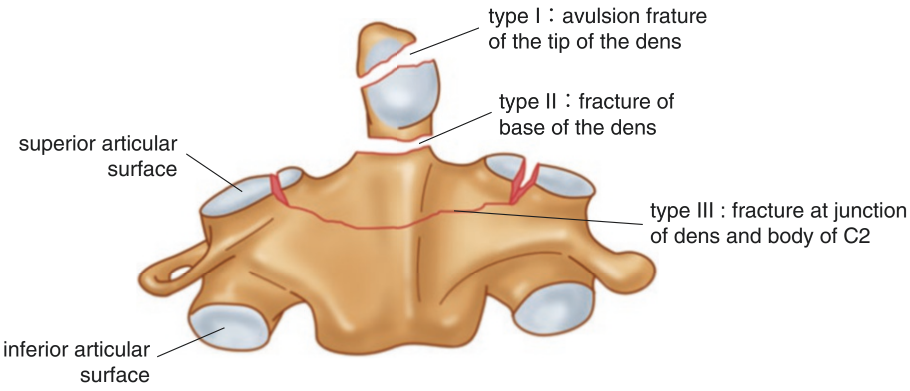


Fig. 1.7 Anderson classification of odontoid fractures



Type II: Fractures of the base of the odontoid process, which has a poor blood supply and little cancellous bone in the cross-section. This type of fracture is difficult to heal, and the healing rate further declines when there is an angulation deformity or a displacement larger than 4 mm.

Type III: Fractures with a fracture line extending to the vertebral body of the axis. Oblique fractures have a high healing rate.

- Traumatic spondylolisthesis of the axis (hangman's fracture): A hangman's fracture refers to a fracture occurring in the junction area of the superior and inferior articular processes of the axis, which is primarily classified using the classification system proposed by Levine and Edwards (Levine and Edwards 1985) (Fig. 1.8).

Type I: Fractures without angulation and with forward slippage <3 mm

Type II: The anterior displacement of the axis is >3 mm or with angulation

Subtype IIa: Hyperflexion traction injuries, in which the axis has severe angulation with the intact anterior longitudinal ligament as a hinge and relatively slight displacement. For this type of fracture, traction is contraindicated because it might lead to displacement deterioration.

Type III: Bilateral vertebral pedicle fractures associated with articular process displacement or inter-

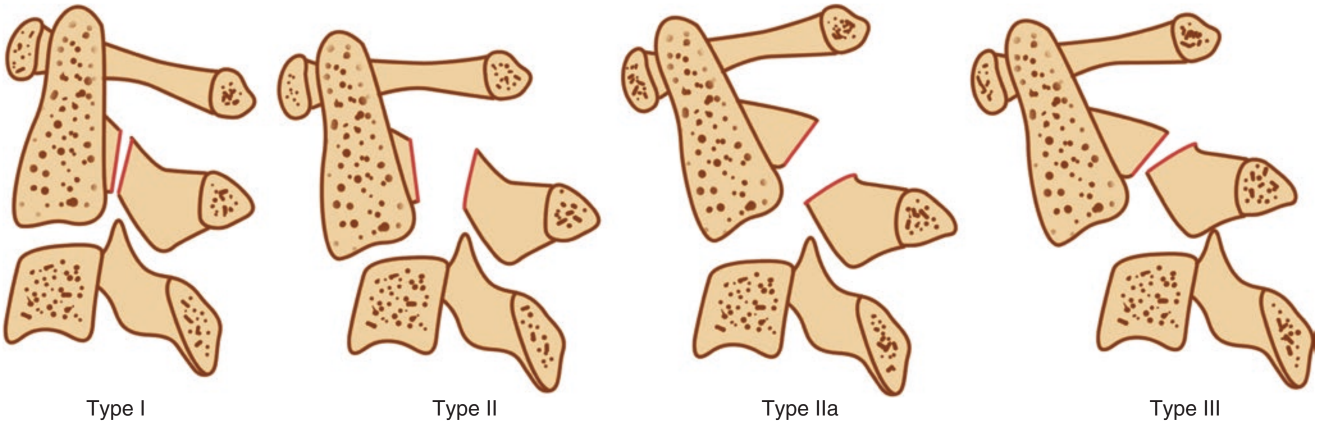


Fig. 1.8 Classification of traumatic spondylolisthesis of the axis

Table 1.2 Classification and severity score of lower cervical spine injury

Characteristics	Points
Injury morphology	
No abnormality	0
Compression	1
Burst	2
Distraction	3
Translation	4
Integrity of the disco-ligamentous complex	
Intact	0
Indeterminate	1
Disrupted	2
Neurological status	
Intact	0
Nerve root injury	1
Complete	2
Incomplete	3
Persistent cord compression	+1

SLIC Subaxial Injury Classification

locking. This type of fracture is highly unstable and often associated with spinal cord damage.

- Classification of lower cervical spine injuries: Lower cervical spine injuries are scored using the SLIC system (Vaccaro et al. 2007) based on the injury severity (Table 1.2).
  - For fractures with an SLIC score < 4, non-surgical treatment is recommended.
  - For fractures with an SLIC score ≥ 5, surgical treatment is recommended.
  - Fractures with an SLIC score of 4 (the cut-off level) can be treated either surgically or non-surgically.

1.1.5 Preoperative Assessment

- Clinical assessment:
  - Spine injuries are often caused by high-energy violence.
  - It is critical to first address the accompanying injuries that might be more life-threatening.
  - It is crucial to ensure airway patency and stability of the circulation system.
  - The consciousness state of the patient is evaluated (usually using the Glasgow scoring scale) (Table 1.3).
- Neurologic injury
  - The force-bearing of the spinal cord at the time of injury and its displacement determine the neurologic outcomes.
  - Neurologic deficits are correlated to but not completely consistent with the decrease in the cross-section area of the spinal canal.
  - Complete spinal cord injury:

    The sensory and motor functions and reflexes below the injured spinal segment are completely lost.

    Patients surviving a complete spinal cord injury of C3 or a higher level also lose most autonomous respiration function and rely on respirators.
  - Classification of incomplete spinal cord injuries (Fig. 1.9).

    Anterior cord syndrome: Patients have motor paralysis but normal deep and proprioceptive sensations.

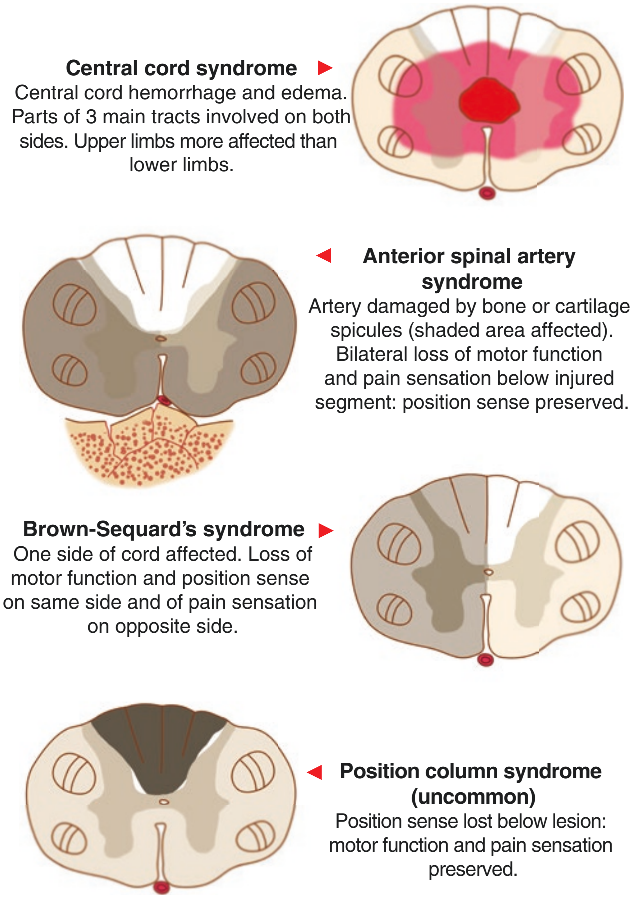
    Posterior cord syndrome: Opposite to anterior spinal cord syndrome, the patients have normal motor function but lose deep and proprioceptive sensation.

    Central cord syndrome: It usually results from damage to the central gray matter and adjacent white matter of the spinal cord and affects the arms more than the legs.

Table 1.3 Glasgow Coma Scale score

Feature	Response
Best eye response	
Open spontaneously	4
Open to verbal communication	3
Open to pain	2
No eye opening	1
Best verbal response	
Orientated	5
Confused	4
Inappropriate words	3
Incomprehensible sounds	2
No verbal response	1
Best motor response	
Obeys commands	6
Localising pain	5
Withdrawal from pain	4
Flexion to pain	3
Extension to pain	2
No motor response	1

Glasgow score criteria is used to evaluate the state of consciousness of patients. Coma caused by severe brain injury is considered when GSC ≤ 8; moderate brain injury is considered when GSC is 9–12; mild brain injury is considered when GSC is 13–15



Central cord syndrome
Central cord hemorrhage and edema. Parts of 3 main tracts involved on both sides. Upper limbs more affected than lower limbs.

Anterior spinal artery syndrome
Artery damaged by bone or cartilage spicules (shaded area affected). Bilateral loss of motor function and pain sensation below injured segment: position sense preserved.

Brown-Sequard's syndrome
One side of cord affected. Loss of motor function and position sense on same side and of pain sensation on opposite side.

Position column syndrome (uncommon)
Position sense lost below lesion: motor function and pain sensation preserved.

Fig. 1.9 Types of incomplete spinal cord injury: central cord syndrome, anterior spinal artery syndrome, Brown-Sequard syndrome, and posterior cord syndrome

    Brown-Sequard syndrome: Movement and position sensation are lost below the level of injury on the injured side. Pain and temperature sensation are lost on the side of the body opposite the injury.

    Anterior spinal artery syndrome: Movement and pain sensation are lost while the position sensation is preserved below the level of the injury.

- Neurologic examination:
  - Sensory function:

    Temperature and touch sensations are examined according to the segmental distribution of the cutaneous nerves.

    The diagnosis can be made by comparing the sensations between the left and right sides of the body, between the upper and lower parts, and between the proximal and distal sides.

    A sensory dermatome body map corresponding to the spinal segments is presented in Fig. 1.10.
  - Motor function:

    The motor function of both the upper and lower extremities is examined, including testing the strength of the muscle groups and comparing the left and right sides.

    The corresponding relationship between the common movements of the upper and lower extremities and the spinal segments is demonstrated in Fig. 1.11.
  - Reflex tests (Fig. 1.12).
- The American Spinal Injury Association (ASIA) scoring scale (Maynard Jr et al. 1997): Imaging assessment
- Radiographs:
  - Cervical AP and lateral radiography.
  - Lateral radiography:

    A sufficient lateral radiograph includes the area from the basis cranii to the T1 vertebra. For patients who have a short neck, the lower cervical spine can be included in the film by pulling the upper arm downwards. Complete overlapping of the joints and mandibular condyles between the left and right sides indicates that the lateral film is taken from an appropriate angle.

    The alignment of all cervical vertebrae is observed to determine whether the following lines are smooth: anterior vertebral body line, posterior vertebral body line, spinous process-vertebral lamina line, and spinous process line. The continuity loss

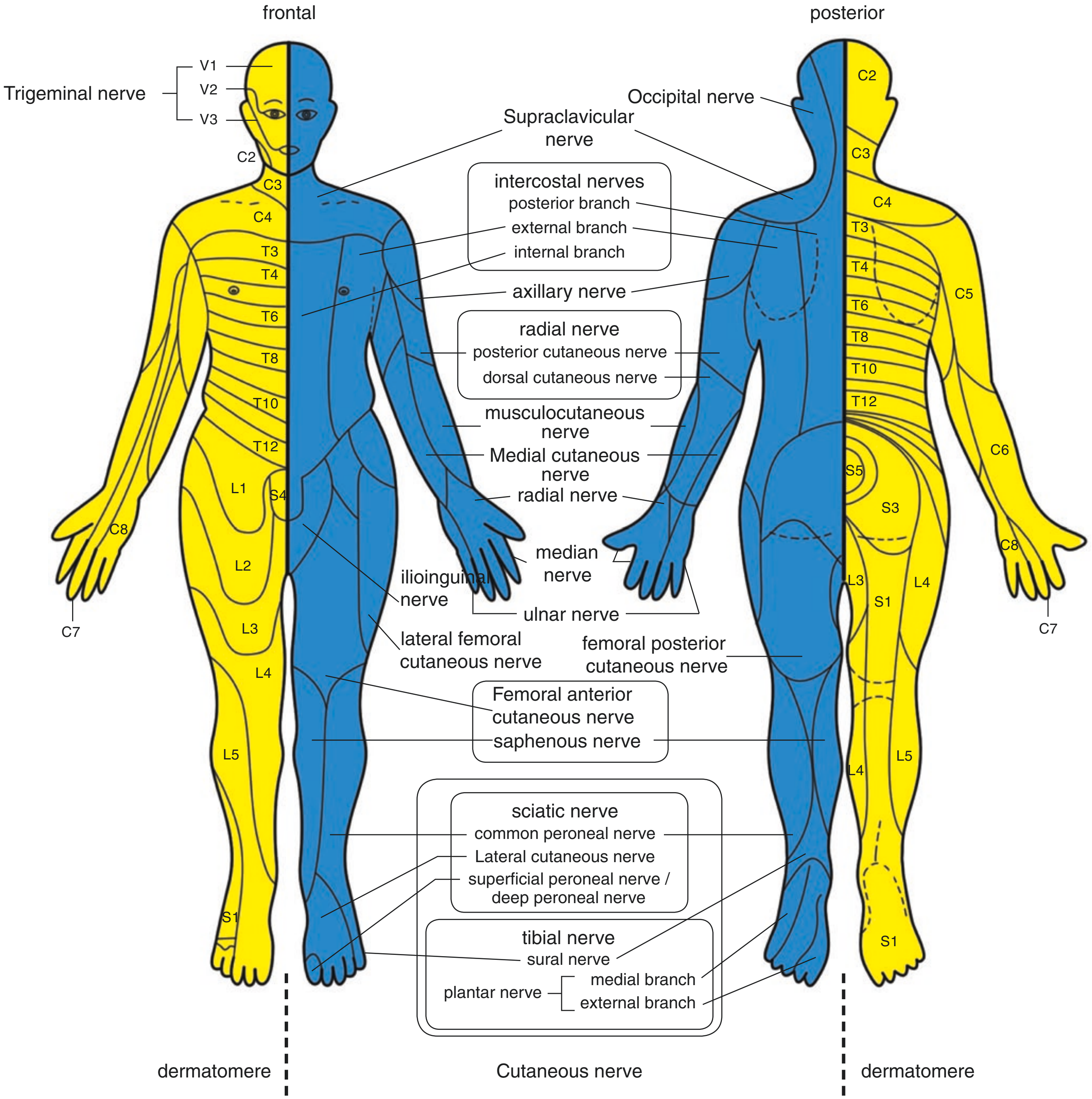


Fig. 1.10 A sensory dermatome body map corresponding to the spinal segments: The commonly used levels include the T4-nipple, T6-the xiphoid process, T10-navel, and T12-the pubic symphysis

of any of these lines indicates a bone fracture or ligament damage (Bucholz and Court-Brown 2010).

Assessment of the occipito-atlantal joint: In the lateral view, normally the odontoid process should not posteriorly pass the extending line of the slope of the occipito-atlantal joint, i.e., the Wackenheim line. The normal Power's ratio, which is the ratio of the distance between the anterior edge of the foramen magnum and the posterior arch of the atlas relative to the distance between the anterior arch of the atlas and the posterior edge of the foramen magnum, should be <1 (Bono et al. 2007).

Assessment of the atlantoaxial joint: An important parameter is the space between the atlas and the odontoid process, which is measured as the distance between the posterior edge of the anterior arch of the atlas and the ventral surface of the odontoid pro-

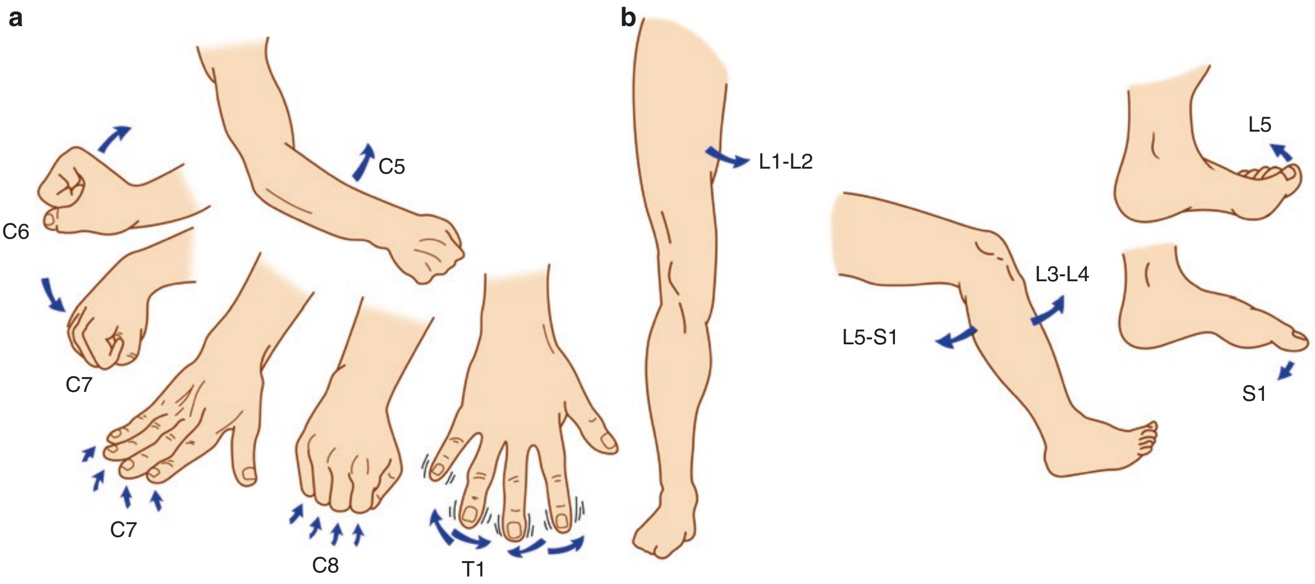


Fig. 1.11 (**a**) The segmental relationship of the spinal cord to the muscle groups for motor function of the upper extremity: C5 for elbow flexion, C6 for wrist extension, C7 for finger extension, C8 for finger flexion, and T1 for finger abduction. (**b**) The segmental relationship of the spinal cord to the muscle groups for motor function of the upper extremity: L1–L2 for hip abduction, L3–4 for knee extension, L5–S1 for knee flexion, L5 for hallux dorsiflexion, and S1 for hallux plantar flexion

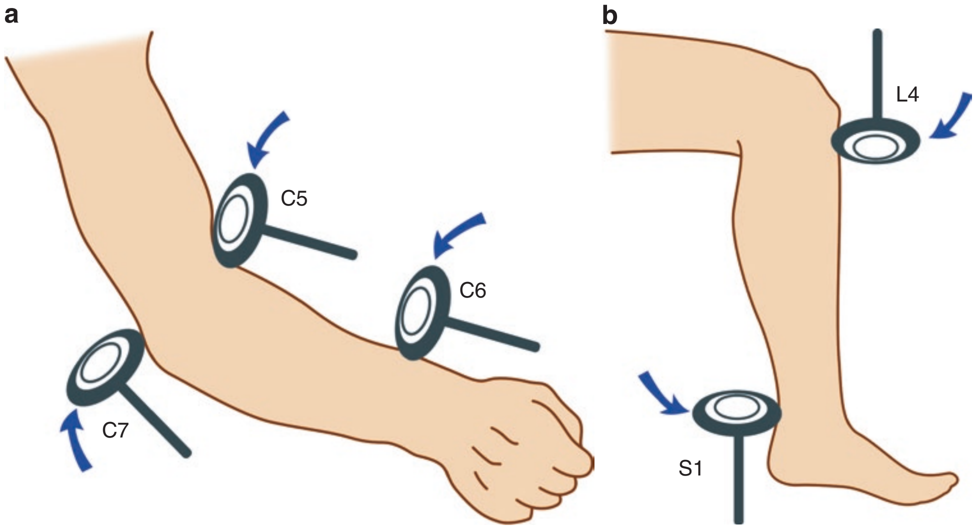


Fig. 1.12 (**a**) The segmental relationship of the spinal cord to the reflexes of the upper extremity: C5 for the biceps reflex, C7 for the triceps reflex, and C6 for the radioperiosteal reflex. (**b**) The segmental relationship of the spinal cord to the reflexes of the lower extremity: L4 for the knee-jerk and S1 for the Achilles tendon reflex

cess. This parameter is normally <3 mm in adults and < 5 mm in adolescents (Bono et al. 2007).

Assessment of the lower cervical spine: The below changes suggest instability of the cervical spine:

- In radiographs obtained in the flexion-extension position, the medial rotation angle is >20° in the sagittal plane.
- In radiographs obtained in the flexion-extension position or neutral position, the displacement of the vertebra is >3.5 mm or 20% of the width of the vertebra in the sagittal plane (White and Panjabi 1990).
- In radiographs obtained in the neutral position, the angle difference (White and Panjabi 1990), which represents the difference in angulation of the vertebral laminae between two adjacent vertebral segments, is >11°.
- In the sagittal plane, the diameter of the spinal canal is <13 mm or the Pavlov ratio (the ratio of the spinal canal diameter to the width of the vertebral body) is <0.8.

An anterior wedge-shaped vertebral compression deformity can cause local kyphosis.

The widening of the inter-spinous-process space suggests a hyperflexion traction injury.

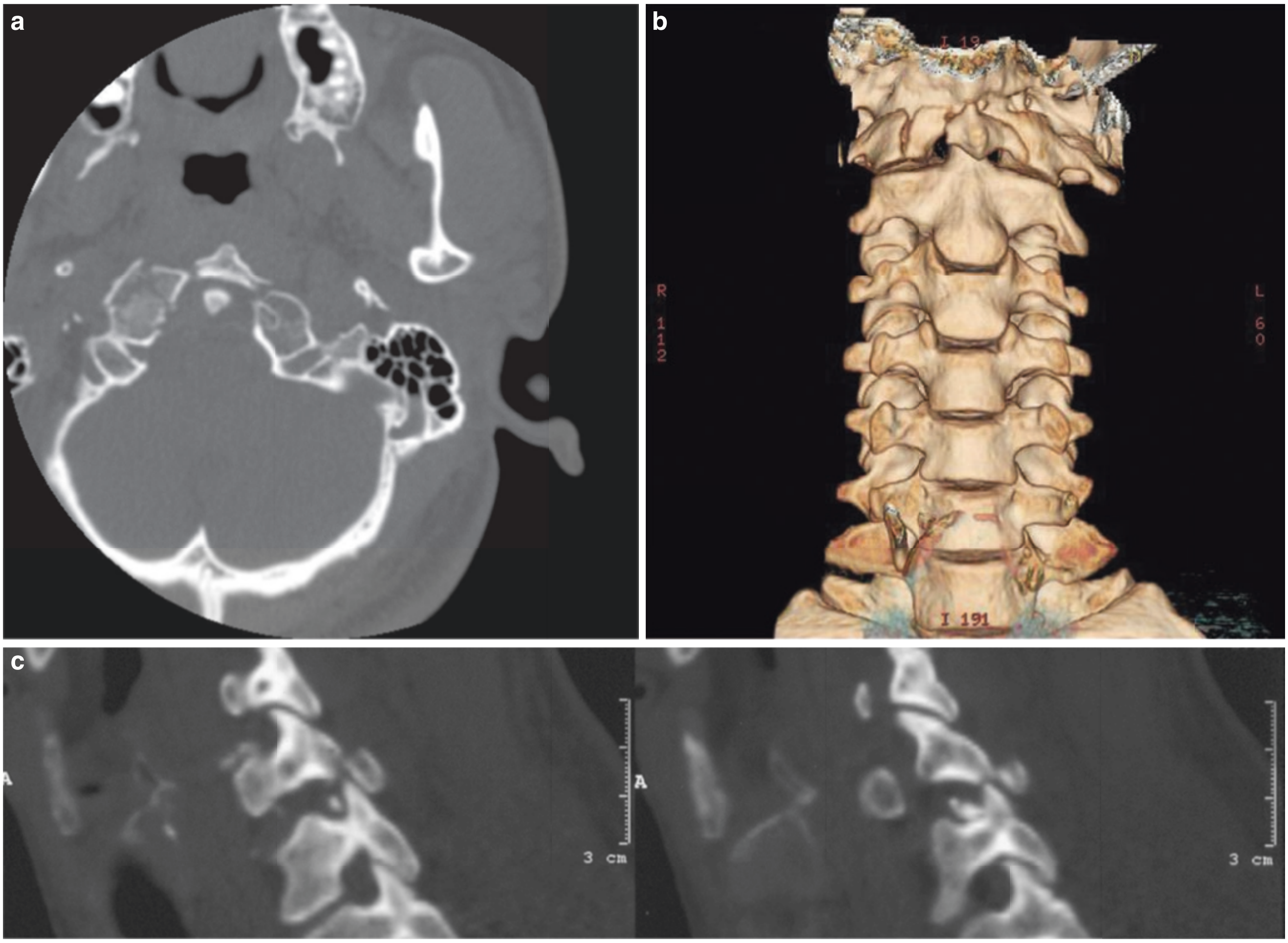


Fig. 1.13 (**a**) Preoperative CT plain scan of a patient with an atlas fracture: The anterior arch of the atlas was fractured at two locations, and the right lateral mass was fractured. (**b**) The 3D reconstructed CT image of the same patient demonstrating the fracture dislocation stereoscopically and comprehensively. (**c**) The CT plain scan and 3D reconstructed image on the joint sagittal plane of another patient with cervical spine fracture and dislocation: joint interlocking can be displayed in detail

    Attention should be paid to observing whether the soft-tissue shadows in the pharyngeal wall are thickened.

  - AP radiography:

    The question of whether the cervical vertebrae have any lateral displacement is addressed.

    The asymmetric shadows of the vertebral pedicles between two sides suggest a rotational dislocation.

    The widening of the shadow of a vertebral pedicle suggests burst of the vertebral body.

    Attention should be paid to observing whether there is a transverse process fracture.

  - Open-mouth radiography:

    It helps examine fractures of the atlas and axis.

- CT (Daffner 2001) (Fig. 1.13):
  - It can be used to evaluate the bone mass damage in detail in multiple planes and sections.
  - The structure at the junction of cervical and thoracic spine can be more clearly demonstrated.
  - Axial CT scans can be used to evaluate the severity of the space-occupying effect of intra-canal fragments in a burst fracture.
  - The sagittal reconstruction helps evaluate the damage to neural elements within the spinal canal caused by a vertebral dislocation.
  - It serves as the best technique for evaluating the vertebral pedicle, vertebral lamina, articular process, and transverse process.
- Magnetic resonance imaging (Katzberg et al. 1999) (MRI):
  - It can be used to precisely evaluate soft-tissue damage.
  - In the acute stage, the increased signal intensity of the spinal cord on T2-weighted images suggests spinal cord edema and hemorrhage.

  - The ligaments are presented by low-intensity signals on T2-weighted images, and a disruption of the signals suggests ligament rupture.
  - Acute intervertebral disc herniation is indicated by an increased signal intensity on T2-weighted images.

1.2 Surgical Treatment

1.2.1 Treatment Goals

- In patients with nerve compression, spinal cord decompression is performed to facilitate recovery of the damaged nerve.
- The displaced vertebra is returned to the normal position, and its alignment is well maintained.
- The spine is well secured, which allows the patient to stand up or sit up as early as possible and avoid being bedridden for a long duration.
- The severity of the deformity at the late stage can be reduced.
- Fewer vertebral segments need to be fused.
- Adverse events can be avoided as much as possible.

1.2.2 Surgical Indications

1.2.2.1 Atlas Fractures

- Patients with Type I, Type II, and Type III fractures primarily undergo conservative treatments of wearing a rigid neck support or external brace such as a halo vest.
- Type IV Jefferson fractures (Verheggen and Jansen 1998)
  - A fracture displaced <6.9 mm is fixed with a halo-vest brace for 3–4 months until it heals.
  - A fracture displaced >6.9 mm should first be reduced by cranial traction until it primarily heals and then immobilized by wearing a halo-vest brace.
  - For a fracture accompanied by spinal cord compression or an atlas-dens interval (ADI) >3.5 mm after healing, the C1 lateral mass screw technique via the posterior approach can be used, or even occipitocervical arthrodesis can be considered if necessary.

1.2.2.2 Odontoid Fractures (Greene et al. 1997; Kontautas et al. 2005)

- Type I fractures are stable and require only fixation with a neck support.
- Type II fractures are difficult to heal.
  - In elderly patients who can tolerant surgery, atlantoaxial arthrodesis via a posterior approach is performed at the early stage.
  - For young patients:

    A non-displaced fracture is fixed with a halo-vest brace for 6–12 weeks.

    Surgical treatment is recommended for displaced fractures.

    - Except for patients with a short neck, kyphosis of the upper thoracic spine, or barrel chest, the fracture can be fixed with odontoid screws via an anterior neck approach.
    - The fracture can be fixed with Magerl screws via a posterior approach, followed by posterior atlantoaxial arthrodesis.
- Type III fractures have a high healing rate, which can be reduced through traction and then immobilized by wearing a halo-vest brace or rigid neck support.

Traumatic Spondylolisthesis of the Axis (Hangman's Fracture) (Vaccaro et al. 2002; Coric et al. 1996)

- For most patients, the fracture can be treated with immobilization by wearing a halo-vest brace or rigid neck support for 6–12 weeks.
- Type II fractures associated with severe angulation and type III fractures associated with C2–3 intervertebral disc rupture or facet joint dislocation can be treated with anterior C2–3 arthrodesis, posterior C1–3 arthrodesis, or C2 pedicle screw fixation.

Lower Cervical Spine Injuries

- The severity of a lower cervical spine injury is scored using the SLIC system (Dvorak et al. 2007; Patel et al. 2010).
  - An injury score < 4 can be treated with immobilization by wearing a halo-vest brace or rigid neck support for 6–12 weeks.
  - For an injury score ≥ 5, surgical treatment is recommended.
  - For an injury score of 4 (a cutoff score), either surgical or non-surgical treatment can be considered.
  - Compression/burst injuries are usually treated via a simple anterior approach.
  - Injuries with a lateral/rotational displacement are usually treated via the posterior or combined anterior and posterior approach.

1.2.3 Surgical Techniques

1.2.3.1 Halo Brace Fixation (Boullosa et al. 2004; Mihara et al. 2001)

- Installation of the halo ring:
  - A halo brace should be installed under the condition that the neck support is well secured.
  - The size of the halo ring is selected to allow a 1-cm distance between the ring and skin of the patient.

  - The safe zone for anterior skull pin placement is 1 cm above and at the junction between the lateral and middle thirds of the ridge of the orbit, which is below the level of the maximal circumference of the skull and higher than the ears. The positions for of two posterior skull pins are roughly opposite to the two anterior pins. After the local skin is disinfected, the pins are placed under local anesthesia.
  - The patient is instructed to close his or her eyes and relax the facial muscles.
  - After all four pins are installed, they are gradually tightened in sequence until the ring is secured onto the skull.
- Vest installation:
  - The neck must be stabilized during installation of the vest.
  - The vest and connecting rods are installed.
- Adjustment of the rods:
  - The four rods are adjusted to ensure that the left and right sides are symmetric and the flexion and extension angles of the neck are appropriate.
  - The purpose of adjustment is to restore the normal alignment of cervical vertebrae and make the patient more comfortable without affecting the visual field and swallowing function.
  - After adjustment, all nuts are tightened, and then the neck support is removed.
- Follow-up and examination:
  - After the halo brace is installed, radiographs are obtained in the sitting position to ensure the positioning of the cervical spine.
  - Radiography and CT scanning should subsequently be regularly performed to monitor the healing of the fracture (Fig. 1.14).

1.2.3.2 Anterior Screw Fixation for Odontoid Fractures

- Body position and preoperative preparation:
  - The patient receives general anesthesia through nasotracheal intubation.
  - The patient lies supine and undergoes Mayfield head holder or halo traction for reduction of the displaced fracture.
  - Anatomical reduction must be achieved prior to internal fixation with a cannulated screw system.
  - The vertical distance between the lower mandible and sternum should be adequate. Before surgery, a Kirschner wire is placed on the side of the neck to test whether the manubrium would obstruct the screw placement. The position of the patient is adjusted to meet the requirement.
  - Screw placement should be performed under C-arm-aided AP and lateral radiography (Fig. 1.15).
- Operative incision according to the projection on the body surface: The Cloward incision at the C5 level (Fig. 1.16).
- Surgical approaches (Fig. 1.17):
  - After the subcutaneous tissue is fully dissociated, the platysma muscle is cut in the muscular fiber direction along the anteromedial edge of the sternocleidomastoid muscle.
  - The sternocleidomastoid muscle is pulled aside laterally, and then the thyroid is pulled medially along with the midline structure. After the carotid artery is identified by palpation, the pretracheal fascia is incised from the medial side of the carotid sheath. If necessary, the superior and inferior thyroid arteries can be ligated on one side.
  - After the tissue is further separated towards the pretracheal fascia until a white shiny structure is observed, the anterior longitudinal ligament, on the midline structure is exposed. An 8-mm-wide Hohmann hook is placed along the C2 lateral mass, and then the anterior longitudinal ligament is cut along the midline at the level of the C2–3 intervertebral disc. Through subperiosteal dissection, the anterior longitudinal ligament and longus colli muscle are dissociated and pulled aside, followed by tissue separation along the front surface of the spine up to the inferoanterior edge of the C2 vertebral body.
- Fracture reduction and fixation:
  - The entry point at the inferoanterior C2 vertebra is determined radiographically. Subsequently, under protection of the sleeve, two 1.25-mm Kirschner wires with the length of 200 mm are placed towards the posterior side of the odontoid tip on the sagittal plane inclining medially by 5° towards the midline on the coronal plane (Fig. 1.18).
  - Both AP and lateral radiographs are obtained to confirm that the Kirschner wires penetrate the cortex of the odontoid process along the correct direction.
  - After the depth measurements, a countersink drill is used to open the bone cortex at the lower edge of the C2 vertebra. The bone mass of the upper edge of the C3 vertebra is filed or nibbled out to an appropriate extent to avoid obstruction of the screw placement.
  - Under radiographic monitoring, two 3.5-mm self-tapping cannulated lag screws are screwed in place along the guide wires until they reach the cortex on the opposite side (Fig. 1.19). It is important to ensure that the guide wires are not bent and that the cannulated screwdriver is not obstructed. In addition, the guide wires must not be screwed in along with the cannulated

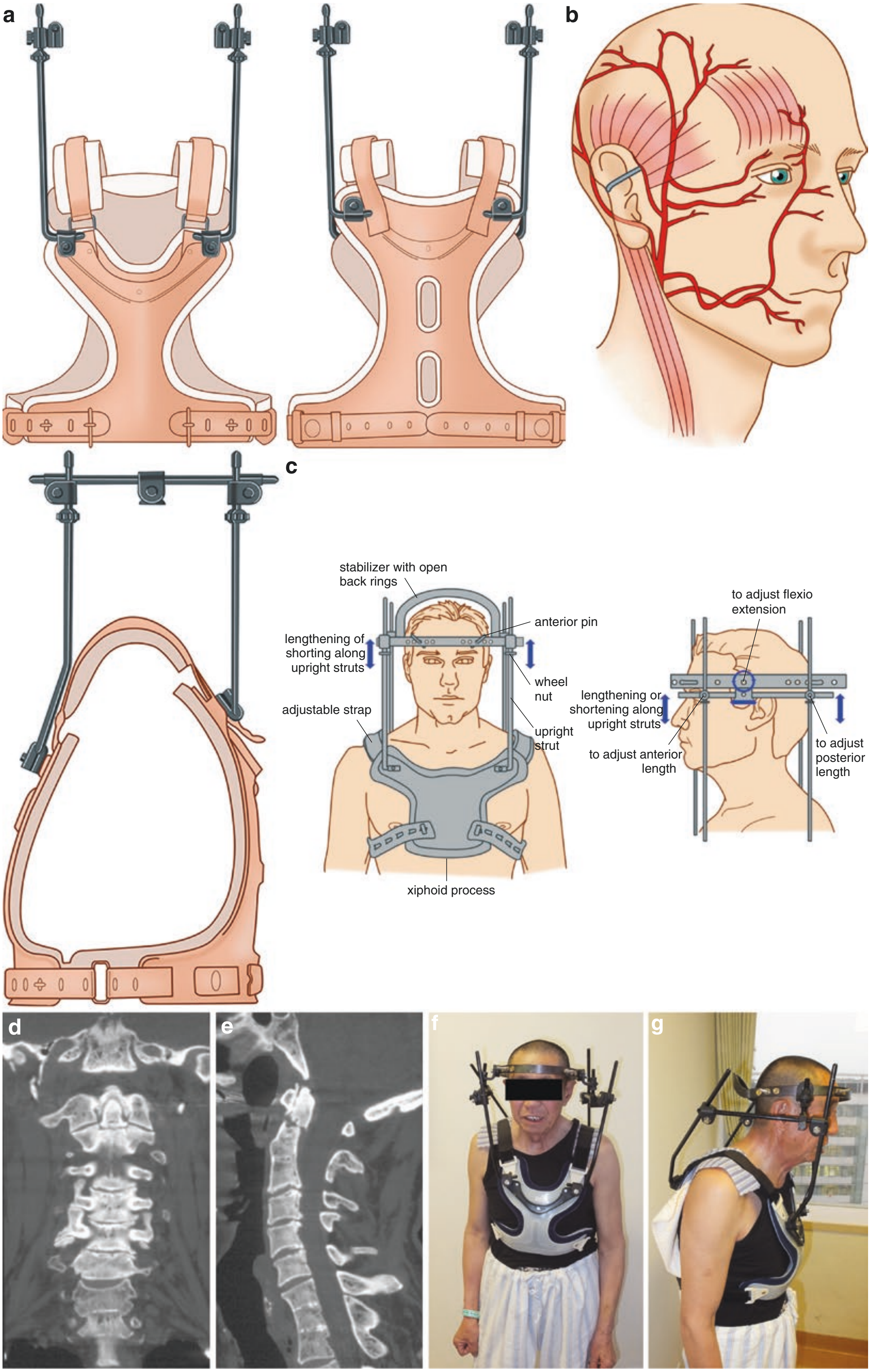


Fig. 1.14 (**a**) Structure of a halo brace: The halo brace consists of three parts: the vest, halo ring, and connecting rod. (**b**) The safe zone for anterior skull pin placement is 1 cm above and at the junction between the lateral and middle thirds of the ridge of the orbit, which is below the level of the maximal circumference of the skull and higher than the ears. (**c**) Schematic diagrams showing how to wear a halo brace: Neck flexion and extension can be controlled by adjusting the positions of the halo ring and connecting rods. (**d**–**g**) A patient with an Anderson type II odontoid fracture of the axis: (**d**, **e**) Coronally and sagittally reconstructed CT plain scans: The base of the odontoid process was fractured without obvious displacement. (**f**, **g**) AP and lateral photos of the patient wearing a halo brace

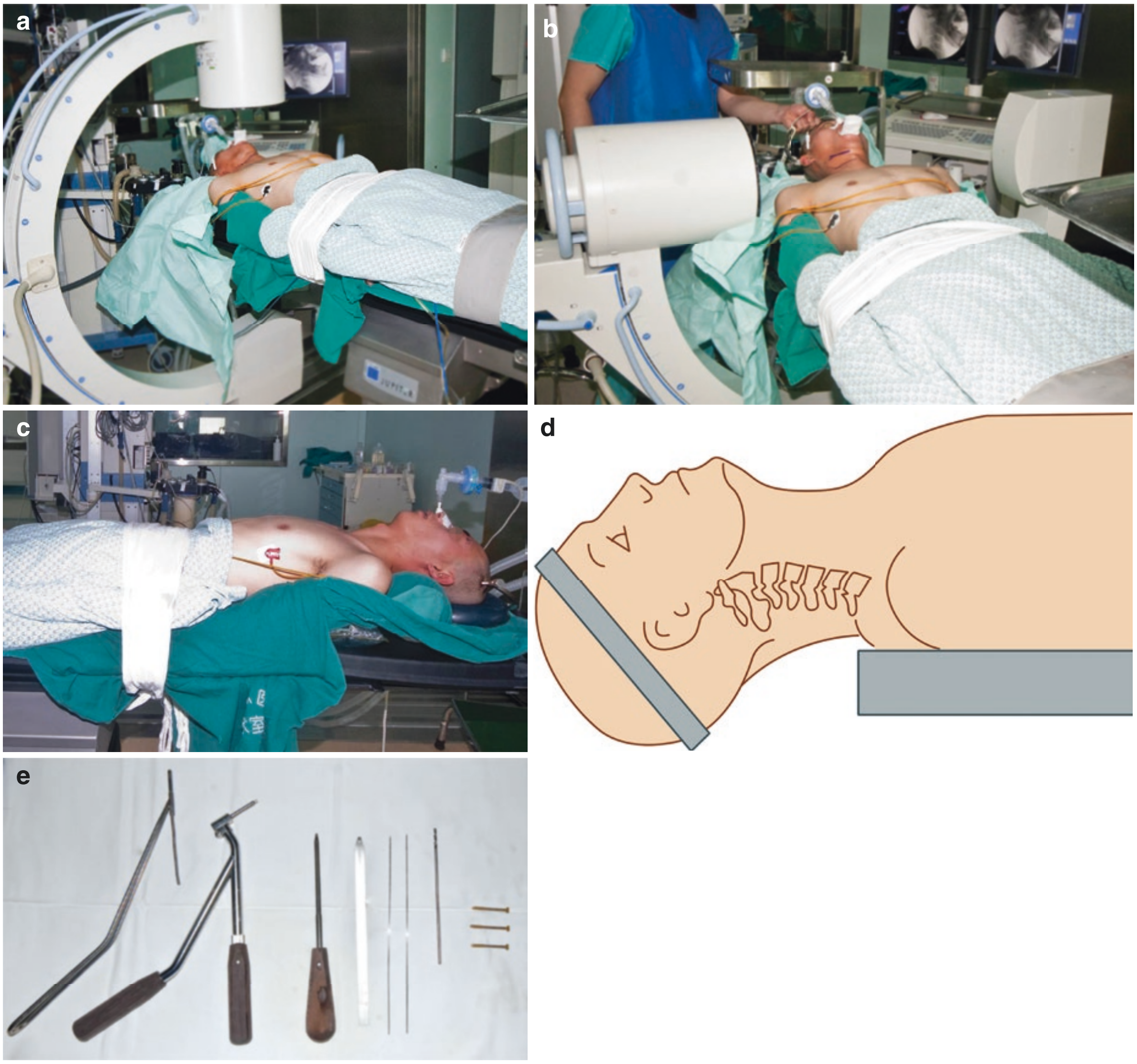


Fig. 1.15 (**a**, **b**) Body position of the patient and positioning of the C-arm device for AP and lateral fluoroscopy during surgery. (**c**, **d**) The patient lies supine with the head tilted backward. Before surgery, a Kirschner wire placed beside the neck is used as a reference for body position adjustment to ensure sufficient posterior extension of the neck under fluoroscopic monitoring, which would prevent the sternal manubrium from obstructing the guide wire placement. (**e**) Special tools and materials used for surgery (the guide wires have been trimmed)

Fig. 1.16 At the C5 level, an incision with a length of 6–7 cm is created along the direction of the dermatoglyphic pattern on one side (usually the right side if the surgeon is right-handed)

screws; otherwise, the damage to the medulla oblongata may cause sudden cardiac and respiratory arrest.

- Incision closure: The surgical field is cleansed, and the incision is sutured layer by layer after placing a drainage tube.
- Postoperative management:
  - The patient is kept in the ICU for 24 h after surgery. Special attention is paid to the presence of difficult breathing caused by hematoma formation and laryngeal edema in the acute stage.
  - The patient wears a neck support for 6 weeks after surgery, particularly those with a superoposterior-to-inferoanterior fracture or osteoporotic patients.
  - Follow-up examinations are performed, and radiographs are obtained to monitor the healing progress (Fig. 1.20).

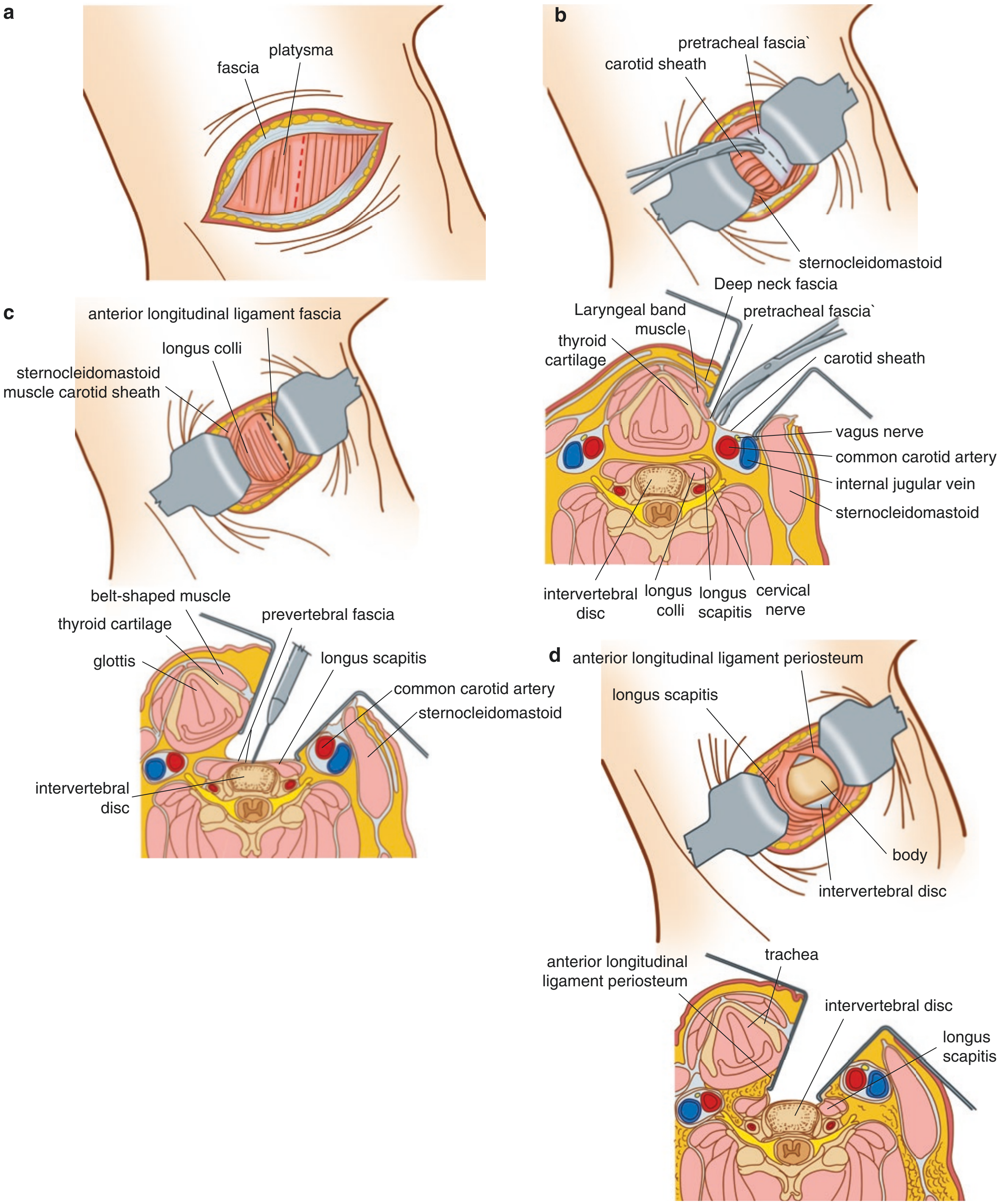


Fig. 1.17 (**a**) The skin, subcutaneous tissue, and platysma muscle are incised. The dotted line denotes the incision direction along the muscle fibers in the platysma. (**b**) The pretracheal fascia is incised from the medial side of the carotid sheath. (**c**) After the anterior longitudinal ligament and the cervical longus muscle of the anterior vertebral body are exposed, the anterior longitudinal ligament is incised horizontally at the level of the C2–3 intervertebral discs. (**d**) The anterior longitudinal ligament and the cervical longus muscle are incised to expose the inferoanterior edge of the C2 vertebral body. The superoanterior edge of C3 vertebral body should be nibbled out with a rongeur to avoid obstruction of the screw placement

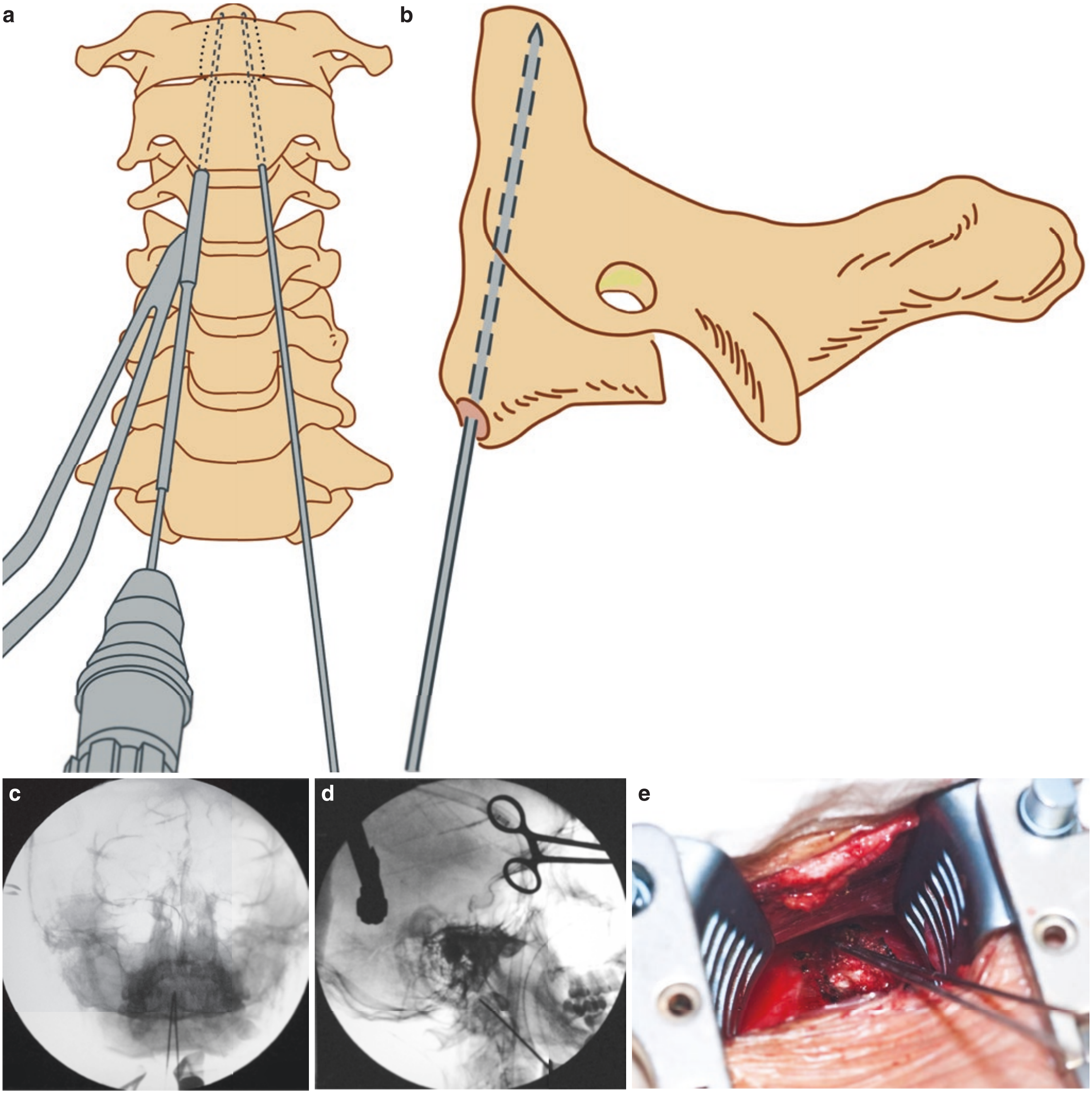


Fig. 1.18 Placement of guide wires for cannulated screw insertion. (**a**) AP view: Two guide wires are placed at a convergence angle of 5°. (**b**) Lateral view: The two guide wires should be placed from the inferoanterior edge of the C2 vertebral body to the superoposterior edge of the odontoid process. (**c**, **d**) Intraoperative fluoroscopy for examination of the guide wire positions. (**e**) An intraoperative photo showing the entry points and convergence angle of the two guide wires

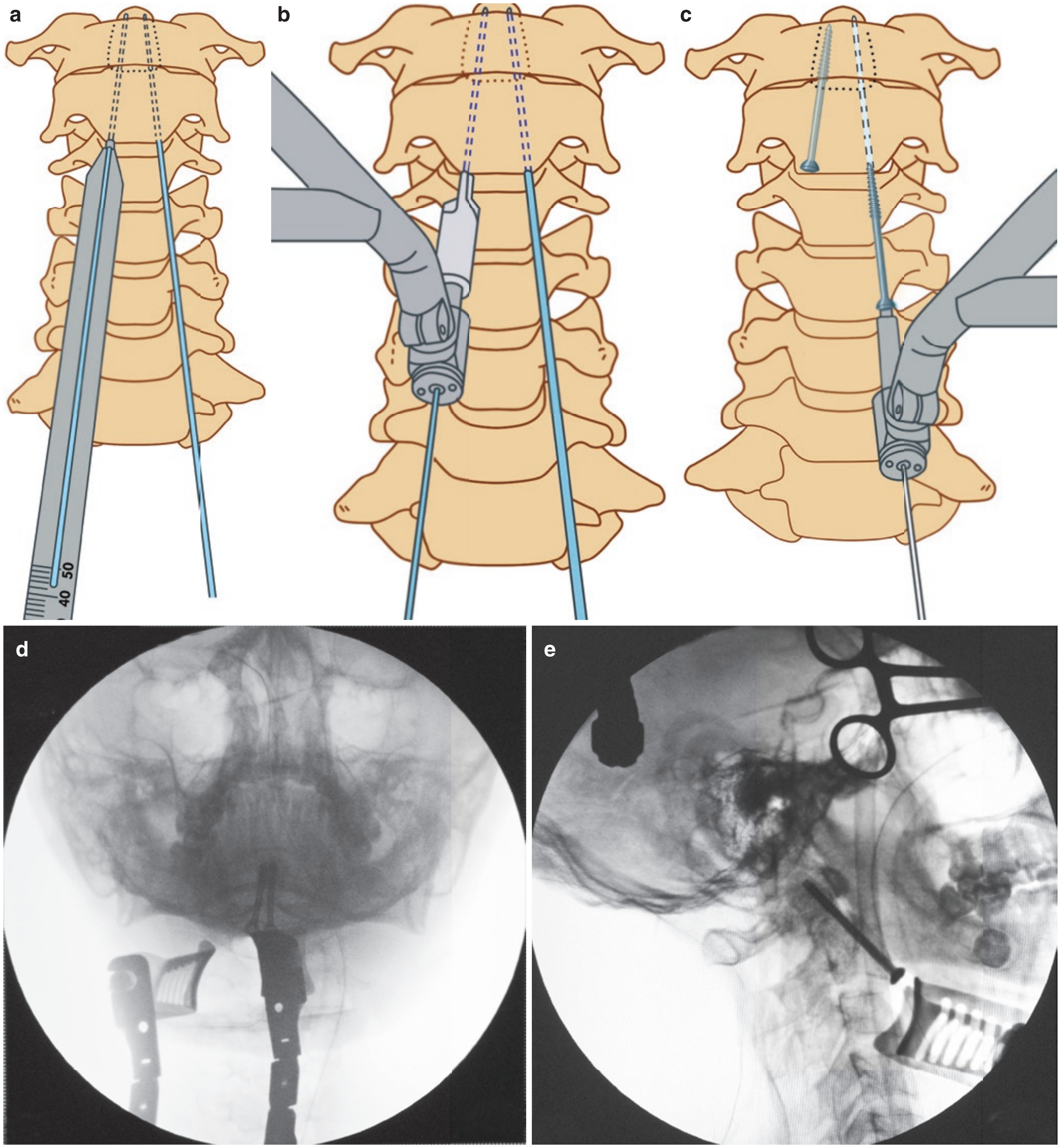


Fig. 1.19 (**a**) Depth measurement with a caliper. (**b**) The lower edge of the C2 vertebral body is opened using a countersunk drill. (**c**) The cannulated screws are screwed along the guide wire sequentially. (**d**, **e**) Under AP and lateral radiographic monitoring, two 3.5 mm self-tapping cannulated screws are screwed in place along the guide wires

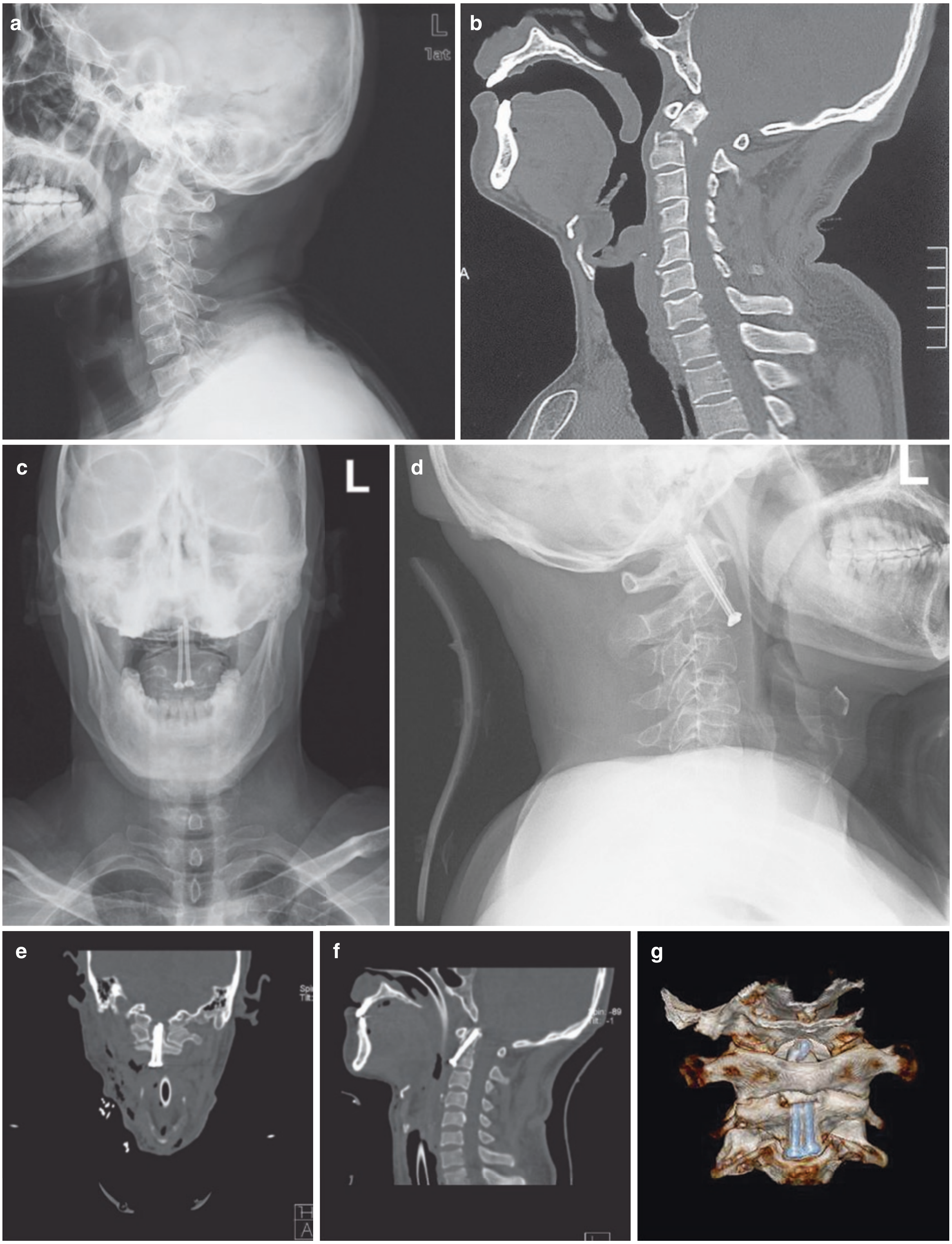


Fig. 1.20 Internal fixation with a cannulated screw for an odontoid process fracture (**a**) A preoperative lateral radiograph: The odontoid process was fractured, and the atlas was dislocated posteriorly. (**b**) Preoperative sagittally reconstructed CT plain scans: There was a transverse fracture at the base of the odontoid process, which belonged to an Anderson type II fracture. (**c**, **d**) Radiographs at the open-mouth and lateral positions after anterior screw fixation of the odontoid process fracture. (**e**) Postoperative reconstructed CT plain scan at the coronal plane of the screws: The screws in the odontoid process had a convergence angle of approximately 5° and reached the cortex on the opposite side. (**f**) Postoperative sagittally reconstructed CT plain scan: The screws were placed along the inferoanterior edge of the second vertebrae body and pointed to the edge of the superoposterior cortex of the odontoid process. (**g**) Postoperative 3D reconstructed CT image: The positional relationship between the reduced fracture and screws was stereoscopically displayed

1.2.3.3 Posterior C1 Lateral Mass Screw and C2 Pedicle Screw Fixation (Bransford et al. 2011)

- Body position and preoperative preparation:
  - Nasotracheal intubation is performed for general anesthesia.
  - The patient lies prone, with the head secured by a Mayfield skull clamp, and the clamp is attached to a Mayfield holder that is connected to the operating table.
  - The C-arm system and/or adjuvant CT scanning system are prepared for reduction quality examination of C1 and C2 during surgery (Fig. 1.21).
- Operative incision according to the projection on the body surface: A posterior neck midline incision with a length of 6–10 cm is created downwards along the external occipital protuberance (Fig. 1.22).
- Surgical approaches:
  - The fascia and nuchal ligament are dissected layer by layer from the posterior midline along the skin incision to expose the C1 posterior tubercle and C2 spinous process.
  - The paravertebral muscle is stripped off subperiosteally using a Cobb stripper. When stripping the area near the atlanto-occipital membrane between the atlas and the occipital bone, special attention should be paid to avoid mis-entering the spinal canal.
  - The C2 lateral mass is exposed with protection of the C2–C3 joint capsule.
  - When creating an access to the C2 isthmus and the C1–C2 joint capsule above, bleeding in the area near the venous plexus around the C2 nerve, which often occurs and is significant, can be controlled by bipolar electrocoagulation or the use of a gelatin sponge.

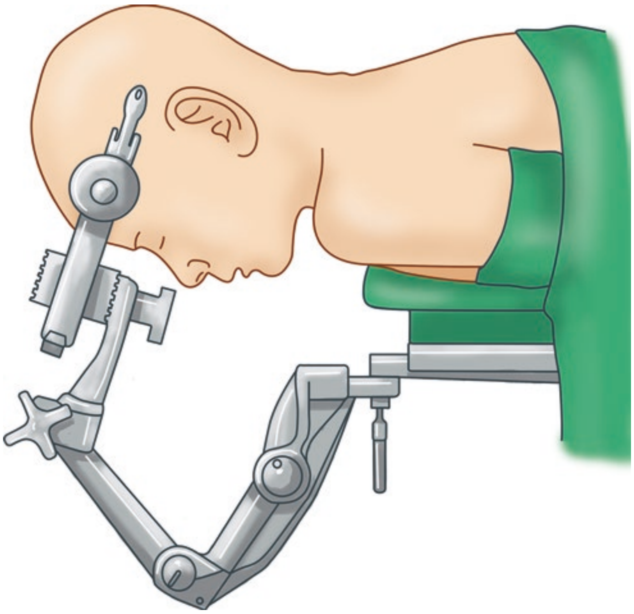


Fig. 1.21 The patient lies prone, with the head secured by a Mayfield skull clamp. The clamp is attached to a Mayfield holder that is connected to the operating table, which maintains the neck in a neutral position. Intraoperative positioning is performed with the aid of the C-arm or CT device

- Fracture reduction and fixation.
  - Because the entry point of the C1 lateral mass screw is above the venous plexus around the C2 nerve, the exposure operation often ruptures the venous plexus and causes bleeding. Therefore, it is recommended that the C2 pedicle screw be placed first.
  - C2 pedicle screw placement (Fig. 1.23):

    The first step is determining the entry points, which are the midpoints of the connecting lines of the superior and inferior articular facets that intersect the perpendicular line passing the center of the C2 articular process.

    The ligamentum flavum is pushed aside using a nerve stripper to expose the medial wall of the C2 vertebral pedicle. The needle entry direction is determined.

    A 2.5-mm drill bit is used to drill a path in an upward 20° inclination angle and a convergence angle of 20°–30° with the medial surface of the C2 vertebral pedicle as a landmark reference.

    An awl is used to open the cortex, and then a hand drill is used to create a path for screw placement.

    The integrity of the wall and end of the path is examined using a ball-tipped probe.

    After depth measurement, a screw with the desired length is screwed in place.
  - C1 lateral mass screw placement (Fig. 1.24).

    The C2 dorsal root ganglion is pushed towards the caudal side to expose the entry point of the C1 lateral mass screw, which is below the C1 vertebral lamina and above the C1/2 joint gap.

    After using a gelatin sponge to stop the bleeding from the venous plexus, a 2.5-mm hand drill is used to drill a hole along the direction medially inclined by 10° and upwardly inclined by 10–20° until both cortical layers are penetrated.

    The integrity of the wall and end of the channel is examined using a ball-tipped probe.

    After depth measurement, a 3.5-mm tapper is used for tapping.

    A multiaxial screw with the desired length is placed.
  - The length of the connection rod is measured and adjusted for further fracture reduction and compression or screw distraction, followed by nut locking.
  - The position of the internal fixator is confirmed by CT or the C-arm system during surgery.

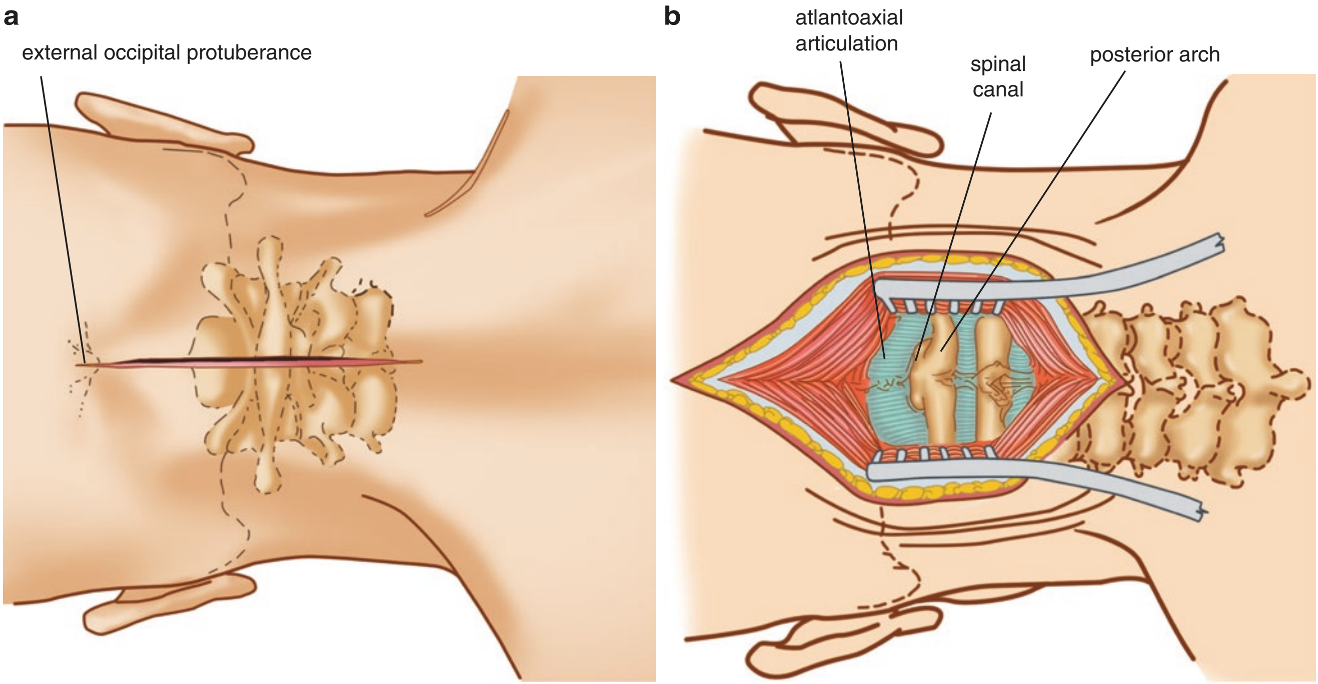


Fig. 1.22 (**a**) A posterior neck midline incision is generated downwards along the external occipital protuberance. (**b**) Tissue separation is performed layer by layer along the midline incision to expose C1–C2

- Incision closure: The surgical wound is cleansed and then sutured layer by layer after placing a drainage tube.
- Postoperative management: The patient is kept in the ICU for postoperative recovery. After 6 weeks of postoperative immobilization with a neck support device, radiographs are obtained to evaluate stability; if the position of the screw is questionable, CT scans should be obtained for confirmation (Fig. 1.25).

1.2.3.4 Posterior C3–C6 Lateral Mass Screw Fixation

- Body position and preoperative preparation:
  - The patient is given general anesthesia and endotracheal intubation.
  - The patient lies prone, with the head secured to the operating table by a Mayfield head holder.
  - To clarify the lateral view of the lower cervical spine under radiography, the arms and elbows of the patient are placed to closely contact the torso, and the shoulders are pulled downwards using rubber bands.
  - C-arm radiography is performed during surgery.
- Incision according to the projection on the body surface: A straight incision is created along the midline of the posterior neck from the center of the affected segment to the protrusion at the level of C7 (Fig. 1.26).
- Surgical approaches:
  - The fascia and nuchal ligament are dissected layer by layer until the spinous process along the midline of the posterior neck.
  - Closely along the periosteum, the deep muscles are stripped off from the spinous process to the lateral edge of the articular process using an electric knife.
  - The C3–C6 lateral masses are exposed with protection of the inferior joint capsule (Fig. 1.27).
- Fracture reduction and fixation:
  - Single-door vertebral laminar decompression and laminoplasty (Fig. 1.28):

    The spinous process should be removed with a bone rongeur; otherwise, the vertebral lamina might lose its “open” state and the muscles on the sides “close the door” after the incision is closed.

    A bone slot is generated at the border between the vertebral lamina and lateral mass on each side. On one side, a high-speed burr drill is first advanced downwards to grind the vertebral lamina and then towards the medial side to grind and remove the outer cortical layer, cancellous bone, and inner cortical layer.

    On the opposite side, a bone slot is created at the same site with only the outer cortical layer and cancellous bone being ground off, while the inner cortical layer is preserved as the “hinge” for “door opening.”

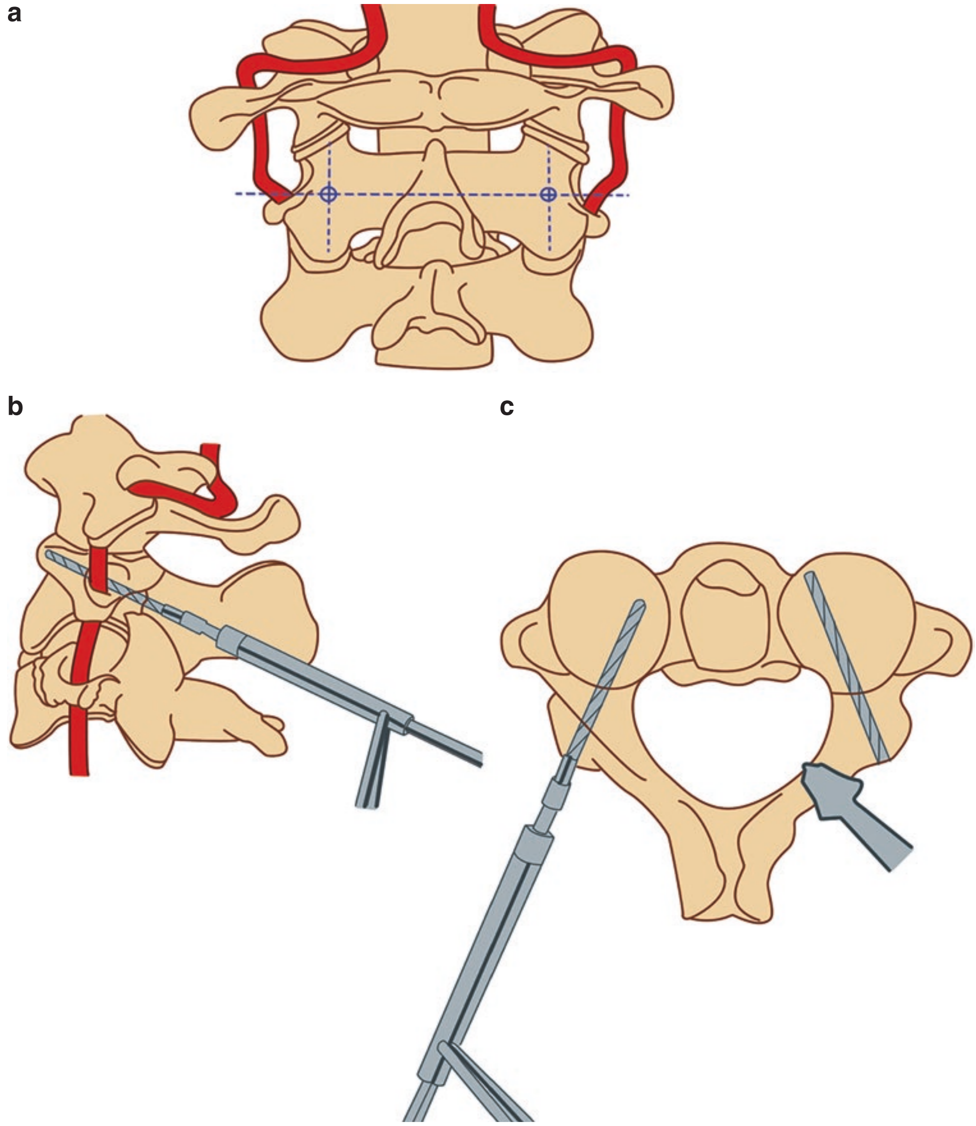


Fig. 1.23 (**a**) The entry points of the C2 pedicle screws. (**b**) The entry direction of the needle should be inclined to the head side by 20°. (**c**) The entry direction of the needle is inclined medially by 20–30°

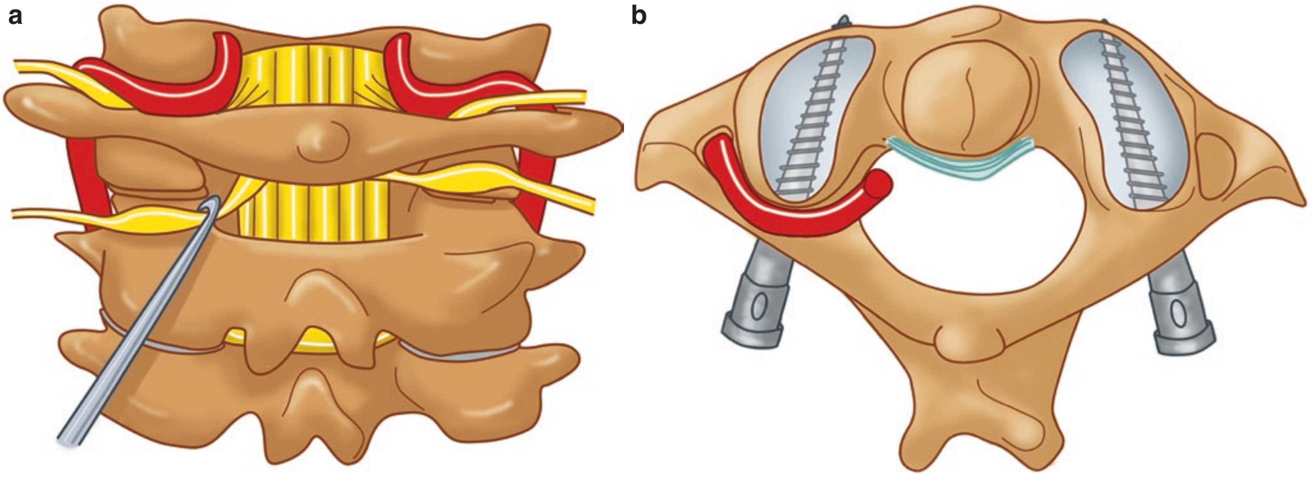


Fig. 1.24 (**a**) The entry point of a C1 lateral mass screw is located below the C1 vertebral lamina and above the C1/2 joint gap. The dorsal root ganglion located herein is gently pulled aside by a nerve stripper to expose the needle entry point. (**b**) Cross-section view: The C1 lateral mass screw should penetrate two cortical layers

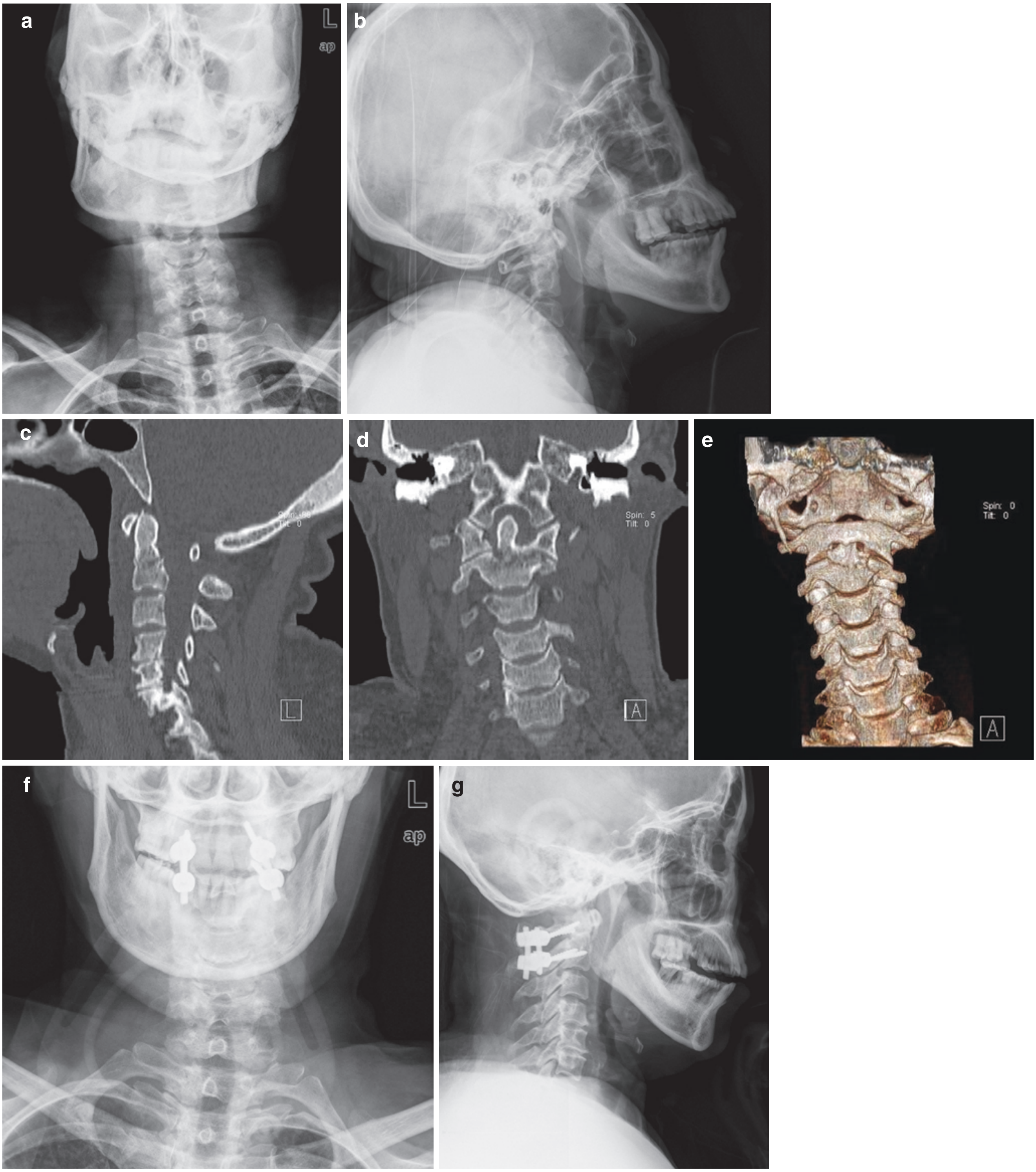


Fig. 1.25 An Anderson type III odontoid process fracture of the axis associated with a lateral mass fracture of the axis. (**a**, **b**) Preoperative AP and lateral radiographs: The atlas was dislocated anteriorly. (**c**) Sagittally reconstructed CT scan: The fracture of the odontoid process extended to the vertebral body. (**d**) Coronally reconstructed CT scan showing a fracture of the left lateral mass of the axis. (**e**) The 3D reconstructed CT scan of the fracture. (**f**, **g**) AP and lateral radiographs obtained after C1 lateral mass screw fixation and C2 pedicle screw fixation combined with atlantoaxial fusion via the posterior approach

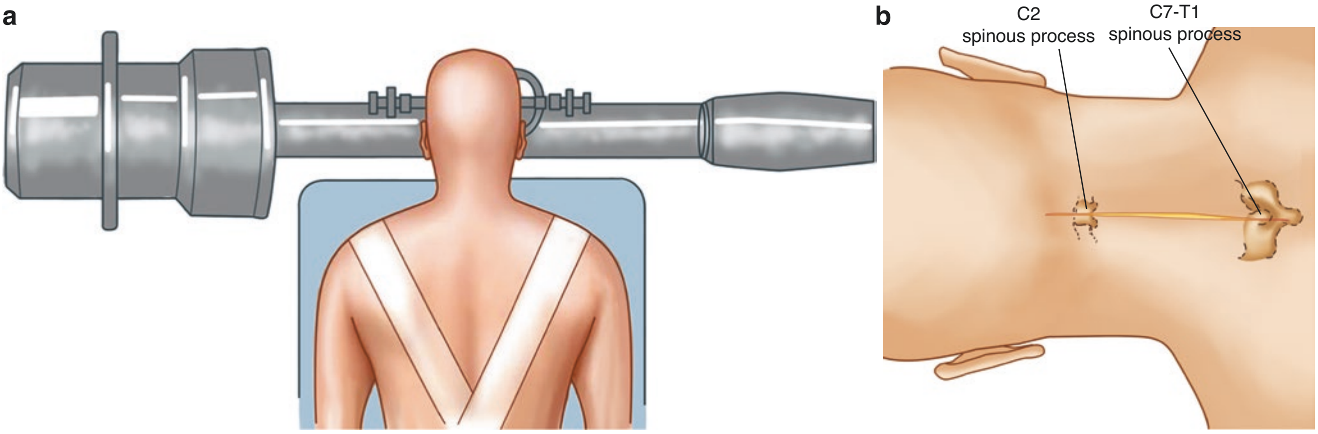


Fig. 1.26 (**a**) The patient lies prone, with the head secured to the operating table by a Mayfield head holder. The head holder is attached to the operating table to maintain the neck in the neutral position. Intraoperative positioning was performed with the aid of the C-arm or CT device. (**b**) The posterior neck midline incision was created up to the C7 protuberance

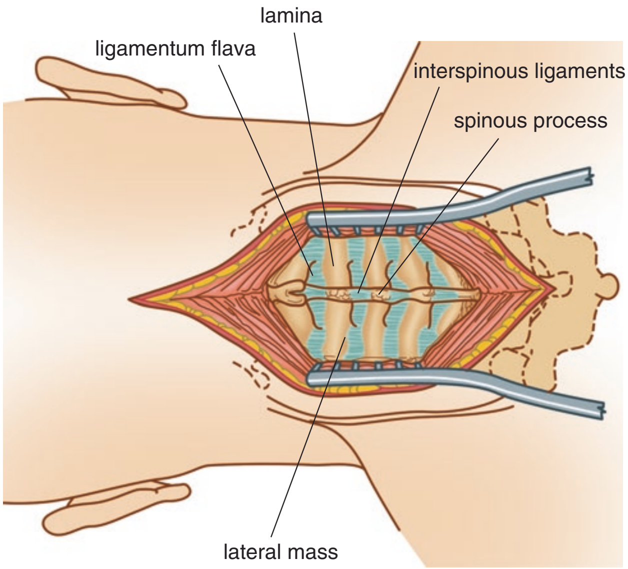


Fig. 1.27 A neck midline incision for exposure of the C3–C6 lateral masses

The ligamentum flavum above and below the area around the decompression "door" is dissociated, and then the vertebral lamina is lifted up with the nerve stripper front the caudal side to the head side.

The epidural veins are coagulated with a bipolar electrocoagulator.

The door can be kept open using a hand surgery miniature plate, inserting and fixing the spinous process fragment in the door, or pulling with a titanium cable.

- C3–C6 lateral mass screw placement:

  According to the Magerl technique, the entry point is 2 mm medial to the center of the lateral mass, and the entry direction is inclined laterally by 20–25° and inclined to the head side by 20–40° (parallel to the space between the articular facets of the articular process) (Fig. 1.29).

  The cortex at the planned entry point is opened with an awl, and then a vertebral pedicle probe is inserted along the entry direction up to the anterior edge of the bone cortex on the opposite side.

  After depth measurement, a 3.5-mm tapper is used to tap the proximal bone cortex.

  The multiaxial screw is placed into each of the C3–C6 lateral masses (Fig. 1.30) following the same procedure.
- Based on the measurement result, a rod is trimmed to an appropriate length and pre-bent.
- The rod is placed and used for compression (or expansion) for reduction, followed by nut tightening.
- A transverse connecting bar is placed if needed (Fig. 1.31).
- The positions of all internal fixators are re-confirmed radiographically during surgery (Fig. 1.32).

- Incision closure: The surgical field is cleansed, and the incision is sutured layer by layer after placing a drainage tube.
- Postoperative management: Postoperative management is performed based on the surgical scope and preoperative condition of the patient. The patient is under routine postoperative monitoring. At 48 h following surgery, the drainage tube is removed if the drainage volume meets the requirement. The patient wears a neck support for 6 weeks. In addition, attention is paid to the presence of wound infection.

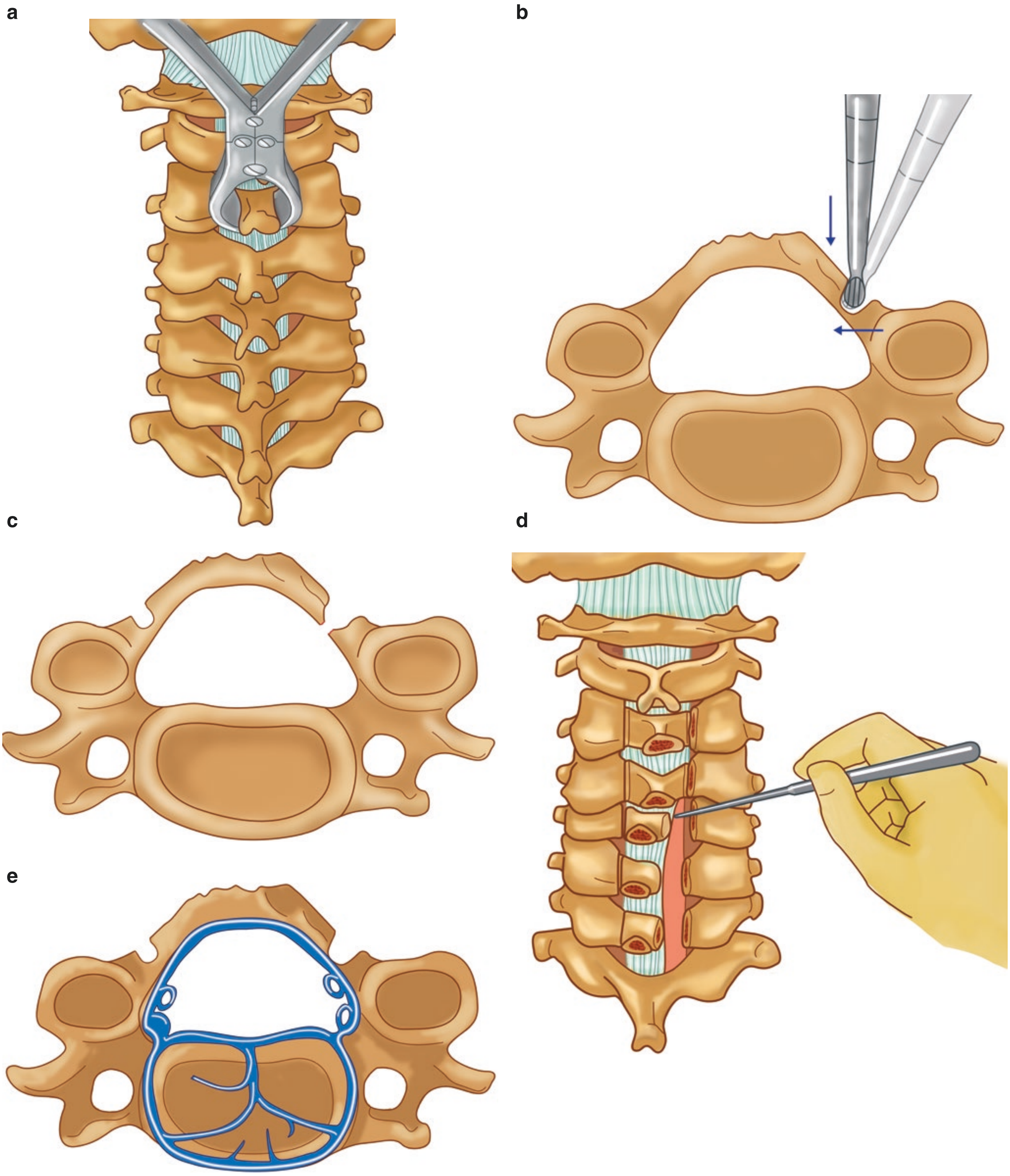


Fig. 1.28 Single-door vertebral laminar decompression and laminoplasty of the cervical spine. (**a**) The spinous process of the decompression segment is nibbled off with a bone rongeur. (**b**) The junction of the vertebral lamina and the lateral mass is ground with a burr drill, first downwards and then inwards under intra-canal space-occupying protection, to remove the outer cortical layer, cancellous bone, and inner cortical layer. (**c**) On the contralateral side, only the outer cortical layer and cancellous bone are ground off, and the inner cortical layer is preserved. (**d**) The vertebral lamina is gradually lifted up from the caudal side with a nerve stripper. (**e**) The bleeding from the epidural veins should be coagulated using bipolar electrocoagulation

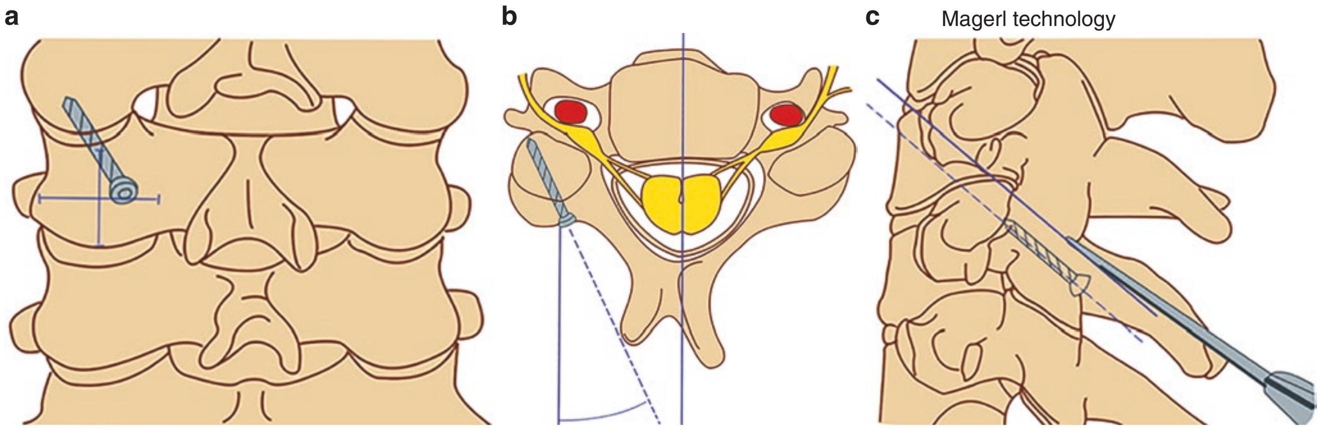


Fig. 1.29 Entry point and direction of lateral mass screws for C3–C6. (**a**) The entry point is located at the site 2 mm medial to the center of the lateral mass. (**b**) The lateral mass screw should be inclined laterally by 20–25°. (**c**) The lateral mass screw should be tilted by 20–40° towards the head side

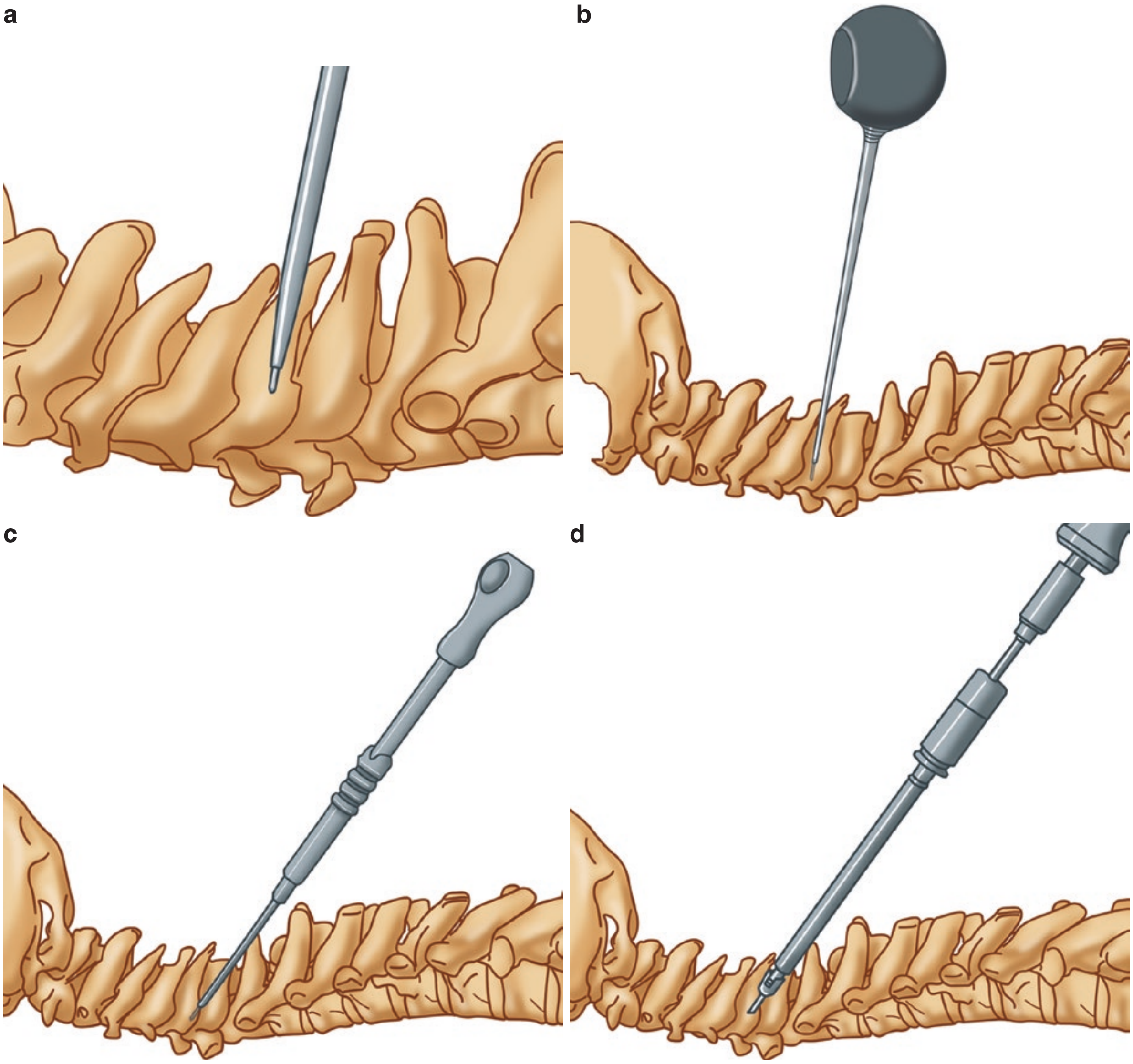


Fig. 1.30 (**a**) The bone cortex at the entry point is opened with an awl. (**b**) The pedicle probe is inserted along the needle direction up to the cortical bone on the opposite side. (**c**) Measurement of the depth. (**d**) A multi-axis screw with the desired depth is placed

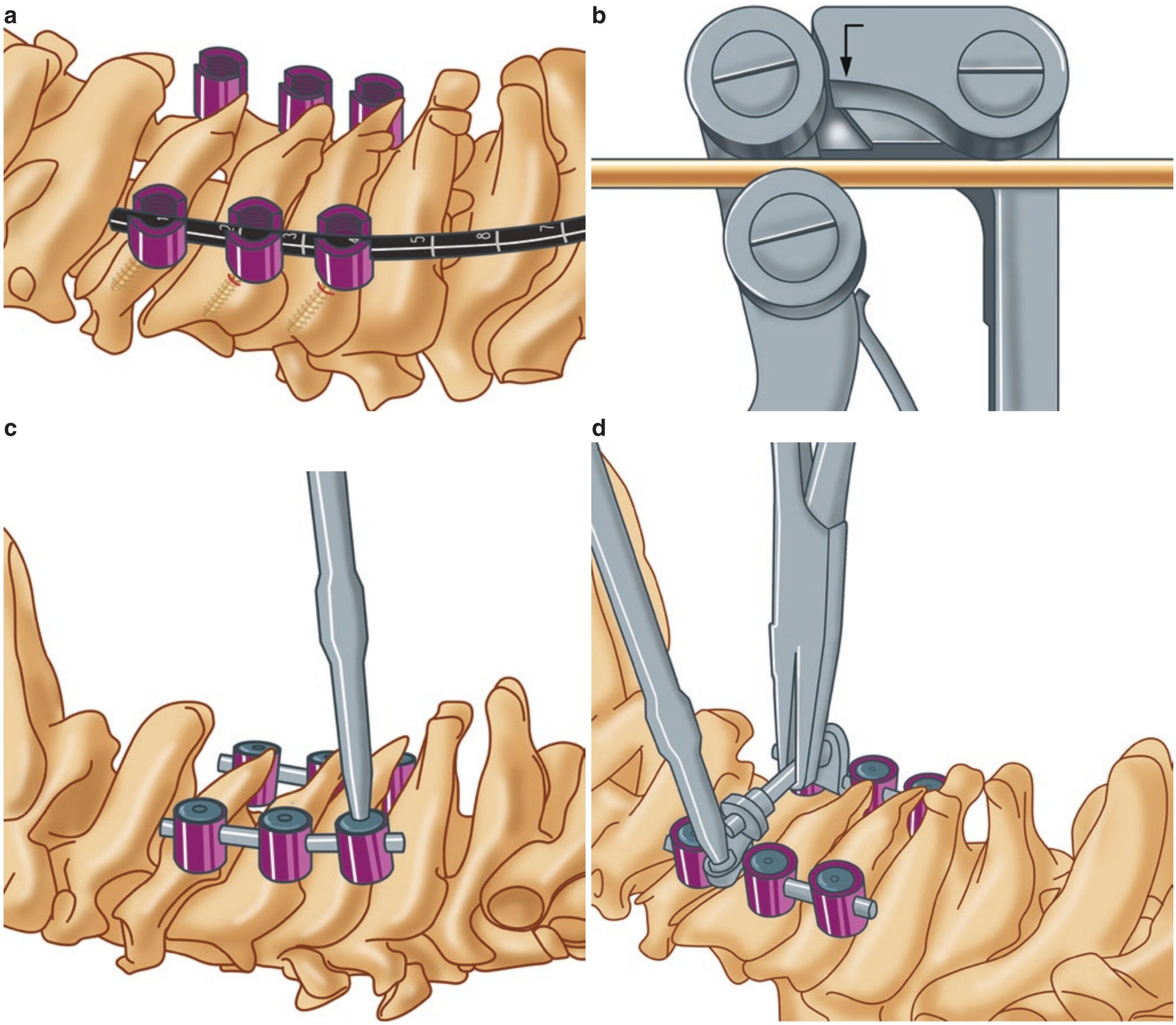


Fig. 1.31 (**a**) The required length of the rod is determined. (**b**) The titanium rod is trimmed to the desired length and pre-bent. (**c**) The multi-axis screw nuts are tightened. (**d**) A transverse connecting bar is placed

1.2.3.5 Posterior Occipitocervical Fusion (OCF)

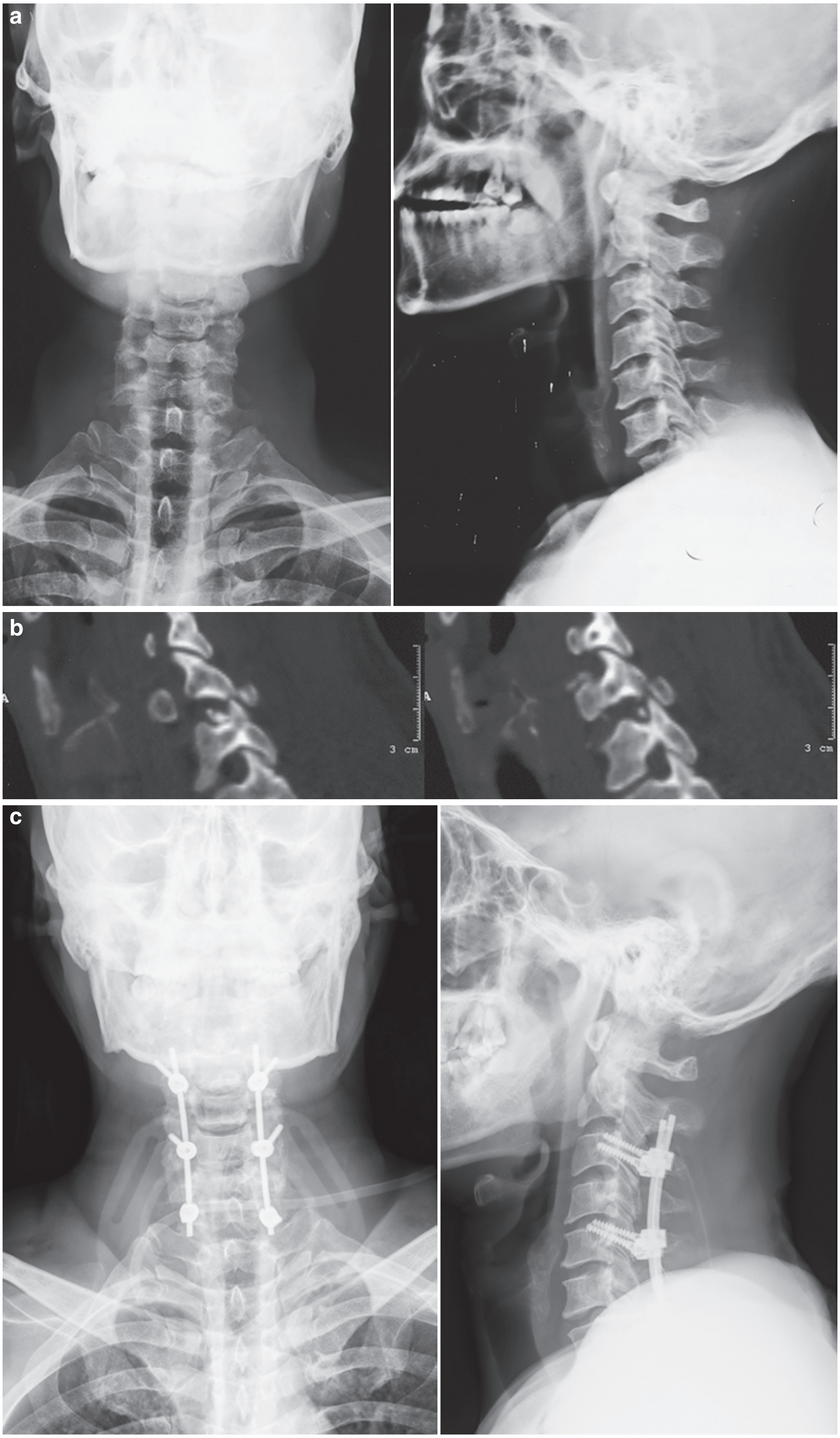
- Body position and preoperative preparation, operative incision according to the projection on the body surface, and surgical approaches are similar to those for C1 lateral mass screw-C2 pedicle screw fixation and posterior C3–C6 lateral mass screw fixation.
- Fracture reduction and fixation:
  - The lateral mass screw and pedicle screw technique for OCF: Please see the relevant description in the preceding part.
  - Skull pin placement (Figs. 1.33 and 1.34):

    The positions of skull pins should be lower than the external occipital protuberance; inner fixators beyond the external occipital protuberance might damage the transverse sinus and cause more extensive soft-tissue injury or a compression injury of the skin over the occipital bone due to excessive protrusion of the inner fixator after surgery.

    The midline area of the posterior occipital bone that is excessively protruding can be trimmed to make the plate contact the plate and bone closer.

    In the view of the interior of the occipital bone, the posterior skull is divided into four quadrants by the internal protuberance of the occipital bone, superior sagittal sinus groove, and transverse sinus groove, and the intersection area has the thickest bone mass and is an ideal site for occipital screw placement.

Fig. 1.32 Cervical spine fracture and dislocation. (**a**) Preoperative AP and lateral radiographs: C6 and C7 are dislocated. (**b**) Reconstructed CT scan on the sagittal plane of the joint: The facet joints are fractured and interlocked. (**c**) After the interlocked joints are unlocked, the lateral mass screw fixations of C3 and C5 and the C7 pedicle screw fixation are performed via the posterior approach



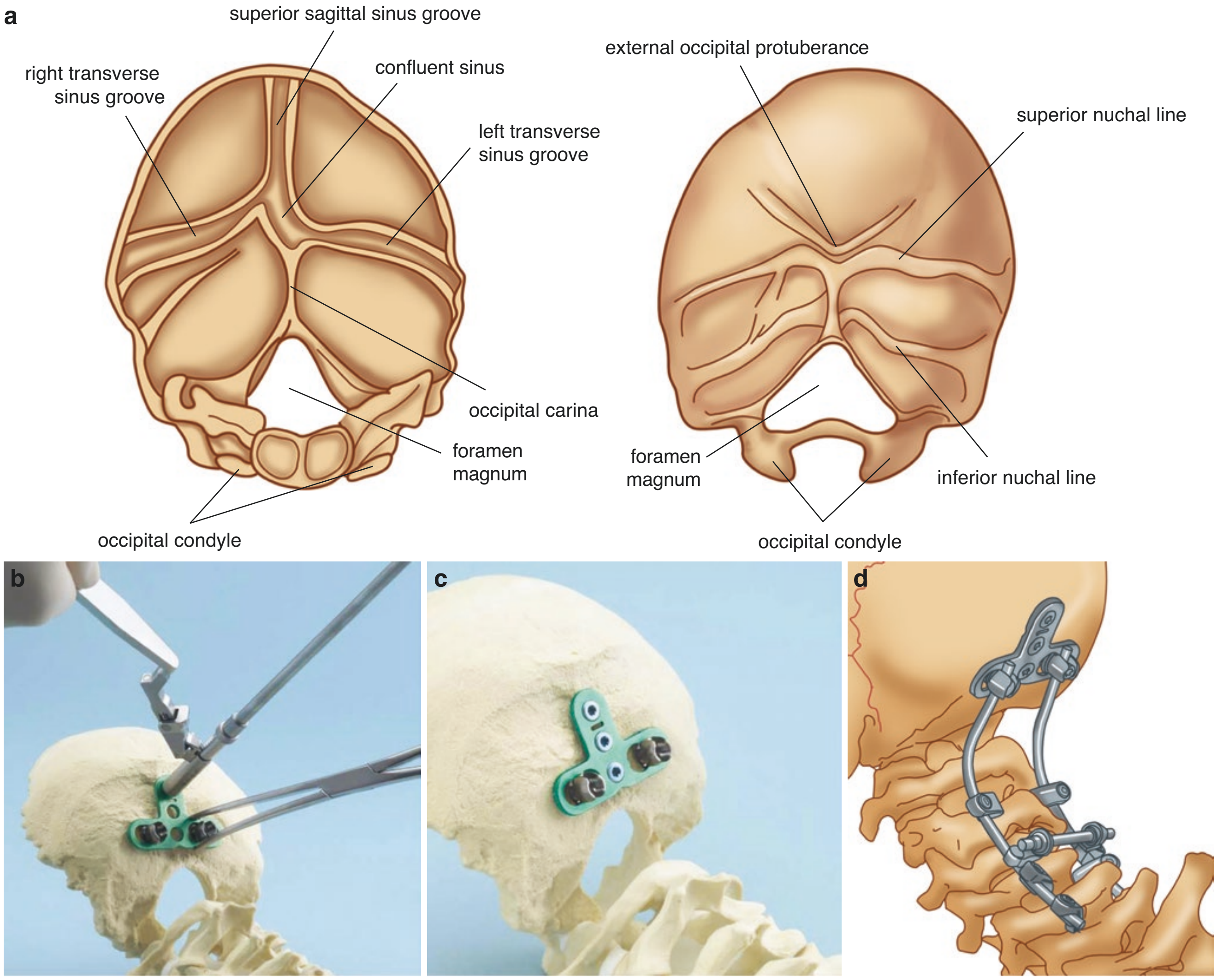


Fig. 1.33 (**a**) Interior and exterior views of the occipital bone: The internal occipital protuberance, superior sagittal sinus groove, and transverse sinus groove divide the inner surface of the occipital bone into four quadrants; the intersection area with the thickest bone is an ideal site for occipital screw placement. The external occipital protuberance is on the outer surface of the occipital bone, below which is an ideal location for steel plate placement. (**b**) An introducer with a depth-limiting mechanism is used to drill the holes, and the drilling starts from a depth of 8 mm and is gradually increased by 2 mm each time to avoid cerebrospinal fluid leakage caused by penetration of the dura mater. (**c**) The steel plate is fixed at a location with thick bone. (**d**) The steel plate is connected to the lateral mass screws, pedicle screws, etc., followed by installation of a transverse connecting rod

A midline screw with a length of 16–20 mm can be placed into the occipital bone, which has a stronger anchorage capacity than the screw placed on the side that reaches a depth of only 8–12 mm (Bransford et al. 2011).

After the plate is pre-shaped, it is placed beneath the external occipital protuberance. Subsequently, an introducer with a depth-limiting mechanism is used to carefully drill holes. The drilling depth starts from 8 mm and is advanced in increments of 2 mm until the desired final depth is achieved, which allows firm double-cortex-layer fixation without complications such as cerebrospinal fluid leakage.

After depth measurement and tapping, the screws with a desired length are screwed in place.

– The cranial plate is connected to the lateral mass screws and pedicle screws; a transverse connecting rod can be considered if necessary.

- The incision is closed following the routine protocol after placement of a drainage tube. The postoperative management is performed as described earlier.

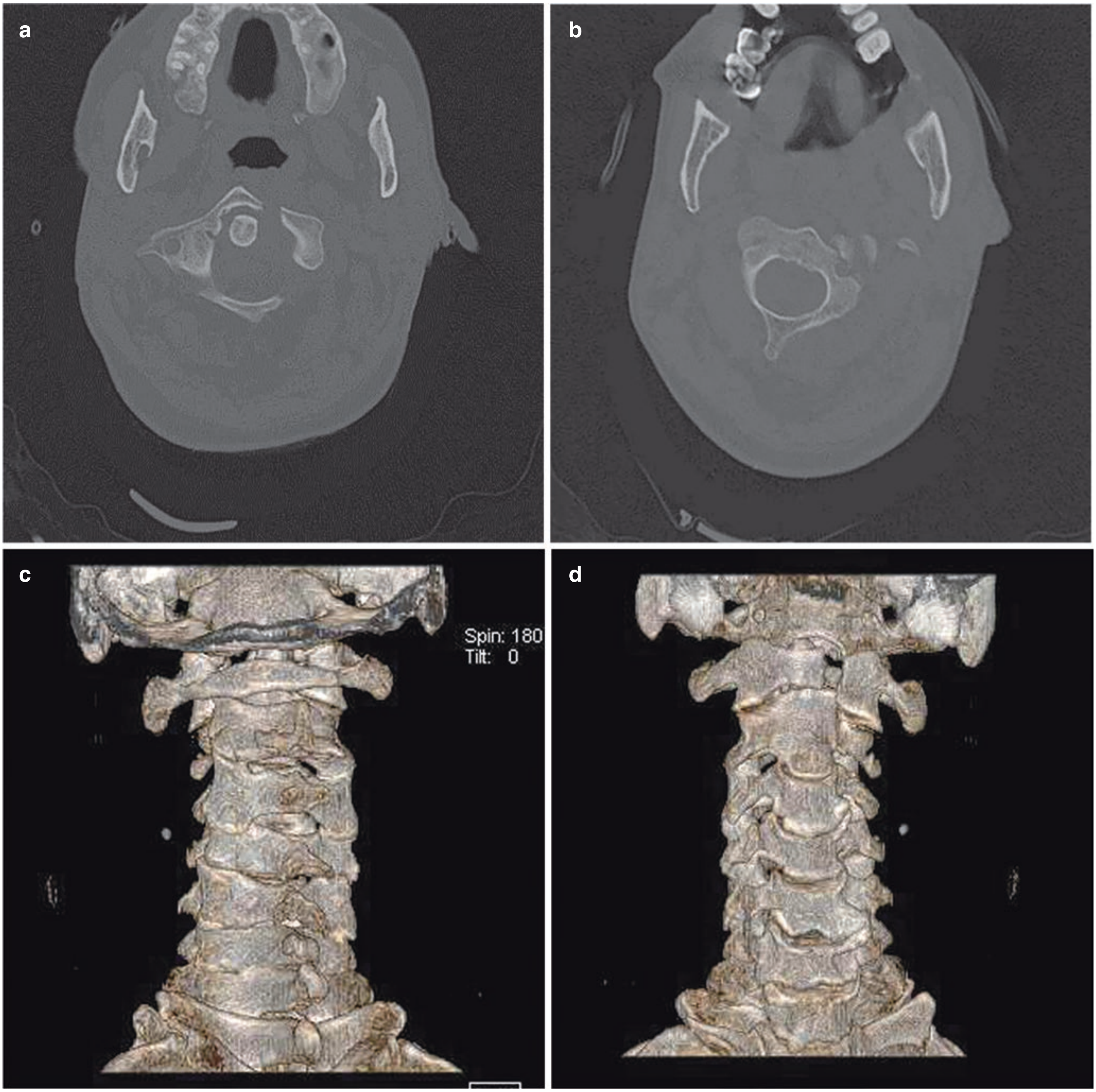


Fig. 1.34 Complex atlantoaxial fractures. (**a**) CT plain scan showing a fracture at the junction between the anterior arch and the left lateral mass of the atlas. (**b**) The left lateral mass of the axis is fractured. (**c**, **d**) Preoperative 3D reconstructed CT scans demonstrating the fractures of the anterior arch of the atlas and the left lateral mass of the axis. (**e**) After the lateral mass screws are placed into C3 and C4 via the posterior approach, cervical occipital fusion is performed

Fig. 1.34 (continued)

1.2.3.6 Anterior Discectomy/Vertebral Arthrodesis and Corpectomy for Decompression with Bone Grafting for Fusion

- Body position and preoperative preparation:
  - The patient undergoes general anesthesia through nasotracheal intubation.
  - The patient lies supine, with the neck posteriorly extended by placing cushions beneath the shoulders.
  - To ease the intraoperative radiography, the arms and hands of the patient are placed to closely contact the torso, and the shoulders are pulled downwards using rubber bands.
  - The head turns slightly towards the opposite side of the incision.
- Operative incision according to the projection on the body surface:
  - Based on the needs for vertebra exposure, an incision is made from the midline to the posterior edge of the sternocleidomastoid muscle along the orientation of the skin texture.
  - The position relationship between the midline structure and the cervical vertebrae: The hyoid bone is on the plane of C3; the thyroid cartilage corresponds to the level of C4–5; the cricoid cartilage corresponds to the level of C6, and the carotid tubercles correspond to the level of C6 (Fig. 1.35).

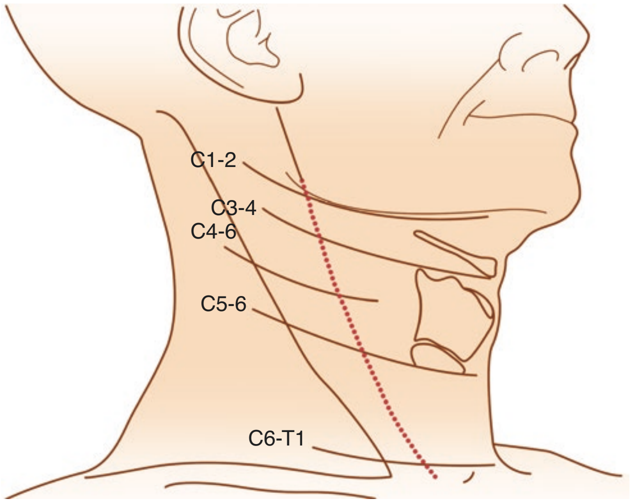


Fig. 1.35 A schematic drawing showing the levels of surgical incisions corresponding to fractures of different segments when the patient lies in a supine position with the head tilted to the contralateral side of the incision

- Surgical approach:
  - The surgical approach is used to expose the two vertebrae above and below the intervertebral disc that must be decompressed following the same procedures described in “Anterior screw fixation for odontoid fractures”;
  - Alternately, the exposure is created until the two vertebral bodies above and below the vertebral body that need to be removed.
- Fracture reduction and fixation:
  - Discectomy and artificial intervertebral disc placement for interbody fusion (Fig. 1.36):

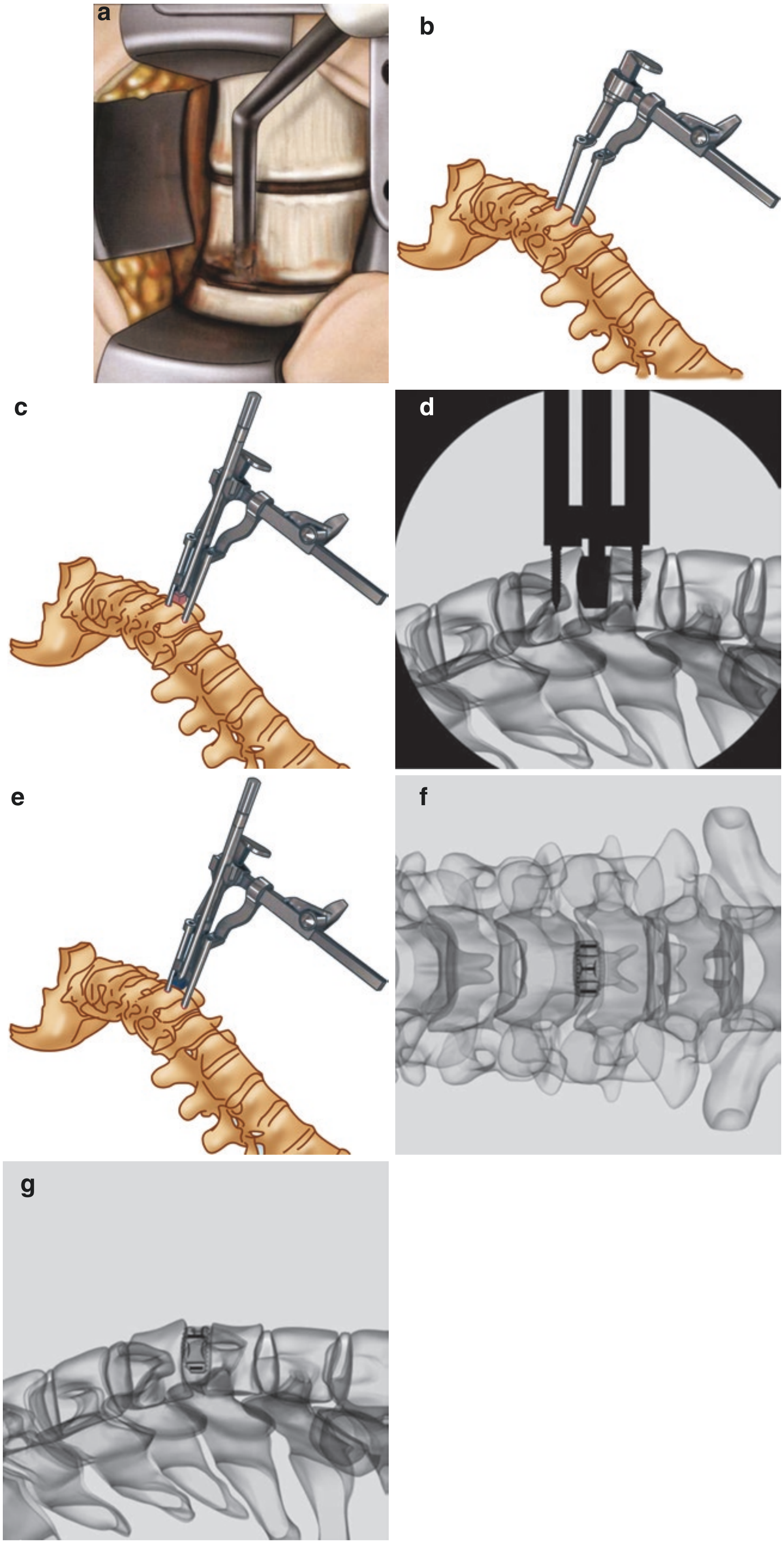
    After removal of the intervertebral disc, the articular cartilage and its end plates above and below are removed using a burr drill, and the resection is extended towards both sides up to the uncovertebral joint for decompression.

    The intervertebral space is distracted using the Caspar distraction system. Subsequently, an intervertebral disc template is placed and examined under C-arm radiography to measure the height of the intervertebral gap and determine the desired height of the interbody fusion cage.

    Traction is discontinued after the interbody fusion cage is placed, and the position of the fusion cage is examined by C-arm fluoroscopy.
  - Subtotal corpectomy for fusion (Fig. 1.37):

    First, the uncovertebral joints on both sides are identified, and the lateral edge of the vertebral body is identified.

Fig. 1.36 (**a**) The intervertebral disc is nibbled off with a bone rongeur, and the articular cartilage and the upper and lower endplates are ground off with a burr drill. (**b**) A Caspar distractor is applied to open the intervertebral space. (**c**, **d**) Under C-arm radiography, an intervertebral disc template is inserted and used to examine whether the height is appropriate and whether the alignment of the cervical spine can be restored satisfactorily. (**e**) After the appropriate height is determined using the disc template, a suitable intervertebral disc prosthesis is implanted. (**f**, **g**) AP and lateral C-arm fluoroscopies are used to examine the position and reduction quality after prosthesis implantation



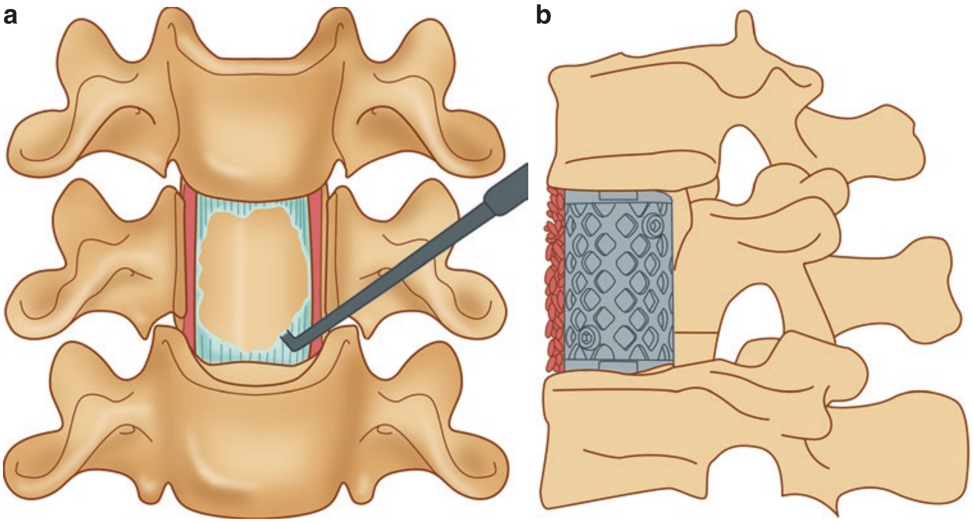


Fig. 1.37 (**a**) Through the anterior approach, the subtotal corpectomy is performed to decompress the affected segment up to the uncovertebral joint from both sides and up to the posterior longitudinal ligament at the posterior aspect. (**b**) The cancellous bone is caged into the titanium cage and then placed into the gap left by the excised vertebral body

After the annular fibrosus is sharply incised, the intervertebral disc of the affected segments is stripped off until the posterior longitudinal ligament.

A subtotal corpectomy is performed with a bone rongeur, which decompresses the affected segment up to the uncovertebral joint from both sides and until the posterior longitudinal ligament at the posterior aspect. The superior and inferior vertebral laminae of the adjacent vertebrae are filed to expose the cancellous bone. Special attention should be paid to the preservation of the posterior rim that can protect the spinal cord from compression caused by backward shifting of the internal fixators.

After length measurement, an ilium fragment with a cortex layer covering three aspects, or a titanium cage with the desired length, is prepared and placed in the remaining space after vertebral body resection.

- Anterior plate fixation (Fig. 1.38):

  Although the anterior cervical plate is a curved plate, its forward curvature can be adjusted using a bender according to the actual cervical spine curvature.

  After placing a guider into the plate, a drill bit with an appropriate size is used to drill the holes.

  Screws are placed diagonally through the plate sequentially, and lastly, all screws are tightened until the screw cap completely enters the area (Figs. 1.39 and 1.40).

- Incision closure: The surgical field is cleansed, and the incision is sutured layer by layer after placing a drainage tube.
- Postoperative management:
  - It is crucial to monitor whether a hematoma in the posterior pharyngeal wall or difficult breathing caused by airway compression is present. The endotracheal tube is retained if needed.
  - Special attention should be paid to examining the presence of recurrent laryngeal nerve damage.
  - The patient must wear a neck support device for 4–6 weeks.

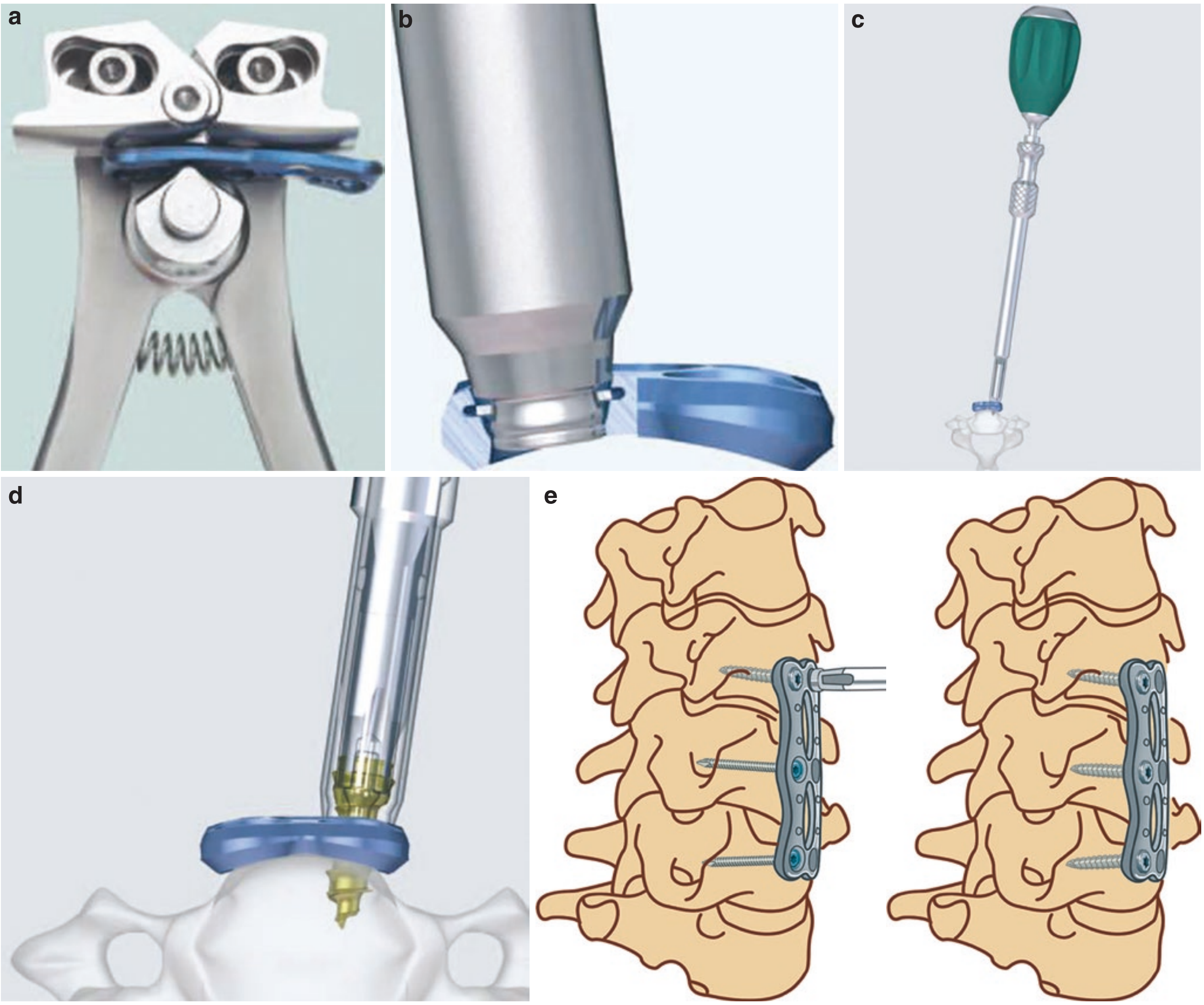


Fig. 1.38 (**a**) The steel plate is pre-shaped to the desired angle with a plate bending during the operation. (**b**) The guider is connected to the steel plate. (**c**) A drill bit with the desired size is used to drill the holes. (**d**) The lock screws are placed. (**e**) The screws are placed diagonally through the plate sequentially, and finally, all the screws are tightened

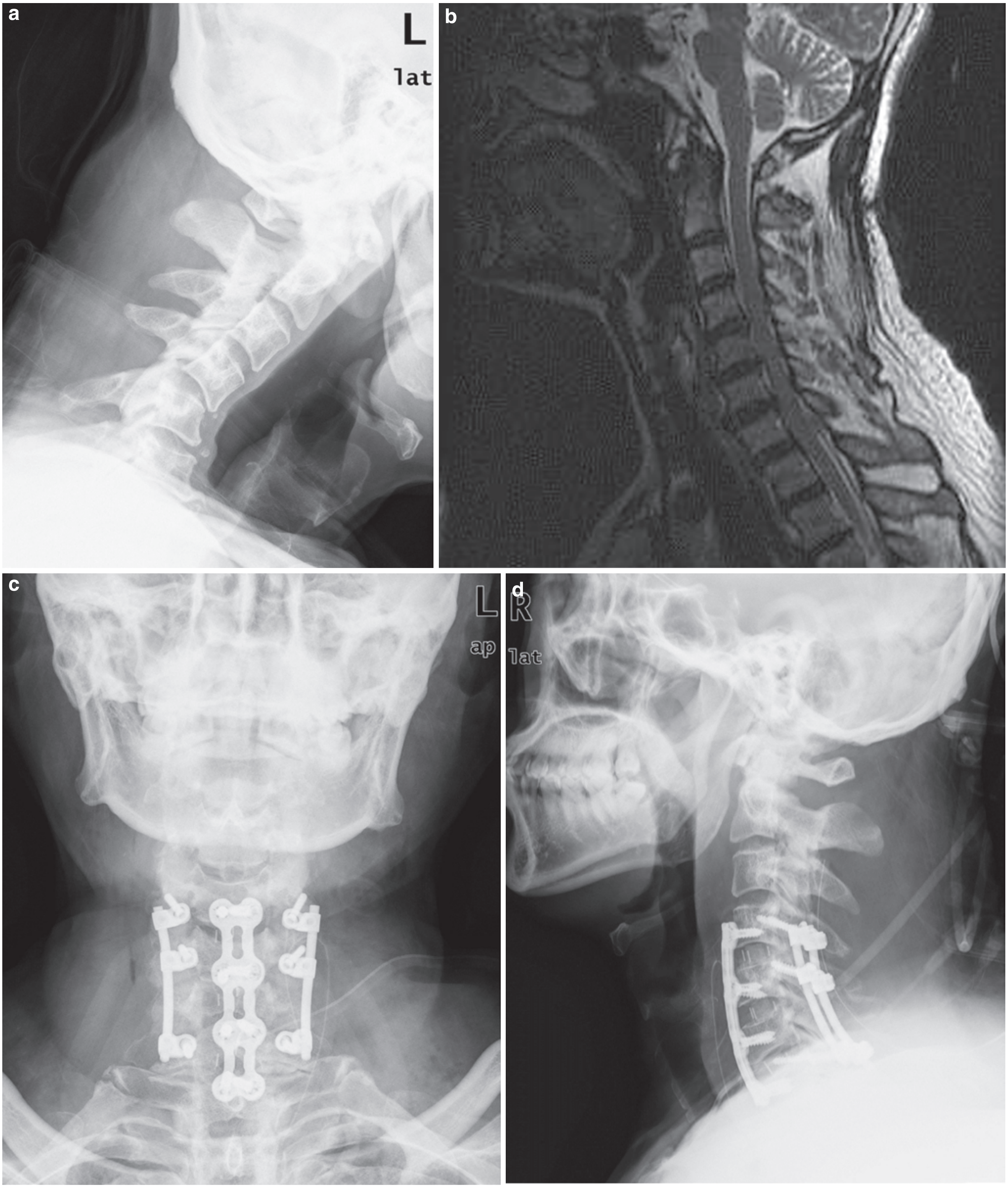


Fig. 1.39 A traumatic C4/C5 dislocation and intervertebral disc herniation causing incomplete paralysis. (**a**) A preoperative lateral radiograph displaying an abnormal angle between the C4 and C5 vertebral bodies. (**b**) Preoperative T2-weighted nuclear magnetic resonance imaging (NMRI): The herniated C4/5, C5/6, and C6/7 intervertebral discs compressed the spinal cord. (**c**, **d**) Due to the serious injury of the posterior tissue, the anterior and posterior approaches were jointly used for surgical treatment. The C3, C4, and C6 lateral mass screws were placed for posterior fixation via the posterior approach. The C4/5, C5/6, and C6/7 intervertebral discs were removed anteriorly, followed by placement of the artificial intervertebral discs and with plate-screw fixation

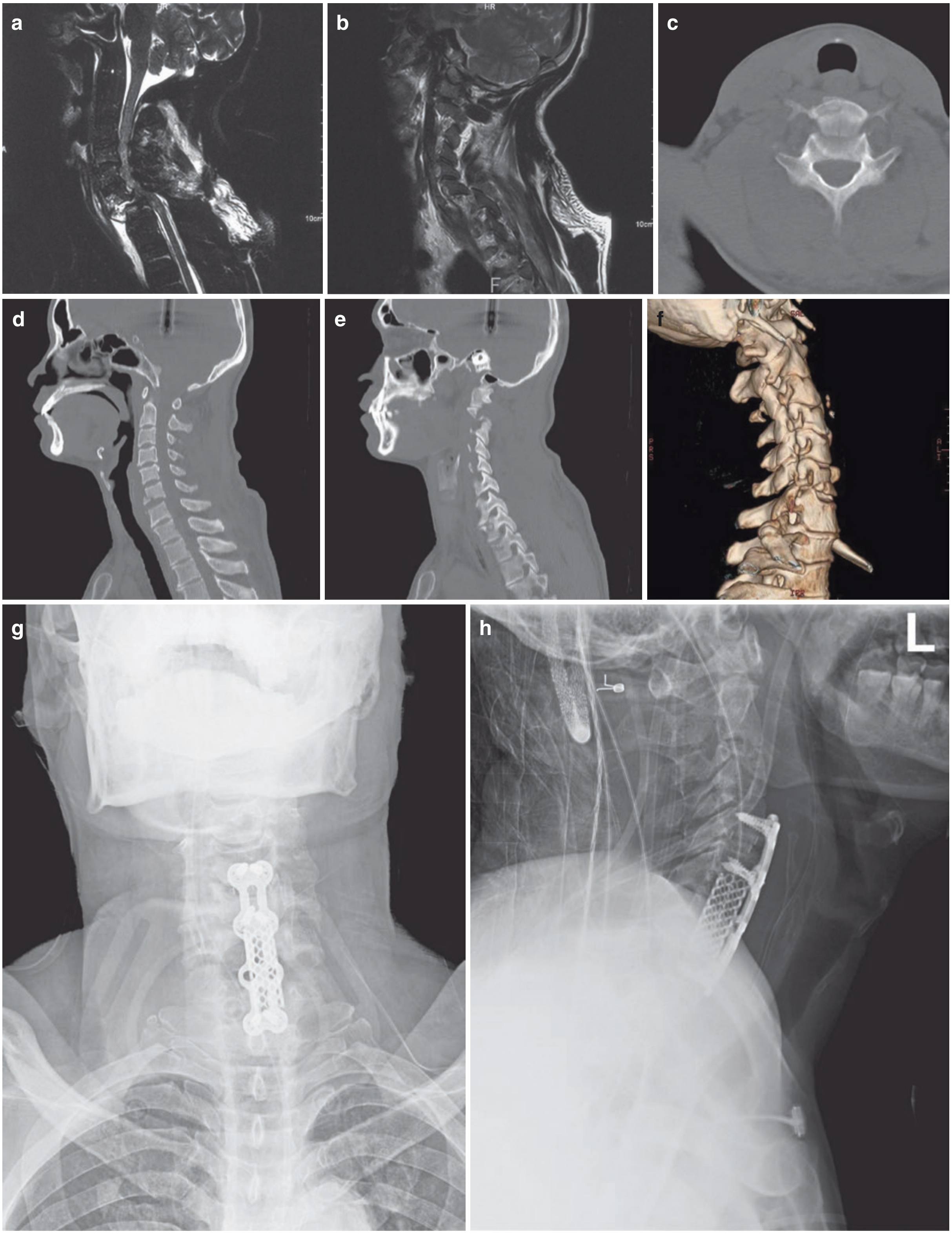


Fig. 1.40 Fracture and dislocation of the C6 vertebral body. (**a**) T2-weighted midline sagittal MRI after injury: The C7 vertebral body was anteriorly dislocated, with obvious compression of the spinal cord. (**b**) Sagittal MRI of the facet joint showing a dislocation and interlocking of the C6 and C7 joints. (**c**) CT plain scan: The C6 vertebral body was fractured and anteriorly dislocated. (**d**) Sagittally reconstructed midline CT plain scan: After skull traction, the vertebral body was partially reduced, and there was a teardrop-shaped bone fragment in front of the vertebral body. (**e**) Sagittal reconstruction of the CT plain scan of the joint: The interlocked joint was reduced, but the C6–C7 intervertebral space was significantly wider than that of other segments, indicating destruction of the ligaments and joint capsule structure. (**f**) The 3D reconstructed CT image: The C6 vertebral body had a teardrop-shaped fracture. (**g**, **h**) Postoperative AP and lateral radiographs: The lesioned vertebral body and intervertebral disc were removed using the anterior approach, followed by titanium caging and plate-screw internal fixation via the anterior approach

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Thoracolumbar Fractures

2

Zhe Zhao, Lihai Zhang, Yong Sun, and Jianheng Liu

2.1 Basic Theory and Concepts

2.1.1 Overview

- Thoracolumbar fractures are caused mostly by high-energy violence, of which 25% are associated with neurologic injury (Koval and Zuckerman 2006):
  - Approximately 65% of thoracolumbar fractures are caused by a motor vehicle accident or a fall from a high place.
  - The remaining 35% are caused by athletic participation or assault.
- Approximately 68% of thoracolumbar fractures are accompanied by other injuries, and 25% are accompanied by serious injuries (Lin and Lane 2004).
- With the aging of the population, the incidence of osteoporosis-related wedge compression fractures in elderly patients has been increasing in recent years (Lin and Lane 2004; Blam and Cotler 2002).
- Treatment goals: Correct deformities and prevent their progression; restore the stability of the spine; perform nerve decompression if needed; minimize the number of vertebrae involved in fusion while ensuring an adequate stability if fusion is unavoidable.

2.1.2 Applied Anatomy

1. The thoracolumbar spine is conceptually divided into three functional regions: the thoracic region, thoracolumbar region (junction), and lumbar region (Fig. 2.1).

a. The thoracic region refers to the segment between T1 and T10 where the incidence rate of fractures is relatively low (Stagnara et al. 1982).
   - The thoracic region is stable due to the participation of the rib cage:
     - The structures, including the sternocostal joint in the anterior aspect, the costovertebral joint in the lateral aspect, and the spinous processes in an imbricated arrangement along with the surrounding ligaments and intervertebral discs in the posterior aspect, further stabilize this region.
     - Fractures within this region, which are rare but indicate highly violent force, are often severe and involve a large number of vertebrae and accessory components.
   - Fractures in this region are often associated with neurologic injury:
     - The thoracic spinal canal is relatively narrow, and the ratio of the cross-sectional areas of the spinal cord and spinal canal is only 40% (25% in the cervical spine), suggesting limited room for buffering after excluding structures such as the dural sac; particularly, the spinal canal has the smallest sagittal and transverse diameters at the level from T4 to T9.
   - Once a compression fracture occurs, the thoracic region is difficult to distract via the posterior approach:
     - Due to the protection of the rib cage and the close relationship between the transverse processes of the thoracic vertebrae and other anatomical structures such as the costal arch, the effect of posterior distraction is limited.

b. The thoracolumbar region (junction) refers to the region from T11 to L2. Approximately 50% of thoracolumbar fractures occur in this region (Gertzbein 1992).

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P. Tang, H. Chen (eds.), *Orthopaedic Trauma Surgery*, https://doi.org/10.1007/978-981-16-0219-1_2

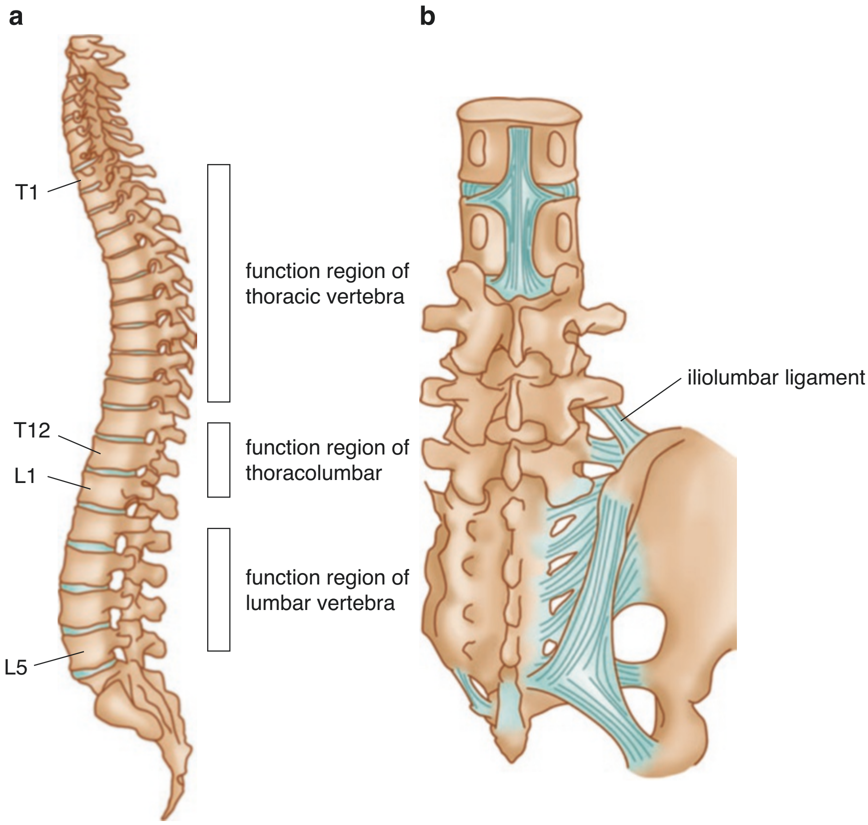


Fig. 2.1 Three functional regions of the thoracolumbar spine. (**a**) The thoracic region is kyphotic, the lumbar region is lordotic, and the thoracolumbar region is the transitional zone between the two natural curves. (**b**) The lower lumbar spine is connected to the pelvis by the iliolumbar ligament, which increases the stability of the spine

- The thoracolumbar region is the junction area for stress transmission and movement of the spine:
  - As the junction of the relatively stiff thoracic spine and the more mobile lumbar spine, this region bears the maximal stress.
  - This region is a biomechanical turning point of the spine because it is the junction of two nature curves, the kyphotic thoracic spine and the lordotic lumbar spine.
- Fractures in this region are often associated with injuries of the spine or cauda equina:
  - The medullary conus has been reported to end at the level of the lower edge of L1 in 55% of Chinese patients, where a horizontal fracture is often associated with a medullary conus injury (Guo 2001).
  - Depending on the level of the spine involved, the injury might cause damage to upper motor neurons, lower motor neurons, or both, which can be identified based on the segmental spinal cord functions and corresponding neurologic examination.

c. The lumbar region includes the region from L3 to L5 and has a relatively low incidence of fractures (White and Panjabi 1978; Vialle et al. 2005).

- Fractures within the lumbar region are primarily treated non-surgically:
  - Fractures of accessory structures often occur, including transverse process and spinous process fractures.
- The incidence of nerve injuries is low, and most of them include incomplete nerve injury.
  - The lumbar spinal canal within this region is wide.
  - The cauda equina, which passes the lumbar spinal canal in this region, is highly resistant to compression.

2. Blood supply to the spinal cord (Fig. 2.2):
   a. The spinal cord receives blood mainly from three vessels: the anterior median spinal artery and two dorsolateral spinal arteries.
   b. At each vertebral level, one pair of segmental arteries supplies blood to the internal and external components of the spine, and the radicular arteries in the thoracolumbar region (junction) mostly originate from the aorta. The branches sent from the segmental arteries near the intervertebral foramen form a vascular network in the spinal epidural loose connective tissue. Therefore, each segment of the spinal cord has an abundant blood supply, even after the corresponding segmental artery is ligated. In addition, many of the radicular arteries and the anterior median spinal artery converge, further increasing the blood supply to the spinal cord.

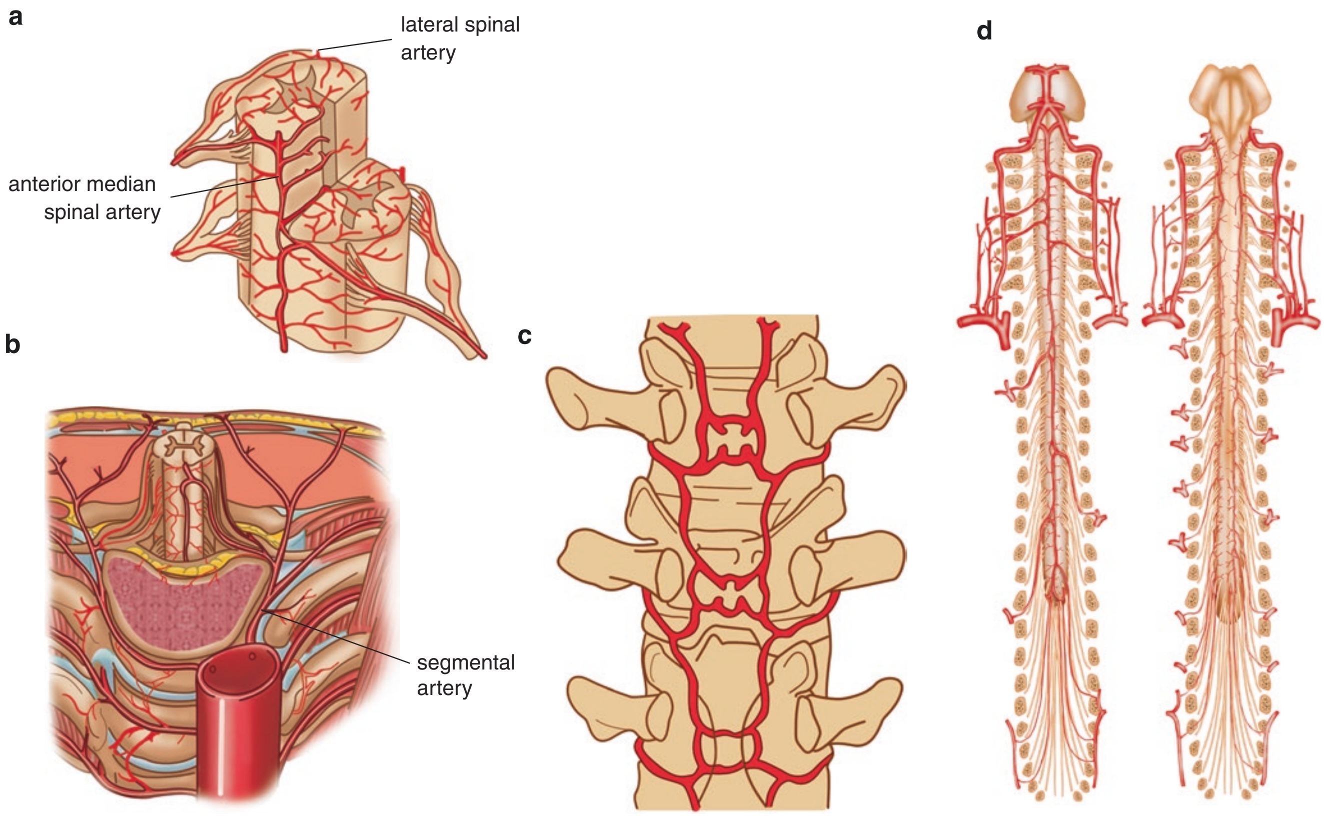


Fig. 2.2 Blood supply to the spinal cord. (**a**) The arterial network of the spinal cord is derived primarily from the anterior median spinal artery and the left and right dorsolateral spinal arteries. (**b**) In the thoracic region, each vertebral segment has one pair of segmental arteries supplying blood to the vertebral body. (**c**) The segmental arteries form the vascular network in the spinal canal. (**d**) Overview of the blood supply of the spinal cord: The location of the Adamkiewicz artery is critical

   c. The Adamkiewicz artery (Alleyne et al. 1998) is the largest blood-supplying vessel to the lumbar spine. It is located on the left side at the level of T9–11 and should be protected with special precautions during surgery.
   d. The region between T2 and T10 is the junction of the areas receiving blood from different origins, which proximally receives blood from the antegrade vessels in the upper thoracic spine and distally from the retrograde flow from the Adamkiewicz artery. In addition, the spinal canal at the level is narrowest between T4 and T9. Therefore, this region has the poorest blood supply and is relatively vulnerable because any trauma or surgical operation that disrupts the blood-supplying system in this region might cause neurologic deficits.
   e. Thoracic spinal cord injury without fracture-dislocation, which is clinically common, is related to avascular necrosis of the thoracic spinal cord following Adamkiewicz artery damage that disrupts the blood supply. The patients are usually presented with immediate paralysis after injury, but pediatric patients might experience paralysis from 2 h to 4 days after trauma, which is called delayed paralysis.
   f. The basivertebral system of veins: The veins around the vertebrae converge to the central vein, which runs out from the nutrient foramen in the middle of the posterior vertebrae and converges to the venous plexus in the spinal canal (Fig. 2.3). Damage to the central vein during surgery may cause massive bleeding.

3. The three-column structure of the spine (Fig. 2.4): This concept was first proposed by Francis Denis (Denis 1983).
   a. The anterior column consists of the anterior longitudinal ligament, anterior half of the vertebral bodies, and anterior fibrous rings.
   b. The middle column consists of the posterior half of the vertebral bodies, posterior fibrous rings, and posterior longitudinal ligament.
   c. The posterior column consists of the posterior osteoligamentous complex (the vertebral lamina, spinous process, supraspinous ligament, interspinous ligament, joint capsule, and ligamentum flavum).
   d. The anterior, middle, and posterior columns bear 40%, 30%, and 30% of the total load, respectively; therefore, a fracture involving two columns is considered unstable.

Fig. 2.3 (**a**, **b**) Cross-section (**a**) and sagittal views (**b**) of the vertebral veins showing that the veins around the vertebral body converge to the central vein, which exits the nutrient foramen in the middle of the posterior vertebrae and converges to the venous plexus in the spinal canal

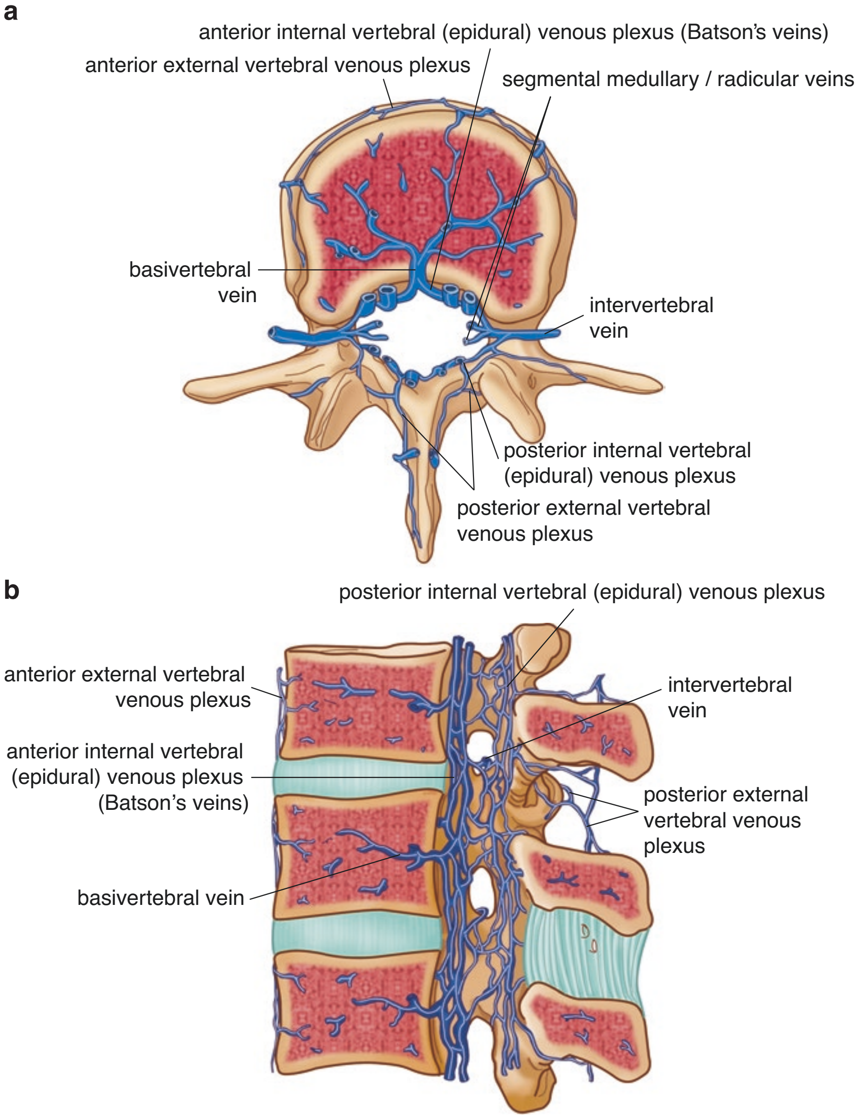
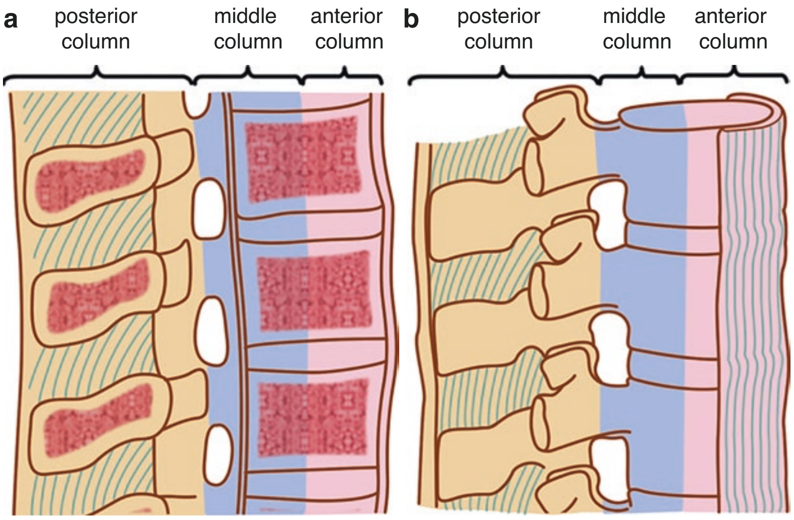


Fig. 2.4 (**a**, **b**) The anterior column consists of the anterior longitudinal ligament, the anterior half of the vertebral bodies, and the anterior fibrous rings. The middle column is composed of the posterior half of the vertebral bodies, the posterior fibrous rings, and the posterior longitudinal ligament. The posterior column is composed of the posterior osteoligamentous complex



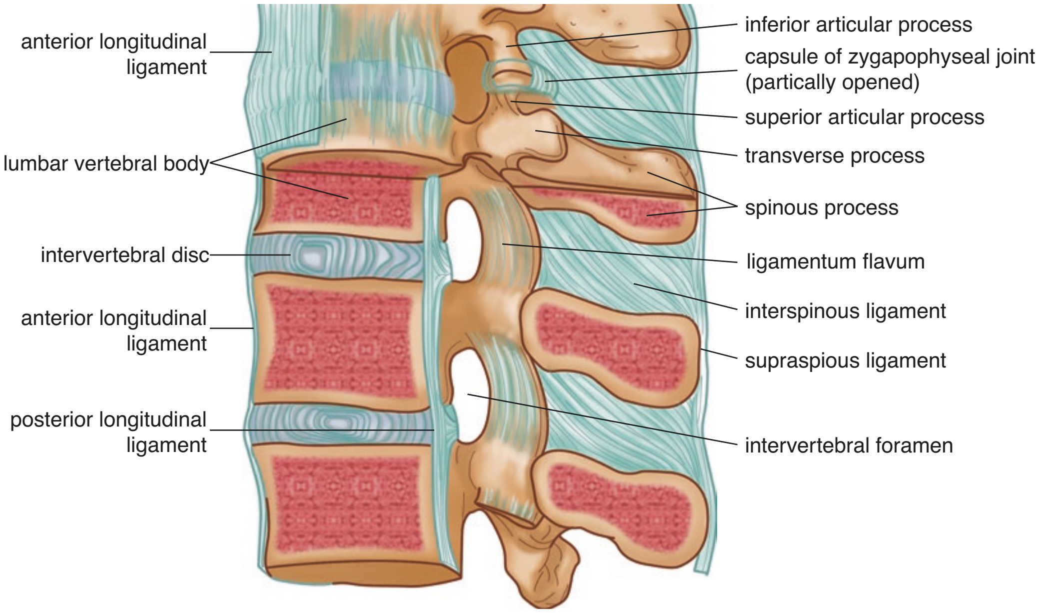


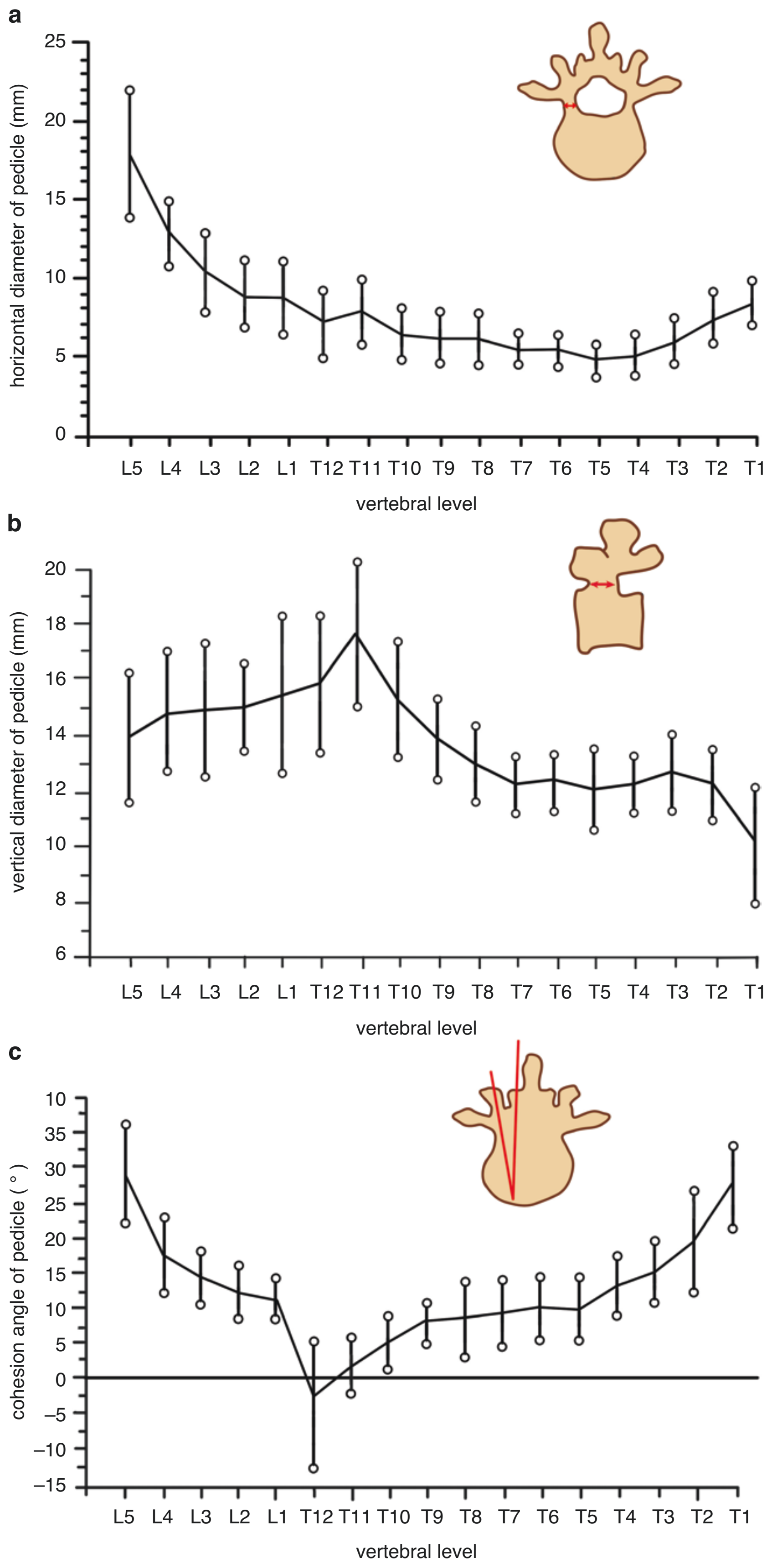
Fig. 2.5 The posterior ligament complex consists of the supraspinous ligament, interspinous ligament, posterior longitudinal ligament, capsule of the facet joint, and ligamentum flavum

4. The posterior ligament complex: It is an important item in the thoracolumbar injury classification and severity score (Vaccaro et al. 2005) (TLICS) system proposed by Vaccaro et al.:
   a. The posterior ligament complex consists of the supraspinous ligament, interspinous ligament, posterior longitudinal ligament, capsule of the facet joint, and ligamentum flavum (Fig. 2.5);
   b. Rupture of the posterior osteoligamentous complex is observed most frequently in flexion-distraction fractures and fracture-displacement injuries, as well as in a portion of burst fractures and occasionally in isolated compression fractures. Magnetic resonance imaging (MRI) serves as the best tool for assessing the integrity of the posterior osteoligamentous complex.
5. The channel for vertebral pedicle pin placement: The diameter of the vertebral pedicle and the position relationship between the vertebral pedicle and vertebral body are crucial for the pedicle screw internal fixation system. The diameter and angle of the vertebral pedicle gradually change from the upper thoracic spine to the lower lumbar spine (Zindrick et al. 1987) (Fig. 2.6).
   a. Horizontal width: The horizontal width shows an overall decreasing trend from the top down, with T7 exhibiting the smallest width.
   b. Vertical diameter: Overall, the lumbar vertebrae are taller than the thoracic vertebrae, with T11 displaying the greatest height.
   c. The inclination angle relative to the horizontal plane—This angle determines the angle at which the pedicle screws point to each other:
      - The thoracic spine has a greater inclination angle on its proximate side, which changes from 27° at the level of T1 to 1° at the level of T11 and to −4° at the level of T12.
      - The inclination angle increases from top to bottom in the lumbar region from 11° at the level of L1 to approximately 30° at the level of L5. However, due to a large size, the L5 vertebral pedicle is a good location for vertebral pedicle pin placement.

2.1.3 Mechanism of Injury

- Thoracolumbar fractures are primarily caused by high-energy violence.
- The violence, including compressive, separative, flexion-distraction, twisting, and shear forces, may be applied to the spine either separately or jointly (Eismont et al. 2009) (Fig. 2.7).
  – Axial compressive forces often cause burst fractures of the thoracolumbar region (junction).
  – Flexion (hyperflexion): The anterior components are compressed, and the posterior components are tensioned, which causes compression fractures of the vertebral body if the force is not too strong and may cause a rupture of the posterior ligament complex as the force increases.
  – Lateral compression: A lateral wedge-shaped compression injury often occurs.
  – Shear: The ligaments are severely ruptured, and the vertebrae above and below are displaced.
  – Extension (hyperextension): The articular process, vertebral lamina, and spinous process are fractured, which may be accompanied by an avulsion of the anterior edge of the vertebra.

Fig. 2.6 (**a**) The horizontal diameter of the vertebral pedicles in different vertebral segments. (**b**) The vertical diameter of the vertebral pedicles in different vertebral segments. (**c**) The convergence angle of the vertebral pedicle in different vertebral segments



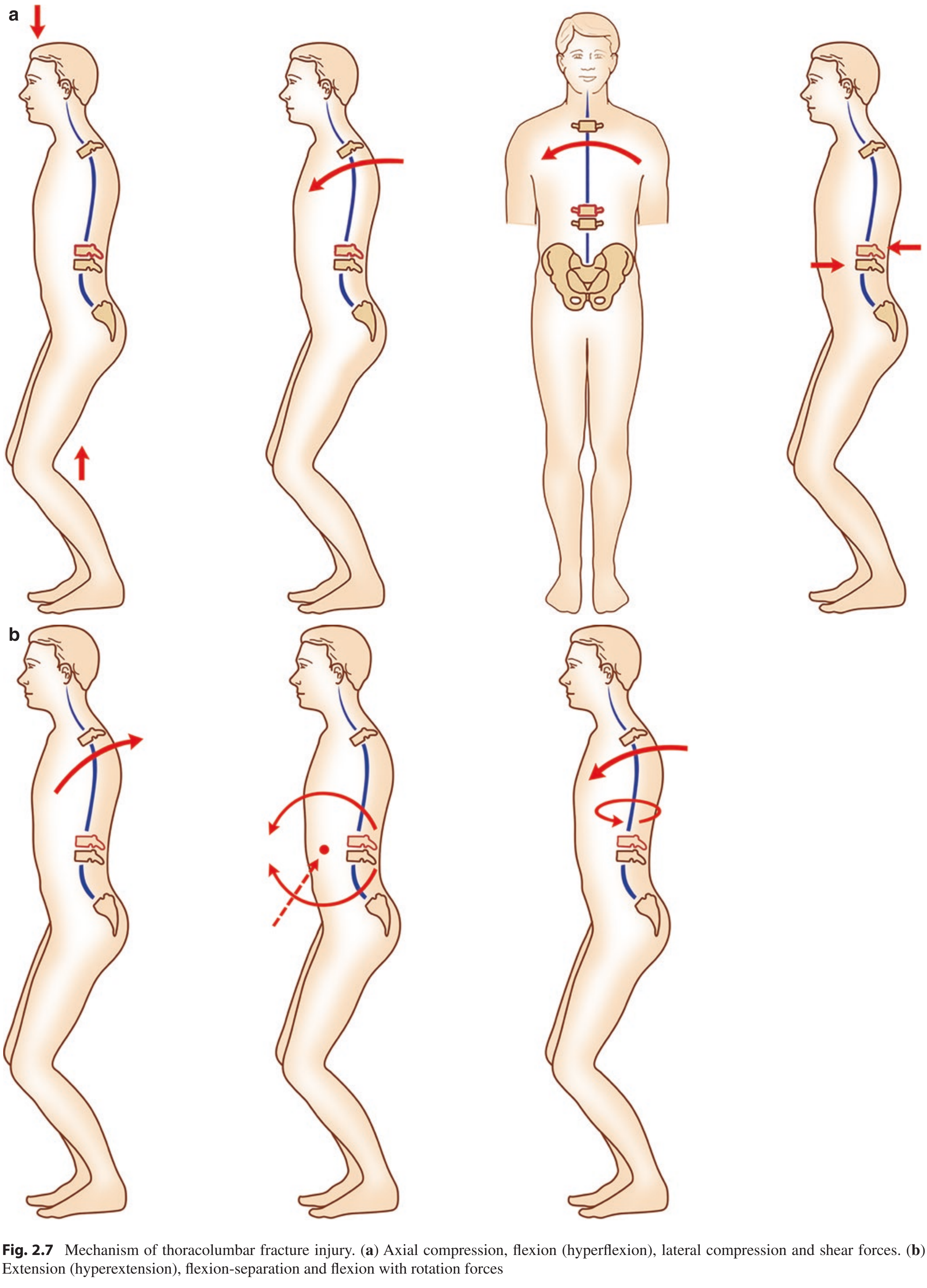


Fig. 2.7 Mechanism of thoracolumbar fracture injury. (**a**) Axial compression, flexion (hyperflexion), lateral compression and shear forces. (**b**) Extension (hyperextension), flexion-separation and flexion with rotation forces

- Flexion-separation: A tension force acts on the spine, causing rupture and avulsion of the intervertebral discs, ligaments, and bones, i.e., Chance injury.
- Flexion with rotation: The posterior articular processes, joint capsules, and ligaments are often injured; the spine is severely damaged.

2.1.4 Fracture Classification

1. Dennis classification (Denis 1983): This method classifies fractures according to radiological manifestations.
   a. Spine secondary fractures include the articular process, transverse process, spinous process, and isthmus fractures.
   b. Primary fractures of the spine:
      - Compression fractures:
        - A compression fracture is a fracture of the anterior edge of a vertebral body with an intact middle column.
        - It is usually stable.
        - A compression injury is unstable when the vertebral body is compressed >50%, the fractured vertebra has an angulation from >20–30°, or multiple adjacent vertebrae are compressed.
        - Compression fractures are divided into four types according to the involvement of the end-plates (Fig. 2.8):

          Type A involves both the superior and inferior end-plates.

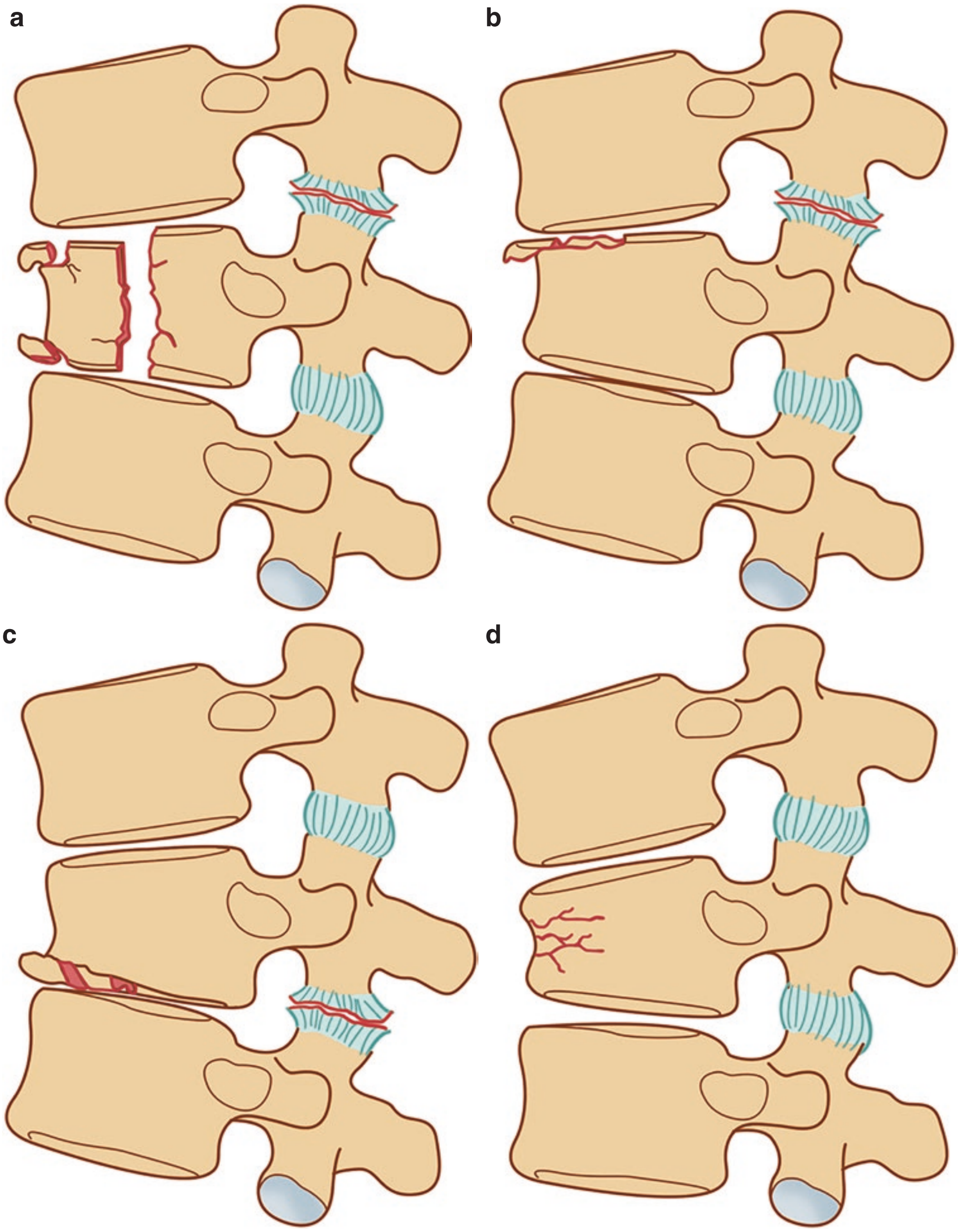


Fig. 2.8 Denis classification of compression fractures. (**a**) The Type A fracture involves both the superior and inferior end-plates. (**b**) Type B involves only the superior end-plate. (**c**) Type C involves only the inferior end-plate. (**d**) The Type D fracture is associated with buckling of the anterior edge of the bone cortex of the vertebral body while both the superior and inferior end-plates remain intact

    Type B involves only the superior end-plate.
    Type C involves only the inferior end-plate.
    Type D shows buckling of the cortex at the anterior edge of the vertebral body while both end-plates remain intact.

- Burst fractures:
  - refer to the burst rupture of the posterior wall of the vertebral body (the middle column of the spinal cord).
  - are unstable if the posterior column is involved.
  - include five types (Fig. 2.9):
    Type A involves both the superior and inferior end-plates.
    Type B involves only the superior end-plate.
    Type C involves only the inferior end-plate.
    Type D is a Type A fracture associated with rotation of the fractured vertebra.
    Type E is caused by lateral violence and demonstrates an asymmetry of the affected vertebra on AP radiographs.

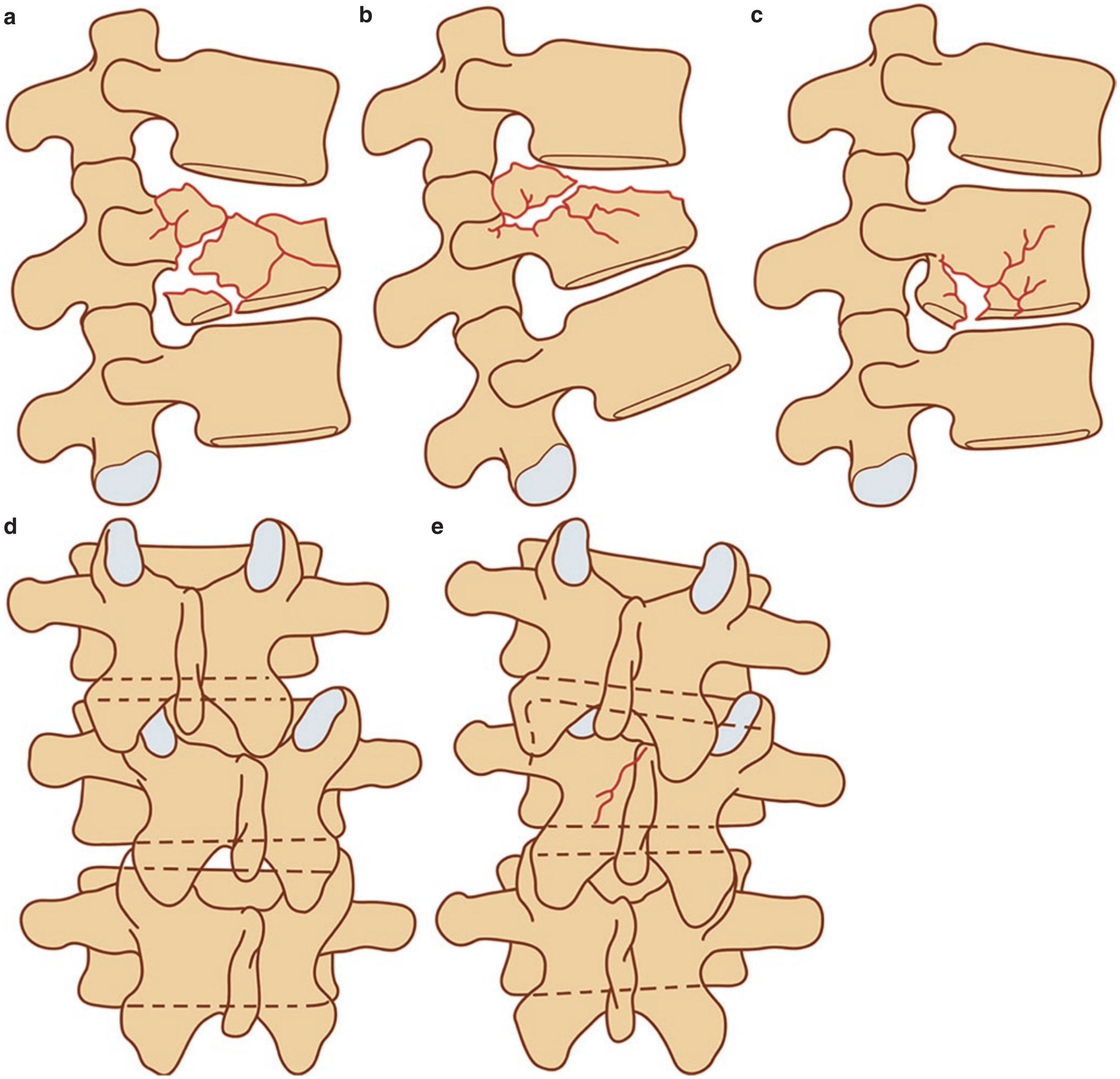


Fig. 2.9 Denis classification of burst fractures. (**a**) Type A involves both the superior and inferior end-plates. (**b**) Type B involves only the superior end-plate. (**c**) Type C involves only the inferior end-plate. (**d**) Type D is a Type A fracture associated with rotation of the fractured vertebra. (**e**) Type E is caused by a lateral violence and demonstrates an asymmetry of the affected vertebra on AP radiographs

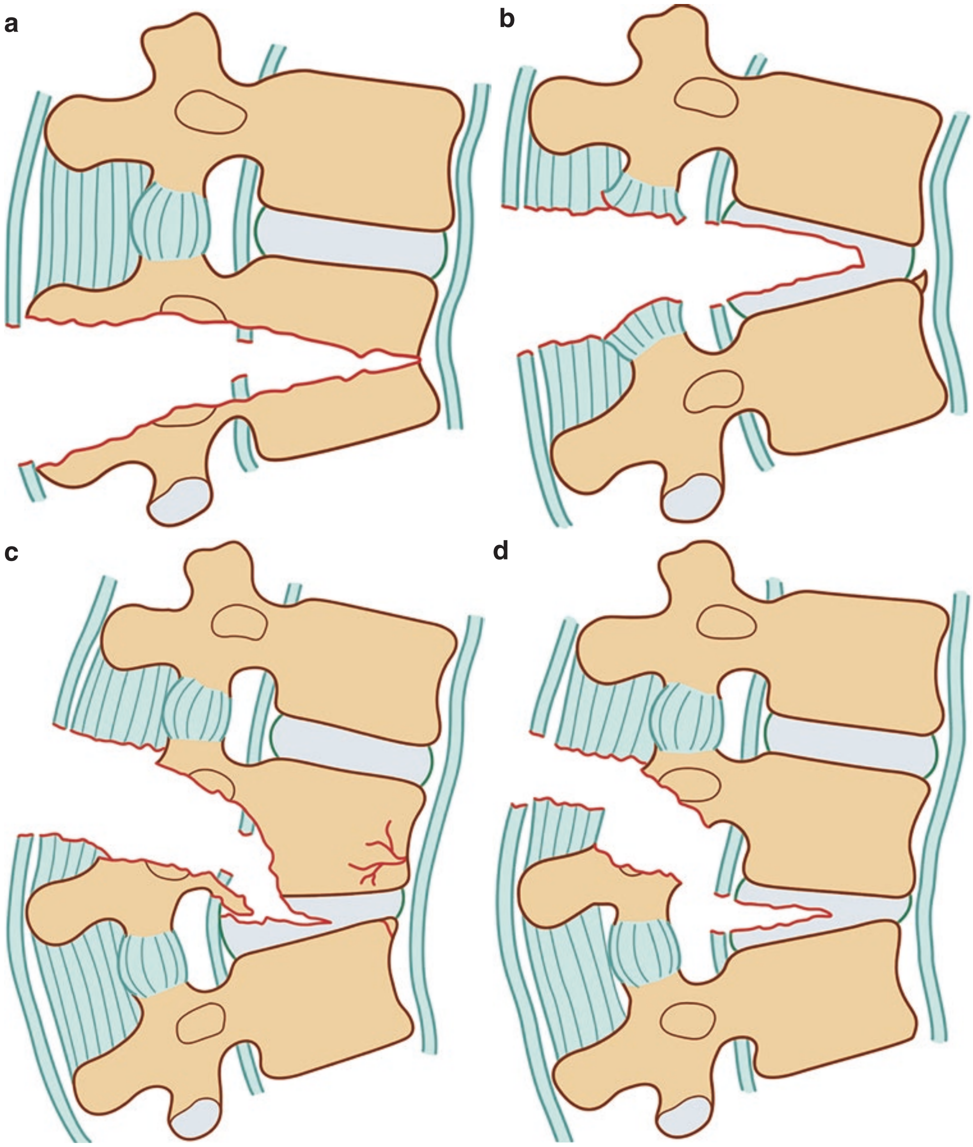


Fig. 2.10 Denis classification of flexion-hyperextension injuries. (**a**) Type A involves only a single spinal segment with the fracture line passing the vertebral body. (**b**) Type B involves only a single spinal segment with the fracture line passing the ligaments and the intervertebral disc. (**c**) Type C involves two spinal segments with the fracture line passing the vertebral body. (**d**) Type D involves two spinal segments with the fracture line passing the intervertebral disc

- Flexion-separation fractures (Chance fracture):
  - With the anterior column as a pivot, the posterior column and the middle column are ruptured under a tension force, which might be accompanied by a compression injury of the anterior column.
  - Most patients do not have any neurologic symptoms.
  - More than 50% of cases are associated with abdominal injury.
  - This type of fracture is unstable.
  - Chance fractures are divided into four types according to the structures passed by the fracture line (Fig. 2.10).

    Type A fractures involve only one single spinal segment with the fracture line passing the vertebral body.

    Type B fractures involve only one single spinal segment with the fracture line passing the ligaments and intervertebral disc.

    Type C fractures involve only two spinal segments with the fracture line passing the vertebral body.

    Type D fractures involve two spinal segments with the fracture line passing the intervertebral disc.
- Displaced fractures:
  - The fracture involves all three spinal columns and displays translation deformity.
  - This type of fracture is unstable.
  - The incidence rate of neurologic injury is highest among all types of thoracolumbar fractures.
  - They are further divided into three types (Fig. 2.11):

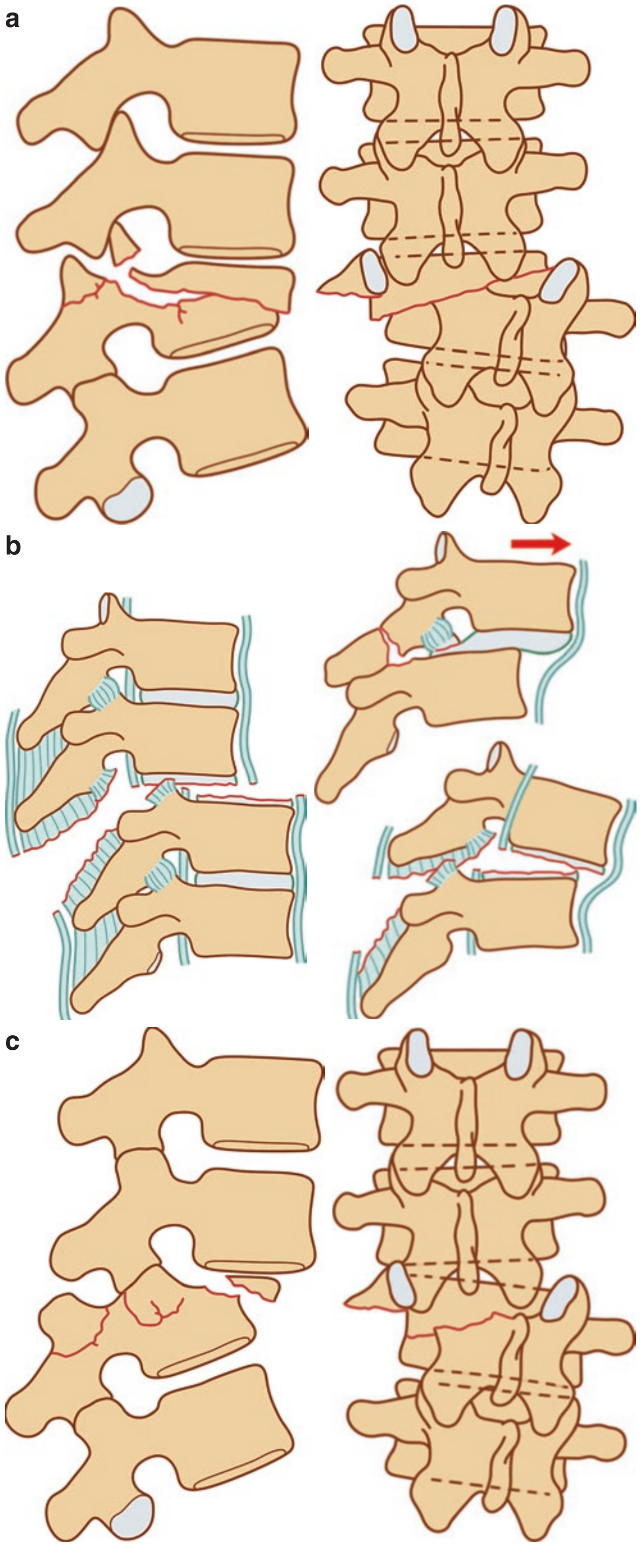


Fig. 2.11 Denis classification of spinal column fracture dislocations. Type **a** is a flexion-rotation injury. Type **b** is a shear injury. Type **c** is a bilateral facet joint dislocation

Type A: Flexion-rotation injury
Type B: Shear injury
Type C: Bilateral facet joint dislocation

2. Spinal column involvement in different types of injuries in the Denis classification (Table 2.1):

2.1.5 Assessment of Thoracolumbar Fractures

2.1.5.1 Clinical Assessment

- Ascertain the patient's injury history.
  - Query for the injury history and determine the mechanism of injury.
  - Query for witnessed head trauma.
  - Query for movement of the lower extremities and level of consciousness immediately following trauma.
- Perform a general physical examination.
  - Complicated injuries: The head, neck, chest, abdomen, pelvis, and extremities are examined to rule out the possibility of injury elsewhere.
  - Deformities, lacerations, and contusions of the skin and soft tissue are visually examined.
  - The injured area is palpated for further evidence, including the "step" sign, widening of the inter-spinous-process space, pain, tenderness, and percussion pain.
  - Fractures elsewhere in the body: The possibility of accompanying fractures elsewhere in the body must not be overlooked; in patients with lower extremity sensory deficits, the calcaneus, tibia, fibula, femoral neck, acetabulum, and other parts must be carefully examined for the possibility of fracture.
  - Special attention must be paid to abdominal contusion and ecchymosis, which suggests a high possibility of a Chance fracture (Chapman et al. 2008; Gertzbein and Court-Brown 1988). It is crucial to rule out the possibility of abdominal organ injuries, and ultrasound or CT scans should be performed if needed.
- Perform a neurologic examination.
  - The injured spinal segments might not be adjacent to each other; therefore, the neurologic examination should include the function of the cervical spinal cord to avoid a missed diagnosis of cervical spine injury.
  - Sensory examination.

    Sensations, including pain, temperature, and touch, are assessed according to the segmental distribution of the cutaneous nerves (Fig. 2.12).

    The diagnosis can be made by comparing sensations between the left and right sides of the body, between the upper and lower parts, and between the proximal and distal sides.

Table 2.1 Spinal column involvement in different types of injuries in the Denis classification

Fracture type	Involved column		
	Anterior column	Middle column	Posterior column
Compression fracture	Compression	Uncompression	Without or with separation
Bursting fracture	Compression	Compression	Without or with separation
Chance fracture	With or without compression	Separation	Separation
Fracture displacement	Compression and (or) forward rotation, shear	Separation and (or) forward rotation, shear	Separation and (or) forward rotation, shear

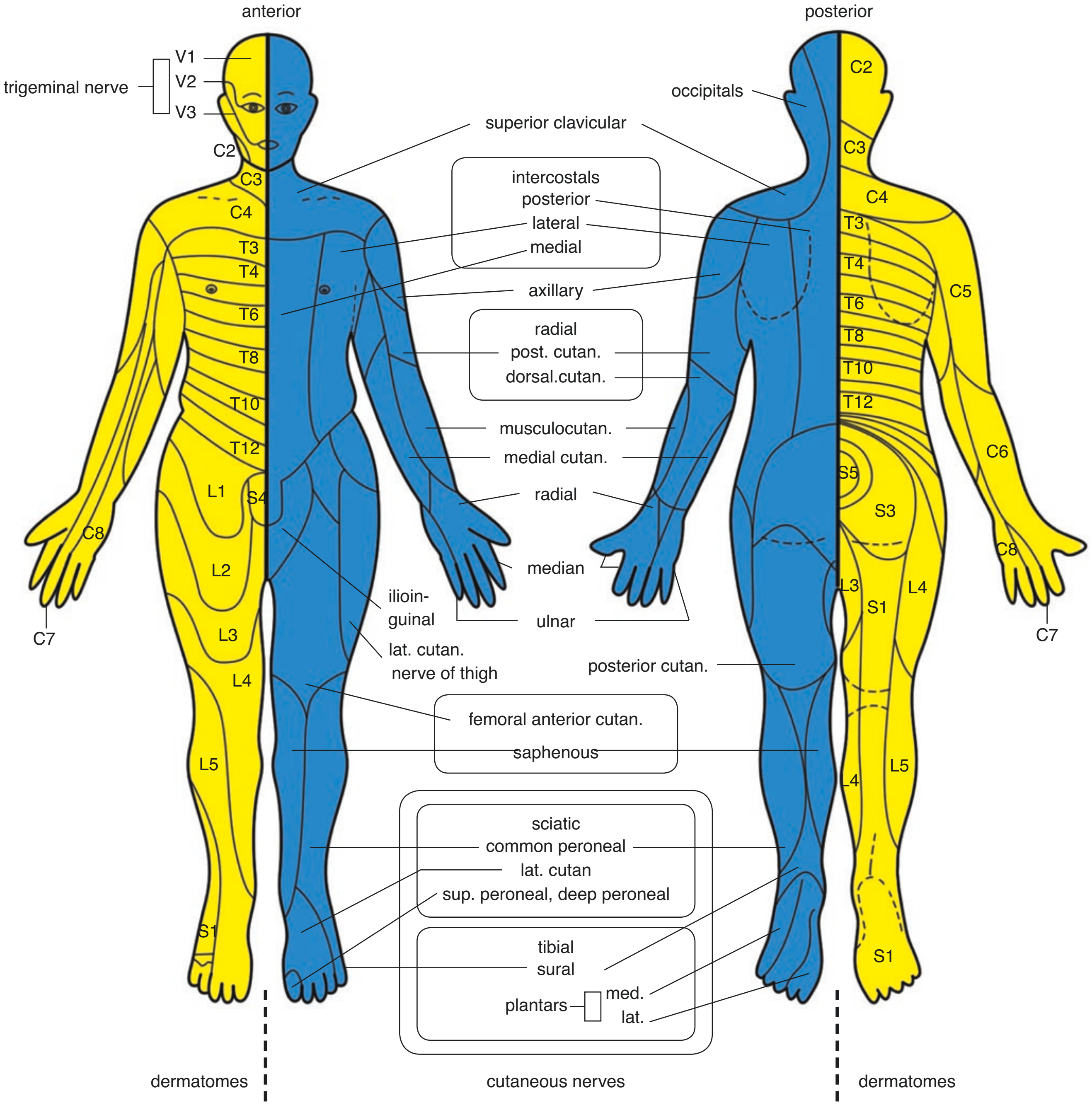


Fig. 2.12 A sensory dermatome body map corresponding to the spinal segments: The commonly used levels include T4-nipple, T6-xiphoid process, T10-navel, and T12-pubic symphysis

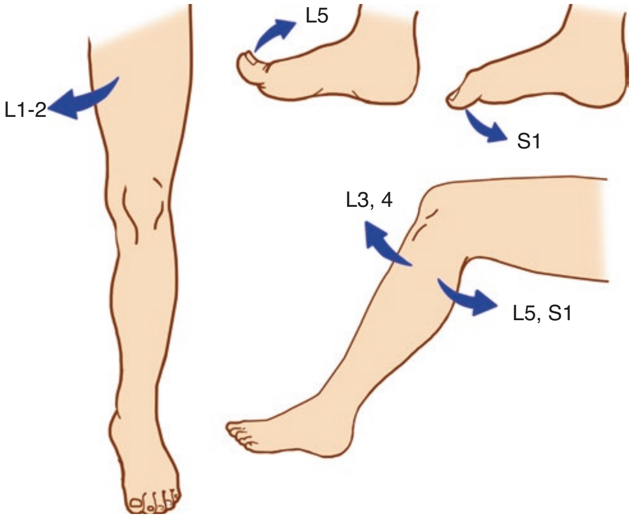


Fig. 2.13 The segmental relationship of the spinal cord to the motor function of the lower extremity: L1–L2 for hip adduction, L3–4 for knee extension, L5–S1 for knee flexion, L5 for hallux dorsiflexion, and S1 for hallux plantar flexion (This figure is a replicate of Fig. 1.11 in "Cervical spine fractures")

- Motor examination.

  Evaluate muscle strength and range of motion of the joints.

  The motion functions of different joints correspond to different spinal segments (Fig. 2.13).
- Reflex examination.

  Include tendon reflexes, the anal wink reflex, the cremasteric reflex, the bulbocavernosus reflex, the sacral sparing, and pathological responses (Figs. 2.14 and 2.15).
- American Spinal Injury Association (ASIA) score (Maynard et al. 1997): Please see the section "Clinical Assessment" of Chapter "Cervical Spine Fractures."

2.1.5.2 Radiographic Evaluation

- Radiography (Fig. 2.16):
  - Both thoracic and lumbar AP and lateral radiographs should be obtained.
  - AP radiography:

    Widening of the space between the vertebral pedicles on the two sides suggests translation of the vertebral burst fracture fragments towards the two sides.

    A blurred contour of the vertebral pedicle suggests a rupture of the vertebral pedicle.

    Lateral bending of the spine indicates a lateral compression displacement of the affected segment.

    An asymmetry between the two sides of the vertebral pedicles and the spinous process indicates a rotational displacement.
  - Lateral radiography:

    Height loss of the vertebral body suggests a compression and/or burst fracture.

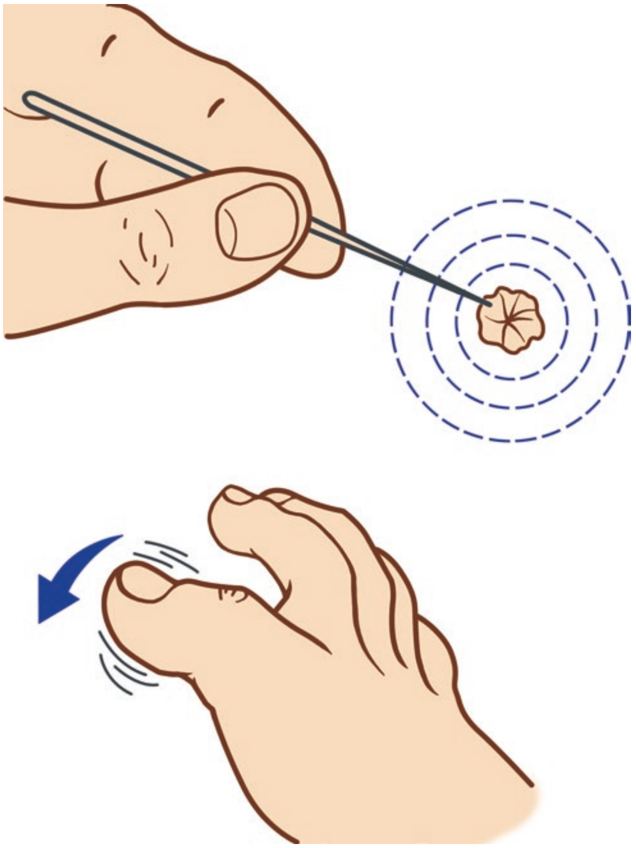


Fig. 2.14 Anal wink reflex and sacral sparing. Examination of the anal wink reflex provides evidence to identify the occurrence and recovery of spinal shock

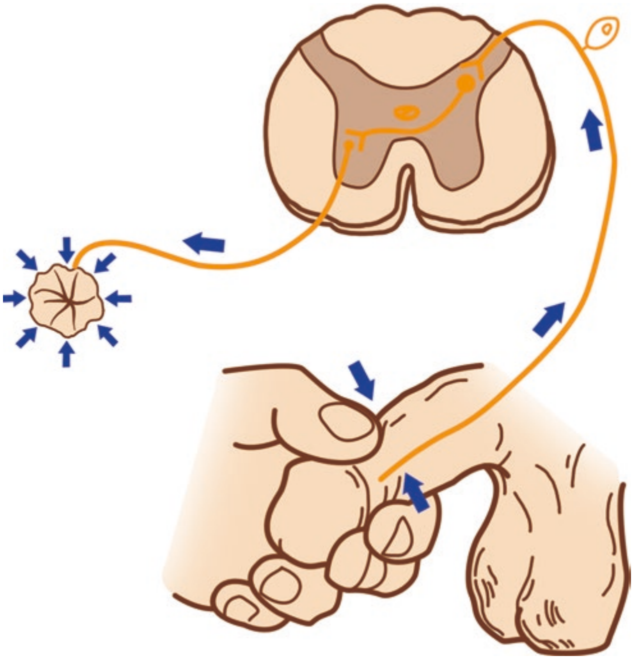


Fig. 2.15 The bulbocavernosus reflex. The bulbocavernosus reflex has a reflex center in the medullary cone and involves the three sacral nerve roots below the medullary cone. It refers to contraction of the anal sphincter in response to a stimulation (e.g., a squeeze) of the glans penis in a male or the clitoris in a female

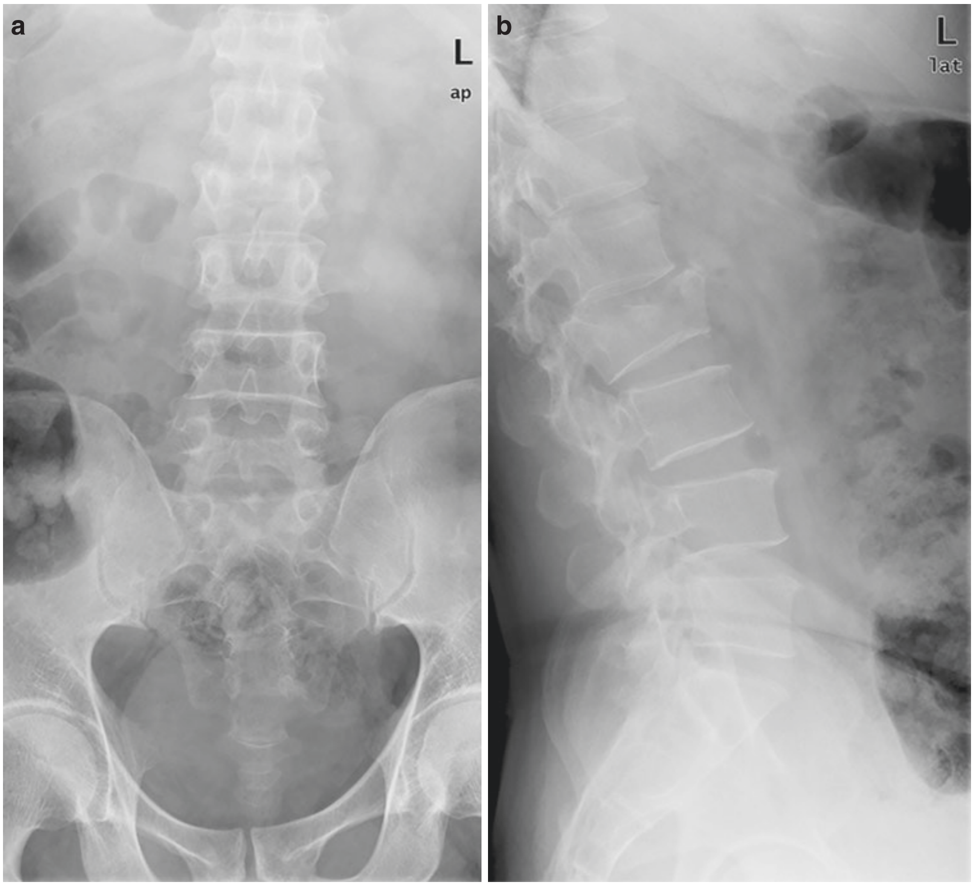


Fig. 2.16 A burst fracture of the L2 vertebral body. (**a**) An AP radiograph showing a height loss of the vertebral body and widening of the space between the vertebral pedicles on the two sides. (**b**) A lateral radiograph: The height of the L2 vertebral body is lost, and the posterior edge line has lost its continuity, accompanied by space-occupancy in the intervertebral foramen, suggesting that the posterior wall has ruptured and that the bone fragment may protrude into the spinal canal

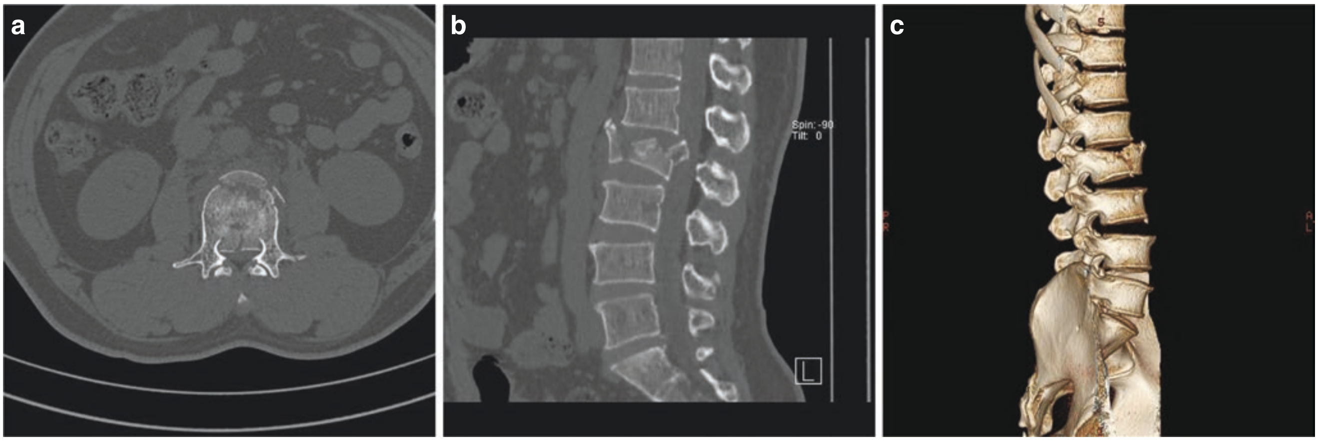


Fig. 2.17 Lumbar CT plain scanning and 3D reconstruction of the same patient in Fig. 2.16. (**a**) Cross-section scan of the L2 vertebral body: The posterior wall of the vertebral body protruded into the spinal canal and occupied >50% of the cross-sectional area of the spinal canal. The anterior column was fractured, and the pedicles remained intact. (**b**) Midline sagittal reconstruction: The posterior wall of the vertebral body protruded into the spinal canal and occupied >50% of the width of the spinal canal, accompanied by rotational displacement of the affected vertebra. (**c**) CT 3D reconstruction providing a full view of the fracture displacement stereoscopically

A change in the Cobb angle suggests a wedge compression fracture.

Disruption of the posterior edge line of the vertebral body and the high-density mass in the intervertebral foramen suggests a space-occupying fragment in the spinal canal.

- CT (Fig. 2.17):
  - CT scanning can be used to precisely evaluate bone damage on multiple planes.
  - For burst fractures, axial CT scans reflect the severity of the space-occupying effect by the fragments in the spinal canal (Vaccaro et al. 2001).

Fig. 2.18 MRI has an extremely high resolution for identifying soft tissue damage. T2-weighted fat-suppressed MRI is helpful for assessments of intramedullary hemorrhage, edema, spinal cord compression, intervertebral disc herniation, etc. (There are no separate caption for Fig. 2.18)

Table 2.2 Stability scoring for the thoracic and thoracolumbar regions

Essentials of assessment	Score
Destruction or failure of anterior structure	2
Destruction or failure of posterior structure	2
Destruction of Sternocostal joint	1
Radiological evaluation	4
Sagittal displacement > 2.5mm	2
Sagittal angulation > 5°	2
Spinal cord or cauda equina injury	2
Dangerous loading anticipated	1

Total score ≥ 5 indicates instability. The dangerous loading anticipated is scored according to the characteristics of different occupations and different types of activities (White and Panjabi 1900)

  - Sagittal reconstruction can evaluate the spinal canal damage caused by a vertebral translation.
  - The CT technology serves as the best tool for examining the vertebral pedicle, vertebral lamina, articular process, and transverse process.
- MRI (Fig. 2.18):
  - MRI can provide more detailed data regarding soft tissue damage.
  - T2-weighted MRI and T2-weighted fat-suppressed MRI serve as useful tools for injury assessment, including intervertebral disc herniation, posterior ligament complex injury, epidural hematoma, and spinal cord edema.

2.1.5.3 Stability Assessment

- Spinal instability refers to the abnormality that under a normal load, the spine loses its intervertebral stability, which causes nerve injury and ultimately chronic pain or malformation (White and Panjabi 1990).
- Stability assessment of the thoracic, thoracolumbar, and lumbar regions was performed according to Tables 2.2 and 2.3.

Table 2.3 Stability scoring for the lumbar spine

Essentials of assessment	Score
Instability of anterior structure	2
Instability of posterior structure	2
Radiological evaluation	4
X-ray photograph in flexion and extension position	
Sagittal displacement > 4.5mm or 15%	2
Sagittal rotation	2
L1/2, L2/3, L3/4 > 15°	
L4/5 > 20°	
L5/S1 > 25°	
Normal X-ray photograph	
Sagittal displacement > 4.5mm or 15%	2
Sagittal angulation > 22°	2
Spinal cord or cauda equina injury	2
Cauda equina injury	3
Dangerous loading anticipated	1

Total score ≥ 5 indicates instability (White and Panjabi 1900)

2.2 Surgical Treatment

2.2.1 Surgical Indications

1. Treatment goals:
   a. Avoid further nerve injury and promote the recovery of neurologic deficits.
   b. Ensure long-term stability of the spine and minimize the number of vertebrae involved in fusion.
   c. Enable early movement of the patient to avoid immobilization-associated complications.
   d. Reduce acute and chronic pain.
2. Indications for surgery:
   a. TLICS system:

Table 2.4 TLICS score scale

Project	Score
Morphological changes	
Compression fracture	1
Bursting fracture	2
Displacement, rotation	3
Traction injury	4
Neurological function	
Complete	0
Nerve root injury	2
Spinal cord, conus medullaris injury	
Incomplete injury	3
Complete injury	2
Cauda equina injury	3
Posterior ligamentous complex	
Complete	0
Uncertain injury	2
Injury	3

- The TLICS system (Table 2.4) evaluates the severity of the thoracolumbar spine injury based on injury-caused morphological changes, neurologic functions, and the condition of the posterior ligament complex, and guides treatment planning.
- Use of TLICS in surgical decision-making (Vaccaro et al. 2005):
  - Decision-making criteria in selecting conservative or surgical treatment: Conservative treatment is recommended when the total TLICS score, which is the sum of the highest scores of the three principle items, is ≤3; surgical treatment is recommended when the total TLICS score is ≥5; the decision is made according to the patient's injury conditions and willingness and the doctor's preference when the TLICS score is at the cut-off level of 4.
  - Decision-making criteria in selecting surgical approaches: For incomplete nerve injury caused by compression of the posterior vertebral wall fragment, a fully anterior decompression must be performed. When the posterior ligament complex is injured, stability reconstruction should be performed via the posterior approach because the complex structure has a poor ability to self-repair. In patients with both of the above situations, the anterior and posterior approaches can be jointly adopted.
  - The significance of TLICS scoring in selecting the surgical approach is controversial.

b. Surgical indications for different types of fractures in the Denis classification (Denis 1983):

- Minor fractures: They can be treated non-surgically, such as thoracolumbosacral orthosis.
- Compression fractures:
  - Stable compression fractures can be treated primarily by wearing a supporting device.
  - For unstable compression fractures, open reduction and internal fixation is performed to prevent the progression of kyphosis and neurologic deficits via the posterior approach.
  - Vertebroplasty is considered after failed conservative treatment.
- Burst fractures:
  - Stable burst fractures are treated with spinal hyperextension orthosis.
  - For unstable burst fractures without neurologic injury:

    Surgical treatment, primarily indirect decompression and internal fixation via the posterior approach, is recommended when the posterior protrusion is >25°, vertebral height loss is >50%, and intra-spinal canal space-occupancy is >40%.

    Fractures with severe anterior collapse or old injury are treated with subtotal corpectomy and supporting material implantation (bone graft or titanium cage) via the anterior approach.
  - For unstable burst fractures associated with neurologic injury:

    The posterior process fragment(s) and intervertebral disc(s) are thoroughly removed via the anterior approach.

    The number of vertebral segments involved in decompression, the amount of graft required, and the necessity for joint use of the anterior and posterior approaches for fixation are decided according to the injury condition.
- Chance fractures:
  - Denis Type A fractures associated with kyphosis <15° and without neurologic injury are treated with spinal hyperextension orthosis.
  - Chance fractures passing ligaments:

    They often heal with scar formation.

    Conservative treatment usually fails due to low healing strength.

    The primary treatment is surgical fixation via the posterior approach.

    Whether there is an intervertebral disc herniation should be determined by MRI prior to surgery.

  - Displaced fractures:
    - They are highly unstable.
    - They are often associated with interlocking of the posterior joint; therefore, pedicle screw fixation via the posterior approach is commonly used.
    - The anterior approach or a joint anterior and posterior approach can be used if needed.
3. Timing of surgery.
   a. The timing of surgery for treating spinal injury remains controversial.
   b. Most researchers believe that progressive neurologic injury is the indication for emergency decompression (Chapman and Anderson 1994).
   c. For non-progressive, incomplete, and complete spinal injuries, some researchers recommend surgery as early as possible, while others recommend delayed surgery, i.e., surgery after recession of spinal edema. For complete spinal injury, it is generally believed that early surgery can shorten the hospital stay of the patient (Chipman et al. 2004; Gaebler et al. 1999).
   d. The necessity for early decompression relies on the potential benefit to the recovery of neurologic deficits, the patient's general condition, accompanying injuries, and the hospital condition (e.g., operating room, treatment team).

2.2.2 Surgical Techniques

2.2.2.1 Open Reduction and Internal Fixation Via the Posterior Approach for Thoracolumbar Fractures

1. Body position and preoperative preparation:
   a. General anesthesia via nasotracheal vs. orotracheal intubation.
   b. The patient lies in the prone position on a radiolucent operating table, with a C-arm or CT system set up for intraoperative radiographic monitoring.
   c. Cushions are placed beneath the upper chest and at the level of the anterior superior iliac spines to suspend the abdominal area.
   d. To avoid overpulling and damaging the brachial plexus, the shoulder joints should not be abducted >90°. In addition, the elbows and wrists should be protected by soft cushions to avoid compressing and injuring the ulnar and median nerves.
   e. The knees are bent and placed on soft cushions to relax the sciatic nerve.
   f. Both feet are relaxed with all toes suspended.
2. Operative incision according to the projection on the body surface: The affected vertebra is identified and located radiographically prior to surgery. With the spinous process of the affected vertebra as the midpoint, a central longitudinal incision is created along it and the adjacent spinous processes (Fig. 2.19).
3. Surgical approaches (Fig. 2.20):
   a. The skin and subcutaneous tissue are cut layer by layer to expose the lumbodorsal fascia and spinous process.
   b. The fascia and periosteum of the spinous process is sharply dissected closely along the spinous process using an electric knife, and a subperiosteal separation is performed closely along the spinous process and vertebral lamina using a periosteum stripper. If the lambdoidal ridge is clearly visible, the sacrospinous muscle is laterally separated up to the lateral facet joint at both sides; otherwise, the sacrospinous muscle is separated laterally up to the transverse process.
   c. The sacrospinous muscles on both sides are pulled aside to expose the vertebral lamina using an auto-

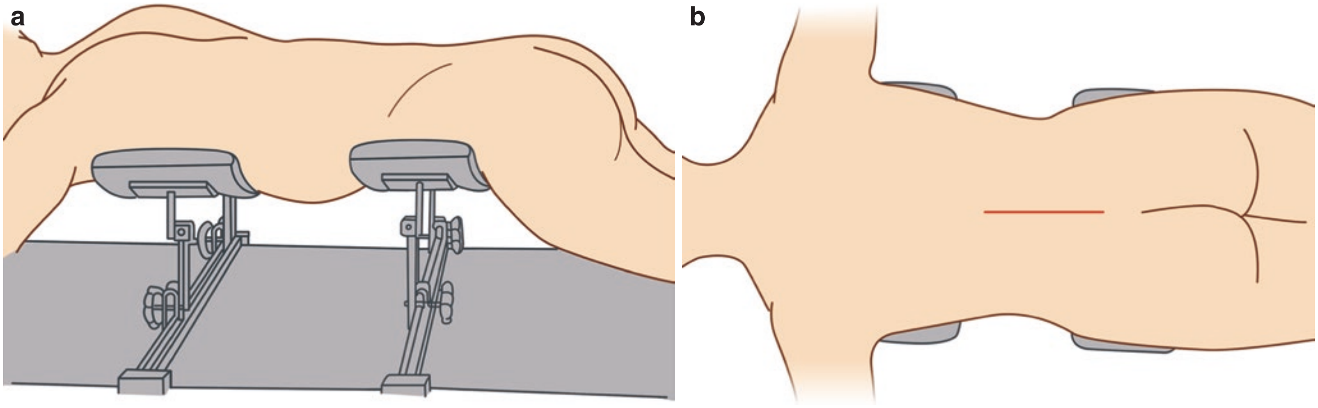


Fig. 2.19 (**a**) Body position for surgery: The patient lies in the prone position on a radiolucent operating table with cushions beneath the upper chest and at the level of the anterior superior iliac spines to suspend the abdominal area. (**b**) The surgical incision is determined according to the location and range of the lesioned area. With the spinous process of the diseased vertebra as the center, a median longitudinal incision is created along the spinous process line and extended appropriately to the distal and proximal ends as required

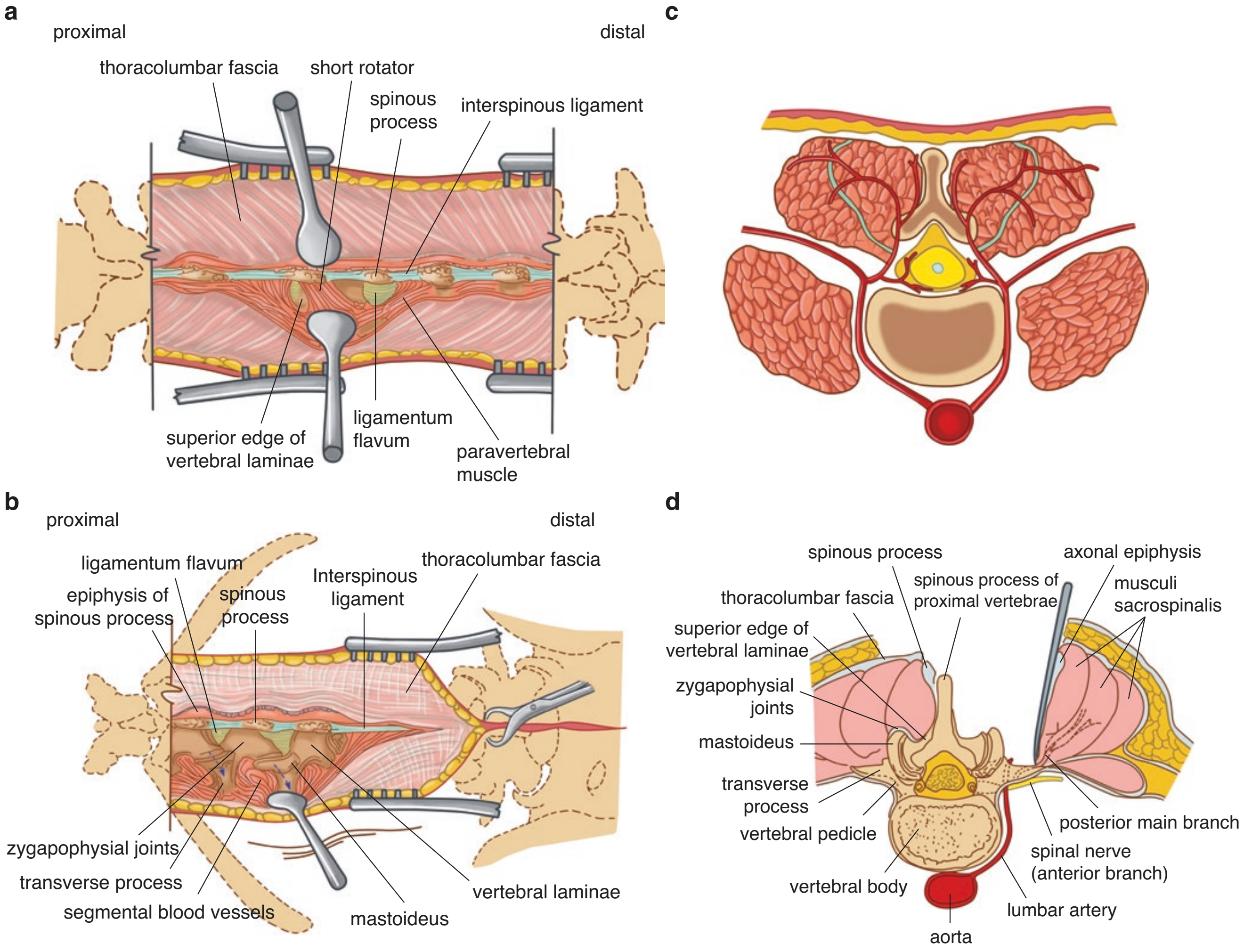


Fig. 2.20 Schematic diagram of the thoracolumbar posterior approach. (**a**) The skin and subcutaneous are cut open layer by layer to expose the lumbodorsal fascia and spinous process, the fascia and periosteum of the spinous process are sharply incised with an electric knife, and the paravertebral muscle is separated subperiosteally. (**b**) The paravertebral muscle is dissected from proximal to distal with a periosteal stripper. Attention should be paid to protecting the joint capsule of the two vertebrae above and below the lesioned vertebra. (**c**) The segmental vessels supplying the paravertebral muscles perforate on the cross-section between the superior and inferior transverse processes. (**d**) During the process of exposing the vertebral lamina, it is important that the bleeding from the segmental blood vessels is stopped by electrocoagulation in a timely manner

matic retractor. There are abundant segmental vessels exiting between the transverse processes; hence, electrocoagulation should be performed in a timely manner to stop bleeding.

   d. The residual soft tissue on the spinous process, vertebral lamina, and capsule of the facet joint is further removed.

4. Fracture reduction and fixation:
   a. Determination of the pedicle screw entry point (Fig. 2.21):
      - Thoracic spine:
         – The entry point is the intersection of the horizontal line passing the upper ridges of the transverse processes and the inferolateral rims of the superior articular processes.
      - Lumbar spine:
         – The lambdoidal ridge technique (Du et al. 2002): The entry point is the apex of the lambdoidal ridge, which avoids overexposure of the transverse process and reduces damage
         – The Magerl method (Magerl 1984): The entry point is the intersection of the horizontal line passing the midpoints of the transverse processes and the line perpendicular to the lateral rims of the articular processes.
   b. Direction of pedicle screw placement (Fig. 2.21):

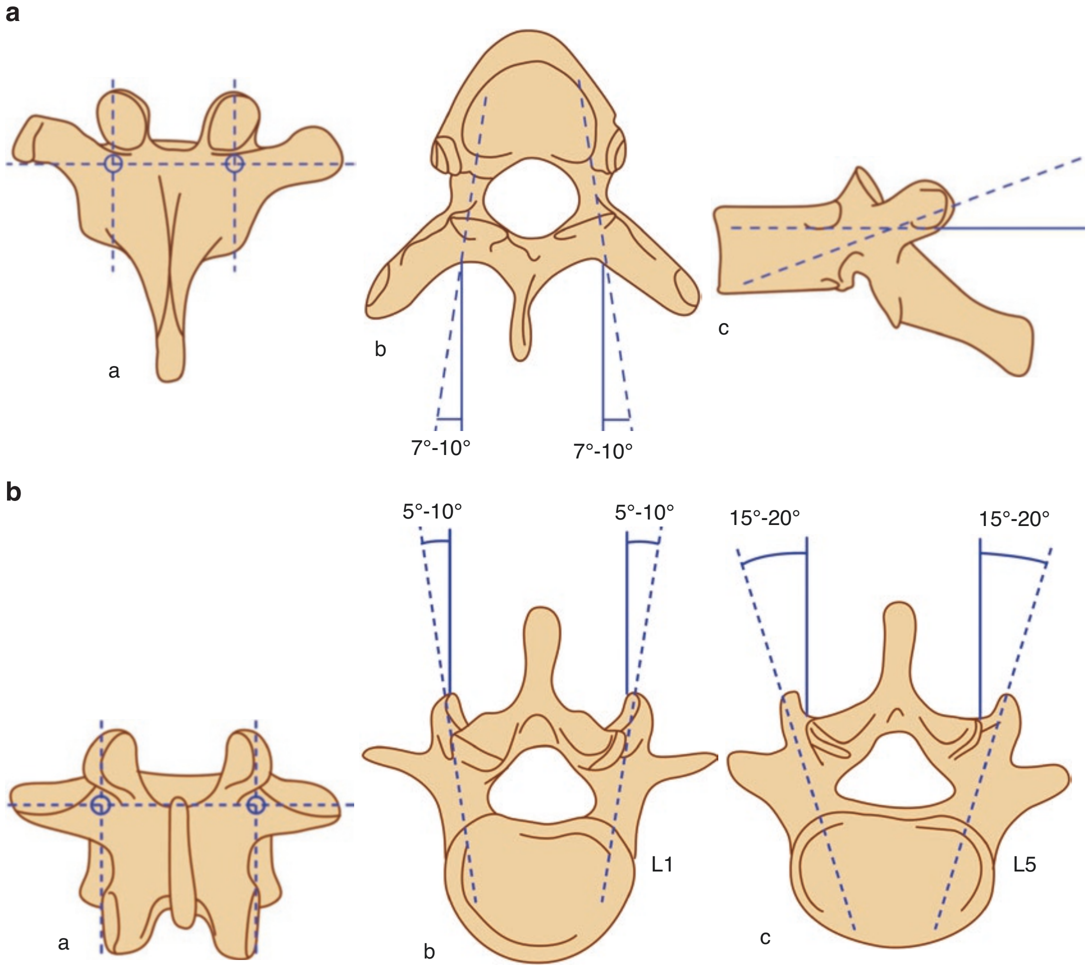


Fig. 2.21 (**a**) The entry point and direction of thoracic pedicle screws: The entry point is located below the superior articular process and at the intersection of the horizontal line of the superior spine of the transverse process and the inferolateral edge of the superior articular process (**a**); the screw tilts laterally by 7–10° (**b**), inclining to the head side by 0–20° (**c**). (**b**) The entry point and direction of lumbar pedicle screws: The entry point is located at the vertex of the lambdoidal ridge, or at the intersection of the horizontal line passing the midpoint of the transverse process and the vertical line through the lateral edge of the articular process (**a**); the convergence angle of the screw is 5–10° at the upper lumbar spine (**b**). The convergence angle of the L5 screw is increased to 15–20° (**c**)

- Lower thoracic spine (taking T10 as an example): On the coronal plane, the pedicle screw should point to the center at an angle of 7–10° relative to the sagittal line; on the sagittal plane, the screw points to the caudal side at an angle of 10–20°.
- Convergence angle of the lumbar pedicle screw: The lumbar pedicle screw on each side has a convergence angle of 5–10° at the upper lumbar spine and 15–20° at L5.

c. Pedicle screw placement technique: Below is an example of Schanz screw placement for reduction and fixation (Fig. 2.22).
    - The bone cortex at the planned entry point is opened using a vertebral pedicle taper or nibbled out with a bone rongeur.
    - A vertebral pedicle probe is inserted at the entry point and advanced for approximately 3 cm along the channel in the vertebral pedicle. Special attention should be paid to the tilt angle when probing, which varies among different vertebral segments.
    - A ball-tipped probe is used to verify whether the wall of the vertebral pedicle is intact and whether the cortex at the end of the channel is penetrated.
    - A Kirschner wire is inserted along the channel, and its appropriate position, angle, and length are confirmed with C-arm fluoroscopy or CT fluoroscopy.
    - After the Kirschner wire is pulled out, a Schanz screw is screwed in using a T-handle. Lateral C-arm fluoroscopy or CT fluoroscopy is used to determine whether the screw has penetrated the cortex at the

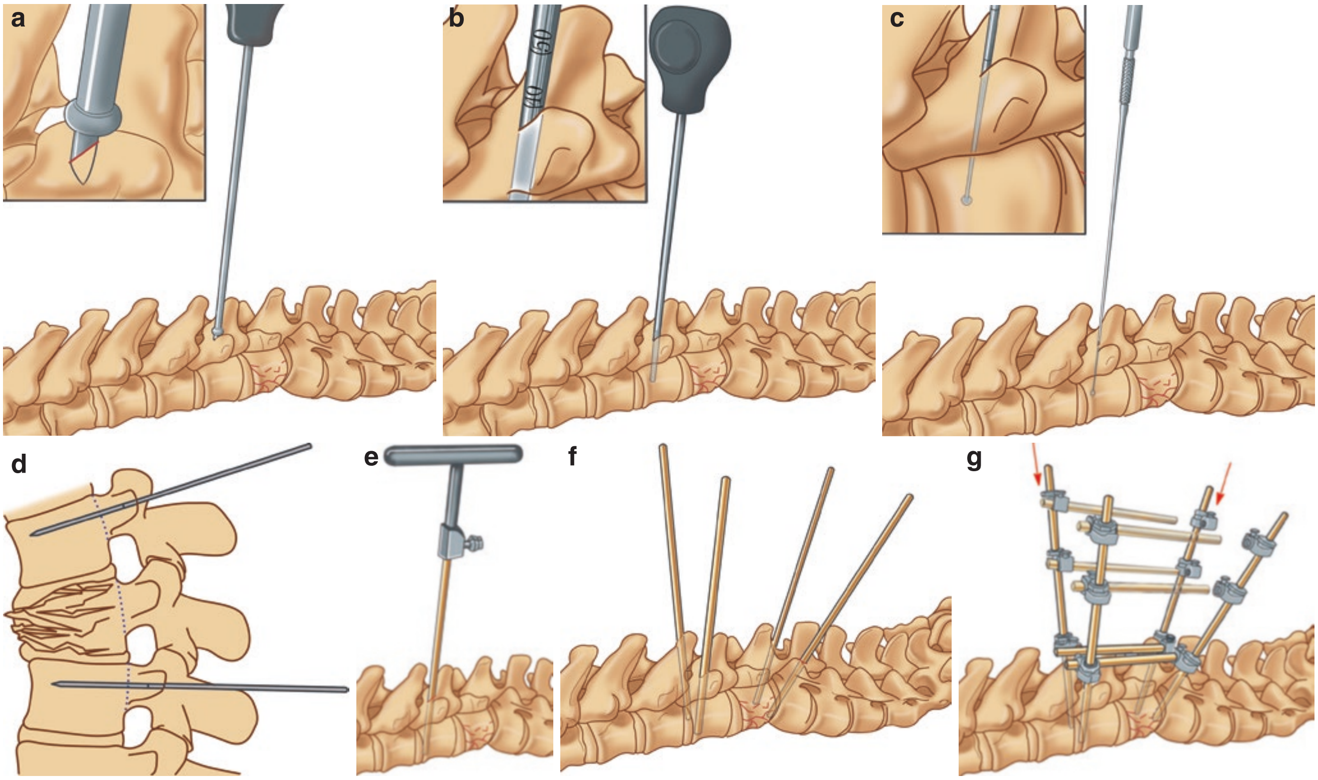


Fig. 2.22 (**a**) The cortical bone at the entry point is opened using a sharp taper. (**b**) The pedicle probe is inserted approximately 3–4 cm in depth. (**c**) The ball-tipped probe is used to examine whether the wall of the pedicle is intact and whether the track breaks through the anterior surface of the vertebral body. (**d**) A Kirschner wire is inserted along the track, and its appropriate position is confirmed radiographically. (**e**) The Schanz screw is advanced with a T-shaped handle. (**f**) Four Schanz screws are placed sequentially. (**g**) The connecting rods are installed; after reduction, the connecting rods and screws are locked

end of the channel, and AP images are obtained to determine whether the screw has crossed the midline.

d. Fracture reduction technique.
   - The primary step of the posterior approach to reduce the fractured vertebra is to distract the vertebrae above and below apart. Vertebral distraction can tighten the posterior longitudinal ligament, and then the restitution force of the tightened ligament pushes and reduces the fragment protruding into the spinal canal. In addition, vertebral distraction helps to restore the height of the affected vertebra.
   - The reduction method varies based on the actual situation of the fracture:
     - Fractures with an intact posterior wall (Fig. 2.23):

       The rear ends of the Schanz screws are pulled closer to each other to restore the natural lordosis of the spine using a hollow cylindrical sleeve.

       The pivot point for distracting vertebrae is on the posterior wall of the affected vertebra.

       The nuts are locked by the hollow cylindrical sleeve to fix the angle between the Schanz screws and the fixation rods.

       With a rod holder or C ring as support, the vertebrae above and below the fractured vertebra are distracted to restore the normal height of the vertebra, followed by locking of the nuts.

       A transverse connector is installed to enhance the stability if necessary.

       After all bolts are tightened again, the Schanz screws are trimmed to an appropriate length using a trimmer.
     - Fractures with a damaged posterior wall (Fig. 2.24):

       The damaged posterior wall of the affected vertebra cannot be a pivot point for distraction; as a result, the pivot point must be posteriorly shifted onto the fixation rod.

       By placing a C-ring or a rod holder at the sites approximately 5 mm away from the clamp on the fixation rod, the kyphosis can be corrected by approximately 10°.

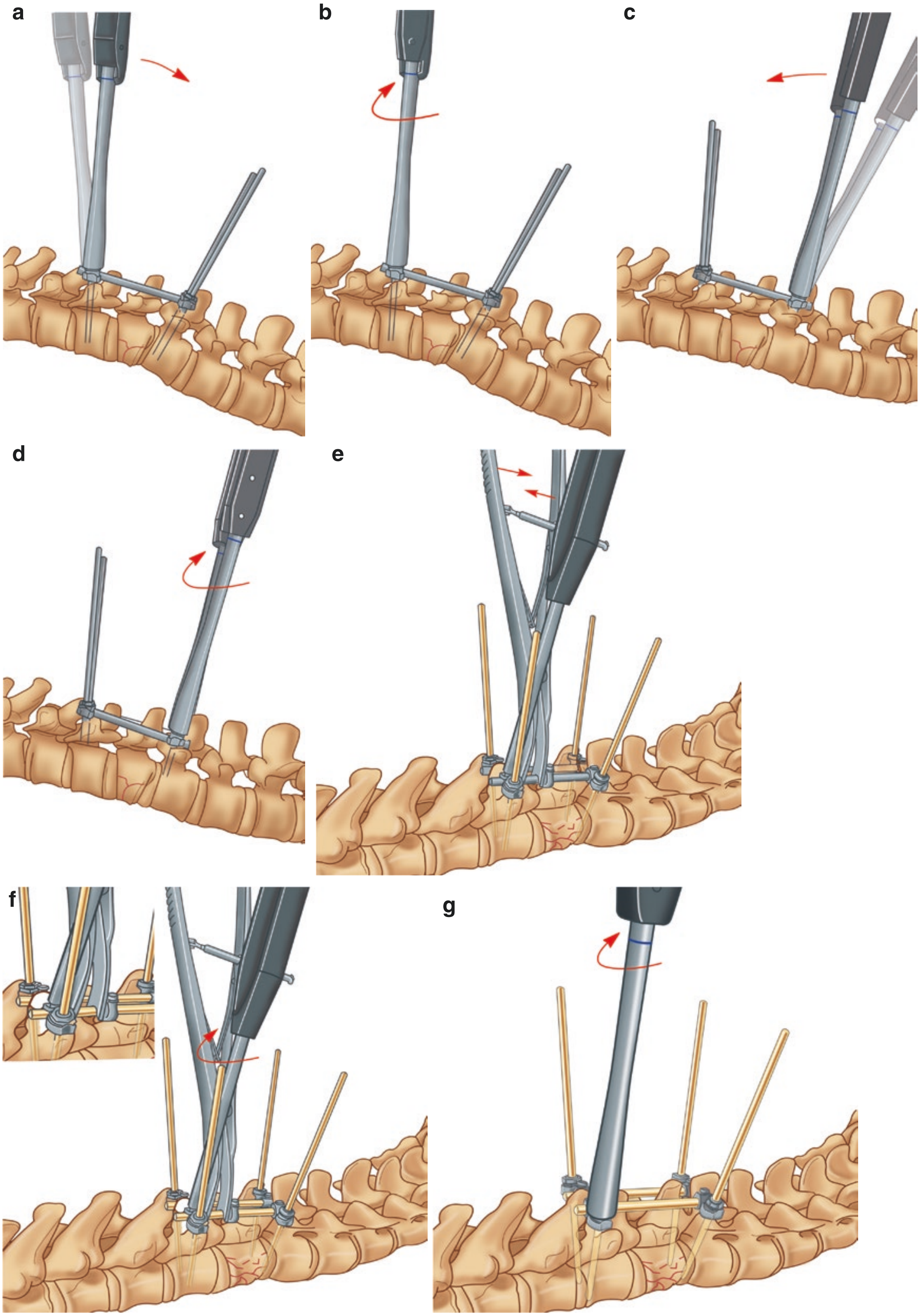


Fig. 2.23 The reduction method for a compression fracture with an intact posterior wall. (**a**, **b**) First, in the vertebral body proximal or distal to the fractured vertebra, a hollow cylindrical sleeve is used to hold the rear end of the Schanz screw to restore lordosis of the spine, followed by locking the nut and securing the angle between the Schanz screw and the fixation rod. (**c**, **d**) The above procedures are repeated on the other side of the fractured vertebra. (**e**, **f**) The C-rings are installed on the connecting rods and distracted open with the distractor. The vertebral height is restored under fluoroscopy, followed by locking the nut and fixing the positions of the Schanz screws and connecting rods. (**g**, **h**) After restoring the lordosis angle and the height of the vertebral body, it is crucial to ensure that all the nuts are locked firmly. (**i**) The Schanz screws are trimmed to the appropriate length with a cutter. (**j**) A transverse rod is installed to increase stability if necessary

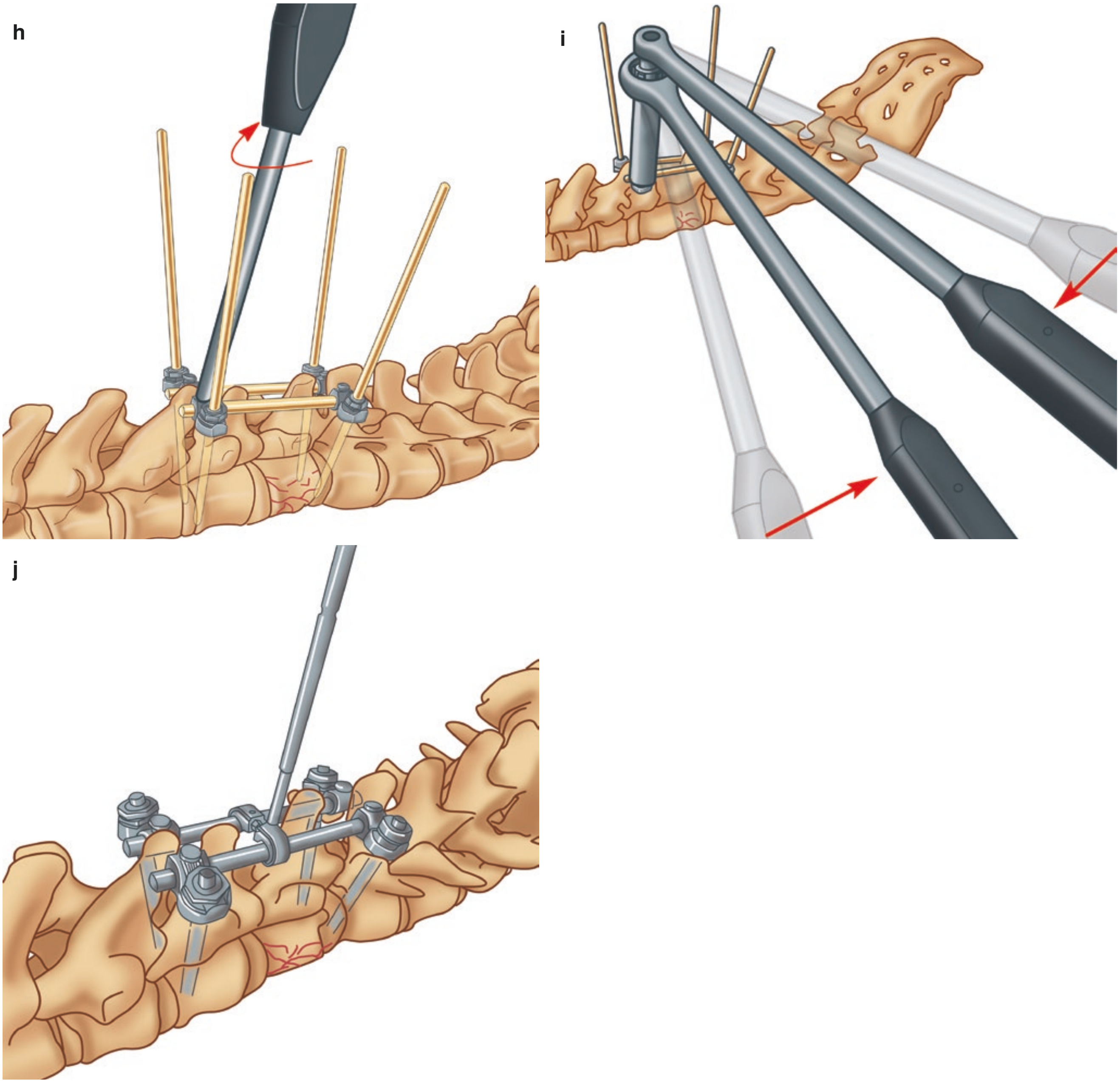


Fig. 2.23 (continued)

During restoration of the natural lordosis of the spine, the fixation clamps are moved closer to shift the pivot point from the posterior wall of the vertebra to the fixation rod.

Distraction is performed with a distractor to restore the height of the affected vertebral segment following the method same as described above.

- Reduction of Chance fractures:

  The implants act as tension band.

  First, natural lordosis of the spine is restored following the method same as described above.

  Next, a C-ring is placed on the connecting rod.

  After slight compression is applied with a retractor, the nuts are locked (Fig. 2.25).

- Advantages of intraoperative CT scanning in repairing ligaments:

  In the Chinese People's Liberation Army General Hospital (the 301 Hospital), the operating room is equipped with a CT system for intraoperative scanning, which demonstrates the quality of ligament repair during reduction via the posterior approach and dynamically and quantitively evaluates

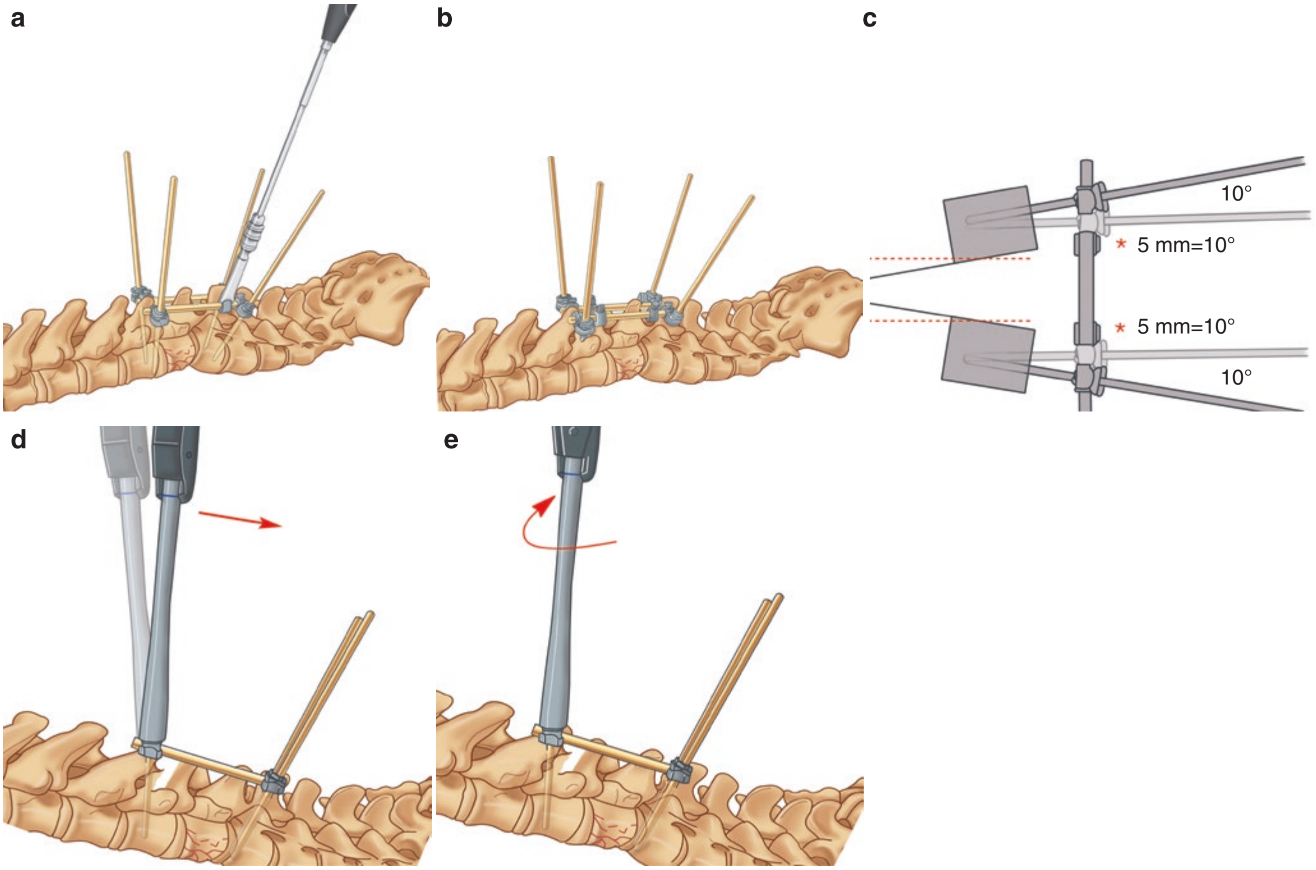


Fig. 2.24 Reduction of fractures with an incomplete posterior wall. (**a**, **b**) Four C-rings are placed on the fixation rod. (**c**) The C-rings are placed 5 mm away from the fixation clamp, which can be used to correct the kyphosis by 10°. (**d**, **e**) The natural lordosis of the spine is restored and fixed with a hollow cylindrical sleeve

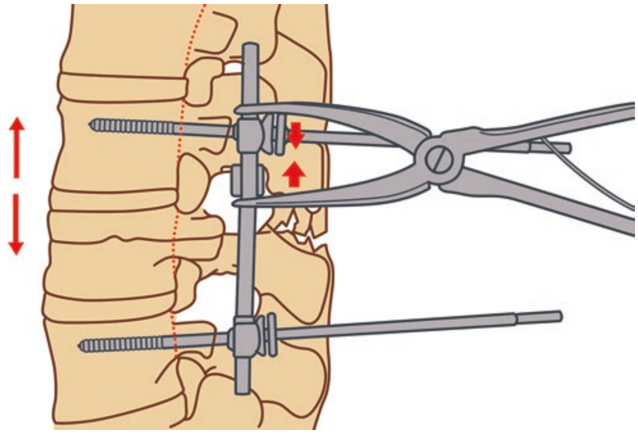


Fig. 2.25 A C-ring is placed between the two fixation clamps. After the segment between the fixation clamp and the C-ring is slightly compressed, the screws are locked firmly

the severity change of the space-occupancy of the fragment protruding into the spinal canal.

After fracture reduction, intraoperative CT scanning can precisely evaluate the quality of ligament repair, thereby decreasing the necessity of the second surgery for unsolved space-occupying in the spinal canal detected by CT scanning after surgery. Similarly, intraoperative CT scanning can precisely identify the protruding fragment in the canal that can be reduced via the posterior approach alone, thus avoiding the unnecessary trauma resulting from the joint use of the anterior and posterior approaches for compression.

When intraoperative CT scanning reveals the presence of the space-occupying fragment in the spinal canal after distraction, full decompression via the anterior approach should be immediately performed.

Intraoperative CT scanning can also be used to three-dimensionally observe the direction and depth of pedicle screw placement and accurately measure the distraction angle and height of the affected vertebra (Figs. 2.26 and 2.27).

5. Incision closure: After a drainage tube is placed, the lumbodorsal fascia and subcutaneous tissue are sutured using

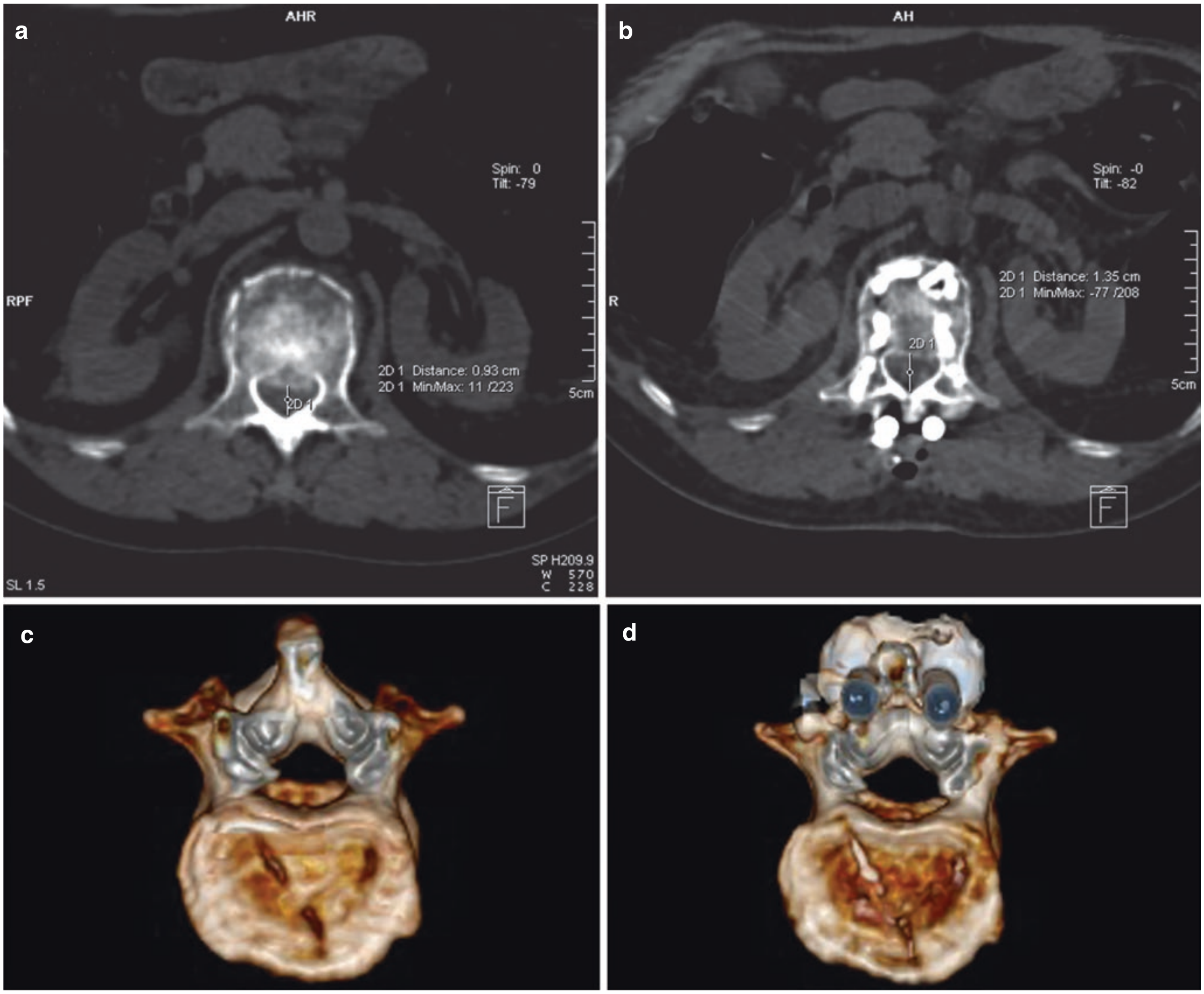


Fig. 2.26 (**a**, **b**) Intraoperative CT measurement of the sagittal diameter of the spinal canal before and after distraction: The anterior sagittal diameter is 93 mm before distraction and 135 mm after distraction. (**c**, **d**) The reduction of the posterior wall fragment can be clearly observed in the 3D reconstructed image. (**e**, **f**) Median sagittal reconstruction: The posterior wall fragment rotated and protruded into the spinal canal before surgery. After distraction, the restitution force of the ligaments rotated and reduced the bone fragment, thereby restoring the sagittal diameter of spinal canal. (**g**) Intraoperative CT scanning was used to measure the depth and angle of Schanz screw insertion, as well as to determine whether the screws protruded from the inner wall of the pedicle and injured the spinal cord

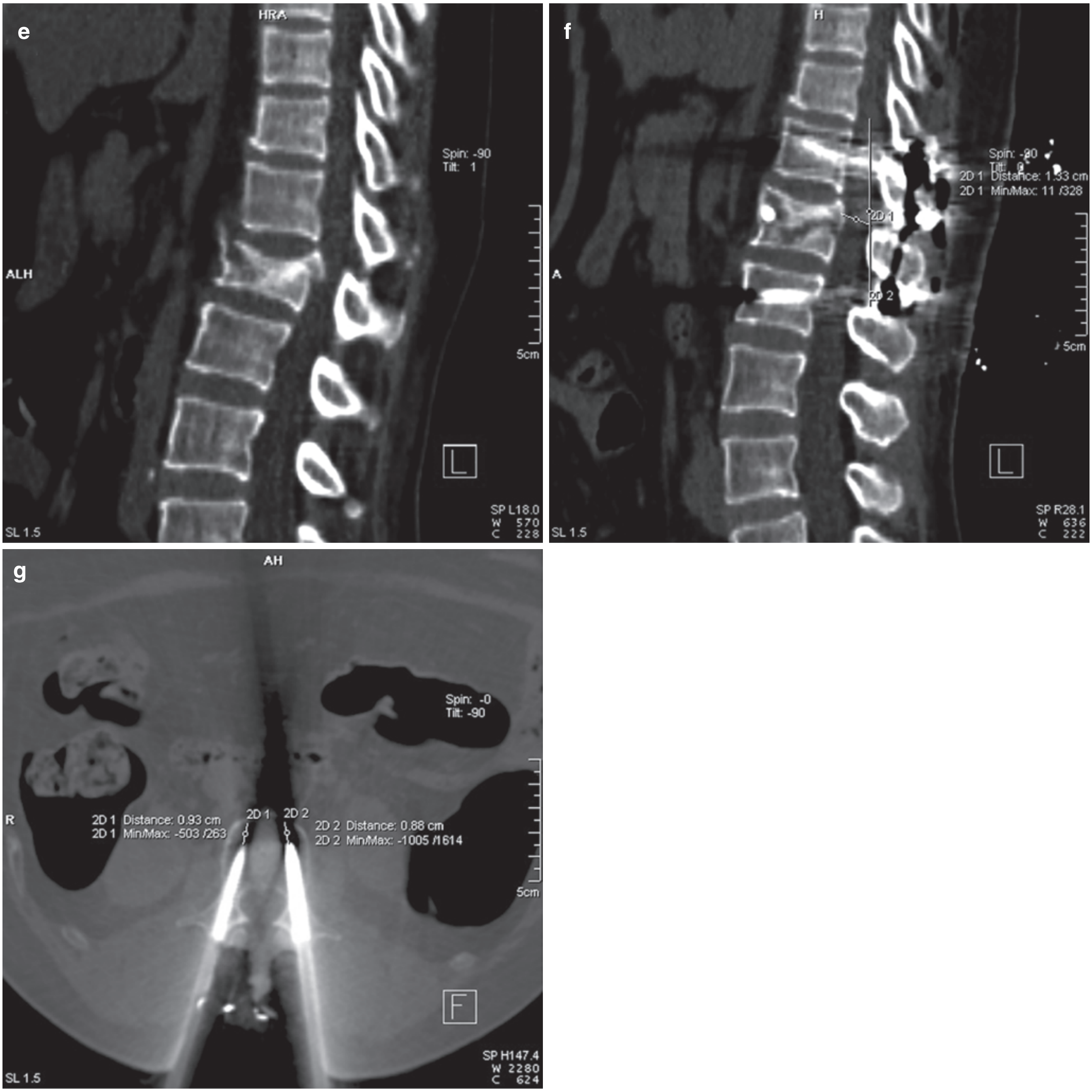


Fig. 2.26 (continued)

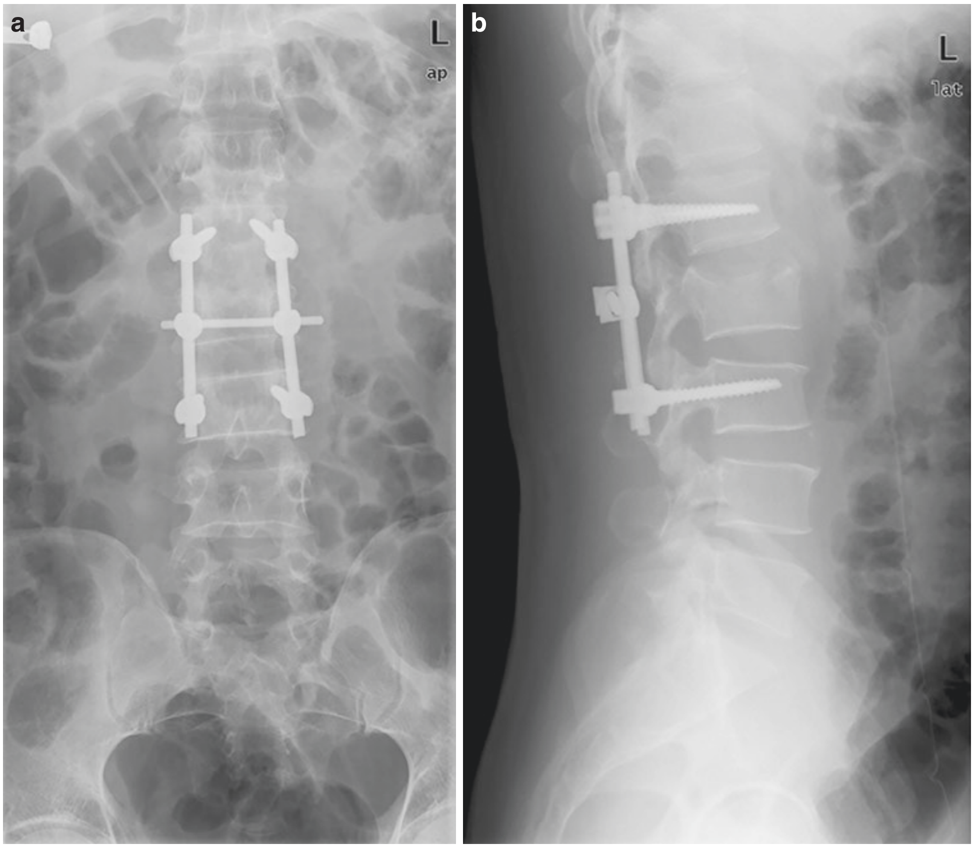


Fig. 2.27 A patient with burst fracture of the L2 vertebral body, for whom the preoperative imaging data are shown in Figs. 2.16, 2.17, and 2.18. The patient underwent open reduction and internal fixation via the posterior approach, in which the adjacent two vertebral bodies were distracted to restore the height of the fractured vertebral body and lumbar lordosis, and the space-occupying fragment in the spinal canal was reduced. (**a**) A postoperative AP radiograph. (**b**) A postoperative lateral radiograph

either an interrupted stitch with silk suture or intradermal stitch with an absorbable suture, and the surgical incision is finally closed.

6. Postoperative management:
   a. The patient lies supine, but the body is flipped periodically to avoid pressure sores within the first 24 h after surgery.
   b. The drainage tube is removed at 48 h postoperatively.
   c. At 4–6 weeks postoperatively, the patient can stand up and move while wearing an orthopedic corset.
   d. At 12–18 months postoperatively, the stability of the spine is assessed, and the timing for the removal of internal fixators depends on the actual situation.

2.2.2.2 Open Reduction and Internal Fixation Via the Anterior Approach for Treating Lumbar Fractures

- Body position and preoperative preparation:
  - The patient undergoes general anesthesia through orotracheal intubation.
  - The patient lies in the right lateral decubitus position. Access to the surgical field is at the left side to avoid obstruction caused by the liver and vena cava.
  - The waist of the patient is positioned at the site of the operating table where the table can be folded, which increases the distance between the twelfth rib and lilac crest and thereby facilitates the operation.
  - A cushion is placed under the armpit to protect the nerves and vessels from compression.
- Incision projection on the body surface: The position of the incision slightly varies with the location of the affected vertebra (Fig. 2.28).
- Surgical approaches (Fig. 2.29):
  - The subcutaneous tissue, fascia, musculus obliquus externus abdominis, musculus obliquus internus abdominis, musculus transversus abdominis, and transversalis fascia are dissected sequentially along the skin incision.
  - After the peritoneum and extraperitoneal fatty tissue are identified, the peritoneum is flipped anteriorly to avoid being damaged in subsequent procedures.
  - The psoas major is an important anatomic landmark of the retroperitoneal space. A series of critical anatomic structures, including the genitofemoral nerve (GFN) and ureter, can be found on the surface of the psoas major. For protective purposes, the ureter is pulled anteriorly along with the peritoneum.
  - The psoas major is bluntly separated from above the lumbar vertebra and pulled laterally. Subsequently, the vessels associated with the affected segment are exposed, ligated, and severed to expose the affected vertebra.
- Decompression and fixation:
  - The vertebral pedicle is carefully dissected with a small periosteum stripper; the vertebral pedicle is nib-

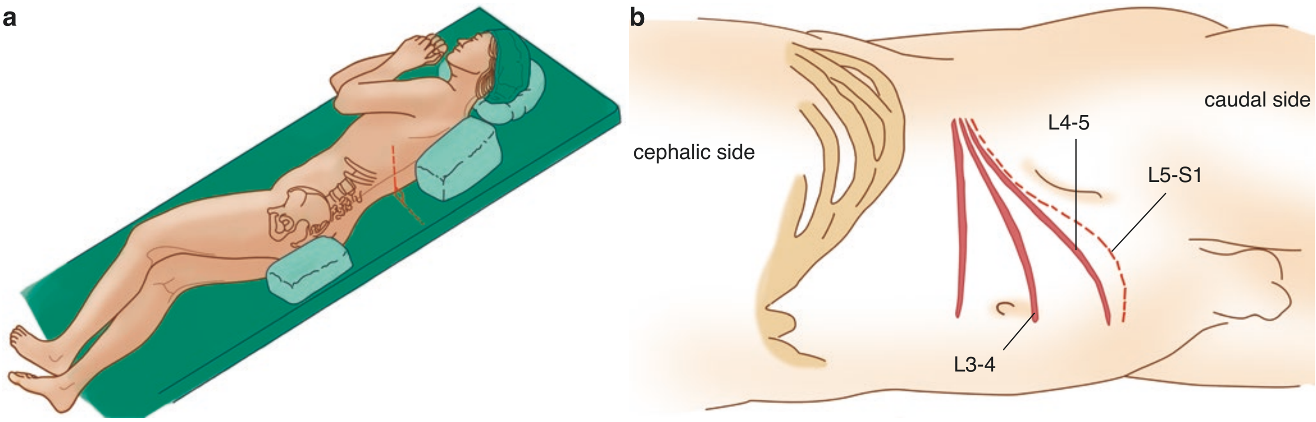


Fig. 2.28 Body position and surgical incision of the anterior approach to the lumbar spine. (**a**) The patient lies in the right lateral decubitus position, and to help improve exposure, the waist is positioned to be at the site of the operating table where the table can be folded. (**b**) Different incisions for exposing different vertebrae

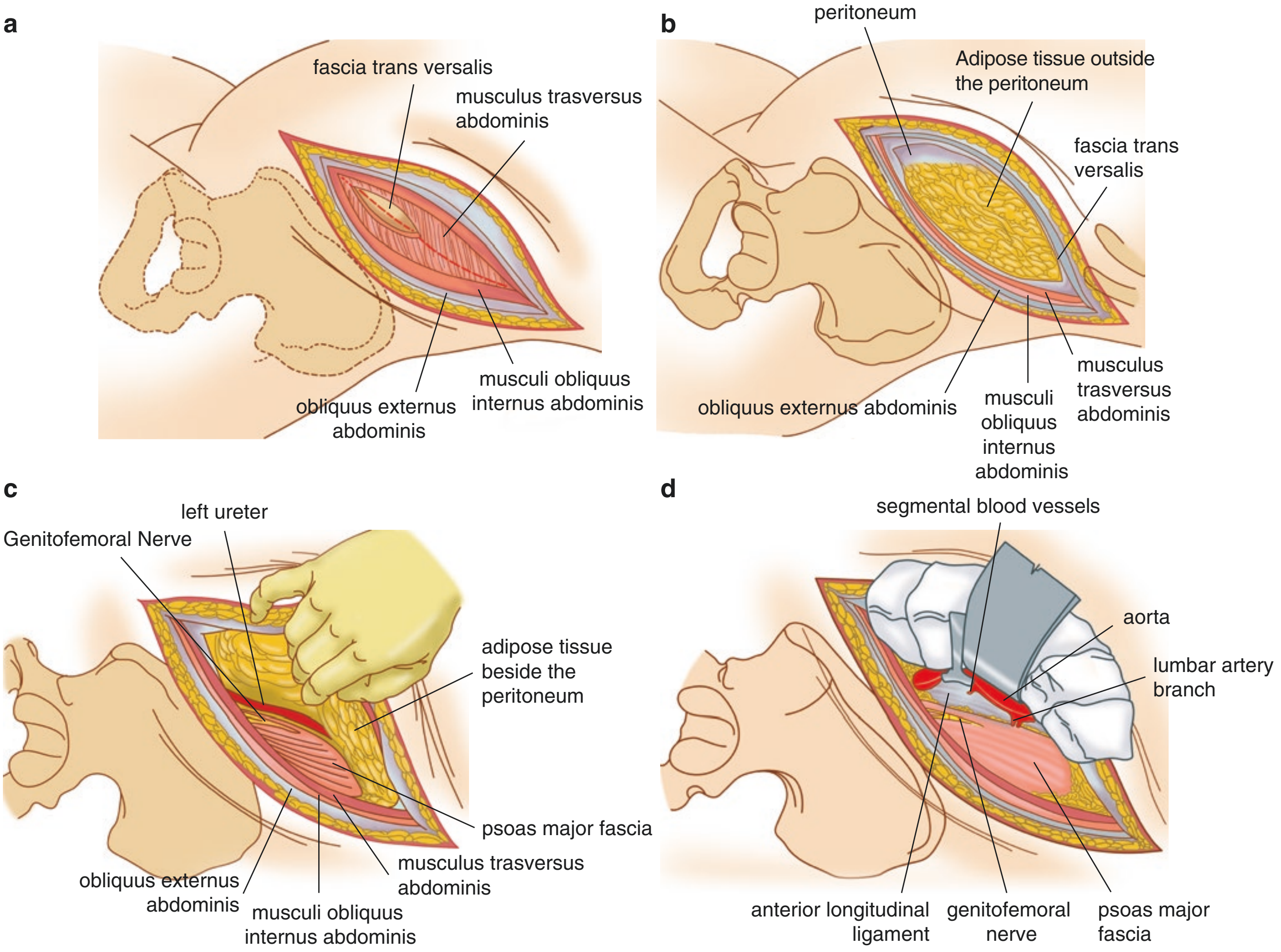


Fig. 2.29 Anatomical schematic of the anterolateral approach to the lumbar spine. (**a**) The skin, subcutaneous tissue, musculus obliquus externus abdominis, musculus obliquus internus abdominis, musculus transversus abdominis, and transversalis fascia are dissected sequentially along the skin incision. (**b**) The peritoneum is flipped anteriorly. Special attention should be paid to protecting the peritoneum and internal organs. (**c**) The important structures such as the genitofemoral nerve (GFN) and ureter can be found on the surface of the psoas major, which should be pulled anteriorly together with the peritoneum for protection. (**d**) The blood vessels of the involved segments are ligated and severed sequentially, and then the affected vertebral body is exposed

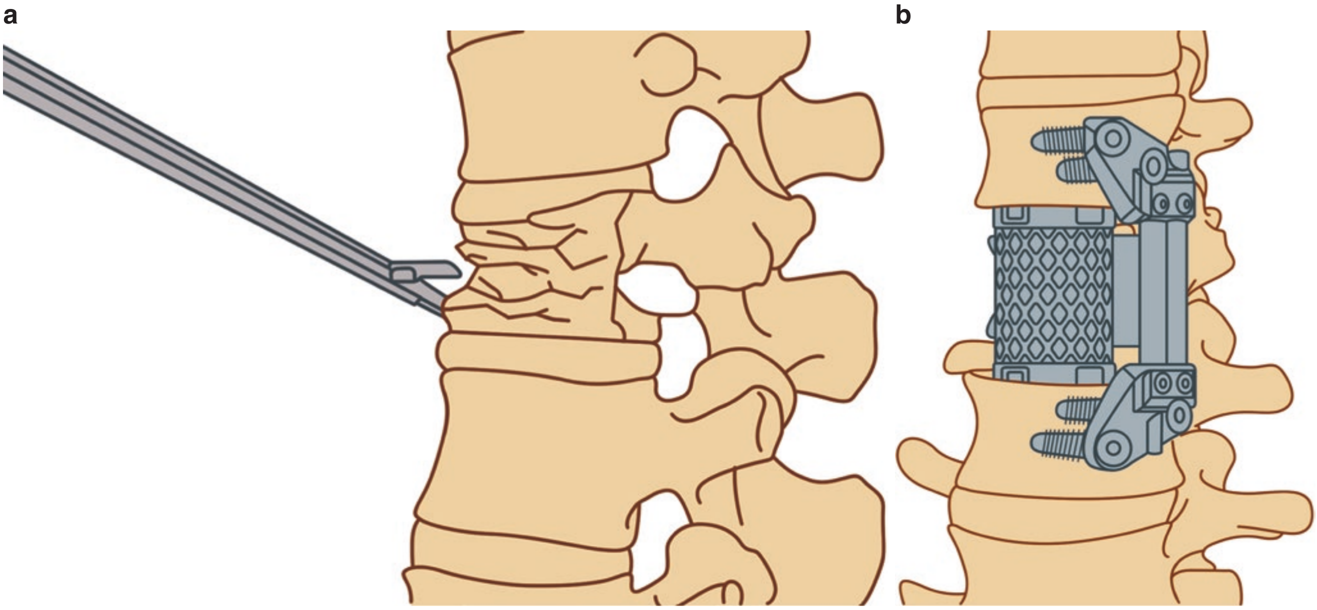


Fig. 2.30 (**a**) The lesioned vertebral body is nibbled off up to the end of the pedicle with a rongeur. (**b**) The mechanical stability of the anterior and middle columns of the spine is reconstructed using a titanium cage and a lateral screw-rod fixation system

  bled out with a bone rongeur if exposure of the endorachis is required.
  - After the intervertebral foramen is identified by tracing along the vessel-nerve bundle, the intervertebral foramen above and below the affected vertebra are dissociated from the surrounding structure up to the affected segment, and then, both the intervertebral discs above and below the affected vertebra are removed. Next, the vertebral body is nibbled out with a bone rongeur up to the end of the vertebral pedicle. It is necessary to examine the intervertebral disc above to avoid any residual ruptured fragment.
  - For full decompression, the posterior longitudinal ligament is cut to expose the dural sac without damaging the nerve root.
  - After removal of the vertebral body, a series of methods, including a lateral pin-rod system, fusion cage, titanium cage, and autologous bone grafting, can be considered to reconstruct the mechanical stability of the anterior and middle columns of the spine (Fig. 2.30).
- Incision closure: The incision is sutured layer by layer according to the anatomical structure after placing a drainage tube at the surgical site.
- Postoperative management:
  - A patient-controlled intravenous analgesia (PCIA) pump can be administered.
  - Movements while wearing a supporting device are allowed beginning at postoperative day 2.
  - The drainage tube can be removed on postoperative day 2.
  - Follow-up AP and lateral radiographs are obtained after surgery (Fig. 2.31).

2.2.3 Experience and Lessons

- Clinical decision:
  - The need for long-segment fixation: Most burst fractures can be reduced by posterior distraction that tightens the structures, including the posterior longitudinal ligament. However, for patients with severe kyphosis and an unstable spine, long-segment fixation might be a better option that achieves higher stability. The disadvantage is that the fixation stress is concentrated at the sites above and below the fixed segments, which might cause a loss of motion range of the lumbar spine and subsequent degeneration of the joints.
- Surgical operations:
  - Subperiosteal stripping: It is crucial to create access to expose the surgical field by subperiosteal stripping rather than dissociation in the muscular layer, as the latter could cause massive bleeding. A good practice is either sharp subperiosteal dissociation using a periosteum stripper or electric knife or blunt subperiosteal separation using gauze.
  - After the segmental arteries are derived directly from the aorta, they travel between the transverse processes and supply blood to the paravertebral muscles. Therefore, bleeding often occurs during separation near the transverse processes, which can be stopped using a bipolar electrocoagulator.

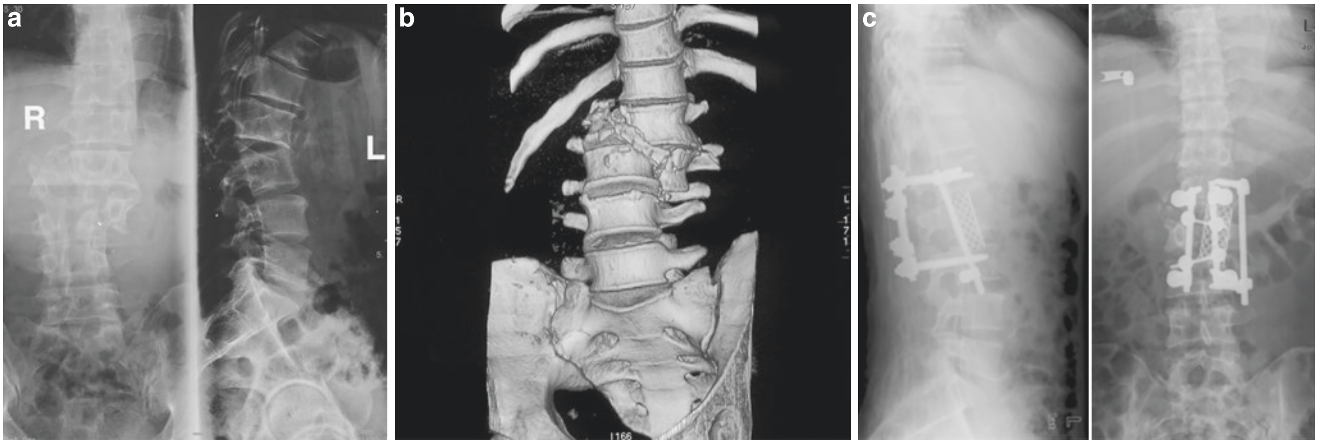


Fig. 2.31 A 37-year-old male patient who was injured from a fall. (**a**) A preoperative radiograph: The L2 vertebral body had a burst fracture and dislocation. (**b**) Preoperative CT 3D reconstruction: The L2 vertebral body was comminuted and luxated to the lateral side. The lower edge of the L1 vertebral body almost overlapped with the upper edge of the L3 vertebral body. (**c**) The anterior and posterior approaches were jointly used. The subtotal corpectomy, decompression of the spinal canal, implantation of a titanium mesh cage, and screw-rod fixation were conducted via the anterior approach. The pedicle screw fixation was performed via the posterior approach

- During Kirschner wire insertion and the subsequent radiographic examination prior to pedicle screw placement, the Kirschner wires can be wrapped with bone wax to reduce intramedullary bleeding.
- Position of the vertebral pedicle screws: Examination with a ball-tipped probe is critical and ensures that the vertebral pedicle is intact and that the planned screw channel does not break the anterior vertebral body prior to placement of a vertebral pedicle. In addition, the vertebral pedicle screws on both sides must not cross the midline while they are advanced as deep as possible up to the subchondral bone to enhance their anchorage. After vertebral pedicle placement, both AP and lateral radiographs are obtained to ensure that all screws are at the correct positions.
- Necessity for fixation of the affected vertebra:

  It has been reported that, in a portion of patients who need long segment fixation, vertebral pedicle screw placement into the affected vertebra can enhance the stability of the spine, and therefore, an additional short-segment fixation is acceptable (Mahar et al. 2007);

  Wang et al. reported a fixation method for the affected vertebra that places the pedicle screws in positions slightly higher than the adjacent vertebrae and then connects the screws with a rod. The advantage of this method is that the affected vertebra can be pushed anteriorly to promote recovery of the natural lordosis.
- Minimally invasive placement of pedicle screws:

  With the advancement of intraoperative radiographic monitoring technologies and the increasing recognition of the minimally invasive surgery, a number of companies, including K2M and Synthes, have designed and manufactured devices for the placement of pedicle screws and rods through a small percutaneous incision.

  However, there is a lack of studies comparing the outcomes of traditional and minimally invasive surgery. We believe that minimally invasive surgery will be greatly developed with the future advancement of technologies and improvement of devices.
- Spinal canal decompression:

  The necessity for decompression depends on the presence of neurologic deficits rather than the severity of space-occupancy in the spinal canal.

  In patients without neurologic deficits, even a space-occupying effect of 50% or more in the spinal canal does not necessitate decompression because the fracture fragment protruding into the canal can be naturally absorbed and reconstructed.

  Decompression is recommended for patients with neurologic deficits. Decompression may be performed indirectly via the posterior approach, directly via the anterior approach or via laminectomy.

    Laminectomy is recommended in patients whose spinal compression is caused by entry of the vertebral lamina fragment or the damaged ligamentum flavum into the spinal canal and in patients who require decompression for a single nerve root (Fig. 2.32).

    The space-occupancy in the spinal canal is often caused by the protruding posterior wall fragment of the vertebra. When the fragment is larger than 50% of the cross-sectional area of the spinal

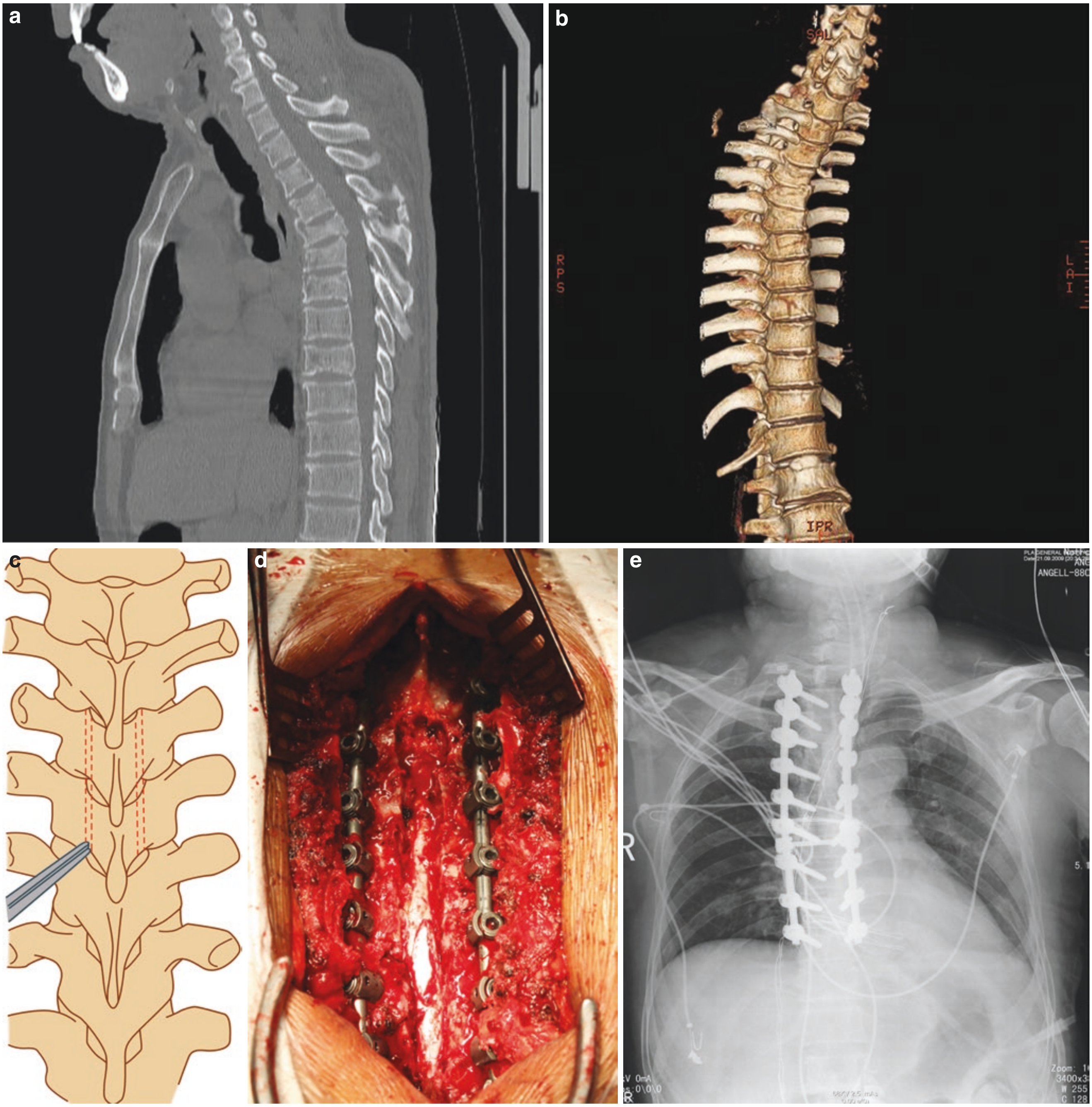


Fig. 2.32 Multiple fractures of the thoracic spine. (**a**) Preoperative CT sagittal reconstruction: The T4, T6, and T8 vertebrae were fractured, with spinal stenosis of the T4 segment. (**b**) Preoperative CT 3D reconstruction. (**c**, **d**) Laminectomy for decompression via the posterior approach: First, a high-speed burr drill was used to create an opening in the vertebral lamina, and then the vertebral lamina was nibbled off with a small rongeur to fully decompress the compressed spinal segment. (**e**) A postoperative AP radiograph

canal and has a reversion angle >45°, it is difficult to indirectly reduce the fracture via restitution of ligaments, and instead, a direct reduction via the anterior approach is required (Kaneda et al. 1997).

In lumbar segments, especially the segments distal to the end of medullary cone where it is relatively safer to pull nerve roots, decompression via the vertebral pedicle can be considered (Fig. 2.33).

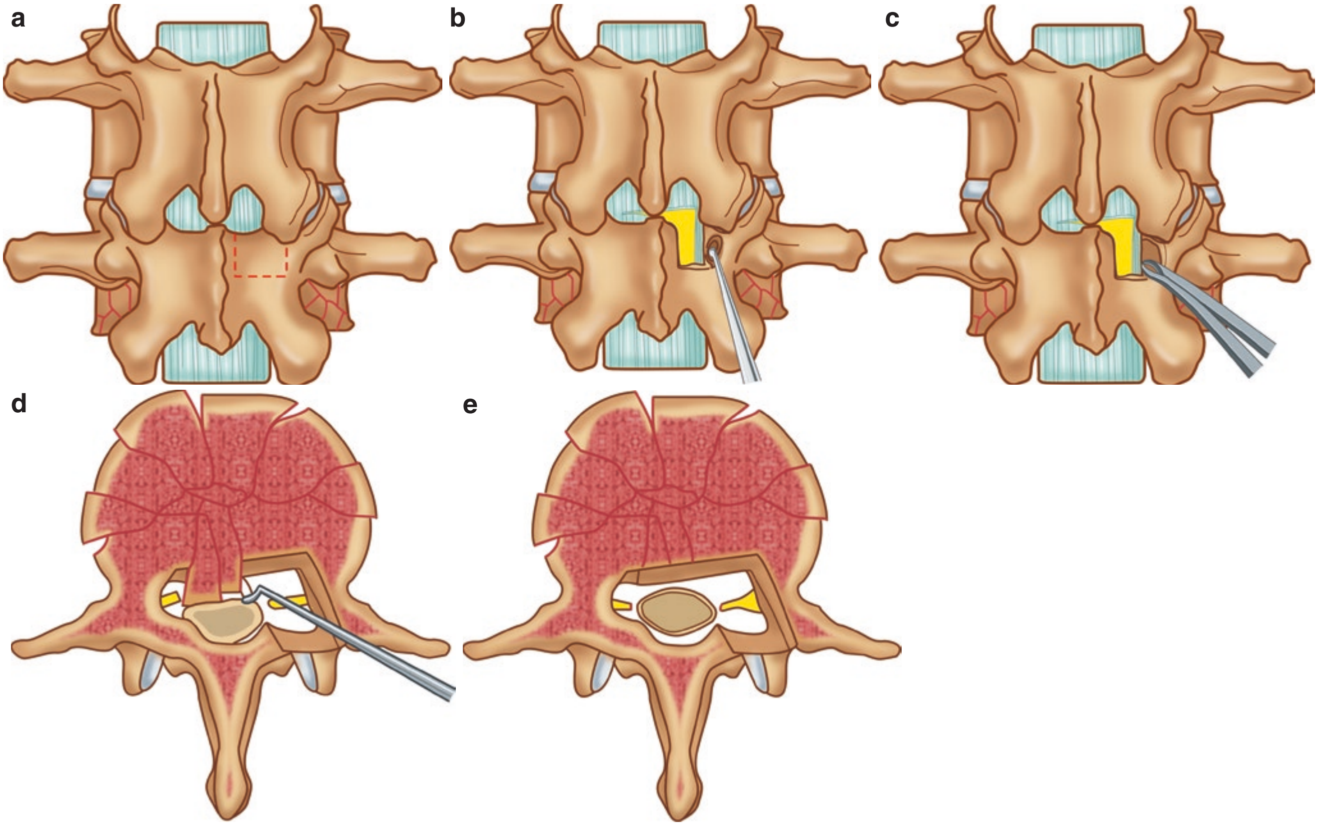


Fig. 2.33 Schematic diagram of transpedicular decompression using the posterior approach to the lumbar spine. (**a**) A portion of the vertebral lamina at the pedicle is removed. (**b**) A channel is created in the pedicle with a burr drill. (**c**) The inner wall of the pedicle is nibbled off with a small rongeur. (**d**, **e**) The bone fragment protruding into the spinal canal is pressed down with a reverse curette to reduce the compression on the spinal cord

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Pelvic Fractures

3

Peifu Tang, Hua Chen, Zhe Zhao, and Yan Wu

3.1 Basic Theory and Concepts

3.1.1 Overview

- Pelvic fractures, which account for 3–8% of all bone fractures (Giannoudis and Pape 2004; Grotz et al. 2005; Mohanty et al. 2005), are difficult to treat and have a high disability and mortality rate ranging from 5% to 50% (Gänsslen et al. 1996; Perry Jr. 1980; Demetriades et al. 2002).
- They are often caused by high-energy mechanisms and accompanied by injuries elsewhere. In clinical practice, 85% of pelvic fractures are accompanied by extremity injury, 70% by chest injury, 60% by abdominal injury, and 60% by head injury. Therefore, a meticulous general examination is critical to avoid a missed diagnosis (Gänsslen et al. 1996; Basta et al. 2007).
- Concepts of stable and unstable pelvic ring injuries (McCormack et al. 2010):
  - A stable pelvic ring injury refers to the condition that the injured pelvic ring can still withstand the normal physiological load without deformation.
  - An unstable pelvic ring injury refers to the condition that the injured pelvic ring cannot withstand the normal physiological load, leading to discomfort and limited functions, or the injured pelvic ring deforms under a normal physiological load.
- Emergency treatment: Emergency treatment should involve multiple disciplines, including orthopedics, general surgery, urology, neurosurgery, and vascular interventional surgery. The orthopedist must determine the severity of the pelvic ring injury immediately, stabilize the pelvis, and control the bleeding effectively with simple methods, such as a pelvic sling, external fixator, and C-clamp, preparing the condition for the subsequent circulation recovery and stabilization. The injured pelvic ring will be further precisely stabilized after the vital signs of the patient are stabilized (Marvin Tile 1996a; Kregor and Routt 1999).

3.1.2 Applied Anatomy

- Basic structure and functions of the pelvis:
  - The pelvis connects the spine and the lower extremities to form a complete load-bearing system, and it protects the organs, vessels, nerves, and other essential structures inside the pelvic cavity.
  - The arc line between the sacral promontory and the pubic symphysis represents the boundary between the true pelvis (small pelvis), which is below the line and contains internal organs, and the false pelvis (large pelvis), which is above the line and makes up the lower part of the abdominopelvic cavity..
  - Comparative anatomy of the pelvis: During the evolutionary process from Australopithecus to Homo sapiens, the pelvis and sacrum evolved tremendously to adapt to upright bipedal standing and walking, and the changes included an increased area of the sacrum and surfaces of the sacroiliac joint, shortening of the ischium, a decrease in the vertical length of the pubic symphysis, a front-facing ilium, and inferoanterior turning of the acetabular angle (Fig. 3.1) (Kardong 2012).
- Anatomy and biomechanica l traits of the pelvis:
  - Bony structures:

    The pelvic ring consists of the sacrum and two innominate bones, which are connected via ligaments.

    The robust ligamentous structure around the three bones and three joints of the pelvic ring mechanically stabilize them.

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P. Tang, H. Chen (eds.), *Orthopaedic Trauma Surgery*, https://doi.org/10.1007/978-981-16-0219-1_3

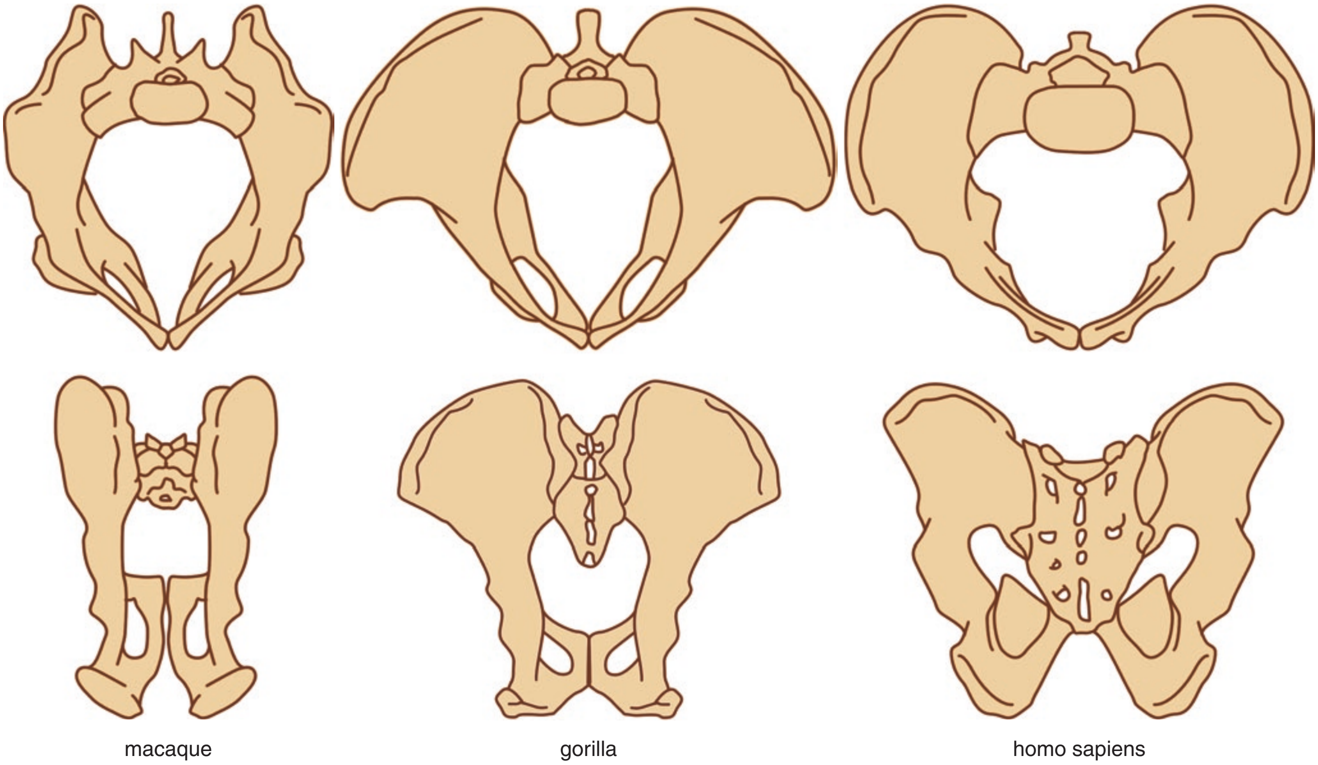


Fig. 3.1 Top and posterior views of the pelvis (macaque, gorilla and Homo sapiens): Compared with macaques and gorillas, the pelvis of Homo sapiens has larger sacrum and sacroiliac joint surface areas, a shorter ischium, and a decreased vertical length of the pubic symphysis, with the iliac bone front-facing and the acetabular angle turned inferoanteriorly

Although there is no internal bony stabilizing structure, the sacroiliac joint is well stabilized by the ligamentous complex (Routt et al. 1994).

- Morphology of the sacrum and arc structure of the pelvis (Marvin Tile 1996b):

  On the coronal plane: The sacrum has a wedge-like shape and is situated on the apex of the pelvic arc. It plays the role of a 'keystone' in weight bearing.

  On the transverse plane: The sacrum displays a reversed wedge-like shape, resulting in instability and a forward-shifting trend of the sacrum. The posterior pelvic ring is stabilized solely by the posterior ligamentous complex (PLC) of the sacroiliac joint, and as a result, an external force can easily dislocate the sacroiliac joint (Fig. 3.2).
- The posterior pelvis-stabilizing structures (Fig. 3.3):

  The PLC plays an important role in maintaining the overall stability of the pelvic ring. As reported in previous research, the biomechanical measurement showed that the anterior and posterior parts of the pelvic ring contribute to the stability of the pelvic ring by 40% and 60%, respectively (Vrahas et al. 1995).

The sacroiliac joint includes two parts, the true joint and the false joint. The true joint is covered by cartilage and is an amphiarthrodial joint. The false joint refers to the part posterior to the true joint and formed by the posterior superior iliac spine and the sacrum, which are connected to each other by robust interosseous ligaments of the sacroiliac joint.

The anterior sacroiliac ligament: This wide and thin ligament originates from the anterior surface of the sacrum and ends on the anterior surface of the ilium that is face-to-face with the former. It prevents the external rotation of the pelvis and helps the pelvis resist shear forces.

The posterior sacroiliac ligament: It contains two types of fibrous bundles. The short ligamentous bundle originates from the sacral spine or sacral tubercle and ends on the posterior superior iliac spine and the posterior inferior iliac spine. The long ligamentous bundle extends from the posterior superior iliac spine to the lateral surface of the sacrum, and it is mixed with the initial part of the sacrotuberous ligament and covers the short ligamentous bundle.

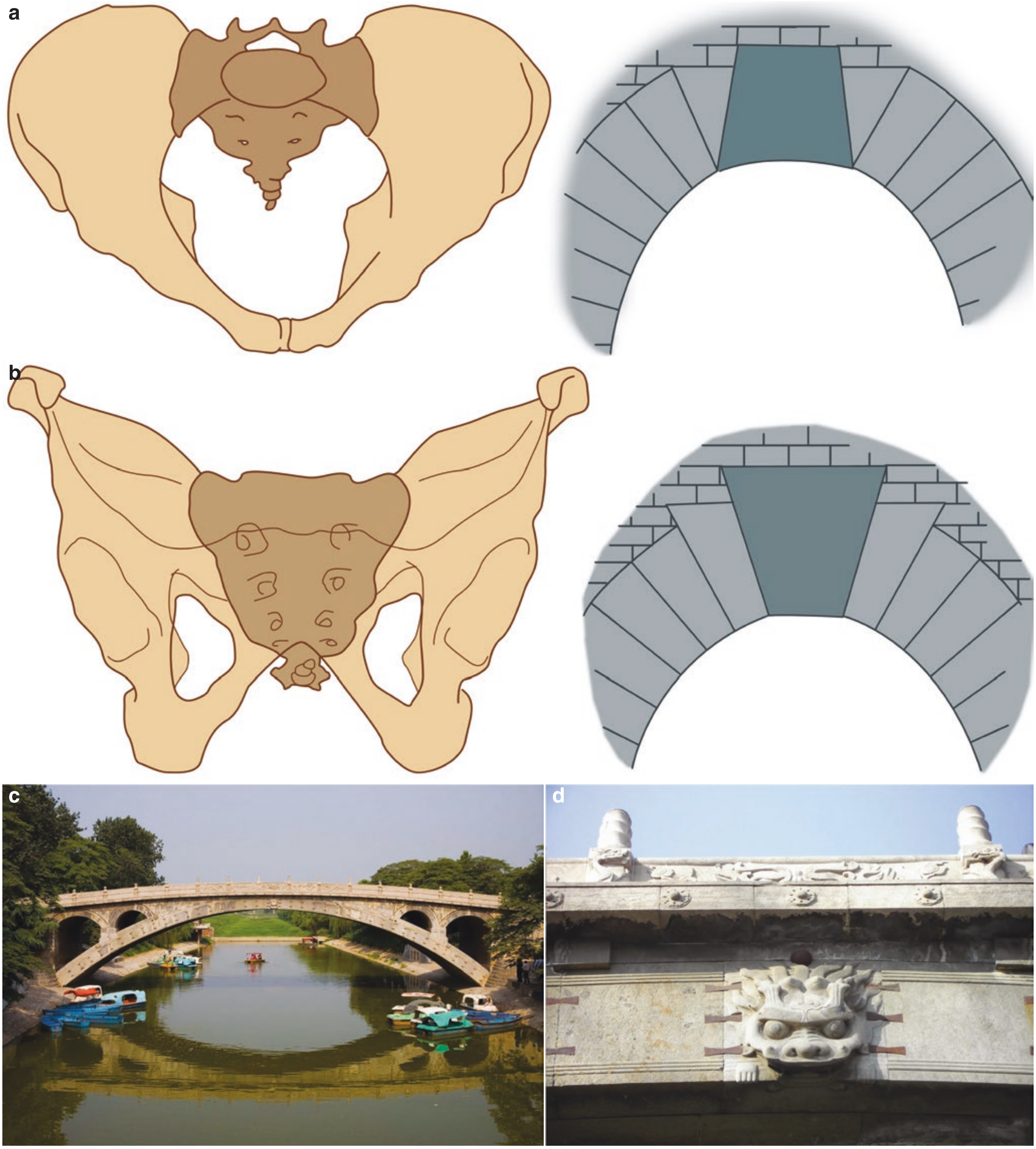


Fig. 3.2 (**a**) In the cross-section, the sacrum displays an inverted wedge-shaped and an unstable structure that can move forward, and the sacrum is kept stable by the posterior ligament complex. (**b**) On the coronal plane, the sacrum is wedge-shaped and stable under weight-bearing. (**c**) The Zhaozhou Bridge built in the Sui Dynasty in the seventh century in my country is a stone arch bridge built using this principle. It has stood for more than 1400 years. (**d**) The picture shows the Zhaozhou Bridge and its keystone

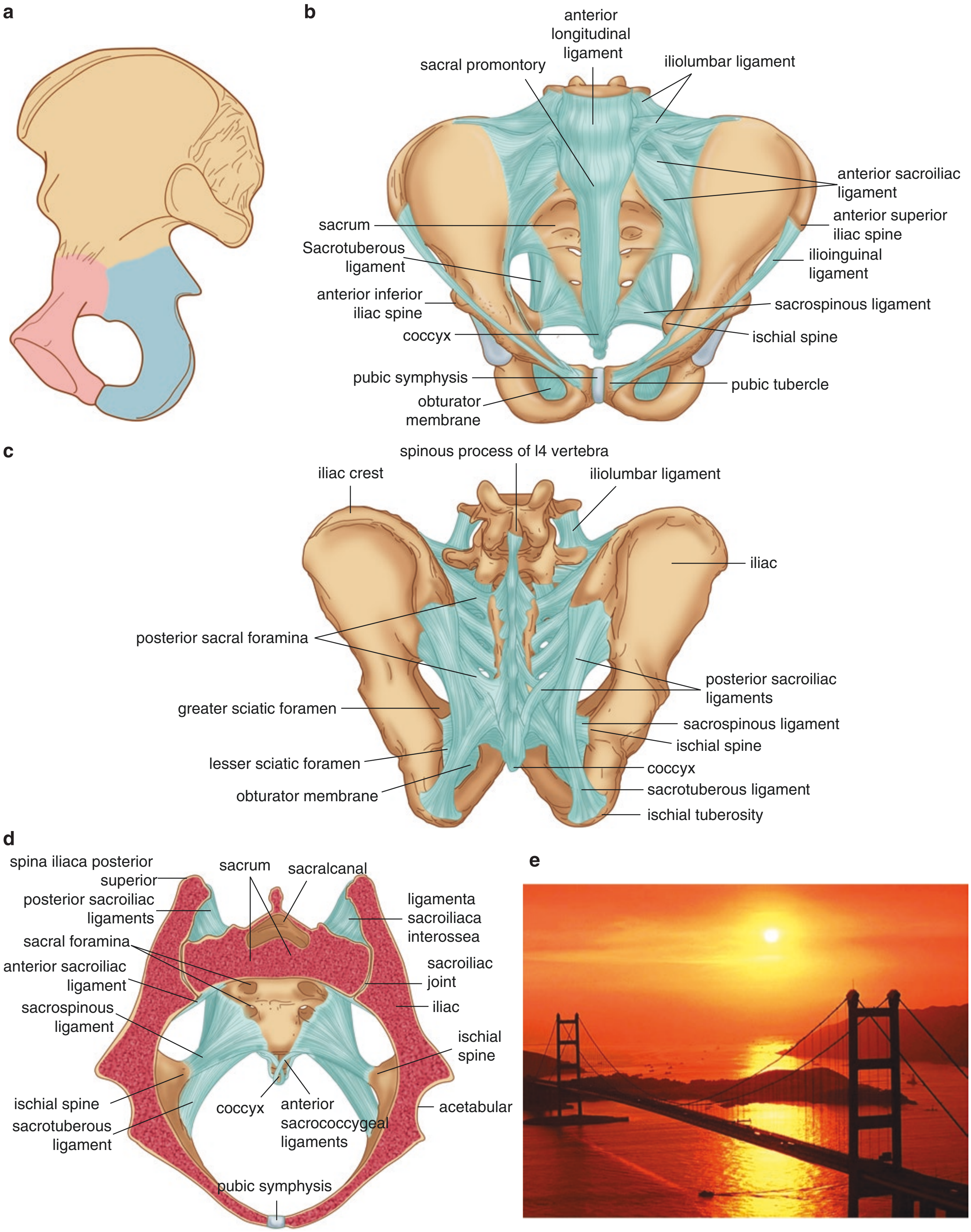

a
b
anterior longitudinal ligament
sacral promontory
iliolumbar ligament
anterior sacroiliac ligament
anterior superior iliac spine
ilioinguinal ligament
sacrum
Sacrotuberous ligament
anterior inferior iliac spine
sacrospinous ligament
coccyx
ischial spine
pubic symphysis
pubic tubercle
obturator membrane
c
spinous process of l4 vertebra
iliac crest
iliolumbar ligament
iliac
posterior sacral foramina
posterior sacroiliac ligaments
greater sciatic foramen
sacrospinous ligament
ischial spine
lesser sciatic foramen
coccyx
sacrotuberous ligament
obturator membrane
ischial tuberosity
d
spina iliaca posterior superior
sacrum
sacralcanal
posterior sacroiliac ligaments
ligamenta sacroiliaca interossea
sacral foramina
sacroiliac joint
anterior sacroiliac ligament
iliac
sacrospinous ligament
ischial spine
ischial spine
coccyx
anterior sacrococcygeal ligaments
acetabular
sacrotuberous ligament
pubic symphysis
e

Fig. 3.3 (**a**) The pelvis is composed of bilateral hip bones (innominate bones) and the sacrum, where the hip bone is formed by the fusion of three bones: the ilium (yellow), ischium (blue), and pubis (red). In the sacroiliac joint of the ilium, the true joint is an amphiarthrodial joint that is covered with cartilage; the rough part medial to the posterior superior iliac spine is the false joint, where the interosseous ligaments of the sacroiliac joint are attached. (**b**) Anterior view of the posterior ligament complex (PLC): The anterior sacroiliac ligament, which is located anteriorly to the sacroiliac joint, prevents external rotation of the pelvis and helps the pelvis resist shear forces. (**c**) Posterior view of PLC: The posterior sacroiliac ligament, sacrospinous ligament, and sacrotuberous ligament. (**d**) Cross-section of the PLC: The posterior sacroiliac ligament and sacroiliac interosseous ligament form a "suspending bridge" structure that holds the sacrum between the posterior iliac spines from both sides and blocks anterior movement of the sacrum. (**e**) The above structure is similar to the suspension bridge structure. The picture shows the Golden Gate Bridge in the United States

The iliolumbar ligament: It is located between the L5 transverse process and the iliac crest.

The lateral lumbosacral ligament: It is located between the L5 transverse process and the sacral ala.

In the transverse view, the PLC acts as the 'steel cable' suspending the 'bridge' (the sacrum), and the interosseous sacroiliac ligament acts as the 'parapet' of the 'bridge' (Marvin Tile 1996b).

- The anterior pelvis-stabilizing structures:

  When standing on both feet, the body weight transmits to the femur along the sacrum, pelvis, and acetabulum. The counter-acting force of the femoral head on the acetabulum can be decomposed into an upward component and an inward component on each side, and then the inward component acts on the pubic symphysis from both sides. Hence, the superior pubic ramus plays an important role in supporting the anterior pelvic ring and preventing it from collapsing under weight bearing (Fig. 3.4).

  When an external force acts on the pelvis to externally rotate or separate one or both sides of the pelvis, the pubic symphysis can resist the external rotating stress to a certain extent.

  The contribution of the pubic symphysis to pelvic stability is less than that of the posterior structure. In a portion of patients with congenital bladder exstrophy and pubic symphyseal diastasis, pregnancy or childbirth may intensify symphyseal diastasis. However, if the posterior structure of the pelvis remains stable, symphyseal diastasis less than 2.5 cm alone does not significantly affect the stability of the pelvic ring (Pennal et al. 1980).

- The stabilization ligamentous structures in the pelvic floor (Vrahas et al. 1995):

  The sacrotuberous ligament: It originates from the dorsal sacrum and the posterior superior and inferior iliac spines and ends on the ischial tuberosity. This strong ligament helps prevent rotation and outflare of the bony structure (Fig. 3.5).

  The sacrospinous ligament: It starts from the lateral rims of the sacrum and ischium and ends on the ischial spine. This ligament functions together with the sacrotuberous ligament.

  The fascia and muscles on the pelvic floor strengthen the two above-mentioned ligaments and together form the pelvic floor structure.

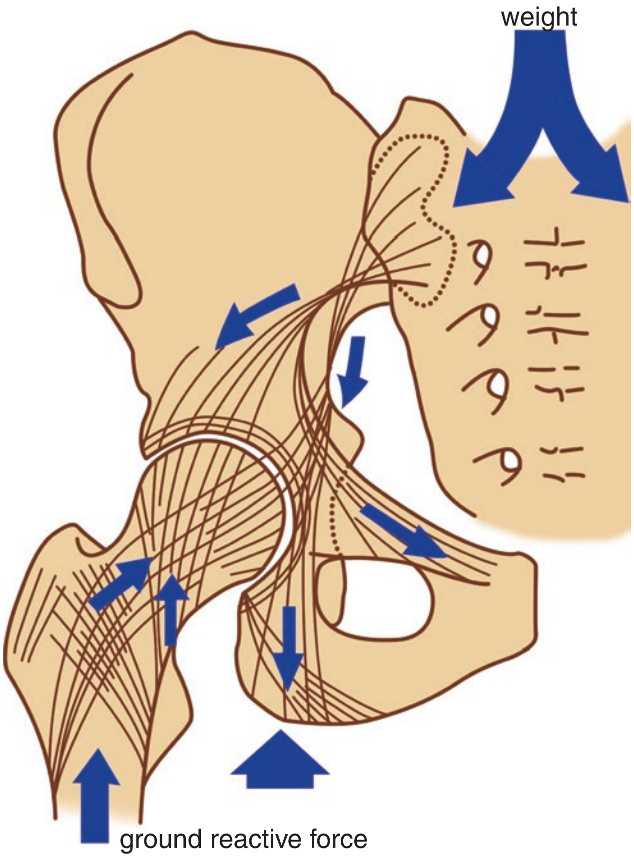


Fig. 3.4 Under a normal weight-bearing condition, the body weight is transmitted through the ilium, pelvis, acetabulum, and femur, and the superior pubic ramus supports the anterior pelvic structure

- The unique structure of the sacrum and sacroiliac joint screw fixation(Routt Jr et al. 1995, 1997, 2000):
  - Applied anatomy (Fig. 3.6):

    The sacrum is formed by five sacral vertebrae fused together, and its shape is complex and variable. The sacral pedicle fuses with the transverse process to form a wing structure on both sides. The sacroiliac

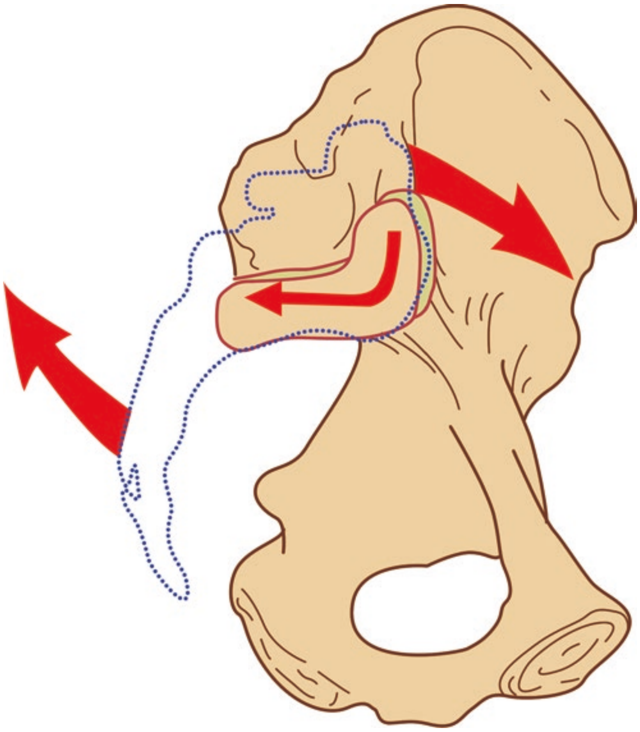


Fig. 3.5 In a sitting or upright standing position, the pelvis tends to rotate posteriorly (i.e., the sacrum rotates anteriorly), and the sacrotuberous ligament and sacrospinous ligament help the pelvis resist the rotational tendency

joint screw can be inserted along the S1 and S2 pedicles to enter the vertebral body.

The S1 pedicle has a cross-sectional area of 1–1.5 cm2 and extends from superomedial to inferolateral in slightly oblique manner.

The boundaries of the S1 pedicle:

- Inferior: The S_1 neural canal and the S_1 anterior neural foramen;
- Anterior: The iliac vessels, the L_5 nerve root, and the ureter;
- Superior: The L_5 and L_5-S_1 intervertebral discs; Posterior: The cauda equina.

The S1 nerve root exits the spinal canal inferiorly, anteriorly, and laterally.

– Anatomic variations: 30–40% of the sacrum has morphological variations, which should be identified via through preoperative CT scanning (Gardner et al. 2010; Conflitti et al. 2010).

The L_5-S_1 intervertebral discs are parallel to the iliac crests on both sides.

The sacral foramina are not perfectly round and may appear oval.

The residual intervertebral disc is presented between the S1 and S2 vertebrae.

The sacral ala suddenly becomes narrower between the vertebral body and the sacroiliac joint.

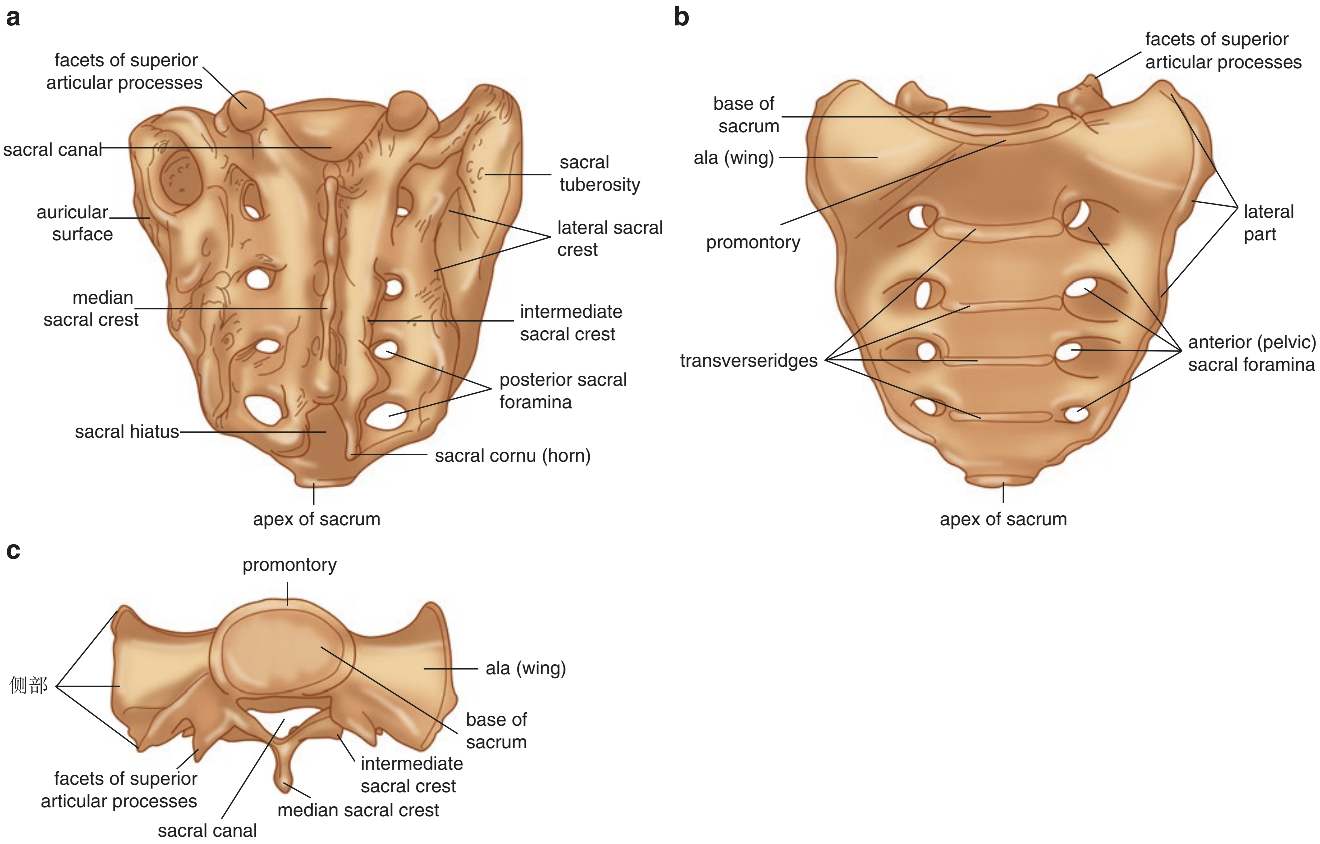


Fig. 3.6 Anatomical schematic diagram of the sacrum. (**a**) Posterior view. (**b**) Ventral view. (**c**) Top view

A mastoid process is presented in the sacral ala.

The sacroiliac joint has a wave-like shape.

- Imaging monitoring: The C-arm is positioned on the side opposite to the surgeon.

  The AP view of the pelvis can be used to evaluate the body position of the patient.

  Inlet radiograph: The overlapping anterior cortexes of the S1 and S2 form a concentric circle in the inlet radiograph, which displays the anterior cortexes of the sacrum and sacral ala.

  Outlet radiograph: The contours of the pubic symphysis and S2 are overlapping in the outlet radiograph, which can be used to display the sacral foramina and the upper edge of the S1. High-quality images can demonstrate the travelling course of the sacral nerve root canal.

  Lateral radiograph: The greater sciatic notches of both sides are completely overlapping, and the image can clearly show the slope of the sacrum.

  The iliac cortical density (ICD) line: The position of the slope of the sacrum can be estimated based on the thickened anterior iliac cortex of the sacroiliac joint, which is visible on a lateral radiograph of the pelvis (Fig. 3.7).

- Applied biomechanics of sacroiliac joint screw fixation:

  For an unstable pelvic fracture that requires only fixation of the posterior pelvic structure, the use of two sacroiliac joint screws, regardless of their placement separately into the S1 and S2 vertebral bodies or both into the S1 and S2 vertebral bodies, demonstrates an anti-rotation performance superior to the use of only one screw (van Zwienen et al. 2004);

  The sacroiliac joint must be reduced before sacroiliac joint screw placement. In fractures in sacral zone II where the ilium is displaced by 5 mm, 10 mm, 15 mm, and 20 mm cranially, the cross-sectional contact area between the two fracture ends decreases by 30%, 56%, 81%, and 90%, respectively. When the displacement reaches 1 mm, it is impossible to place two sacroiliac joint screws in 50% of patients due to a limited space for screw fixation (Templeman et al. 1996; Reilly et al. 2003).

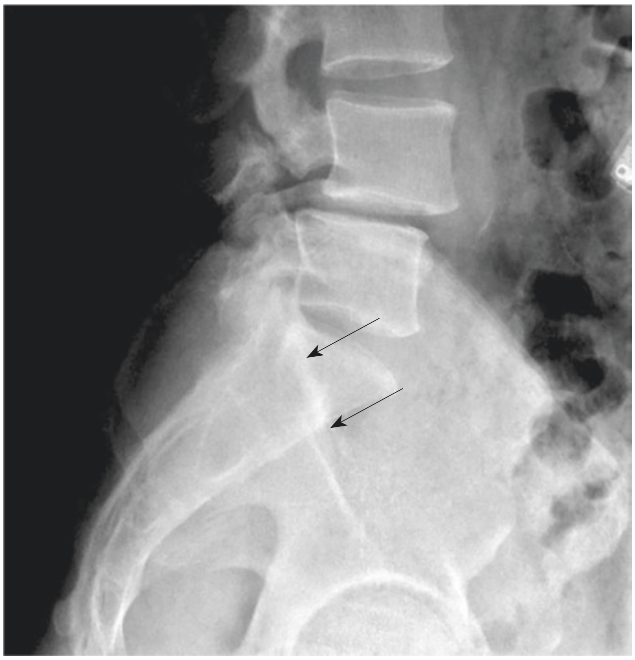


Fig. 3.7 Lateral pelvic radiograph: The arrows denote the iliac cortical density (ICD) line

- Important nerve structures involved in pelvic fractures (Fig. 3.8) (Gibbons et al. 1990):
  - A portion of the anterior branches of the T_{12} nerve root and the L_1-S_4 nerve roots form the lumbar, sacral, and coccygeal nerve plexuses.
  - Lumbosacral trunk:

    A portion of the anterior branches of the L_4 nerve root and the anterior branches of the L_5 nerve root constitute the lumbosacral trunk, which is very likely to be damaged by pelvic fracture displacement:

    - The L_4 nerve branches pass through the L5 transverse process;
    - The L_5 nerve passes the anterior edge of the sacral ala at a site 12 mm medial to the sacroiliac joint.
  - The superior gluteal nerve:

    The anterior branches of the L4 and L5 nerves travel downwards and enter the true pelvis, and they converge with the anterior branches of the S1 nerve root in front of the sacroiliac joint.

    The superior gluteal nerve originates from the sacral nerve plexus (L4, L5, and S1), travels along with the superior gluteal artery and vein, and exits the pelvis via the greater sciatic notch to innervate the gluteus medius and minimus.

    The damage to the superior gluteal nerve causes gluteus medius and gluteus minimus dysfunction, which is an important sign of lumbosacral trunk damage.
- Vascular injury involved in pelvic fractures (Dyer and Vrahas 2006):
  - The most serious complication of pelvic fractures is pelvic bleeding. Knowledge of the vascular anatomy is crucial for controlling pelvic bleeding by interventional embolization.
  - The internal iliac artery and vein are the most important vessels in the pelvis (Fig. 3.9).

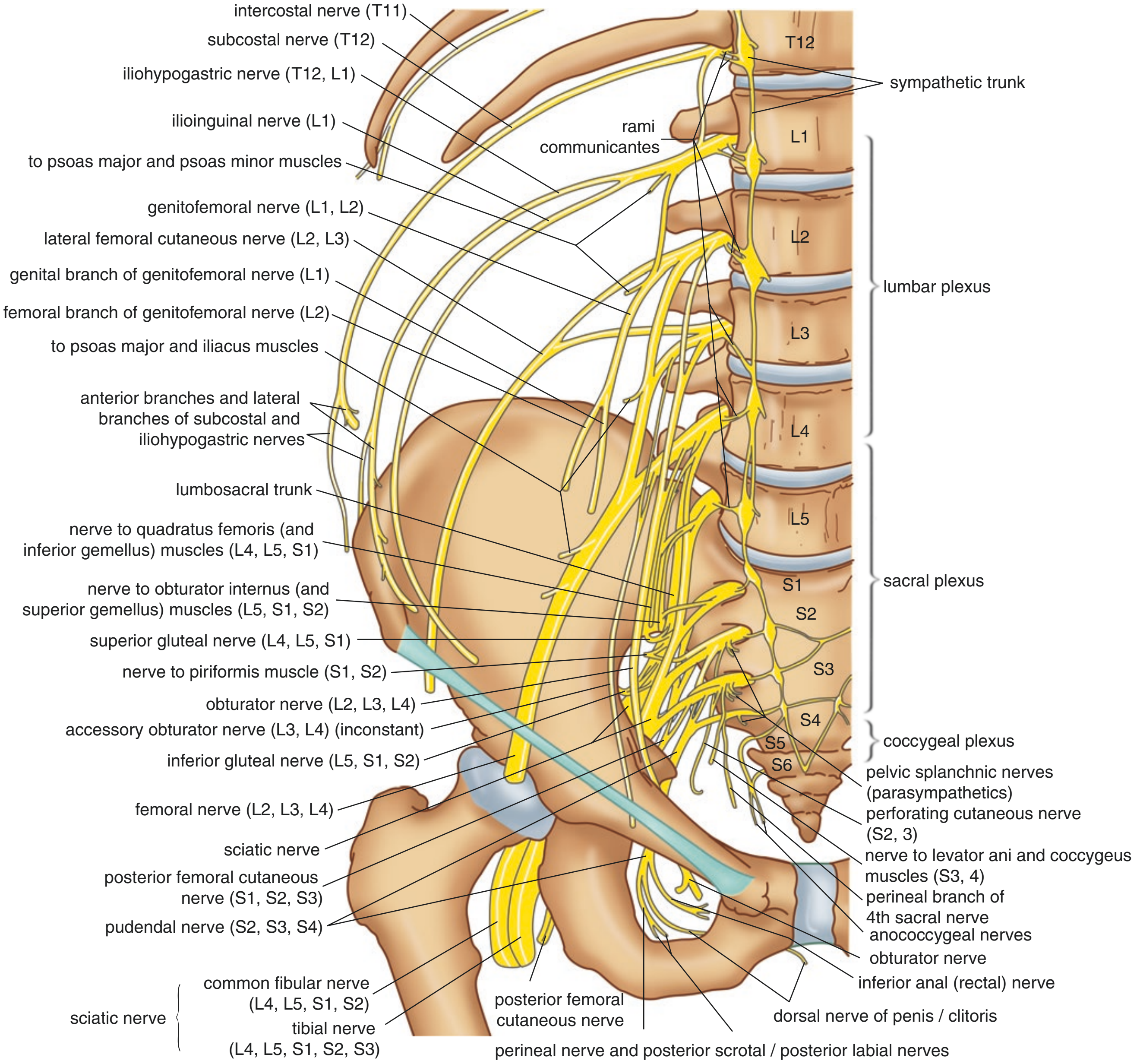


Fig. 3.8 Complete view of the lumbosacral nerves: A portion of the L4 anterior branches and the L5 anterior branches form the lumbosacral trunk, which passes the anterior edge of the sacral ala at the site 12 mm medial to the sacroiliac joint and is highly likely to be injured by the displaced pelvic fracture

- The superior gluteal artery:

  It is an important branch of the internal iliac artery. It travels inferoanteriorly along the sacroiliac joint and exits the pelvis from the superior edge of the greater sciatic notch.

  The portion of the superior gluteal artery directly located on the surface of the bone when it runs through the greater sciatic foramen is vulnerable to damage.
- The median sacral artery is anterior to the midline of the sacrum.

- Important organs (Aihara et al. 2002):
  - The urinary bladder is located above the pelvic floor muscles.
  - In women, the urethra, vagina, rectum, and supportive ligaments travel in the intermuscular septum of the pelvic floor muscles. The female urethra is short and less likely injured in pubic ramus fractures. However, the displaced fractured pubic ramus might puncture the vagina and cause open pelvic fractures;
  - In men, the prostate resides between the urinary bladder and the pelvic floor and is wrapped in dense fascia;

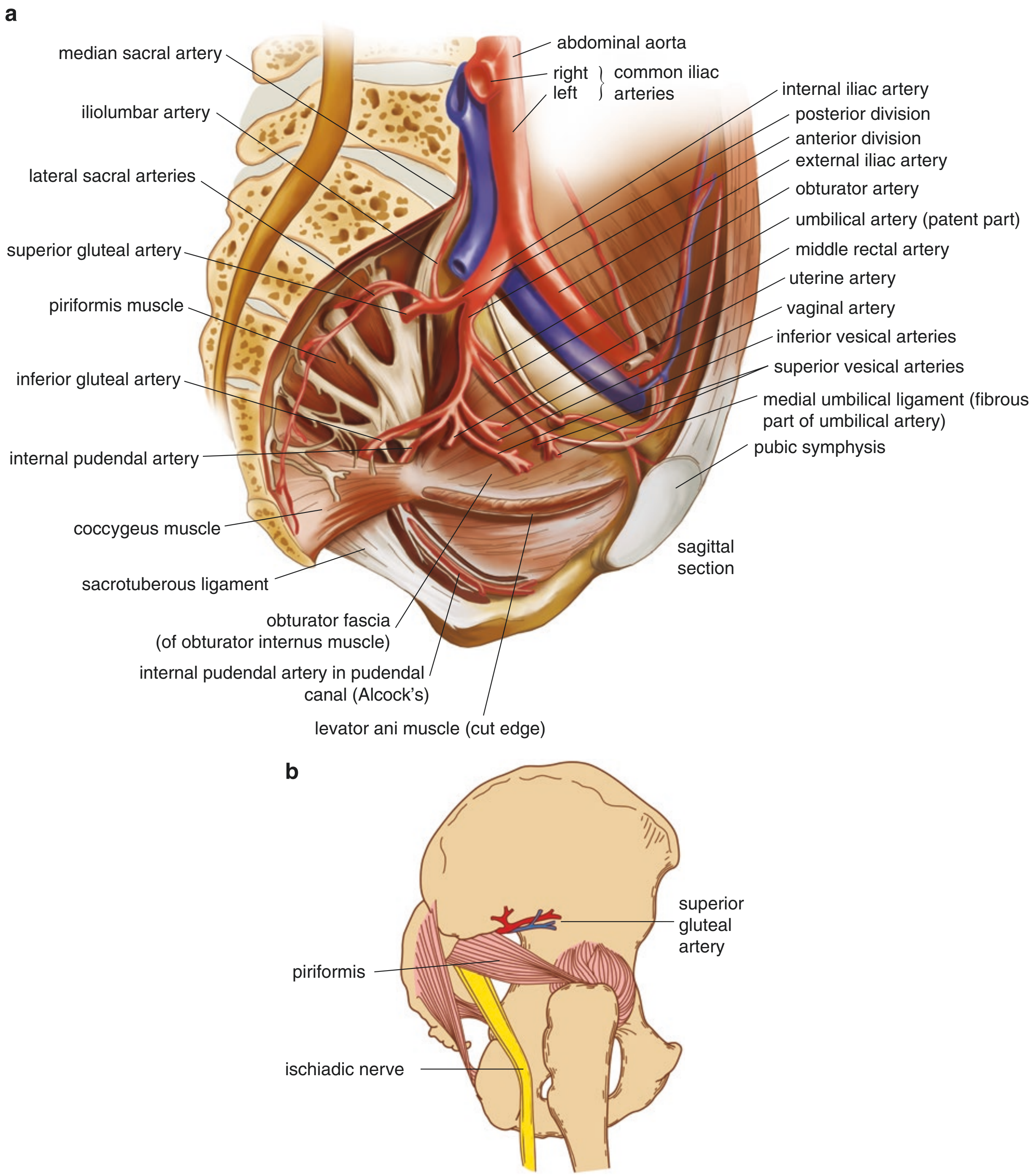


Fig. 3.9 (**a**) Schematic diagram of the distribution of internal iliac vessels. (**b**) Superior gluteal nerves and vessels are immediately adjacent to the bone surface, thereby requiring special attention for damage avoidance during surgery

the urethra passes through the prostate and leaves the pelvis.

The membranous part of the urethra is the weak area of the urethra distal to the prostate and is also the most immobile part of the urethra (Fig. 3.10). The urethra might be ruptured within the membranous part when the perineum area is compressed, and the urinary bladder is stretched.

The presence of the blood at the external urethral orifice indicates a urethral injury, but it does not necessarily occur in all urethral injuries; therefore, for patients with suspected urinary tract injury, retrograde urographic images should be obtained prior to urinary catheter placement; if an abnormality is detectable in the images, it is necessary to consult with a urologist (surgeon).

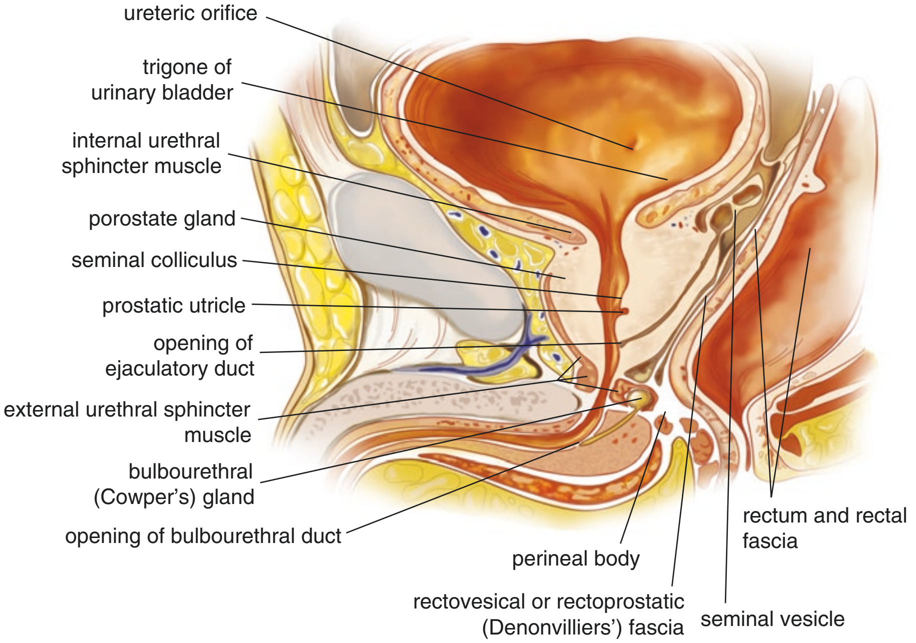


Fig. 3.10 Pelvic fractures are often associated with rupture of the urethra in its membranous portion

3.1.3 Mechanism of Injury

- Low-energy violence: The fractures are often single-site or osteoporotic, such as avulsion fracture of the pelvic ring.
- High-energy violence: Falls from a high place and motor vehicle accidence may crush the pelvic ring. The type of fracture and the severities of comminution and displacement are associated with the direction, strength, and characteristics of the external force.
- Detailed knowledge regarding the posture of the patient at the time of injury and the type, direction, and duration of the violence are crucial for determining the type of fracture.
- Characteristics of the fractures caused by different types of violence (Marvin Tile 1996b; Young et al. 1986):
  - Open-book pelvic injury:

    Violence causing open-book injuries (Fig. 3.11a):
    - Simultaneous crushing of both sides of the anterior superior iliac spine towards the middle;
    - Direct crushing of the anterior superior iliac spine;

      Sudden external rotation of the femur.

    Relationship of the severity of external rotation injury and pelvic stability (Fig. 3.11b–d):
    - The first stage: First, the pubic symphysis is disrupted. The pelvic stability remains unchanged when the symphyseal diastasis is less than 2.5 cm and the sacrospinous ligament, sacrotuberous ligament, and PLC remain intact.
    - The second stage: If further outflare of the pelvis results in the contact of the posterior superior iliac spine and the sacrum and subsequent rupture of the sacrospinous ligament, sacrotuberous ligament, and anterior sacroiliac ligament while the posterior sacroiliac ligament and interosseous ligament remain intact, the pelvis is still vertically stable.
    - The third stage: If the outflare of the pelvis exceeds the range that the posterior ligaments can withstand, the posterior sacroiliac ligament and the interosseous ligament may be completely ruptured, causing a complete loss of pelvic stability, which is no longer considered a simple "open-book injury".
  - Lateral compression injury of the pelvis (Fig. 3.12):

    Mechanism of injury: The type of injury, such as sacroiliac gapping or compression fracture of the sacrum, varies with the location and direction of violence.

    A force (for example, violent trauma) acting on the posterior ilium may cause a compression fracture of the sacroiliac joint with fragment intercalation; the surrounding ligaments remain intact, and the pelvis retains a certain level of stability.

    A force (for example, violent trauma) acting on the anterior ilium may cause an inflare of the pelvis, pubic fracture, and compression fracture of the anterior sacrum, which might be accompanied by a rupture of the PLC of the sacroiliac joint in some patients. A stronger violence might further act on the ipsilateral pelvis to inflare and push the contralateral hemipelvis, causing an open-book injury of the contralateral hemipelvis, which is

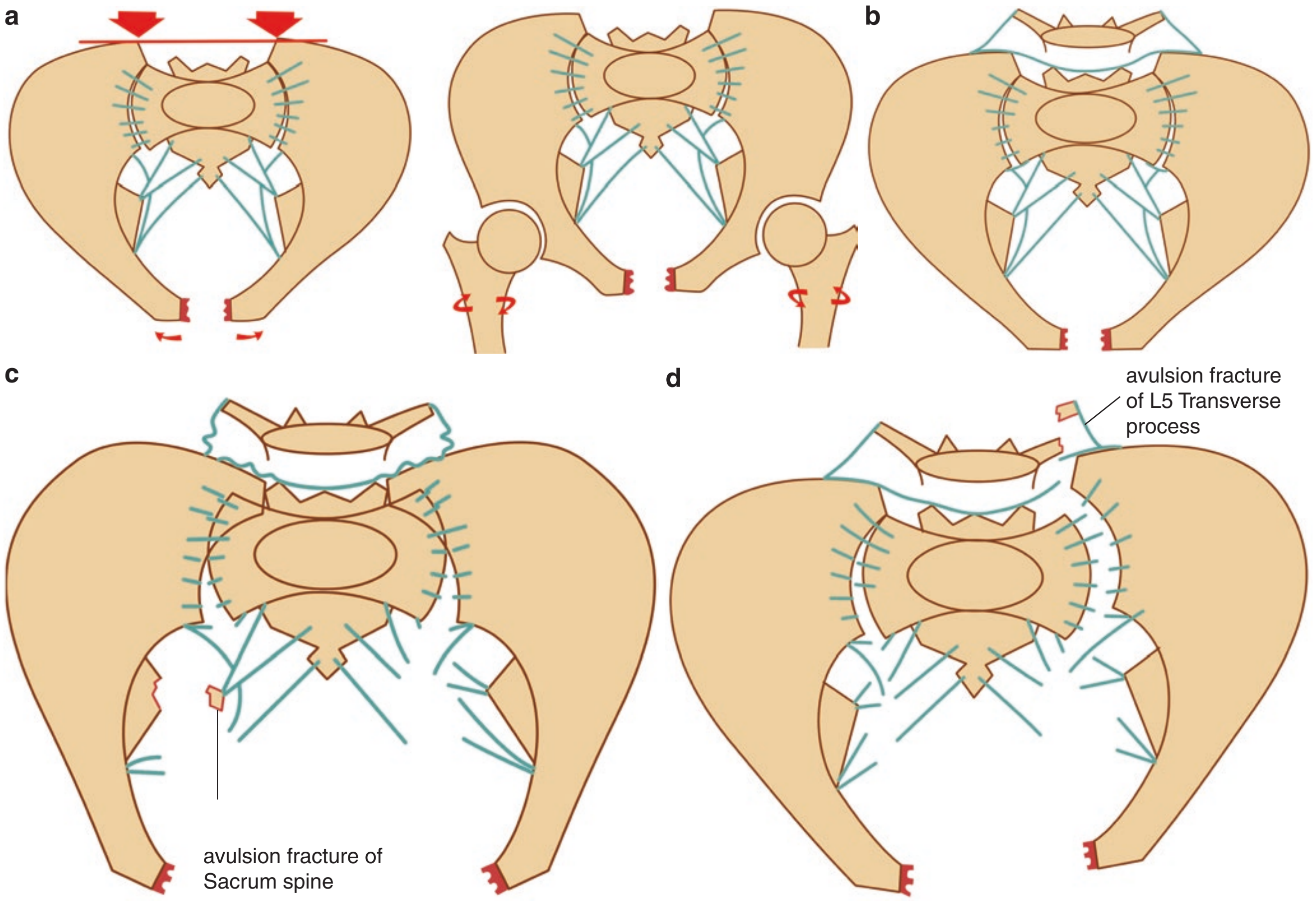


Fig. 3.11 (**a**) Simultaneous crushing of both sides of the posterior superior iliac spines towards the middle or sudden external rotation of the femur can result in pelvic outflare injuries. (**b**) The first stage of injury: The pubic symphysis is disrupted, and the symphyseal diastasis is larger than 2.5 cm, but the pelvic stability remains unchanged. (**c**) The second stage: Further outflare of the pelvis results in the contact of the posterior superior iliac spine and the sacrum and rupture of the sacrospinous ligament, sacrotuberous ligament, and anterior sacroiliac ligament; the pelvis is vertically stable. (**d**) The further outflare of the pelvis causes the rupture of the posterior sacroiliac ligament and interosseous ligament, resulting in complete pelvic instability

called windswept pelvis. In young patients, the violence often ruptures the PLC of the sacroiliac joint first because the bone is robust.

A force (for example, violent trauma) acting on the greater trochanter or transmitting along the lower extremities causes the femoral head to collide with the acetabulum and subsequent ‘inflare’ injury of the pelvis, which is often accompanied by a transverse fracture of the acetabulum and central dislocation of the femoral head. It is worth noting that the displacement in this type of injury includes an inflare and internally rotational displacement on the sagittal plane of the ipsilateral pelvis.

Injuries of the anterior pelvic ring caused by a lateral compressive force:

- Diastasis and overlapping of the pubic symphysis, which may be accompanied by an interlocking of the pubic symphysis in a small portion of patients.
- Unilateral pubic ramus fracture of either the ipsilateral or contralateral pelvis, which is called a bucket-handle-like injury.
- Bilateral pubic ramus fractures, i.e., straddle fractures or butterfly fractures, which are bilateral superior and inferior pubic ramus fractures.
- Fracture and rotational displacement of the pubic ramus: After a superior pubic ramus fracture, further lateral violence might rotate or even vertically displace the pubic ramus fragment, which is often accompanied by urinary bladder injury and/or vaginal injury in women.

– Vertical injury of the posterior pelvic ring: A PLC displacement greater than 1 cm caused by a shear force perpendicular to the sacroiliac joint indicates a complete disruption of the posterior ligamentous structure of the sacroiliac joint and loss of pelvic stability (Fig. 3.13).

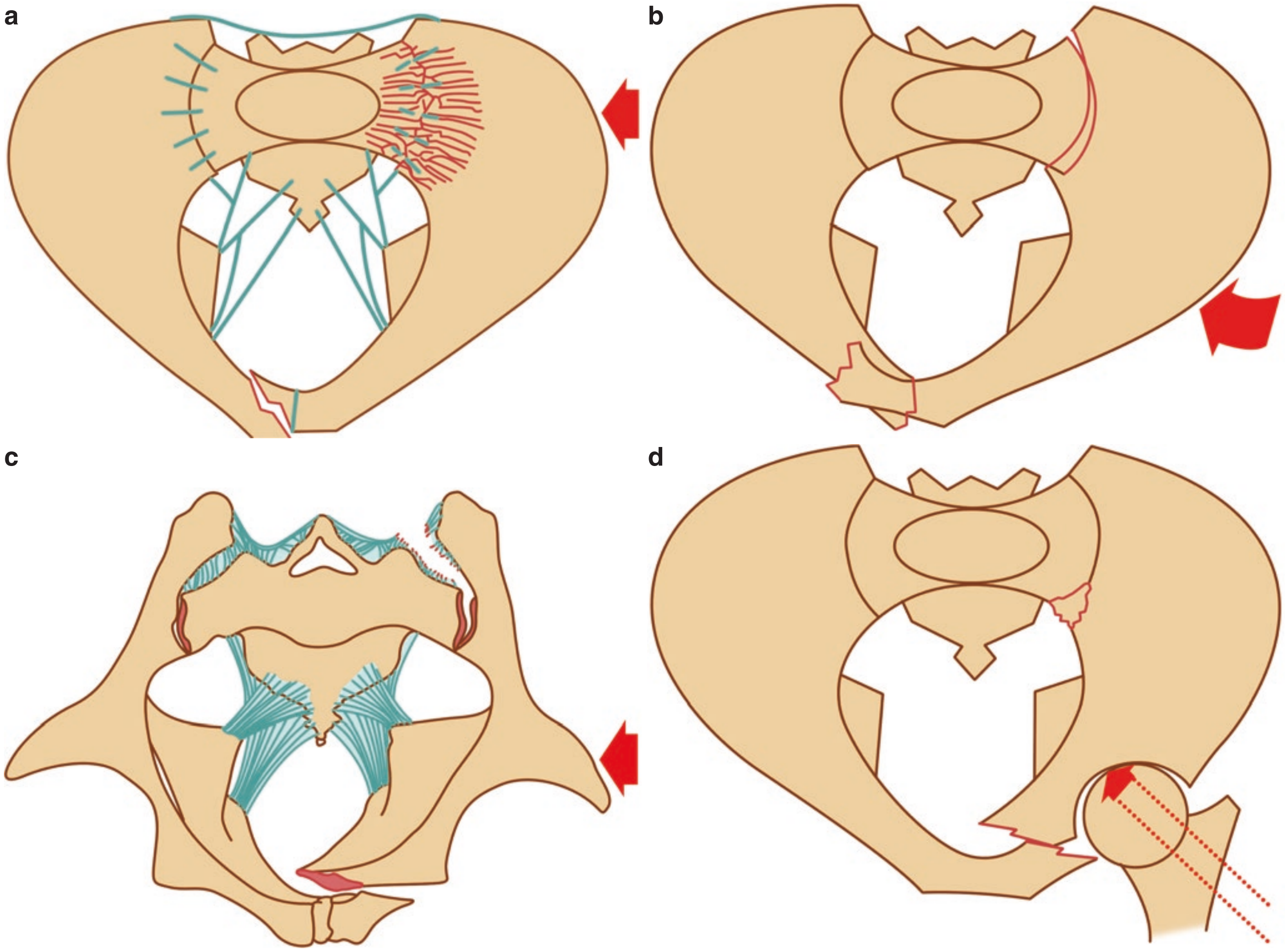


Fig. 3.12 (**a**) A external force acting on the posterior ilium may cause a compression fracture of the sacroiliac joint with fragment intercalation; the surrounding ligaments remain intact, and the pelvis retains a certain level of stability. (**b**) A violence acting on the anterior ilium may cause an inflare of the pelvis, a fracture of the pubis, and compression of the anterior sacrum that fractures the sacrum, which might be accompanied by a rupture of the PLC of the sacroiliac joint in a portion of patients. (**c**) In young patients, the violence often first ruptures the PLC of the sacroiliac joint because the bone is robust. (**d**) A violence acting on the greater trochanter or transmitting along the lower extremities causes the femoral head to collide with the acetabulum and a subsequent 'inflare' injury of the pelvis, which is often accompanied by a transverse fracture of the acetabulum and central dislocation of the femoral head

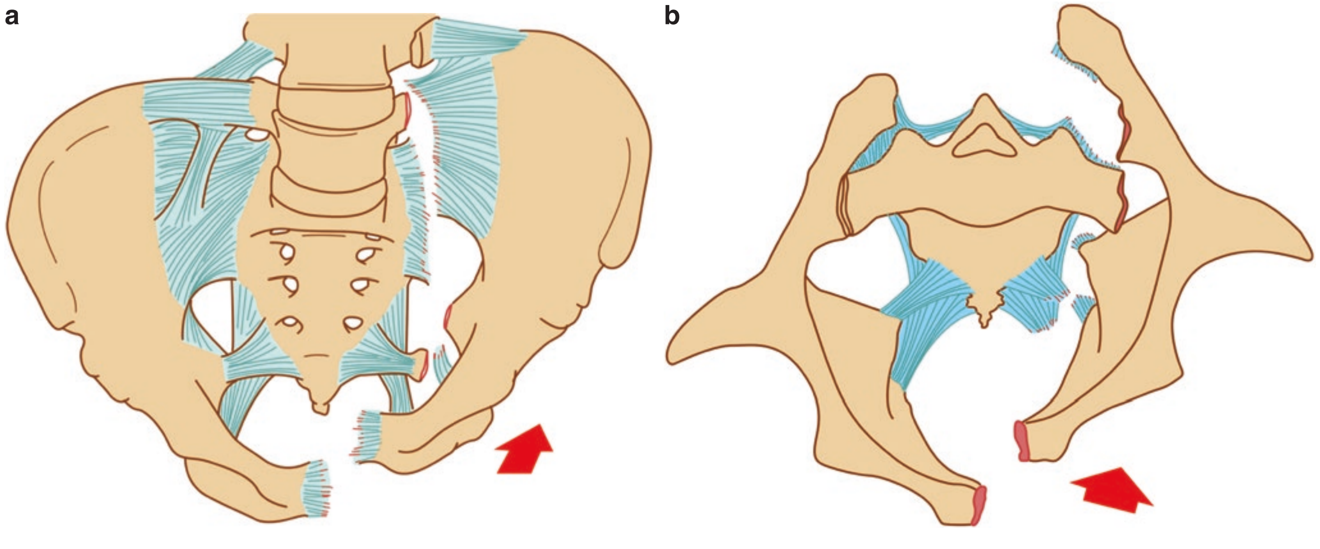


Fig. 3.13 (**a**) A shear force in the vertical direction can cause hemipelvic displacement towards the cephalic side. (**b**) A shear force that is perpendicular to the sacroiliac joint and towards the posterior direction may cause a posterior hemipelvic displacement

  - Complex pelvic fractures: In most cases, the mechanism of a pelvic fracture involves multiple types of the above-mentioned external forces, and the displacement status of the pelvis is complex.

3.1.4 Classification of Pelvic Ring Injury (Young et al. 1986)

- Young & Burgess classification of pelvic fractures: Pelvic fractures are divided into four types according to the mechanism of injury and pelvic stability (Fig. 3.14) (Young et al. 1986).
  - Anteroposterior compression (APC) injury:

    APC I: A symphyseal diastasis ≤ 2.5 cm accompanied by unilateral or bilateral pubic ramus fractures, with the sacrospinous ligament, the sacrotuberous ligament, and the PLC remaining intact.

    APC II: A symphyseal diastasis > 2.5 cm accompanied by a rupture of the anterior ligament of the sacroiliac joint, widening of the sacroiliac joint space, and rupture of the sacrospinous and sacrotuberous ligaments; an open-book injury with rotational instability. The posterior ligaments of the sacroiliac joint and the interosseous ligament remain intact, and the pelvis is vertically stable.

    APC III: In addition to the above-mentioned injuries, an APC III fracture also displays complete ruptures of the posterior ligaments of the sacroiliac joint and the interosseous ligament, as well as a complete loss of pelvic stability and diastasis of the sacroiliac joint, which is highly likely to be accompanied by vascular injuries.
  - Lateral compression (LC) injury:

    LC I: This type of pelvic fracture is stable and caused by a violence acting on the posterior pelvis. It is char-

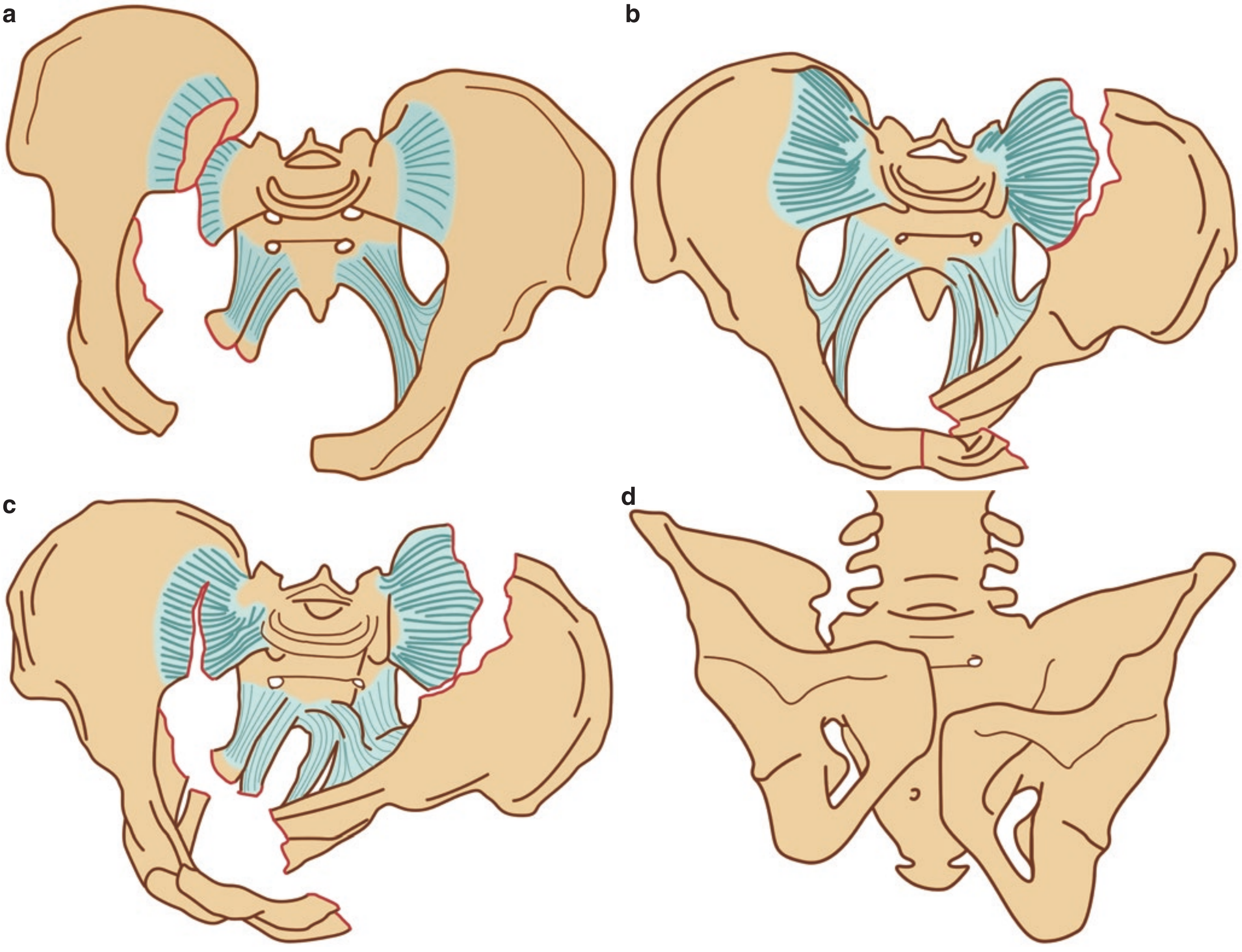


Fig. 3.14 Young & Burgess classification of pelvic fractures. (**a**) APC III fracture: Anterior-posterior crushing leading to a complete rupture of the pubic symphysis, sacrospinous ligament, sacral tuberous ligament, anterior sacroiliac ligament, posterior sacroiliac ligament, and interosseous ligament. (**b**) LC II fracture: Lateral crushing fracturing the iliac alar at the site lateral to the sacroiliac joint. (**c**) LC III fracture: Further lateral crushing causing a contralateral "open-book" injury. (**d**) VS fracture: An axial violence that disrupts both anterior and posterior stabilizing structures of the pelvis and causes cephalic displacement of the fractured bone

acterized by compression fracture of the ipsilateral ilium and transverse fracture of the pubic ramus.

LC II: A violent force acting on the anterior pelvis fractures the ipsilateral ilium on the lateral side of the sacroiliac joint, which is a crescent fracture and accompanied by varying degrees of PLC injuries of the sacroiliac joint. The pelvic ring retains its vertical stability due to intact sacrospinous and sacrotuberous ligaments.

LC III: A lateral violent force continuously acting on the contralateral pelvis ruptures the sacrospinous ligament, sacrotuberous ligament, and anterior ligaments of the sacroiliac joint of the contralateral pelvis, resulting in a "windswept" pelvis.

- Vertical shear (VS) injury: An axial force (for example, violent trauma) disrupts both anterior and posterior structures of the pelvis, causing a complete loss of pelvic stability and the accompanying cephaloposterior displacement of the ilium. This type of injury is often associated with severe retroperitoneal hemorrhage and nerve injury.
- Combined mechanical (CM) injury: The injury involves two or more mechanisms of injury mentioned above, the most common of which is a combination of LC and VS injuries.

- Tile classification of pelvic fractures: This classification system is commonly used and divides pelvic fractures into stable (type A), partially stable (type B), and unstable (type C) fractures according to the stability of the pelvis (Marvin Tile 1996b).
  - Type A fracture: Stable pelvic fractures with an intact posterior ring (Fig. 3.15):

    Type A1: Avulsion fractures of the ilium, primarily involving the protruding parts of the ilium, includ-

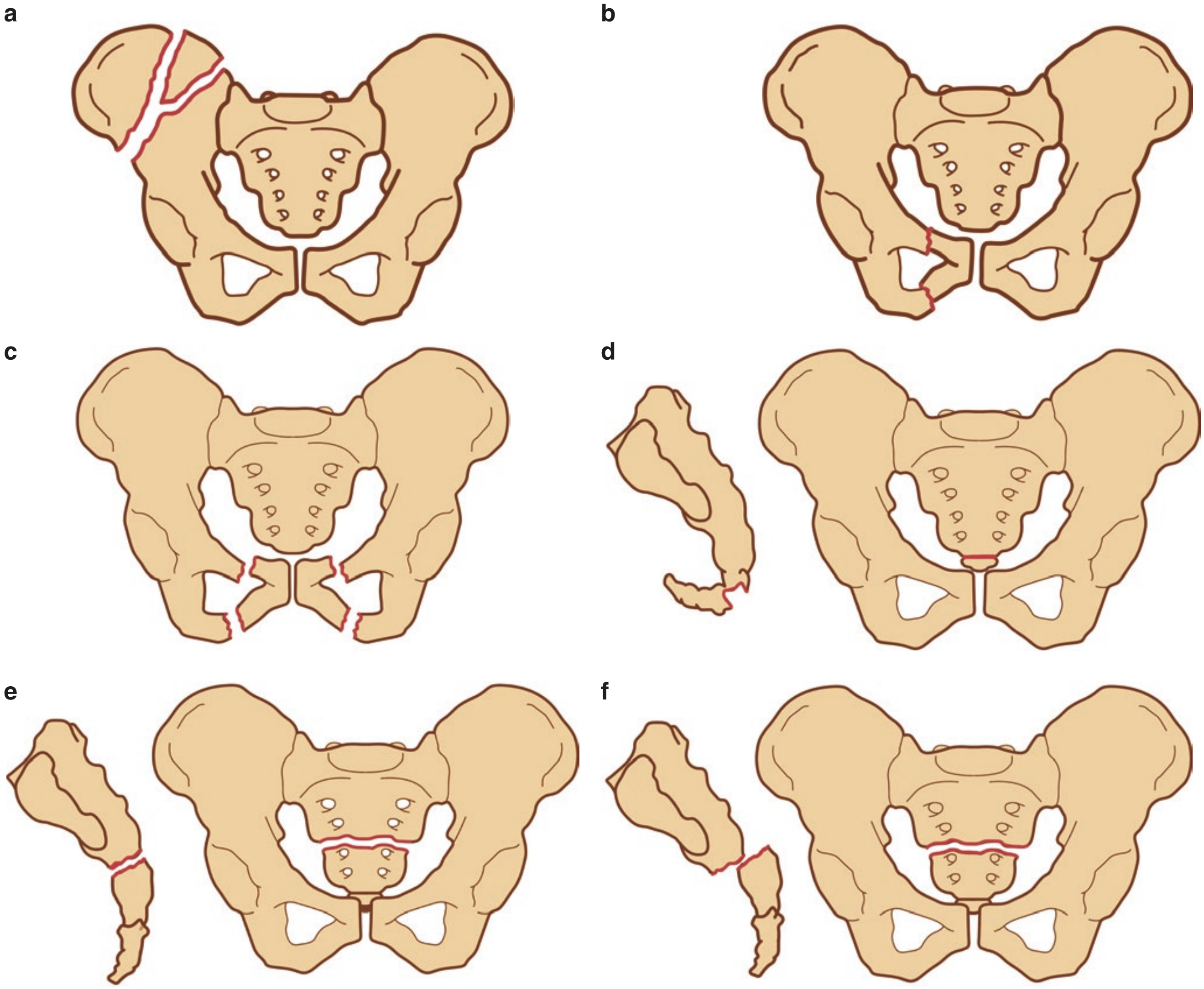


Fig. 3.15 Tile classification type A pelvic fractures. (**a**) Type A2.1: A separation of the iliac ala without fracture of the pelvic ring. (**b**) Type A2.2: A stable fracture without displacement or with a slight displacement of the pelvic ring. (**c**) Type A2.3: A diastasis of the anterior pelvic ring accompanied by anterior four-column fracture. (**d**) Type A3.1: A coccyx fracture or dislocation of the sacrococcygeal joint. (**e**) Type A3.2: A non-displaced transverse fracture of the sacrum. (**f**) Type A3.3: A displaced transverse fracture of the sacrum

ing the anterior superior iliac spine, anterior inferior iliac spine, and ischial tuberosity.

Type A2: Fractures of the pelvic ring with a separation or minor displacement of the iliac ala:

- Type A2.1: A separation of the iliac ala without a fracture of the pelvic ring;
- Type A2.2: A stable fracture without displacement or with slight displacement of the pelvic ring;
- Type A2.3: A diastasis of the anterior pelvic ring accompanied by anterior four-column fracture.

– Type A3: Transverse fractures of the sacrum or coccyx;

Type A3.1: Coccyx fractures or dislocation of the sacrococcygeal joint;

Type A3.2: Non-displaced transverse fractures of the sacrum;

Type A3.3: Displaced transverse fractures of the sacrum.

– Type B: Partially stable pelvic fractures with an incomplete disruption of the posterior ring (Fig. 3.16):

Type B1: Open-book injury, i.e., a pelvic fracture that is externally rotationally unstable.

Type B2: Lateral compression injury, i.e., a pelvic fracture that is internally rotationally unstable:

- Type B2.1: The anterior and posterior sides of the pelvic ring are fractured on the same side of the pelvis;
- Type B2.2: The fractures of the anterior and posterior sides of the pelvic ring occur on different sides of the pelvis, i.e., bucket-handle-like injury.

Type B3: Partially stable fractures on both sides:

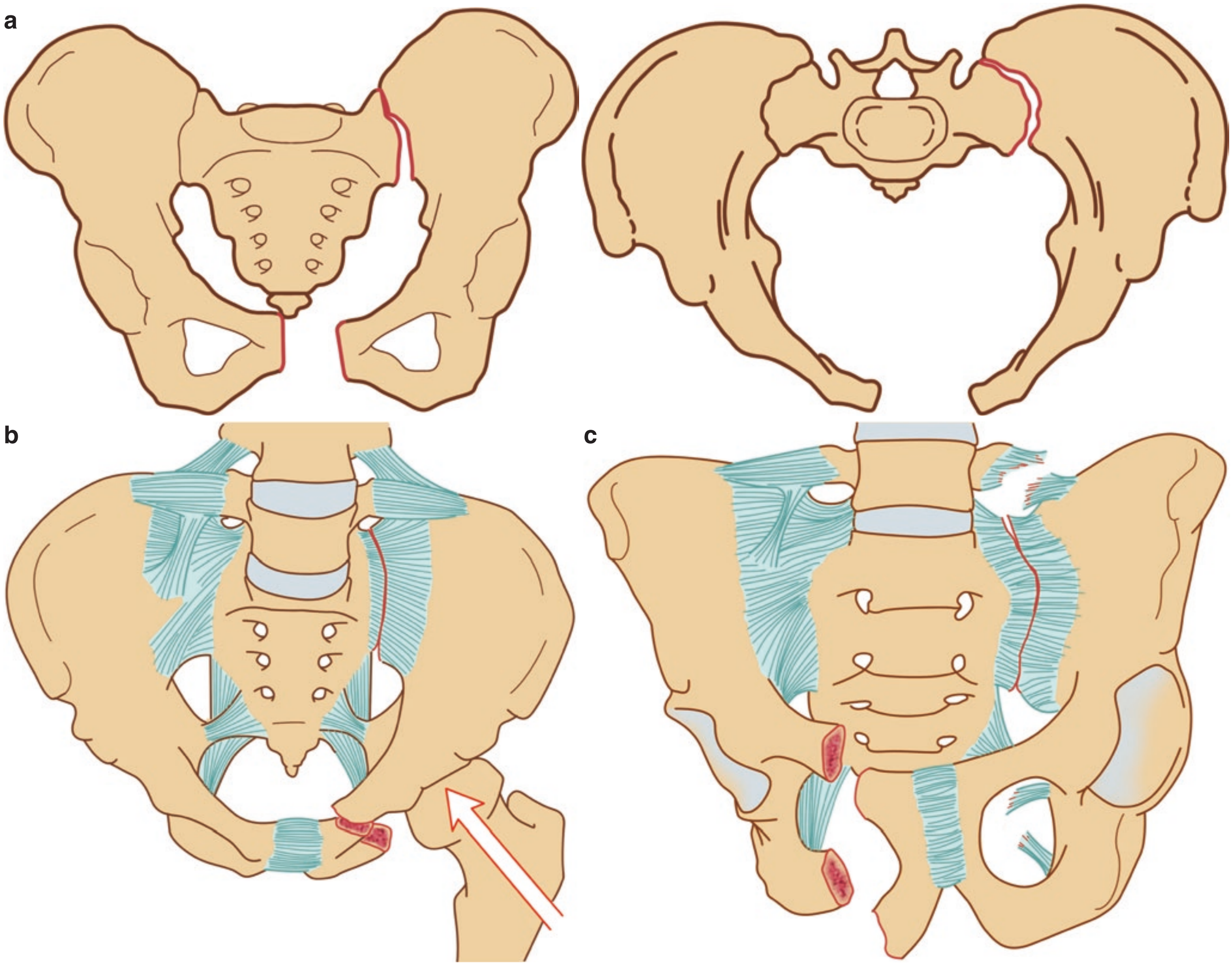


Fig. 3.16 Tile classification type B pelvic fractures. (**a**) Type B1: An open-book injury of the pelvis. (**b**) Type B2.1: A lateral compression fracture and an anterior fracture on the same side of impact. (**c**) Type B2.2: A lateral compression fracture and an anterior fracture on the opposite side of impact

  - Type B3.1: Type B1 fractures on both sides;
  - Type B3.2: A type B1 fracture on one side and a type B2 fracture on the other side;
  - Type B3.3: Type B_2 fractures on both sides.
- Type C: Unstable fractures involving ruptures of the PLC of the sacroiliac joint, sacrotuberous ligament, and sacrospinous ligament (Fig. 3.17).

Type C1: Unilateral unstable fractures:

- Type C1.1: An iliac fracture at the posterior pelvis;
- Type C1.2: Sacroiliac joint dislocation or fracture dislocation at the posterior pelvis;
- Type C1.3: A sacral fracture at the posterior pelvis.

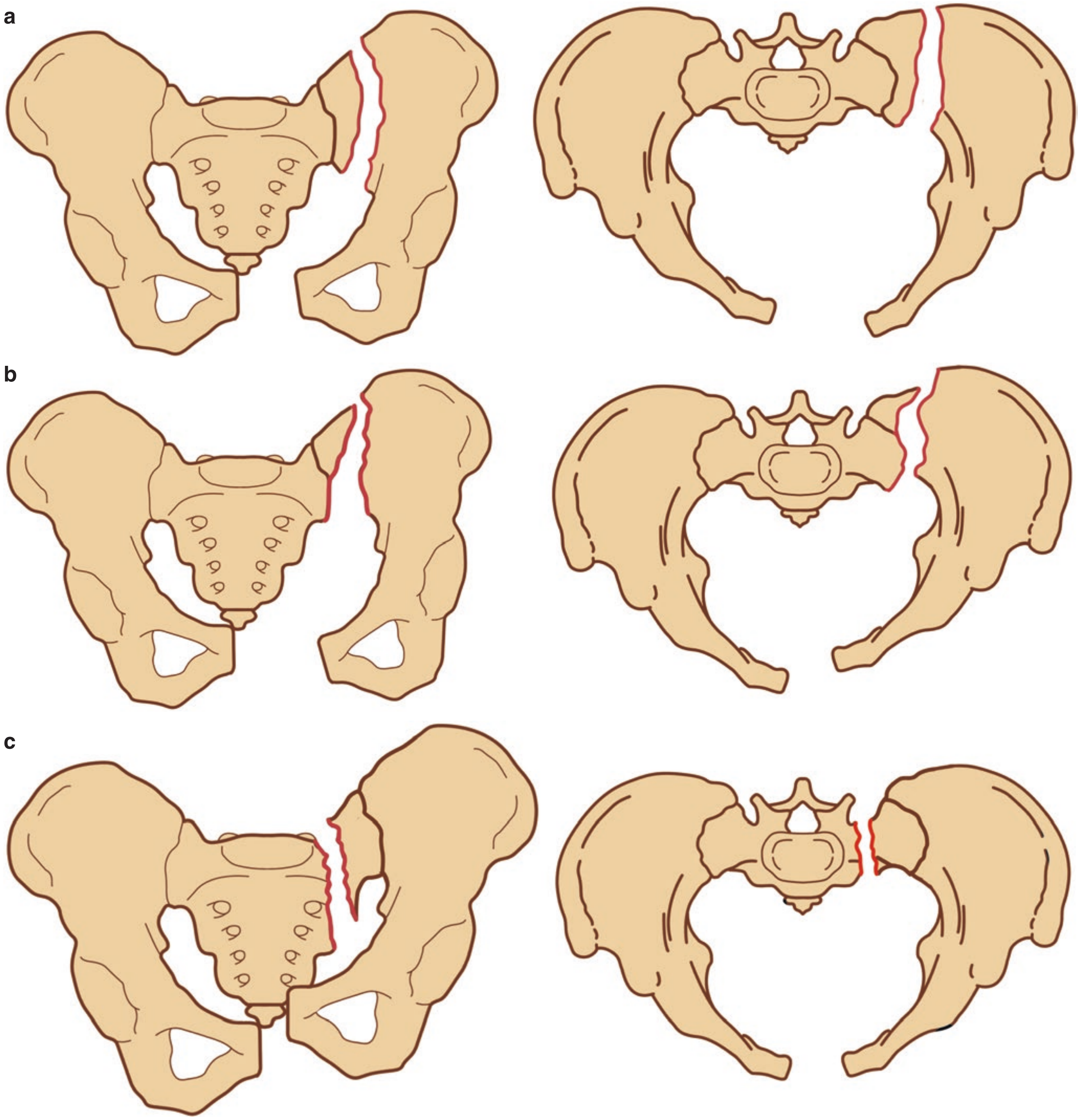


Fig. 3.17 Tile classification type C pelvic fractures. (**a**) Type C1.1: An iliac fracture at the posterior pelvis. (**b**) Type C1.2: A sacroiliac joint dislocation or fracture displacement at the posterior pelvis. (**c**) Type C1.3: A sacral fracture at the posterior pelvis

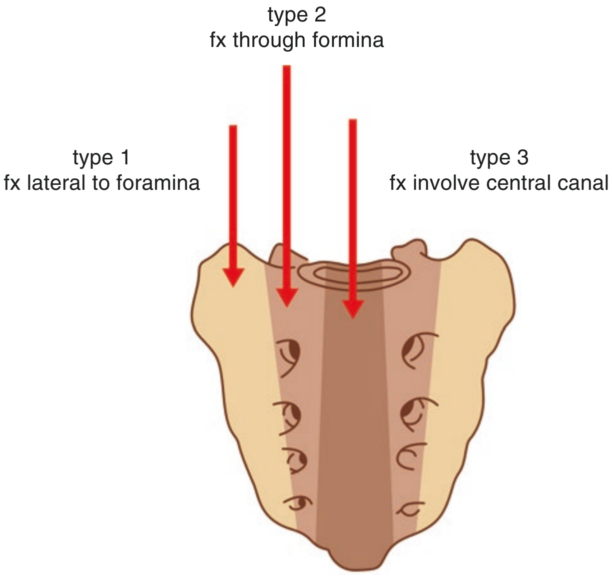


Fig. 3.18 Type I fractures have a fracture line outside the neural foramen; a Type II fracture is a sacral fracture that crosses the neural foramen; a Type III fracture involves the sacral canal in the center of the sacrum

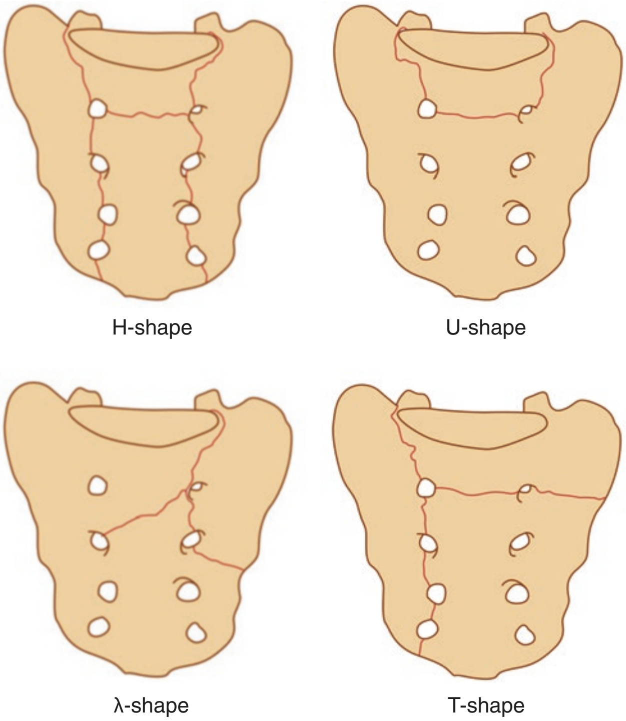


Fig. 3.19 Complex sacral fractures are descriptively divided into H-, U-, λ-, and T-shaped fractures based on the shape of the fracture line

Type C2: A partially stable fracture on one side and an unstable fracture on the other side.

Type C3: Unstable fractures on both sides. The rare type of injury that involves sacroiliac joint dislocation on both sides with the intact anterior ring is also classified as a type C_3 injury.

- Danis classification of sacral fractures (Denis et al. 1988):
  - This classification method is used for vertically displaced pelvic fractures, which can be divided into three types (types I, II, and III) according to the position relationship of the fracture line and neural foramen.
  - Danis classification and nerve injury (Fig. 3.18) (Denis et al. 1988):

    5.9% of type I sacral fractures are accompanied by nerve injury, mostly involving the L5 nerve root;

    28.4% of type II sacral fractures are accompanied by nerve injury, mostly involving sciatic nerve damage and seldomly affecting the function of the urinary bladder;

    56.7% of type III sacral fractures are accompanied by nerve injury, which often causes defecation function, urinary bladder, and sexual dysfunctions.
- Descriptive classification of sacral fractures (Vaccaro et al. 2004):
  - Complex sacral fractures are descriptively divided into H-, U-, λ-, and T-shaped fractures based on the shape of the fracture line (Fig. 3.19).

3.1.5 Preoperative Assessment of Pelvic Fractures

- Clinical assessment (Gonzalez et al. 2002).
  - Through queries regarding the witnessed trauma and physical examination, the stability of the pelvic ring and severity of soft tissue damage are primarily determined. Repeated examinations should be avoided to minimize the risk of secondary pelvic bleeding.
  - Clinical assessment has two levels: Level 1 is mostly focused on the comprehensive evaluation of vital signs related to the respiratory and circulatory functions of the patient, in particular life-threatening organ injuries; Level 2 is mostly focused on the pelvic fracture itself for surgical planning.
  - Level 1 assessment is focused on the items described in the previous chapter as “Femoral shaft fractures”. For patients with a marginal-stability, unstable, or near-death status, priority is given to resuscitation, and “Damage Control Surgery” actions should be initiated immediately.
  - In the fracture assessment, attention should be paid to the following signs or indicators:

    Shortening or obvious rotational deformity of the lower extremity, which indicates an accompanying unstable pelvic fracture;

Massive subcutaneous hemorrhage, swelling, and bruising in the waist and hip areas, which indicates massive pelvic bleeding;

A large hematoma posterior to the lumbosacral spine, which suggests a sacroiliac joint dislocation or sacral fracture displacement;

A palpable depression of the pubic symphysis, which suggests anterior pelvic ring damage and symphyseal diastasis;

The intactness of the pelvic ring, which is evaluated by anteroposterior-lateral pelvic compression tests, and the vertical stability of the pelvis, which is evaluated by drawer tests;

The presence of blood during the finger palpation examination of the anal canal, which suggests a possible rectal injury;

Inability to pass a transurethral bladder catheter or the presence of hematuria, which suggests a urethral or urinary bladder injury.

- Imaging examination (McCormack et al. 2010):
  - Plain radiography examination is the most basic evaluation method, which can provide a definitive diagnosis in 90% of patients. Further examinations include radiographs of the pelvic inlet and outlet, which help determine the direction of the fracture displacement (e. g., towards the anterior or posterior, cranial or caudal, and the direction of rotation).
  - AP plain radiography (Fig. 3.20):

    The presence of a symphyseal diastasis or pubic ramus fracture suggests anterior pelvic ring injury.

    The presence of an iliac fracture, diastasis of the sacroiliac joint, or sacral fracture suggests posterior pelvic ring injury.

    The presence of a L5 transverse process fracture, avulsion fracture of the sacrospinous ligament, or sacrotuberous ligament suggests that the pelvis is unstable and has a large displacement.
  - Pelvic inlet radiography (Fig. 3.21):

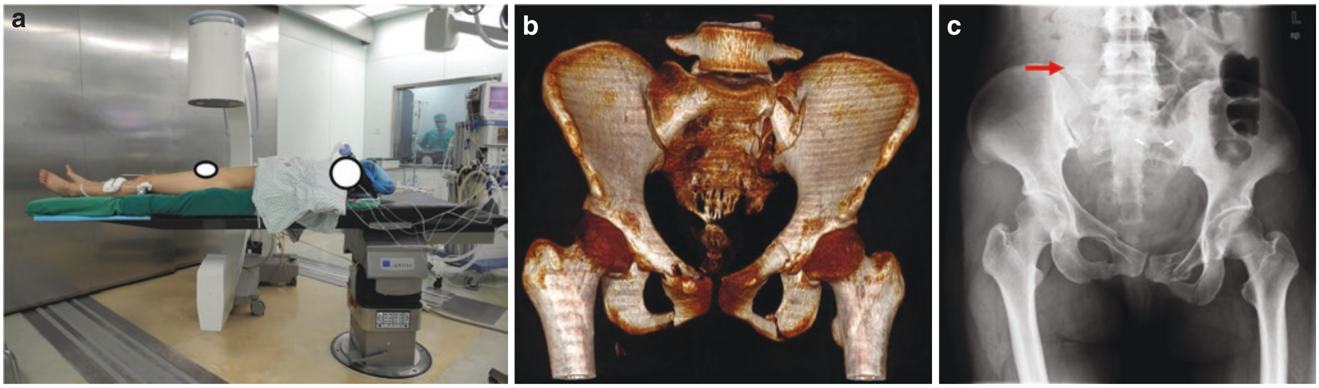


Fig. 3.20 (**a**) AP projection of the pelvis. (**b**) A 3D model reconstructed from CT images showing the position of the pelvis under an AP projection. (**c**) Pelvic AP plain radiograph: There is a fracture of the left L5 transverse process, suggesting that the pelvis is longitudinally unstable

Fig. 3.21 (**a**) The projection angle for inlet radiography of the pelvis. (**b**) A 3D model reconstructed from CT images showing the position of the pelvis in the inlet view. (**c**) A pelvic inlet plain radiograph clearly showing the injuries of the posterior complex, including the dislocation and widening of the sacroiliac joint and an iliac fracture

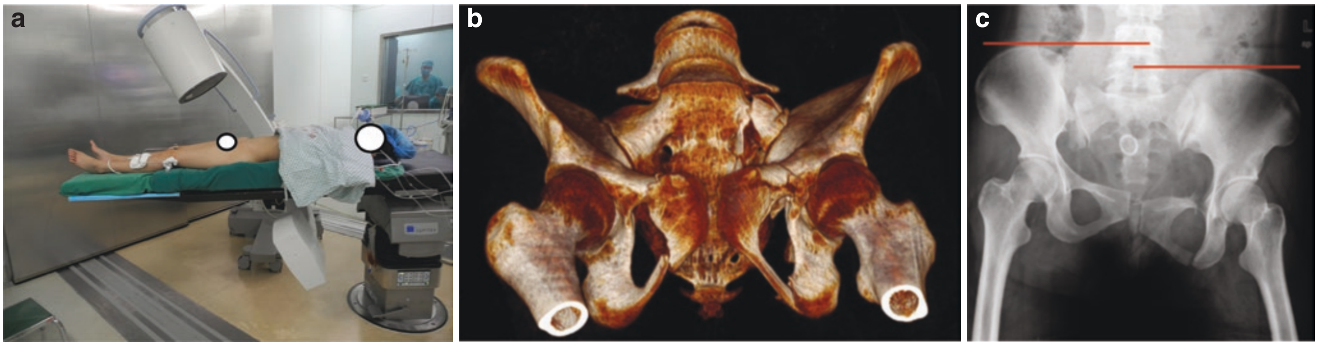


Fig. 3.22 (**a**) The projection angle for outlet radiography of the pelvis. (**b**) A 3D model reconstructed from CT images showing the position of the pelvis in the outlet view. (**c**) A pelvic outlet plain radiograph clearly showing the proximal displacement of the right hemipelvis, resulting in a shortening deformity of the affected extremity

  The pelvic inlet radiographs are obtained by projecting the x-ray beam at an angle of 50° relative to the patient from the cranial to the center of the pelvis.

  The radiographs can demonstrate the anterior and posterior displacement status of the injured posterior pelvic ring.

  The radiographs can demonstrate the internally rotational displacement caused by lateral compression.

  The radiographs can display the external rotation of the pelvis caused by a vertical shear force in acetabular fractures.

- Pelvic outlet radiography (Fig. 3.22):

  The pelvic outlet radiographs are obtained by directing the x-ray tube at an angle of 45° relative to the patient from the caudal side to the pubic symphysis.

  The radiographs can demonstrate the upward displacement status of the injured posterior pelvic ring and provide accurate information regarding the shortening of the affected extremity.

  The radiographs can display the fracture of the sacral foramina.

- Lateral radiography: The greater sciatic notches on the two sides completely overlap in the lateral radiographs, which can clearly display the slope structure (Fig. 3.23).

  The lateral radiographs are obtained by projecting the x-ray beam perpendicular to the patient.

  The radiographs can be used to evaluate the fracture and dislocation of the lumbosacral joint, sacrum, coccyx, and other bony structures.

  The radiographs help precisely position the entry point for percutaneous sacroiliac joint screw fixation.

- Radiographic characteristics of unstable pelvic fractures: These characteristics are crucial for fracture diagnosis and evaluation (Tile 1988)..

  A symphyseal diastasis >2.5 cm, indicating rotational instability of the pelvis.

  A cranial displacement of the hemipelvis >1 cm, indicating vertical instability of the pelvis.

  The push-pull test of the pelvis: Under anesthesia, a radiograph is obtained when one lower extremity is pushed upwards and the other lower extremity is pulled downwards, and then another radiograph is obtained after switching the sides that are pushed and pulled. Subsequently, the maximum displacement of the ilium is obtained by comparing the two images. Bucholz et al. considered a displacement greater than 1 cm to be a sign of vertical instability of the pelvis. This test can be performed once only and is prohibited in patients who have unstable hemodynamics or have a fracture in zone II or III of the sacrum.

  The presence of a sacroiliac joint dislocation larger than 0.5 cm on the radiographic images at any projection angle suggests an unstable fracture.

  Posterior pelvic ring fractures with separated fragments as indicated by a visible gap but not a depression at the fracture site are considered unstable fractures.

  A fracture of the L5 transverse process along with avulsion fractures of the sacrospinous ligament (avulsion of the ischial spine) or the sacrotuberous

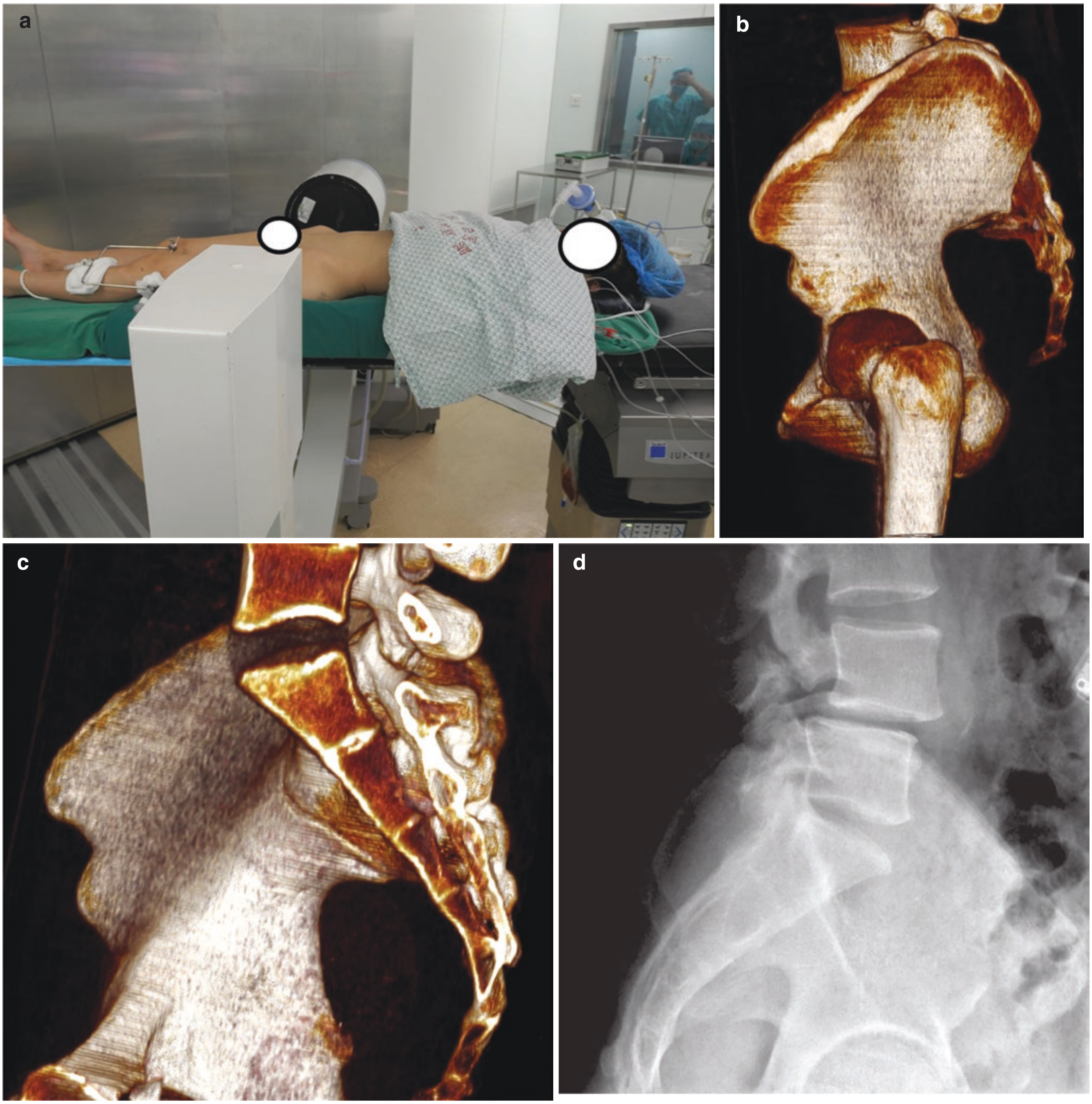


Fig. 3.23 (**a**) The projection angle for lateral radiography of the pelvis. (**b**) A 3D model reconstructed from CT images showing the position of the pelvis in the lateral view. (**c**) Cross-sectional view showing the margins of the true pelvic and ilium and the position of the first sacral vertebra. (**d**) Lateral plain radiograph: It displays the rotational displacement status of the pelvis, and during sacroiliac joint screw fixation, it can serve as a monitoring tool to determine the entry point and direction of screwing

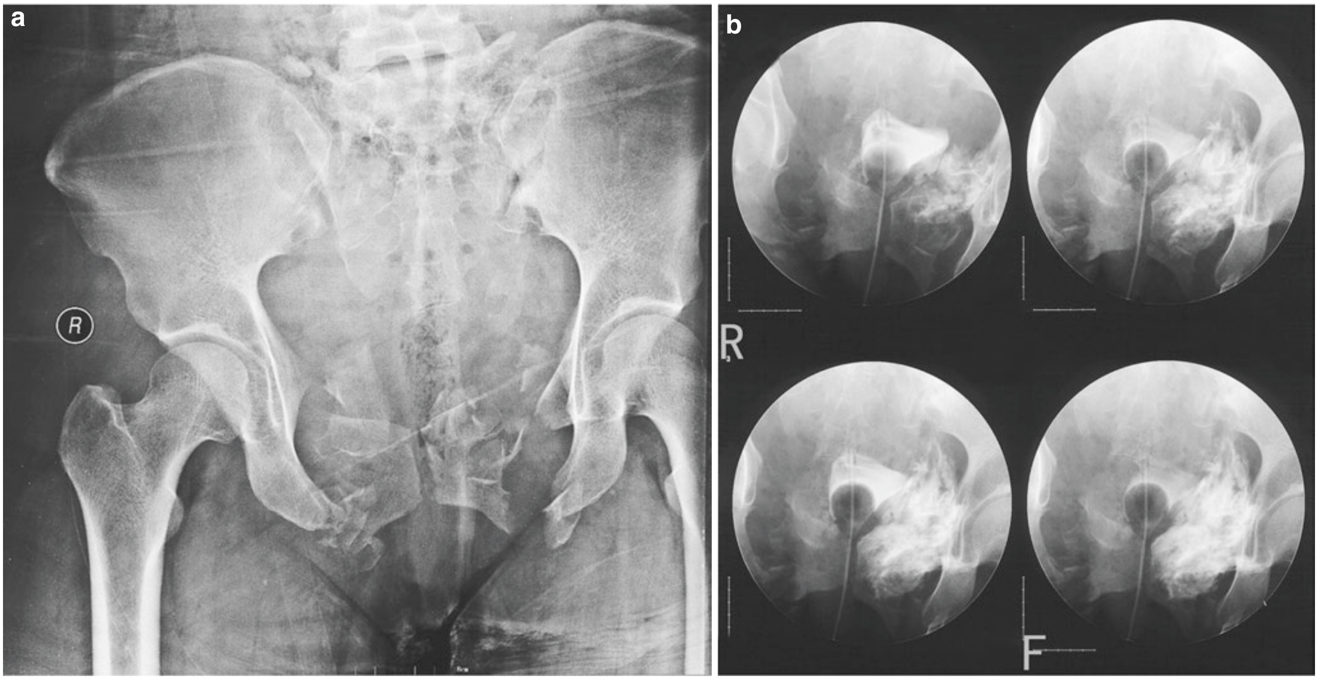


Fig. 3.24 (**a**) Tile classification type B1 pelvic fracture: Fractures of the bilateral superior and inferior pubic rami. (**b**) Retrograde cystography is performed after catheterization due to suspected bladder injury, and the images sequentially show the leakage of the contrast agent into the pelvis from the ruptured bladder

    ligament (avulsion of the lateral rim of the sacrum) is indicative of an unstable pelvis.
  - Retrograde cystography should be obtained in patients with suspected urinary tract injury (Fig. 3.24).
- CT scanning (Matta and Yerasimides 2007):
  - Patients with a pelvic fracture must receive CT scanning for bone mass and soft tissue demonstration, which can display the fracture-caused changes precisely and provide information for stability assessment of the PLC of the sacroiliac joint.
  - The 3D reconstruction technology can demonstrate the type and complications of the fracture more precisely, thereby playing a significant role in the preoperative assessment and surgical planning (Fig. 3.25).
  - CT angiography helps determine the vascular injury by allowing clear visualization the vessels (Fig. 3.26).

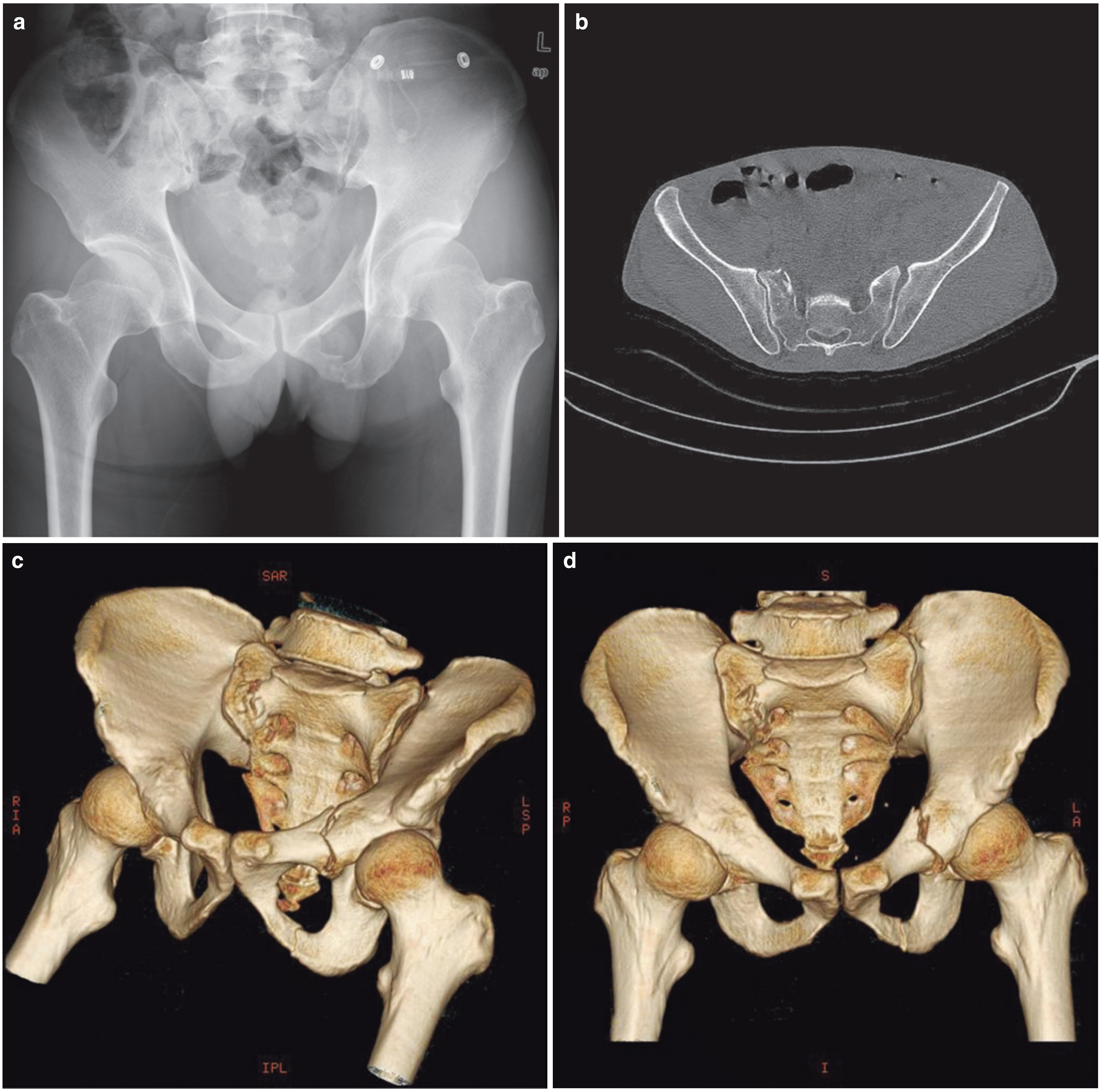


Fig. 3.25 Pelvic fracture. (**a**) As shown in the pelvic AP radiograph, the left sacroiliac joint space is widened, and the left pubic and sciatic rami are fractured. Therefore, the injury is considered a Young & Burgess classification type APC injury. (**b**) CT plain scan revealing a compression fracture in right iliac zone I. (**c, d**) The 3D-reconstructed CT images clearly show the location and severity of the fracture. This injury is a type LC injury

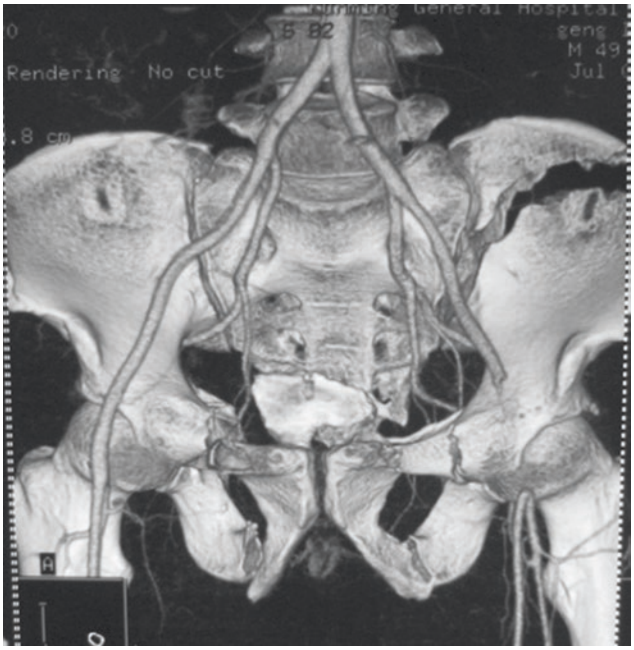


Fig. 3.26 3D-reconstructed CT image can more precisely demonstrate the fracture type and vascular injury, e.g., the obstructed left external iliac artery and femoral artery are displayed in the image

3.2 Treatment for Pelvic Fractures

3.2.1 Clinical Treatment Principles for Pelvic Fractures

- For patients with pelvic fractures at high risk of death: Special precaution must be taken in patients with the following situations.
  - The injury has completely disrupted the structure of the posterior pelvic ring, including type APC III, VS, or LC III injury;
  - A high Injury Severity Score (ISS) score;
  - Complications of head and abdominal injury;
  - Unstable hemodynamics at the time of hospital visit;
  - The patient requires a massive blood transfusion;
  - Presence of accompanying perineal rupture or open pelvic fracture;
  - Old age.
- Treatment strategies for pelvic fractures (Giannoudis and Pape 2004; McCormack et al. 2010; Marvin Tile 1996a):
  - Following the procedures described earlier, the first step is to classify the general condition and pelvic stability of the patient with a fractured pelvis: (1) unstable general condition and unstable pelvic ring; (2) unstable general condition and stable pelvic ring; (3) stable general condition and unstable pelvic ring; and (4) stable general condition and stable pelvic ring.
  - Patients with an unstable general condition and unstable pelvic ring:

    In patients with a dislocated pelvic fracture, 80–90% of the bleeding comes from the presacral venous plexus and the broken ends of the fractured bone, and it is very difficult to stop the bleeding directly by surgery. In pelvic fractures, especially type APC fractures, the negative pressure (suction force) caused by the increase in pelvic volume results in massive bleeding.

    Emergency treatment at the scene: The immediate action at the scene includes the use of medical anti-shock trousers, a pelvic girdle, or a self-made simple pelvic sling. This action can reduce the bone bleeding via reduction of the pelvic volume (creating a void-filling effect) in patients with an open-book pelvic fracture caused by anterior-posterior compression (i.e., type APC). However, for a type LC fracture caused by lateral compression, this method is not suitable due to a high risk of increasing the fracture displacement because it applies the compression force in the same direction as the force that caused the injury.

    Treatment in the emergency room: External fixation technologies stabilizing the pelvis can be applied to stop the bleeding.

    - External fixation brace: It is used in patients whose posterior pelvic ring has not been completely destroyed. In patients whose posterior pelvic ring has been destroyed, the compressive force applied on the anterior pelvic ring by the external brace might further separate the sacroiliac joint and aggravate the bleeding.
    - Pelvic C-clamp: In patients whose posterior pelvic ring has been destroyed, a C-clamp is used to compress the posterior pelvic ring and decrease the volume of the true pelvis. Because the pelvic C-clamp does not interfere with the open abdominal surgery, it is ideal for patients with the accompanying abdominal organ injury and who require exploratory laparotomy.

    If the bleeding cannot be effectively controlled by measures to reduce the pelvic volume, rupture of the named arteries should be considered, and angiographic embolization should be performed in a timely manner.

    If angiographic embolization cannot be performed or the bleeding cannot be stopped by all the above-described measures, patients whose blood pressure continue to drop and who show signs of hemorrhagic shock should receive pelvic packing hemostasis in a timely manner.

After the bleeding is controlled by an emergency operation, the patient is transferred to the ICU for further monitoring and resuscitation and then to a regular ward after his or her condition becomes stable. The ultimate internal fixation can be given within one to 2 weeks (no more than 3 weeks after injury) based on the condition of the patient.

– Patients with an unstable general condition and stable pelvic ring: First, necessary resuscitation measures and hemorrhage control are administered. After serious injuries elsewhere in the body are treated, the pelvic fracture is assessed after the general condition is stabilized. Special attention should be paid to avoiding further displacement of the fractured bone during treatment.
– Patients with a stable general condition and an unstable pelvic ring:

  Potential or latent hemorrhage must be ruled out by 24–48 h of close monitoring; if the general condition is stable, subsequent treatment is planned based on a thorough imaging assessment. A strong femoral condyle traction up to 1/4 of the body weight on the ipsilateral side can be administered in patients with a vertically unstable fracture during the assessment period.

  Type B1 fractures:

  - Fractures with a symphyseal diastasis less than 2.5 cm are amenable to conservative treatment.
  - In fractures with a symphyseal diastasis greater than 2.5 cm, a high possibility of massive hemorrhage necessitates close monitoring of vital signs due to severe soft tissue damage of the pelvic wall and floor and an increased pelvic volume. The treatment options include external fixation, closed reduction combined with pubic symphysis screw fixation, and pubic symphysis plate stabilization.

  Type B2 fractures:

  - Type B2.1: Factures with the ipsilateral extremity internally rotated <30° are amenable to conservative treatment. They can also be fixed with an external fixation brace to ease the care. However, if the pubic symphysis is interlocked, internal reduction is impossible, or the pubic ramus is largely rotationally displaced, surgical reduction and fixation with pubic symphysis screws and/or pubic ramus screws is performed.
  - Type B2.2: These bucket-handle-like injuries, which might cause shortening and internal rotation malformation of the affected extremity, are mostly treated surgically. If internal reduction is possible, the injured PLC can be stabilized by sacroiliac joint screws, and the anterior pelvic ring can be stabilized using pubic ramus screws or an external fixation brace. If internal reduction has failed and the affected extremity is shortened more than 2 cm or internally rotated more than 30°, open reduction and fixation are necessary.

  Type B3: The fractures on both sides are treated following the above-described protocols.

  Type C1 fractures:

  - Type C1.1: This type of fracture (crescent) can be reduced by closed reduction technologies, and an iliac fracture can be fixed with LC II screws. In patients with an internal reduction failure, the iliac fracture is treated with open reduction and plate-screw fixation via the anterior approach. The anterior fractures are treated according to their locations, e.g., the pubic ramus fracture can be fixed with pubic ramus screws, and the separated pubic symphysis can be fixed with pubic symphysis screws or an external fixation brace.
  - Type C1.2: This type of fracture can be reduced by closed reduction technologies. The fracture of the posterior ring is fixed with sacroiliac joint screws. In patients with an internal reduction failure, fracture of the posterior pelvic ring is treated with open reduction and plate-screw fixation via the anterior approach.
  - Type C1.3: This type of fracture can be reduced by closed reduction technologies and does not necessitate decompression by laminectomy. The fracture of the posterior ring is fixed with sacroiliac joint screws. In patients with an internal reduction failure, the fracture of the posterior pelvic ring is treated with open reduction and plate-screw fixation via the posterior approach.

  Types C2 and C3 fractures: The fractures on both sides are treated following the above-described protocols.

– Patients with a stable general condition and stable pelvic ring: Treatment strategies for Tile A stable fractures vary with the subtypes.

  Type A1: A type A1 fracture can heal by itself as long as the patient reduces the amount of physical activities and avoids further damage. Patients who have a large avulsion fragment or demand a higher level of functional recovery can be treated with surgical fixation.

  Type A2:

  - Type A2.1: Due to abundant muscles surrounding the ilium, a type A2.1 fracture can heal by

conservative treatment, which might cause residual malformation. To avoid malformation and improve muscular function, surgical iliac ala screw or plate-screw fixation can be considered.
  - Type A2.2: The treatment methods vary with individual situations. Elderly patients with a non-displaced or slightly displaced fracture are given conservative treatment, with special attention paid to the prevention of complications caused by a long period of being bedridden or thrombosis and lung-related complications. In young patients with a non-displaced or slightly displaced fracture, the injury is likely caused by a highly violent force, and therefore, it is crucial to rule out any potential unstable injury; surgical treatment is given if necessary.
  - Type A2.3: Anterior four-column fractures that have been significantly displaced should be surgically treated, i.e., open reduction and pubic ramus screw fixation.

Type A3:

  - Type A3.1: Type A3.1 fractures are primarily amenable to conservative treatment.
  - Type A3.2: Type A3.1 fractures are primarily amenable to conservative treatment.
  - Type A3.3: Type A3.3 fractures accompanied by neurological dysfunctions, such as urinary and defecation dysfunctions or a sensory loss of the saddle area, must be treated with open reduction in combination with decompression by laminectomy.

3.2.2 Surgical Techniques

3.2.2.1 External Fixation and Emergency Treatment of Pelvic Fractures

- External fixation of the anterior pelvic ring (Burgess 1995).
  - Mechanical characteristics of external fixation of the anterior pelvic ring using a brace:

    For type B1 pelvic fractures, which are vertically stable, external fixation of the anterior pelvic ring with a brace can sufficiently stabilize the pelvic ring.

    For type C pelvic fractures, which are both rotationally and vertically unstable, external fixation of the anterior pelvic ring alone can only partial stabilize the pelvis and cannot provide sufficient stability for weight-bearing walking. The pelvic ring can be well stabilized by internal fixation of the posterior ring combined with external fixation of the anterior ring with a brace.
  - Surgical indications:

    Emergency treatment for severe pelvic fractures aims to control pelvic bleeding and temporarily stabilize the pelvic ring.

    For patients with multiple traumas, the use of an external fixation brace of the anterior pelvic ring helps reduce the pain and eases the care.

    External fixation of the anterior pelvic ring using a brace may become the ultimate treatment for rotationally unstable pelvic fractures.

    External fixation of the anterior pelvic ring using a brace can be jointly used with internal fixation of the posterior ring to enhance the overall post-fixation stability of the pelvic ring.
  - Body position and preoperative preparation:

    Anesthesia: The patient is under general anesthesia;

    The patient lies supine on a radiolucent operating table, with a cushion placed behind the hip to help reduce the fracture;

    A C-arm system is set up for intraoperative fluoroscopic monitoring;

    The skin in the surgical area is disinfected, followed by surgical draping;
  - Operative incision according to the projection on the body surface: The screws mounting the external fixator are usually placed in the iliac crest, anterior inferior iliac spine, or iliac ala, among which the first two methods are more commonly used in clinical practice.

    For screwing the acetabulum: An incision with a length of 3.4 cm is created distal to the anterior superior iliac spine, with the medial edge of the incision on the extension line of the lateral edge of the patella. It is worth noting that because this incision is within the area where the lateral femoral cutaneous nerve passes, the blunt separation technique should be used after the skin is cut open, and the nerve should be protected using a retractor;

    For screwing of the iliac crest: An arcuate incision is created along the iliac crest (Fig. 3.27).
  - Fracture reduction and fixation:

    Surgical procedure with screws entering the anterior inferior iliac spine (Fig. 3.28):
    - After the subcutaneous tissue and deep fascia are cut, the lateral femoral cutaneous nerve is pulled aside and protected. A blunt separation is performed, and the locations of the anterior inferior iliac spine and the apex of the acetabulum are identified by palpation.
    - Two Kirschner wires are placed along the medial and lateral surfaces of the iliac crest, which are used to mark and guide the insertion direction of the screws.

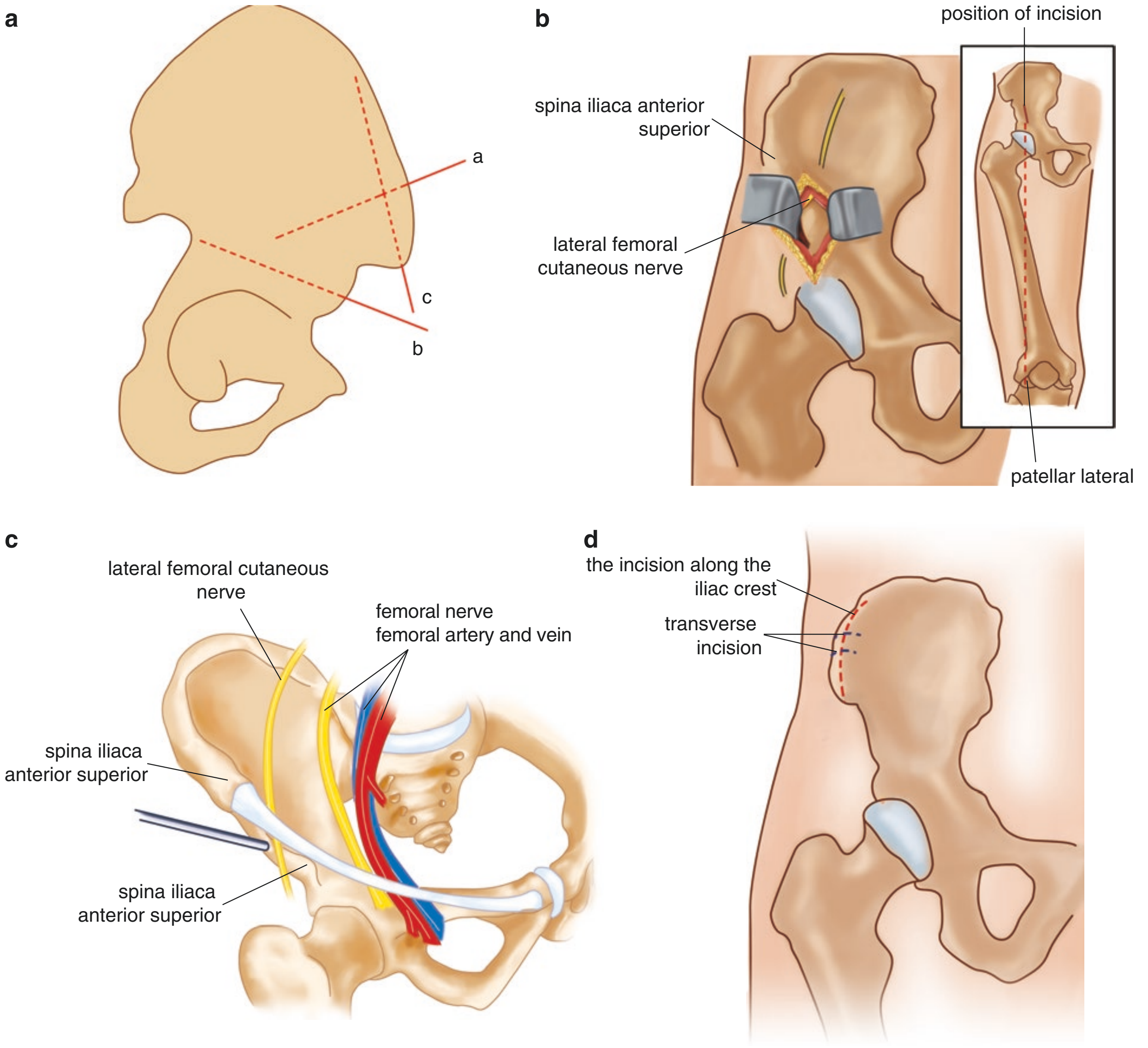


Fig. 3.27 (**a**) Three methods commonly used in the pelvis for screw-mounting the external fixator: screwing of the iliac crest (a), screwing above the acetabulum (b), and screwing of the iliac ala (c). (**b**) Operative incision according to the projection on the body surface for screwing above the acetabulum: an incision with a length of 3.4 cm is created distal to the anterior superior iliac spine, with the medial edge of the incision on the proximal extension line of the medial edge of the patella. (**c**) The screw entry point above the acetabulum is close to traveling area of the lateral femoral cutaneous nerve. Attention should be paid to pulling the lateral femoral cutaneous nerve aside with a hook when the blunt separation of soft tissue reaches the bone surface, and a protective sleeve should be applied during screw placement. (**d**) Operative incision according to the projection on the body surface for screwing of the iliac crest: An arc incision is created along the iliac crest

- The entry points of the screws are at least 1 cm higher than the apex of the acetabulum, and the screws are advanced at a 30° angle pointing to the cephalic side on the sagittal plane pointed towards the direction marked by the two Kirschner wires.
- In young patients, the bone cortex is opened using a drill, followed by screwing. In elderly osteoporotic patients, self-tapping self-drilling screws with a length of 5–6 mm can be directly placed while protecting the surrounding soft tissue with a sleeve. The screwing depth is approximately 4–5 cm.
- On each side, after the first screw is placed, a connecting block is assembled, through which the second screw is placed proximal to the first one.
- The upper part of the acetabulum is dense, allowing it to serve as a handle for reducing up-down and rotational displacements of the pelvic fracture.

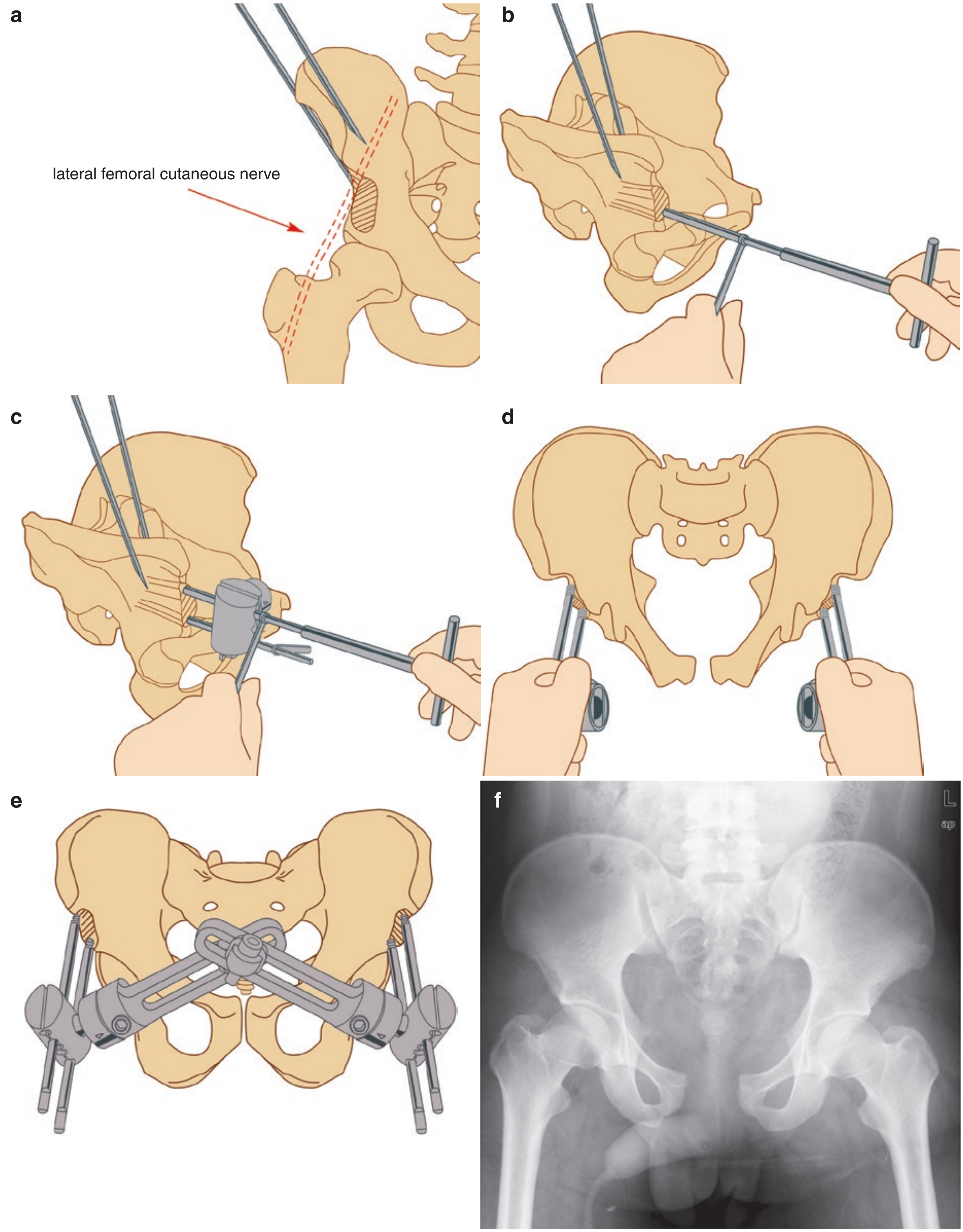


Fig. 3.28 (**a**) Two Kirschner wires are placed along the medial and lateral surfaces of the ilium in the vicinity of the iliac crest to guide the insertion direction of the screws. The subcutaneous tissue and deep fascia are cut while avoiding damage to the lateral femoral cutaneous nerve. (**b**) The entry points of the screws are at least 1 cm higher than the top of the acetabulum; the insertion direction is inclined 30° cephalically on the sagittal plane and points to the direction marked by the two Kirschner wires. (**c**) After a screw is inserted, the connecting block is installed, through which a Schanz screw is screwed into the proximal end of the first screw. Following the same procedure, two screws are placed on the opposite side. (**d**) The upper part of the acetabulum is dense, allowing it to serve as a handle for reducing the up-down and rotational displacements of the pelvic fracture. (**e**) The connecting bar is installed, and all screws are tightened for fixation after the iliac ala is compressed by a medially applied force. (**f–i**) For a Young & Burgess classification type APC III pelvic fracture, external bracing was performed by screwing above the acetabulum after sacroiliac screw placement to stabilize the posterior structures

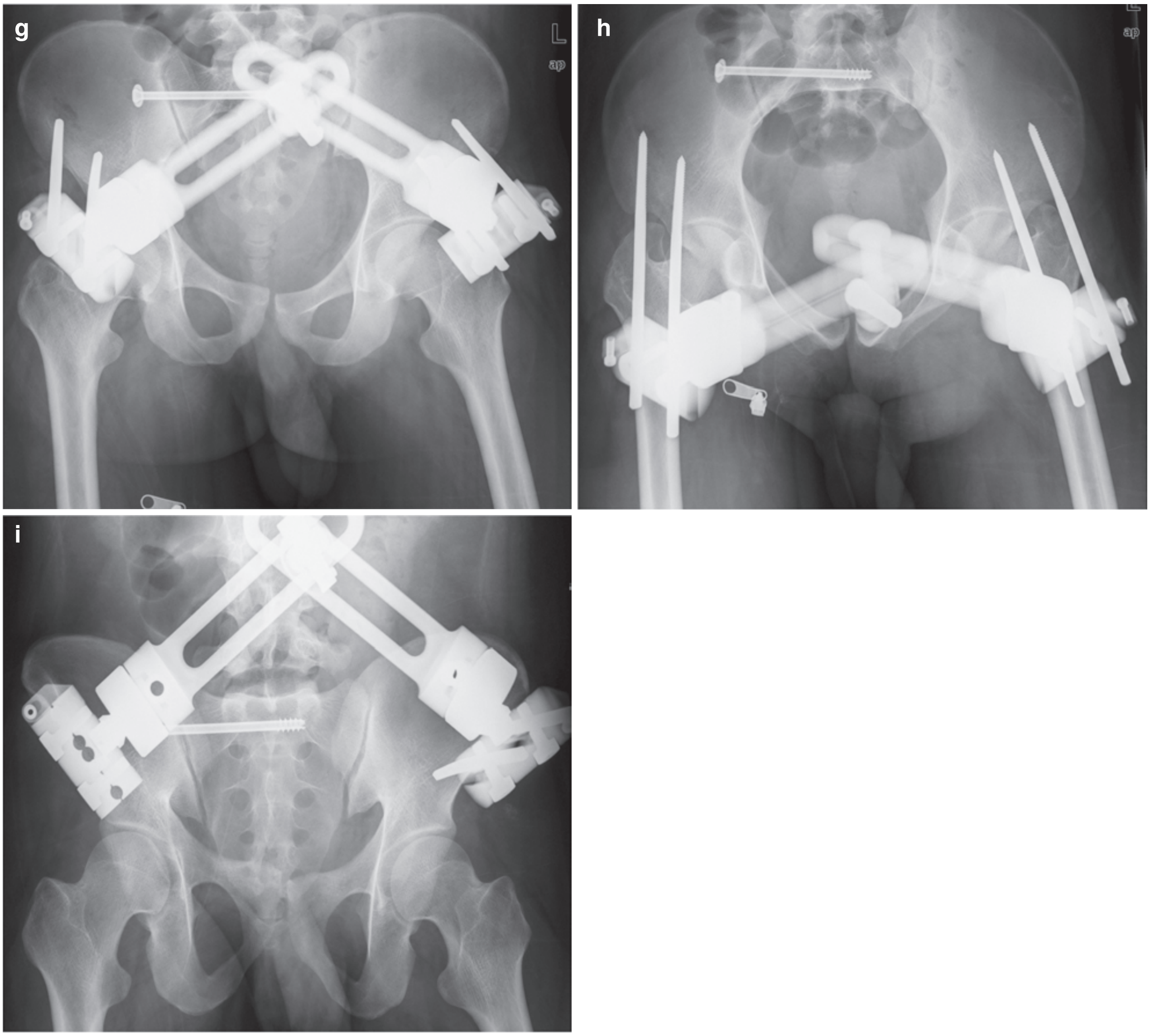


Fig. 3.28 (continued)

- The connecting bar is installed, and all screws are tightened for fixation after the iliac ala is compressed by a medially applied force.

Surgical procedure with screws entering the iliac crest (Fig. 3.29):

- After the skin and subcutaneous tissue are cut up to the iliac crest, two Kirschner wires are placed along the medial and lateral surfaces of the ilium, which are used to mark and guide the insertion direction of the screws.
- The first screw is placed 2 cm posterior to the anterior superior iliac spine. Because the edge of the iliac crest is protruding, the screw entry point should be positioned at the medial half of the edge of the iliac crest.
- The screw is inserted along the direction at an approximately 45° angle relative to the sagittal plane and converging towards the medial. The screwing depth is approximately 5 cm.
- On each side, a connection block is assembled after the first screw is placed, through which the second screw is placed proximal to the first one.
- The connecting bar is installed. Because the iliac crest is not as robust as the apex of the acetabulum used to screw the anterior inferior iliac spine, excessively strong compression on the screws should be avoided; instead, it is more appropriate to medially push and compress the iliac ala using both hands and then tighten all the nuts to finalize the fixation.

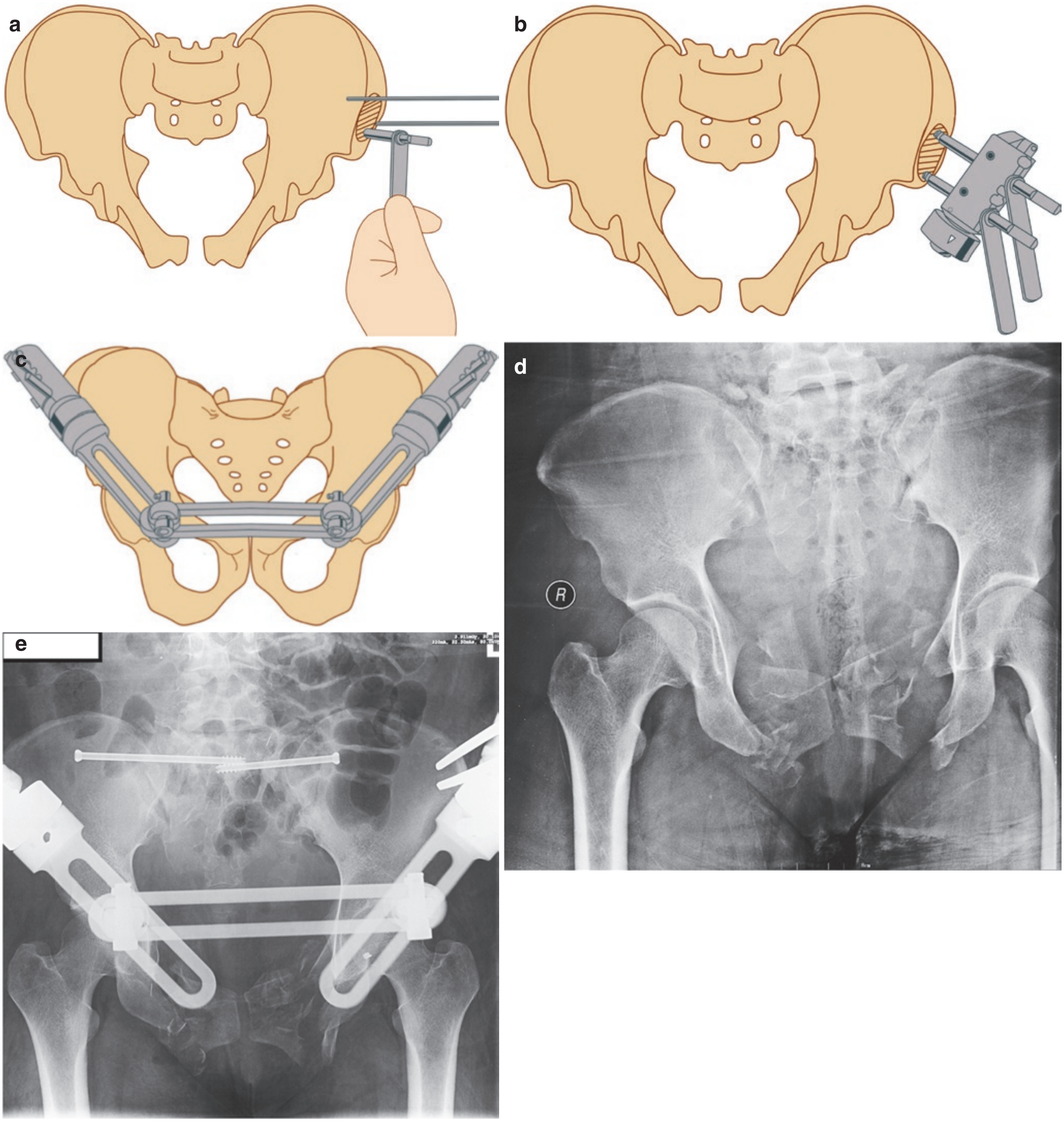


Fig. 3.29 (**a**) Two Kirschner wires are placed along the medial and lateral surfaces of the ilium, which are used to mark and guide the insertion direction of the screws. The first screw is placed 2 cm posterior to the anterior superior iliac spine and in the medial half of the edge of the iliac crest. The screw is inserted along the direction at an approximately 45° angle relative to the sagittal plane and converging towards the medial region. The screwing depth is approximately 5 cm. (**b**) On each side, a connecting block is assembled after the first screw is placed, through which another Schanz screw is placed posterior to the first one. (**c**) The connecting bar is installed, and all the screw nuts are tightened for fixation after the iliac ala is compressed by a medially applied force. (**d, e**) In a patient with type C3 pelvic fracture, two sacroiliac joint screws were used for posterior fixation, and anterior external fixation was performed via screwing of the iliac crest

- Postoperative management:

  Attention should be paid to avoiding excessive wound skin tension during incision closure.

  If exudation from the screw path occurs, the screws should be wrapped with sterile gauze, and the dressing should be changed daily.

  After surgery, thrombosis prevention is critical.

- C-clamp fixation for pelvic fractures (Ganz et al. 1991).
  - Surgical indications:

    Pelvic fractures with a PLC disruption and vertical instability, for which the bleeding can be controlled by compressing the broken ends, immobilizing the pelvis, and reducing the pelvic volume.

    Posterior iliac ala fractures (crescent fractures), where a fracture occurs at the screw insertion sites of the C-clamp, are relative contraindications for C-clamp fixation.
  - Body position and preoperative preparation:

    The patient lies supine.

    The skin over the sacrococcygeal region near the screw entry point must be thoroughly disinfected.

    The operation is performed under local anesthesia, with a C-arm system set up for intraoperative fluoroscopic monitoring.

    The patient can be gently moved to a slightly lateral decubitus position. One side of the sacrococcygeal region is disinfected and covered by a sterile surgical drape, and then the other side is disinfected and protected with a sterile surgical drape. Subsequently, the skin over the anterior pelvis is disinfected.
  - Projection of the incision point on the body surface:

    The screw entry point is at the junction of the middle and posterior thirds of the line connecting the posterior superior iliac spine and the anterior superior iliac spine, which can be localized by palpating the anatomical landmarks. Approximately, the pins are placed at sites 3.4 finger widths anterolateral to the posterior superior iliac spine.

    Because of the difficulty in palpating the posterior superior iliac spine of the patient in the supine position, alternatively the screw entry point may be placed at the intersection points between the long axis of the femur and the perpendicular line of the anterior superior iliac spine on both sides (Fig. 3.30).
  - Fracture reduction and fixation (Fig. 3.31):

    Through the skin incision, the Kirschner wire guide handle is advanced until the surface of the ilium. The screws mounting the C-clamp are placed at the surface projection points of the sacroiliac joint. The localization can be assisted with intraoperative fluoroscopy. Screws placed too anteriorly might penetrate the pelvic bone and injure the pelvic organs and vessels; screws placed too posteriorly might injure the superior gluteal vessels and nerves; and screws placed too distally might damage the sciatic nerve.

    After the desired screw entry point is determined, a Kirschner wire is hammered in along the guide handle to ensure the accuracy of the entry point on the affected side. It is unnecessary to apply a Kirschner wire on the unaffected side.

    The cannulated screws of the C-clamp are inserted along the Kirschner wire.

    Closed reduction must be completed before compression. Proximal displacement of the fractured bone is reduced by pulling the affected extremity distally. The iliac crest is pushed medially if an outflare of the pelvis is presented; the fractured bone is reduced by rotating and pulling with a T-shaped handle connected to a Schanz screw that has been placed in the anterior superior or inferior iliac spine if the pelvis has a rotational deformation or the hemipelvis is displaced posteriorly.

    After reduction, compression and fixation of the fracture is completed by applying a compression force through the transverse bar and then tightening the screws with a wrench.

    The Kirschner wire is removed after fixation. The transverse bar can be turned towards the foot side to provide an access to abdominal surgery by a general or urological surgeon.

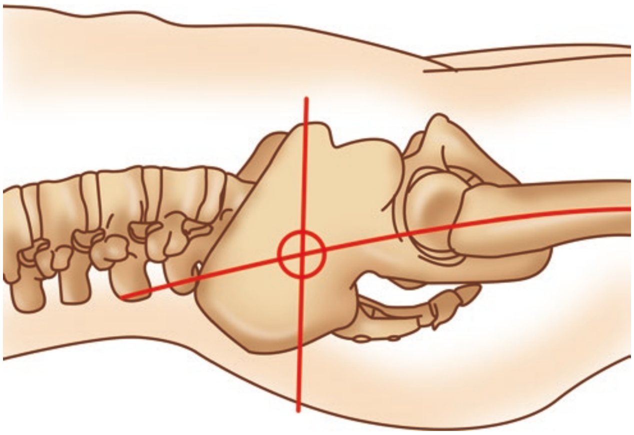


Fig. 3.30 The patient is placed in the supine position, and the intersection of the long axis of the femur and the perpendicular line of the anterior superior iliac spine is the screw entry point

- Pelvic packing for hemostasis (Nunn et al. 2007).
  - Surgical indications:

    The bleeding cannot be effectively controlled even 10–15 min after external fixation.

    The patient remains in shock 2 h after blood transfusion or infusion.

    The shock cannot be corrected by rapid transfusion of more than 4000 mL of blood.

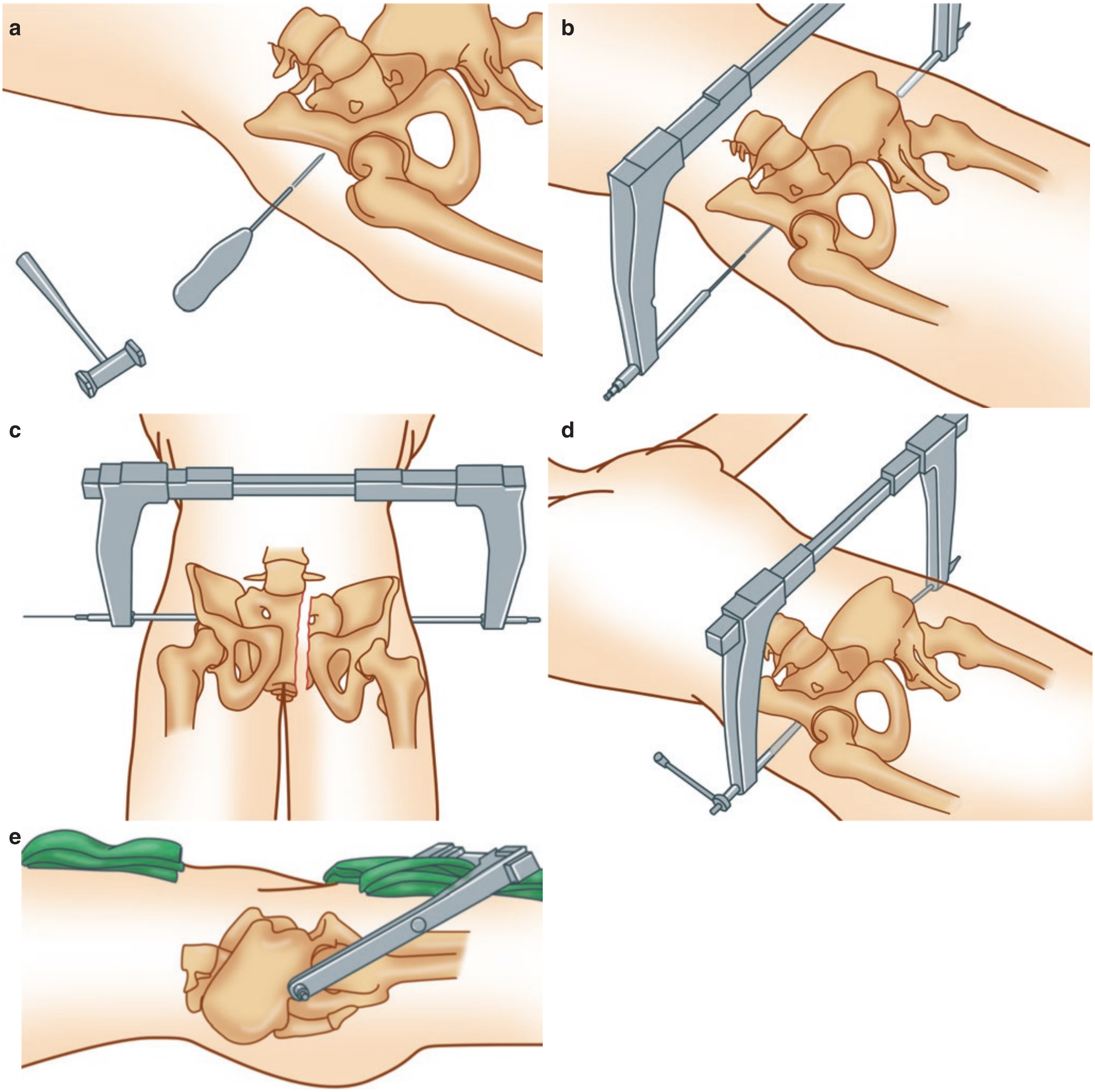


Fig. 3.31 (**a**) After the desired pin entry point is determined, a Kirschner wire is hammered in along the guide handle to ensure accuracy of the screw entry point. (**b**) The prepared cannulated screws of the C-clamp are inserted along the Kirschner wire. (**c**) Closed reduction must be completed before compression. The proximal displacement of the fractured bone is reduced by pulling the affected extremity distally. (**d**) After reduction, the screws are compressed first by the transverse bar, and then the screws are tightened with a wrench to complete the compression fixation. (**e**) If an abdominal surgery is required, the transverse bar can be turned towards the foot side

Angiographic embolization may be used as the first option for hemostasis in hospitals where technical conditions allow.

- Body position and preoperative preparation:

  The prerequisite for packing hemostasis is that the posterior pelvic ring is stable, i.e., it must be performed after C-clamp fixation.

  The patient is under general anesthesia.

  The patient lies supine. The skin over abdominal area and around the pelvis is disinfected and covered with a sterile surgical drape.

- Operative incision according to the projection on the body surface:

  The incision is created at the midline of the lower abdomen. It can be proximally extended for exploration of abdominal parenchyma organ hemorrhage if the preoperative ultrasound B examination suggests abdominal hemorrhage.

- Surgical approach:

  The skin, subcutaneous tissue, and sheath of the rectus abdominis are cut layer by layer up to the prevesical space. Because the fascia around the pelvis has been severely damaged, the presacral region can be reached without separation.
- Hemostatic process:

  Hemorrhage from the named arteries is stopped by clamping, ligation, repair, or other methods.

  For hemorrhage from large abdominal arteries, the incision should be proximally extended for exploration and hemostasis.

  Packing hemostasis (Fig. 3.32):
  - Packing hemostasis serves as a suitable method to control bleeding from the presacral venous plexus or fracture ends where the bleeding site is very difficult to determine.
  - Packing of the true pelvis reduces the volume of the true pelvis and compresses the presacral region.
  - Sterile gauze (named "Gong Sha" in China because it is widely used in uterine packing) is used for packing. After several gauze rolls are knotted together into one piece, the urinary bladder is pulled to one side, and the gauze is placed to fill the presacral region with a pair of long forceps, followed by filling of the post-pubic area along the margin of the true pelvis. The same packing procedure from posterior to anterior is repeated on the other side.
  - Alternatively, gauze rolls can be used for packing from the sacroiliac joint to the posterior area of the pubic symphysis following the same procedure.
  - Packing hemostasis might fail because of instability or large displacement of the posterior pelvic ring, which can be re-stabilized by adjusting the C-clamp before another packing hemostasis attempt.
- Incision closure:

  The incision is closed layer by layer, with the end of the packing gauze marked.
- Post-operative management:

  The filling material is removed or changed after 24–48 h of packing according to the bleeding control status.

  In cases where bleeding that cannot be controlled by packing indicates the existence of unknown bleeding origins, angiographic embolization should be considered.

3.2.2.2 Open Reduction and Internal Fixation for Pelvic Fractures

- Open reduction and internal fixation for symphyseal diastasis.
  - Surgical indications:

    For patients with a symphyseal diastasis >2.5 cm, a length difference between two lower extremities

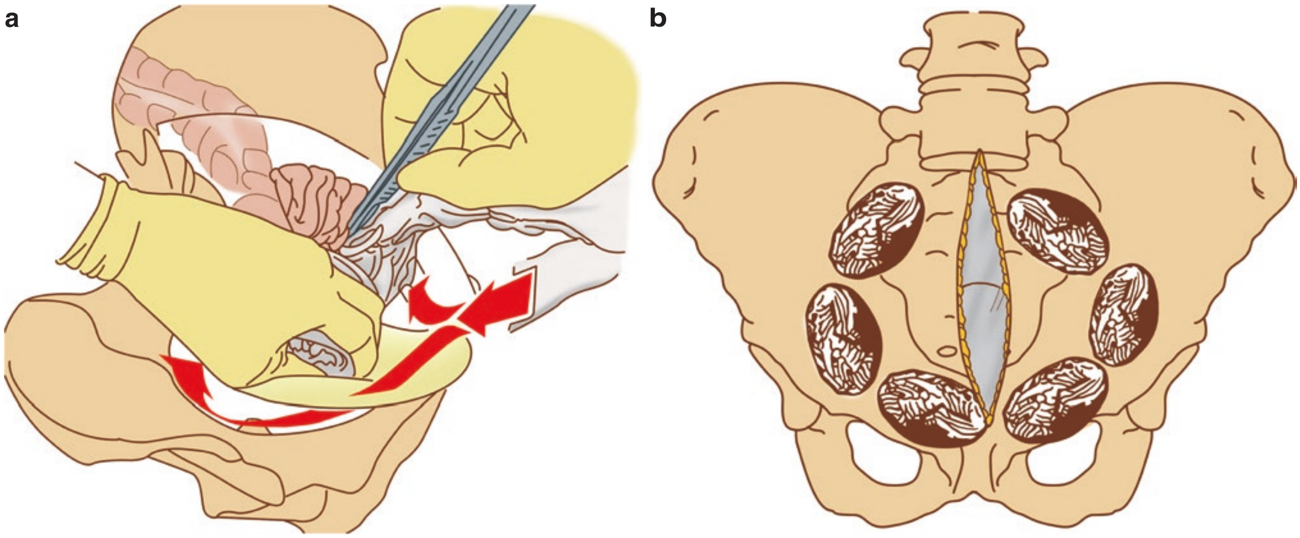


Fig. 3.32 (**a**) Sterile gauze ('Gongsha') is used for packing. After several gauze rolls are tied together, the urinary bladder is pulled to one side, and the gauze is used to fill the presacral region with a pair of long forceps, followed by filling of the post-pubic area along the margin of the true pelvis. The same packing procedure from posterior to anterior is repeated on the other side. (**b**) Alternatively, gauze rolls can be used for packing from the sacroiliac joint to the posterior area of the pubic symphysis following the same procedure

  >1.5 cm due to a fracture displacement of the pubic ramus >2 cm or rotational instability of the fractured pelvis, or severe pelvic malformation, internal fixation is performed to enhance the stability of the anterior pelvic ring..

  For Tile B1 fractures with a symphyseal diastasis >2.5 cm and rotationally unstable and vertically stable pelvic ring, plate fixation of the pubic symphysis should be applied.

  For Tile C fractures with a symphyseal diastasis and disruption of the posterior pelvic ring, both the posterior and anterior rings must be reduced and fixed.

  Severe soft tissue damage that causes an intolerance of the patients to surgery, severe open fracture, indwelling transabdominal catheterization due to injuries of the urinary bladder and urethra, and a stoma constructed anteriorly near the surgical incision site due to rupture of the intestinal duct are contraindications to internal fixation of the pubic symphysis. External fixation with a brace is a more suitable method in these cases.

- Body position and preoperative preparation:

  The patient lies supine under general anesthesia on a radiolucent operating table. The skin over the surgical area is disinfected and covered with a surgical drape, with the pubic symphysis and both sides of the pubic tubercles exposed.

- Operative incision according to the projection on the body surface:

  A Pfannenstiel incision, which is a transverse arc-shaped incision 2 cm above the pubic symphysis, is created.

- Surgical approach (Fig. 3.33):

  After a cut parallel to the inguinal ligament is created to open the aponeurosis of the musculus obliquus externus abdominis, the spermatic cord or round ligament is identified.

  A cut is made on the linea alba of the rectus abdominis along the direction of the muscular fibers. It is worth noting that the tendon of the rectus abdominis must not be transversely severed.

  After the aponeurosis of the two heads of the rectus abdominis is loosened at its ending point on the superior pubic ramus, the pubic ramus is partially exposed laterally.

  A wide distractor is placed in the Retzius space to expose the surgical field and protect the urinary bladder.

- Fracture reduction and internal fixation (Fig. 3.34):

  A large size reduction clamp is used to hold and clamp the pubic tubercles on both sides for reduction with a two-point clamping technique.

  After the success of reduction is radiographically confirmed, a six-hole reconstruction plate is placed above the pubic symphysis for fixation.

  For hole drilling and screwing, the direction accuracy can be determined by palpation with a finger placed in the Retzius space.

  Vertically unstable pelvic fractures can be fixed using two plates, i.e., an additional plate is placed on the anterior pubic symphysis.

- Incision closure:

  Through a drainage tube placed in the Retzius space, sealed negative-pressure drainage is administered after surgery.

  The linea alba of the rectus abdominis is sutured in an interrupted manner, followed by layer by layer incision closure.

- Post-operative management:

  The drainage tube is removed after 24–48 h according to the volume of drain fluid.

  Timing and duration of partial weight-bearing exercise are determined according to the fracture type and the fixation method of the patient.

- Open reduction and internal fixation for iliac fractures or sacroiliac joint dislocation via the anterior approach:
  - Surgical indications:

    The indications for open reduction and internal fixation include the following: (1) sacroiliac joint dislocation or fracture displacement after a failed closed reduction; (2) sacroiliac joint dislocation or fracture displacement accompanied by an iliac ala fracture; (3) with accompanying fractures of the iliac ala and anterior pelvic ring that require simultaneous treatment; and (4) with posterior skin damage that does not allow surgery via the posterior approach.

    For sacral fractures, external bracing of the anterior pelvic ring and stomas constructed near the incision are contraindications to the anterior approach.

  - Body position and preoperative preparation:

    The patient is under general anesthesia.

    Body position: The patient lies supine or in a lateral decubitus position based on the surgical needs.

    A C-arm system is set up for intraoperative fluoroscopic monitoring.

  - Incision and surgical approach:

    The incision is created from the posterior iliac crest and extended anteriorly until the anterior superior iliac spine.

    After the attachment points of the abdominal muscles on the iliac crest are cut, subperiosteal dissection is conducted along the medial plate of the ilium, and then the iliacus and abdominal organs are

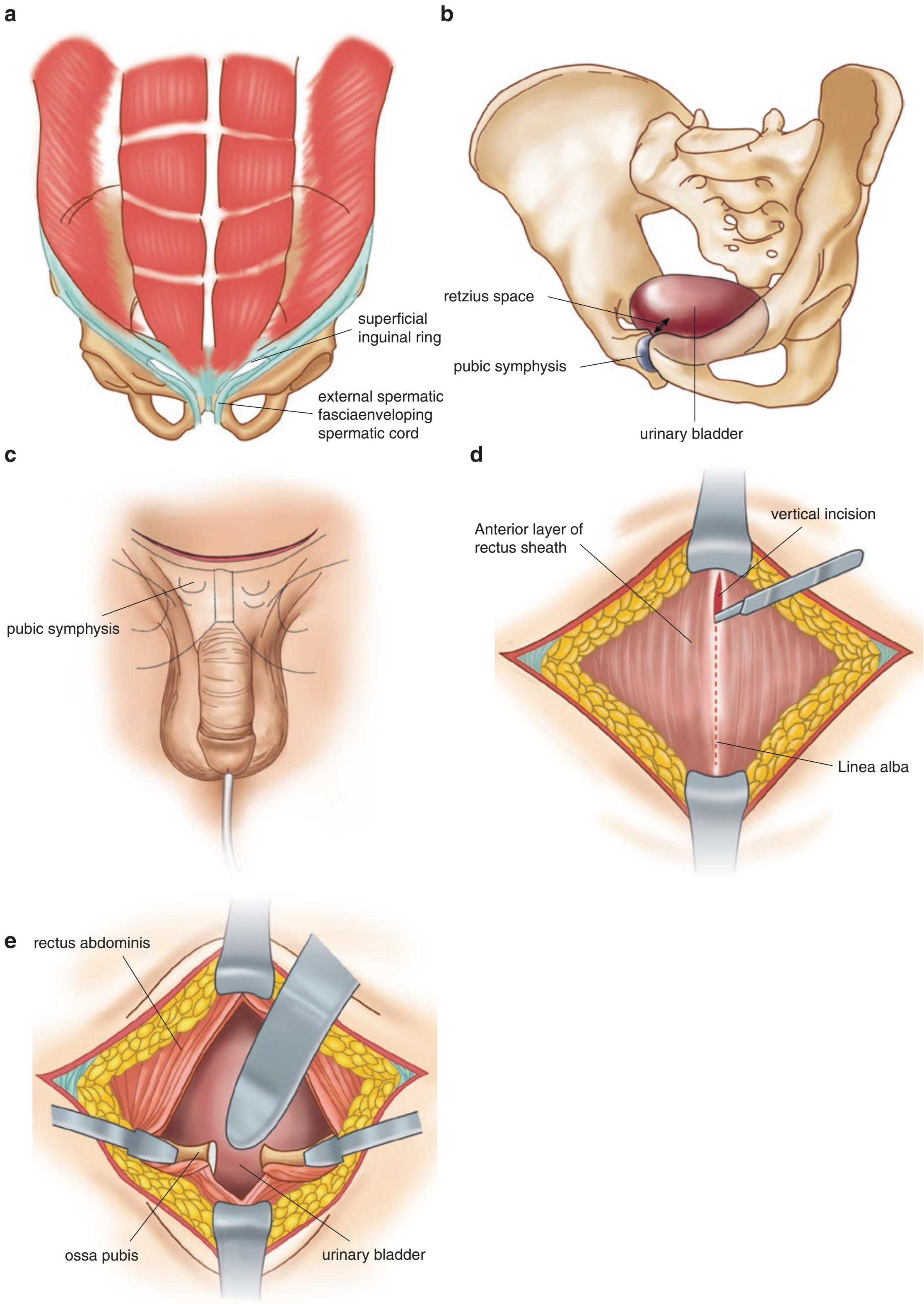


Fig. 3.33 (**a**) Lower abdominal wall structure: The location of the anterior inguinal ring and spermatic cord in men is where the round ligament of the uterus passes in women. (**b**) There is a potential space (Retzius space) between the posterior pubic symphysis and the bladder. Following dissociation in this space, a hook is placed to pull the bladder aside for protection. (**c**) Pfannenstiel incision: An arc incision 2 cm above the pubic symphysis. (**d**) A cut is created on the linea alba along the direction of the muscular fibers. It is worth noting that the tendon of the rectus abdominis must not be transversely severed. (**e**) After the aponeurosis of the two heads of the rectus abdominis is loosened at its ending point on the superior pubic ramus, the pubic ramus is partially exposed laterally. A wide distractor is placed in the Retzius space to expose the surgical field and protect the urinary bladder

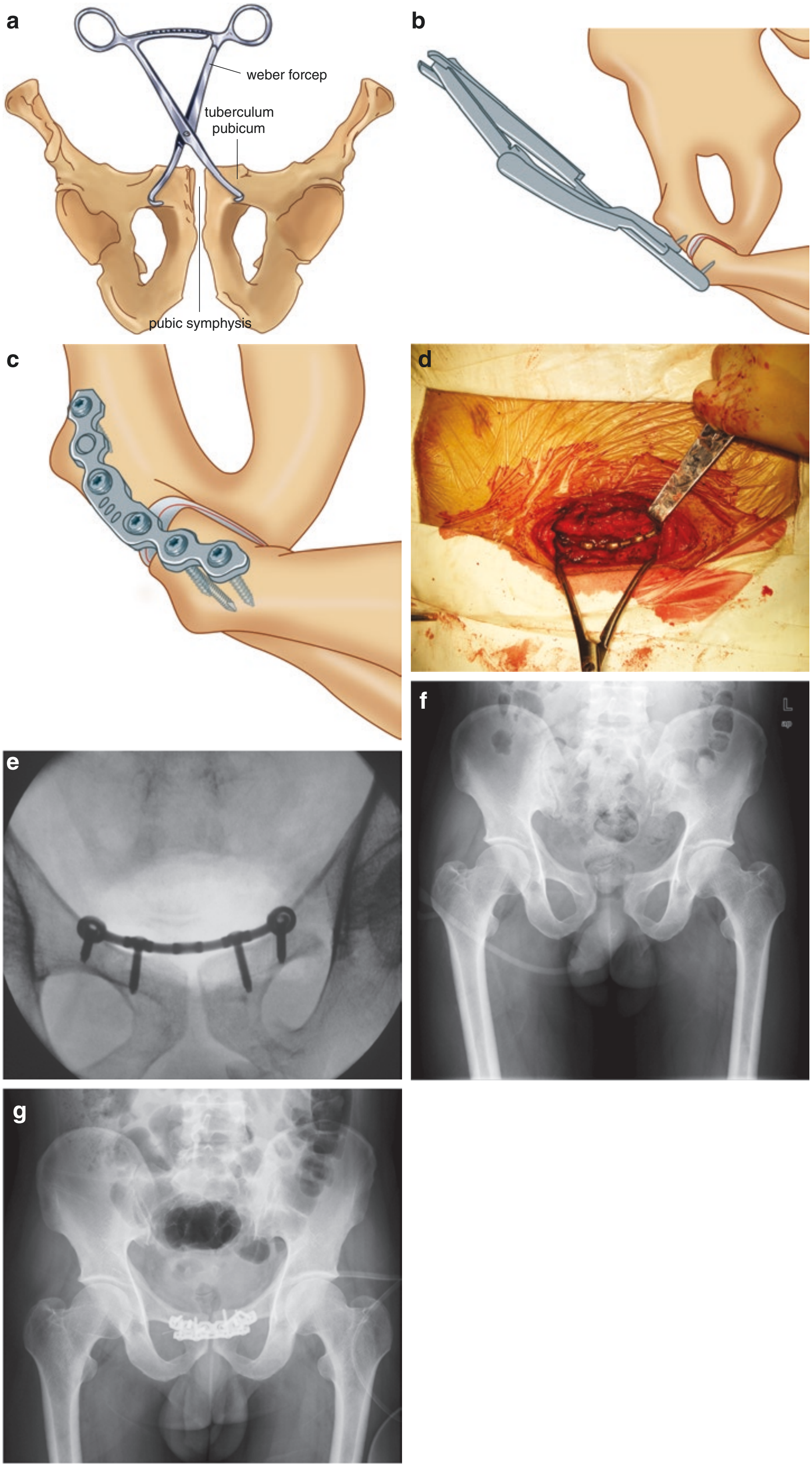


Fig. 3.34 (**a**) Pubic symphysis reduction can be performed with a large size pointed reduction clamp, which clamps the pubic tubercles on the both sides. (**b**) The two-point clamping technique can also be used to clamp and reduce the fractured bone. (**c**) The fracture can be fixed with a 6-hole plate. (**d, e**) An intraoperative photo and radiograph of pubic symphysis plate fixation. (**f, g**) A patient with a Tile classification type B1 pelvic fracture: Open reduction and internal fixation were performed, in which two plates were used to fix the symphysis fracture

pulled medially until the sacroiliac joint is exposed. During the separation process, the tension of the iliopsoas can be reduced by flexing and adducing the hip joint to increase exposure.

Attention should be paid to controlling the surface bleeding of the ilium using bone wax and gauze packing. It is critical not to excessively dissect the surface of the sacrum and not to excessively pull the iliopsoas medially to avoid damaging the L5 nerve root.

  - Fracture reduction and internal fixation (Fig. 3.35):

    The most common fracture displacements of the pelvis are outflare, proximal displacement, and posterior displacement of the ilium.

    Hence, distal traction of the affected extremity can be performed to correct the proximal displacement.

    By rotating and pulling with a T-shaped handle connected to a Schanz screw that has been placed in the iliac crest or the anterior inferior iliac spine, the posterior displacement of the ilium can be corrected. In addition, the rotational deformation of the ilium may be corrected by rotating the hemipelvis.

    After the success of reduction is confirmed, Kirschner wires or a pointed reduction clamp may be used to maintain the reduction for subsequent fixation.

    Alternatively, a reduction clamp is used to hold the screws that have been placed on each side of the sacroiliac joint.

    Two three-hole plates are pre-shaped and used for trans-sacroiliac fixation. One screw is placed in the sacrum, which should not break into the sacral canal, in the direction parallel to the sacroiliac joint. Two screws are placed in the ilium in the direction perpendicular to the plate.

  - Incision closure: A drainage tube is placed, and then the incision is sutured layer by layer for closure.
  - Post-operative management: The patient is followed up at postoperative 2, 6, and 12 weeks. Partial weight-bearing walking with crutches is encouraged after 6 weeks, and complete weight-bearing walking without crutches is encouraged after 3 months.

- Open reduction and internal fixation of U-shaped sacral fractures (Gribnau et al. 2009):
  - Indications: U- or H-shaped sacral fractures, for which sacroiliac joint screwing can also be jointly used.
  - Body position and preoperative preparation: The patient lies prone under general anesthesia, and a C-arm system is set up for intraoperative fluoroscopic monitoring.
  - Incision projection on the body surface: The midline incision is created from the L3 spinous process to the intergluteal cleft.
  - Surgical approach (Fig. 3.36):

    Along the incision projection line, the skin and subcutaneous tissue are incised, and then the erector spinae muscle is dissociated from the lumbar and sacral vertebrae; the attached part of the erector spinae muscle on the sacrum can be severed and flipped over if necessary.

    Patients who have nerve compression symptoms may be given sacral laminectomy and nerve root decompression.

  - Fracture reduction and internal fixation:

    For closed reduction, the hip joint of the patient is hyperextended under lateral fluoroscopic monitoring, i.e., the two lower extremities are kept straight and lifted posteriorly.

    A USS (Universal Spine System) standard internal fixation system is used to fix the fracture (see the related chapters on spine fractures), and the pedicle screws are placed in the L4 and L5 vertebrae.

    Pedicle screws can also be used in the ilium, and they are inserted in the direction from the posterior superior iliac spine to the anterior inferior iliac spine.

    A pre-bent titanium rod is used to connect three pedicle screws on each side, and then the two rods are connected with two transverse bars to enhance the rotational stability.

  - Incision closure and post-operative management:

    The incision is closed with an indwelt drainage tube.

    Because the surgical area is covered by only a thin soft tissue layer, special attention should be paid to avoiding the occurrence of pressure sores.

    Chemoprophylaxis against deep venous thrombosis should be administered.

    Partial weight-bearing activity of the affected extremity is allowed 12 weeks after surgery.

    At 6–9 months postoperatively, the internal fixator may be removed once the fracture healing is confirmed by imaging.

3.2.2.3 Closed Reduction and Minimally Invasive Percutaneous Fixation of Pelvic Fractures

- Types of pelvic fracture displacement (Fig. 3.37):
  - Basic displacement types include upward displacement, outflare, inflare, anterior rotation, and posterior rotation.
  - The common combinations of two basic types include upward shift-outflare, upward shift-inflare, upward shift-anterior rotation, upward shift-posterior rotation, anterior rotation-outflare, anterior rotation-inflare, posterior rotation-outflare, and posterior rotation-inflare, which have a fracture displacement in two directions simultaneously.

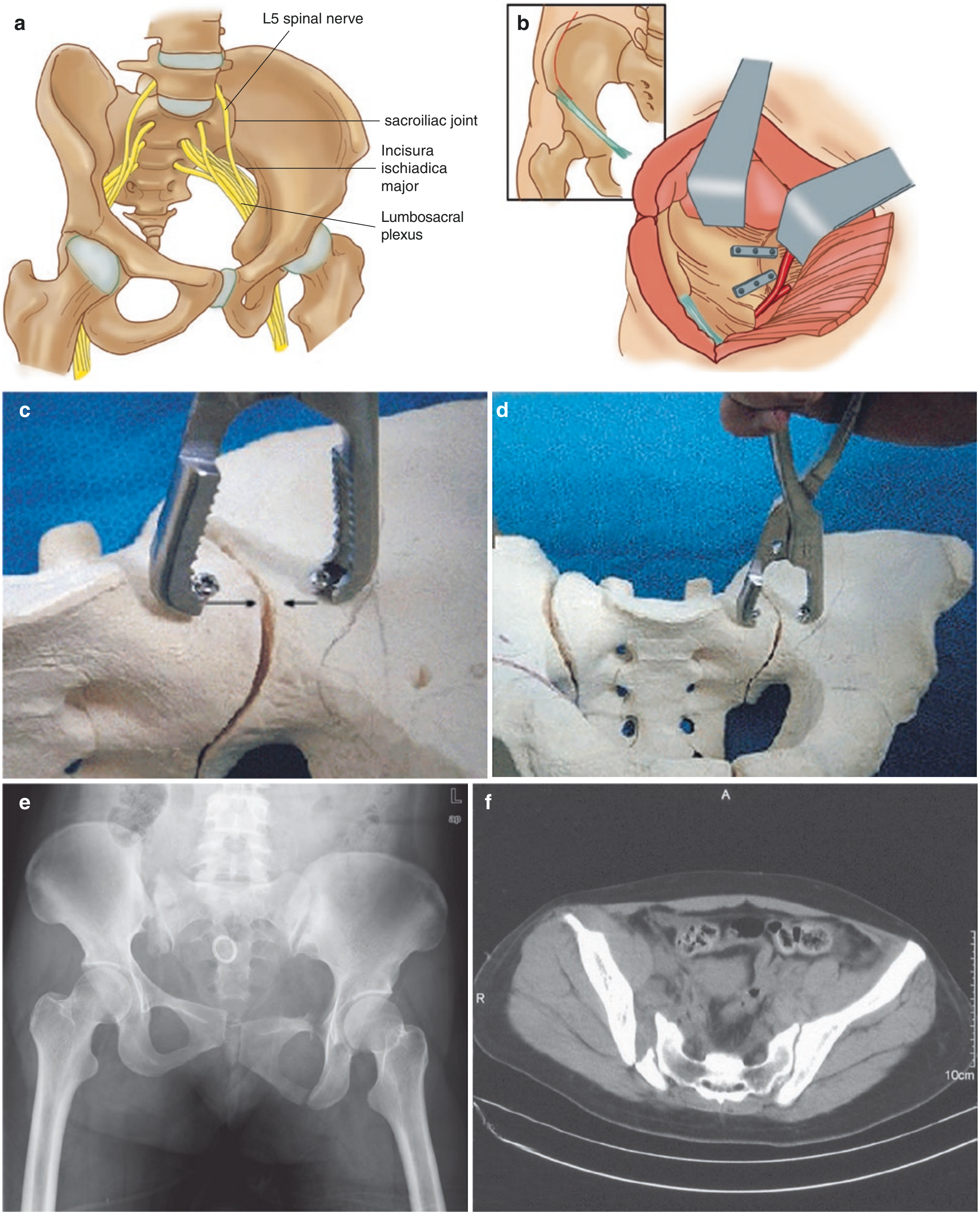


Fig. 3.35 (**a**) The L5 nerve root is located on the sacroiliac alar approximately 2 cm medial to the sacroiliac joint and on the medial side of the anterior approach, and it should be paid attention to for damage avoidance. (**b**) An arc incision along the iliac crest is created up to the anterior superior iliac spine and the muscle ending point on the iliac spine is sharply separated, followed by subperiosteal dissection along the medial surface of the ilium. Subsequently, the iliacus and abdominal organs are pulled medically up to the sacroiliac joint. Attention should be paid to preventing L5 nerve root damage. (**c**) A reduction clamp is used to hold the screws that have been placed on each side of the sacroiliac joint for reduction. (**d**) A patient with a Tile classification type C1.2 pelvic fracture: The right sacroiliac joint was separated, the ilium was proximally displaced, and the contralateral pubic and sciatic rami were fractured. (**e**) Preoperative cross-section CT scan showing that the right sacroiliac joint was separated, and the posterior superior iliac spine was partially fractured. (**f–h**) AP, outlet, and inlet radiographs: After open reduction, the sacroiliac joint was internally fixed using two steel plates, and the anterior pelvic ring was fixed with an external brace

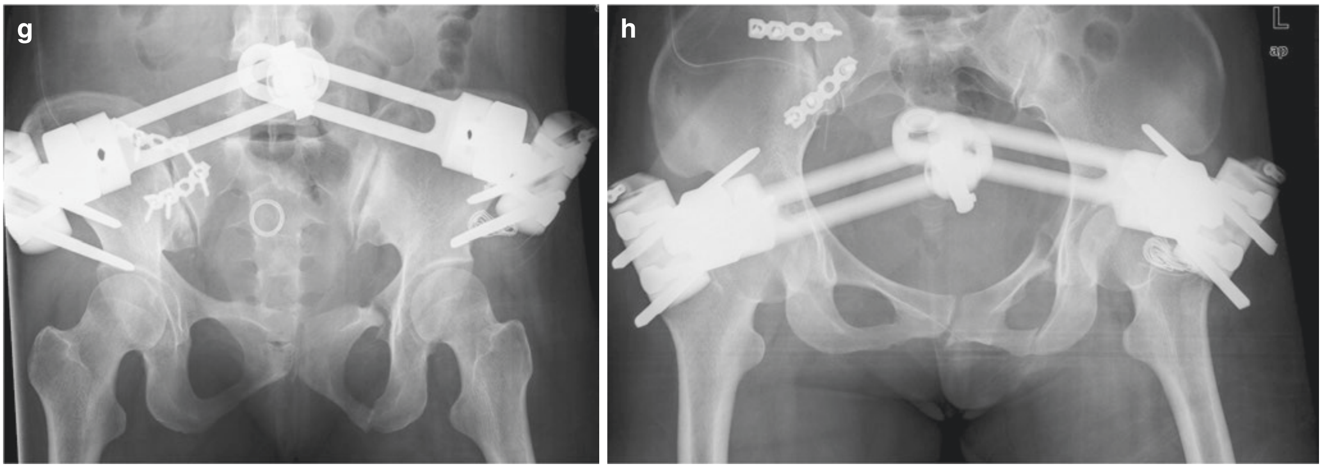


Fig. 3.35 (continued)

- The common combinations of three basic types include outflare-anterior rotation-upward shift, outflare-posterior rotation-upward shift, inflare-anterior rotation-upward shift, and inflare-posterior rotation-upward shift, which have a fracture displacement in three directions simultaneously.
- The internal reduction method should be planned based on the types of pelvic displacements on both side, which is determined according to radiographs and 3D-reconstructed CT images.

- Closed reduction (Fig. 3.38):
  - Minimally invasive percutaneous treatment for pelvic fractures requires internal fixation of the fracture first, which greatly increases the difficulty of the surgery.
  - A fracture within 10 days after injury is relatively easy to reduce, and a fracture after 10 days post-injury is extremely difficult to reduce.
  - The upward displaced posterior ring may be reduced by large-weight traction or by using a traction table during the surgery if necessary.
  - The pelvis with other types of displacements, including inflare, outflare, and anteriorly or posteriorly rotational displacement, can be reduced by a maneuver technique using screws placed in the ilium for control.
  - Maintaining the reduced pelvic fracture is very difficult; therefore, a bracing system has been specifically designed for pelvic fractures, which can be used to reduce the fracture and maintain the reduction.
  - The reduction sequence for compound fracture displacements:

    For a fracture with both outflare and anterior/posterior rotation, the rotational displacement should be corrected first.

    For a fracture with both inflare and anterior/posterior rotation, the inflare should be corrected first.

- Sacroiliac joint screw fixation.
  - Surgical indications:

    The indications include the sacroiliac joint dislocation and sacral fractures.

    The relative contraindications include sacral malformation and obesity.
  - The sacroiliac joint screw path: The sacroiliac joint screw must enter the S1 vertebral body slightly obliquely from superomedial to inferolateral along the S_1 pedicle, which has a cross-sectional area of approximately 1–1.5 cm^2 (Fig. 3.39):

    Anterior border: As shown clearly in the lateral view, the sacral promontory protrudes from the anterior pedicle, and the two sides of the sacral alae appear as depressions between the sacral promontory and the sacroiliac joint. The upper rim of the sacral promontory forms the slope, along which the L5 nerve root, ureter, and internal iliac vessels travel. Normally, the ICD line is in the same plane as the slope; therefore, the ICD line is considered the anterior border of the safe zone for sacroiliac joint screwing.

    Posterior border: The lower halves of the S_1 pedicle and vertebral body form the upper halves of the S_1 nerve root canal and sacral foramina, which are directed outward and downward. Hence, to reduce the risk of damaging the S1 nerve in the nerve root canal, it is crucial to ensure that the tip of the sacroiliac joint screw is in the anterior rather than posterior part of the S1 vertebral body.

    Positions for screw placement in the S_1 vertebral body: The screw is placed in the center of the safe zone (the white area in Fig. 3.39c) when only one screw is needed; if two screws are required, the upper screw is placed in the middle of the vertebral body, and the lower screw is placed more anteriorly.

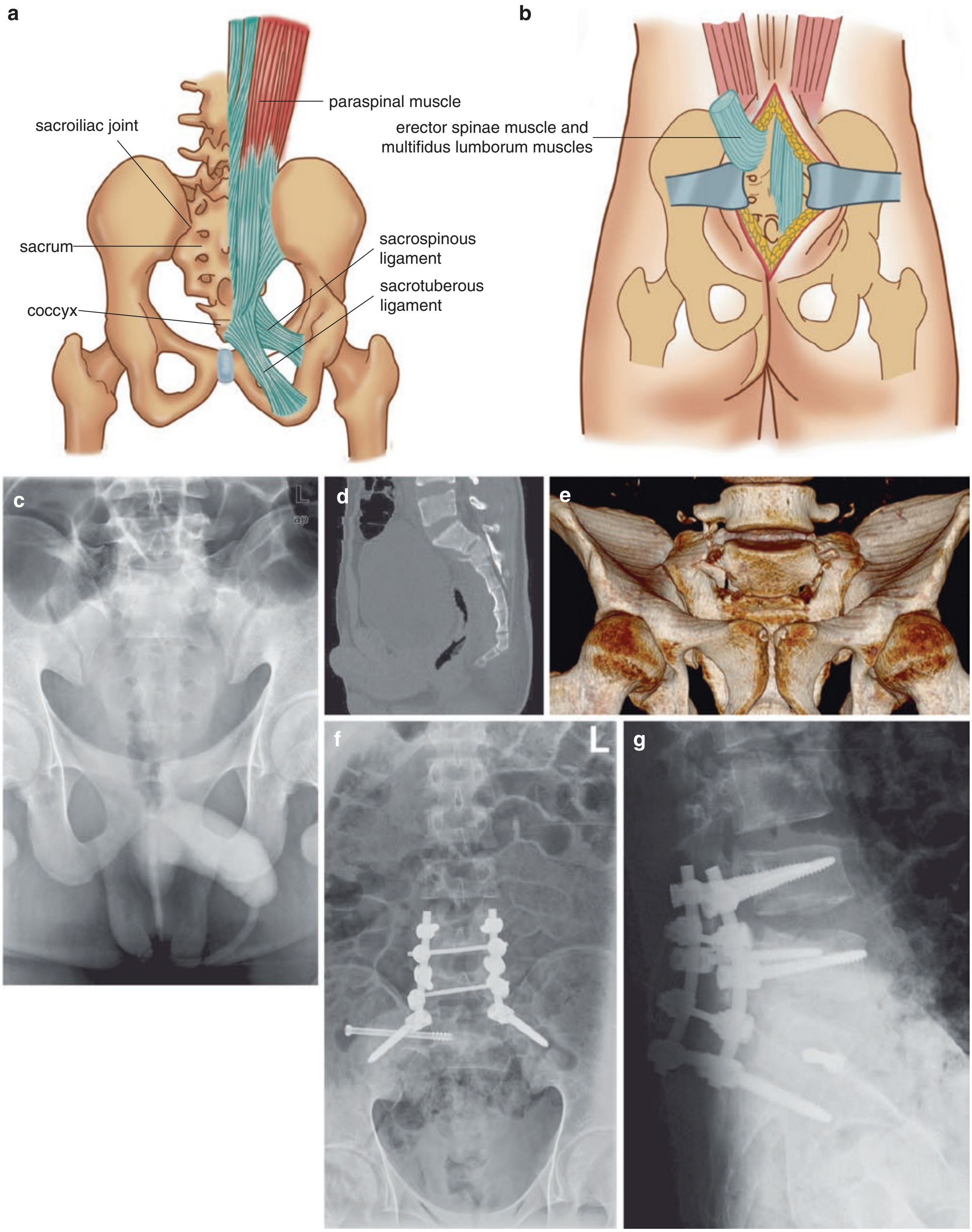
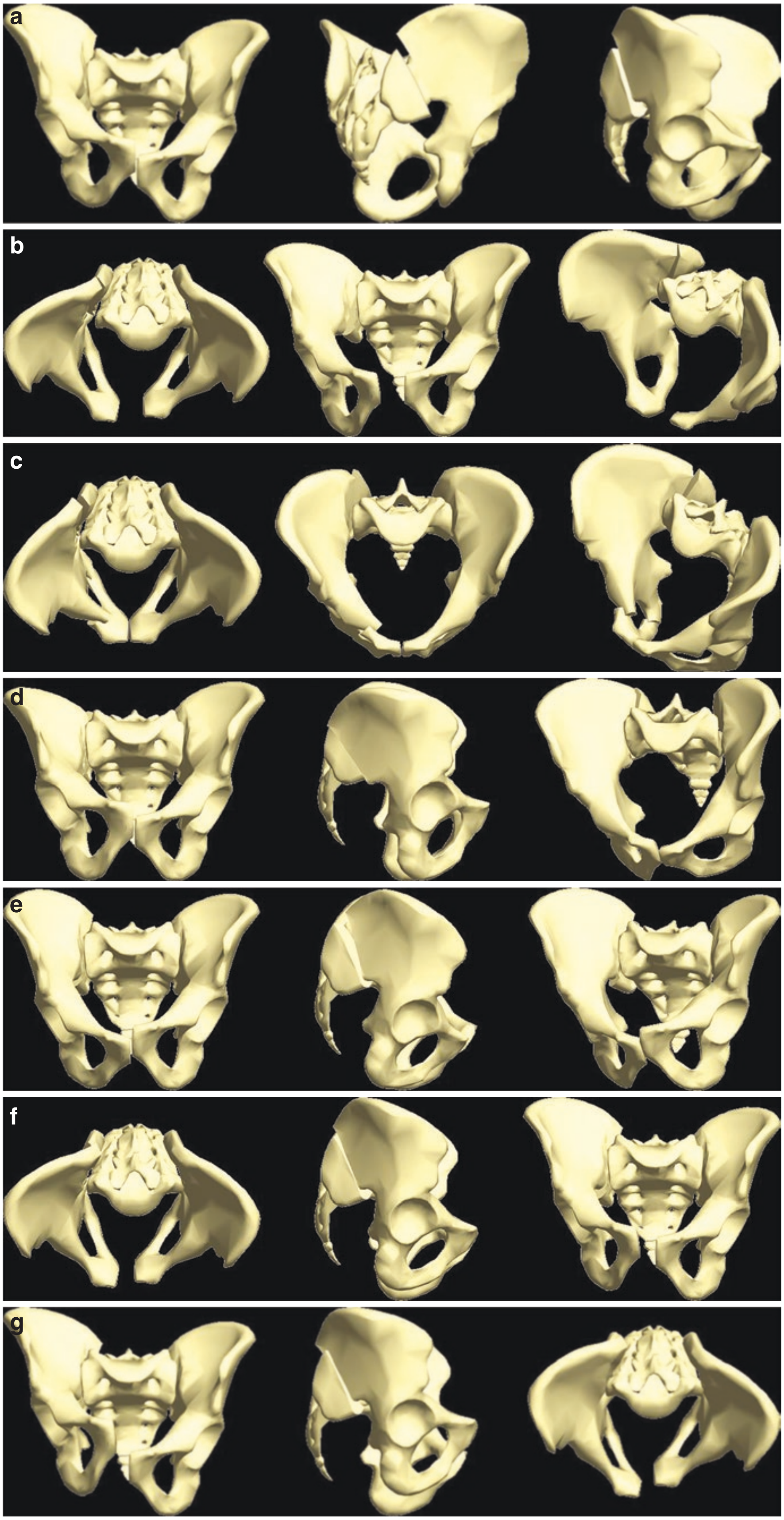


Fig. 3.36 (**a**) The surface of the sacrum is covered with the erector spinae. During the operation, the erector spinae is separated and pulled aside, or its attachment to the sacrum is cut off; the erector spinae is then flipped over to expose the sacrum. (**b**) A midline incision is created from the spinous process of the L3 vertebral body to the intergluteal cleft, and after the skin and subcutaneous tissue are cut, the erector spinae is dissociated to expose the sacrum. (**c**) Preoperative sacral radiograph of a patient with a type U sacral fracture showing bilateral fractures across the sacral foramina. (**d**) Preoperative CT median sagittal-reconstructed image showing that the S2 vertebra was fractured and posteriorly protruded, which caused compression of the sacral canal. (**e**) Preoperative 3D-reconstructed CT image showing a type U sacral fracture. (**f, g**) Open reduction and internal fixation: The S4 and S5 vertebral pedicles on both sides were fixed and connected with the ilium. In addition, sacroiliac joint screwing was applied for fixation on the right side

Fig. 3.37 (**a**) Upward shifting of the right hemipelvis. (**b**) Outflare of the right hemipelvis. (**c**) Inflare of the right hemipelvis. (**d**) Anterior rotational displacement of the right hemipelvis. (**e**) Posterior rotational displacement of the right hemipelvis. (**f**) Outflare-upward shift of the right hemipelvis. (**g**) Outflare—anterior rotation-upward shift of the right hemipelvis



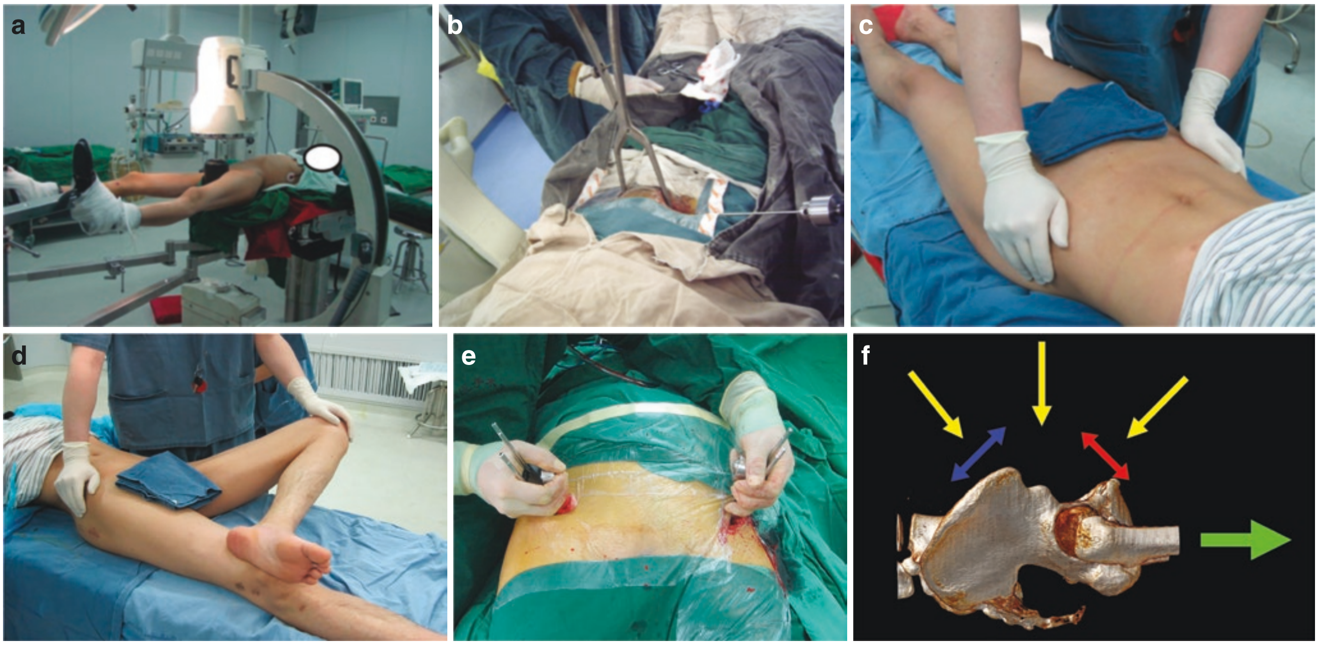


Fig. 3.38 Closed reduction for a pelvic fracture. (**a**) The vertical displacement can be reduced by preoperative large-weight traction or intraoperative traction on an orthopedic traction table. (**b**) For diastasis of the pubic symphysis caused by outflare of the ilium, a large reduction clamp can be used to percutaneously clamp the bilateral pubic tuberosity for reduction. (**c**) An outflare or inflare of the ilium can be reduced by pushing the iliac ala medially or pressing the iliac ala down on both sides with both hands simultaneously. (**d**) For a partially interlocked pubic symphysis, the affected extremity is positioned to form a "4" shape, and then reduction is achieved by pressing down the ipsilateral thigh while holding the contralateral iliac ala to rotate and abduct the hip joint. (**e**) The pelvis with an upward/downward shift—rotational displacement or inflare/outflare displacement can also be reduced using a joystick technique by assembling a handle onto the Schanz screw that has been placed on each side of the anterior superior or inferior iliac spines. (**f**) Movement directions of the pelvis during the reduction in the three common radiographic positions: The three yellow arrows from left to right denote the inlet, AP, and outlet positions, respectively. The blue arrow denotes the actual displacement direction of the pelvis on the inlet view when it moves up or down; the red arrow denotes the actual displacement direction of the pelvis on the outlet view when it moves up or down; and the green arrow denotes the actual shifting direction of the pelvis following traction of the lower extremity

It is necessary to rule out the possibility of developmental malformations of the sacrum by CT scanning before surgery. In some patients, the sacral alae appear as wavy depressions, and the ICD line is in the same plane as the sacral slope; in these cases, the screws must be placed even more anteriorly.

Entry point positioning: The entry point is beside the midpoint of the line that is parallel to the posterior edge of the ilium and 1.5 cm away from the posterior superior iliac spine.

- Body position and preoperative preparation:

  The patient is under general anesthesia.

  Body position: The patient lies supine, with a pillow placed underneath him or her to elevate the midline area of the lumbosacrum and ease the operation on the posterior pelvis.

  Intraoperative fluoroscopic monitoring: With the C-arm positioned on the side opposite to the surgeon (i.e., the unaffected side), inlet, outlet, and lateral images are obtained. The images must have a high quality and clearly display the anatomical structure of the sacrum; otherwise, the surgery should be selectively performed.

  Disinfection: The skin over the lower abdominal area and around the pelvis, perineal region, and affected extremity is disinfected.

- Fracture reduction and fixation (Fig. 3.40):

  Reduction: Successful reduction must be achieved prior to screw placement; in particular, for fractures crossing the sacral foramina, anatomical reduction is required because incarceration of the sacral nerve between the fracture fragments might occur and cause iatrogenic nerve injury. In patients with an internal reduction failure, open reduction should be performed to minimize the risk.

  - Anatomical reduction and fixation of the anterior ring facilitates reduction of the posterior ring. For example, after anatomical reduction and plating fixation of a symphyseal diastasis, the posterior ring is often reduced naturally.

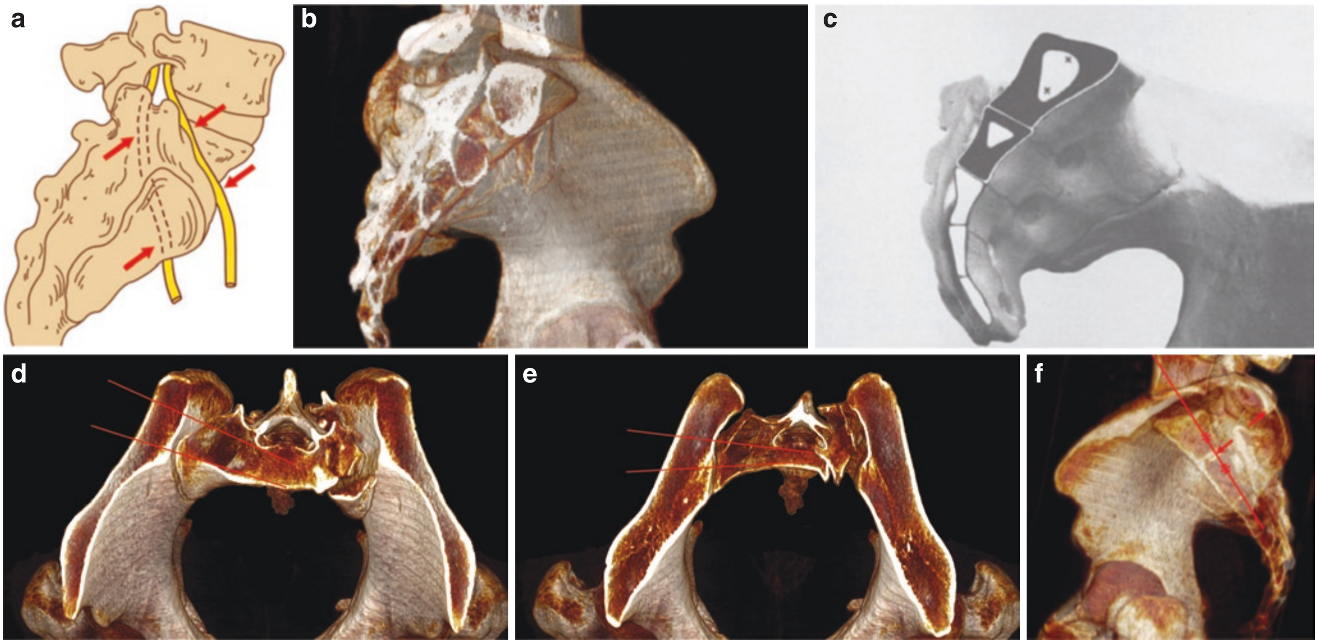


Fig. 3.39 (**a**) The safe area for screw placement is the part of the S1 pedicle posterior to the posterior slope of the sacral ala and anterior to the S1 nerve root canal. (**b**) The S1 and S2 pedicles and the S1 nerve root canal displayed on the 3D-reconstructed CT image: The S1 nerve root canal travels from superomedial to inferolateral, and its upper part is enclosed by the S1 vertebral body and the lower part of the S1 pedicle. (**c**) Sagittal section of the sacrum with the white area denoting the safety zone: When only one screw is needed, it should be placed in the center of the white area; if two screws are required, the upper screw is placed in the middle of the vertebral body and the lower screw is placed more anteriorly. (**d–f**) For patients with depressions of the sacral ala, the safe path of the screws must be ensured under CT monitoring: (**d**) The S1 screws should be placed more anteriorly; (**e**) safety paths for the S2 screws. (**f**) Entry point positioning: The entry point is beside the midpoint of the line that is parallel to the posterior edge of the ilium and 1.5 cm away from the posterior superior iliac spine

- A traction of the affected lower extremity can correct the cranial displacement. The traction under the hip flexion position, followed by adduction or abduction, can reduce the rotated fragments.
- The reduction operation can be aided by Schanz screws placed in the iliac crest or the anterior superior iliac spine. Through the Schanz screws, operations such as pulling, lifting, up-down rotating, and internal-external flipping can be conducted to correct displacements, including anterior-posterior and rotational displacement.
- A large-size distractor is used to assist in the reduction via the pelvis on the unaffected side.
- A pusher with a rounded head can be used to assist in closing the gap between the fracture end.
- Kirschner wires are used for temporary fixation to maintain the reduction.

Reduction: A 7.3 mm cannulated screw is placed percutaneously.

- Under radiography with the C-arm positioned laterally, the screw entry point is marked on the skin when the tip of the guide wire overlaps with the S1 vertebral body. Alternatively, the supero-posterior quadrant divided by the intersection of the long axis of the femur and the perpendicular line crossing the anterior superior iliac spine is the safe zone for screw entry.
- The guide wire is advanced in the same direction as the beam projection of the C-arm system until it reaches the outer wall of the ilium. Under fluoroscopic monitoring, the guide wire is adjusted until its tip overlaps with the target area, and then the guide wire is tapped into the outer wall of the ilium.
- The direction of the guide wire is confirmed in both inlet and outlet views by rotating the C-arm. Subsequently, the guide wire is further advanced until its tip is close to the top of the S1 sacral foramina. After lateral radiography confirms that the guide wire tip is exactly in the center of the S1 vertebral body, its advancement is continued under fluoroscopic monitoring for both inlet and outlet views until the guide wire passes the midline.
- It is critical that the tip of the guide wire must be exactly in the sacral vertebral body without passing the sacral foramina, without entering the sacral promontory and sacral canal and without

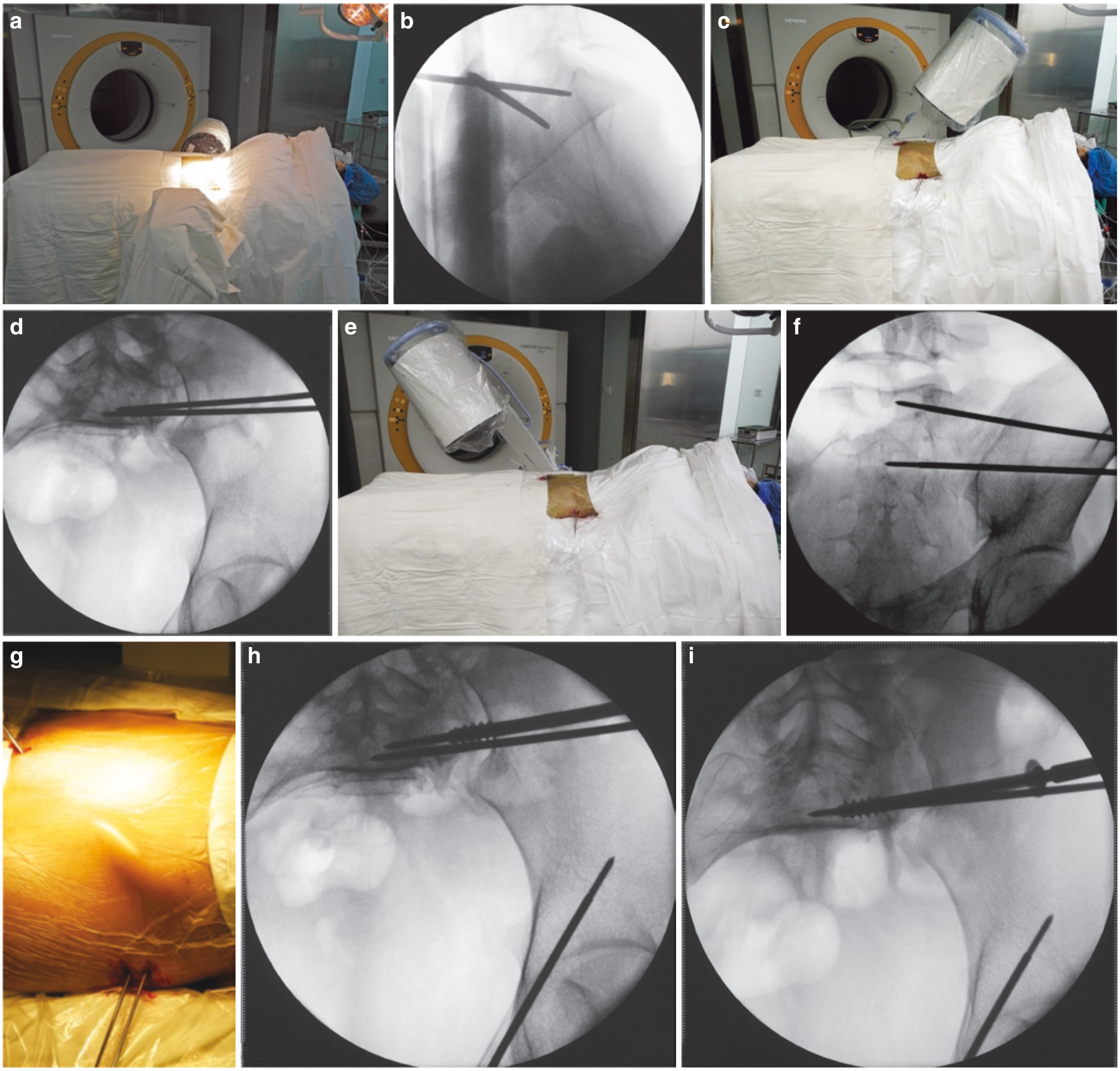


Fig. 3.40 (**a**) C-arm positioning for the lateral view: In the standard lateral view, the bilateral greater sciatic notches are overlapped, and overlapping of the bilateral ICD lines is also clearly visible. (**b**) Lateral radiograph showing two guide wires that enter the S1 and S2 pedicle and reach the S1 and S2 vertebral bodies. (**c**) The projection angle of the C-arm for inlet radiography: The tube is approximately 60° relative to the patient. (**d**) The projection angle is carefully adjusted until the anterior edges of the vertebral bodies of S1 and S2 are overlapped under fluoroscopy. Fluoroscopy at this position can display whether there is a depression deformity of the iliac alar and whether the guide wire is protruding into the anterior cortex of the iliac alar during its advancement. (**e**) The projection angle of the C-arm for outlet fluoroscopy: The tube is approximately 45° relative to the patient. (**f**) Outlet fluoroscopy can display whether the guide wire is beyond the superior edge of the iliac alar and whether the screw tips enter the L5/S1 intervertebral disc. (**g**) Incisions and guide wires for placing the S1 and S2 screws. (**h, i**) The reduction and compression status of the sacroiliac joint must be monitored during screwing of the 7.3 mm screw along the guide wire

penetrating the upper end-plate and entering the L5-S1 intervertebral space. Ideally, the guide wire is situated at the site exactly below the upper end-plate of the S1 vertebra where the bone mass has the best quality and offers the strongest screw anchorage.

- Normally, the guide wire passes three layers of bone cortex, i.e., the outer wall of the ilium and the cortical layers of the ilium and sacrum in the sacroiliac joint. If the advancement of the guide wire encounters a resistant force for the fourth time, which indicates the guide wire tip has again contacted the cortical bone and might be advancing in the wrong direction, radiographic observation for inlet, outlet, and lateral views must be conducted immediately to ensure the accuracy of the guide wire position before its further advancement.

- The depth is measured, and then a 7.3 mm cannulated screw is placed along the guide wire. Additional drilling is usually unnecessary because the screw is self-tapping and self-drilling.
- A fracture of the sacroiliac joint or the sacral ala can be fixed with the use of partially threaded screws, which eases the compression on the fracture ends. However, for sacral fractures crossing the sacral foramina, fully threaded screws are a better option, which can effectively maintain the position of the fractured bone and prevent nerve damage during compression of the fracture ends.
- If two screws are needed for fixation, the lower screw must be placed within the anterior 1/3 of the S1 body to avoid damaging the S1 nerve.
- The sacroiliac joint screw is inserted from the posterior and caudal part of the ilium and advanced cranially and anteriorly in the direction perpendicular to the sacroiliac joint. This approach can avoid damaging the cartilage facet of the sacroiliac joint. The fractured sacrum is fixed using a long screw, which is often placed horizontally to pass the sacroiliac joint (Fig. 3.41) (Matta and Tornetta 3rd. 1996; Majeed 1989; Griffin et al. 2003; Khaled et al. 2015).

– Post-operative management: The patient is followed up in the outpatient clinic at 2, 6, and 12 weeks postoperatively. Partial weight-bearing walking with a walker is encouraged 6 weeks after surgery, complete weight-bearing walking is encouraged 3 months after surgery, and in general, the physical activity of the patient fully returns to the pre-injury level 6 months after surgery.

- Percutaneous pelvic ring fixation (Giannoudis et al. 2007).

  – Percutaneous superior pubic ramus screw fixation (anterior column screw fixation).

    Indications: pubic ramus fractures of the anterior pelvic ring.

    The path for screw placement (Fig. 3.42):

    - The screw can be placed anterogradely or retrogradely. The screw entry point (the screw exit point) is inferomedial to the pubic tubercle, and the exit point (entry point) is within the area 2.5 cm superolateral to the greater sciatic notch.
    - The structures near this path, which might be easily damaged, include the femoral artery, vein, and nerve that travels superiorly and medially to the pubic ramus, the obturator nerve that travels inferiorly to the pubic ramus, and the spermatic cord or round ligament that travels above the pubic tubercle.

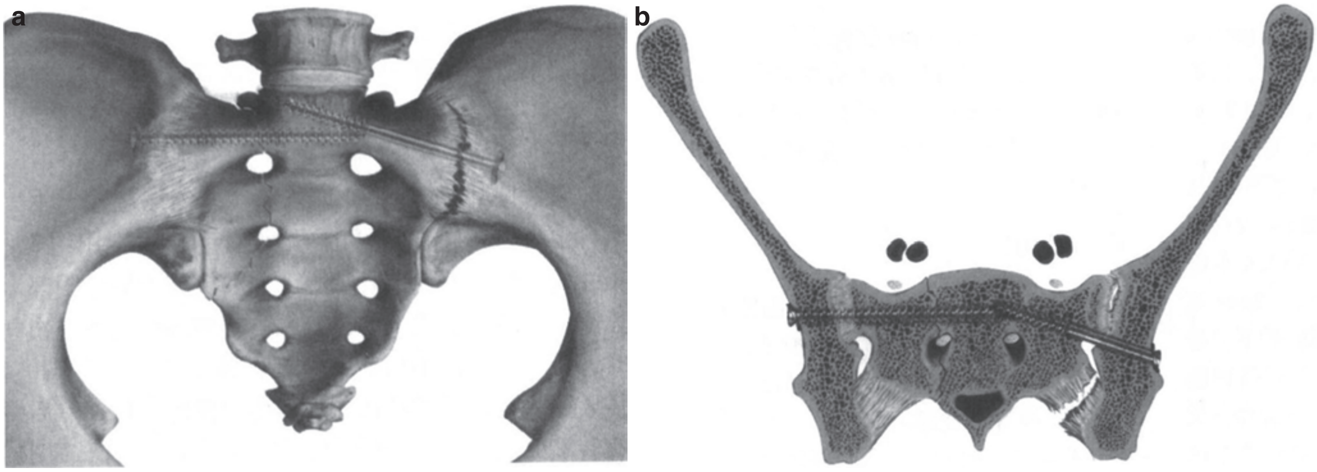


Fig. 3.41 The direction of screw placement varies slightly with the situation of sacroiliac joint dislocation and sacral fracture. The sacroiliac joint screw is inserted from the posterior and caudal part of the ilium and advanced cranially and anteriorly in the direction perpendicular to the sacroiliac joint. The fractured sacrum is fixed using a long screw, which is often placed horizontally to pass the sacroiliac joint. (**a**) Outlet view: A full-threaded sacral lag screw is placed on the right side, and a partially threaded sacroiliac joint lag screw is placed on the left side. (**b**) Inlet view

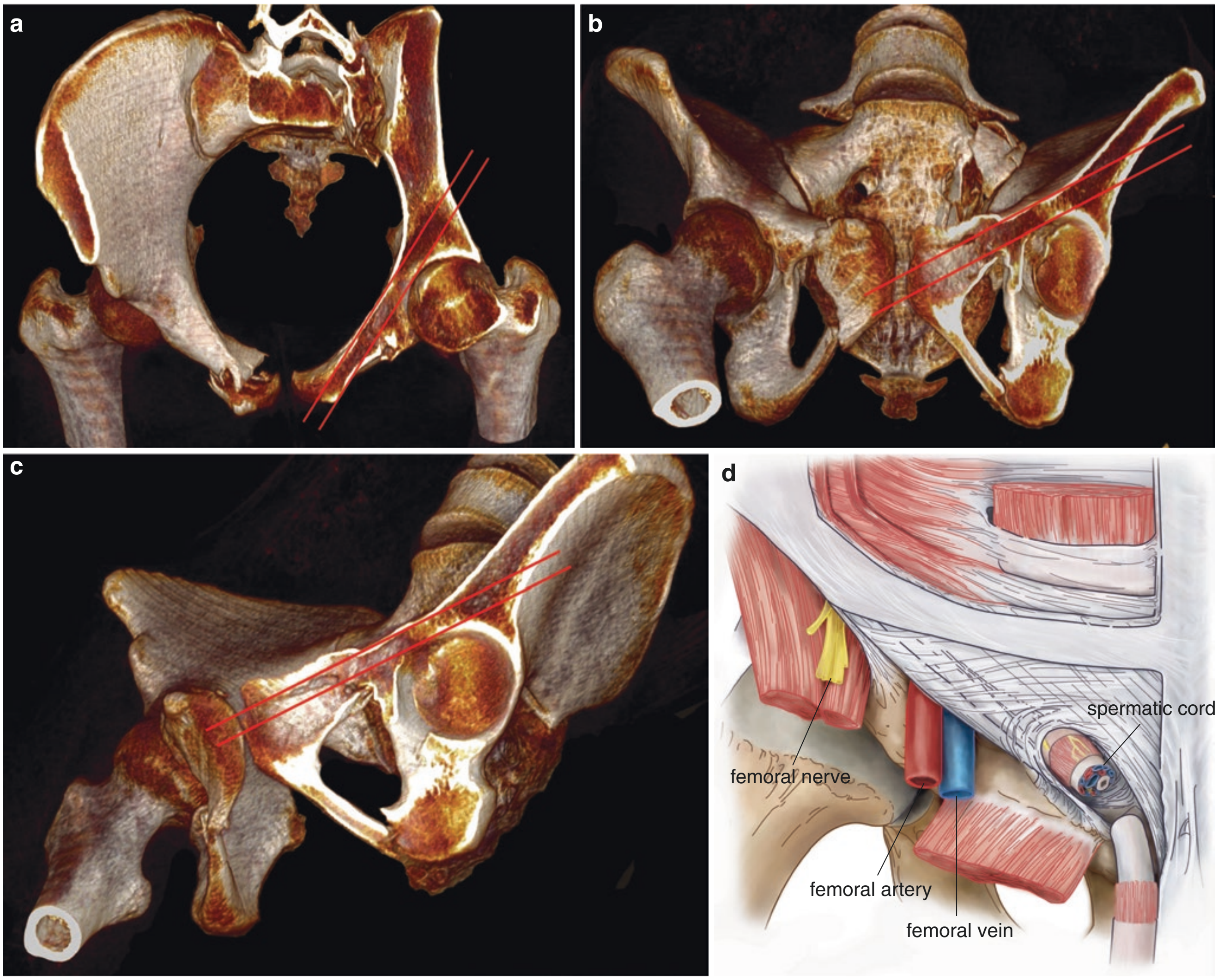


Fig. 3.42 (**a**–**c**) A schematic diagram of the path for percutaneous screwing of the superior pubic ramus. The path ends are positioned at the medial pubic tubercle and the protruding part of the gluteus medius muscle above the acetabulum. (**a**) Inlet view. (**b**) Outlet view. (**c**) Obturator foramen-outlet view. (**d**) The most vulnerable structures during the operation include the spermatic cord (or the round ligament of the uterus), femoral vein, femoral artery, and femoral nerve (from medial to lateral)

- Because the subchondral bone has a high quality, the closer the screw is to the acetabulum, the stronger is the fixation strength. However, it is critical that the screw does not penetrate the acetabulum and injure the joint cartilage; therefore, the position of the screw should be confirmed in both inlet and outlet views radiographically.

Body position and preoperative preparation:

- The patient lies supine on a radiolucent operating table.
- The patient undergoes general anesthesia.
- The skin over lower abdominal area and around the pelvis, perineal region, and affected extremity is routinely disinfected and covered with a sterile drape.

Intraoperative fluoroscopic monitoring (Fig. 3.43):

- The C-arm is positioned on the affected side and the surgeon on the unaffected side of the patient.
- By rotating the C-arm to the obturator foramen projection position based on the outlet position, the obtained obturator foramen-outlet radiograph can display the upper rim of the pubic ramus.
- By rotating the C-arm to the ilium projection position based on the inlet position, the obtained ilium-inlet radiograph can display the lateral rim of the pubic ramus.

Fracture reduction and fixation (retrograde screw placement technique):

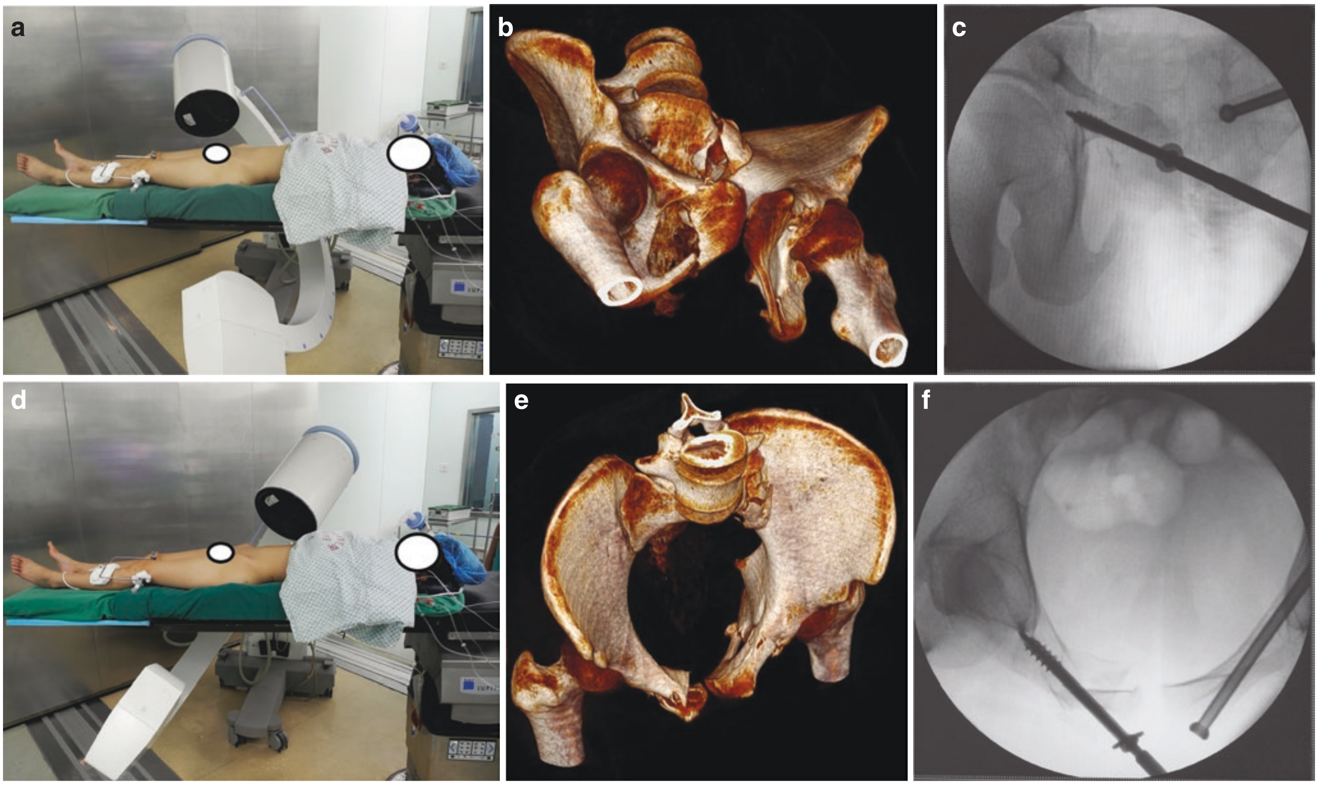


Fig. 3.43 Fluoroscopic monitoring for pubic superior ramus screwing: the obturator foramen-outlet position (**a–c**) and ilium-inlet position (**d–f**). (**a**) C-arm positioning: After the outlet image is obtained, the C-arm is rotated to obtain the obturator-position view. (**b**) The position and morphology of the pelvis in the obturator foramen-outlet radiograph. (**c**) The obturator foramen-outlet radiographs can accurately demonstrate whether the screw exceeds the superior edge of the pubic ramus. (**d**) C-arm positioning: After the inlet image is obtained, the C-arm is rotated to obtain the ilium-position radiograph. (**e**) The position and morphology of the pelvis in the ilium—inlet radiograph. (**f**) Ilium—inlet fluoroscopy can accurately demonstrate whether the screw protrudes from the anterior margin of the pubic ramus and whether the screw enters the acetabulum

- At the level of the pubic tubercle on the unaffected side, a 1-cm-long incision is created near the penis or the base of the pubic region. Subsequently, the tissue is bluntly separated in the same direction as the pubic region on the affected side, and the separation passes the midline of the pubic symphysis and ends at the ipsilateral pubic tubercle.
- Under fluoroscopic monitoring for inlet and obturator foramen—outlet views, the guide wire is placed laterally to the pubic symphysis and inferiorly to the pubic tubercle.
- For a fracture with the fracture line medial to the acetabulum and close to the pubic tubercle, it is unnecessary to advance the screw to cross the acetabulum. However, for a fracture that is excessively close to or even affecting the acetabulum, the fixation screw must cross the acetabulum.
- The guide wire is advanced in the cancellous bone by gentle tapping, during which little resistance should be felt by the operator..
- Advancement of the guide wire should be performed under fluoroscopic monitoring of the medial and lateral rims of the pubic ramus in the inlet view and the upper and lower rims of the pubic ramus in the obturator foramen-outlet view.
- A pusher or arc-shaped guide wire is used as a joystick to facilitate the localization of the guide wire tip at the desired position of the fracture site.
- When the guide wire reaches the area above the acetabulum, it is critical to ensure the guide wire is not entering the acetabulum or penetrating the cortex on top of the acetabulum under fluoroscopic monitoring in the inlet and obturator foramen-outlet views.

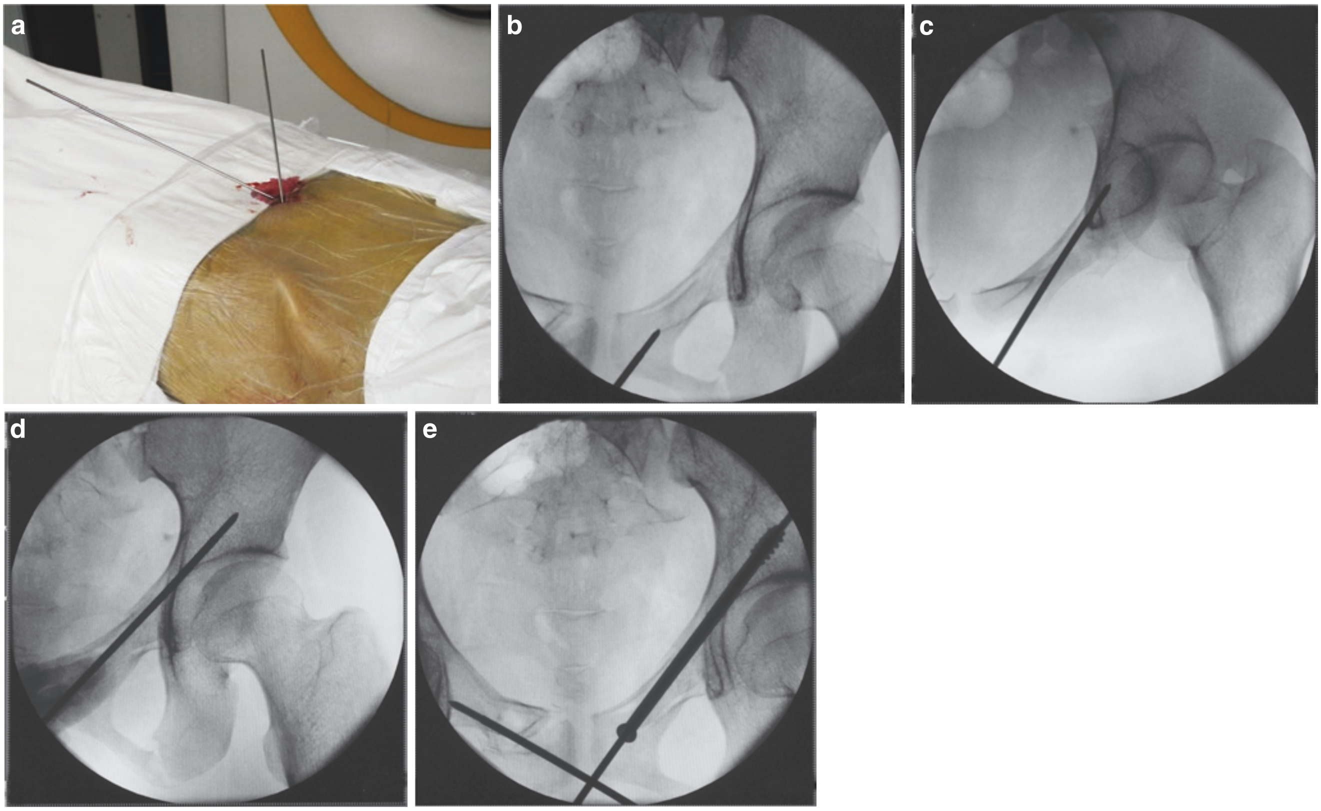


Fig. 3.44 Case example of fractures of the bilateral superior and inferior pubic rami. (**a**) A skin incision for closed reduction and internal fixation with pubic superior ramus screwing was created at the base of the mons pubis. (**b–d**) The screw entry position was inferomedial to the pubic tubercle. Both outlet and inlet fluoroscopy were used to ensure that the guide wire did not penetrate the pubic ramus and finally reached the site above the acetabulum without entering the acetabulum. (**e**) A 4.5 mm cannulated screw was inserted along the guide wire

- The depth is measured, and then a 4.5 mm or 7.3 mm cannulated screw is placed (Fig. 3.44).
- The screw can also be placed in the direction opposite to the one described above, i.e., antero-grade screwing, which is suitable for obese patients(Fig. 3.45).

– Percutaneous LCII screw fixation:

Indications: The screw was named after its indications, i.e., Young & Burgess type LC II pelvic fractures, which consist of a ruptured posterior pelvic ring caused by a fracture across the iliac ala or a crescent fracture of the iliac ala.

Screwing path (Fig. 3.46a):

- The screw enters from the anterior inferior iliac spine and points to the posterior superior iliac spine;
- This path has multiple uses. For example, a Schanz screw placed through this path serves as a joystick to reduce the pelvic fracture during external fixation bracing with the screws placed above the acetabulum; for sacrum U-shaped fractures, the pedicle screw can be placed through this path to fix the ilium.

Body position and preoperative preparation: the same as that used for superior pubic ramus screw placement.

Intraoperative fluoroscopic monitoring (Fig. 3.46b–g):

- ‘Teardrop’ view: After the outlet view is obtained, the projection beam is rotated for approximately 20° towards the affected side to overlap the contour of the anterior inferior iliac spine with that of the posterior superior iliac spine and form a teardrop-like shadow above the acetabulum. At this position, the desired path of the LC II screw is directly visible, and the screw entry point should be in the center of the path.
- Top view of the iliac ala: After the inlet view is obtained, the projection beam is rotated approximately 20° to 30° towards the affected side to

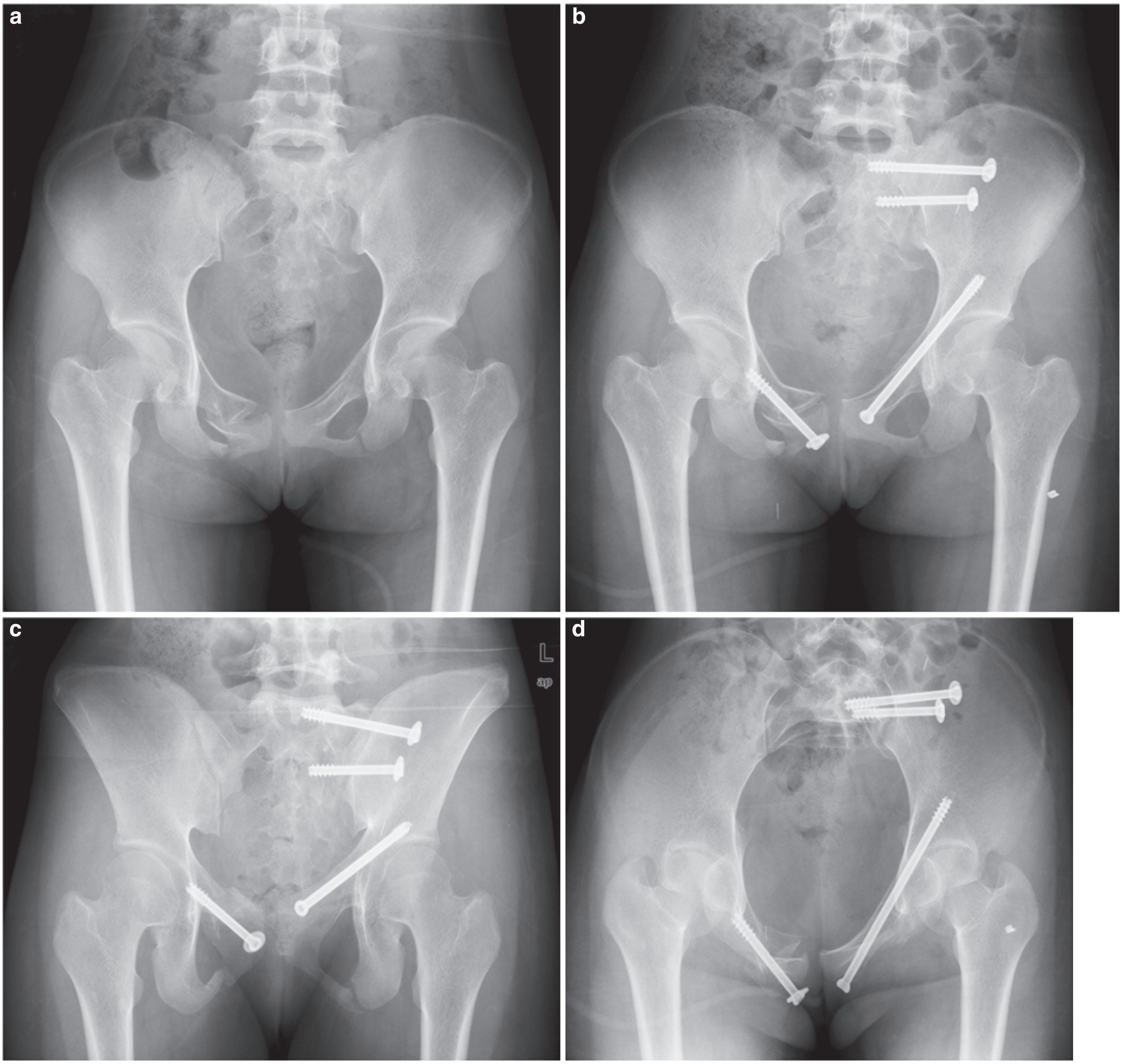


Fig. 3.45 Closed reduction and internal fixation for pelvic fracture: Two sacroiliac joint screws were placed through the left S1 and S2 pedicles. A superior pubic ramus screw was placed on each side, of which a longer one was used on the left side to cross the acetabulum because the left fracture line was close to the acetabulum. (**a**) Preoperative AP radiograph showing visible fractures of the bilateral superior and inferior pubic rami and right sacral fracture. The preoperative 3D-reconstructed CT image of this patient is shown in the figure related to body positioning for radiography. (**b**) Postoperative AP radiograph. (**c**) Postoperative outlet radiograph. (**d**) Postoperative inlet radiograph

allow the projection to center on the lateral cortex of the ipsilateral iliac ala. At this position, the entire posterior cortex of the ilium is clearly visible, providing a top view of the screwing path of the LC II screw.

- Oblique view of the ilium: After the AP view is obtained, the projection beam is rotated by 45° to allow the projection to center on the ipsilateral ilium. At this position, the greater sciatic notch and the posterior superior iliac spine is clearly displayed, which eases the monitoring of the entry depth of the guide wire for screwing the LC II screw.

Fracture reduction and fixation (Fig. 3.47):

- An incision is created below the anterior superior iliac spine, followed by a blunt separation, during which the lateral femoral cutaneous nerve should be protected. The trocar is placed on the surface of the anterior inferior iliac spine.

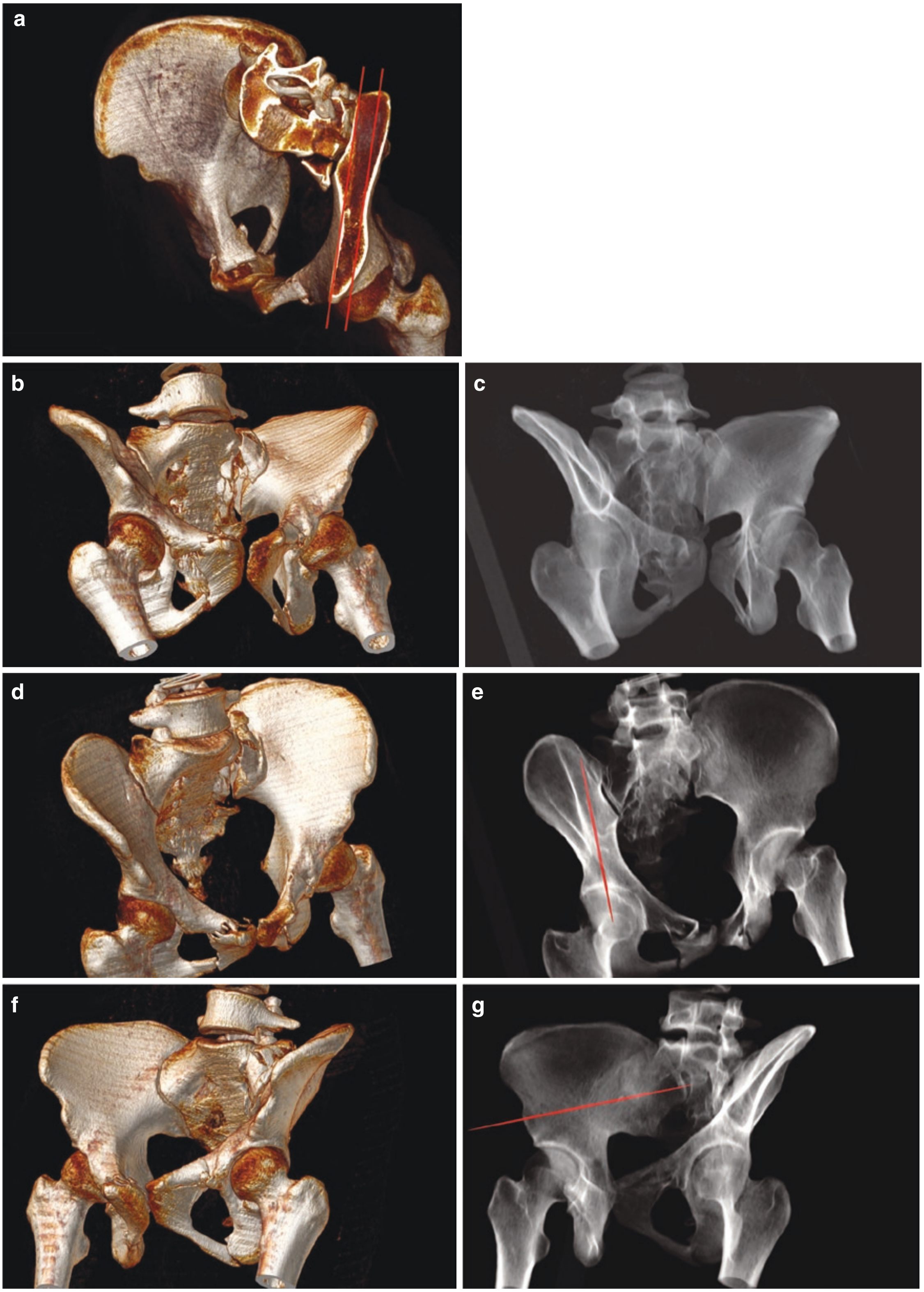


Fig. 3.46 (**a**) LCII screw path: This path is located between the anterior inferior iliac spine and the posterior superior iliac spine, and it passes between the two layers of bone plates in the top view of the iliac ala. (**b, c**) Intraoperative fluoroscopy in the "teardrop" position: 3D-reconstructed CT image displaying the position and morphology of the pelvis (**b**) and radiograph (**c**). Overlapping of the anterior inferior iliac spine and the posterior superior iliac spine results in a low-density teardrop shape. The red dot in the image denotes the entry point and the projection of the guide wire. (**d, e**) Intraoperative fluoroscopy of the top view of the iliac ala: 3D-reconstructed CT image displaying the position of the pelvis (**d**) and radiograph (**e**). The red line denotes the position of the guide wire, which is located between the high-density medial and lateral bone plates. (**f, g**) Intraoperative fluoroscopy of the ilium oblique view: 3D-reconstructed CT image displaying the position of the pelvis (**f**) and radiograph (**g**). The desired depth of the guide wire is determined and measured, which should not exceed the posterior superior iliac spine

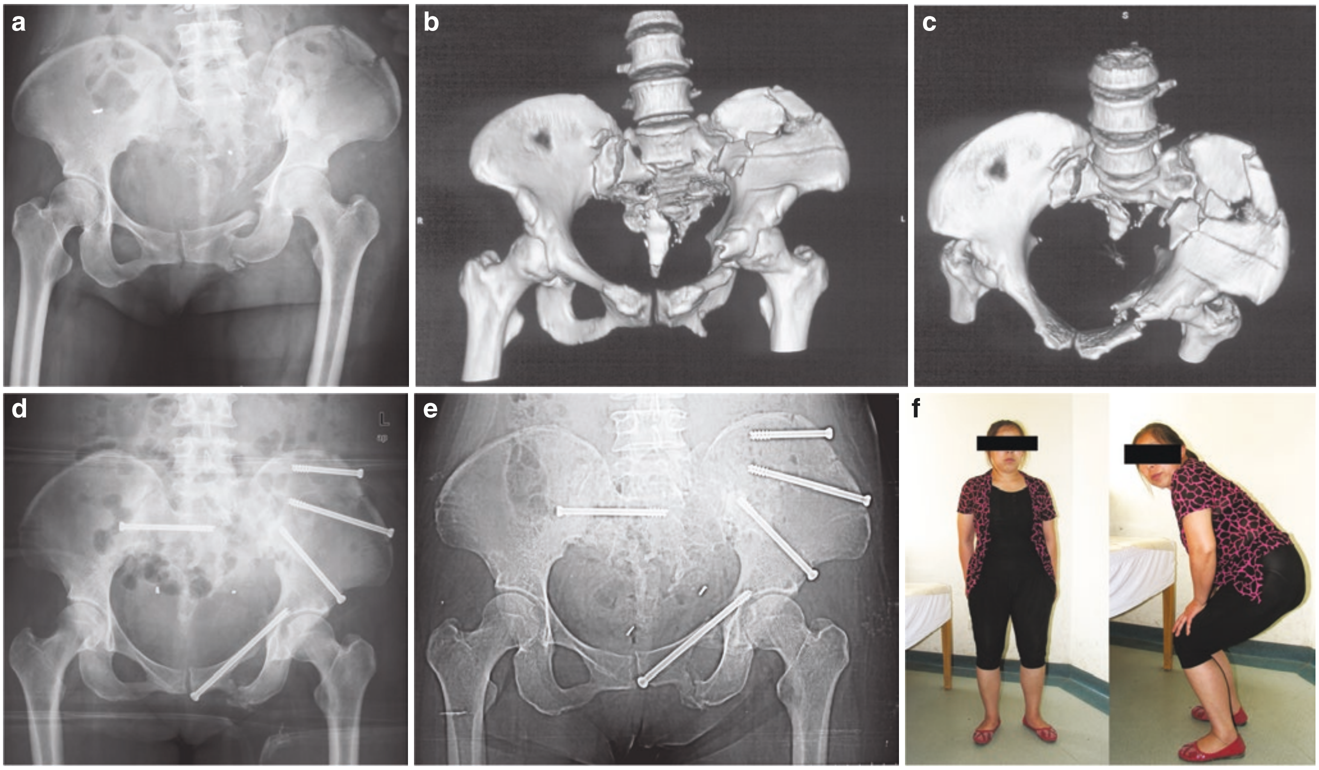


Fig. 3.47 A Young & Burgess classification type LC III pelvic fracture. (**a**) Preoperative AP radiograph showing a lateral compression fracture of the left ilium and open-book injury of the right hemipelvis. (**b, c**) Preoperative 3D-reconstructed CT mages showing a left iliac ala fracture, pubic ramus fracture, and right sacral zone I fracture. (**d**) AP radiograph after closed reduction and internal fixation: One LC II screw, one superior pubic ramus screw, and two iliac ala screws were used on the left side; one sacroiliac screw was applied for fixation on the right side. (**e**) AP radiograph at 7 months postoperatively showing fracture healing. (**f**) The patient had no length discrepancy between the lower extremities and no difficulties in standing or walking

    - Under fluoroscopic monitoring for the ‘teardrop’ view, the entry point is within the displayed path. With the trocar perpendicular to the projection direction, the guide wire is inserted along the desired path.
    - Under fluoroscopic monitoring of the top view of the iliac ala, the guide wire must be advanced along the space between the two bone lamellae.
    - Under fluoroscopic monitoring for the oblique view of the ilium, the guide wire should not be excessively advanced, and its tip should not exceed the posterior superior iliac spine.
    - After the position of the guide wire is verified, a 4.5 mm cannulated screw is placed along the guide wire.

– Percutaneous symphyseal screw placement:

Indications: symphyseal diastasis >2.5 cm.

The path for screwing is slightly below the pubic symphysis.

Body position and preoperative preparation: the same as that for superior pubic ramus screw placement.

Intraoperative fluoroscopic monitoring: An outlet radiograph can display the depth of the screw and the upper and lower rims of the superior pubic ramus; an inlet radiograph can display the anterior and posterior rims of the pubic ramus.

Fracture reduction and fixation:

- An incision at a length of approximately 1 cm is created on the skin over the pubic tubercle, followed by soft-tissue blunt separation reaching the pubic tubercle;
- A pelvic clamp is inserted via the incision to reach the pubic tubercle, and it is used to firmly hold the separated pubic symphysis and close the gap under fluoroscopic monitoring.
- After the position of the pelvic clamp is fixed, a guide wire with a diameter of 2 mm is inserted

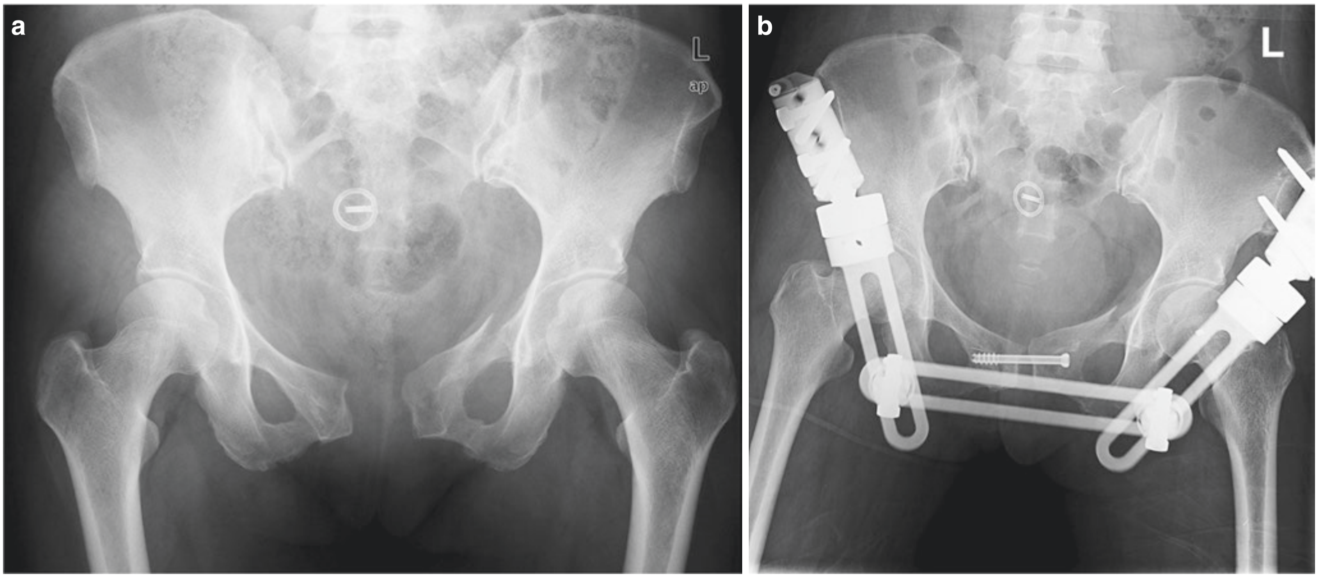


Fig. 3.48 A Tile classification type B1 pelvic fracture. (**a**) Preoperative radiograph showing a symphyseal diastasis and left pubic ramus fracture. (**b**) Radiograph after closed reduction and fixation with pubic symphysis screwing combined with anterior ring external bracing

from the site slightly below one side of the pubic tubercle and advanced horizontally towards the opposite side.

  - The screw is placed along the guide wire to fix the pubic symphysis.
  - External bracing can be performed to further enhance the stability of the anterior pelvic ring (Fig. 3.48).

- Experience and lessons.
  - Fixation and biomechanical stability of pelvic fractures:

    The fundamental goal of pelvic fracture fixation is to restore the integrity and stability of the pelvic ring; therefore, the biomechanical stability reconstructed at each fracture site should contribute to improving the overall stability of the pelvic ring.

    The internal fixation is superior to the external fixation for the anterior pelvic ring. The joint anterior and posterior fixation of the pelvic ring can provide sufficient mechanical stability in treating unstable pelvic fractures.

    For a type C fracture, which has both vertical and rotational instabilities, external fixation alone is insufficient to mechanically stabilize the fracture.

    For an unstable pelvic fracture, internal fixation of both anterior and posterior rings can maximally stabilize the pelvic ring.

    For unilateral sacroiliac joint dislocation or sacroiliac joint fracture displacement, most fixation methods, including sacroiliac joint screwing, fixation with the screw nut through the ilium, posterior sacral plating, or anterior plating of the sacroiliac joint, can provide sufficient stability to the entire pelvic ring when the anterior ring is stable. Sacroiliac joint screwing and double plating of the pubic symphysis can maximally stabilize the pelvic ring mechanically.

    For sacral fractures across the sacral foramina, most fixation methods, including sacroiliac joint screwing, fixation with the screw nut through the ilium, posterior sacral plating, or anterior plating of the sacroiliac joint, can provide sufficient stability to the pelvic ring when the anterior ring is stable.

    For bilateral injury of the posterior pelvic ring, at least the axial bone on one side must be connected to the sacroiliac fixator to maintain the mechanical stability between the axial bone and the sacrum. Connecting the pedicle screw with the ilium screw or sacral internal fixator can effectively enhance the sacroiliac stability on both sides.

    Screw placement on the anterior inferior iliac spine improves the stability of the anterior external bracing.

    Sacroiliac screw placement in the sacrum can provide maximal stability.

    For pelvic fractures with damage to both anterior and posterior rings, the pelvis with both anterior and posterior fixed rings can only bear 1.5-fold the

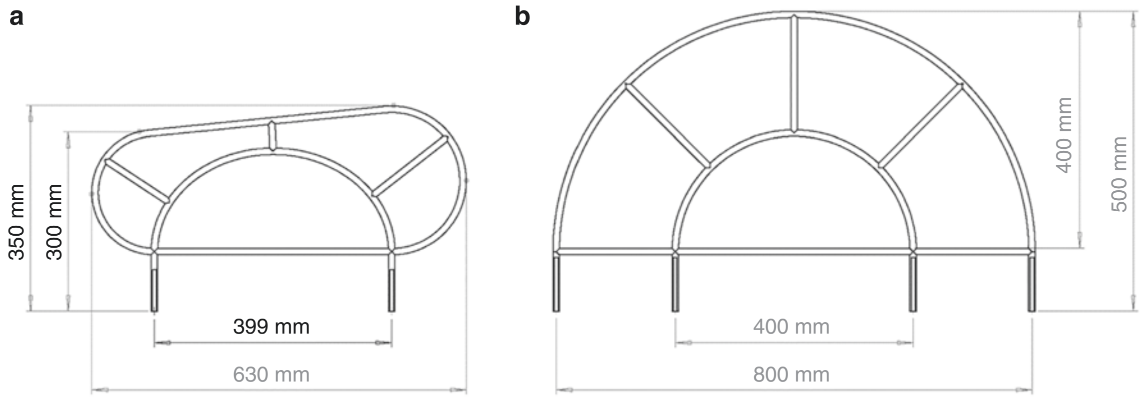


Fig. 3.49 This figure demonstrates and compares the dimensions of the modified Starr frame (**a**) used in this study and the Starr frame (**b**)

body weight and has a high risk of re-displacement, necessitating the avoidance of excessive weight-bearing.

– Achieve closed reduction of irreducible, unilateral vertically displaced pelvic ring disruption with an unlocking closed reduction technique technique:

Pelvic ring disruption (PRD) accounts for 3% of all adult fractures, and the majority of these cases, especially cases of irreducible, unilateral vertically displaced pelvic ring disruption (UVDPRD), requires surgical treatment (Grotz et al. 2005). Closed reduction for adult PRD is preferred over open reduction and is often achieved through transcondylar traction-based corridor screw (CS) fixation despite its flaw: A tremendous amount of caudad traction via transcondylar traction is required to reduce the cranially displaced posterior ring, but there are no good methods to resist this transcondylar traction (Thaunat et al. 2008; Lindsay et al. 2016; Ruatti et al. 2019; Abou-Khalil et al. 2020; Boudissa et al. 2020). Several tools were developed to resist the transcondylar traction, including Matta frame (Matta and Yerasimides 2007), Starr frame (Lefaivre et al. 2009a,b; Zhao et al. 2018), percutaneous Schanz screw in the greater trochanter (Elzohairy and Salama 2017), and femoral distractor (Routt Jr and Simonian 1996; Gardner and Nork 2007). However, when used with these tools, current closed reduction techniques have difficulties in achieving complete or nearly anatomical reduction of irreducible UVDPRD because hematoma maturation and soft tissue fibrosis often develop, which likely increase the risk of failed closed reduction of irreducible UVDPRD (Thaunat et al. 2008; Boudissa et al. 2020; Routt Jr and Simonian 1996; Olson and Pollak 1996). As a result, open reduction is often employed to treat irreducible UVDPRD, and an accepted closed reduction technique for irreducible UVDPRD is not established.

To be able to treat irreducible UVDPRD using closed reduction, a new technique named Unlocking Closed Reduction Technique (UCRT) is invented by Pro. Tang and chen's team (Chen et al. 2021; Luo et al. 2022; Wu et al. 2022). UCRT's ability to achieve complete or nearly anatomical reduction in patients with UVDPRD is evaluated in this retrospective cohort study using the improved pelvic closed reduction system (PCRS) (Fig. 3.49), which constitutes the radiolucent surgical table, modified Starr Frame, auxiliary reduction pins, connecting rod and clamp, framed-based unlocking reduction device (FBURD), and transcondylar traction system.

3.2.2.3.1 Improved Pelvic Closed Reduction System (PCRS)

In addition to radiolucent surgical table, auxiliary reduction pins (6 mm in diameter and 40 cm in length), connecting rod and clamp, and transcondylar traction system, the improved PCRS used in this our hospital constitutes two newly developed equipment, modified Starr frame (Fig. 3.49a) and FBURD (Fig. 3.50a). The existing Starr frame has an arch shape (Fig. 3.50b) and requires a not easily accessible 12-inch image intensifier for fluoroscopy because the frame is large (length: 0.8 m; width: 0.5 m). By comparison, the modified Starr frame used in this study has an oblique trapezoid shape that better secures the patient during transcondylar traction. Also, the modified Starr frame is significantly smaller (length: 0.6 m; width: 0.3 m) than the existing Starr frame, so fluoroscopy can be achieved through 9-inch or 6-inch image intensifier, which are more accessible. Moreover, the modified Starr frame is compatible with intraoperative CT, the TiRobot system (TINAVI Medical Technologies Co. Ltd., China) for more accurate CS placement, and all kinds of beds, including wooden beds.

Improving upon the T-handle (Fig. 3.50b), FBURD is a spin stretcher device that is easier to use, achieving push or pull of the long Schanz screw through rotation. Also, compared with T-handle, FBURD has a small size that minimizes interference with fluoroscopy.

3.2.2.3.2 Surgical Procedure

The patient is placed in a supine position with a 3-cm-thick, padded cushion under patient's lumbosacral region. After sterile preparation, PCRS is fixed to the surgical table to build a spatial reduction construct. Reduction pins are symmetrically driven into both sides of the pelvis at the following locations (Fig. 3.51): (1) 2 transverse supra-acetabular pins driven into superior cortex just above the dome of acetabulum under AP view monitoring; (2) 2 LC-2 pins driven into pelvis from anterior inferior iliac spine to posterior superior iliac spine under iliac oblique and iliosacral joint up-down view. For transcondylar traction, the traction pin penetrates femoral condyle and is connected to the traction bow.

UCRT is then performed to achieve UVDPRD reduction (OTA tile C1.2 shown with animation 1 and OTA tile C1.3 with animation 2). The uninjured hemipelvis is secured to the surgical table through the connection of transverse supra-acetabular pin to the modified Starr Frame and the connection of LC-2 pin to the connecting rod. Then, the flexion/extension of the injured hemipelvis is adjusted by sliding the connecting rod against the modified Starr Frame. When the connecting rod is horizontally leveled and clamped to the modified Starr Frame, the abduction/adduction of the injured hemipelvis is adjusted by sliding the LC-2 pin against the connecting rod. The position of the anterior pelvis ring is corrected once the LC-2 pin on the injured hemipelvis is positioned symmetrically with respect to that of the uninjured hemipelvis and subsequently clamped to the modified Starr frame. Posterior ring reduction is achieved under fluoroscopy. FBURD is connected to the transverse supra-acetabular pin on the injured side and rotated, pulling the posterior ilium laterally to unlock the dislocated iliosacral joint or overlapping edges of the sacral fracture. Subsequently, transcondylar traction is applied to correct cranial and posterior displacement, setting the posterior pelvis ring in circular motion centered on the connecting point of the LC-2 pin and the connecting rod. Finally, the transverse supra-acetabular pin is pushed medially by rotating the FBURD to accurately

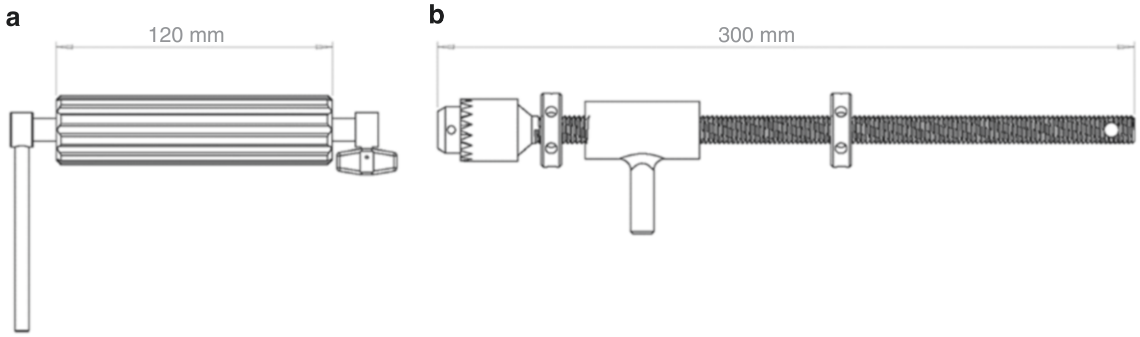


Fig. 3.50 This figure demonstrates and compares the dimensions of FBURD (**a**) used in this study and the T-handle (**b**)

Fig. 3.51 This figure indicates the drilling locations of 2 transverse supra-acetabular pins (1, 2), 2 LC-2 pins (3, 4), and the traction pin (5). This figure also indicates the placement of the connecting rod (6) and FRURD (7), which is connected to the transverse supra-acetabular pin (2) for unlocking the iliosacral joint dislocation. The red star stands for the dislocated iliosacral joint of the right side of the pelvis

reduce the posterior ring. Once C-arm examination reveals satisfactory reduction of the pelvis, an appropriate CS is implanted via a minimally invasive approach to fix the fracture. Posterior fixation is achieved through a 7.3-mm, partially threaded transsacral screw. Anterior fixation is achieved using external fixation or subcutaneous supra-acetabular pedicle screw internal fixation (INFIX) unless the facture is associated with symphyseal separation, which we treat with cannulated screw fixation before proceeding with anterior fixation (Tonetti et al. 1998; Van den Bosch et al. 2002; Routt Jr et al. 1996).

3.2.3 Surgical Complications and their Prevention and Treatment

- Open injury and infection of the pelvis:
  - Pelvic fractures accompanied by anorectal injury (Fakhry et al. 2000; Niederee et al. 2003):

    The incidence of open pelvic fractures associated with rectal injury is between 17% and 64%. Pelvic fractures associated with anorectal injury have an infection rate up to 70% and a mortality up to 45%. The major causes for death are sepsis and multi-organ failure after a missed diagnosis or ineffective drainage.

    Anorectal injury is difficult to diagnose by exploratory laparotomy due to anorectal anatomical characteristics; therefore, it is critical to determine whether blood is present upon finger palpation examination prior to surgery.

    Colostomy must be performed immediately in patients with confirmed or highly suspected anorectal injury. The infection rate is reportedly approximately 20% and 75% among patients who have received a colostomy within and after 48 h post-injury, respectively.

    In addition to colostomy, the excrement in the distal colon and rectum is cleaned up to reduce the possibility of infection, and an indwelt presacral drainage is placed. Antibiotic prophylaxis is administered before and after surgery (Fig. 3.52).
  - Pelvic fractures accompanied by urinary bladder and urethra injury:

    Urinary bladder injury (Lynch et al. 2005; Gomez et al. 2004; Dreitlein et al. 2001):
    - Urinary bladder injury is commonly seen in patients with multiple traumatic injury. It accounts for 2% of abdominal injuries that require surgical treatment. Approximately 5–30% of pelvic fractures are accompanied by urinary bladder injury, of which 65–85% is caused by blunt trauma and 25% by perforating injury.
    - Extraperitoneal urinary bladder rupture accounts for 55%, intraperitoneal urinary bladder rupture accounts for 38%, and joint extraperitoneal and intraperitoneal injuries account for 5–8%.
    - Patients with urinary bladder rupture typically present with visible hematuria, a tensioned abdominal wall, and other symptoms such as an incapability to urinate, bruising above the pubic region that expands into the abdominal area, and swelling of the perineal region, scrotum, or thigh caused by urine leakage depending on the location of the rupture.
    - The intraperitoneally ruptured urinary bladder must be surgically repaired in emergency exploratory laparotomy, followed by stage-one plate-screw fixation of the pubic symphysis. For

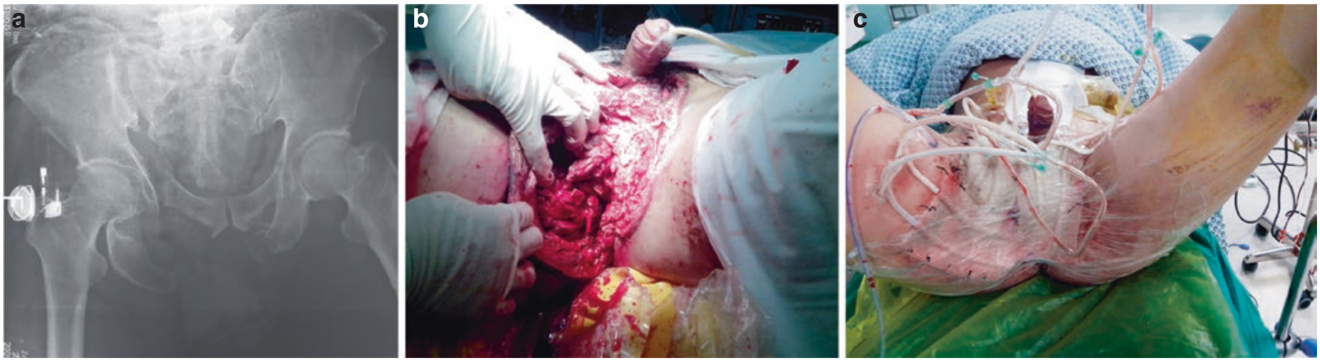


Fig. 3.52 (**a**) Preoperative radiograph of a patient with a type C1.1 pelvic fracture showing a diastasis of the right sacroiliac joint and fracture of the right pubic ramus. (**b**) The patient had a perineal laceration involving the anal canal. Therefore, a series of emergency treatments, including exploratory laparotomy, colostomy, cleaning of the excrement in the distal colon, and perineal debridement, were performed. (**c**) Negative-pressure wound therapy

extraperitoneal urinary bladder rupture, conservative treatment with the placement of an indwelt urinary catheter for approximately 3 weeks is often employed; nevertheless, bladder repair in emergency exploratory laparotomy can also be considered.

Urethral injury (Pape et al. 2011):

- Urethral injury occurs in 6–10% of pelvic fractures.
- According to the severity of the urethra injury, the American Association for the Surgery of Trauma (AAST) has established a grading system:
  - Grade I:
    Contusion of the urethra: Blood is present at the external urethral orifice, and the retrograde urography is normal;
  - Grade II:
    Stretch injury of the urethra: The urethra is injured by an excessive stretching force, with or without urine leakage, as shown by urography;
  - Grade III:
    Partial disruption of the urethra: An extravasation of urethrography contrast is observed at the injury site with visualization in the bladder;
  - Grade IV:
    Complete disruption of the urethra: An extravasation of urethrography contrast agent at the injury site without visualization in the bladder and a urethral separation smaller than 2 cm is observed;
  - Grade V:
    Complete disruption of the urethra: The urethral is completely disrupted, with a urethral separation >2 cm.
- Treatment for urethra injury: The treatment approach varies with gender, location of the injury (anterior or posterior urethra), or grade of the injury.
  - Male:
    For grades I and II urethra injury, a urinary catheter is placed through the urethra;
    For grade III urethra injury, after a temporary neostomy is performed by placing a catheter above the pubic region, 50% of patients can self-heal, and others might require surgery to open a stenosis occurring at the injury site or even a delayed urethral anastomosis or urethroplasty;
    Grade IV anterior urethra injury is treated with end-to-end anastomosis;
    Grade V anterior urethra injury is treated with urethroplasty;
    For grades VI and V posterior urethra injury: If the injury is accompanied by rectal injury, the injury to the urethra and rectum should be repaired and separated via omentum majus via laparotomy; otherwise, the injury can be treated with endoscopic urethral realignment. Urethral realignment and pelvic hematoma clearance via laparotomy is not recommended.
  - Female:
    Distal urethra injury can be treated with a transvaginal suture, and proximal urethral injury is sutured via the urinary bladder approach.
    The indwelling suprapubic drain is a relative contraindication for open reduction and internal fixation; in this case, external brace fixation of the anterior pelvic ring is a better choice (Fig. 3.53).

- Pelvic fractures accompanied by vaginal injuries (Brown et al. 2005):
  Mechanism of injury: The broken pubic ramus or ischial ramus directly punctures the vagina;
  Pelvic fractures with vaginal injury are open injuries that are easily missed and may cause serious consequences;
  Emergency repair should be performed once the diagnosis is confirmed;
  In patients with significant fracture displacement, the displaced fragment should be open reduced and internally fixed; otherwise, serious sexual difficulties might occur after fracture healing.

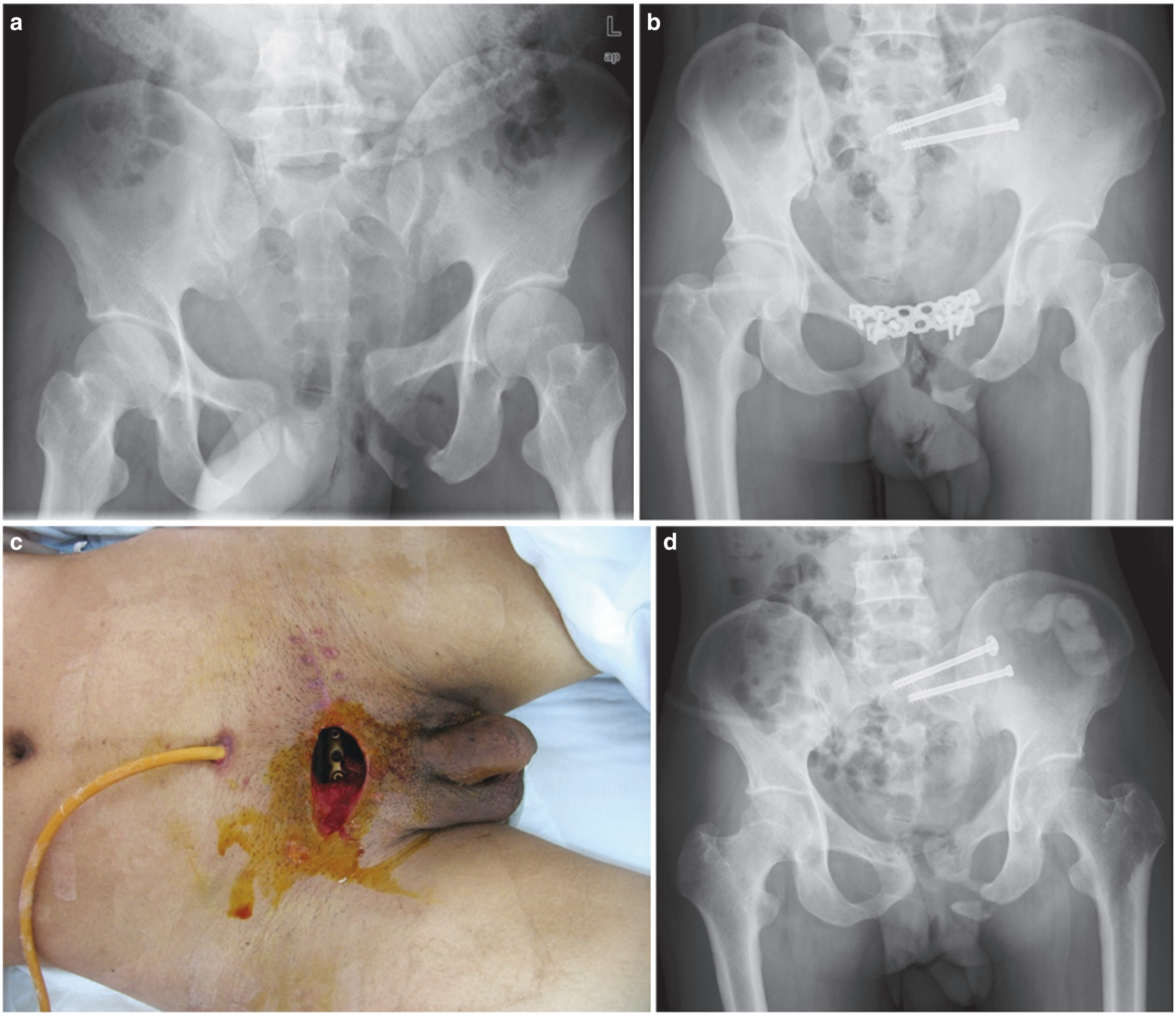


Fig. 3.53 A Tile type B1 pelvic fracture. (**a**) Preoperative radiograph showing a diastasis of the sacroiliac joint, fracture of the left inferior pubic ramus, and diastasis of the left sacroiliac joint. (**b**) Due to the accompanying urethral rupture, the patient underwent temporary cystostomy. Concomitantly, pubic symphysis double-plate fixation combined with sacroiliac joint screwing was performed. (**c**) Postoperative infection and dehiscence of the incision caused exposure of the steel plate above the pubic symphysis. (**d**) At 3 months after surgery, the plates were removed after preliminary healing of the sacroiliac joint

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Acetabular Fractures

4

Peifu Tang, Hua Chen, Zhe Zhao, and Yan Wu

4.1 Basic Theory and Concepts

4.1.1 Overview

- Acetabular fractures are caused mostly by high-energy traumas, which are often associated with posterior dislocation of the hip (Laird and Keating 2005).
- Acetabular fractures caused by osteoporosis and falling in elderly patients are mostly characterized by low-energy damage.
- The severity of the comminuted and displaced fracture, injury in the weight-bearing area, and reduction quality of the displaced fracture are significant factors affecting the long-term therapeutic outcomes.
- An accurate diagnosis, appropriate surgical approach, consummate surgical techniques, and matching surgical instruments are essential for a good prognosis of acetabular fractures.
- The goal of surgical treatment is to restore the natural anatomical structure of the acetabulum and to obtain the normal distribution of intra-articular pressure.
- Acetabular fractures are intra-articular fractures requiring anatomic reduction and rigid internal fixation.
- Given the long learning curve for the surgical treatment of acetabular fractures, this surgery should be carried out by experienced senior surgeons.
- Acetabular fractures result in the loss of the normal anatomical alignment between the femoral head and the acetabulum. In addition, the contact area between the femoral head and the acetabulum is significantly reduced, and the weight-bearing of the articular surface is uneven, all of which facilitate the development of post-traumatic arthritis (Mears et al. 2003; Moed et al. 2003).

4.1.2 Applied Anatomy

- Bony components of the acetabulum (Fig. 4.1):
  - Column structure: The acetabulum is formed and supported by two bony columns, which form an inverted “Y”-shaped structure (Judet et al. 1964; Letournel and Judet 1993).

    The column structure is the bases for the fracture classification, surgical approach, and selection of internal fixator.

    The anterior acetabular column consists of the anterior part of the iliac ala, iliac crest, anterior wall of the acetabulum, and superior pubic ramus.

    The posterior acetabular column consists of the ischial ramus and ischial spine, posterior wall of the acetabulum, and compact bone that forms the sciatic notch.
  - The anterior and posterior walls of the acetabulum are parts of the anterior and posterior acetabular columns, respectively, including the edge of the acetabulum, part of the articular surface, and part of the articular cartilage of the acetabulum. Anterior or posterior wall fractures of the acetabulum may be accompanied by either forward (anterior) or backward (posterior) dislocation of the femoral head.
  - The acetabular dome is a significant weight-bearing part of the articular facet of the acetabulum.

    The critical steps in the treatment of acetabular fractures are to reduce and fix the acetabular dome, concentrically reduce the femoral head, and restore the articular surface of the acetabulum with a normal anatomical alignment of the femoral head.

    Fracture of the acetabular dome without reduction will inevitably result in post-traumatic hip arthritis.
  - The quadrilateral plate of the acetabulum.

    The medial wall of the acetabulum can prevent femoral head dislocation to the medial side.

    Whether the quadrilateral plate belongs to the anterior acetabular column or the posterior acetabular column remains controversial.

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P. Tang, H. Chen (eds.), *Orthopaedic Trauma Surgery*, https://doi.org/10.1007/978-981-16-0219-1_4

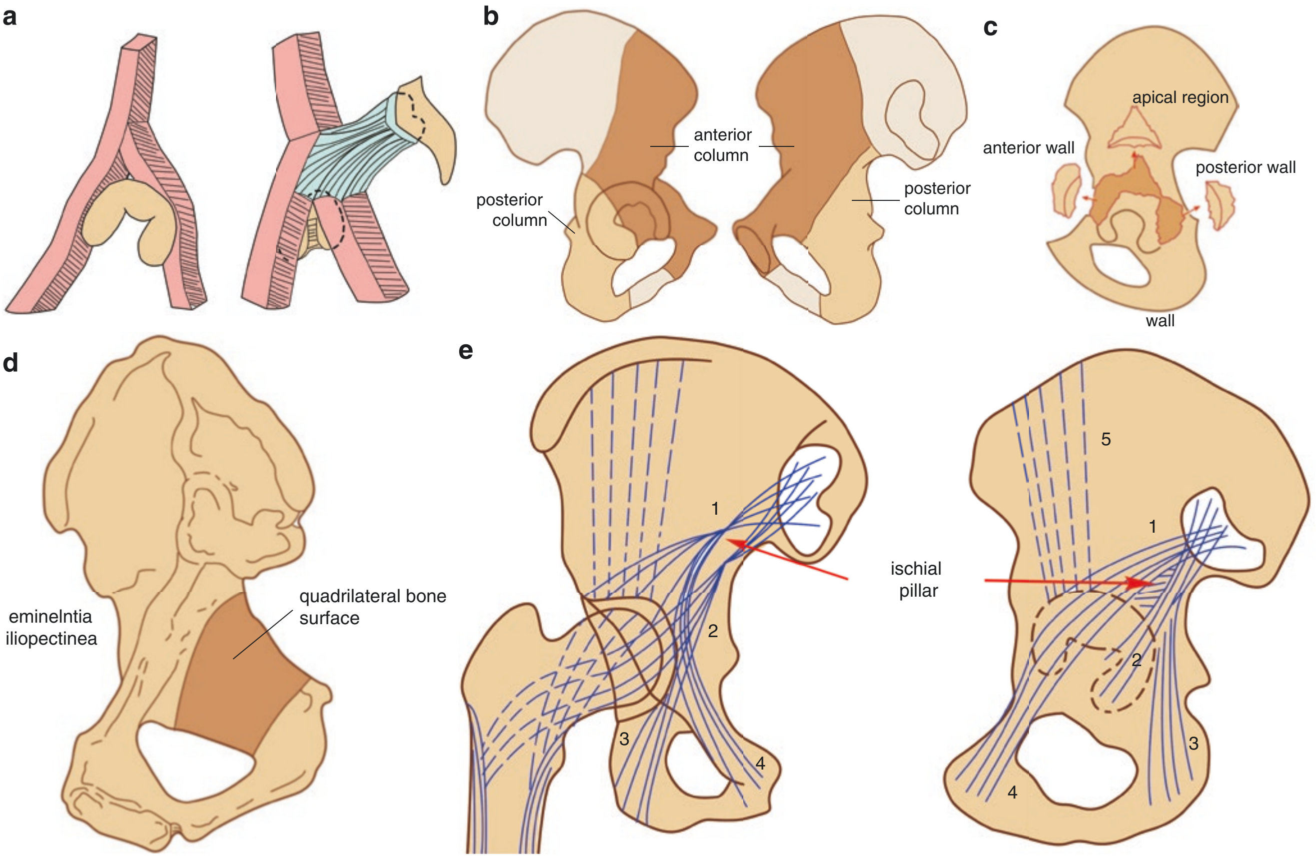


Fig. 4.1 (**a**) As shown in the schematic diagram, the acetabulum is surrounded by an inverted Y- shaped column structure and connected to the spine through the ilium. (**b**) The anterior acetabular column consists of the anterior part of the iliac ala, iliac crest, anterior wall of the acetabulum, and superior pubic ramus. The posterior acetabular column consists of the ischial ramus and spine, the posterior wall of the acetabulum, and the compact bone that forms the sciatic notch. (**c, d**) In addition to the anterior and posterior columns, the significant part of the acetabulum also includes the anterior and posterior walls and dome area. (**e**) The bone trabecular structures in the hip: According to the orientation pattern, the trabeculae can be divided into three groups, i.e., the sacrum-acetabulum trabeculae (1, 2), the sacrum-ischium trabeculae (3), the sacrum-pubis trabecula (4), and the ilium-acetabulum bone trabecula (5)

Quadrilateral plate fracture is relatively complicated to reduce and fix; therefore, some scholars refer to the quadrilateral plate as a narrow third column.

- Matching of the acetabulum and femoral head (Olson and Matta 1993; Tornetta III 1999):

  As the hip joint is a ball-and-socket joint, precise alignment of the acetabulum and femoral head plays an important role in good function of the hip; Fractures of the anterior and posterior walls of the acetabulum lead to a change in stress in the acetabulum from uniform to local increase at the acetabular dome, which, if severe, exceeds the load that the cartilage can bear, leading to post-traumatic arthritis in the future.

- Trabecular bone structure and screw-holding area of the acetabulum (Zinghi et al. 2004):

  The internal structure of the hip bone is closely related to the stress transmission from the femoral head to the spine.

  In 1940, Rouviere proposed that stress is transmitted along the tangential direction of the iliac articular surface of the acetabulum to a cortical bone area and referred to this highly concentrated area of cortical bone as the ischial strut.

  In 1967, Campanacci defined three trabecular systems in the hip by radiology based on the direction of arrangement, i.e., sacrum-acetabulum, sacrum-ischium, and sacrum-pubis. The posterior column contains the sacrum-acetabulum and sacrum-ischium trabeculae of the inferoposterior acetabulum. The anterior column contains the sacrum-acetabulum, sacrum-pubis, and ilium-acetabulum trabecula in the anterior part of the acetabulum.

  As acetabular fractures are fixed internally, the screws should be placed in the dense area of bone trabecula to increase the holding force and prevent the screws from being pulled out.

- Important soft tissue structures related to acetabular fractures and surgical approaches (Fig. 4.2):

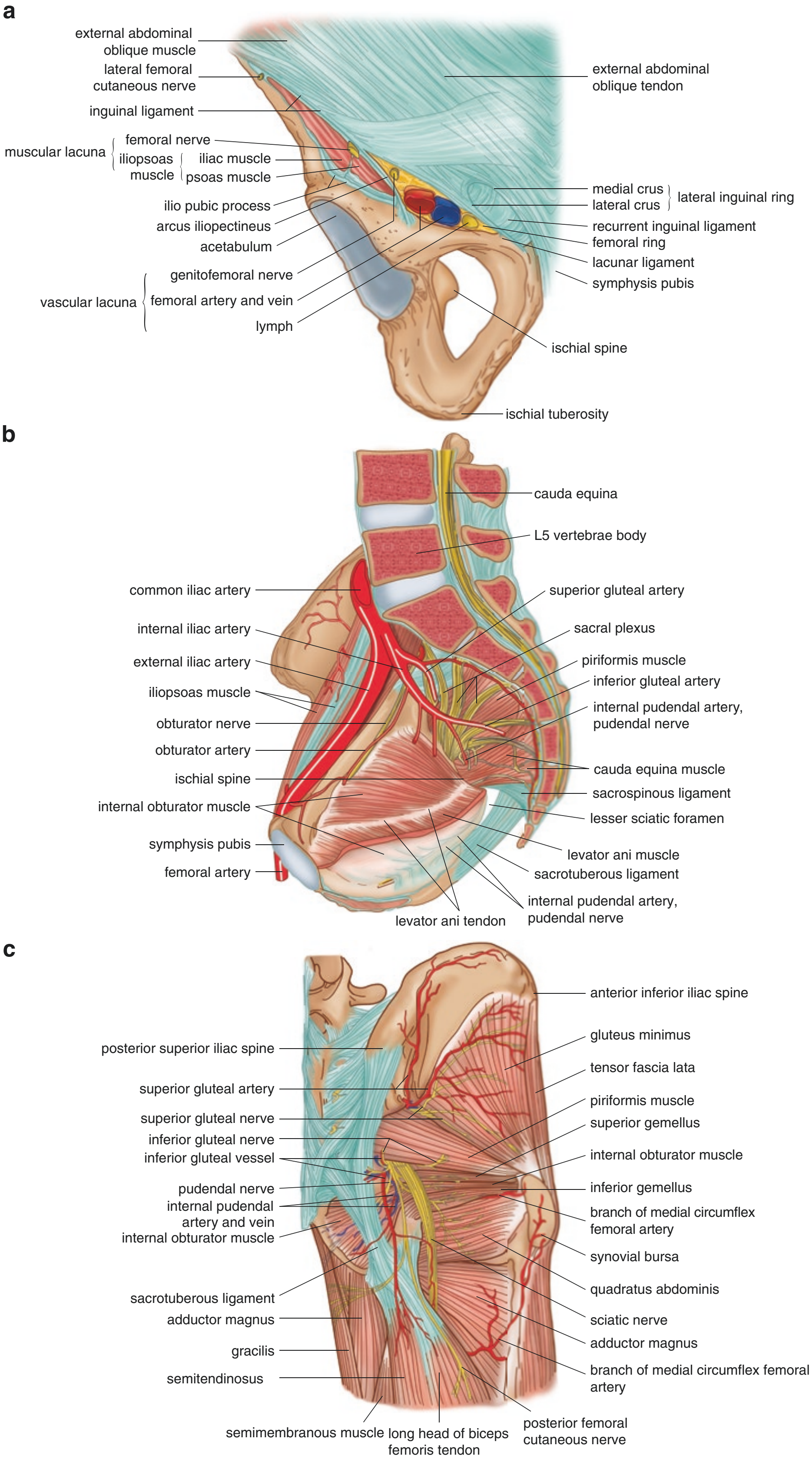


Fig. 4.2 (**a**) The iliopectineal fascia is located between the femoral vessels and the femoral nerve. Identification of the structure in the anterior surgical approach to the acetabulum is conducive to dissecting and protecting the vessels and nerves. (**b**) Arterial supply surrounding the acetabulum: The "corona mortis" is an anastomosis between the external iliac artery or the inferior epigastric artery and the obturator artery. It should be paid special attention and ligated during surgery via the ilioinguinal approach. (**c**) Nerves and muscles surrounding the acetabulum: The sciatic nerve pierces out below the piriformis muscle, and the superior gluteal artery pierces out beneath the greater sciatic notch and runs upward.

- Iliopectineal fascia: attached to the edge of the pelvis.

  It is located and separates between the femoral vessel and the femoral nerve.

  Identification of the structure in the anterior surgical approach to the acetabulum is conducive to dissecting and protecting the vessels and nerves.
- A common vascular variant known as the "corona mortis" is susceptible to pelvic trauma: 85% of patients have this vascular variant (Teague et al. 1996; Tornetta et al. 1996).

  It is an anastomosis between the external iliac artery or the inferior epigastric artery and the obturator artery.

  The average distance between this blood vessel and the pubic symphysis is 6 cm.

  Ligation of the blood vessel is recommended when the ilioinguinal approach is adopted; otherwise it may cause uncontrolled heavy bleeding with dissociation of the external iliac vessels.
- The sciatic nerve passes the greater sciatic notch from the infrapiriform foramen; the nerve can be injured when the posterior side of the acetabulum is fractured and dislocated.
- Superior gluteal artery and nerve: these anatomical structures are frequently involved in acetabular fractures (Beck et al. 2003).

  They pass along the top of the greater sciatic notch and are bound to the surface of the bone by the fascia.

  Fractures involving the top of the greater sciatic notch can directly lead to injury of the superior gluteal artery.

  When performing surgery for posterior wall acetabular fracture, if the vessel is injured by accident, the proximal end of it retracts into the pelvic cavity, resulting in pelvic bleeding, which will be difficult to control.

4.1.3 Mechanisms of Injury

- The age of the patient and the energy of injury are closely related to the degree of comminution of the acetabular fracture.
- Direct trauma: A direct external force acting on the greater trochanter causes acetabular fractures. The position of the femoral head relative to the acetabulum determines the type of acetabular fracture.
  - External rotation and abduction of the lower extremities may damage the anterior acetabular column.
  - Internal rotation of the lower extremities causes damage to the posterior acetabular column.
  - Injury caused by direct violence on the greater trochanter while the lower extremity is in the neutral position may lead to a transverse fracture of the acetabulum. Hip abduction and adduction may result in low-level and high-level transverse fractures of the acetabulum, respectively (Fig. 4.3).
- Indirect trauma: Both hip and knee joints are in flexion during indirect trauma. Indirect trauma leads to posterior wall fractures of the acetabulum. It is also known as a dashboard injury. The degree of hip flexion determines the posterior wall fracture location of the acetabulum (al-Qahtani and O'Connor 1996; Dakin et al. 1999).
  - The more adequate the flexion of the hip, the lower is the location of the posterior wall fracture of the acetabulum.
  - The more inadequate the flexion of the hip, the higher is the position of the posterior wall fracture of the acetabulum.

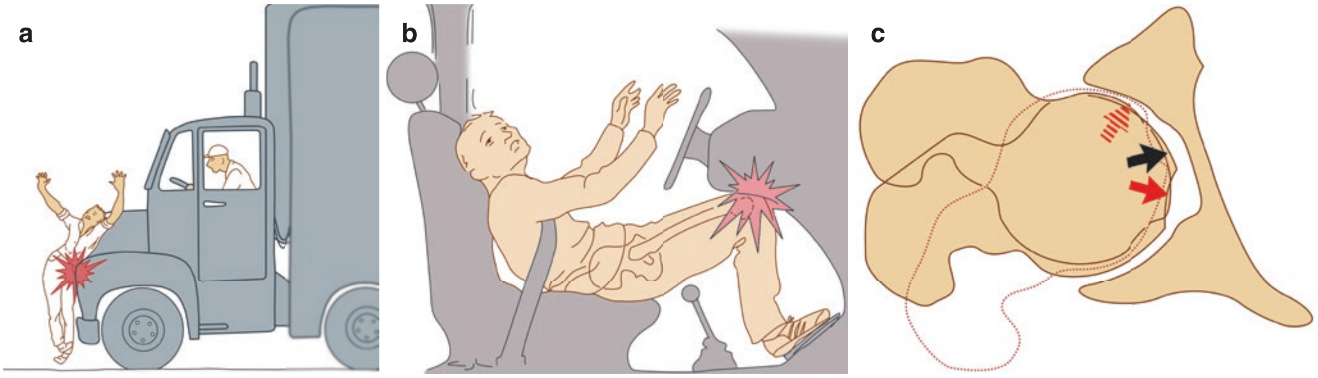


Fig. 4.3 (**a**) A direct violent force onto the greater trochanter of the femur can lead to acetabular fractures, i.e., direct trauma. (**b**) Violence acting on the patella is transmitted through femoral shaft and fractures the acetabulum, i.e., indirect trauma. (**c**) The position of the femoral head in the acetabulum at the time of injury determines the type of fracture. The external rotational stress of the hip joint acting on the greater trochanter may cause a fracture of the anterior acetabular column. The neutral stress of the hip joint often leads to a transverse fracture. The internal rotational stress of the hip joint often leads to a posterior column fracture

4.1.4 Fracture Classification

The most commonly used classification system for acetabular fractures in clinical practice is the Judet and Letournel classification, which is based on the anatomical structures of the acetabulum.

- A simple acetabular fracture refers to a transverse acetabular fracture or a separated site fracture involving a single column or a single wall, including posterior wall fracture, posterior column fracture, anterior wall fracture, anterior column fracture, and transverse fracture of the acetabulum (Fig. 4.4).
  - Posterior wall acetabular fracture: Obturator oblique-position radiography can distinctly show posterior wall acetabular fractures. Posterior wall acetabular fractures can easily merge with the posterior dislocation of the femoral head but do not affect the stability of the posterior column structure. The involved or collapsed part of the articular surface requires prying reduction; otherwise, it will affect the mechanics of the acetabulum, resulting in post-traumatic arthritis secondary to the injury.
  - Posterior column acetabular fracture: The fracture line of the posterior column acetabular fracture starts from the greater sciatic notch, passes through the articular surface of the posterior wall of the acetabulum, and ends at the obturator foramen. It is often accompanied by central dislocation of the femoral head.
  - Anterior wall acetabular fracture: The anterior wall is fractured while the anterior column remains intact, and the ischial ramus or pubic symphysis has no fracture.
  - Anterior column acetabular fracture: In anterior column acetabular fractures, the continuity of the iliopubic line is interrupted with anteromedial dislocation of the femoral head, and the higher the fracture location, the greater is the involved area of the acetabulum weight-bearing region.
  - Transverse acetabular fracture: The acetabulum is divided into the upper and lower parts by the fracture line of the transverse acetabular fracture, which can be divided into transparietal, paraparietal, and subparietal fractures based on the position of the fracture line. The injury of the acetabular dome and the prognosis are worse when the fracture occurs at a higher position. The positional relationship between the iliosciatic line and teardrop remains normal.
- Complex acetabular fracture: A complex acetabular fracture refers to a combination of two simple fractures, such as T-shaped acetabular fracture, associated posterior wall and posterior column acetabular fracture, associated transverse and posterior wall acetabular fracture, associated anterior column and posterior semi-transverse acetabular fracture, and double-column acetabular fracture (Fig. 4.5).
  - T-shaped acetabular fracture: It is a combination of a transverse acetabular fracture and longitudinal fracture, with the fracture line dividing the pubis and ischium into two parts through the ischium. Given the two bone fragments are detached, it is difficult to simultaneously achieve reduction and fixation of the two bone fragments through a single surgical approach.

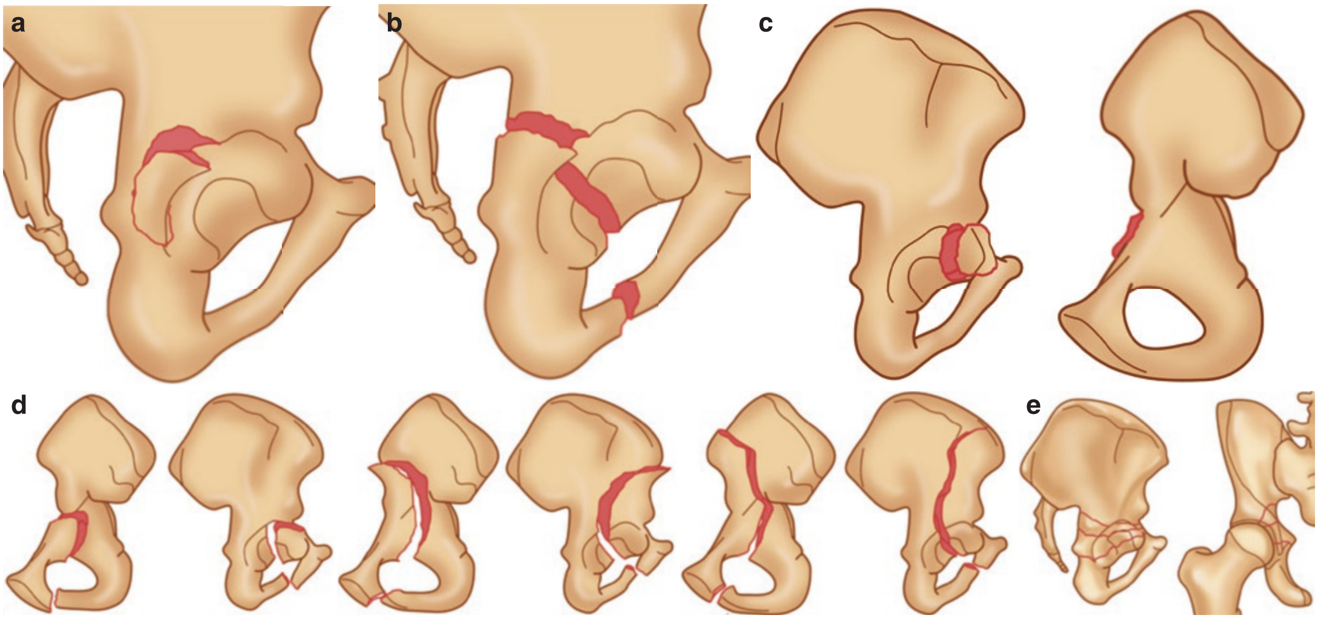


Fig. 4.4 Simple acetabular fracture. (**a**) Posterior wall acetabular fracture. (**b**) Posterior column acetabular fracture. (**c**) Anterior wall acetabular fracture. (**d**) Diagram of low-, medium-, and high-level acetabular fractures. (**e**) Transverse acetabular fracture: The fracture lines in the figure are transparietal, paraparietal, and subparietal fracture lines from top to bottom

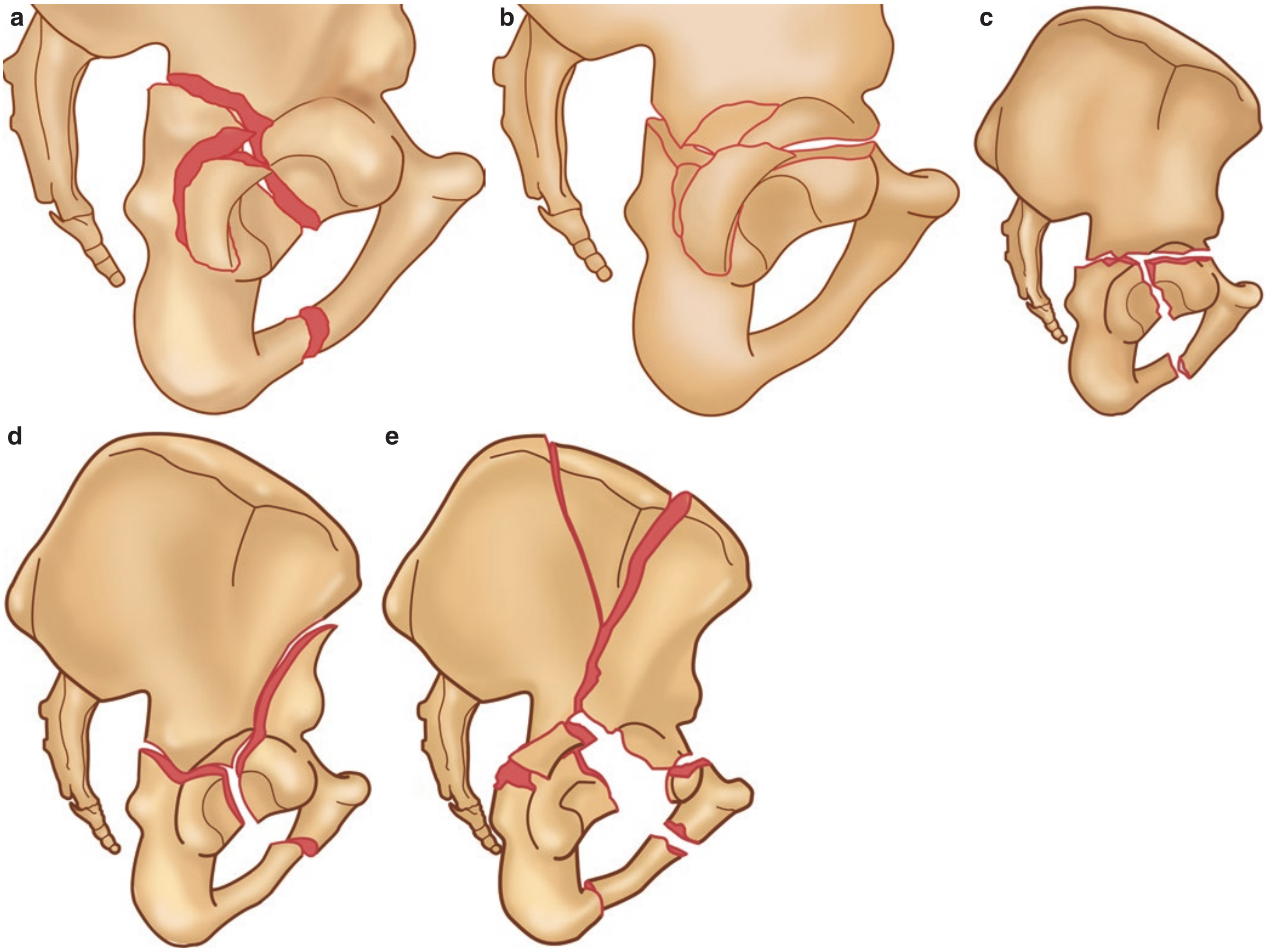


Fig. 4.5 Complex acetabular fracture. (**a**) Associated posterior wall and posterior column acetabular facture. (**b**) Associated posterior wall and transverse acetabular fracture. (**c**) T-shaped acetabular fracture. (**d**) Associated anterior column and posterior semi-transverse acetabular fracture. (**e**) Double-column acetabular fracture

- Associated posterior wall and posterior column acetabular fracture: The posterior wall fracture is significantly displaced or rotated relative to the posterior column and often combined with dislocation of the femoral head, resulting in sciatic nerve injury.
- Associated transverse and posterior wall acetabular fracture might be combined with posterior dislocation or central dislocation of the femoral head. The obturator oblique radiograph is very important for observing the fracture and its displacement.
- Associated anterior column and posterior semi-transverse acetabular fracture: In the associated anterior column and posterior semi-transverse acetabular fracture, the articular surface of the acetabular dome remains in the natural position, which provides a reference for fracture reduction and fixation.
- Double-column acetabular fracture: After the acetabulum is fractured, the fracture fragment loses its connection with the axial skeleton, i.e., the sacroiliac joint loses its connection with the fracture fragment. Correspondingly, the loss of the normal anatomical position of the acetabular dome together with the loss of the reference for fracture reduction and fixation make the double-column acetabular fracture the most complex type of fracture in acetabular fractures. The anterior and posterior columns are separated from each other and from the axial skeleton, forming the “floating acetabulum”.

4.1.5 Assessment of Acetabular Fractures

- Clinical assessment.
  - Acetabular fractures result from high-energy trauma and are often associated with important injuries of parenchymal organs, such as the abdomen and pelvis;

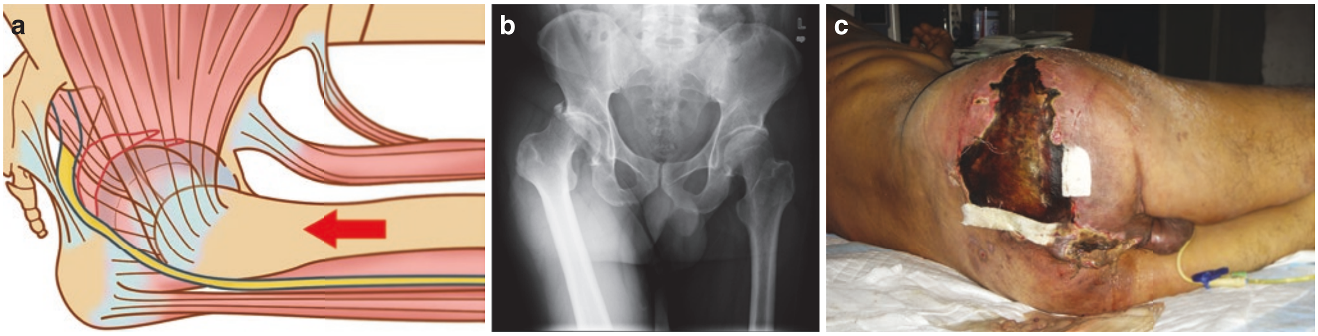


Fig. 4.6 (**a**) A posterior wall acetabular fracture associated with posterior dislocation of the femoral head often results in sciatic nerve injury. (**b**) A posterior wall acetabular fracture associated with posterior dislocation of the femoral head fracture. (**c**) Photo of a patient with acetabulum and pelvic fractures associated with extensive skin degloving injury and necrosis of the hip, i.e., Morel- Lavallée lesion, caused by highly violent trauma

attention should be paid to rule out multiple injuries, such as patellar fracture, knee dislocation, femoral shaft fracture, and femoral neck fracture.

  - Fracture displacement can cause vascular damage. Injury to the internal iliac vessels, especially the superior gluteal artery, should be considered when the hemodynamics and hemorrhagic shock of the patient is unstable and difficult to rectify, respectively. Angiography and embolization techniques can be used to control active bleeding if necessary.
  - Attention should be paid to the associated injuries of the ipsilateral extremity, such as femoral neck fracture, patellar fracture, and knee joint injury.
  - An accurate nerve examination must be performed to evaluate nerve injury. A posterior wall acetabular fracture can result in 40% sciatic nerve damage.
  - Digital rectal examination (DRE) and vaginal examination can rule out an open fracture and identify pelvic organ injuries; patients with hematuria may have an acetabular fracture combined with bladder or urethral injury.
  - Soft tissue contusions in the greater trochanter and iliac ala of the femur indicate a potential Morel-Lavallée lesion (Tseng and Tornetta 3rd. 2006) (Fig. 4.6), which is an extensive degloving injury of the skin that manifests as giant subcutaneous hematoma and fat necrosis and is often accompanied by secondary bacterial infection. Thorough debridement should be performed before definite surgery; otherwise, the probability of infection is very high, with an incidence rate reaching 1/3.

- Imaging evaluation.
  - Plain radiography (Letournel and Judet 1993) (Fig. 4.7).

    AP position: The six basic radiographic marker lines proposed by Letournel appear in the AP view.

    Iliac oblique radiograph: The radiograph is obtained by turning the pelvis to the affected side 45°, i.e., the radiograph is obtained when the pelvis is externally rotated 45° to display the entire ilium, posterior column, and anterior lip, thereby facilitating evaluation of the posterior column and anterior wall fractures of the acetabulum.

    Obturator oblique radiograph: The radiograph is obtained by turning the pelvis to the unaffected side 45°, i.e., the radiograph is obtained when the pelvis is internally rotated 45° to show the acetabulum anterior column and posterior wall, thereby facilitating evaluation of the anterior column and posterior wall fractures of the acetabulum. At this point, the iliac ala is in the vertical position, and the so-called "spur sign" above the acetabulum can be observed in the case of the double-column acetabular fracture.
  - CT scan (Moed et al. 2009) (Fig. 4.8).

    CT provides more information for the diagnosis of acetabular fractures. It can accurately determine the severity of comminution fractures, compression fracture of articular surface, intra-articular loose fracture fragment, hip dislocation, and injury of the sacroiliac joint.

    The 3D CT image stereoscopically displays the overall displacement of the fracture.

    The 3D CT view with the femoral head subtracted allows visualization of the acetabular articular surface, facilitating the identification of fracture types and selection of treatment options.
  - Magnetic resonance imaging (MRI).

    MRI has little significance for the classification and diagnosis of acetabular fractures, but it is very useful for evaluating the blood supply of the femoral head and predicting the survival of the disconnected bone fragments.

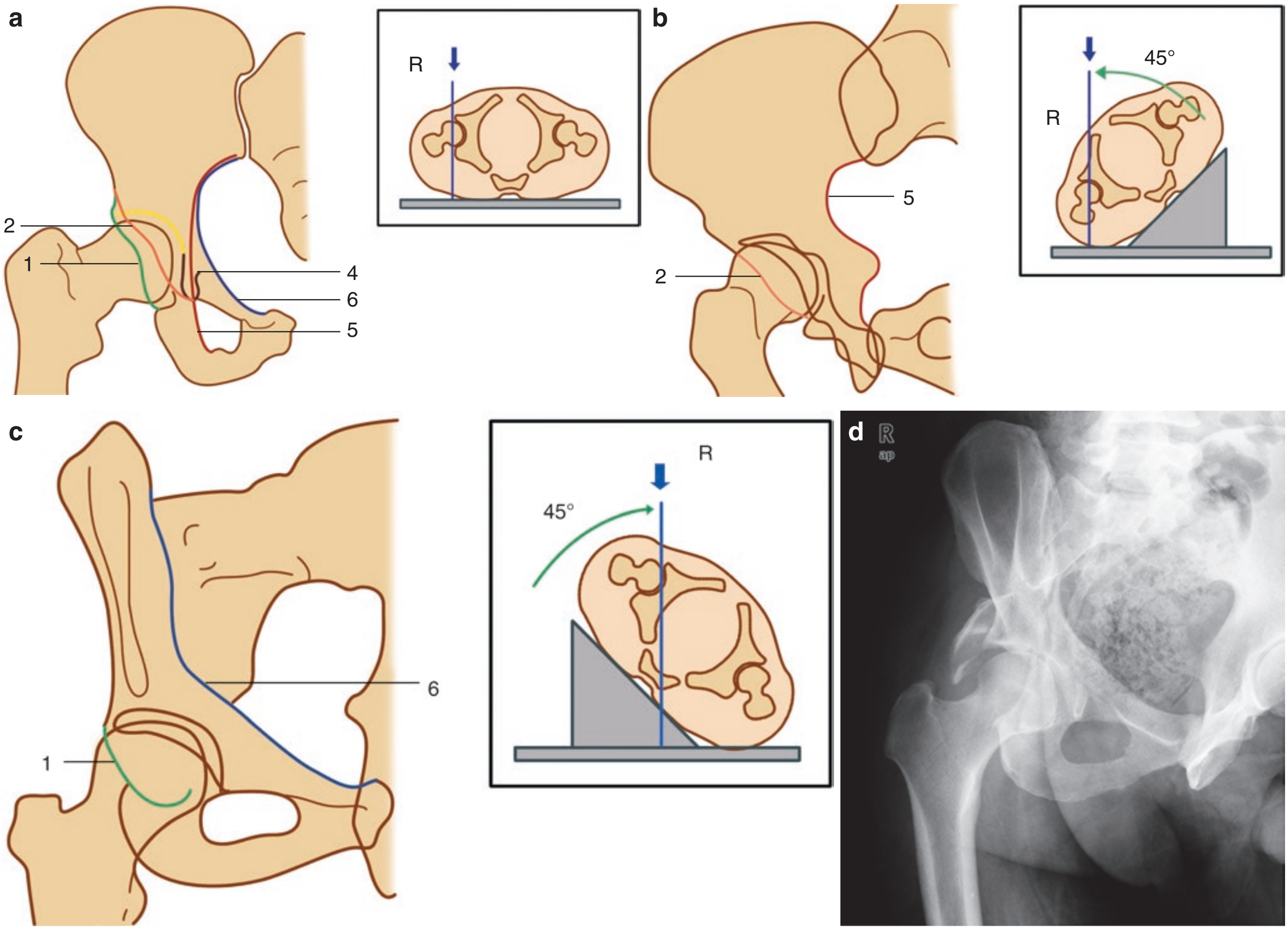


Fig. 4.7 (**a**) Six radiologic markers in the hip AP view: The posterior edge (1), anterior edge (2), and dome (3) of the acetabulum, the 'teardrop' (4), the iliosciatic line (posterior acetabular column) (5), and the iliopubic line (anterior acetabular column) (6). (**b**) A diagram of iliac oblique view: Radiography is performed when the pelvis is externally rotated 45° to display the entire ilium, posterior column, and anterior lip, which aids in evaluating posterior column and anterior wall fractures of the acetabulum. The markers are the acetabulum anterior edge (2) and iliosciatic line (5). (**c**) A diagram of the obturator oblique view: Radiography is obtained by turning the pelvis towards the unaffected side by 45° to display the anterior column and posterior wall of the acetabulum, which facilitates evaluation of the anterior column and posterior wall fractures of the acetabulum. The markers are the acetabulum posterior edge (1) and iliopubic line (6). (**d**) In the case of a double-column acetabular fracture, a "spur sign" can be observed in the obturator radiograph

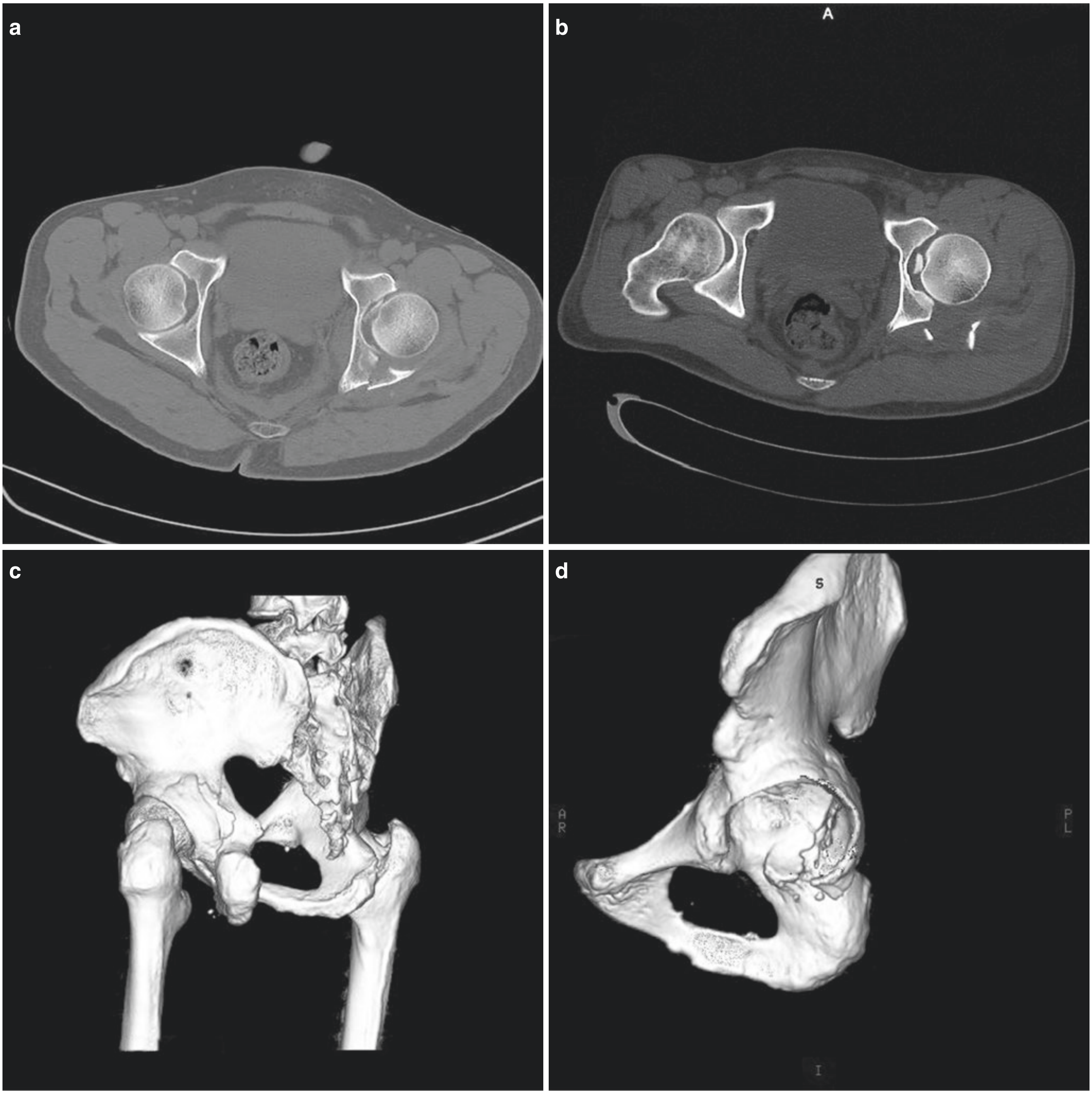


Fig. 4.8 (**a**) Plain CT scan of an acetabular fracture showing the left posterior wall acetabular fracture and the partial articular surface compression. (**b**) Left posterior wall acetabular fracture: An avulsion fracture is apparent at the round ligament of the femoral head. (**c**) The 3D-reconstructed image of the posterior wall acetabular fracture stereoscopically displays the gross displacement of the fracture. (**d**) The 3D-reconstructed image after femoral head and neck subtraction more clearly reveals the morphology of the acetabular fracture

4.2 Surgical Treatment of Acetabular Fractures

4.2.1 Surgery Timing

- The optimal time for surgical treatment of acetabular fractures is 5–7 days post-trauma. Organized hematoma, soft tissue contracture, and callus formation all impede the fracture reduction once they exceed the above time frame. If the surgery is delayed by more than 2–3 weeks, more extensive surgical exposure is required to achieve good reduction of the fracture end.
- Indications for emergency surgery are as follows: (1) irreducible fracture and dislocation are usually suggestive of fracture or soft tissue incarcerated in the joint; (2) the hip joint is unstable and is prone to re-dislocation after fracture reduction; (3) injury of the sciatic nerve is aggravated after closed reduction, and the nerve compression is diagnosed clinically; (4) accompanying vascular injury is present; and (5) open acetabular fracture.
- In acetabular fracture patients with accompanying fractures elsewhere in the ipsilateral lower extremity, the accompanying fractures should be treated first because they affect the mobility and traction of the lower extremity required for surgical reduction and fixation of acetabular fractures during surgery.
- Due to the complicated conditions of the disease, patients who fail to undergo surgery for acetabular fracture within a week after the injury should receive traction of the affected lower extremity to prevent soft tissue contracture at the fracture end, which may cause reduction difficulties in the later surgery.

4.2.2 Indications for Surgery

- Overview: According to the surgical indications of acetabular fractures (Tile et al. 2003), patients who need surgical intervention have main manifestations of hip joint instability and mismatch between the femoral head and acetabulum.
- Hip instability.
  - Posterior wall acetabular fracture: Regardless of a simple posterior wall acetabular fracture or a posterior wall acetabular fracture associated with a transverse or posterior column acetabular fracture, hip instability is possible as long as the posterior wall fracture fragment is sufficiently large, which is also the absolute indication for open reduction and internal fixation. Patients with a range of posterior wall fracture involving more than 50% of the articular surface are generally considered as being vulnerable to joint instability at 90° hip flexion.
  - Anterior wall acetabular fracture: The large fragment in the anterior wall fracture may cause instability or dislocation of the hip joint.
  - Quadrilateral plate fracture: When a medial wall fragment of the quadrilateral plate is large, the central dislocation of the femoral head causes instability of the hip joint.
- Mismatch between the femoral head and acetabulum.
  - Fracture displacement of the acetabular dome: A fracture involving the acetabular dome often generates a triangular bone fragment, which is prone to rotation and difficult to be anatomically reduced by traction. Open reduction and fixation should be performed to decrease the vulnerability to post-traumatic osteoarthritis. This type of fracture fragment rarely occurs alone but often is observed as part of a transverse, T-shaped, or double-column acetabular fracture.
  - High-level transverse or T-shaped acetabular fracture: In the transverse or T-shaped fracture involving the acetabular dome, the fracture fragments are often stuck and thus not suitable for closed reduction due to a high shear stress. Even if closed reduction is successful, it is very difficult to maintain, necessitating surgical reduction and fixation.
  - Displaced double-column acetabular fracture: The coronal fracture line of the ilium passes directly through the hip joint and causes coronal displacement, which requires surgical reduction and fixation.
  - Residual bone fragments in the hip joint: The fracture fragments remaining in the hip joint prevent anatomical reduction of the hip joint. Removal of these bone fragments and anatomical reduction are absolute surgical indications.
  - Femoral head fracture: Dislocation of acetabular fractures can result in a large avulsion fracture of the femoral head, where the fracture fragments are attached to the round ligaments, and often prevents hip reduction, requiring surgical reduction and fixation (Fig. 4.9).
  - Soft tissue intercalation: The joint capsule is intercalated between the femoral head and the acetabulum, which affects the femoral head reduction and requires surgical open treatment.
  - The criteria for successful reduction include the following: a restored concentric anatomical structure of the acetabulum; a return of pelvic landmark structures, including the iliopubic line and iliosciatic line, to normal.
- Other surgical indications.
  - Femoral nerve or sciatic nerve injury or aggravation of the injury after fracture reduction, which indicates that the nerve may be trapped by bone fragments and requires open surgery to release the compression.

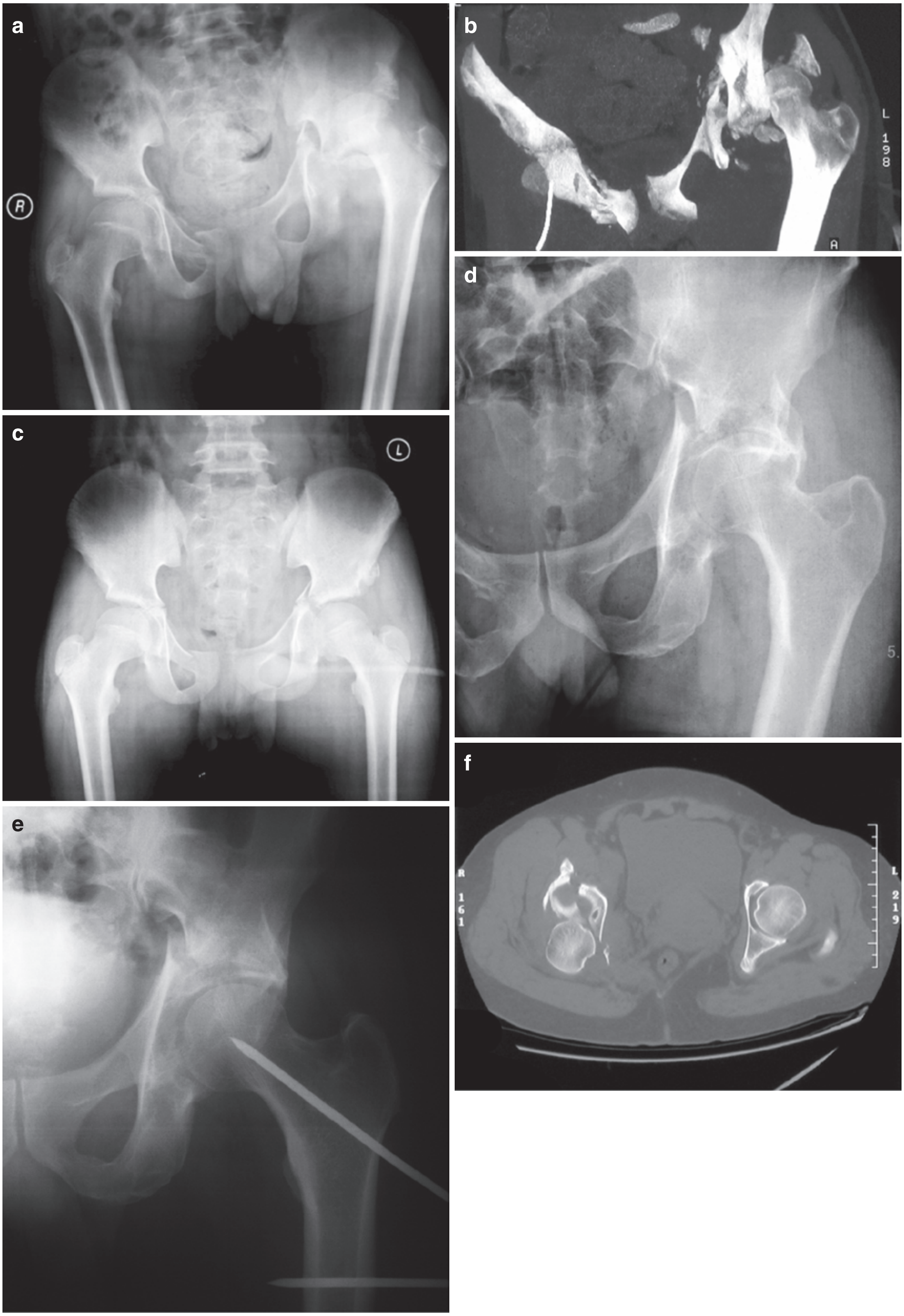


Fig. 4.9 (**a**) An AP radiograph of a patient with double-column acetabular fracture associated with posterior dislocation of the femoral head: A triangular fracture fragment on the dome of the acetabulum was rotationally displaced. (**b**) Coronal-reconstructed CT image revealing the displacement of the triangular fracture fragment. (**c**) After traction reduction, the fragment remained to be rotationally displaced. (**d, e**) Radiographs of a patient with a high-level transverse acetabular fracture showing the residual fragment in the acetabulum after traction. (**f**) A left acetabular fracture with a large bone fragment was apparent in the acetabulum, which was indicative for surgical removal of the fragment and anatomical reduction

  - Anterior column acetabular fracture associated with femoral vascular injury: Acetabular fractures are reduced and fixed along with blood vessel repair.
  - Traction and reduction cannot be performed when an acetabular fracture is accompanied by an ipsilateral femoral shaft fracture or knee injury. In this situation, all injuries can be repaired by surgery simultaneously.

4.2.3 Selection of the Surgical Approach

4.2.3.1 Common Surgical Approaches

- Anterior approaches: These include the ilioinguinal approach, modified Stoppa approach, and iliofemoral approach.
- Posterior approaches: These include the Kocher-Langenbeck approach and approach via the greater trochanter.
- Extended (extensile) approaches: These include the extended iliofemoral approach and "Y"-shaped approach via the trochanter.
- Combined anterior and posterior approaches: These include the ilioinguinal approach combined with the Kocher-Langenbeck approach.
- Established principles should be followed when selecting the surgical approach.
  - No universal approach can expose all fractures. Thus, accurate preoperative fracture classification is very important for optimal selection of the surgical approach.
  - The type of fracture determines the surgical approach.
  - Anterior approaches are necessary for simple anterior column and/or anterior wall acetabular fractures.
  - Posterior approaches are necessary for simple posterior column and/or posterior wall acetabular fractures.
  - Under circumstances in which both anterior and posterior approaches can be selected, anterior approaches are a better choice because they are safer and cause fewer complications.
  - Simple approaches are preferable to extensile approaches, and combined anterior and posterior approaches are recommended if necessary because extensile surgical approaches have a significantly higher risk of complications.
  - Extensile approaches can be used for complex or old acetabular fractures.

4.2.3.2 Ilioinguinal Approach (Letournel 1993)

- Indications: The ilioinguinal approach is suitable for anterior fractures of the acetabulum, such as anterior column acetabular, anterior wall acetabular, transverse acetabular, and associated anterior column and posterior semi-transverse acetabular fractures. An experienced surgeon can complete the reduction and fixation of double-column and T-shaped acetabular fractures using this approach.

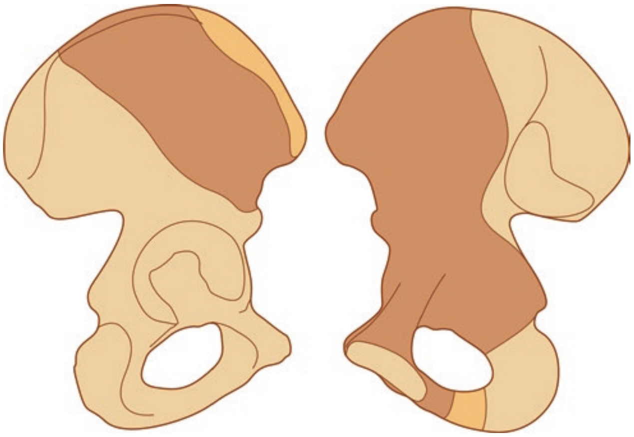


Fig. 4.10 Range of surgical exposure of the ilioinguinal approach: The dark brown area denotes the exposed area under direct vision, and the yellow area denotes the area that can be reached with a finger

- Range of surgical exposure: This approach provides access to the medial side of the iliac ala, i.e., the anterior aspect of the iliac fossa and the sacroiliac joint, quadrilateral plate (i.e., the pelvic surface of the acetabulum), superior pubic ramus, and pubic symphysis (Fig. 4.10).
- Advantages: The surgical exposure is wide. The pelvis and anterior and medial walls of the acetabulum can be highly exposed. The heterotopic ossification rate is relatively low.
- Disadvantages: This approach provides an access for palpating and observing fracture displacement by moving three windows instead of a direct view of the hip joint surface. Therefore, it allows only indirect reduction without exposing the posterior wall and posterior column.
- Risks: Surgical retraction/pulling might injure the lateral femoral cutaneous nerve, femoral vessel, and femoral nerve. Improper handling of the "corona mortis" vessel can cause bleeding. Deep vein thrombosis may occur.
- Body position and preoperative preparation:
  - Anesthesia: The patient undergoes general anesthesia.
  - The patient lies supine on a radiolucent operating table, followed by disinfection of the entire lower abdomen, pelvis, and affected lower extremity and draping.
- Surgical incision according to body surface projection:
  - The incision originates from the midpoint of iliac crest, extends arcuately to the anterior superior iliac spine and then parallel to the inguinal ligament, and ends at the site 2 cm above the pubic symphysis (Fig. 4.11).
- Surgical approaches (Fig. 4.12):
  - The periosteum is incised along the iliac crest to cut off the attachment points of the rectus abdominis and ilia-

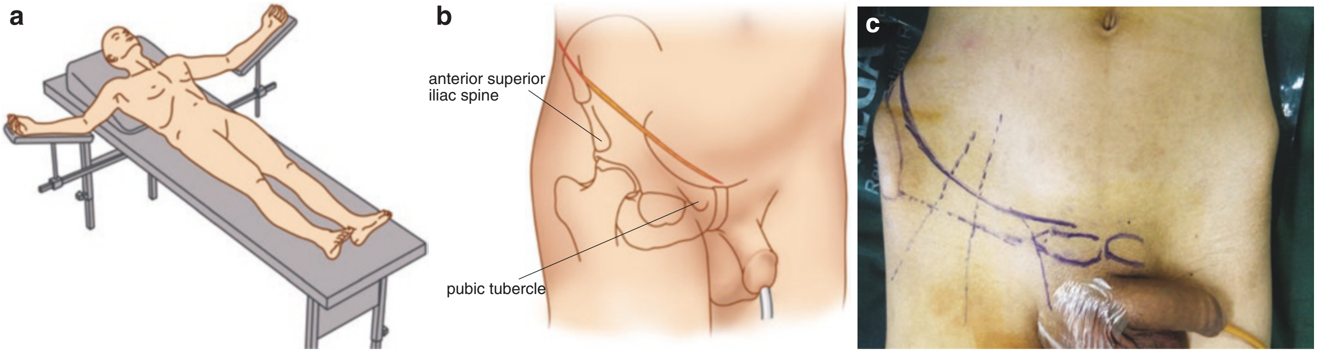


Fig. 4.11 (**a**) The patient lies supine on a radiolucent operating table. (**b**) The incision originates from the mid-point of the iliac crest, extends arcuately to the anterior superior iliac spine and then parallel to the inguinal ligament, and ends at the site 2 cm above the pubic symphysis. (**c**) The running direction of the pubic tubercle, anterior superior iliac spine, femoral artery, lateral femoral cutaneous nerve, and spermatic cord are marked on the body surface

cus muscles. Subperiosteal dissection is performed to expose the iliac fossa and can reach the sacroiliac joint posteriorly and the greater sciatic notch inferiorly. Bone wax or gauze packing is used to stop the bleeding.

- From the anterior superior iliac spine to the external ring of the inguinal canal, the external oblique aponeurosis is cut at the site 5 mm away from the ending point of the inguinal ligament, and the inguinal canal is opened to expose the spermatic cord or round ligament, which is protected with a silicone tube to facilitate exposure of the deep tissue during surgery.
- The conjoint tendon is identified from the lateral side of the incision and cut along the inguinal ligament. Attention should be paid to preserving 2 mm of the tendon for suture and reconstruction of the inguinal canal and to protecting the underlying lateral femoral cutaneous nerve.
- The incision is created medially and inferiorly, through which the fold back of the iliopectineal fascia can be palpated, with the femoral artery and vein on the medial side of the fascia and the femoral nerve and lateral femoral cutaneous nerve on the lateral side. Care must be taken when exposing and dissociating the femoral vessels. To preserve the integrity of the conjoint tendon above the femoral artery, vein, and lymphatic system, pulling during surgery should be minimized to reduce injury to these structures.
- The conjoint tendon is cut open on the medial side of the vessel, and further exposure can be achieved by cutting the rectus abdominis muscle at the site 1 cm away from its ending point if necessary to expose the pubic tubercle to the pubic symphysis, up to the Retzius space (retropubic space) behind the pubis. Catheterization can reduce bladder tension and intraoperative damage. When placing a plate across the pubic symphysis, it is necessary to cut off part of the contralateral rectus abdominis muscle.
- After identification and careful separation, the iliopectineal fascia is cut along the pelvic edge to expose the quadrilateral plate. On the lateral side of the iliopectineal fascia, a periosteal stripper is used to gently push to lift the iliopsoas muscles and femoral nerves, which are wrapped and protected in a thick rubber tube. On the medial side of the iliopectineal fascia, the structures above the pubic bone, such as the femoral artery, veins, and lymphatic vessels, are pushed along the pubic surface; the integrity of these structures should be maintained. Subsequently, a silicone tube is used to protect the femoral blood vessels, nerves, and surrounding lymphoid tissue.
- By further dissociating the underlying vessel/nerve bundles, the quadrilateral plate is exposed up to the sacroiliac joint. Attention should be paid to the anastomoses between the femoral artery and the obturator artery, namely the “corona mortis”, which must be carefully separated and ligated under direct vision to prevent massive bleeding.
- Manipulation of the silicone tube can facilitate exposure of the surgical field. The iliopsoas muscles and femoral vessels are pulled to the medial side simultaneously to expose the iliac fossa and the front of the sacroiliac joint, i.e., the lateral window of the ilioinguinal approach. The iliopsoas muscles and femoral nerves are pulled laterally, and the femoral vessels are pulled medially to expose the quadrilateral plate and the pelvic edge, i.e., the middle window. The pubic symphysis is exposed by laterally pulling aside the femoral vessel and medially pulling aside the spermatic cord, i.e., the medial window. When the spermatic cord and femoral vessels are pulled laterally, the rear of the pubic symphysis can be simultaneously exposed, i.e., the median window. The obturator nerve and blood vessels can be observed in the middle window or medial window and should be protected during fracture reduction (Fig. 4.13).

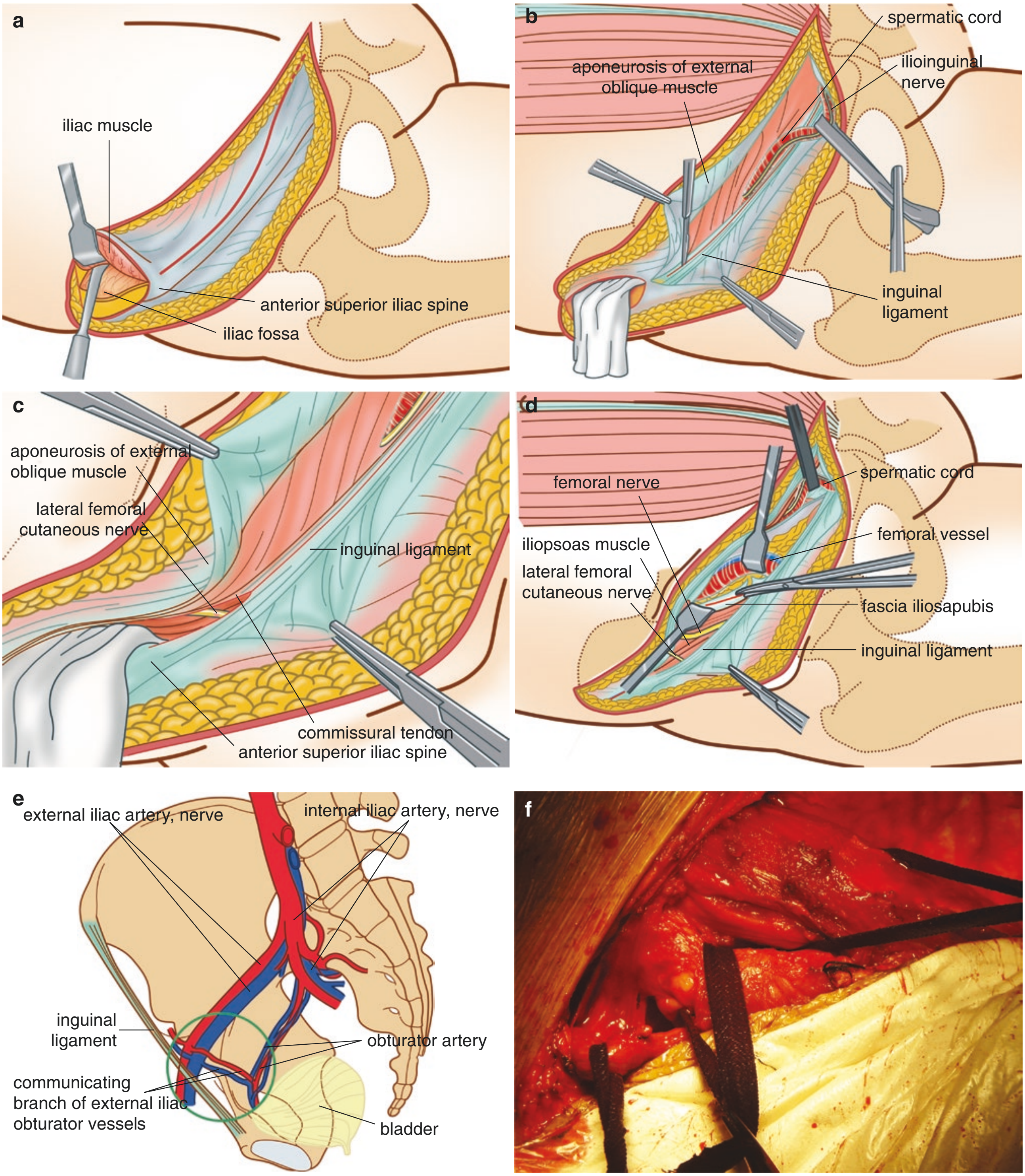


Fig. 4.12 (**a**) The skin and subcutaneous are cut open. The periosteum is incised along the iliac crest to cut off the attachment points of the rectus abdominis muscle and the iliacus muscle. The subperiosteal dissection is performed to expose the iliac fossa, and it can reach the sacroiliac joint posteriorly and the greater sciatic notch inferiorly. Bone wax or gauze packing is used to stop the bleeding. (**b**) From the anterior superior iliac spine to the outer ring of the inguinal canal, the external oblique aponeurosis is severed at the site 5 mm away from the ending point of the inguinal ligament, and the inguinal canal is opened to expose the spermatic cord or round ligament, which is protected with a silicone tube to facilitate exposure of the deep tissue during surgery. The tube can also be manipulated to assist exposure during surgery. (**c**) Intraoperative protection of the lateral femoral cutaneous nerve: The lateral femoral cutaneous nerve often resides in the deep layer of the conjoint tendon, 1–2 cm medial to the anterior superior iliac spine, which should be preserved. (**d**) The femoral artery and vein are pulled medially, and the femoral nerve and iliopsoas muscle are pulled laterally to expose the iliopubic fascia. The fascia is cut up to the base of the pubis under direct vision. (**e**) The anastomoses between the obturator vascular bundle and the inferior epigastric vascular bundle or the external iliac vascular bundle, known as the "corona mortis", must be ligated or dissected before release of the iliac vessels. (**f**) From top to bottom, the structures that are protected by three slings are the iliac muscle along with the femoral nerve, the femoral vessels, and the spermatic cord

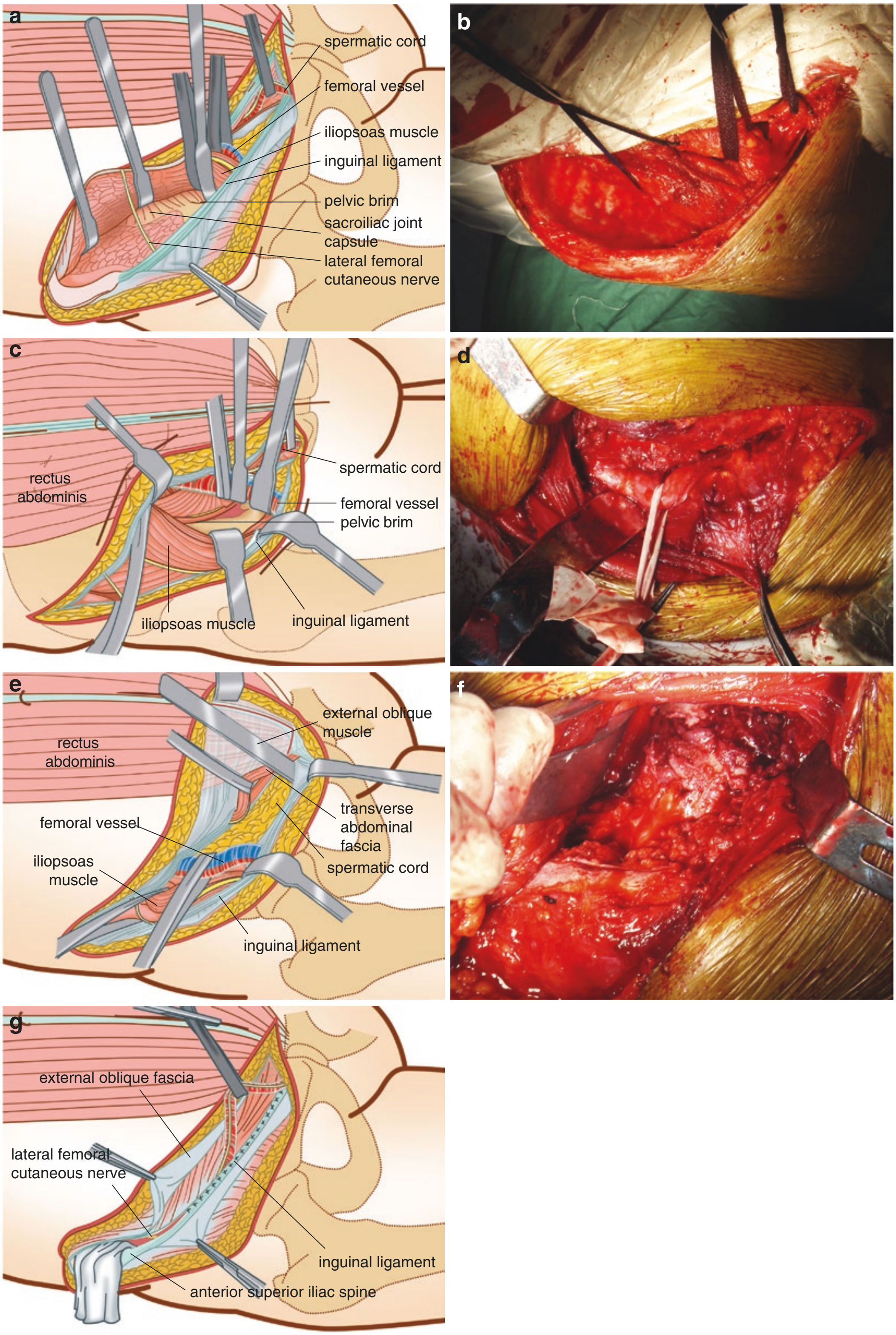


Fig. 4.13 (**a, b**) Through the lateral window, the area from the entire iliac fossa behind the iliopubic carina to the sacroiliac joint can be exposed. During exposure through this window, the femoral nerve, iliopsoas, and femoral vessels should be gently pulled medially. (**c, d**) Through the middle window, the lateral 1/3 of the pelvic rim and quadrilateral plate lateral to the sacroiliac joint and pubic ramus can be exposed. The femoral nerve, iliopsoas muscle, and femoral vessels should be gently pulled medially during exposure through this window. (**e, f**) Through the medial window, the obturator nerve and blood vessels can be observed. For surgical exposure through this window, the ending point of the rectus abdominis should be incised according to needs, and the pubic tubercle should be exposed up to the Retzius space while the spermatic cord or soft ligaments and femoral vessels are gently pulled to the lateral side. (**g**) For incision closure, the conjoint tendon is sutured to the inguinal ligament to reconstruct the floor of the inguinal canal, followed by suturing the external oblique muscle aponeurosis and rectus sheath. The suture must be effective and firm to prevent the formation of an incisional hernia

- Incision closure and reconstruction:
  - After fracture reduction and fixation, the drainage tube should be placed in the Retzius space on the surface of the quadrilateral plate. The anatomical structures of the inguinal canal and the stability of the abdominal wall are reconstructed by suturing the rectus abdominis muscle, conjoint tendon, and external oblique inguinal aponeurosis in situ.

4.2.3.3 Modified Stoppa Approach (Archdeacon et al. 2011)

- Indications: The modified Stoppa approach is mainly used for fractures involving the medial wall of the acetabulum.
- Range of surgical exposure: This approach can provide good exposure of the quadrilateral plate, and further stripping reveals the anterior aspect of the sacroiliac joint and the iliac fossa.
- Advantages: The anatomic structures of the pelvis and anterior aspect and inner surface of the acetabulum are well exposed without exposure of the lateral femoral cutaneous nerve, femoral blood vessels, and lymph. The heterotopic ossification rate is low.
- Disadvantages: The articular surface is indirectly reduced. There is no access to the posterior wall. For a fracture more than 3 weeks old, the surgical exposure range of the modified Stoppa approach is slightly inadequate. Abdominal distension and intestinal obstruction, which might cause a high abdominal wall tension, is a relative contraindication for this approach.
- Risks: The modified Stoppa approach may cause damage to the structures including the lateral femoral cutaneous nerve, femoral blood vessel, and femoral nerve. Enlargement of the surgical exposure may also result in obturator nerve and concomitant vascular injuries.
- Surgical techniques (Fig. 4.14).
  - Body position and preoperative preparation:

    The patient lies supine on a radiolucent operating table.

    Anesthesia: The patient undergoes general anesthesia.

    Disinfection of the abdomen, perineum, and pelvis areas, followed by surgical draping.
  - Surgical incision according to the body surface projection: A transverse incision is made 2 cm above the pubic symphysis and between the external rings of the

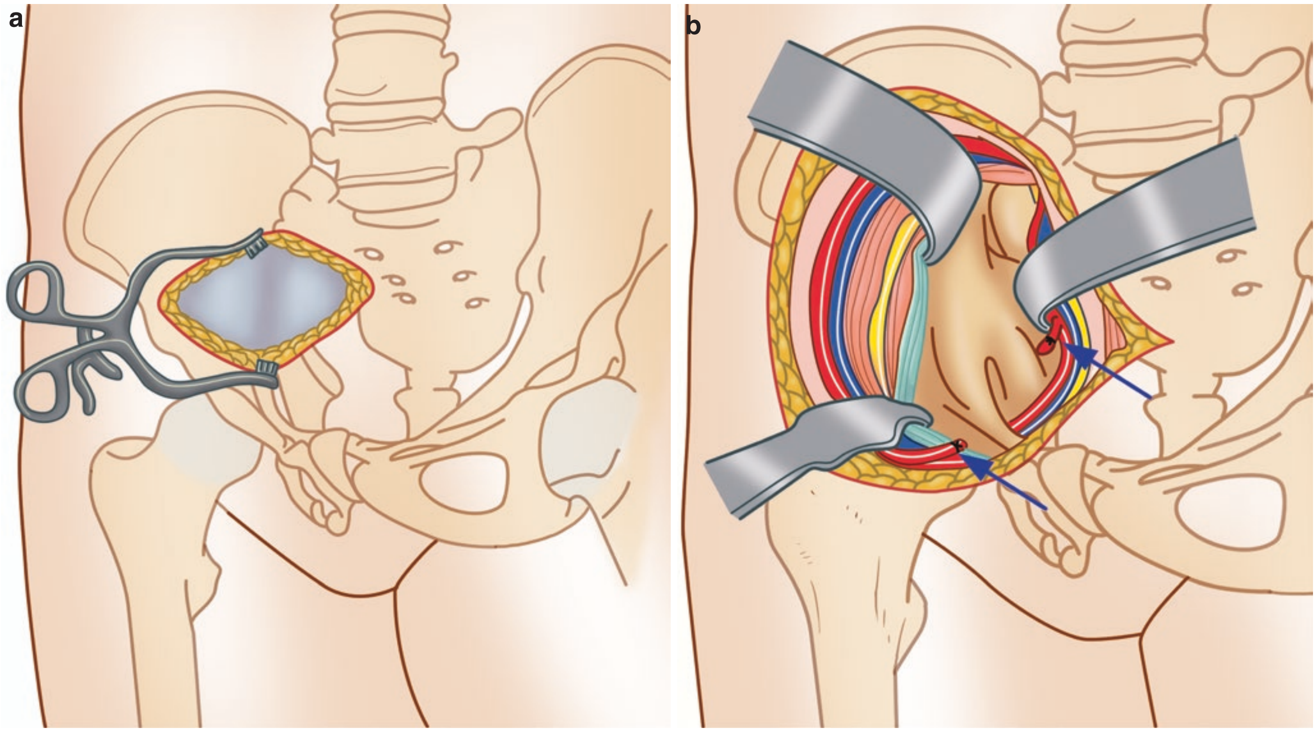


Fig. 4.14 Drawing of the Modified Stoppa approach from the angle of the surgeon's view while the patient lies in a supine position. (**a**) The incision is created at the site 2 cm above the pubic symphysis. (**b**) The anastomosis between the inferior epigastric artery or femoral artery and the obturator artery (denoted by the black arrow) is dissociated and ligated. A Hohmann hook is placed at the pubic tubercle, a Deaver hook is placed under the iliopsoas muscle for laterally pulling and to protect the iliopsoas muscle and femoral vessels, and another hook is placed at the sciatic notch to protect the obturator artery and vein

inguinal canal on both sides. The subcutaneous tissue is cut open and properly dissociated in an up-down direction.

- Surgical approach:

  After the rectus abdominal muscle is longitudinally split open along the linea alba, the Retzius space is opened extraperitoneally, and the bladder is pushed to the side of the abdominal cavity for protection.

  The rectus abdominal muscle is dissected at its ending point on the pubic symphysis and the superior pubic ramus to expose the pubic symphysis and superior pubic ramus.

  The rectus abdominal muscle, femoral vessels, and nerve bundles are pulled laterally and protected. The pubic symphysis and the medial wall of the acetabulum are exposed below the femoral vessels, nerves, and iliopsoas muscles.

  It is crucial to ligate the anastomoses between the inferior abdominal and obturator arteries. There are also many anastomoses between the bladder and the internal iliac artery, which should be ligated sequentially.

  The anastomosis between the inferior epigastric artery or femoral artery and the obturator artery, also known as the "corona mortis", must be carefully dissected and ligated.

  During stripping of the iliac muscle, attention must be paid to ligating the nutrient vessels of the iliolumbar artery; otherwise, bleeding might unnecessarily occur.

  The exposure range is expanded through upward dissection of the iliopectineal fascia, downward dissection of the obturator fascia, and posterior dissection to expose the sacroiliac joint, to better expose the pelvic edge and the ischial retinaculum.

- Incision Closure and Reconstruction:

  The drainage tube is placed in the Retzius space, and the incision is subsequently sutured and closed layer by layer.

4.2.3.4 Kocher-Langenbeck Approach (Judet et al. 1964)

- Surgical indications: reduction and fixation of the posterior wall or posterior column acetabular fracture. Experienced surgeons can use this approach for the reduction and fixation of transverse acetabular fractures and T-shaped acetabular fractures.
- Range of surgical exposure: The posterior wall of the acetabulum can be viewed directly from the entire posterior column, including the greater sciatic notch and ischial tuberosity. The fracture displacement and reduction of the quadrilateral plate can also be examined by finger palpation through the greater sciatic notch (Fig. 4.15).

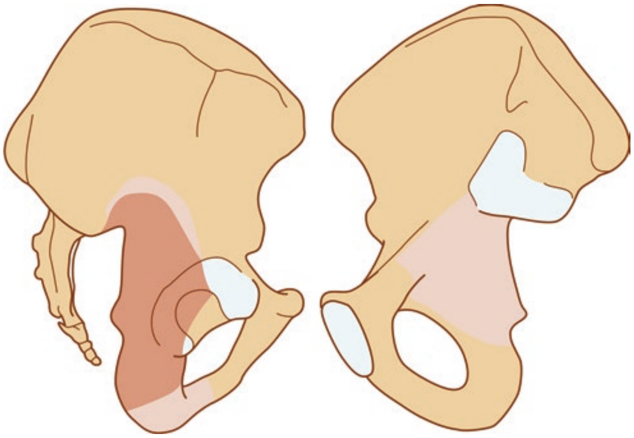


Fig. 4.15 The Kocher-Langenbeck approach provides access to the posterior column and posterior wall of the acetabulum. The dark red area in the picture denotes the directly visible area, and the light red area denotes the palpable area

- Advantages: The posterior wall and posterior column of the acetabulum are fully exposed, and the fracture displacement and reduction of the anterior column and quadrilateral plate can be examined by finger palpation through the greater sciatic notch.
- Disadvantages and risks: Attention must be paid to avoid damaging the blood vessels and nerves.
  - Injury of the superior gluteal neurovascular bundle: The superior gluteal neurovascular bundle passes rearwardly from the pelvic cavity through the greater sciatic notch and travels on the surface of the ilium. There is a risk of injury to the neurovascular bundle during exposure of the posterior column or reduction and fixation of the fracture. The probability of injury reported by Letuornel et al. is 3.5%. Intraoperative attention must be paid to protecting the structure. Superior gluteal nerve injury can cause permanent abduction weakness of the gluteal muscles. The injured superior gluteal vessels might retract into the pelvic cavity, resulting in massive bleeding. It is crucially important to protect the superior gluteal nerve from ligation along with the superior gluteal blood vessels to avoid paralysis of the superior gluteal nerve.
  - Sciatic nerve injury: The sciatic nerve is adjacent to the posterior column and the ischial tuberosity and travels through the greater sciatic notch into the pelvic cavity. It is easy to damage this nerve when exposing the posterior column. The risk of sciatic nerve injury can be reduced by maintaining the hip in the extension position and the knee in the flexion position to relax the sciatic nerve during surgery. In addition, intraoperative neuromonitoring can provide a real-time warning to the surgeon and reduce the risk of sciatic nerve injury.

- Heterotopic ossification is mostly caused by intraoperative soft tissue injury, bleeding, and tissue necrosis. It has a very high incidence rate, reaching 18% to 90%, and is mainly distributed along the gluteus minimus.

- Surgical procedures.
  - Body position and preoperative preparation.

    Anesthesia: The patient undergoes general anesthesia.

    Body position: The patient lies laterally on the unaffected side or in the prone position. The lateral decubitus position allows movements of the hip joint during the operation, which is convenient for anesthesia and the operative procedure but not for reduction. The advantage of the prone position is that the femoral head is maintained in the reduction status. Maintenance of the position of knee flexion and hip extension during operation can reduce the risk of sciatic nerve injury.

    The area around the pelvis, chest and abdomen, perineal region, and lower extremities are disinfected. The surgical field exposure and surgical draping are the same as those for hip replacement, with all requiring exposure of the posterior superior iliac spine.

    Surgical incision according to the body surface projection:

    - The surgical incision is centered over the apex of the greater trochanter. It extends proximally to the distal end of the posterior superior iliac spine for 5 cm and distally along the femoral shaft, ending at the site 8 cm below the greater trochanter (Fig. 4.16).

    Surgical approach (Fig. 4.17):

    - The subcutaneous, iliotibial tract, and gluteus maximus muscle fascia are cut layer by layer. The gluteus maximus muscle fibers are bluntly separated at the junction of the middle and upper thirds of the gluteus maximus muscle. The gluteus maximus muscle is split at its junction of the middle and upper thirds because this region is an interface of blood supply, i.e., the upper third of the gluteus maximus is supplied by the superior gluteus artery, and the lower 2/3 receives blood from the inferior gluteal artery. When the gluteus maximus muscle is cut too medially, the inferior gluteus artery and nerve may be damaged. Therefore, the splitting range of the gluteus maximus muscle should end at the proximal vessel/nerve pedicles of the incision. In some cases, the gluteus maximus muscle can be loosened at the ending point of the femur to achieve greater exposure. However, special attention should still be paid to avoid injuring the first perforating branch of the deep femoral artery.

- The sciatic nerve is identified and protected. The sciatic nerve travels on the surface of the quadratus femoris and proximally passes through the infrapiriform foramen. Acetabular fractures rarely involve the quadratus femoris, which can serve as a reference point for identifying the sciatic nerve. The sciatic nerve can be exposed on the surface of the quadratus femoris by removing the connective tissue on the surface of the quadratus femoris. After determining the anatomical position of the sciatic nerve, it is then dissociated toward the proximal end up to the greater sciatic notch.
- The piriformis muscle and its adjacent superior and inferior gemellus and obturator internus are distinguished, separated, and labeled, and they are cut off at the site 1.5 cm from the ending point of the femur and turned laterally. Importantly, incision of the lateral rotator group should be not too close to the femur to avoid damaging the ascending branch of the medial circumflex femoral artery, which passes through this area and is a vital blood-supplying vessel to the femoral head.
- The lateral rotator group is pulled to the lateral side. Two blunt retractor hooks are inserted into the greater sciatic foramen and the smaller sciatic foramen, allowing exposure of the entire posterior column, a direct view of the posterior wall of the acetabulum, and simultaneous protection of the sciatic nerve. Attention should be paid to avoid damaging the superior gluteal neurovascular bundle.
- Dissection posteromedially along the greater sciatic notch is continually performed until a finger can be placed into the pelvic cavity to palpate the fractures of the quadrilateral plate and anterior column. If necessary, the sacrospinous ligament can be loosened to expand the surgical exposure. If exposure of the inferoposterior part of the acetabulum is required, the quadratus femoris can be severed at the beginning of the ischial tuberosity rather than at the femoral ending point where the media circumflex femoral artery is positioned adjacent to the quadratus femoris, minimizing the risk of accidental blood vessel injury.

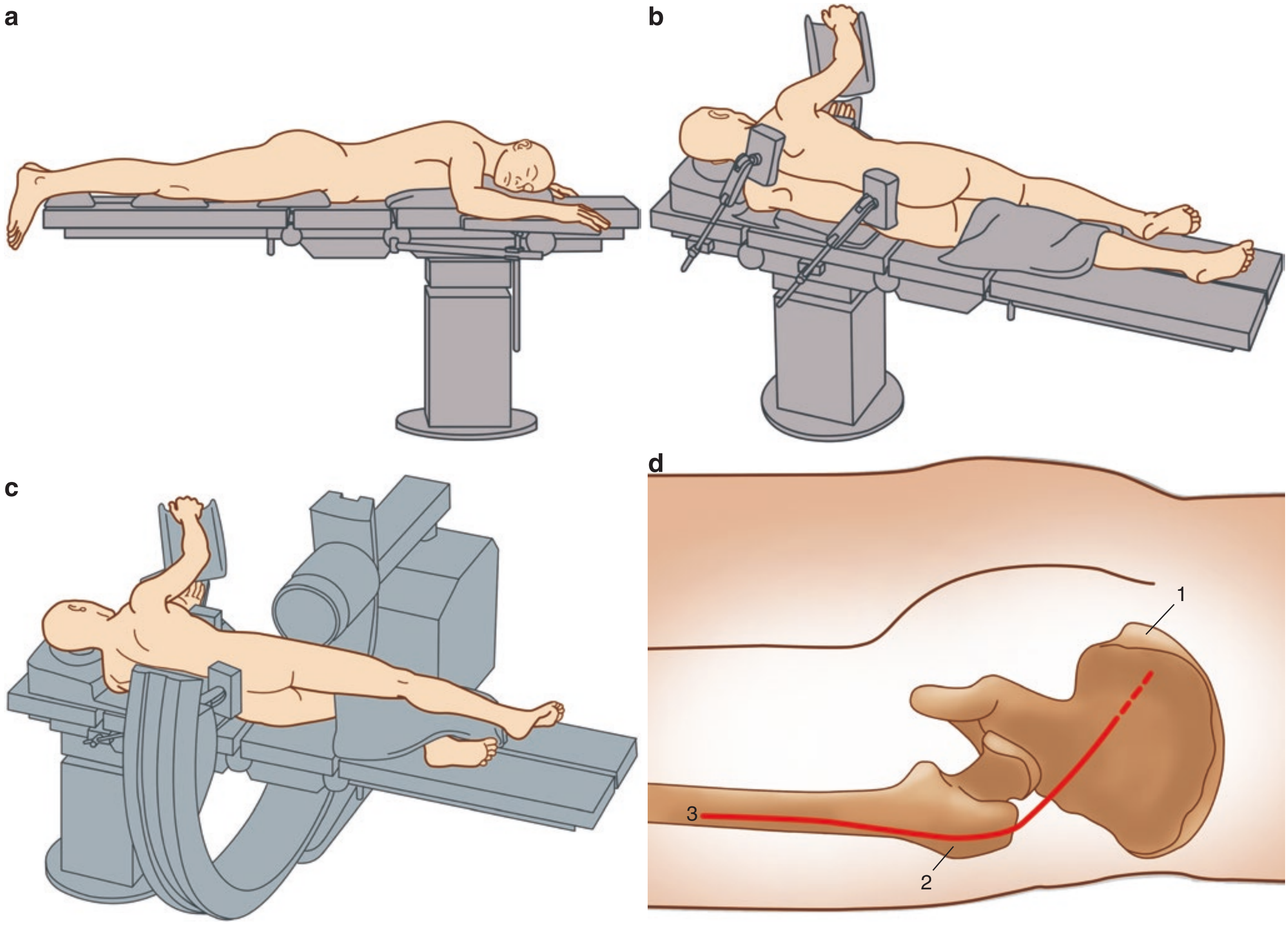


Fig. 4.16 (**a**) The patient lies prone on the radiolucent operating table. (**b, c**) The patient can also lie in the lateral decubitus position on the radiolucent operating table. Intraoperative C-arm fluoroscopy can be used to obtain an AP view of the acetabulum, oblique view of the ilium, and oblique view of the obturator. (**d**) The surgical incision is centered over the apex of the greater trochanter. It extends proximally to the distal end of the posterior superior iliac spine for 5 cm and distally along the femoral shaft, ending at the site 8 cm below the greater trochanter

- During the surgical exposure process, the hip joint capsule should be preserved optimally if possible, and damage to the blood supply of the femoral head should be minimized. The joint capsule attached to the bone fragment should be protected because it is the source of blood supply to the bone fragment.

Incision closure and reconstruction:

- The tendons of the piriformis muscle and obturator internus are re-fixed to the ending point on the femur. If the ending point of the gluteus maximus muscle has been loosened, it must be re-fixed. After the drainage tube is replaced under the lateral rotator muscles, the iliotibial tract is carefully sutured, and the incision is closed.

4.2.3.5 Combined Anterior and Posterior Approaches

- Indications: Transverse acetabular fractures, T-shaped acetabular fractures, and double-column acetabular fractures.
- Surgical exposure range: The posterior approach can reveal the entire posterior column and posterior wall of the acetabulum; the anterior approach can expose the entire anterior column, sacroiliac joint, and pubic symphysis.
- The patient lies laterally on the unaffected side or in the free position (the so-called “floating position”), which facilitates forward and backward tilting of the pelvis during surgery to facilitate exposure.
- The anterior and posterior surgery areas are simultaneously disinfected. After placing the sterile surgical drape,

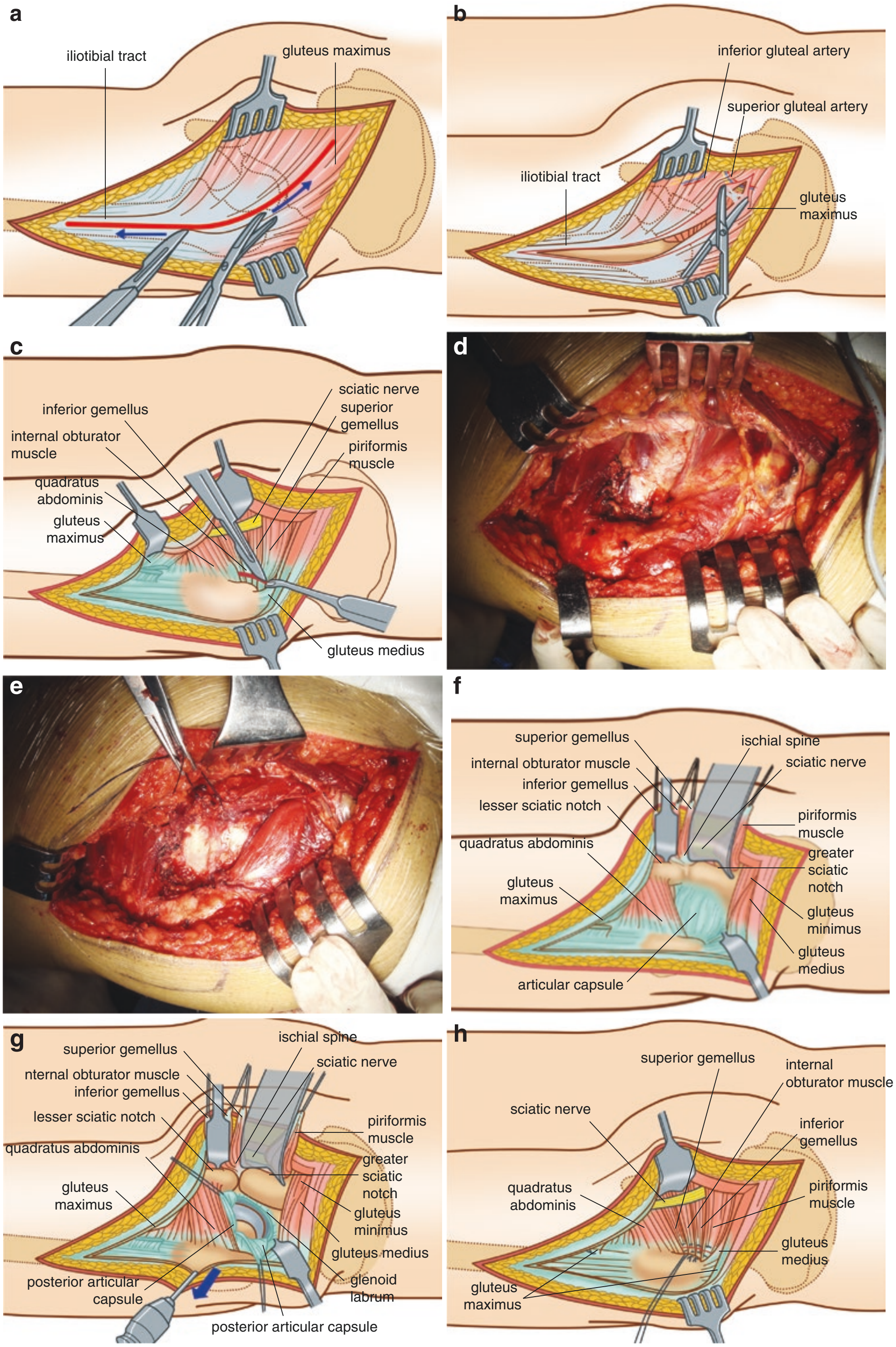


Fig. 4.17 (**a**) The skin and subcutaneous are sharply incised. The gluteus maximus muscle fibers are bluntly separated at the junction between the middle and upper thirds of the gluteus maximus muscle, and the iliotibial tract is separated downward. (**b**) Along the gluteus maximus muscle fibers, the gluteus maximus muscle is separated from the greater trochanter of the femur to its proximal end until the first transverse nerve/vascular bundle. (**c**) The piriformis muscle and its adjacent superior and inferior gemellus and obturator internus are separated, severed at the site 1.5 cm from their ending point on the femur, and then turned laterally. If necessary, the gluteus maximus can be isolated at its ending point on the femur. (**d, e**) A photo obtained during surgery showing that the labeled lateral rotator group is severed and pulled to the lateral side. (**f**) Two blunt retractor hooks are inserted into the greater sciatic foramen and the smaller sciatic foramen, allowing exposure of the entire posterior column, a direct view of the posterior wall of the acetabulum, and simultaneous protection of the sciatic nerve. (**g**) If joint exposure is required, a T-shaped capsulotomy can be performed with a cut made from the site 0.5 cm lateral to the edge of the joint to avoid damaging the glenoid labrum. (**h**) Incision closure: Attention should be paid to repairing the incised ending point of the lateral rotator muscles and gluteal muscle

the patient can freely change between the supine position and prone position. Attention must be paid to sterile operations when changing position.

- Advantages: It can provide adequate surgical exposure, enabling good-quality reduction even for complex fractures.
- Disadvantages: One incision alone does not permit a complete view of the fracture. The combined anterior and posterior approaches result in extensive surgical trauma, massive bleeding, and an increased risk of infection.
- Surgical procedures: The Stoppa approach or ilioinguinal incision is used on the anterior side, and the Kocher-Langenbeck approach is used on the posterior side. The two approaches are used in combination.
- The combined anterior and posterior approaches are not a simple superposition of the anterior and posterior approaches. The location of the first incision is the most critical. The general principle of the combined anterior and posterior approaches is that the first incision is generated on the side of the fracture with a large displacement and severe comminution, considering that the fracture can be reduced and fixed through the first incision alone while the second incision serves as an observation window or an auxiliary reduction incision.

Extended Iliofemoral Approach (Judet et al. 1964).

- Indications:
  - High-level transverse acetabular fracture involving the acetabular dome;
  - T-shaped acetabular fractures involving the acetabular dome;
  - Transverse acetabular fractures of the posterior half of the anterior column; and.
  - Double-column acetabular fracture accompanied by a posterior wall acetabular fracture, a fracture of the acetabular dome, or a fracture line extending to the sacroiliac joint.
- Surgical exposure: The lateral surface of the entire ilium, posterior column and posterior wall, and hip joint can be exposed directly. After further stripping, the iliopsoas and abdominal muscles are pulled medially to reveal the medial side of the ilium (Fig. 4.18).
  - Advantages: A wide surgical exposure range; almost an entire half of the pelvis is exposed.
  - Disadvantages and risks: Obstruction by the iliopsoas muscles and iliopectineal fascia makes it difficult to expose the lower part of the anterior column. Moreover, the medial blood vessels and nerves are vulnerable to damage. Severe surgical damage often causes ischemic necrosis of the hip musculocutaneous flap.
  - Surgical procedures.

    Body position and preoperative preparation:
    - Anesthesia: The patient undergoes general anesthesia.
    - Body position: The patient lies laterally on the unaffected side on a radiolucent operating table, with a soft cushion placed underneath the body.
    - The entire lower abdomen, pelvis, and affected lower extremity are disinfected, followed by surgical draping.

    Surgical incision according to the body surface projection: The surgical incision originates from the posterior superior iliac spine, rounds the iliac crest to the anterior superior iliac spine, and then extends downward in the direction of the lateral edge of the patella.

    Surgical approach (Fig. 4.19):
    - The skin, subcutaneous tissue, and periosteum are incised along the iliac crest. The gluteus muscle is stripped off from the iliac crest, while

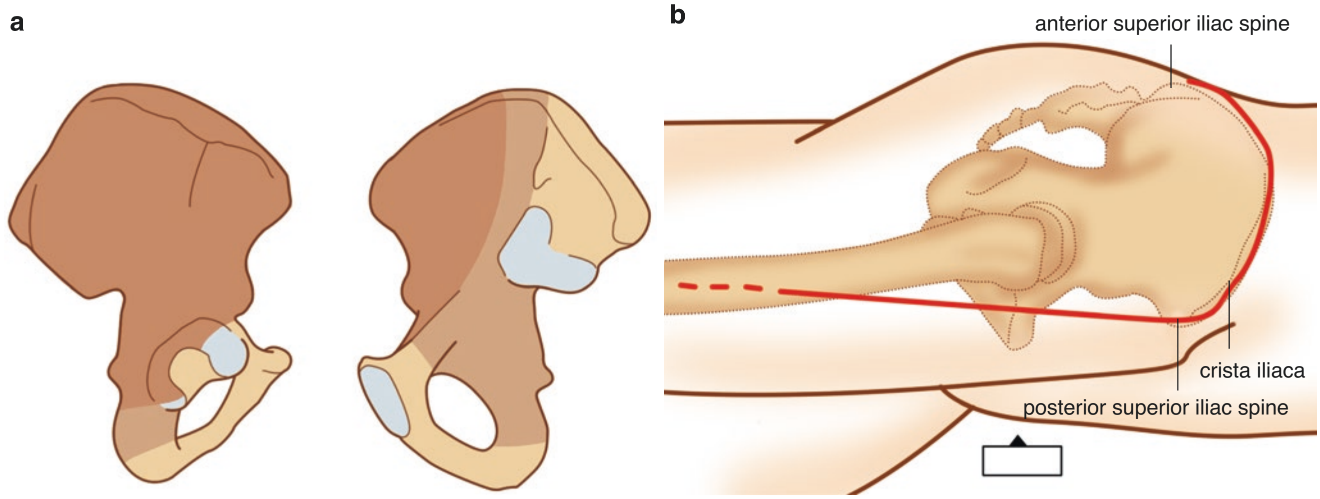


Fig. 4.18 (**a**) Exposure range of the extended iliofemoral approach: The area in dark red denotes the exposure range under direct vision, and the area in pink denotes the palpable area. (**b**) The surgical incision starts from the posterior superior iliac spine, travels around the iliac spine to the anterior superior iliac spine, and then extends downward in the direction of the lateral edge of the patella

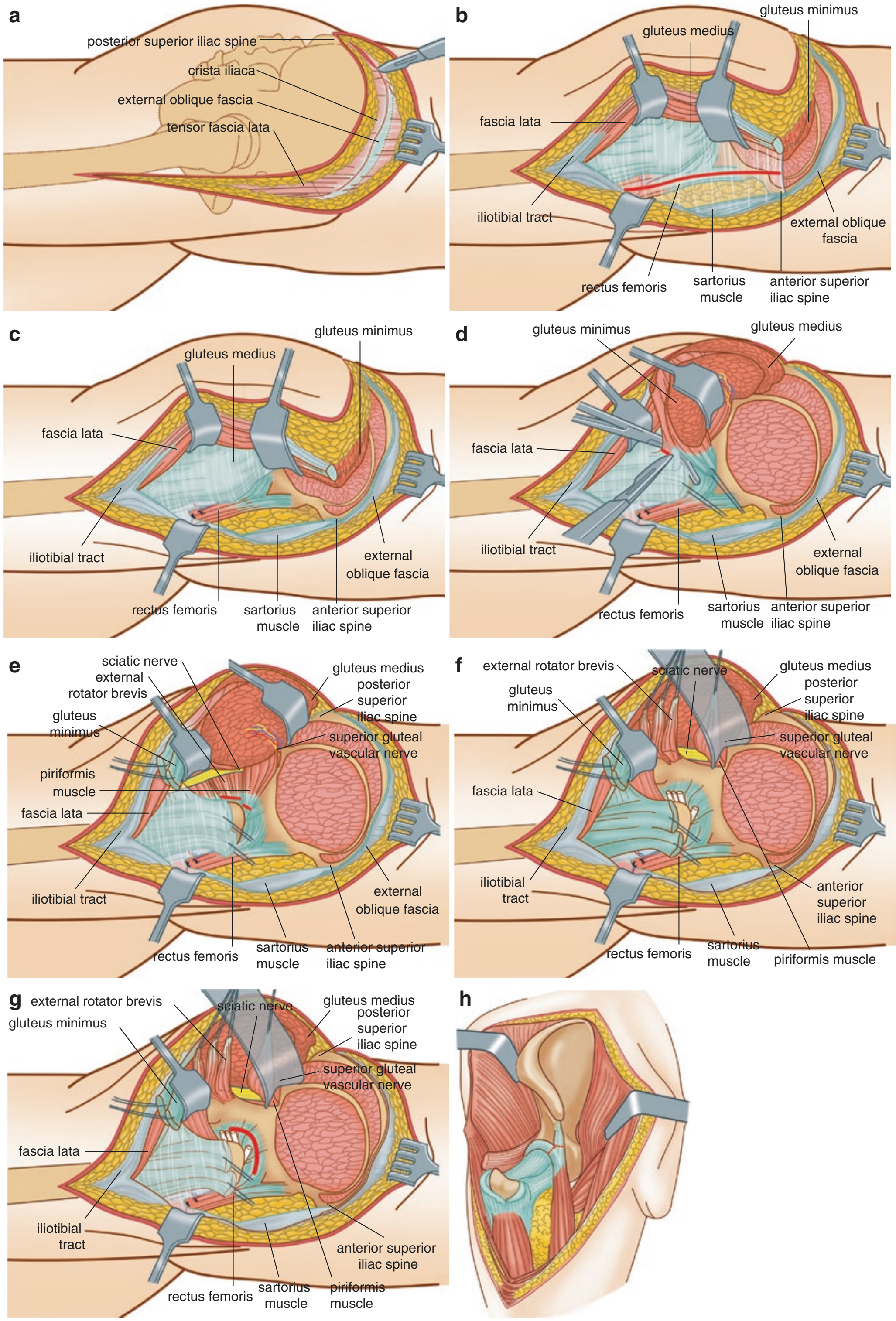


Fig. 4.19 (**a**) The skin, subcutaneous tissue, and periosteum are incised along the iliac spine. The gluteus muscle is stripped off from the iliac crest while the attachment of the abdominal muscles to the iliac crest is retained. (**b**) An incision is created between the sartorius muscle and the tensor fascia lata, and then the tensor fascia lata attachment point on the anterior superior iliac spine is stripped subperiosteally to pull the muscle posteriorly. (**c**) At the distal end of the incision, after the fascia between the tensor fascia lata and the sartorius muscle is cut, and the anterior branch of the anterior femoral circumflex blood vessel is ligated and the straight and folded head of the rectus femoris are exposed. (**d**) The attachment point of the gluteus minimus muscle is loosened at the site approximately 0.5 cm from the greater trochanter. After the gluteus minimus muscle is pulled aside, the ending point of the gluteus medius muscle is transversely cut off while preserving 0.5 cm of the tendon. (**e, f**) The lateral rotator group is exposed by pulling out the gluteus medius and minimus muscles and cutting off at the site approximately 1 cm medial to the ending point on the greater trochanter of the femur. (**g**) The joint capsule is cut open arcuately at the distal end of the glenoid labrum of the joint. (**h**) The iliac fossa is exposed by subperiosteally dissecting the attached point of the abdominal muscles medial to the iliac fossa

the attachment of the abdominal muscles to the iliac crest is preserved.

- The incision is generated between the sartorius muscle and the tensor fascia lata, and the tensor fascia latae attachment point on the anterior superior iliac spine is stripped subperiosteally to pull the muscle posteriorly.
- Exposure of the iliac ala: The gluteal muscle attached laterally to the iliac ala is dissected subperiosteally from anterior to posterior and from proximal to distal up to the posterior superior iliac spine posteriorly and the greater sciatic notch distally. During this step, attention should be paid to the superior gluteal vessels and nerves exiting from the greater sciatic notch.
- At the distal end of the incision, after the fascia between the tensor fascia lata and the sartorius muscle is cut, the anterior branch of the anterior femoral circumflex blood vessel is ligated and the straight head and the folded head of the rectus femoris is exposed.
- Release of the gluteus medius and gluteus minimus muscle attachment to the greater trochanter: The attachment point of the gluteus minimus muscle is released at the site approximately 0.5 cm from the greater trochanter and marked with bold lines to facilitate repair after the operation. After the gluteus minimus muscle is pulled aside, the attachment of the gluteus medius muscle to the greater trochanter can be exposed. With the tendon of 0.5 cm preserved for later repair, the ending point of the gluteus medius muscle is transversely cut off.
- Exposure and disconnection of the lateral rotator group: The lateral rotator group is exposed by pulling out the gluteus medius and minimus muscles and then severed at the site approximately 1 cm from the medial part of the greater trochanter of the femur, followed by marking with a bold line to facilitate later repair. During the operation, attention should be paid to protecting the superior gluteal vessel/nerve bundle.
- If joint exposure is required, the joint capsule can be cut open at the distal end of the glenoid labrum of the joint.
- Exposure of the iliac fossa: Following the same method used for the ilioinguinal approach, subperiosteal dissection can be performed along the iliac crest, and the abdominal muscles are separated from the attachment of the iliac fossa to expose the entire iliac fossa.

4.2.4 Reduction and Fixation of Acetabular Fractures

4.2.4.1 Acetabulum Wall Fracture

- Acetabulum wall fractures are simple anterior and posterior wall fractures of the acetabulum that share similar reduction and fixation techniques, as discussed in the following section.
- Femoral traction: The assistant can either tract the femur by hand or pull the femur laterally and distally to expose the hip joint through a T-shaped handle that is installed on a Schanz screw placed into the greater trochanter of the femur.
- Clean up the loose bodies in the acetabulum:
  - The articular capsule and soft tissue attached to the bone fragment are used as the hinge to open the fracture piece to explore and clean the hip joint.
  - Residual large bone fragments in the acetabulum will lead to difficult reduction of the femoral head, as well as post-operative traumatic arthritis, which necessitates fracture reduction.
  - However, small-piece avulsion fractures at the attachment point of the round ligament of the femur can be left untreated (Fig. 4.20).
- Assessment and reduction of wall fractures of the acetabulum (Fig. 4.21):
  - Injury of the anterior and posterior wall of the acetabulum can be classified as either a simple fracture or a compression fracture. Compression fracture results in an incomplete joint surface, causing a poor prognosis.
  - For comminuted or compressed anterior and posterior wall fractures of the acetabulum, the femoral head can be used as a template to pry and reduce the articular surface fragments.
  - The reduction is maintained with Kirschner wires, and bone grafting is performed in the compression area, followed by reduction of the bone fragments in the outer layer.
  - Maintenance of the reduction: After reduction of the fracture fragments with a pusher, reduction of the fracture is maintained with the reduction clamp, and re-displacement of the intra-articular bone fragments should be avoided.

    For posterior wall acetabular fracture, one tip of the reduction clamp is placed on the greater sciatic notch.

    For anterior wall fracture of the acetabulum, one tip of the reduction clamp is placed on the quadrilateral surface and the other on the lateral side of the anterior inferior iliac spine. Attention should be paid to the strength of the clamping force to ensure the quadrilateral plate is not pierced.

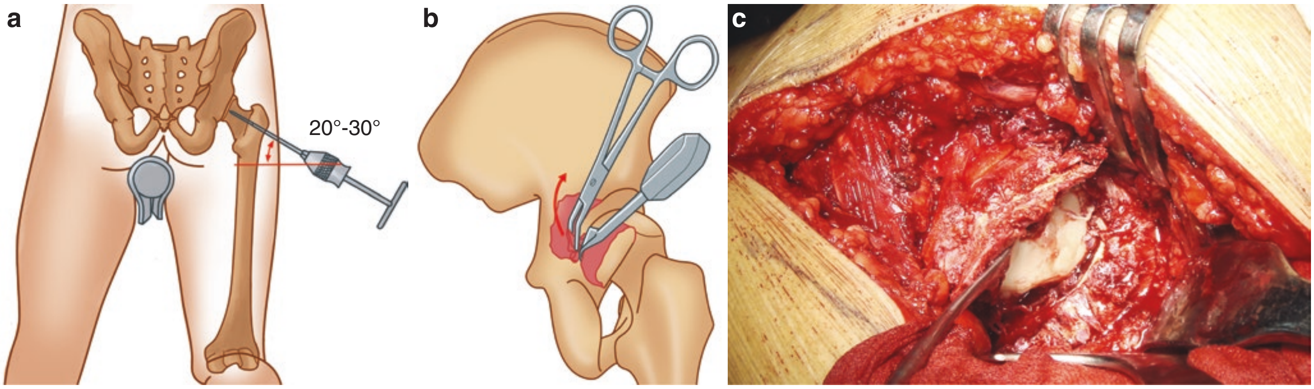


Fig. 4.20 (**a**) A Schanz screw is placed in the greater trochanter, and the assistant then uses a T-shaped handle to pull the femur laterally and distally. (**b**) With the soft tissue connecting the acetabular fragment and the joint capsule as a hinge, the bone fragments of the acetabular wall are turned open, and the free fragments are explored and removed. (**c**) A photo obtained during the operation: The acetabular fragments were turned open while the connection between the joint capsule and bone fragment was retained to allow blood supply to the bone fragment

- Fixation of wall fractures of the acetabulum (Fig. 4.22):
  - Fixation of large bone fragment(s) from posterior wall acetabular fracture:

    It can be fixed with lag screws and 3.5-mm or 4.5-mm reconstruction plates.

    Dangerous zone for fixation of posterior wall acetabular fractures: When the fracture is fixed with a reconstruction plate, special attention should be paid to the dangerous zone of the posterior wall of the acetabulum (the red area in Fig. 4.22), where screw placement should be avoided if possible. If the screw must be placed in this area, the screwing direction should be reversed to point towards the acetabulum.

    Two to three screws are usually placed at each end of the reconstruction plate on the ischium and ilium.
  - Fixation of the small bone fragment(s) in the posterior wall acetabular fracture:

    Small bone fragments, which are not suitable for lag screw fixation, can be fixed with an elastic hook-like plate. After one hole is cut off, the 1/3 annular plate is bent into a hook-like shape and slightly excessively pre-bent to achieve a compressive effect for fixing the acetabular fractures.

    Subsequently, the reconstruction plate can be superimposed on the elastic hook plate.
  - Fixation of anterior wall acetabular fracture:

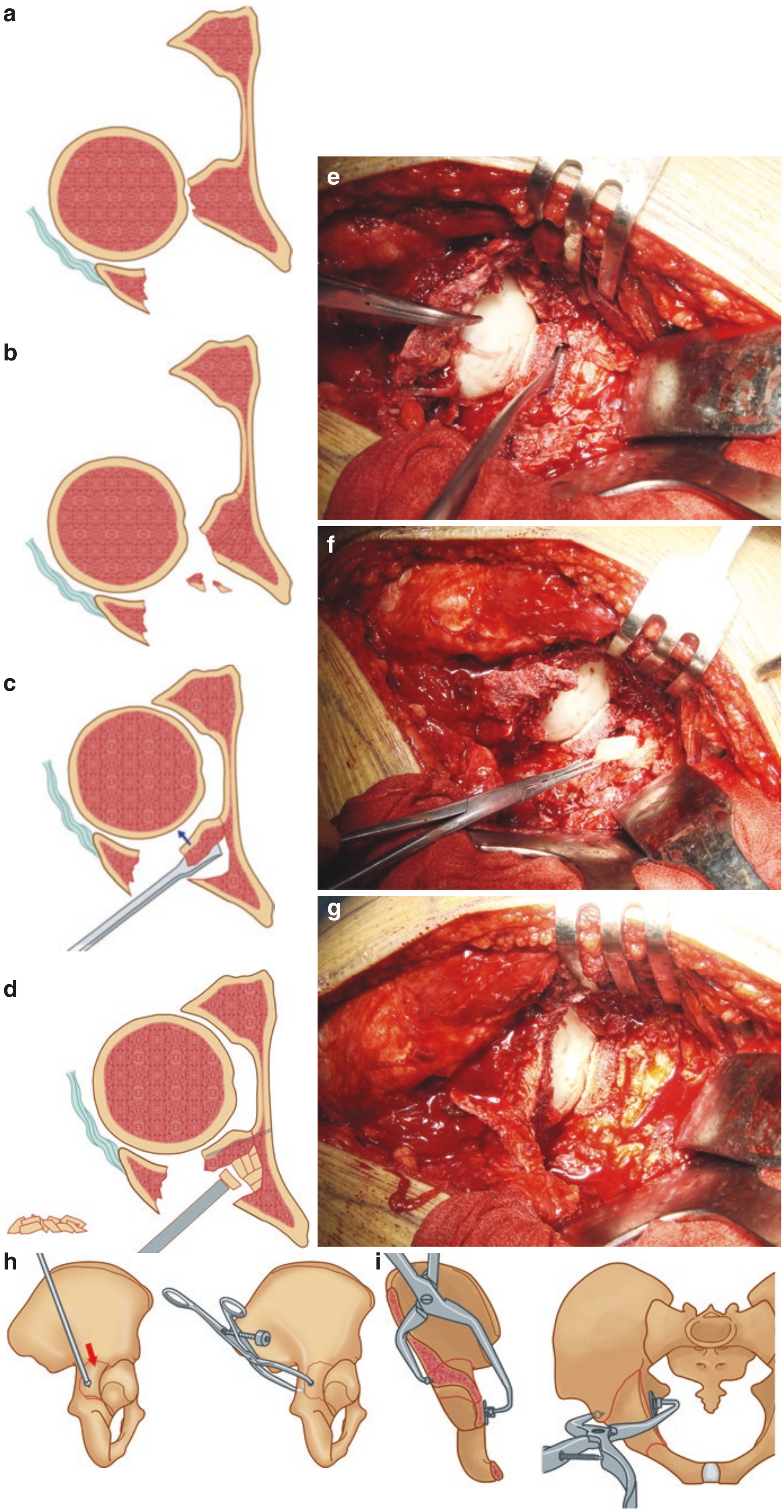
    After reduction, the lag screws are placed for preliminary fixation first, with sufficient space left for plate screw placement.

    The reconstruction plate is used to fix the anterior wall acetabular fracture. First, the reconstruction plate is pre-bent. Its proximal end is positioned in front of the sacroiliac joint, and its distal end reaches the superior pubic ramus and the pubis. At least two screws should be placed at both ends of the fracture. Lag screws can be inserted through the plate, and it is critical that no screw enters the joint.

4.2.4.2 Posterior Column Acetabular Fracture

- Like a posterior wall acetabular fracture, a posterior column acetabular fracture first requires cleanup of the fractured ends, especially for the old fracture. The removal of granulation tissue embedded in the broken ends is crucial for the reduction and fixation success.
- The intra-articular loose bodies are cleaned under direct observation of the articular surface through the fractured posterior column.
- Reduction method for posterior column acetabular fracture:
  - For posterior column acetabular fractures, the distal end of the fracture is often medially rotationally displaced along with the ischial tuberosity, which can be corrected using a Schanz screw inserted into the ischial tuberosity.
  - Reduction with a pelvic reduction clamp: A large pointed reduction clamp or square-headed reduction clamp can be applied by placing one tip on the quadrilateral plate through the greater sciatic notch and the other tip on the ilium above the acetabulum to facilitate the reduction. Importantly, the placement of the reduction clamp through the greater sciatic notch should not be too long or too deep; otherwise, it may damage the sciatic nerve.
  - In the safe area of the acetabulum, a 4.5 mm cortical screw is placed on both sides of the fracture line to allow nail cap protrusion from the cortical bone. The screw cap is clamped with a pair of special clamping forceps to complete the reduction operation, including lifting, rotating, and compression of fracture end. The screws should be placed in a safe place. The clamping forceps not only effectively correct the rotational dis-

Fig. 4.21 Reduction and temporary fixation of acetabular wall fractures. (**a**) Simple fracture of the posterior wall of the acetabulum associated with a hip dislocation and without joint surface compression fracture. (**b**) Complex acetabular wall fracture associated with joint surface compression and accompanied by a hip dislocation and compression collapse of the acetabular fragment. (**c**) The femoral head is used as a template to pry and reduce the articular surface fragments. (**d**) The bone fragments in the outer layer begin to be reduced after the reduction is maintained with a Kirschner wire, and bone grafting is performed in the compression area. (**e-g**) Intraoperative photos: The compressed joint surface of the acetabulum is reduced by prying, and bone grafting is performed. (**h**) The fracture fragments are reduced with a pusher and maintained with a reduction clamp. (**i**) Anterior wall fracture of the acetabulum: One tip of the reduction clamp is placed on the quadrilateral surface, and the other end is placed on the lateral side of the anterior inferior iliac spine. Attention should be paid to the strength of the clamping force to avoid piercing quadrilateral plate



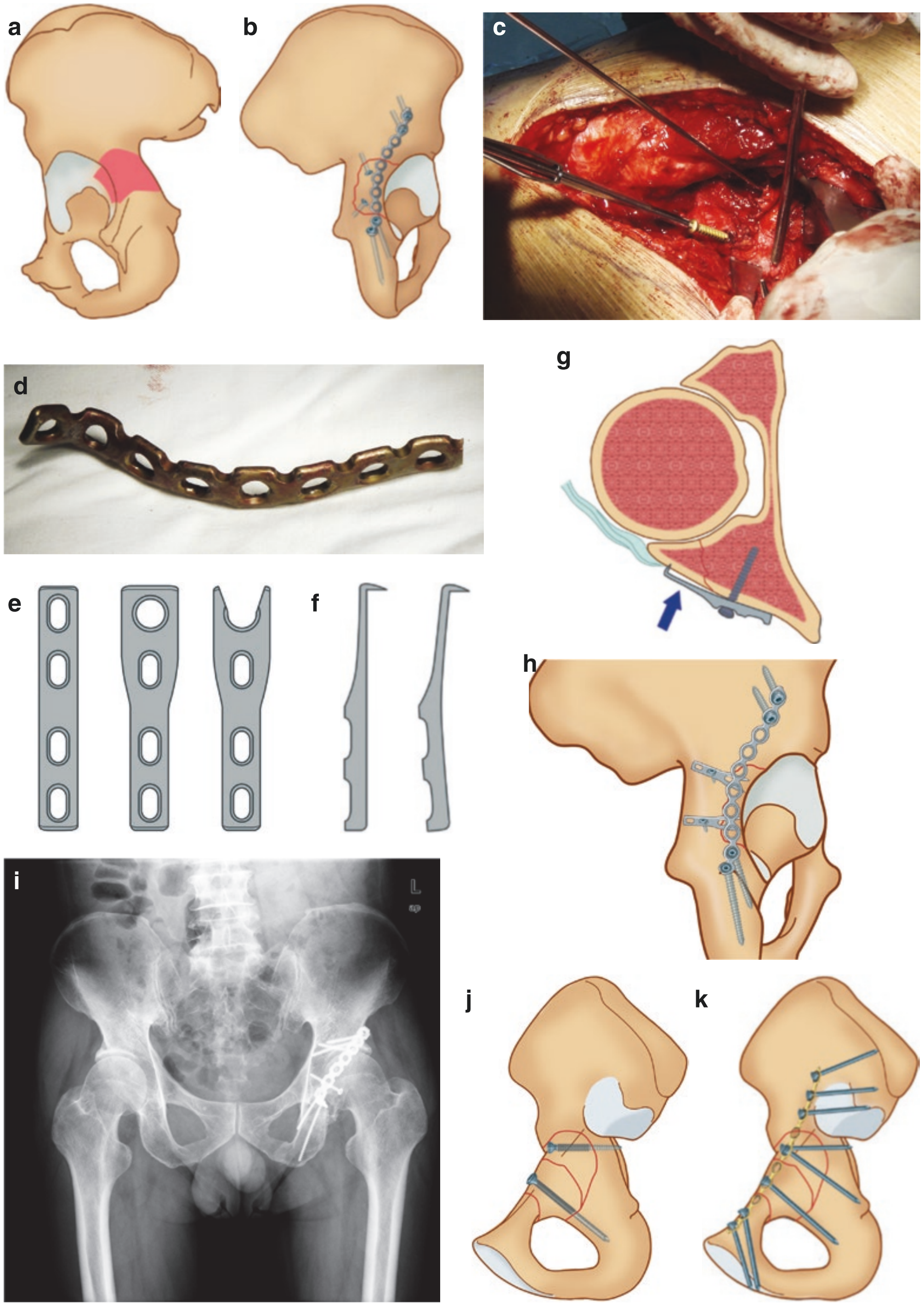


Fig. 4.22 (**a**) During fixation of a posterior wall acetabular fracture with a reconstruction plate, special attention should be paid to the dangerous zone (red area) on the posterior wall of the acetabulum where screw placement should be avoided if possible. (**b**) Fixation of the posterior wall acetabular fracture with lag screws and a reconstruction plate: The screws used to fix the reconstruction plate should be placed in the ischium and ilium. If the screws must be placed in the dangerous area, the screwing direction should be reversed to point towards the acetabulum. (**c**) For a posterior wall acetabular fracture with a large fracture fragment, the reduced fragment can be temporarily maintained with a Kirschner wire, and then a lag screw can be placed for compression and preliminary fixation. (**d**) A 3.5 mm reconstruction plate is pre-bent according to the shape of the acetabulum. (**e, f**) A 1/3 annular plate is trimmed and bent into an elastic hook-like plate. (**g**) The hook- like plate should be slightly pre-bent to achieve a compressive effect on the bone fragments during fixation. (**h**) The reconstruction plate can be superimposed on the elastic hook-like plate. (**i**) Postoperative AP radiograph: The posterior wall acetabular fracture has been anatomically reduced and fixed with lag screws and plates. (**j**) For an anterior wall acetabular fracture, the lag screws are first used for preliminary fixation after reduction, with sufficient space left for plate screw placement. (**k**) A drawing of the reconstruction plate fixation of an anterior wall acetabular fracture: The proximal end of the pre-bent reconstruction plate is positioned in front of the sacroiliac joint, and its distal end reaches the superior pubic ramus and pubis. At least two screws should be placed at both ends of the fracture. Lag screws can be inserted through the plate, and it is critical that no screw enters the joint

placement of the posterior column, but they also complete the compression of fracture end.

- Assessment of the reduction of the posterior column acetabular fracture: The reduction of quadrilateral plate fractures is examined by forward palpation through the greater sciatic notch. Effective reduction of the quadrilateral plate indicates successful reduction of the articular surface.
- Fixation of the posterior column acetabular fracture:
  - Temporary fixation is performed using Kirschner wires after satisfactory reduction.
  - It is preliminarily fixed with lag screws or with a short steel plate at the medial edge of the posterior column, and steel plate fixation can reduce the fracture.
  - Finally, a 3.5 mm reconstruction plate is placed for fixation. The plate is carefully shaped according to the surface morphology and placed on the outer edge of the posterior column of the acetabulum. Insufficient pre-shaping may cause iatrogenic displacement when tightening the screws; therefore, a slightly excessively pre-bent plate is used for compressive fixation of the fracture.
  - For the final fixation, with reference to the preceding description of the posterior wall dangerous zone in the acetabulum, the reconstruction plate across the fracture line is fixed in the ilium and the ischium away from the hip joint to avoid entry of the screws into the acetabulum (Fig. 4.23).

4.2.4.3 Anterior Column Acetabular Fracture

- Reduction of the anterior column acetabular fracture (Fig. 4.24):
  - Keeping the hip in the flexion position during surgery contributes to relaxation of the anterior structure of the hip and eases the observation of the fracture and reduction status.
  - The reduction sequence of the anterior column acetabular fracture occurs from peripheral to central, starting from the iliac ala and, finally, reduction of the acetabulum. It is crucial that the small fragments stuck between the fracture ends be removed before reduction, and anatomical reduction of each fragment is required to obtain anatomical reduction of the acetabulum.
  - Starting from iliac ala, anatomical reduction of the iliac ala is completed first using bone holding forceps or a pointed reduction clamp, and then each bone fragment is anatomically reduced in a sequential manner.
  - One tip of the pelvic reduction clamp is placed in the quadrilateral and another tip is placed on the lateral side of the anterior inferior iliac spine.
- Fixation of anterior column acetabular fracture:
  - The iliac ala fracture at the proximal end of the anterior column can be fixed using lag screws or by placing a reconstruction plate at the edge of the ilium.
  - The fracture is fixed with the pre-shaped reconstructed plate along the small pelvic ring, and the plate should not cross the pubic symphysis unless the fracture involves the pubic symphysis. The anterior inferior iliac spine is the basic anatomical landmark of the acetabular dome and can be used as a reference for screw fixation to avoid protrusion of the screw in the hip joint.

4.2.4.4 Transverse Acetabular Fracture

- Reduction of the acetabulum transverse acetabular fracture:
  - Transverse acetabular fractures are often accompanied by lateral and rotational displacement.
  - Simultaneous reduction of the anterior and posterior columns is crucial. Successful reduction of one column does not necessarily indicate a reliable reduction of the fracture because satisfactory reduction of the posterior column is very common while the anterior structure has residual rotational displacement.
  - A Schanz screw can be placed into the sciatic tuberosity and assembled with a T-shaped handle for fracture reduction.
  - Two pairs of reduction clamps can be used to simultaneously control the posterior column and anterior column to assist in reduction of the fracture:

    The tips of a pair of reduction clamp are placed on the distal segment (the ischium) and proximal segment (the ilium) through two screws to correct the fracture displacement of the posterior column.

    Another reduction clamp is placed through the greater sciatic notch, with one tip on the surface of the quadrilateral and the other tip at the front of the proximal fractured end, to correct the anterior displacement of the transverse fracture.
  - The reduction can be evaluated by palpating the smoothness of the quadrilateral surface with a finger through the greater sciatic notch.
- Fixation of the transverse acetabular fracture:
  - For anterior and posterior column acetabular fractures that can be anatomically reduced through the posterior approach, 3.5 mm or 4.5 mm anterior column lag screws can be used for minimally invasive fixation (Fig. 4.25):

    Screw entry point: Posterior to the gluteal tuberosity of the lateral ilium and 2–4 cm above the acetabulum.

    Direction of screw entry: The direction of the screw can be determined by palpating the pubic tubercle.

    Screwing technique: Under fluoroscopic monitoring, the sliding hole is first drilled with a 3.5 cm or 4.5 cm drill bit, and then a 2.5 cm or 3.2 cm drill bit is used to drill into the pubic bone through the hole. During drilling, the “door-knocking” tech-

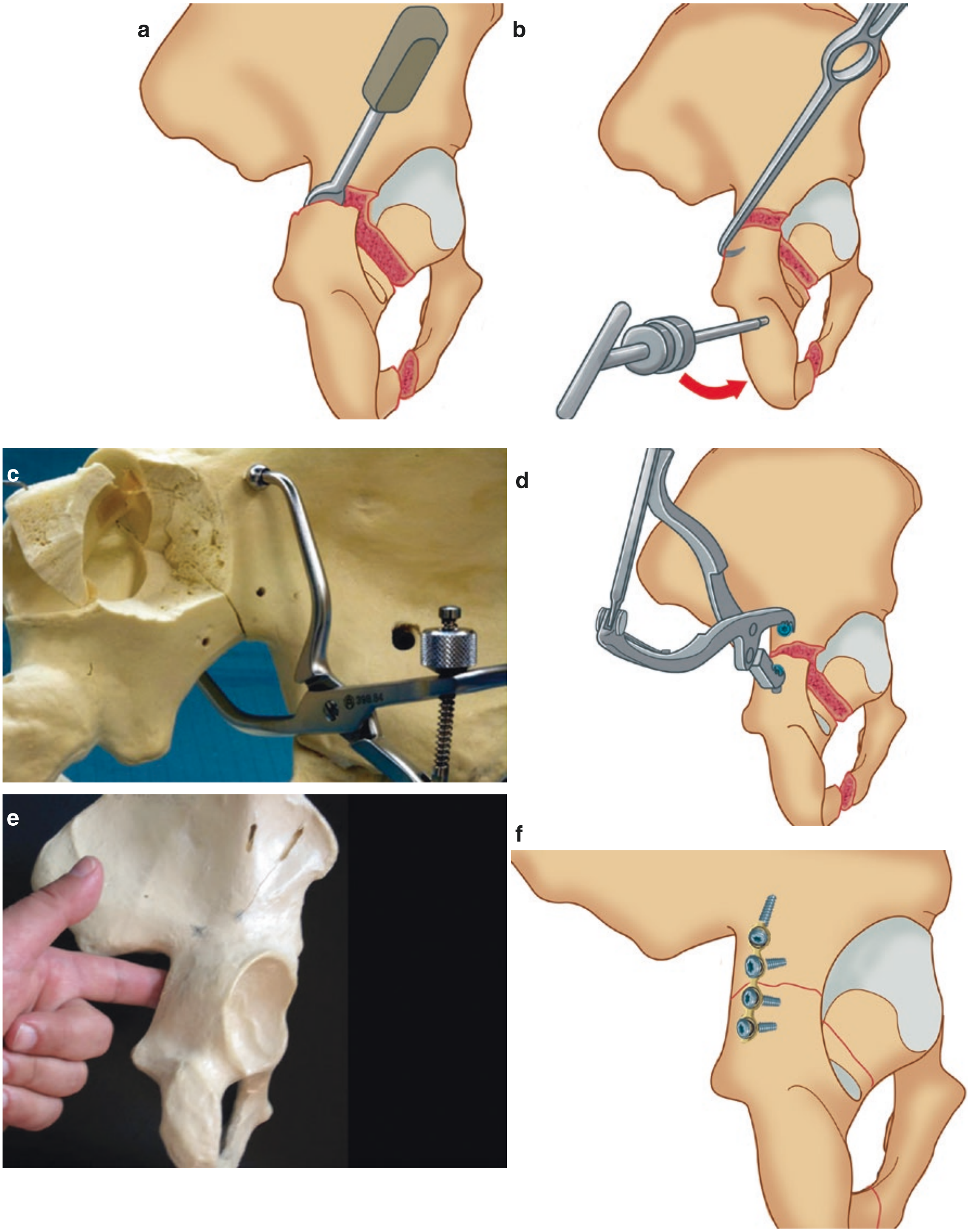
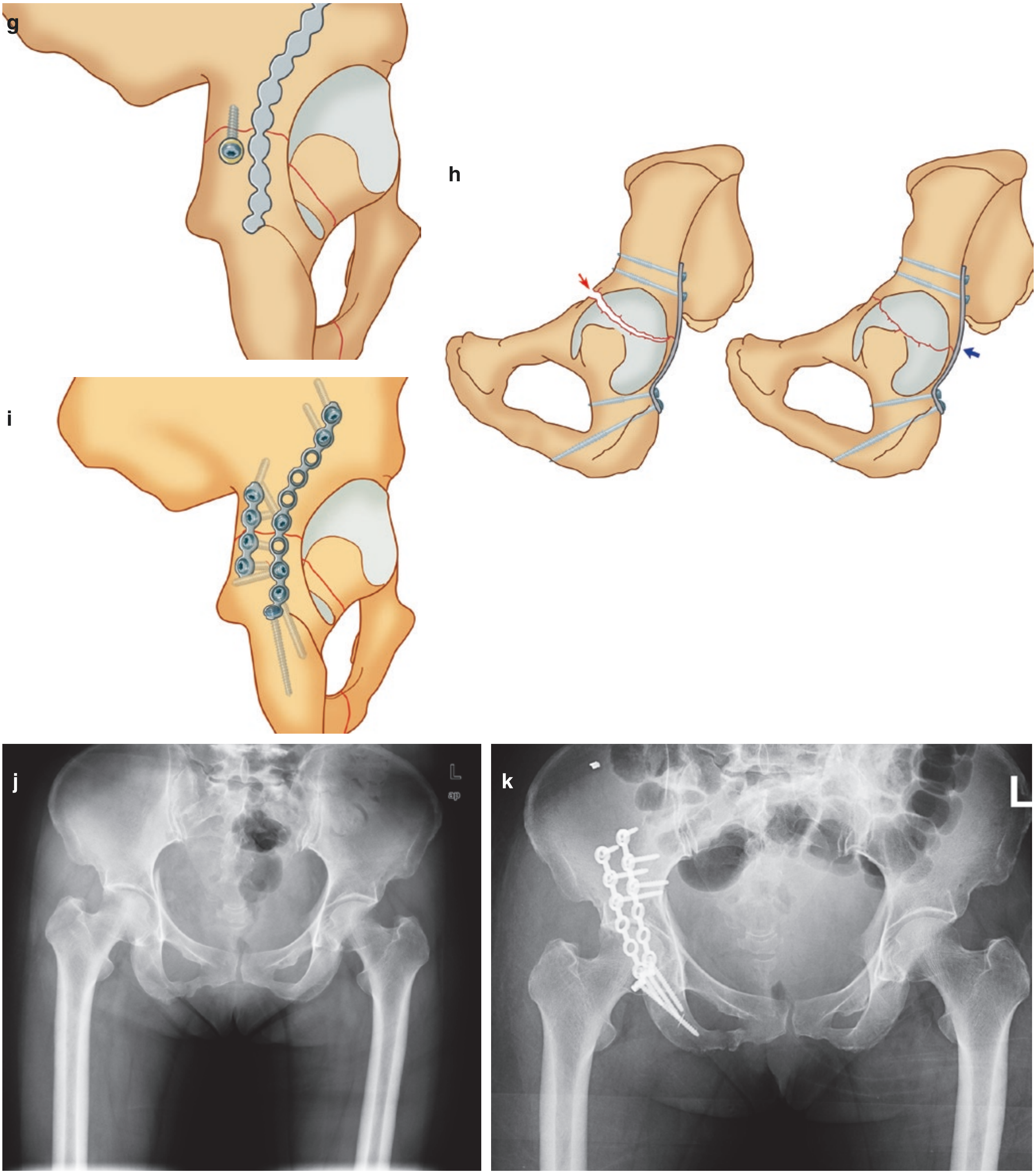


Fig. 4.23 (**a**) The fractured ends, soft tissue, and loose bodies in the acetabulum are cleared under direct vision through the posterior column fracture. (**b**) Medial rotational displacement of the distal end fracture is corrected using a bone hook and Schanz screw inserted into the ischial tuberosity. (**c**) A large-sized point reduction clamp or square reduction clamp can be applied to assist the reduction by placing one tip on the quadrilateral surface through the greater sciatic notch and the other tip on the ilium above the acetabulum. (**d**) A 4.5 mm cortical screw is placed on each side of the fracture line, and the tail cap of the screw is clamped with a pair of special clamping forceps to complete the reduction actions, such as lifting, rotating and compression of the fracture end. (**e**) Reduction of the quadrilateral plate fracture is examined by palpation through the greater sciatic notch. Successful reduction of the quadrilateral plate indicates satisfactory reduction of the articular facet. (**f**) The fracture is preliminarily fixed using lag screws or with a short steel plate at the medial edge of the posterior column. (**g**) Finally, a 3.5 mm reconstruction plate is placed for fixation. The plate should be precisely shaped according to the surface morphology and placed on the lateral edge of the posterior column of the acetabulum. (**h**) Insufficient pre-shaping may cause iatrogenic displacement when tightening the screws; therefore, a slightly excessively pre-bent plate is used for compressive fixation of the fracture. (**i**) The reconstruction plate across the fracture line is fixed in the ilium and the ischium away from the hip joint to avoid entry of the screws into the acetabulum. (**j, k**) Posterior column acetabular fracture. The interrupted iliac line can be observed on an AP radiograph, and the fracture is fixed with a 3.5 mm reconstruction plate via the Kocher-Langenbeck approach



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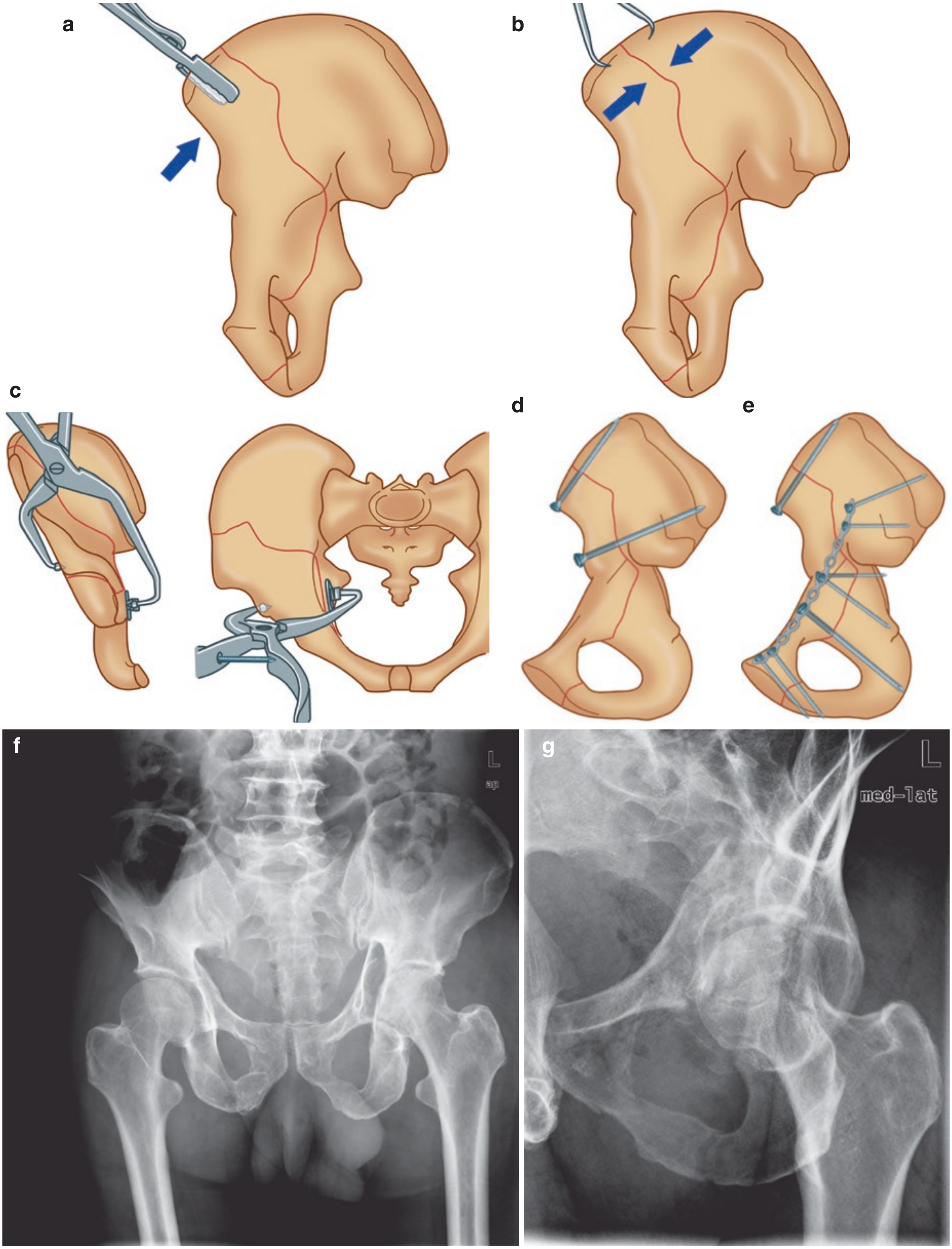

Fig. 4.24 (**a, b**) First, the reduction process starts from the iliac ala, which can be anatomically reduced using a pair of bone holding forceps or a pointed reduction clamp. (**c**) One tip of the pelvic reduction clamp is placed in the quadrilateral plate, and another tip is placed lateral to the anterior inferior iliac spine. (**d**) The iliac ala fracture at the proximal end of the anterior column can be fixed using lag screws or by placing a reconstruction plate at the edge of the ilium. (**e**) Reconstruction plate fixation is applied at the edge of the small pelvis. (**f**) AP radiograph of an anterior column acetabular fracture showing the interrupted iliopubic line. (**g**) Obturator oblique radiograph displaying an anterior column acetabular fracture. (**h, i**) To fix the anterior column acetabular fracture, a 3.5 mm reconstruction plate is placed at the edges of the small pelvis and iliac ala via the ilioinguinal approach

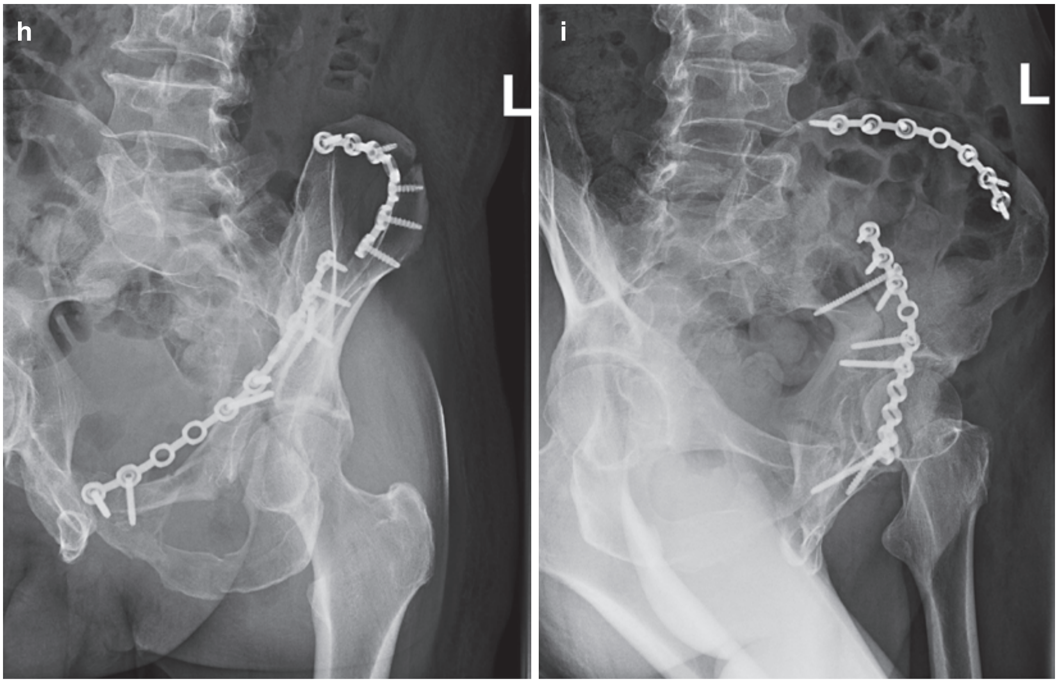

Fig. 4.24 (continued)

nique should be used, i.e., keep the drill bit rotating at high speed and perform back and forth movement to determine whether the drill bit enters the bony channel in the anterior column of the acetabulum.

Precautions: During drilling, in addition to an AP radiograph, both obturator and ilium oblique radiographs should be obtained to ensure that the screw path is in the anterior column. If the drilling direction is adjusted multiple times, it is possible that sounding and screwing might be performed in the previous path. To avoid accident, it is best to freeze the final radiographic image as a comparison guide during screwing. Special attention should be paid to ensure the anterior column screw not protrudes from the pubic cortex anteriorly and does not damage the structure of the femoral vessel, nerve, spermatic cord, or round ligament. In addition, screw mis-entry into the hip joint should be avoided.

- The posterior column of the acetabulum is fixed using the aforementioned steel plate and screw technique:

  The posterior main steel plate that fixes the transverse acetabular fracture must be specially pre-bent. Insufficient pre-bending increases the risk of iatrogenic displacement of the acetabular fractures when the screws are tightened.

  According to the principle of reverse engineering, combined with CT scanning, point cloud measurement, and other technologies, the 301 Hospital (The General Hospital of the People's Liberation Army) has established a morphological database of the acetabulum among the Chinese. Based on this database, a series of anterior and posterior column acetabulum anatomical locking plates in accordance with the Chinese acetabular morphology were designed and manufactured, which have been patented (Meng et al. 2013) (Fig. 4.26).

  This steel plate not only avoids the iatrogenic displacement caused by insufficient pre-bending, but it is also reliable for anatomical reduction during the operation. In addition, the screwing direction for placement of the steel plate avoids the dangerous zone in the acetabulum, and the characteristic angulation stability of the screw also makes it more suitable for patients with osteoporosis.

4.2.4.5 Complex Acetabular Fractures

- Complex acetabular fractures include associated posterior wall and posterior column acetabular, associated posterior wall and transverse acetabular, T-shaped acetabular, associated anterior column and posterior semi-transverse acetabular, and double-column acetabular fractures. They can be treated through the appropriate approach selected as previously mentioned, and the reduction and fixation methods are an effective combination of the aforementioned various reduction methods (Fig. 4.27).

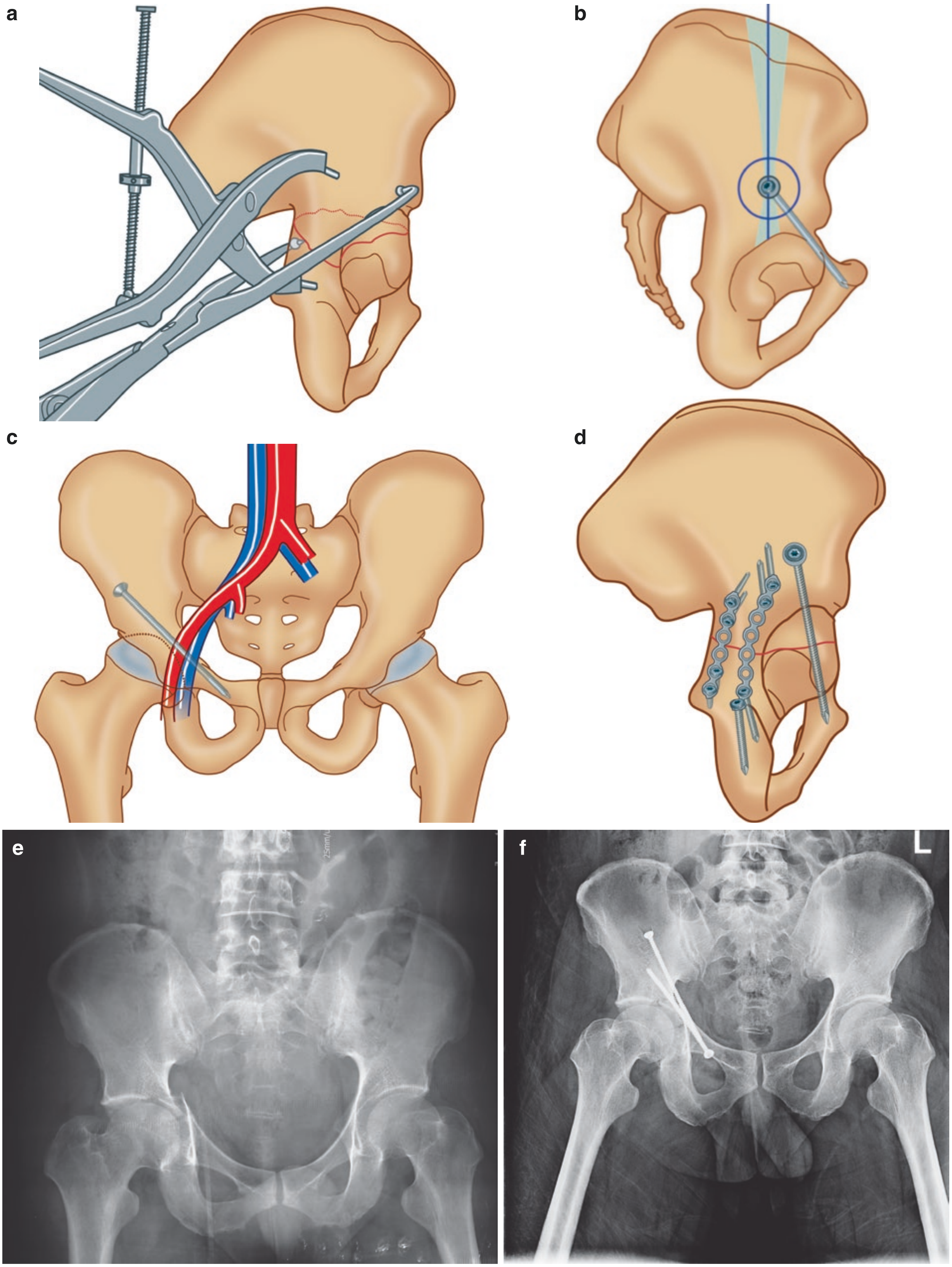

Fig. 4.25 (**a**) After fracture reduction, two pairs of reduction clamps are used to simultaneously stabilize the posterior and anterior columns. (**b**) The screw entry position in the anterior column of the acetabulum is posterior to the gluteal tuberosity of the ilium and 2–4 cm above the acetabulum. (**c**) The anterior column screw of the acetabulum points directly to the pubic tuberosity, and it is critical for the screw not to protrude from the pubis anteriorly and damage the vessels and nerves in front of the pubis. (**d**) After the anterior column is fixed with screws, the posterior column acetabular fracture is fixed with a steel plate and screws. (**e, f**) For acetabular transverse fractures, the minimally invasive screw fixation technique is performed to fix the anterior column of the acetabulum

Fig. 4.26 A new type of anatomical locking plate of the acetabulum designed for treating transverse acetabular fractures in the 301 Hospital (The General Hospital of the People's Liberation Army). (**a-c**) The shape of the plate is designed according to the anatomical data for the Chinese acetabular surface. The direction of the pre-positioned locking screw can avoid misplacement into the acetabulum. B is the posterior column plate, and C is the posterior wall plate. (**d**) Preoperative radiograph showing a left transverse acetabular fracture accompanied by a femoral shaft fracture. (**e, f**) Postoperative oblique and AP radiographs: The fracture was fixed with the new type of acetabular anatomical locking plate via the Kocher-Langenbeck approach. The radiographs demonstrated that the fracture was satisfactorily reduced, and the plate and bone surface showed good contact. (**g**) Postoperative 3D reconstruction of the CT with subtraction of the femoral head: The acetabular fracture has been anatomically reduced. (**h, i**) Postoperative CT 3D reconstruction: The anatomical plate matched the shape of the acetabulum well, and as designed, all screws avoided the acetabulum

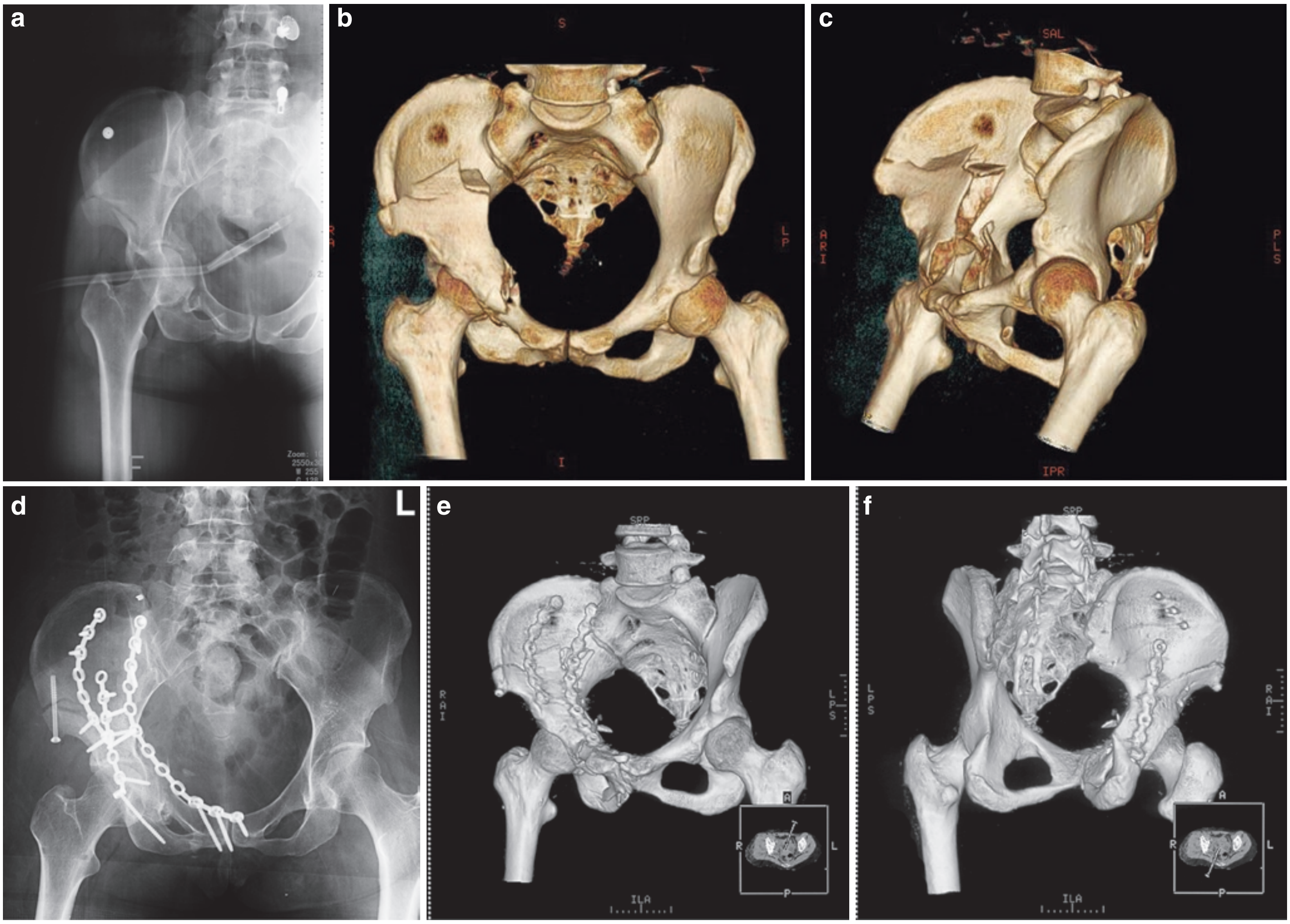

Fig. 4.27 Open reduction and internal fixation of acetabular fractures via the anterior and posterior combined approaches. (**a**) Preoperative AP radiograph showing a right acetabular comminution fracture and central dislocation of the femoral head. (**b, c**) Preoperative 3D-reconstructed CT mages demonstrating the fracture involving the anterior and posterior columns and the quadrilateral plate as well as the central dislocation of the femoral head. (**d**) Postoperative radiograph: The fracture was fixed via the joint anterior and posterior approaches with a 3.5 mm reconstruction steel plate and lag screws. The radiograph demonstrated that the fracture reduction was satisfactory, and the internal fixation was firm. (**e, f**) Postoperative 3D-reconstructed CT mages stereoscopically displaying the reduction and plate fixation status

4.2.5 Closed Reduction and Minimally Invasive Percutaneous Treatment for Acetabular Fractures (Bates et al. 2011)

- The minimally invasive percutaneous treatment method for acetabular fractures was developed based on the minimally invasive treatment of pelvic ring fractures and has been gradually promoted in recent years. It is worth emphasizing that minimally invasive fixation of acetabular fractures must be performed on the basis of good-quality reduction. In addition, because the screws are not placed in the direction perpendicular to the fracture line, they play a role in maintaining the reduction but cannot contribute to reducing the fracture.
- Screws in the anterior column:
  - Indications: Suitable for low-level anterior column acetabular fractures or complex acetabular fractures associated with low-level anterior column acetabular fractures.
  - Placement method: The method is similar to the placement method for screwing of the superior pubic ramus described in the “Pelvic fracture” chapter. However, when treating acetabular fractures, the screw can be placed either anterogradely or retrogradely, i.e., the screw enters at the gluteal muscle column above the acetabulum and is advanced towards the pubic tuberosity. The intraoperative fluoroscopic monitoring method is the same as that applied for superior pubic ramus screw placement in “Pelvic fracture”.
- LC II screws:
  - Indications: Medium and high-level anterior column acetabular fractures, or complex acetabular fractures associated with this type of fracture.
  - Placement method: The same as that described for LC II screws in “Pelvic fracture”.

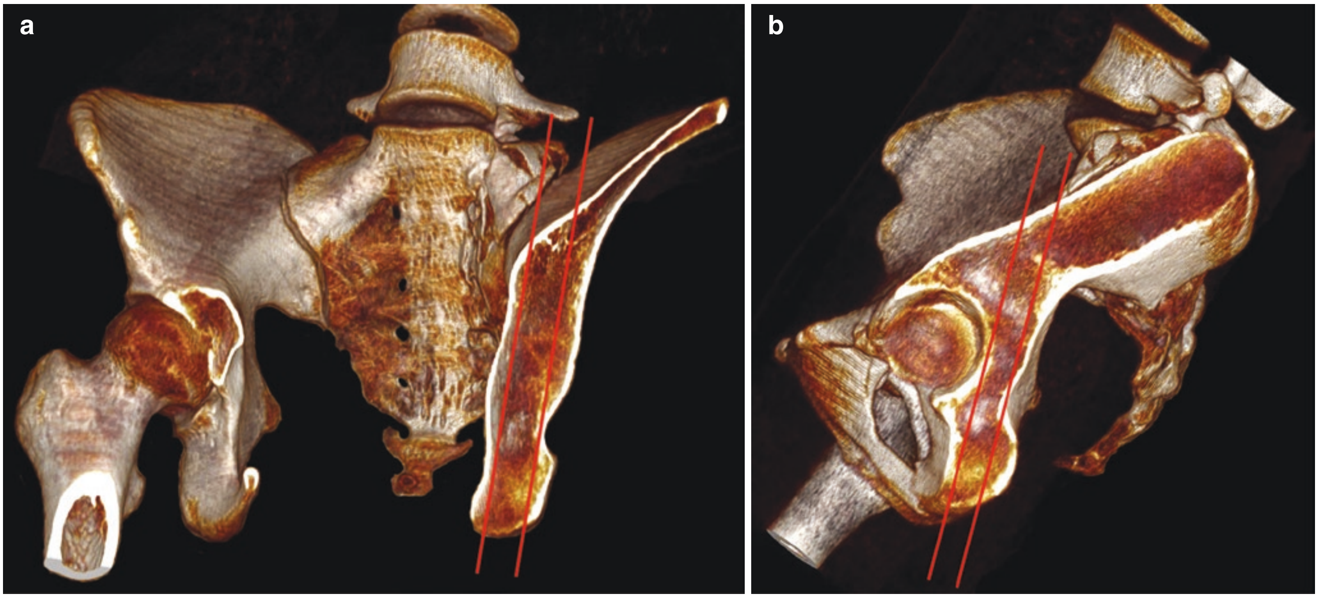

Fig. 4.28 Screw path in the posterior column of the acetabulum (**a**) AP view: The posterior column screw path originates from the ischial tuberosity, passes between the medial and lateral bone plates of the ilium, and exits from the upper edge of the true pelvis. (**b**) Lateral view: The screw entry point on the posterior column occurs on the ischial tuberosity and passes through the posterior side of the acetabulum

- Screws in the posterior column:
  - Indications: fractures involving the posterior column of the acetabulum.
  - When applied alone, the patient should lie in the supine position with the hip and knee flexed. For plate and screw fixation of complex acetabular fractures, the patient lies in the lateral decubitus position with the hip and knee flexed based on needs.
  - Screw path (Fig. 4.28):

    The method of anterograde or retrograde placement can be adopted. It is more difficult to determine the entry point for anterograde than for retrograde placement. However, retrograde placement requires more experience in body positioning and fluoroscopy.

    The screw is placed retrogradely into the posterior column of the acetabulum. The entry point is in the ischial tuberosity; the screw path passes through the posterior side of the acetabulum, travels between the medial and lateral iliac plates, and exits from the upper edge of the true pelvis.
  - Intraoperative fluoroscopy (Fig. 4.29):

    AP view: To ensure the guide wire is advanced within the projection of the sciatic tuberosity.

    Obturator view: To ensure the guide wire is advanced within the projection of the sciatic tuberosity and does not protrude into the depression of the lesser sciatic notch above the sciatic tuberosity projection.

    Iliac oblique view: Under ilium oblique fluoroscopic monitoring, the guide wire passes through the posterior of the acetabulum to avoid entering the acetabulum.

    Lateral view: The lower edge of the sciatic tuberosity and the true pelvic edge are clearly identified at the lateral position to determine the depth of the guide wire.
  - Reduction and internal fixation of the fractures:

    Taking retrograde screw placement as an example, this method can be used for posterior column acetabular fractures or transverse acetabular fractures without significant displacement; or, it can serve as part of complex acetabular surgery and can be combined with plate-screw fixation or other minimally invasive techniques.

    The patient should flex his/her knees and hip by 90° to relax the sciatic nerve.

    The entry point of the guide wire is on the sciatic tuberosity. A high position of entry may cause protrusion of the guide wire tail, resulting in discomfort during sitting. In addition, the guide wire can be inserted closer to the medial side to avoid injury to the sciatic nerve.

    Under AP and obturator-position fluoroscopic monitoring for guide wire placement, the guide wire should be within the projection of the sciatic tuberosity. Under fluoroscopic monitoring in the iliac oblique position, the guide wire should be located at the posterior of the acetabulum to ensure that it is not mistakenly inserted into the acetabulum.

    In the lateral view, the guide wire is advanced to the edge of the true pelvis, and the depth is measured.

    A cannulated screw is placed along the guide wire to fix the fracture.

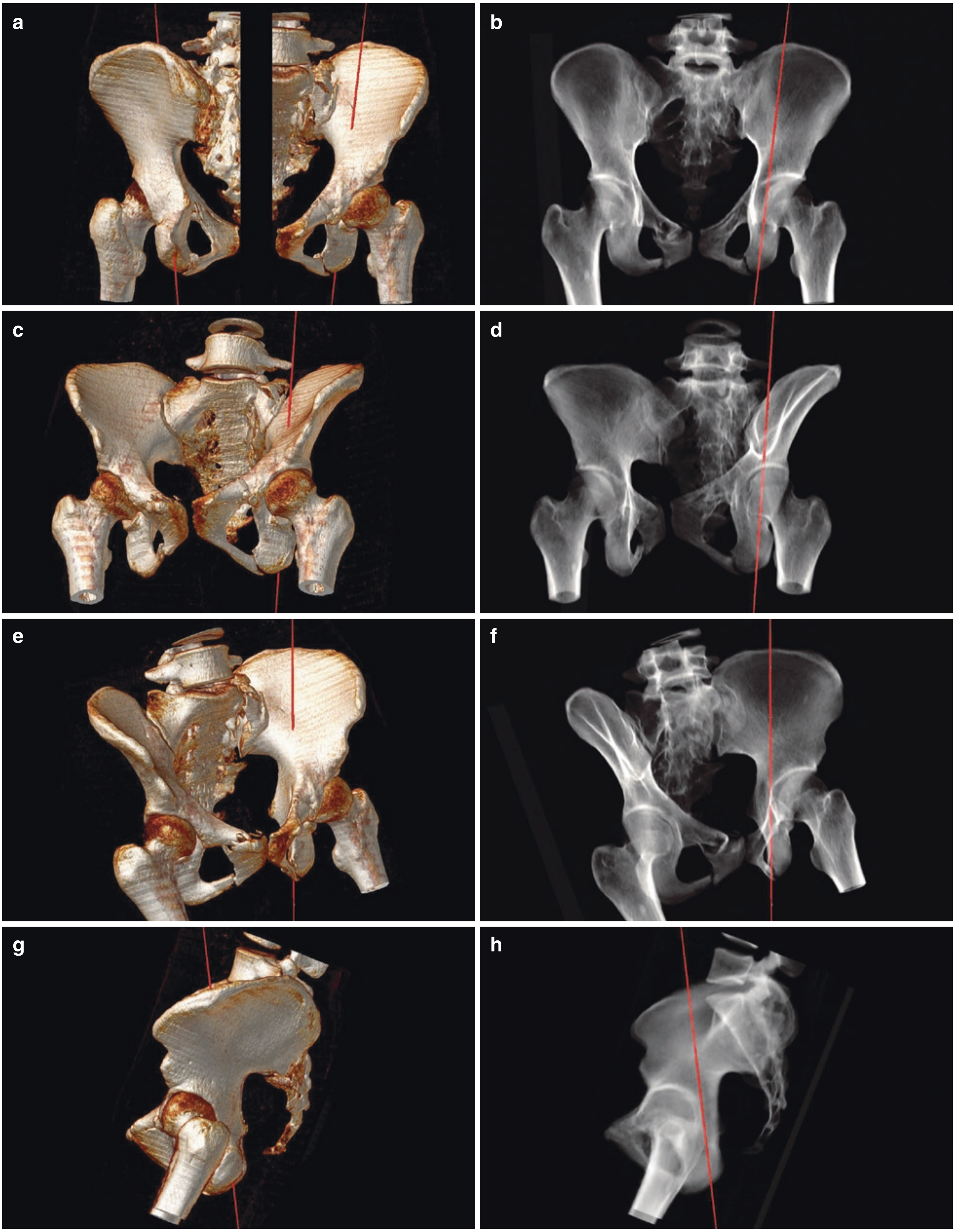

Fig. 4.29 (**a**) AP view showing the path for posterior column acetabular screws: The entry point is in the sciatic tuberosity, and the exit point is at the edge of the true pelvis in retrograde placement. (**b**) AP radiograph showing that the guide wire is within the projection of the sciatic tuberosity. (**c**) Positions of the pelvis and guide wire in the obturator view. (**d**) Obturator-position radiograph: The guide wire should also be within the projection of the sciatic tuberosity. The lesser sciatic notch is visible, and the projection of the guide wire should not appear in the depression of the lesser sciatic notch. (**e**) Positions of the pelvis and guide wire in the ilium oblique view. (**f**) Ilium oblique radiograph showing that the guide wire is posterior to the acetabulum. (**g**) Positions of the pelvis and guide wire in the lateral view. (**h**) Lateral radiograph: The projection line of the edge of the true pelvis and the edge of the sciatic tuberosity is visible and can be used to determine the depth of the guide wire insertion

- Magic screw:
  - Indications: A magic screw is used to fix the reduced quadrilateral plate fracture because it can pass through the posterior column of the acetabulum and can partially serve the same role as the posterior column screw;

    Screw path: The screw is difficult to position. It enters the gluteal tuberosity above the acetabulum, moves in the direction pointing to the ischial spine, and exits at the medial side of the ischial spine (Fig. 4.30).
  - Intraoperative fluoroscopy (Fig. 4.31):

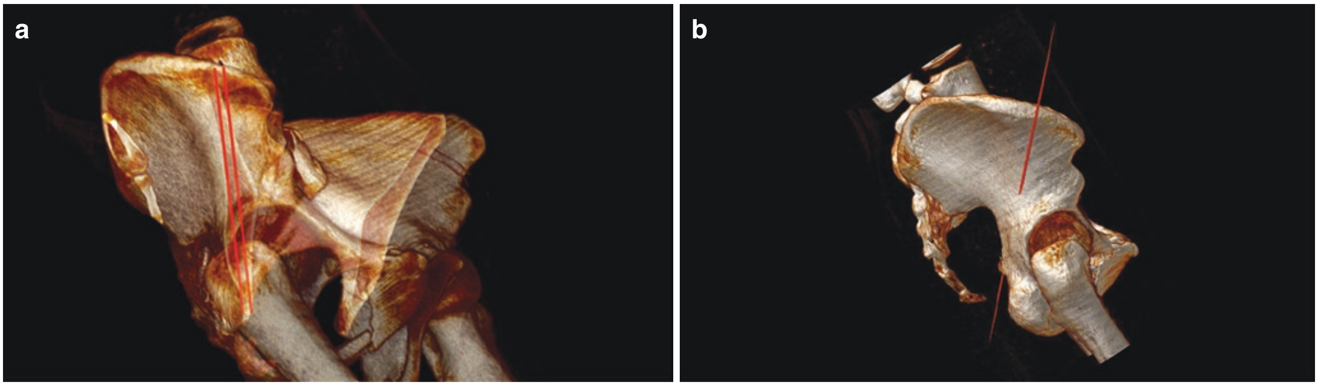

Fig. 4.30 (**a**) In the image in which the anterior hemipelvis is transparentized, there is a visible bony access in the direction from the site slightly anterior to the gluteus trochanter towards the sciatic spine. This access passes through the partial posterior column of the acetabulum and can be used as the path for Magic screw placement (between the two red solid lines in the figure). (**b**) The guide wire enters the gluteal tuberosity above the acetabulum, points to the ischial spine, and exits at the medial side of the ischial spine

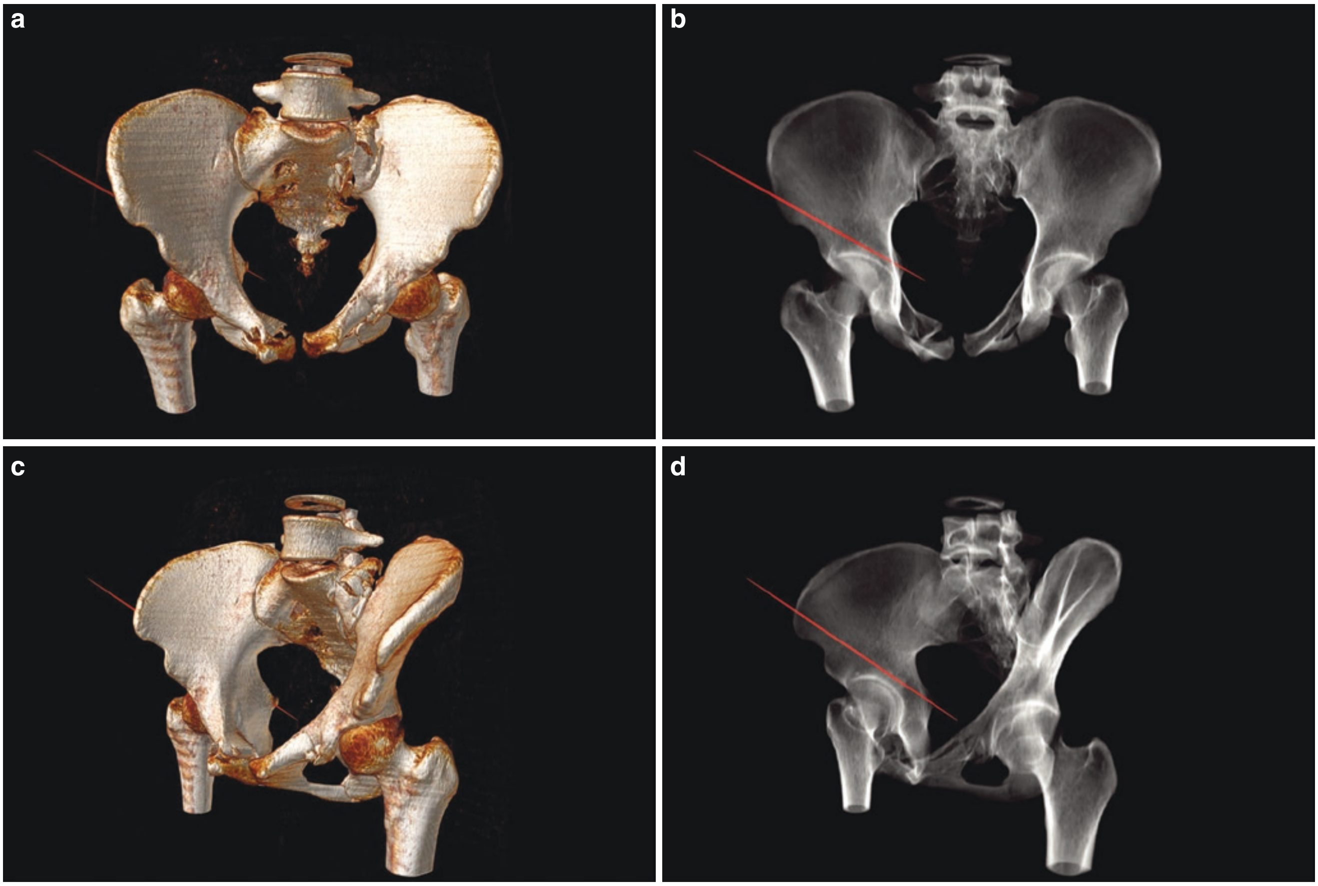

Fig. 4.31 (**a, b**) AP views of the pelvis: In the AP position view, the guide wire should be placed above the acetabulum, and its exit point is located on or slightly medial to the ischial spine. (**c, d**) Iliac oblique position: When viewing the iliac oblique position, the guide wire should be placed posterior to the acetabulum, and the exit point is at the ischial spine

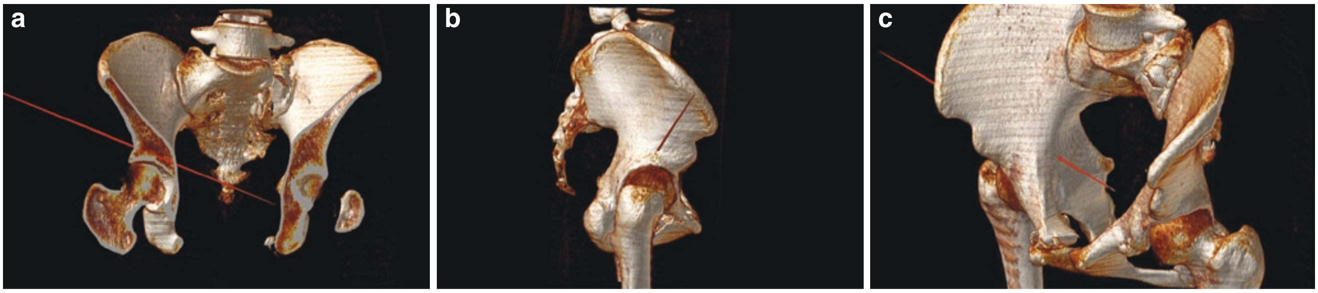

Fig. 4.32 Transverse screw path above the acetabulum. (**a**) The transverse screw path above the acetabulum is above the weight- bearing area of the acetabulum, and its travelling direction is almost perpendicular to the quadrilateral plate; therefore, this path can be used to reduce and fix the medially displaced quadrilateral plate fragment. (**b**) The entry point of the transverse screw above the acetabulum is 1 cm vertically above the acetabulum. (**c**) The exit point of the transverse screw above acetabulum is below the edge of the true pelvis and above the quadrilateral plate

AP position: Under fluoroscopic monitoring in the AP position, the guide wire should be placed above the acetabulum, and its exit point is located on or slightly medial to the ischial spine.

Iliac oblique position: Under fluoroscopic monitoring in the iliac oblique position, the guide wire should be inserted on the posterior of the acetabulum; the exit point is located at the ischial spine.

  - Reduction and fixation of the fracture:

    Because the screw is not perpendicular to the displacement direction of the quadrilateral plate fracture, the magic screw can only be used to fix the reduced quadrilateral plate fracture.

    A small incision can be created through the iliac ala, through which a reduction clamp and other tools can be placed to reduce the quadrilateral plate.

    Similar to the anterior column screw, the entry point is located on the gluteal tuberosity above the acetabulum, pointing to the sciatic spine or the site slightly medial to the sciatic spine.

    Under fluoroscopic monitoring in the AP position and oblique position of the ilium, one must ensure that the guide wire neither mistakenly enters the acetabulum nor penetrates into the greater sciatic notch.

- Transverse screws above the acetabulum:
  - Indications: The screw is almost perpendicular to the quadrilateral plate and can be used to reduce the medially displaced quadrilateral plate fragment. In addition, the screw is placed above the weight-bearing area of the acetabulum and thereby supports this area.
  - Screw access (Fig. 4.32):

    The screw passes through the weight-bearing area of the acetabulum from the superolateral to the inferomedial direction.

    The screw entry point is located 1 cm above the acetabulum, which is below the path of the LC II screw and anterior to the anterior column screw placed in an anterograde direction; therefore, these screws can be placed concurrently without affecting each other.

    The exit point is below the edge of the true pelvis and above the quadrilateral plate.

  - Intraoperative fluoroscopy (Fig. 4.33):

    AP position: Under the AP view, the guide wire enters the bone cortex above the acetabulum and is always advanced above the acetabulum without mis-entering the acetabulum.

    Obturator—inlet position: It is not the standard inlet-obturator position, but instead the image is obtained by positioning the C-arm in the AP position first and then slightly rotating it towards the inlet and obturator position. The exit point of the guide wire is monitored at the fluoroscopic position where the medial wall of the quadrilateral plate appears as a line.

  - Reduction and fixation of the fracture(Fig. 4.34):

    A small incision at the edge of the ilium can be used to place the reduction clamp and reduce the quadrilateral plate.

    The guide wire is placed under intraoperative fluoroscopic monitoring. To avoid damage to the pelvic vessels and obturator nerves, attention should be paid to ensuring that the guide wire does not excessively protrude from the quadrilateral plate.

    The cannulated screw is placed along the guide wire.

4.2.6 Postoperative Management (Borrelli Jr et al. 2006; Davoli et al. 1998)

- After surgery, the patient receives routine antimicrobial prophylaxis to prevent infection as well as 2–3 weeks of anticoagulant therapy, such as subcutaneous injection of low-molecular-weight heparin or oral rivaroxaban to prevent deep venous thrombosis in the lower extremities.

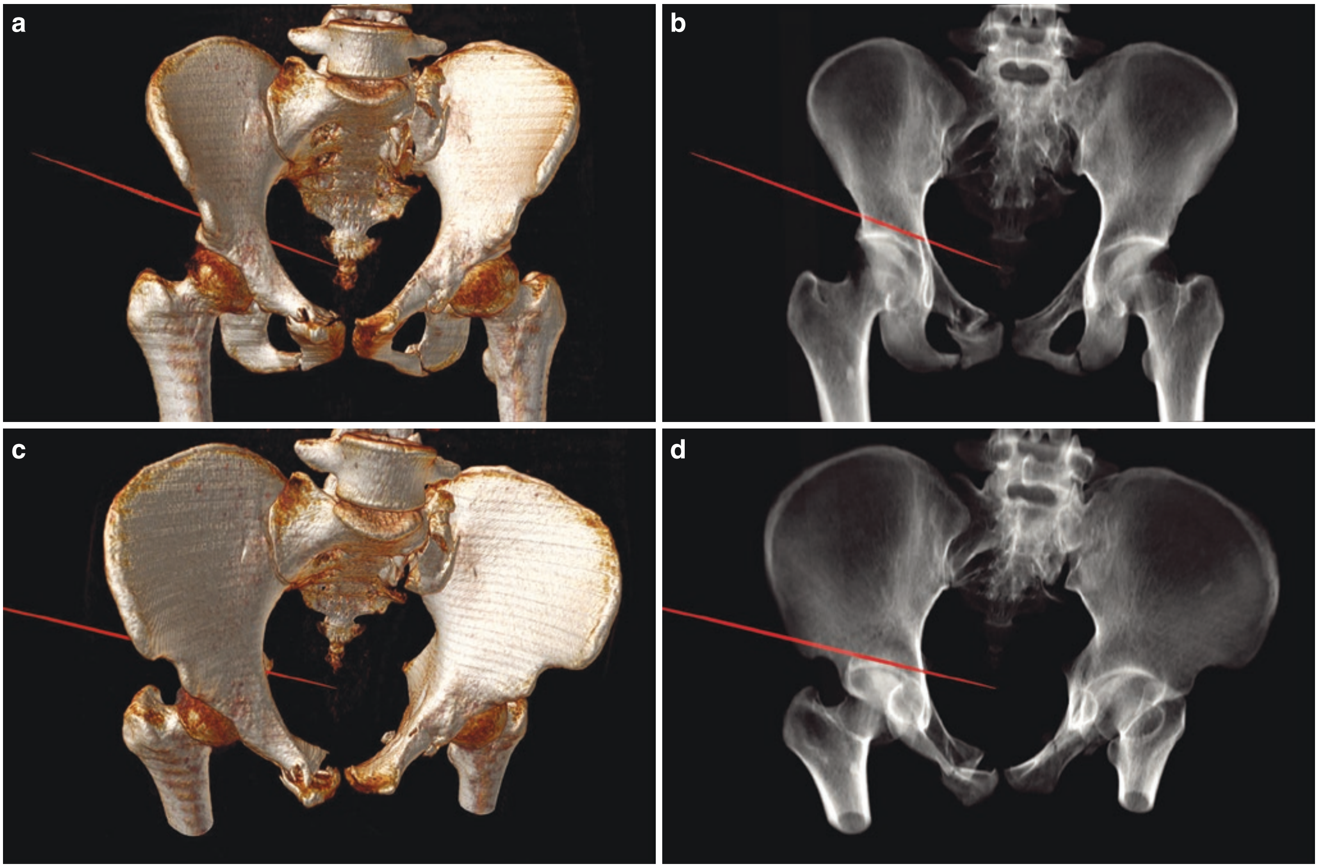

Fig. 4.33 (**a**) Positions of the pelvis and guide wire in the AP view. (**b**) In the AP view, the guide wire enters the bone cortex above the acetabulum and is always advanced above the acetabulum without mis-entry into the acetabulum. (**c**) Obturator-inlet view showing the positions of the pelvis and the guide wire. (**d**) The image is obtained first by positioning the C-arm in the AP position and then slightly rotating it towards the inlet position and obturator position, rather than the standard obturator-inlet position. The exit point of the guide wire is monitored at the radiographic position where the medial wall of the quadrilateral plate appears as a line

- Oral administration of 25 mg of indomethacin three times a day is given to prevent heterotopic ossification if necessary, especially for patients with a combined head injury.
- If the drainage volume decreases in 48–72 h postoperatively, the drainage tube should be removed.
- The continuous passive motion (CPM) device is used from postoperative day 10 to day 14 to optimally restore the joint function.
- For patients with extreme osteoporosis and old fractures, skeletal traction can be used to protect the reconstructed acetabulum after the operation.
- Weight-bearing: Fracture healing usually requires 3 months. During this time, patients are required to walk on crutches, and full weight-bearing is prohibited. Partial weight-bearing of less than 20 kg is superior to full weight-bearing because the muscle around the hip joint contracts strongly, and the hip joint bears greater stress when the affected extremity is suspended from the ground. For patients with two-part fractures and good bone quality who have achieved good reduction and fixation, weight-bearing can gradually be increased beginning at postoperative week 6. Patients with osteoporosis and comminution fractures cannot perform weight-bearing exercises until the fracture is healed.
- Follow-up: Radiographs should be obtained at postoperative week 6 and week 12, and a CT scan is obtained if necessary.

4.2.7 Postoperative Complications and their Prevention and Treatment Strategies

- Nerve injury.
  - Sciatic nerve injury (Letournel and Judet 1993; Vrahas et al. 1992) (Fig. 4.35).

    The reported post-traumatic sciatic nerve injury rate reaches 36%. The causes of sciatic nerve injury include a displaced posterior column acetabular fracture, posterior dislocation of the femoral head, excessive intraoperative traction, and direct surgical injury, among others.

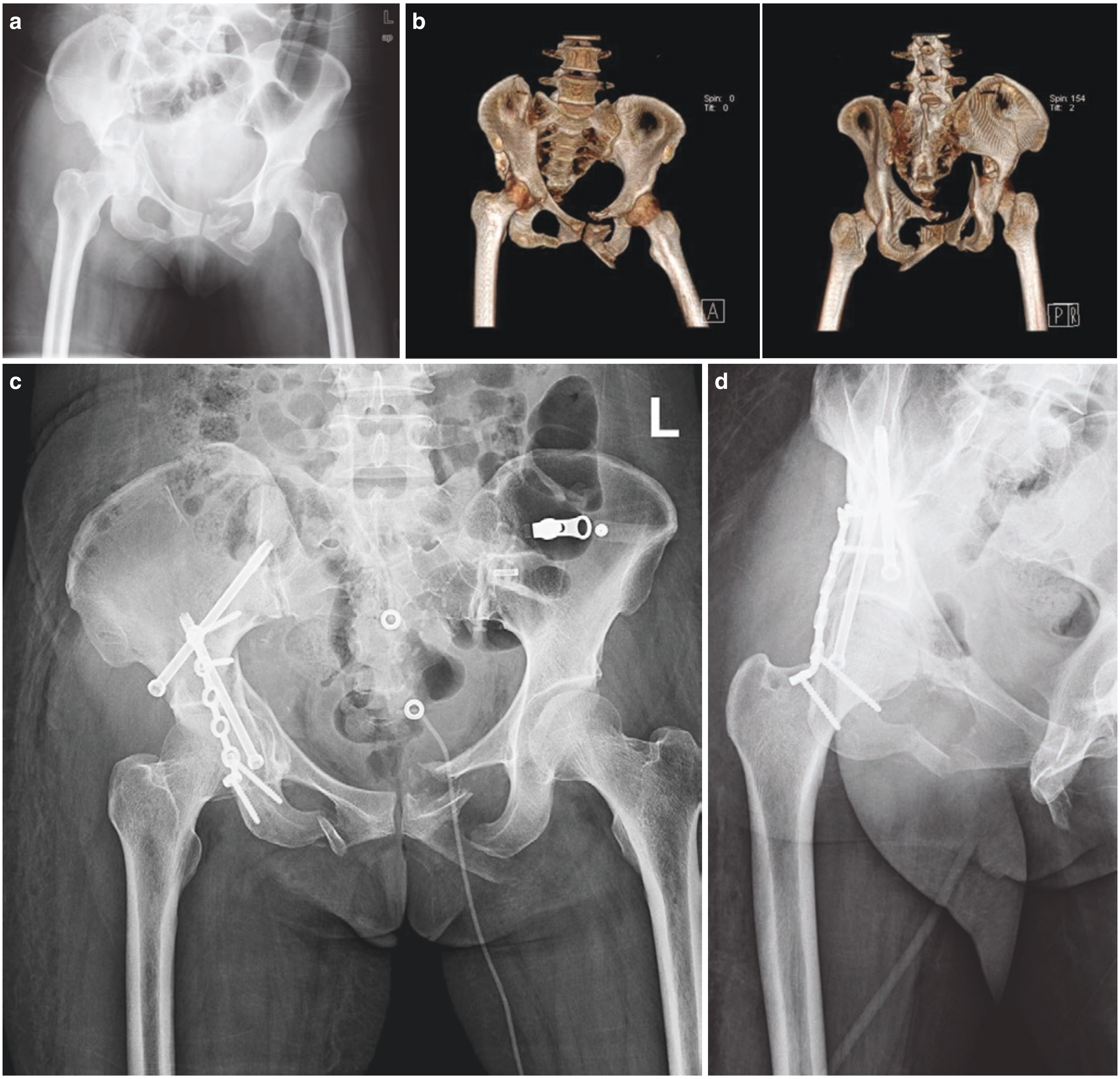

Fig. 4.34 Double-column acetabular fracture associated with a contralateral pubic superior and inferior ramus fracture. (**a**) Preoperative AP radiograph displaying a right acetabular fracture and the accompanying superior and inferior ramus fracture of the left pubis. (**b**) 3D reconstruction of the CT scan: The fracture involves the posterior wall of the acetabulum, anterior and posterior columns of the acetabulum, and contralateral pubis ramus. (**c-d**) After posterior wall plating is completed via the posterior approach, two lag screws are placed to fix the fractures of the posterior column and the iliac ala in the anterior columns of the acetabulum

Posterior dislocation of the femoral head should be reduced in a timely manner, and attention should be paid to changes in sensation and mobility of the lower extremities before and after reduction.

During the posterior approach, the sciatic nerve should be protected. The presence of variations in the relationship between the sciatic nerve and the piriformis muscle in a minority of patients should receive special attention. During surgery, the hip should be extended, and the knee should be flexed to relax the sciatic nerve;

During surgery according to the Kocher-Langenbeck approach, after the lateral rotator group is severed, a Hohman hook can be placed in the lesser sciatic notch to hold the sciatic nerve posteriorly for protection.

– Femoral nerve injury (Hardy 1997; Gruson and Moed 2003) (Fig. 4.36).

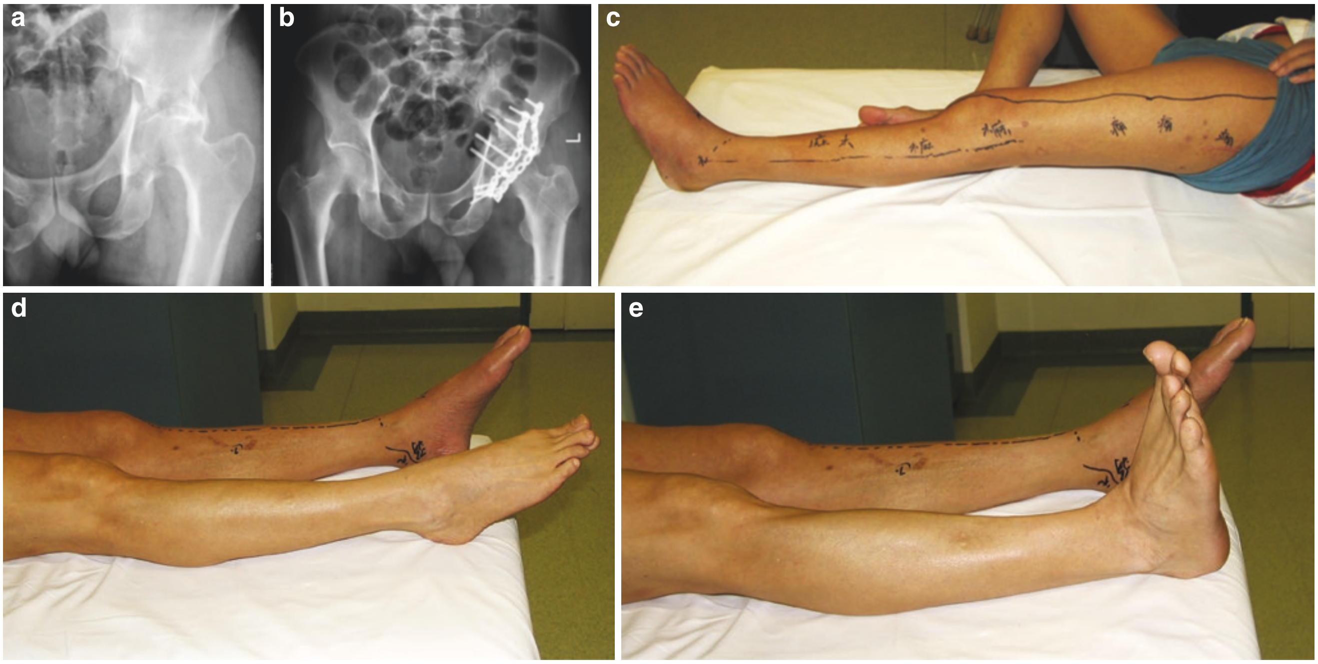

Fig. 4.35 Case example of a 43-year-old male patient with a left acetabular fracture: After treatment with open reduction and internal fixation via the Kocher-Langenbeck approach, the patient presented left lower extremity numbness and movement disorders. No significant improvement was observed at 5 months postoperatively. A second exploratory surgery was performed and showed that the sciatic nerve was partially ruptured in the vicinity of the piriformis muscle. (**a**) Preoperative AP radiograph. (**b**) Postoperative AP radiograph. (**c**) The area in the left lower extremity with abnormal skin sensation at 5 months after surgery. (**d, e**) Loss of motor function below knee level of the affected lower extremity

The incidence rate of femoral nerve injury is lower than that of sciatic nerve injury. The main causes of femoral nerve injury are direct damaged by the fractured anterior column of the acetabulum, anterior dislocation of the femoral head, and iatrogenic injury during the ilioinguinal approach.

In the ilioinguinal approach, especially when the iliopsoas muscle and femoral nerve are pulled, appropriate hip flexion during surgery can relax the femoral nerve to avoid nerve damage.

- Injury of the superior gluteal nerve (Bruce et al. 2006).

  The superior gluteal nerve passes the greater sciatic notch, and the causes of superior gluteal nerve damage include direct trauma caused by the fracture at the time of injury or reduction clamp insertion through the greater sciatic incision during surgery or iatrogenic injury caused by dissection of the lateral attachment of the gluteal muscle at the ilium during the extended iliofemoral approach.

  Injury of the superior gluteal nerve may result in paralysis of the gluteus medius and gluteus minimus muscles.
- Injury of the lateral femoral cutaneous nerve:

  The lateral femoral cutaneous nerve passes the area exposed during the ilioinguinal approach and may be injured during surgery, which may cause abnormal sensations in the lateral thigh skin.

- Malunion:
  - Risk factors associated with malunion:

    Fracture complexity, age, weight, and other objective factors of the patient may lead to difficulty in fracture reduction during surgery.

    Time from injury to surgery of more than 2 weeks: A fibrous connection of the fractured end develops if the time from the injury to surgery is greater than 2 weeks, causing difficulties in the anatomic reduction.

    The quality of reduction is closely related to the skill and experience of the surgeon, which are embodied in the choice of surgical approach. The operative skills involve fracture exposure and the completion of fracture exposure, reduction, and fixation.

    Surgical treatment of acetabular fractures is one of the most difficult surgical procedures in traumatic orthopedics. It is even difficult for the most experienced surgical team to achieve anatomic reduction success in a portion of patients.
  - Precise preoperative imaging assessment:

    The most basic evaluation methods include preoperative AP radiography, obturator foramen radiography, and oblique radiography of the ilium, CT scanning, and 3D reconstruction.

    The items to be assessed include the type of fracture, the degree and direction of displacement,

Fig. 4.36 Case example of a 38-year-old male patient with an acetabular fracture: The patient was treated with open reduction and internal fixation via the ilioinguinal approach. However, the reconstruction plate was not placed at the edge of the small pelvis correctly, but was directly fixed at the anterior inferior iliac spine. The plate misplacement caused restricted hip mobility, cutaneous sensory disturbance of the skin over the anterior aspect of the affected extremity, atrophy of the left quadriceps femoris, and weakness of knee extension, while the distal extremity functioned normally. The patient was diagnosed with femoral nerve injury. The second exploratory surgery revealed that the femoral nerve was compressed below the plate, partially interrupted, and scarred. The hip joint could be extended straight after the plate was removed, and the iliac muscle was loosened. (**a**) Postoperative AP radiograph. (**b**) The skin area over the anterior aspect of the affected extremity with a sensory disturbance. (**c**) The left quadriceps femoris was atrophic, and the left knee had extension dysfunction. (**d, e**) The distal joints including the ankle and foot showed normal mobility. (**f**) The left hip joint had restricted mobility without straight extension ability

  whether the fracture of the acetabular wall and dome is accompanied by a compression fracture of the joint surface, whether there are free bone fragments in the acetabulum, and whether the fracture is associated with the femoral head fracture.

- Suitable surgical approaches: The strategies for surgical approach selection for different types of fractures have been described in detail in the preceding section.
- Appropriate reduction techniques:

  Excluding the extensile ilium approach, other approaches cannot provide a direct and complete view of the weight-bearing area of the acetabulum. Therefore, the combination of direct reduction and indirect reduction is a very important technique.

  The Kocher-Langenbeck approach allows a direct view of the posterior wall and posterior column of the acetabulum. When the anterior column is indirectly reduced, one tip of the reduction clamp should be placed on the quadrilateral plate through the greater sciatic notch; the reduction is indirectly evaluated by intraoperative fluoroscopy and palpation of the quadrilateral plate.

  The ilioinguinal approach offers a direct view for the iliac fossa, medial wall of the acetabulum, quadrilateral plate, and pelvic edge. When the posterior

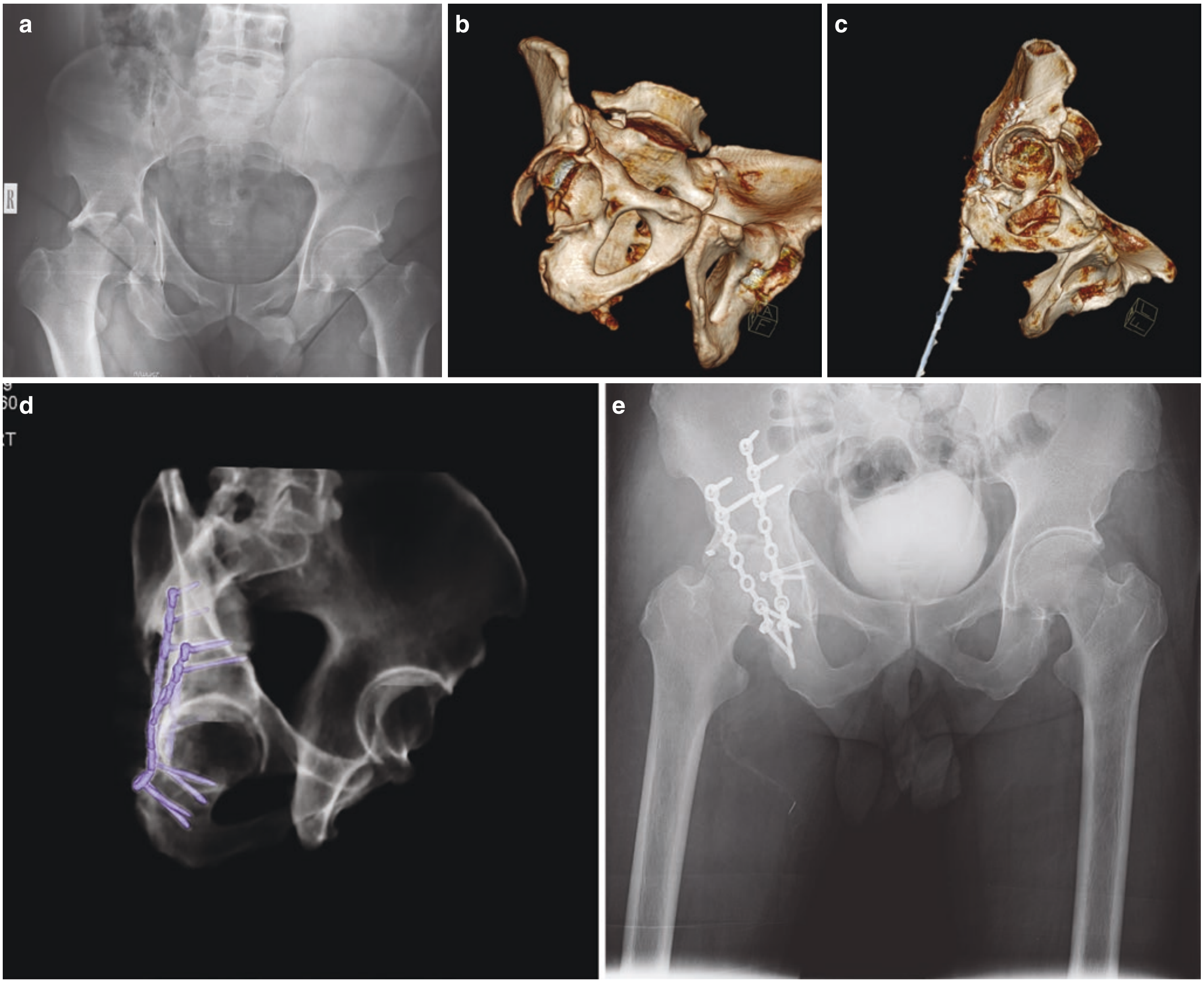

Fig. 4.37 Case example of an associated transverse and posterior wall acetabular fracture. (**a**) Preoperative radiograph: There was a transverse acetabular fracture and 'spur sign', which indicated a posterior wall fracture. (**b**) Preoperative CT plain scan and reconstruction with subtraction of the proximal femur: The transverse acetabular fracture was clearly visible and associated with posterior wall fracture displacement. (**c**) Intraoperative CT scan and reconstruction with subtraction of the proximal femur: The acetabulum was successfully reduced, the plate was placed in the appropriate position, and no screw entered the acetabulum. (**d**) Intraoperative CT-reconstructed image showing the position relationship among the plate, screw, and acetabulum. (**e**) Postoperative radiograph

  column is indirectly reduced, one tip of the reduction clamp should be placed under the iliac crest or the greater sciatic notch on the lateral side of the acetabulum. The reduction is examined indirectly by intraoperative fluoroscopy and palpation.

  - Intraoperative imaging and monitoring:

    The C-arm system should be used in intraoperative fluoroscopy to obtain the AP, obturator oblique, and iliac oblique views for monitoring the fracture reduction and screw placement around the acetabulum.

    For complex acetabular fractures, the 301 Hospital (The General Hospital of the People's Liberation Army) currently uses intraoperative CT combined with multiplanar and 3D reconstruction to monitor the fracture reduction and screw location (Fig. 4.37). Compared with two-dimensional (2D) radiography, an intraoperative CT scan can display in a more direct manner the fracture reduction status and screw position in the cross-section and in three dimensions, which is of great guiding significance for an accurate intraoperative evaluation of the fracture reduction and fixation quality.

- Complications associated with internal fixation:
  - Screw misplacement into the hip joint: Screw placement in the dangerous zone of the acetabulum should typically be avoided as previously mentioned. If it is unavoidable, the screws should be placed facing away

from the acetabulum. Screw mis-entry into the hip joint may damage the cartilage (Fig. 4.38).

- Heterotopic ossification:
  - Related risk factors for heterotopic ossification (Matta 1996):

    Surgical approach: The study by Matta et al. has shown that heterotopic ossification occurrence is significantly associated with the surgical approach, with a 20% incidence in the extended iliofemoral approach, 8% in the Kocher-Langenbeck approach, and a minimal incidence of 2% in the ilioinguinal approach.

    Traumatic craniocerebral injury is another important factor related to heterotopic ossification.

    Other studies have proposed other related factors, including the fracture severity, the accompanying thoracoabdominal injury, and a delayed operation time.
  - Prevention of heterotopic ossification:

    Surgery: Approaches that reduce heterotopic ossification by optimizing the surgical methods and approaches remain undeveloped. Most researchers believe that ectopic ossification can be reduced by reducing the injury to the abductor muscle. Some studies have shown that the risk of heterotopic ossification can be reduced by minimizing the extent of greater trochanter osteotomy. Some researchers have even proposed that removal of the gluteus minimus muscle after fixation can reduce the incidence of heterotopic ossification.

    Medication: Indomethacin reportedly prevents heterotopic ossification, but its therapeutic effect has remained controversial.

    Radiotherapy: Local radiotherapy within 72 h after surgery reduces the occurrence of heterotopic ossification. However, routine radiotherapy for heterotopic ossification is not recommended because it often leads to incision complications.
- Traumatic arthritis and femoral head necrosis:
  - Post-traumatic arthritis of acetabular fractures can cause hip ankylosis and pain (Ragnarsson and Mjoberg 1992). The incidence of traumatic arthritis is associated with poor reduction and cartilage damage, especially at the acetabular dome (Mears et al. 2003; Mears 1999).
  - Femoral head necrosis is a catastrophic complication after surgical treatment of hip fractures. It often occurs in patients whose accompanying femoral head dislocation has failed to be reduced in a timely manner (Helfet et al. 1991). In addition, there is a small potential for the occurrence of ischemic necrosis and joint collapse of the acetabulum (Fig. 4.39).
  - Total hip arthroplasty can be performed in patients with ischemic necrosis of the femoral head.
  - For elderly patients with a severe comminution fracture or patients with a severe combined fracture of the femoral head, stage-one total hip arthroplasty can be performed after acetabular fixation, for which the cementless acetabular cup is fixed with screws (Fig. 4.40).

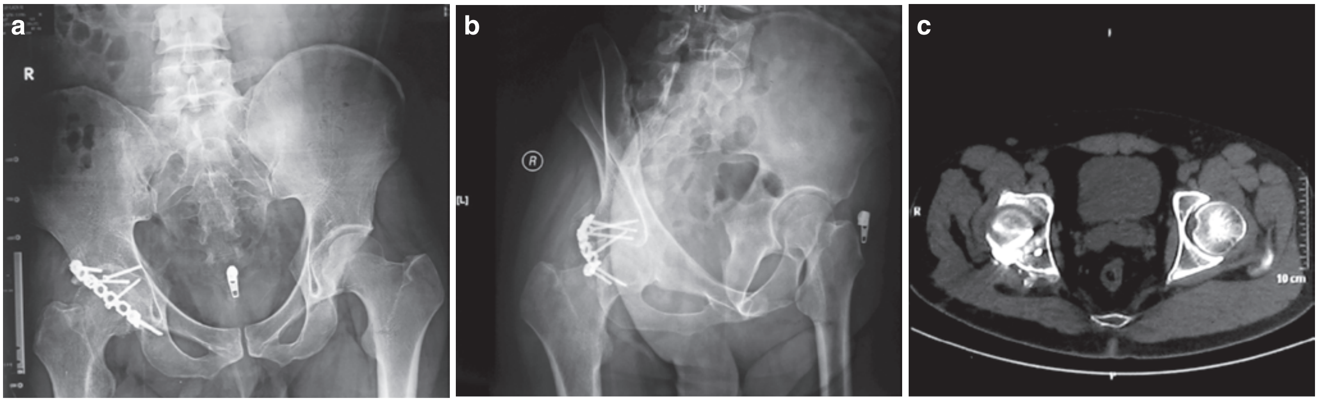

Fig. 4.38 Case example of an acetabular fracture: After internal fixation with a reconstruction plate and lag screws via the Kocher-Langenbeck approach, the patient suffered from severe hip pain upon movement. Radiography and CT scan revealed screw misplacement in the hip joint cavity, representing a typical iatrogenic injury caused by inadequate surgical exposure and the use of an excessively short plate, which might be attributed to a lack of experience of the operator. (**a**) AP radiograph of the pelvis: The screw tip protruded into the joint cavity of the hip. (**b**) Obturator oblique radiograph: The fracture was well reduced, but the screw was misplaced in the hip joint cavity. (**c**) CT plain scan: The scan further confirmed that the screw tip entered the joint cavity

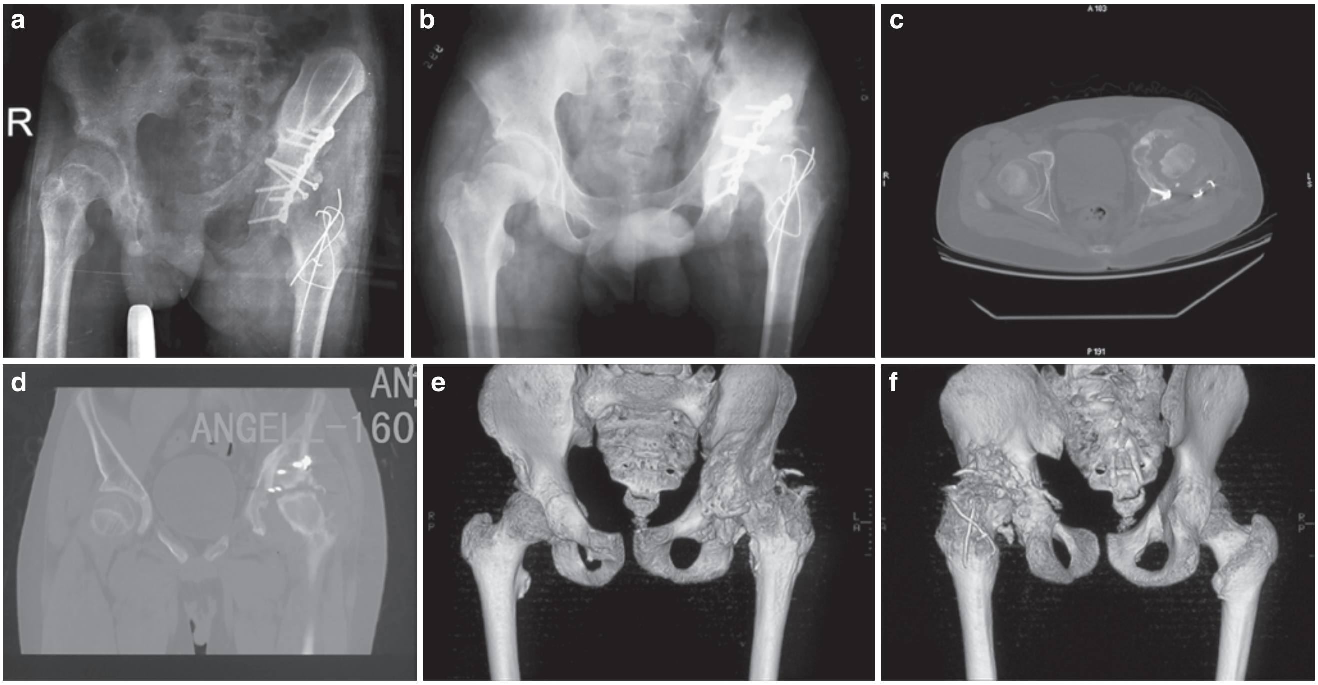

Fig. 4.39 Case example of a 14.year-old male patient with a left acetabular fracture, left clavicle fracture, and craniocerebral injury caused by a traffic accident. The patient began weight-bearing walkingat 4 months post-operatively and experienced pain after exercise at 7 months post-operatively. The original preoperative image data were lost. (**a**) Postoperative AP radiograph: The acetabular fracture was reduced and fixed through the greater trochanter osteotomy approach. The radiograph confirmed that the quality of the fracture reduction and fixation was acceptable. The greater trochanter was reconstructed with Kirschner wires and a tension band, and the hip joint space was basically normal. (**b**) AP radiograph obtained at 10 months post-operatively: The hip joint space disappeared, and heterotopic ossification occurred around the joint; the femoral head was necrotic and showed an irregular morphology. (**c-f**) CT images obtained 11 months post-operatively: The cartilage of both the acetabulum and femoral head were damaged and disappeared, and there was a large amount of heterotopic ossification around the hip joint

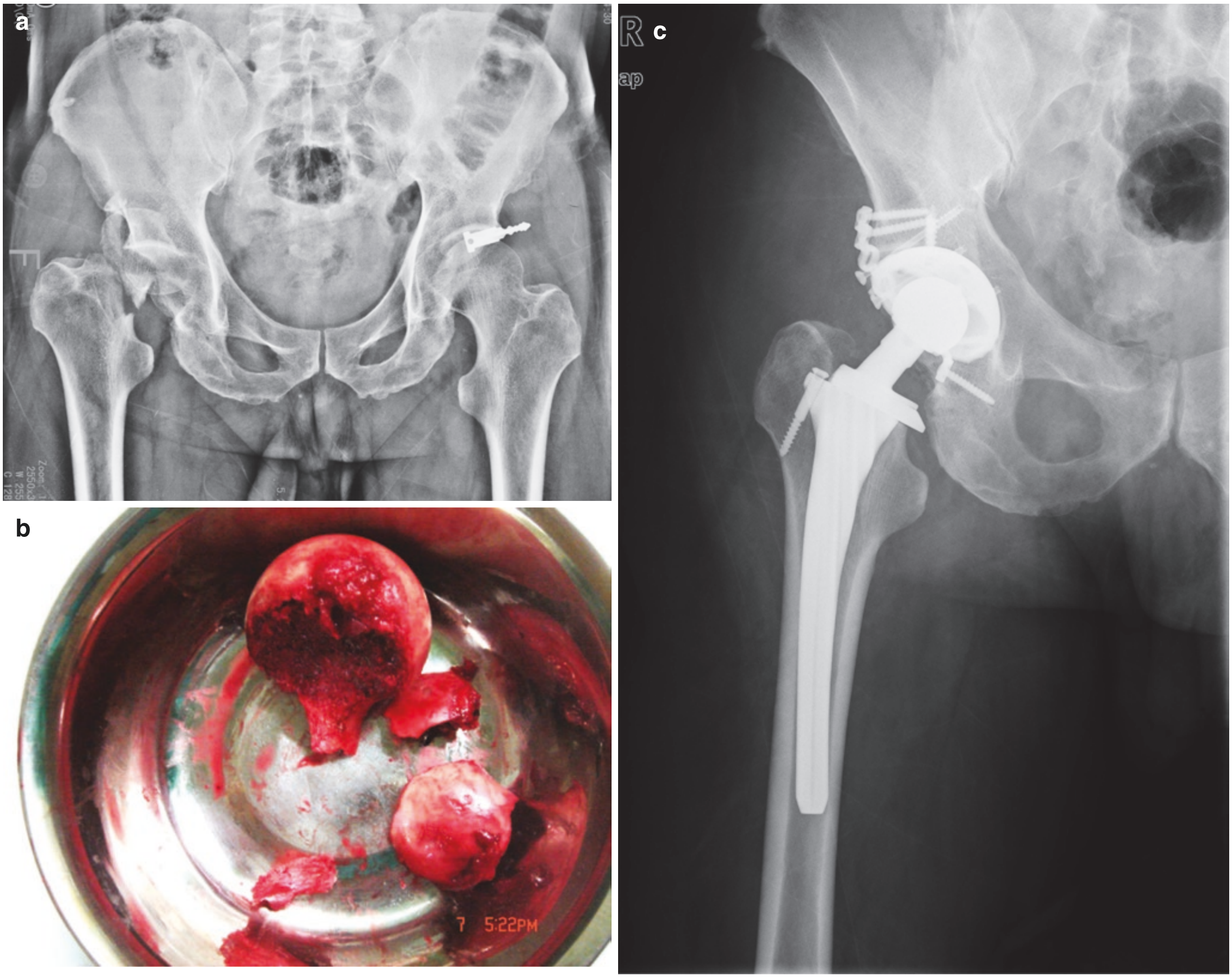

Fig. 4.40 Case example of a 57-year-old male patient who suffered a traffic accident injury. (**a**) Preoperative AP radiograph showing a posterior wall fracture of the right acetabulum associated with ipsilateral femoral head and femoral neck fractures. (**b**) The patient was elderly with multiple fractures of the acetabulum, femoral head, and femoral neck, which significantly increased the risk of postoperative ischemic necrosis of the femoral head after reconstruction. Therefore, reduction and reconstruction of the acetabulum along with total hip arthroplasty were performed immediately. The intraoperative observation revealed that the femoral head was comminuted and that the femoral neck had a subcapital fracture. (**c**) During stage 1 treatment, the posterior wall of the acetabulum was fixed with a reconstruction plate, and total hip arthroplasty with biological prostheses was also performed

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Nonunion

5

Peifu Tang, Zhe Zhao, and Wei Zhang

5.1 Basic Theory and Concepts

5.1.1 Overview

- A delayed union is defined by a fracture that does not heal within the expected time. The healing time of fractures at different sites varies, usually from 3 to 6 months. Delayed union can usually be cured by brace fixation or other conservative treatments.
- The definition of nonunion is still controversial. According to the American Academy of Orthopaedic Surgeons (AAOS), nonunion refers to a fracture with no signs of healing for at least 9 months after the injury or three consecutive months of dynamic observation. However, the AAOS criteria do not consider the fracture healing rate to vary at different fracture sites. In addition, they overlook the possibility of related factors in the fracture site that affect fracture healing during treatment. Once nonunion occurs, the healing process is very difficult without surgical intervention (Weitzel et al. 1994; Milgram 1991).
- Two key diagnostic criteria for nonunion:
  - Time for healing: The fracture does not heal after 6–9 months.
  - Dynamic healing profile of the fracture site: No sign of healing is observed at the fracture site for three consecutive months, i.e., radiographic examinations reveal no change in the fracture gap or callus growth and even show absorption and atrophy at the fracture ends.
- Epidemiology: The incidence of nonunion is 2–7% (Saleh et al. 2001; Heppenstall 1980; Boyd et al. 1965; Connolly 1991).

5.1.2 Pathogenesis of Nonunion

- Fracture healing conditions: Full contact of the fracture ends, viable biological environment, and a stable biomechanical environment.
- Natural healing process of fractures (Ruedi et al. 2007) (Fig. 5.1):
  - Inflammatory phase (1–7 days): The inflammatory response is initiated from the beginning of the fracture. Hematoma is initially formed at the fracture ends, which contain abundant fibrin, collagen fibers, etc. Platelet degranulation and other damaged tissues release inflammatory mediators to, on the one hand, increase the blood supply to fracture ends and, on the other hand, recruit more cells to participate in fracture reconstruction. Subsequently, the hematoma is gradually replaced by granulation tissue, and the osteoclasts begin to engulf the partially necrotic bone tissue at the fracture ends (Mizuno et al. 1990).
  - Cartilaginous callus formation (2–3 weeks): Cartilaginous callus formation occurs at the endosteum and periosteum near the fracture site. Intramembranous osteogenesis begins after the stem cells in the germinal layer are stimulated. Both the inner and outer surfaces of the two fracture ends gradually merge into each other. The periosteum of the fracture ends is often damaged, and mesenchymal stem cells begin to proliferate and differentiate into chondrocytes after migration to complete the stabilization and connection of fracture with the initiation of mineralization of ingrowing blood vessels (Sarmiento et al. 1995).
  - Hard callus formation (3–4 months): Due to low peripheral deformation, mineralization of the hard callus occurs from the periphery to the fracture ends for osteogenesis, eventually through cartilage, which is replaced by woven bone at the fracture ends (Perren et al. 1980).

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P. Tang, H. Chen (eds.), *Orthopaedic Trauma Surgery*, https://doi.org/10.1007/978-981-16-0219-1_5

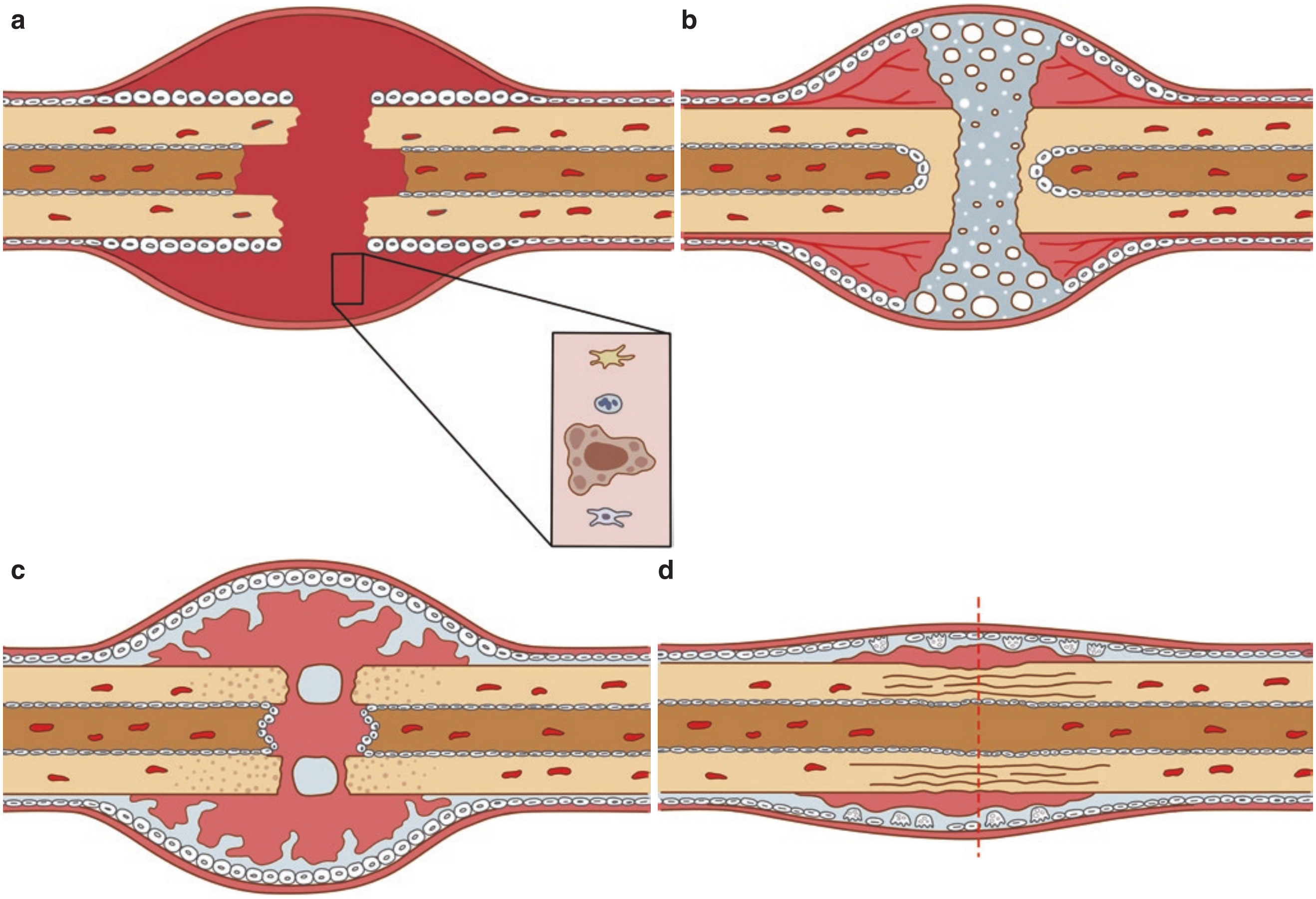


Fig. 5.1 (**a**) Inflammatory phase: The formed hematoma at the fracture ends gradually forms granulation tissue through release of inflammatory factors within the hematoma. (**b**) Cartilaginous callus formation: Cartilaginous callus is formed at the fracture site through intramembranous osteogenesis of the endosteum and periosteum and entochondrosis of the fracture fragments. (**c**) Hard callus formation: Cartilaginous callus tissue is gradually mineralized from the periphery to the fracture site and eventually forms woven bone to connect the fracture ends. (**d**) Bone remodeling phase: The bone unit is reconstructed by osteoclast and osteoblast activities to convert woven bone into lamellar bone

  - Bone remodeling phase (a few months to a few years): After fracture healing, the bone unit is reconstructed by osteoclast and osteoblast activities to convert woven bone into lamellar bone (Frost 1989).
- Primary and secondary bone (fracture) healing (Ruedi et al. 2007).
  - Primary fracture healing (direct fracture healing):

    Characteristics of primary fracture healing: A very small amount of or no callus is present in radiographs. The osteon (Haversian system) is directly reconstructed at the fracture ends by osteoclasts and the osteoblasts (Schenk et al. 1963).

    The biomechanical feature of primary fracture healing is “absolute stability”: The deformation of the fracture end under physiological load during the fracture repair process is eliminated by pre-pressurizing the fracture end and generating sufficient friction, thereby achieving the so-called absolute stability and primary fracture healing.

    Requirement to fulfil in primary fracture healing:

    - Anatomical reduction, <1 mm gap between the two fracture ends.
    - Pre-pressurization of the contact zone between the two bone fragments.
    - Steel plate and appropriate number of screws are applied to prevent deformation of the fracture ends and ensure no fatigue fracture of the internal fixators and no loss of reduction throughout the healing process.
    - Maintenance of the blood supply around the fracture ends.
  - Secondary fracture healing (indirect fracture healing):

    Characteristics of secondary fracture healing: Absorption at the fracture ends caused by micromotion and fracture repair mainly through callus formation.

    The biomechanical feature of primary fracture healing is “relative stability”:

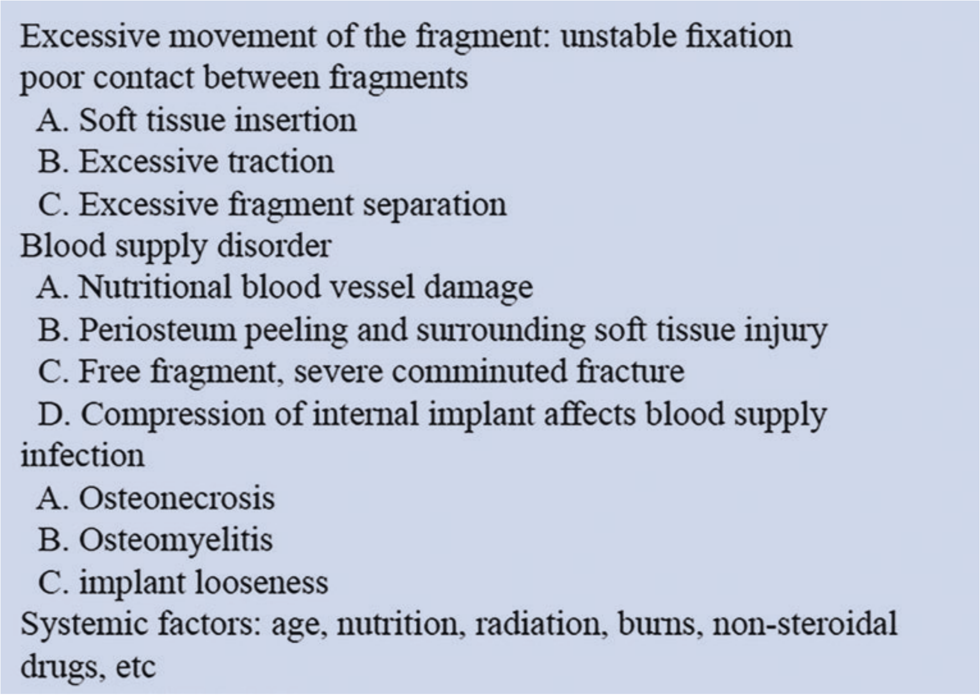
    - The fracture ends can be relatively displaced under physiological loading, and the degree of displacement is positively related to the external force and inversely related to the stiffness of the fixation materials.

  - Perren's interfragmentary strain theory (Perren et al. 1980): Strain is a deformation of tissue (e.g., granulation tissue, soft callus, and hard callus) under external force. It is defined as the ratio of the deformation length ($Дl$) to the total length (l) as a unit of percentage (%). The strain capacities of bone, soft callus, and granulation tissue are 2%, 10%, and 100%, respectively. When the local strain is less than the bearing capacity of woven bone, the callus undergoes synostosis; when the local strain becomes too large to narrow the permissible range, which is also the cause of hypertrophic nonunion, the body will increase the callus quantity (increasing the denominator l).

  Secondary and primary fracture healings: Secondary fracture healing is closer to the bone healing process under natural conditions, with a shorter healing duration and higher healing intensity than that of primary fracture healing, and because of factors such as osteoporosis caused by stress shielding after the absolute stability of fixation, the incidence of fracture after primary facture healing is higher than that of secondary fracture healing. Primary fracture healing is only applied to some simple fractures or intra-articular fractures.

- Healing patterns of different implants:
  - External fixator: Excluding some circular external fixators, which provide pressure and absolute stability, most external fixators are relatively stable and result in secondary fracture healing (Stein et al. 1997).
  - Intramedullary nail: An intramedullary nail is a flexible fixture. An interlocking intramedullary nail reduces the rotational movement and vertical movement of the fracture and facilitates callus formation, resulting in secondary fracture healing (Perren 1996).
  - Stainless steel dynamic compression plate (DCP) and limited contact dynamic compression plate (LC-DCP): The compression on the fracture ends is completed by dynamic pressurization, and DCP and LC-DCP theoretically lead to primary fracture healing.
  - Stainless steel locking compression plate (LCP): The application is flexible. For a simple fracture, it can be absolutely stabilized and fixed by LCP in a pressurized manner to achieve primary fracture healing. For a comminuted fracture, the effect of internal fixation is achieved by bridging and fixing using LCP, and the fixation is relatively stable and results in secondary fracture healing (Borgeaud et al. 2000).
- Systemic factors of nonunion (Table 5.1): Advanced age; chronic diseases, such as diabetes and human immunodeficiency virus (HIV) infection; smoking; alcohol dependence; endocrine diseases, such as hypothyroidism; malnutrition; post-radiation; vascular diseases; long-term application of non-steroidal drugs, fluoroquinolone antibiotics; and antiplatelet drugs (Marti and Kloen 2010).
- Local environmental factors contributing to nonunion (Table 5.1):
  - Poor blood supply (Pao and Chang 2003; Migues et al. 1996; Soucacos et al. 1995):

Table 5.1 Causes of nonunion



Excessive movement of the fragment: unstable fixation
poor contact between fragments
  A. Soft tissue insertion
  B. Excessive traction
  C. Excessive fragment separation
Blood supply disorder
  A. Nutritional blood vessel damage
  B. Periosteum peeling and surrounding soft tissue injury
  C. Free fragment, severe comminuted fracture
  D. Compression of internal implant affects blood supply
infection
  A. Osteonecrosis
  B. Osteomyelitis
  C. implant looseness
Systemic factors: age, nutrition, radiation, burns, non-steroidal drugs, etc

Nutrient vessels of some bones receive only a single blood supply, and as a result, if a fracture occurs, one of the fracture ends will lack a blood supply, which affects fracture healing (Fig. 5.2), for example, fracture of the distal one-third of the tibia, scaphoid fracture, and femoral neck fracture.

High-trauma fractures are often associated with severe soft tissue injuries and even vascular rupture. Factors such as excessive exposure of the fracture ends and osteonecrosis after excessive heat exposure in high-speed, excessive intramedullary reaming may lead to a poor blood supply at the fracture ends. The fracture still has a chance to heal, but slowly, if one of the fracture ends lacks or has a poor blood supply. However, if both fracture ends have a poor blood supply, fracture healing will be difficult (Fig. 5.3).

Unless the blood circulation of the area of osteonecrosis is re-established, any mechanical treatment of the fracture is futile.

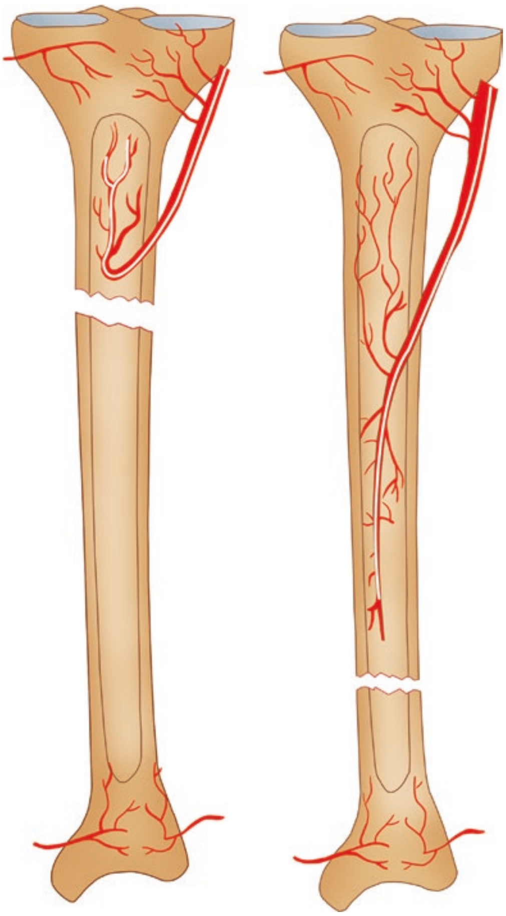


Fig. 5.2 Loss of the blood supply to the fracture fragment in a bone that receives blood from only one source: Taking the tibial shaft as an example, it receives blood from a single nutrient vessel so that its distal fragment will lose its blood supply once it is fractured

- Mechanical stability:

  Osteopenia of open fractures caused by high energy can lead to poor mechanical stability after internal fixation (Fig. 5.4).

  Selection of an improper internal fixation device (e.g., application of the one-third circular steel plate with low strength, Kirschner wire, and ultra-fine intramedullary nail for fixation) can cause poor mechanical stability. When the degree of activity at the fracture ends exceeds the range that the osteoblasts can withstand, the repeated activities will cause fatigue fracture of the steel plate.

  Application of an incorrect fixation conception, such as leaving a gap between the fracture ends of a simple fracture without achieving contact and pressurization, can lead to excessive stress concentrated at the fracture end steel plate.

  In bones where the mechanical structure is special, for example, the proximal femur, poorly reduced fracture or fractured bone with a residual varus deformity may lead to excessive prolongation of the lever arm and internal fixation failure.
- Infection (Malik et al. 2004; Toh and Jupiter 1995) (Fig. 5.5):

  Infection of the fracture ends and peripheral soft tissues is the direct cause of nonunion.

  Infection can lead to noxious vascular occlusion and fracture necrosis.

  Infectious granulation tissue grows into the fracture ends, resulting in poor contact at the fracture ends.

  Infection can also lead to loosening of the internal fixation, resulting in mechanical instability.
- Poor contact at the fracture ends and bone defects (Frangakis 1966):

  Direct contact between the viable fracture ends or fracture fragments facilitates fracture healing.

  Soft tissue insertion, poor fracture reduction, fracture separation, and bone defects can lead to poor contact at the fracture ends, resulting in fracture healing failure.

- Understanding plate breakage:
  - When the amplitude and strength of the limb movement exceed the load limit of the internal fixator, the internal fixator becomes fatigued and broken.
  - The main causes of internal fixator fracture are as follows:

    Nonunion: Any fixation of the nonunion fractures is temporary. The relationship between the fracture and internal fixator is interpreted as a competitive relationship. Under normal circumstances, as the fracture heals, mechanical loading on the internal fixator will gradually be shared, and the effect of internal fixation will gradually be lost after fracture

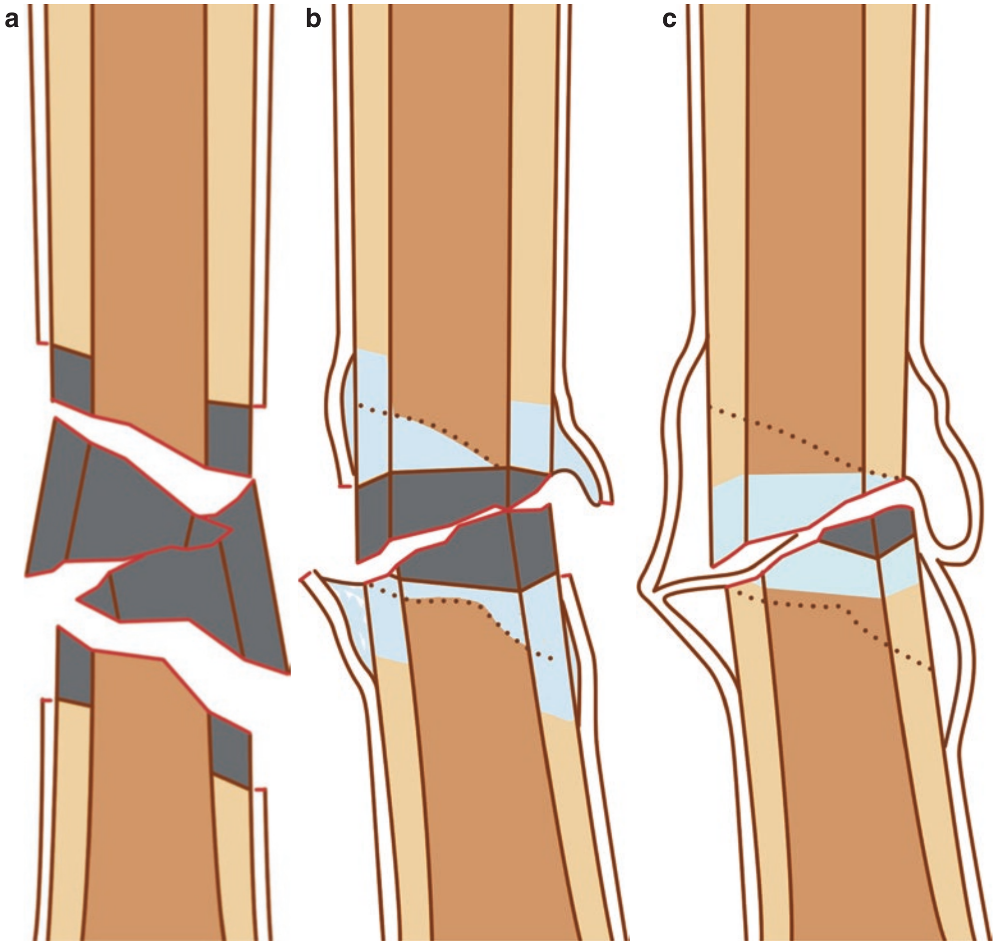


Fig. 5.3 (**a**) In the case of complex fractures, the free bone fragments at the fracture site are ischemic (dark areas in the figure). (**b**) Several months after the fracture, the two fracture fragments have united with their corresponding main bone ends via callus formation, but the central area of the fracture remains ununited. (**c**) Several years after the fracture, the unhealed area of the fracture is still present despite the progress of periosteal osteogenesis and creeping substitution

healing. If the fracture does not heal within a predetermined period, internal fixation under repeated stress will cause complications, such as fatigue fracture or screw loosening, especially in the presence of a bone defect.

Improper application of internal fixation: Incorrect selection of the internal fixation, a nonstandard operation, poor surgical techniques, and an insufficient understanding of the fracture can lead to a failed internal fixation. Two principles, including biomechanics and biology, should be considered during internal fixation. On the premise of sacrificing the blood supply to the soft tissue, excessive anatomical reduction leads to delayed bone healing and even nonunion, which is another major cause of steel plate fracture (Perren 2002).

Inappropriate functional training: In the initial stage of internal fixation when the fracture is not healed, excessive functional training will exceed the mechanical limit of the stainless-steel plate, and fatigue fracture will occur.

Quality problem of the internal fixator: With the advancement of casting and processing technology, the quality of internal fixator has gradually improved. Plate breakage due to quality problems of internal fixation is very rare.

5.1.3 Nonunion Classification

- The Weber-Cech classification (Weber and Cěch 1973) has been widely used for nonunion classification. Through radiographic testing, bone absorption of strontium-85 radionuclide, and histopathology, nonunion is classified into two major categories (i.e., hypervascular nonunions and avascular nonunions) based on the blood supply and the regenerative activity of the fracture ends:
  - Hypervascular-vitalized nonunions: These nonunions are subdivided into the three subcategories as follows (Fig. 5.6):

    "Elephant foot" nonunion: Hypertrophic at the fracture ends with exuberant callus formation and good activity, which are mostly associated with factors such as unstable fixation, inadequate immobilization, or premature weight-bearing.

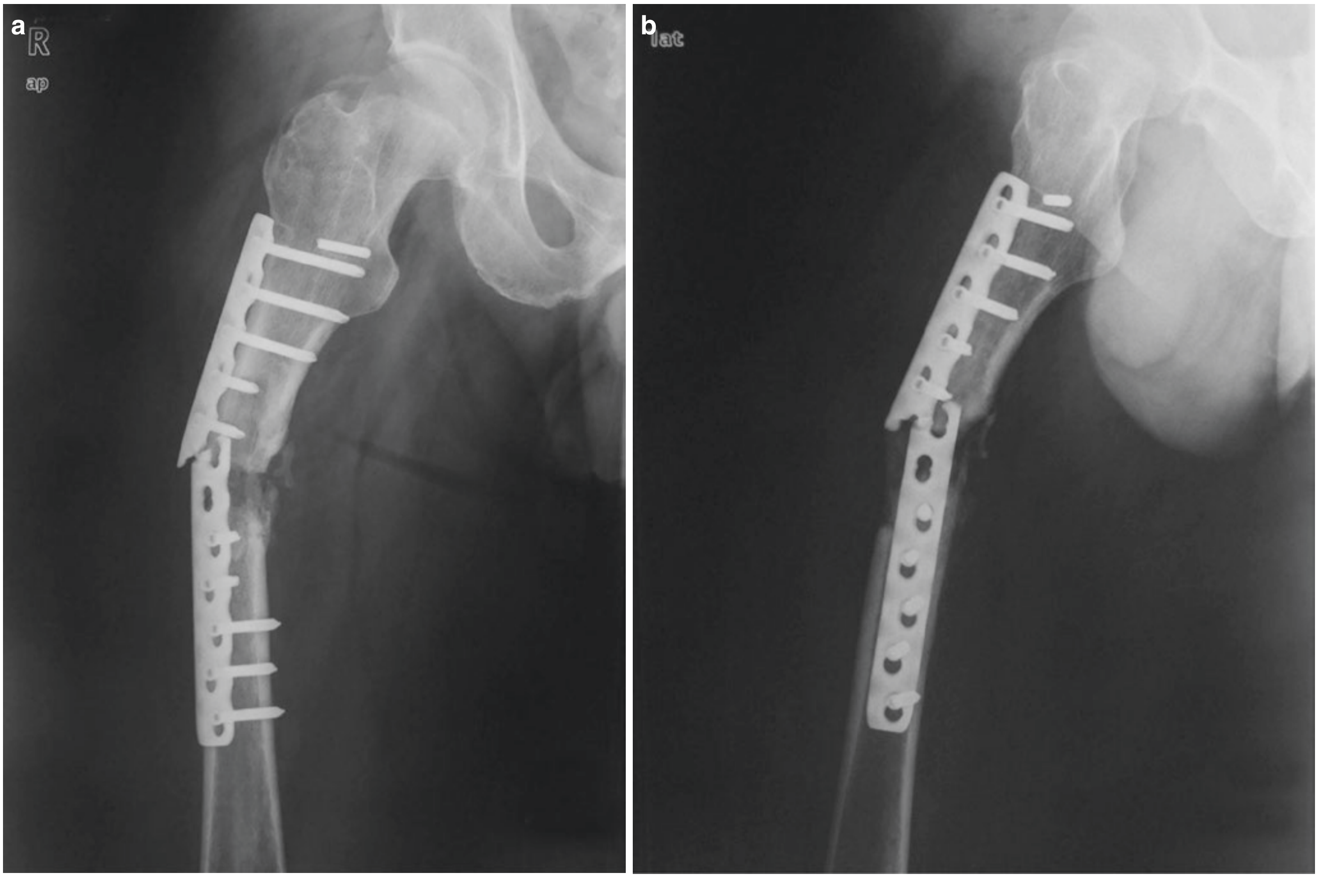
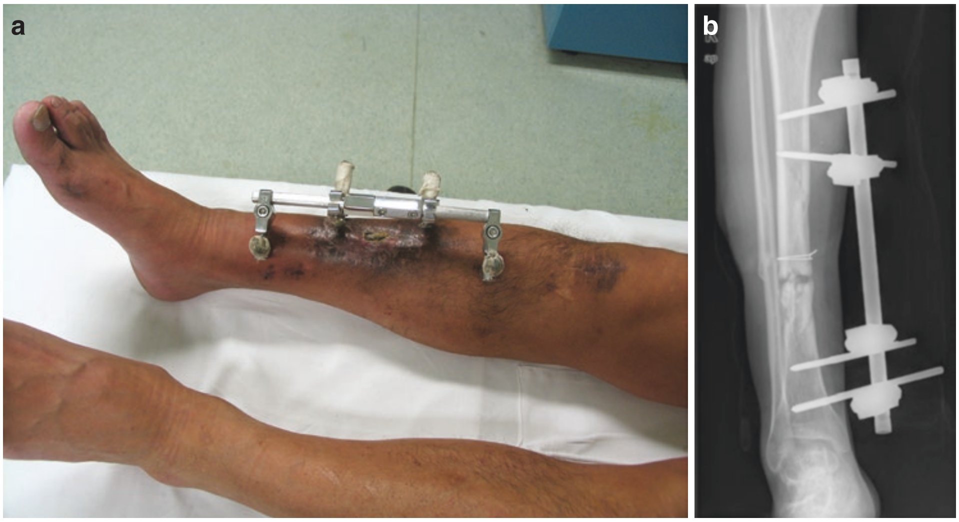


Fig. 5.4 Due to insufficient support caused by the medial bone defect of the femur, the internal fixator is severely mechanically unstable, and the plate is fatigued and broken. (**a**) AP view. (**b**) Lateral view

Fig. 5.5 A patient with infectious nonunion. (**a**) There is a local cutaneous sinus and purulent secretion. (**b**) A radiograph: The absorption at the fracture site is visible; a cerclage wire remains in its place; there is the formation of sequestrum and sclerosis



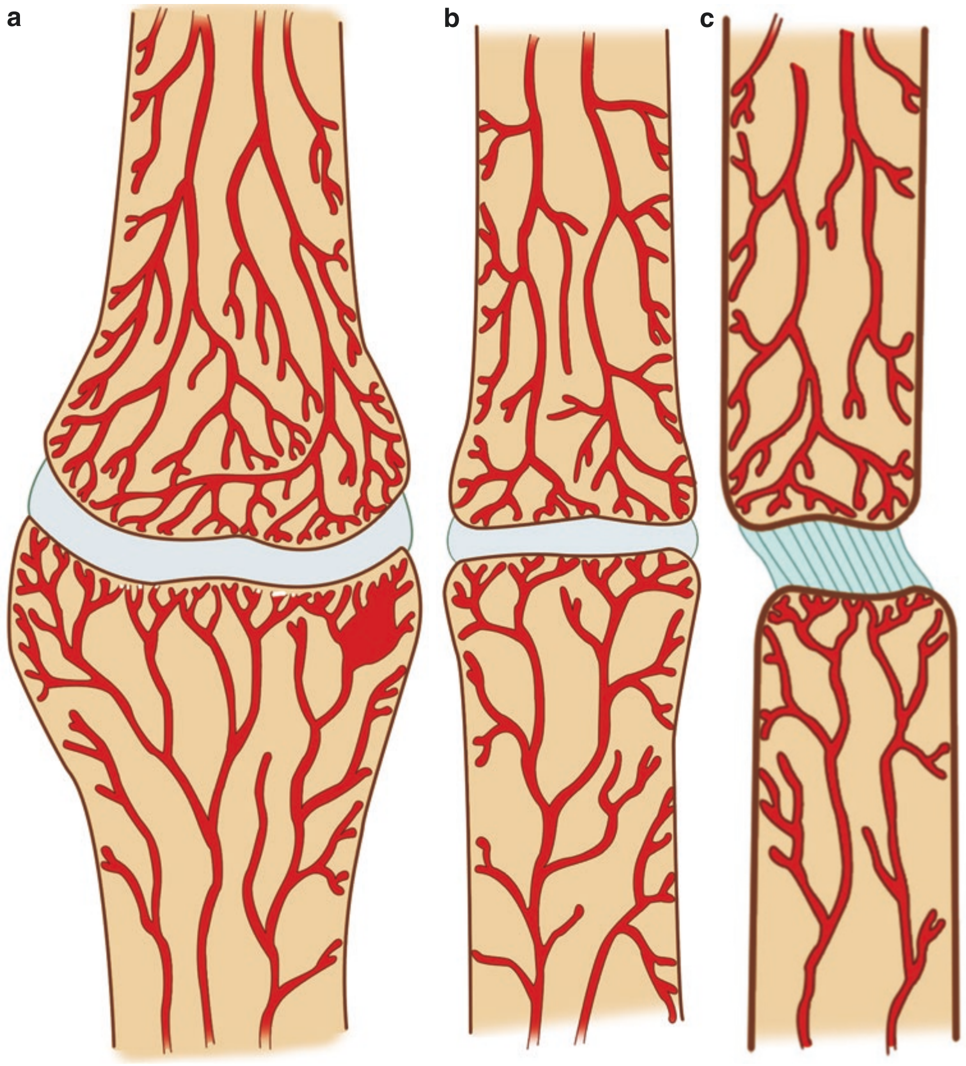


Fig. 5.6 Classification of hypervascular-vitalized nonunions. (**a**) "Elephant foot" nonunion. (**b**) "Horse hoof" nonunion. (**c**) Oligotrophic nonunion

"Horse hoof" nonunion: Moderately hypertrophic at the fracture ends with less exuberant callus formation, which are mostly associated with moderate instability after internal fixation with plates and screws. A certain callus is formed at the fracture ends but is insufficient for fracture healing. A small amount of fracture end hardening may occur.

Oligotrophic nonunions: The fracture ends have poor blood circulation but demonstrate the formation of blood vessels and a callus. Oligotrophic nonunions are often associated with severely displaced and clearly separated fracture ends or poor fracture reduction.

– Avascular-devitalized nonunions: They are subdivided into four subcategories as follows (Fig. 5.7):

Torsion wedge nonunions: The intermediate wedge fragment in the fracture region has a reduced or absent blood supply. This wedge fragment heals to one side of the main fragment but not to the other end. Torsion wedge nonunions are often secondary to a wedge fracture of the tibial shaft fixed with steel plates and screws.

Comminuted nonunions: In comminuted nonunions, necrosis occurs in one or more intermediate fragments in the fracture region, and no sign of callus formation is shown in the radiographs. Comminuted nonunions are often secondary to the comminuted fractures fixed with steel plates and screws.

Defected nonunions: Defected nonunions have segmental loss in the diaphysis of long bone. The fracture ends are initially viable, but fracture healing cannot be achieved through the defect area. As time passes, the fracture ends become atrophic. Defective nonunions are often secondary to open fractures, surgical osteotomy due to osteomyelitis, or bone tumor resection.

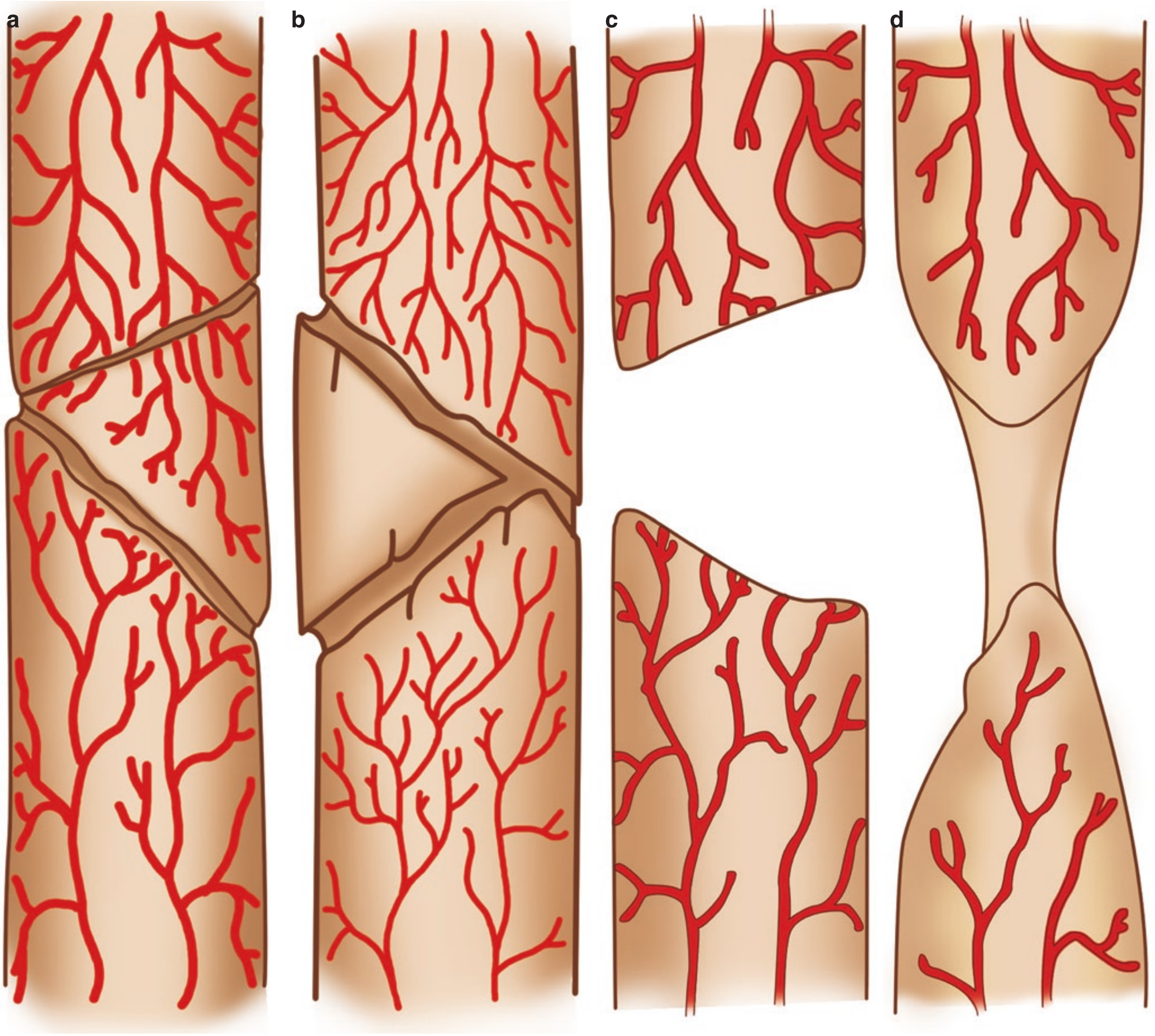


Fig. 5.7 Avascular-devitalized nonunions. (**a**) Torsion wedge nonunions. (**b**) Comminuted nonunions. (**c**) Defected nonunions. (**d**) Atrophic nonunions

Atrophic nonunions: Atrophic nonunions are osteoporosis and atrophy at the fracture ends and are secondary to the absence of intermediate fragment scar tissue lacking osteogenic potential, which is embedded into the fracture ends.

- The above nonunion classification is based on the local blood supply and anatomical morphology. The classification based on etiology has more guiding significance for the clinical treatment of nonunion:
  - Hypertrophic nonunions:

    In hypertrophic nonunions, the biological environment of the fracture ends is favorable with good blood circulation and biological activities. An adequately stable biomechanical environment is absent at the fracture ends, and excessive activities at the fracture ends lead to exuberant, soft callus formation.

    The radiograph shows the hypertrophic "elephant foot" or "horse hoof" nonunion (Fig. 5.8).
  - Oligotrophic nonunions (Fig. 5.9):

    A lack of blood supply at the fracture ends due to trauma and iatrogenic injury affects the fracture healing, with or without accompanying bone defects.

    A fracture fragment lacking sufficient blood supply can be connected to the main fragment but rarely achieves union between the two fragments due to an inadequate blood supply.

A type of nonunion between hypertrophic nonunions and atrophic nonunions that belongs to an intermediate state between the two nonunions.

- Atrophic nonunions (Fig. 5.10):

  The fracture ends are absorbed and diminished, accompanied by cortical bone thinning.

  The fracture fragments lacking a blood supply and force transmission become atrophic. The probability of atrophic nonunions in the upper limbs is relatively high.

  A radiograph showing the "rat-tail sign."
- Infected nonunions (Fig. 5.11):

  Surrounding pus and bone erosion, leading to bone infection accompanied by nonunion.

  Radiographs show a moth-eaten appearance, periosteal reaction, and sequestrum at the fracture ends.
- Pseudarthrosis (synovial pseudarthrosis) (Fig. 5.12):

  The fracture ends are filled with liquid in an enclosed mode, a pseudobursa, which is movable and similar to the joint structure.

  This condition often occurs in patients with conservative fracture treatment. It is caused by unstable fixation and early excessive activities of the patients.

Fig. 5.8 A radiograph showing the hypertrophic "elephant foot" or "horse hoof" nonunion

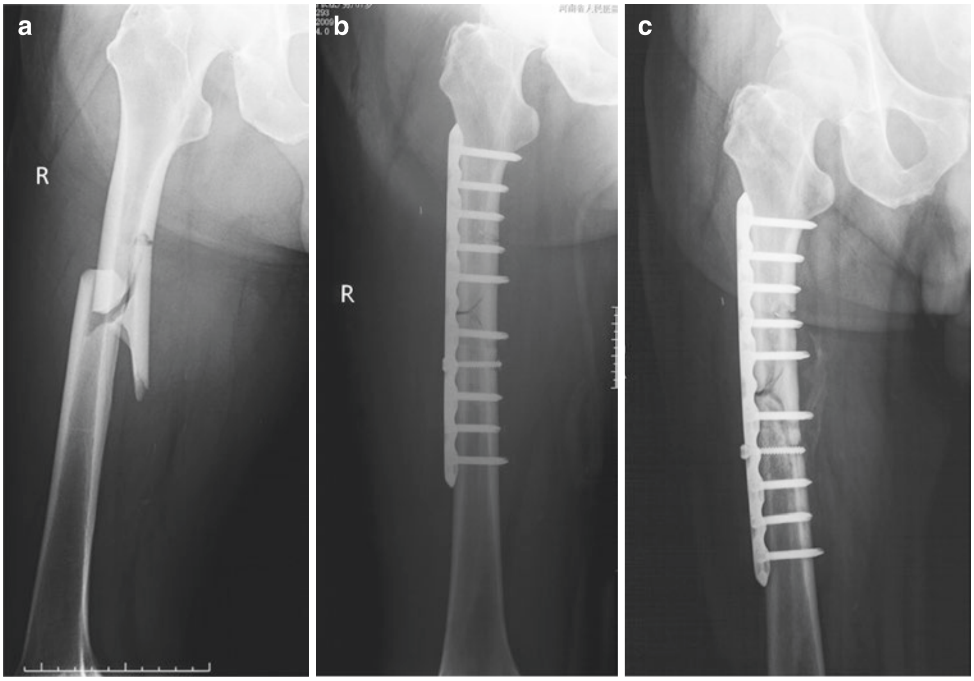


Fig. 5.9 Nonunion of the femoral shaft fracture after plate. (**a**) A preoperative radiograph showed a type B1 fracture. (**b**) Open reduction and internal fixation: The fracture was reduced anatomically. However, no compression was applied between the butterfly fragment and the main bone fragment, the plate was too short, and the screws were placed too close to each other, which inevitably generated a largely concentrated stress at the fracture site. (**c**) A radiograph obtained at 7 months after the operation: The butterfly fragment was not united with the main bone fragments on both sides, the fracture gap was enlarged, and the callus growth was not noticeable

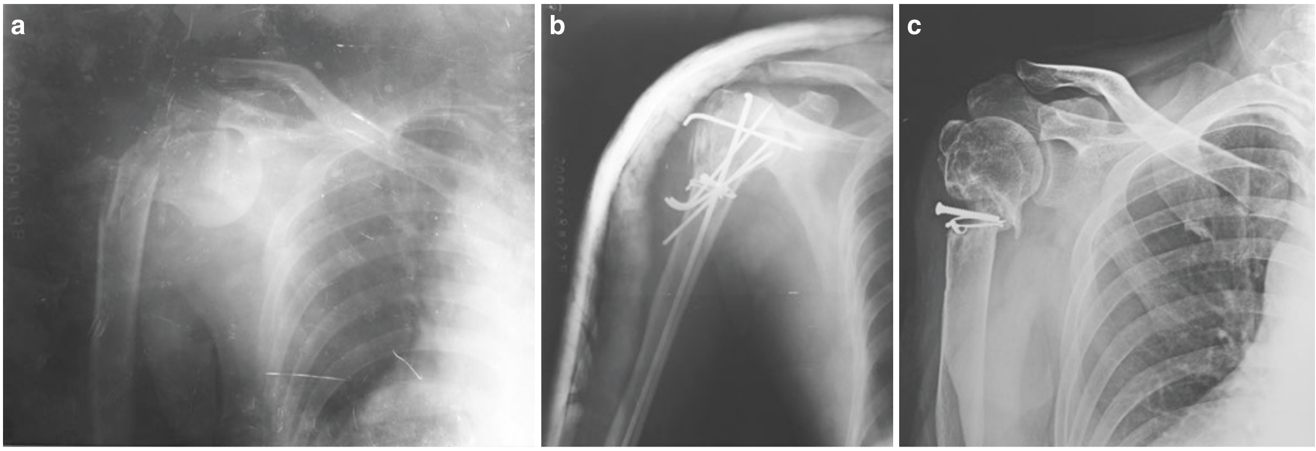


Fig. 5.10 A surgical neck fracture of the humerus. (**a**) A preoperative radiograph. (**b**) The fracture was treated with open reduction and screw fixation, wire binding, and Kirschner-wire fixation, and the affected extremity was then immobilized with a plaster cast after surgery. (**c**) The Kirshner wires were removed at 4 months after surgery. The radiograph obtained at 16 months after surgery displayed bone absorption of the fracture site and atrophic nonunion

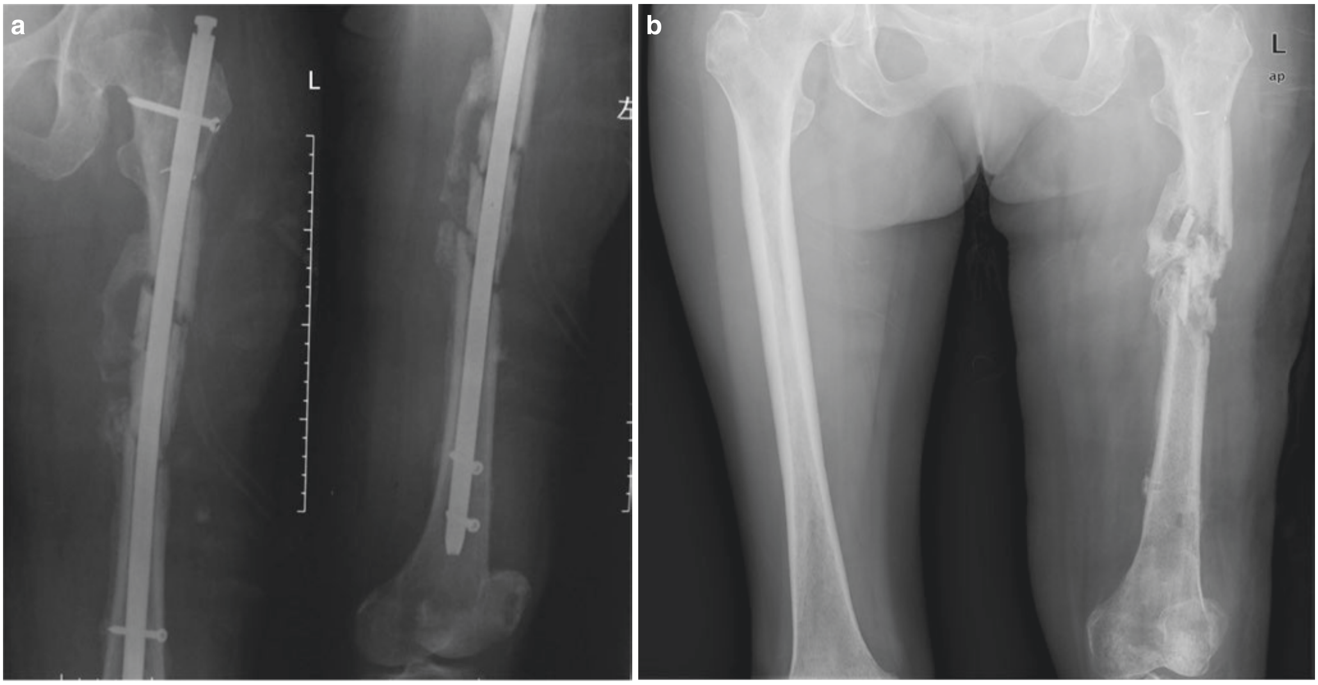


Fig. 5.11 (**a**) The patient with a left femoral shaft fracture had a postoperative infection after intramedullary nail. (**b**) The patient underwent removal of the nail, followed by catheterization and lavage for infection control; however, secondary infectious nonunion occurred. Periosteal reaction and sequestrum are present in the radiograph

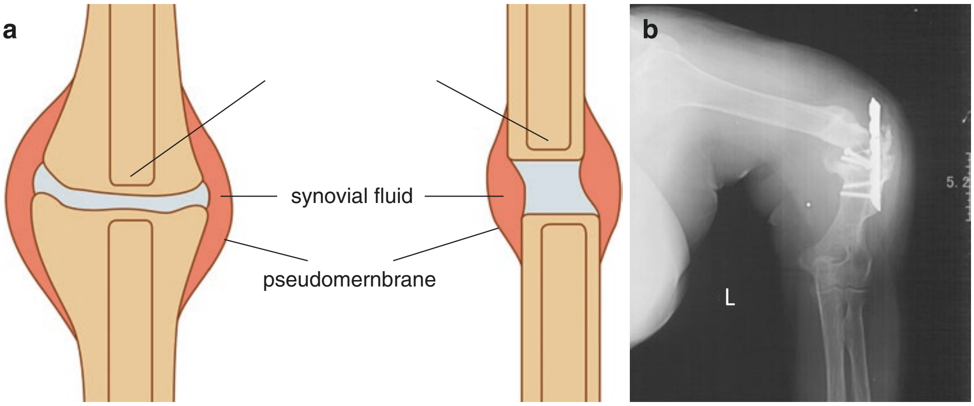


Fig. 5.12 (**a**) Schematic diagram of pseudarthrosis showing the pseudobursa, synovial fluid, and bone marrow cavity occlusion. (**b**) A radiograph of a patient with a left humeral shaft fracture who received open reduction and internal fixation but subsequently suffered pseudarthrosis due to plate fixation failure

5.1.4 Diagnosis and Evaluation

- The differential diagnosis of postoperative pain includes nonunion, infection, traumatic arthritis, nerve injury or neuroma, joint stiffness or joint fibrosis, unstable fracture fixation or malunion, complex regional pain syndrome, and the impact of the internal fixation device.
- Diagnosis:
  - After 9 months of fracture treatment, the active limbs present pain and local abnormal activities, and nonunion should be highly suspected.
  - After internal fixation of the fractures, even if nonunion occurs, as long as internal fixation is firmly attached, abnormal activities will not resume.
  - However, if the plate is broken, the nonunion will be clearly diagnosed.
- Imaging evaluation:
  - Correct classification and evaluation are very helpful in determining the treatment plan and prognosis.
  - Standard anteroposterior and lateral position: Internal fixation obstruction sometimes challenges an accurate visualization of the fracture line; under this circumstance, the addition of oblique radiography and stress radiography will help determine the stability of the internal fixation.
  - Signs of nonunion: (Connolly 1991).

    The X-ray diagnostic rate of nonunion is greater than 90%.

    Typical performance: Discontinued trabecular structure between calluses; gap between fracture ends; fracture end hardening; medullary cavity closure; atrophic and diminished fracture ends; osteoporosis; failed internal fixation; pseudoarticulation formation; and stress radiography showing instability at the fracture ends.
  - Computed tomography (CT) can more precisely evaluate the range and severity of nonunion because it is not affected by the shielding effect of internal fixation (Weitzel et al. 1994) (Fig. 5.13).
- Laboratory evaluation:
  - Evaluation of general conditions: Complete blood count, biochemistry, electrolytes, and even immune and hormonal response tests are performed to focus on evaluating the patient's nutritional status, metabolic status, and comorbidities.
  - Inflammatory indexes: Erythrocyte sedimentation rate and C-reactive protein not only suggest the diagnosis of infection but also serve as a dynamic monitoring indicator for the effective treatment for infection.
  - Etiological examination: Puncture biopsy and microbe culture of the nonunion site is performed to identify the pathogen types and to select sensitive antibiotics.
- Comprehensive evaluation:
  - Location of nonunion: Intra-articular, metaphyseal, and diaphyseal fractures of the long bones.
  - Accompanied or not by deformation.
  - Presence of active infection.
  - With or without a bone defect or loss of soft tissue coverage.
  - With or without the formation of pseudoarticulation covered by synovia.
  - To determine the local blood supply according to the types of nonunions.
  - With or without internal fixation instability.

Fig. 5.13 Radiography at 15 months postoperatively of a patient who underwent intramedullary nail fixation after debridement for an open fracture of the femoral shaft. (**a**) Lateral radiograph: The anterior cortex of the two fracture ends shows slight signs of re-connection. (**b–d**) Fracture nonunion was confirmed by both CT plain scan and sagittal reconstruction on continuous slices

5.2 Treatment for Nonunions

5.2.1 Treatment Principles

- General principles:
  - Removal of unstable internal fixation.
  - Treatment of infectious agents: Debridement of infected and necrotic bone or soft tissues and the application of systemic or topical antibiotics.
  - Deformity correction.
  - Treatment of bone defects: Bone grafting, bone grafting with vascular pedicle, bone transport techniques, etc.
  - Treatment of fracture ends: Medullary cavity recanalization, decortication, and other surgical techniques to improve the blood supply to the fracture ends.
  - Rigid internal fixation.
  - Local biological stimulations (e.g., autologous bone grafting) to promote healing, and application of biological factors to promote the recovery of the blood supply, including bone morphogenetic protein (BMP), intramedullary blood, and stem cell therapy.
  - Reconstruction of adequate soft tissue coverage.
  - Loosening of adjacent joints and restoration of joint movement.
- Principles of individualized treatments.
  - Hypertrophic nonunions:

    Adequate blood supply at the fracture ends with mechanical instability.

    The core of treatment is to enhance the stability of the fracture ends by compression via external fixators, replacement of an existing intramedullary nail with a larger diameter intramedullary nail, etc.

    Fracture end treatment and bone grafting are usually not required.

    In the case of deformity and shortening, partial bone grafting is required after correction.
  - Oligotrophic nonunions:

    Lack of blood supply, malnutrition, and poor contact at the fracture ends.

    Rigid internal fixation and massive bone grafts are required.
  - Atrophic nonunions:

    No vitality, malnutrition, and atrophy at the fracture ends.

    Both biological and biomechanical factors must be considered to improve the local blood supply and achieve stable internal fixation. In addition, massive bone grafts are required.
  - Infected nonunions:

    Infection control and removal of the sequestrum, scar tissue, and granulation tissue from the fracture ends.

    The connection of fractured bones should be completed by bone grafting and bone transport.
  - Pseudarthrosis (synovial pseudarthrosis):

    The fracture fragments have an adequate blood supply, and the treatment methods are similar to those for hypertrophic nonunions.

    Due to the bone shortening after fracture, medullary activity canalization/recanalization, robust fixation, and bone grafting are necessary.
- Clinical decision for the treatment of nonunions:
  - The first step is to determine if it is an infected nonunion. The therapeutic strategy for infected nonunions differs greatly from that for non-infected nonunions, and infected nonunions should be treated specifically. The 301 Hospital (The General Hospital of the People's Liberation Army) often adopts bone transport techniques to treat infected nonunions. The advantages of the bone transport techniques are the complete removal of the sequestrum at the infected site and complete control of the infection. Repair of the bone defect through bone transport techniques achieves bone healing between healthy bone tissues and reduces the risk of refracture.
  - The decision regarding the therapeutic strategy for non-infected nonunions is based on distinguishing the cause between mechanical instability or destruction of the local biological environment.

    For non-infectious nonunions caused by destruction of the local biological environment, local stimulation via decortication, recanalization of the medullary cavity, bone grafting, and medullary blood injection should be adopted.

    For non-infectious nonunions with mechanical instability, the stabilized fracture end should be targeted, and the selection of a specific therapeutic strategy should be integrated with various factors, such as fixation of the previous fracture, the validity of the internal fixation, the biomechanical properties of the fracture site, and the severity of the bone defect.

5.2.2 Surgical Treatment

1. Debridement of the fracture ends and decortication: (Judet 1965; Cech and Stryhall 1967).
   a. The first step: Scar tissue and necrotic bone tissue, which hinder fracture healing, are removed to achieve active bone healing and restart the bone healing process.
   b. When treating nonunion fracture ends, cancellous bone grafting alone has a limited therapeutic effect. Decortication should be applied for the hardened frac-

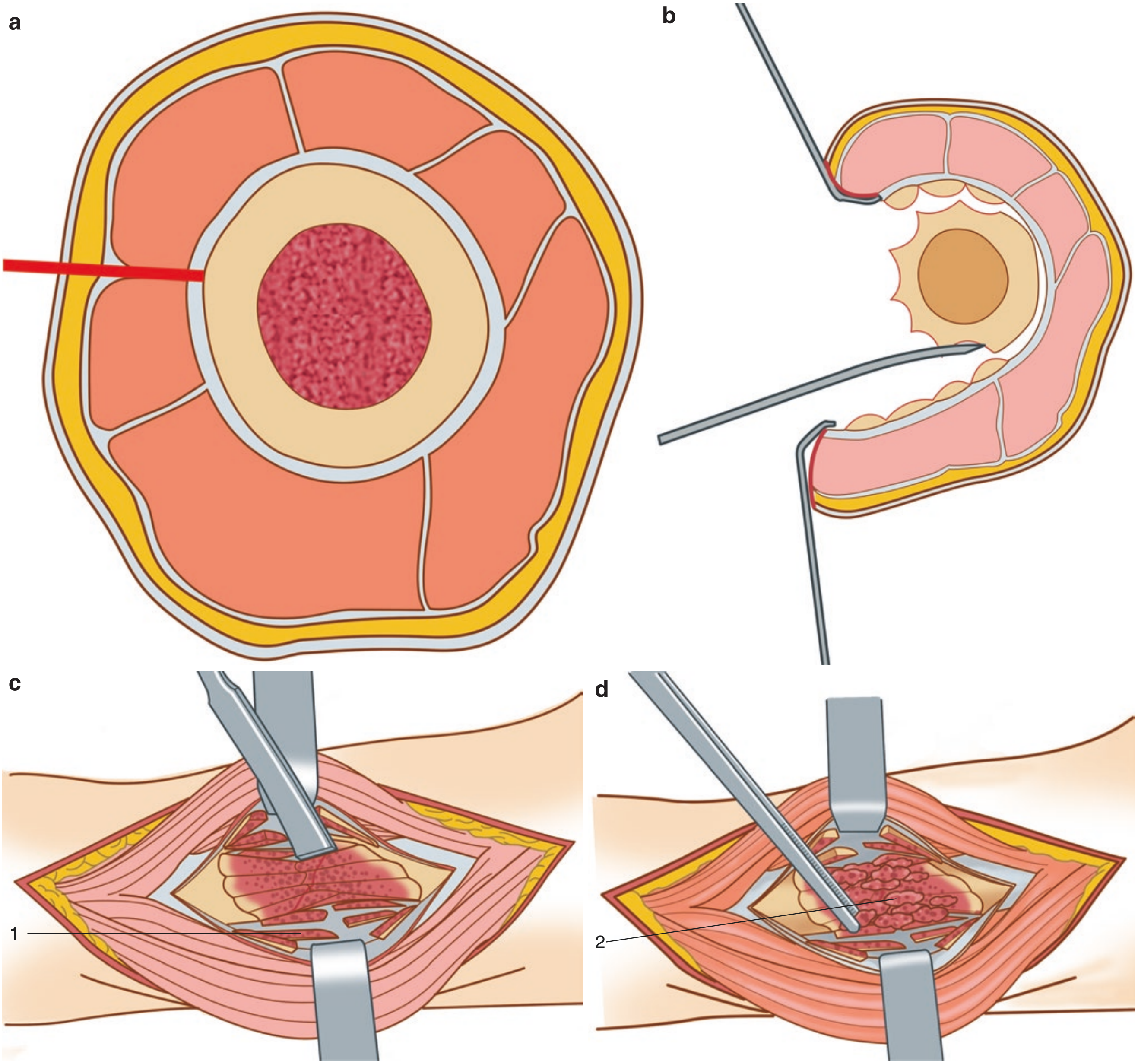
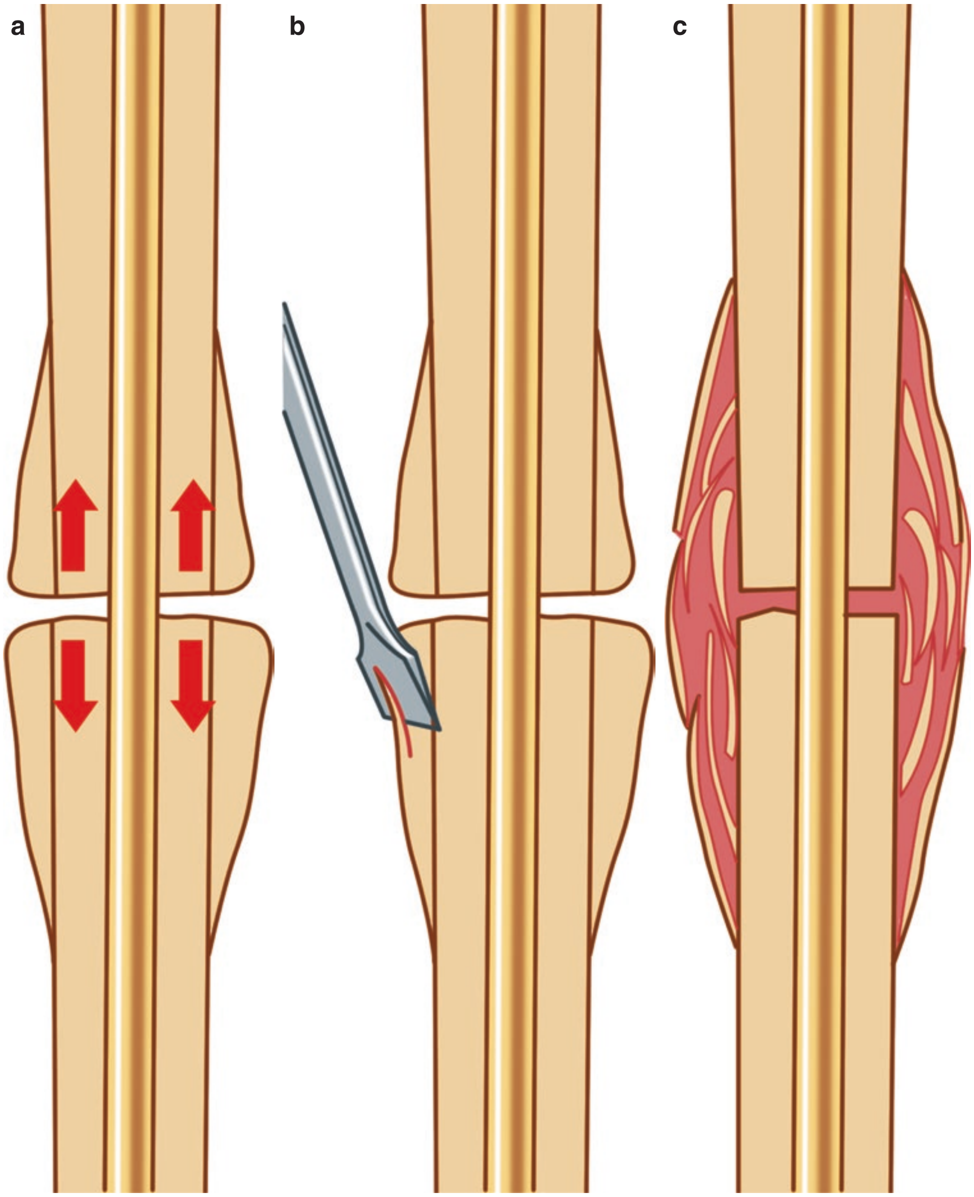


Fig. 5.14 Schematic diagram of decortication. (**a**) Most of the blood supply to the lateral cortical bone and callus is derived from the periosteum. (**b**, **c**) An osteotome is used to remove the cortical bone. It is crucial that the bone pieces should be attached to the periosteum and receive the periosteal blood supply (1 denotes the bone piece attached to the periosteum). (**d**) The decortication should be extended distally and proximally to sites more than 2–4 cm from the distal and proximal ends of the callus, and the autologous cancellous bone is transplanted in the cortical stripping area (2 denotes autologous cancellous bone)

ture ends. The keys of the surgical procedures are as follows:

- Exposure of the fracture ends: A skin incision is made up to the periosteum and without peeling the soft tissue. An osteotome is used to cut through the cortical bone in a ring but keep the cortical bone attached to the periosteum, muscle, and other soft tissues.
- An osteotome is used to cut the fracture end into thin slices to expose the fracture ends of the nonunion. The bone pieces should be attached to the periosteum, muscle, and soft tissues. These bone pieces have a very good blood supply and can be used as autogenous bone grafts with a blood supply to wrap the fracture ends of the nonunion (Figs. 5.14 and 5.15).
- Decortication is performed up to 8 cm in long tubular bones, such as the femur and tibia, and approximately 4–6 cm in the forearm bones. After decortication, medullary cavity recanalization is

Fig. 5.15 (**a**) Hypervascular-vitalized nonunion after intramedullary nail. (**b**) Thin cortical bone pieces with an abundant blood supply are stripped off from the fracture using an osteotome. (**c**) Implant into the cancellous bone to stimulate fracture healing



performed to treat the fracture ends as described below.

- Common surgical errors/precautions in decortication:
  - A periosteal stripper is misused to directly expose the fracture ends.
  - For patients who require removal of the old steel plate, screw, or wire located just below the incision, the internal fixation should be removed prior to decortication; if the internal fixation is not underneath the incision, decortication should be carried out until the internal fixation is revealed, which can then be removed. Peeling of the periosteum to expose the internal fixation should be avoided; otherwise, the periosteal blood supply to the bone cortex will be destroyed, thereby reversing the beneficial effect of decortication.
  - As the bone pieces have a blood supply, electrocautery should be used to reduce bleeding.
  - The exposed/trimmed bone pieces should not be too thick because only the outer layer of the bone pieces is vascularized; the inner layer of the bone pieces may be hardened and dead. This layer of hardened bone would be an obstacle for postoperative recovery of the blood supply at the fracture ends.
- Decortication is one of the basic techniques for the treatment of nonunions. It can be applied alone or in combination with bone grafting and other techniques in the treatment hypervascular-vitalized nonunion with an adequate blood supply and

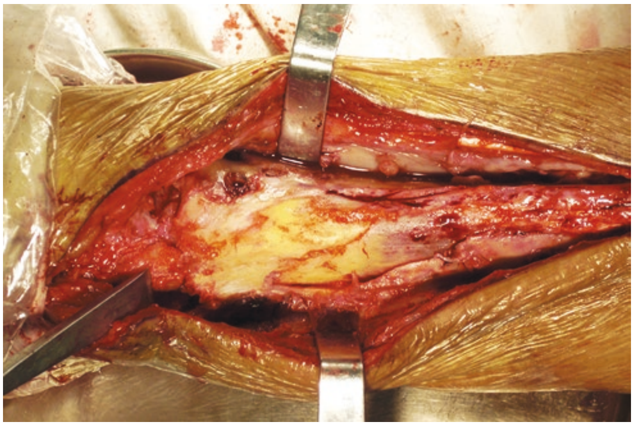


Fig. 5.16 Dead bone is waxy yellow in color and extremely hard. It is covered with scar tissue and does not bleed after stripping

avascular-devitalized nonunions with an inadequate blood supply.

c. Identification of the sequestrum is a common problem encountered in the treatment of fracture ends: Common indicators used for the identification of the sequestrum include the bone color, hardness, and hemorrhage after peeling the periosteum. Comparison of the bone color between living and dead bones shows that living bone is rosy and dead bone is waxy yellow in color. Dead bone is harder than living bone. Hemorrhage is observed on the living bone surface after peeling the periosteum, whereas no hemorrhage is found on the dead bone surface after removing the scar tissue (Fig. 5.16).
d. For infected nonunions, in addition to removing the vitalized tissue on the fracture ends as aforementioned, thorough debridement is necessary to control the infection.

2. Medullary cavity recanalization (Figs. 5.17 and 5.18):
   a. For hardened nonunions with an inadequate blood supply, compression fixation at the fracture ends can hardly achieve fracture healing. Therefore, combination therapy together with decortication and recanalization of the medullary cavity will be necessary.
   b. A suitable drill bit should be used to canalize the hardened medullary cavity so that the fracture fragments can receive intramedullary blood and achieve a biological environment that is favorable for fracture healing.
   c. The above procedure should be carried out precisely to only canalize the hardened tissues at the fracture ends and allow a connection between fracture ends and the medullary cavity. Deep drilling should be avoided to prevent damaging the intramedullary blood supply (Marti and Kloen 2010).
3. Bone grafting:
   a. Bone grafting is an important method for the treatment of nonunions. Its therapeutic effects are based on the grafting materials and methods:
      - For bone regenerations: The grafts contain active osteoblasts and periosteal cells for direct osteogenesis.
      - For osteoinduction: The grafts contain growth factors to recruit local mesenchymal cells and promote cellular differentiation.
      - For osteoconduction: The grafts provide a scaffolding structure for creeping substitution.
   b. Graft materials (Marti and Kloen 2010):
      - Autologous bone is still considered the gold standard among graft materials despite the donor site complications. It contains all the functions of bone regeneration, osteoinduction, and osteoconduction, which are incomparable to allogeneic bone and artificial bone substitute material.
      - If the bed for bone grafting in nonunion surgery is poor, grafts with dual properties of osteoinduction and osteoconduction should be selected. Allogeneic bone will only be considered if autologous bone is not available or is insufficient for the grafting.
      - Synthetic graft materials with only osteoconduction properties have a high failure rate in bone grafting and should be used with caution.
   c. Many graft shapes and bone grafting techniques are available, and several bone grafting techniques are often used in combination in clinical practice.
   d. Common methods used to harvest autologous bone as bone grafting materials:
      - Iliac bone graft harvesting (Fig. 5.19):
        - The iliac graft is the most preferred autologous bone graft in the whole body. Other autologous bone grafts, including the greater trochanter, tibial plateau, and medial malleolus, have higher risks of damaging the mechanical properties and causing a secondary fracture compared with the iliac graft.
        - Different bone grafting materials, such as cancellous bone, the cortical-cancellous bone strip, and the cortical-cancellous bone plate, are obtained from the harvested ilium.
        - Anterior approach:

          The patient is placed in the supine position with extra padding underneath the hip on the side where the ilium will be harvested.

          An arc-shaped incision is created parallel to the iliac crest. Attention should be paid to preserve the lateral femoral cutaneous nerve distal through the anterior superior iliac spine.

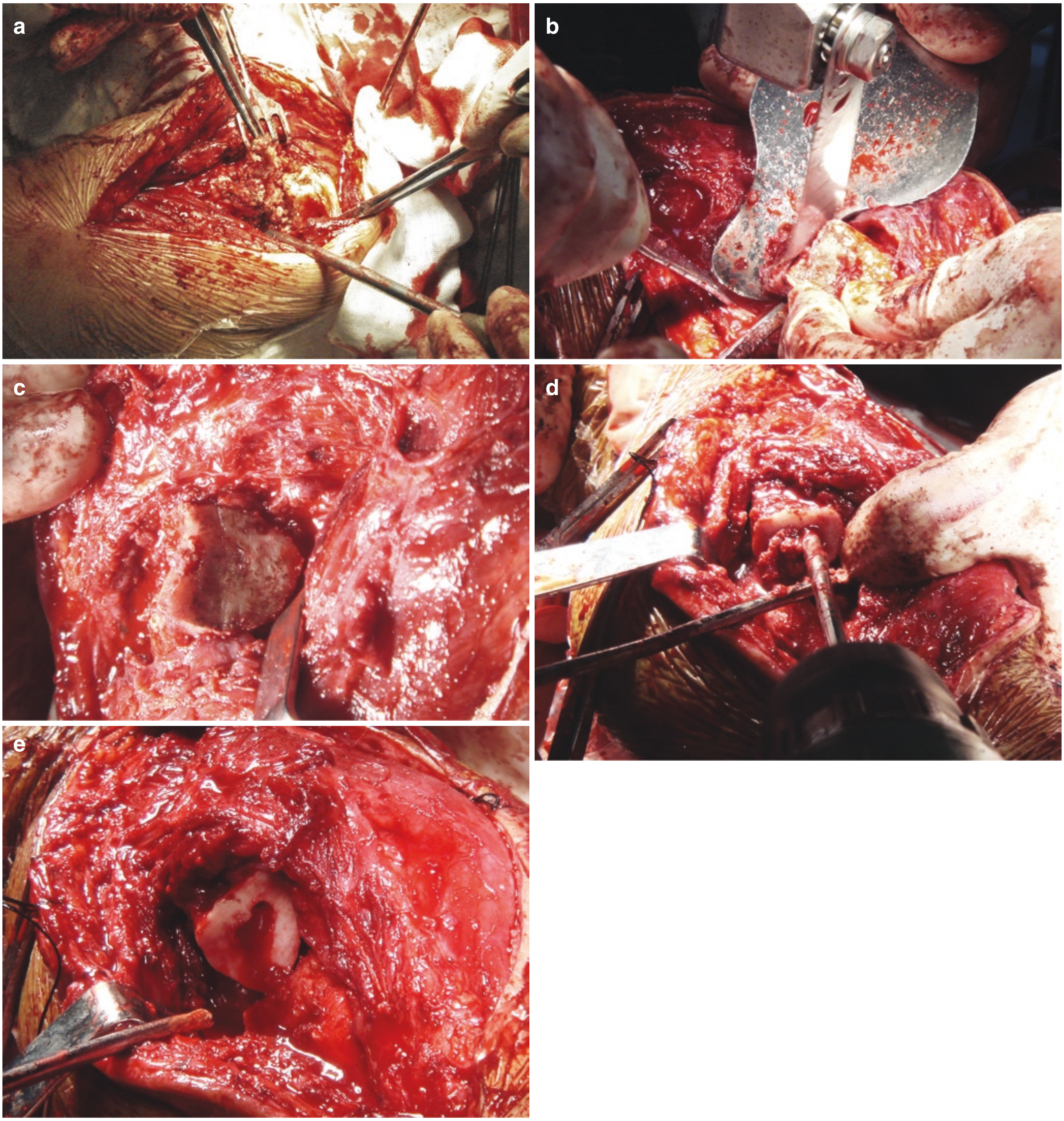


Fig. 5.17 Surgery for patients with atrophic nonunion of the humeral shaft. (**a**) The fracture site was debrided and cleaned, and the devitalized scar tissue intercalated between the fracture ends was removed. (**b**) The atrophic and hardened fracture end was removed by cutting. (**c**) The closed medullary cavity appeared after the fracture end was cut off. (**d**) The closed medullary cavity was drilled using an electric drill. Cooling with normal saline is important at the same time of drilling/grinding to avoid thermal necrosis caused by overheating. (**e**) Blood outflowing from the medullary cavity indicated re-opening of the medullary cavity

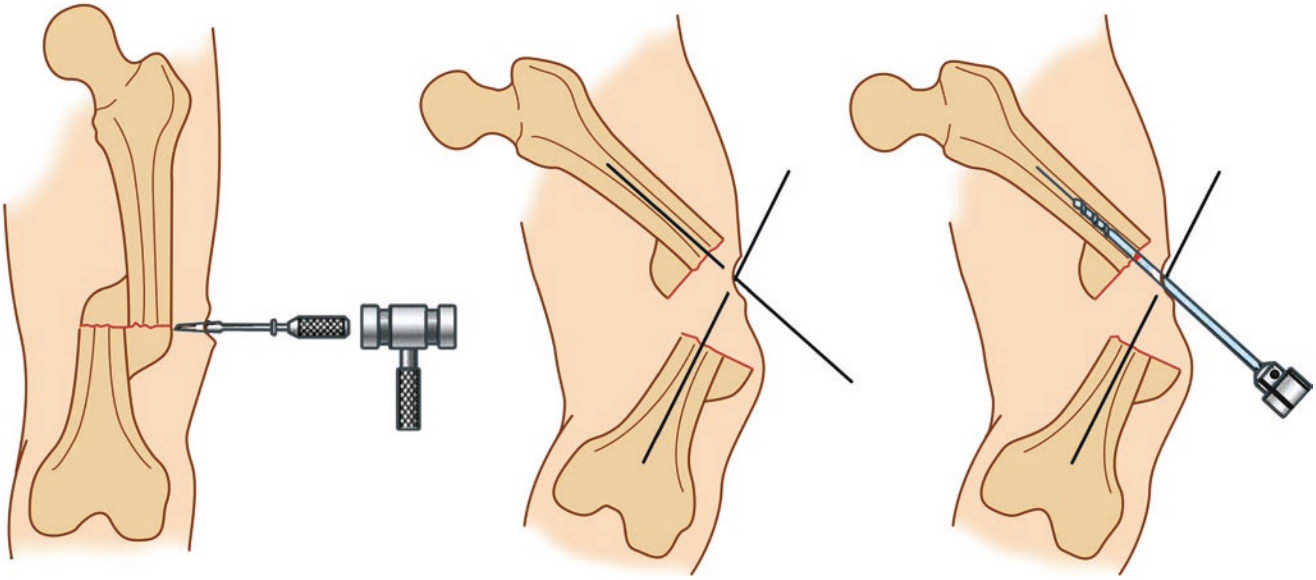


Fig. 5.18 For a displaced malunited fracture, the fracture ends are cut off first, and then the medullary cavity is recanalized after the insertion of a guide wire

Subperiosteal stripping should be performed when exposing the ilium. Electrical cautery is forbidden in the medial part of the periosteum and soft tissue flap to avoid damaging the iliohypogastric nerve and ilioinguinal nerve.

Cancellous bone harvesting: A sharp spatula is used to scrape the cancellous bone granules.

Cortical-cancellous bone strip harvesting: A curved osteotome is used to scrape the cortical-cancellous bone strip.

Cortical-cancellous bone plate harvesting:

- Direct harvesting of the bone plate: The target bone plate is harvested by drilling at a distance of more than 2 cm behind the anterior superior iliac spine. An area too close to the anterior superior iliac spine should be avoided during harvesting, as it may lead to a fracture of the anterior superior iliac spine or an avulsion fracture of the sartorius muscle after surgery.
- The Wolfe-Kawamoto technique: If the iliac crest is not needed, subperiosteal stripping can be performed, followed by wedge-splitting of the surface of the iliac crest to harvest the target bone plate and suturing of the internal and external surfaces of the layer of bone plate to maintain the appearance of the iliac crest (Wolfe and Kawamoto 1978).

Hemostasis and incision closure: Bone wax and gel foam are not recommended for stopping hemorrhages. Instead, thrombin powder is recommended, followed by careful suturing of the incision and placement of a catheter for negative pressure drainage for 24–48 h.

– Posterior approach:

The patient is placed in the prone position. An incision is created perpendicular to the direction of the posterior superior iliac spine and approximately 8 cm lateral along the posterior superior iliac crest, where the region of superior cluneal nerves is located, to avoid damaging the nerves.

The remaining procedures are similar to those employed in the anterior approach.

– The ilium as an autologous bone graft:

Bone granule preparation and filling: The cancellous bone is trimmed into pea-sized bone fragments, which are filled in the voids at the bone end and possess strong osteogenic properties. Filling bone defects with bone granules is a reliable procedure; the bone granules are not easily washed away by tissue fluid. This procedure is often used in combination with other bone grafting methods.

Bone strip and fence grafting: The cancellous bone is trimmed into matchstick-shaped bone strips, which are evenly distributed

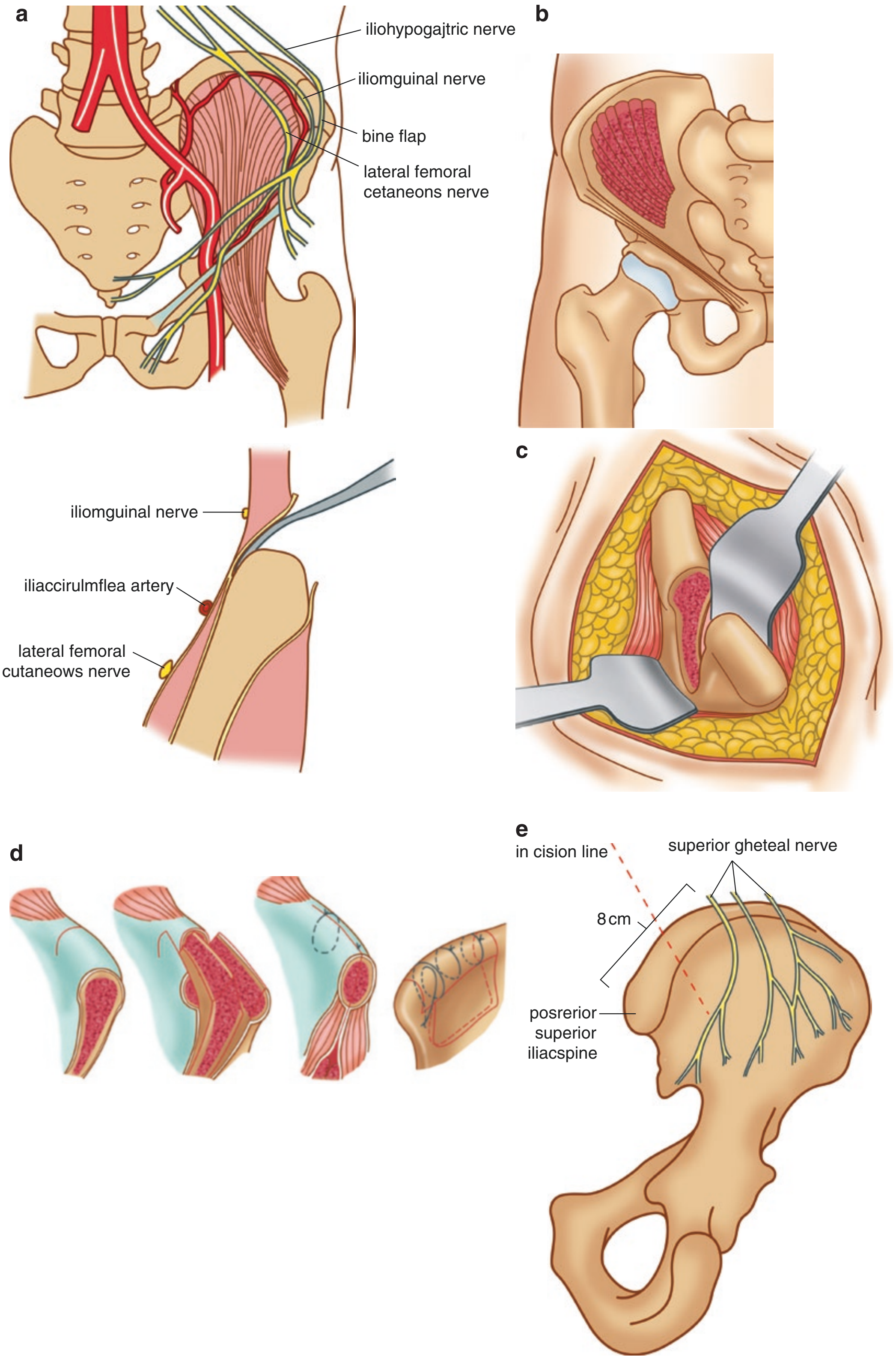
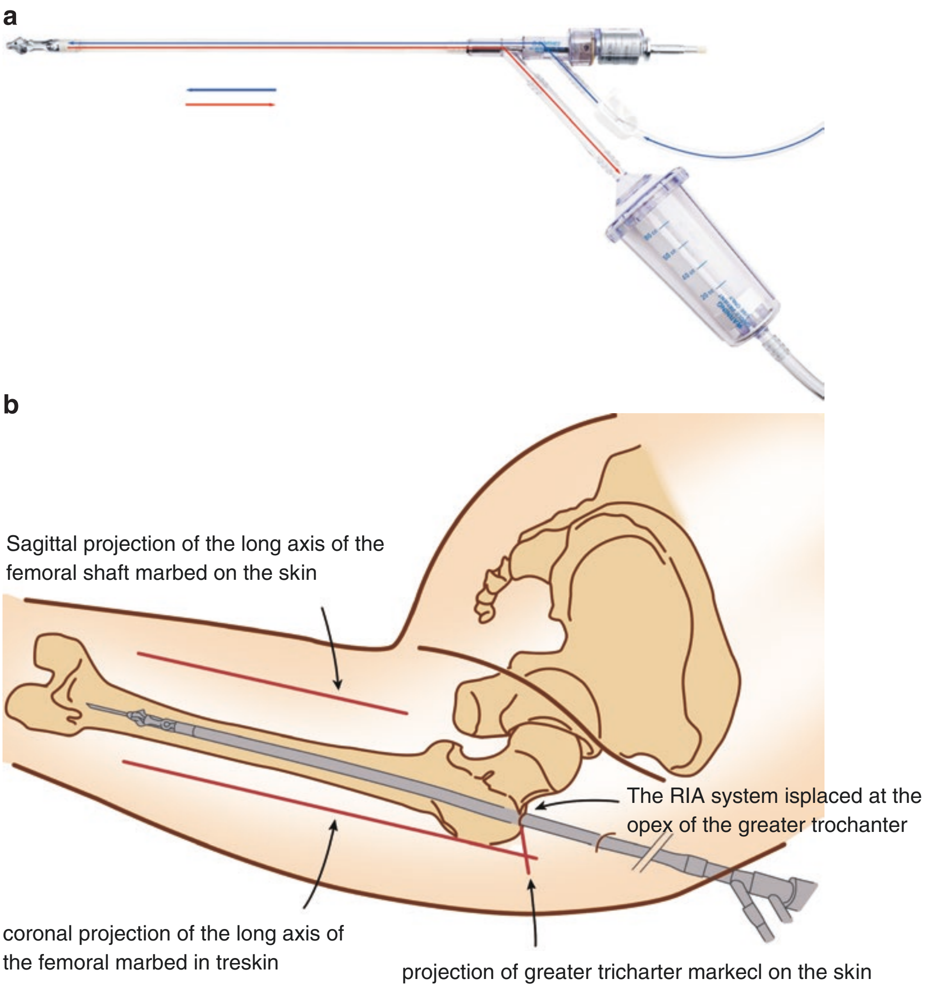


Fig. 5.19 Iliac bone graft harvest. (**a**) Because the ilioinguinal nerve, iliohypogastric nerve, and lateral femoral cutaneous nerve travel near the iliac crest and anterior superior iliac spine, the incision should not be lower than the anterior superior iliac spine. Subperiosteal stripping is performed to expose the iliac crest. It is noteworthy that the medial periosteum and soft tissue flaps should not be cauterized with an electric knife. (**b**) Cortical-cancellous bone strips can be harvested using a curved periosteal stripper. (**c**) The target bone is cut out at a site more than 2 cm posterior to the anterior superior iliac spine. (**d**) Wolfe-Kawamoto technique: After wedge-splitting of the medial and lateral edges of the iliac crest, subperiosteal stripping is performed, followed by removal of the required bone plate. Finally, the inner and outer layers are sutured to maintain the appearance of the iliac crest. (**e**) A schematic diagram of the incision for the posterior approach: The incision should not be created too close to the lateral side to avoid damaging the superior gluteal nerve

Fig. 5.20 (**a**) The reamer-irrigator-aspirator (RIA) system developed by Synthes can be used to obtain bone paste from the femoral medullary cavity. (**b**) Using this system, bone paste is obtained via intramedullary reaming similar to the technique used for intramedullary nailing of the femoral shaft



around and along the axis of the defect bone. The loose bone strips can also be bundled with wires to avoid loosening. The arrangement of the bone strips is similar to a fence and is therefore known as fence grafting. The bone strips must be placed 4 cm across each side of the fracture ends. The central region of the nonunion can generally have two to three bone graft layers.

Bone graft preparation and padding for grafting: When the bone defect is >2.5 cm, the ilium can be trimmed into three-sided cortical bone grafts, which are then embedded in the bone defect to, on the one hand, restore the bone connection and, on the other hand, maintain biomechanical support that is equivalent to structural bone grafting. Because this bone grafting method is like adding a bone pad, it is called padded bone grafting.

- Bone paste and its filling:
  - During the process of replacing the intramedullary nail of nonunions with a larger diameter intramedullary nail (see below for specific methods), medullary reaming bone paste will automatically be pressed into the gap of fracture ends to achieve the purpose of inlay bone grafting.
  - A reamer-irrigator-aspirator (RIA) system (Synthes, Paoli, PA) can be used for the same procedure as intramedullary nailing of femoral shaft fractures to obtain bone paste through reaming for bone grafting (Fig. 5.20) (McCall et al. 2010). Bone graft materials harvested by this method have bone regeneration and osteoinduction but no osteoconduction properties.
  - The cancellous bone quantity harvested by the above method is similar to the harvesting quantity from the anterior superior iliac spine and posterior superior iliac spine, with rapid recovery and less damage.
- Bone plate grafting: Bone plate grafts are harvested from the cortical bone plates of autologous long bone or allogeneic bone plates. Based on their mechanical support and bone healing properties,

bone plate grafts are used to repair large bone defects. Many methods are available for bone plate grafting, such as the onlay bone grafting technique, sliding bone grafting technique, inlay bone grafting, and nailing combined with bone grafting. The bone plate is dense with weak osteoinduction and osteoconduction properties. Its effect is more like internal fixation, but its strength is inferior to the steel plate and other internal fixators. Bone plate grafting is rarely applied with the maturity of surgical methods, such as external fixation and bone-transport techniques.

- Fibular grafting: The fibula is a tubular bone with a hard texture. The whole segment of a fibula graft can bridge bone defects in the ulna and radius. In larger long tubular bone defects, fibular grafting has dual effects of bone grafting and auxiliary fixation. Because the fibula is relatively brittle, a single fibular graft is prone to refracture. Fibular grafting is a destructive reconstruction that is not easily adopted by patients. With the extensive application of bone-transport techniques, the segmental bone defects of long tubular bones can be satisfactorily treated and the application of fibular grafting also reduced.

4. Medullary blood injection for stimulating fracture healing (Healey et al. 1990; Hernigou et al. 2005) (Fig. 5.21):
   a. Medullary blood injection at the fracture ends can increase the local osteogenic stem cells and accelerate the bone healing process.
   b. Indications: No failure of the internal fixation and avascular-devitalized nonunion with fewer bone defects.
   c. First, C-arm fluoroscopy is used to intraoperatively guide the insertion of Steinmann pins at the fracture end to prepare for the subsequent injection.
   d. A bone wire is used to puncture the anterior superior iliac spine or the posterior superior iliac spine to draw medullary blood. No more than 10–15 mL of medullary blood is allowed to be drawn at the same puncture to avoid mixing of excessive peripheral blood that dilutes the stem cell components. Medullary blood can be drawn from multiple punctures.
   e. Generally, the medullary blood should be immediately injected into the fracture ends after drawing and should not be added with an anticoagulant such as heparin.
   f. This injection can be repeated 1–2 times (usually) every 2 weeks.
5. Nonunion surgical treatment to increase stability of the fracture ends:
   a. Techniques to replace the original intramedullary nail with a larger diameter intramedullary nail:

- Overview: The nonunions that occur after intramedullary nailing are mostly of the hypervascular-vitalized type and are mainly due to unstable fracture fixation, which is associated with multiple factors such as the fracture type, surgical technique, and selection of an intramedullary nail that is too fine. Replacing the original intramedullary nail with a larger diameter intramedullary nail after reaming increases the contact area between the nail and the medullary cavity, thereby achieving better mechanical stability (Fig. 5.22). During the reaming process, ground bone debris can be used to fill the fracture end, which is equivalent to bone grafting through the medullary cavity to the fracture end. Studies have shown that the blood supply to the cortical bone after repeated reaming is elevated, and the local tissue is stimulated to regain fracture healing, which is the so-called switching phenomenon. The replacement of intramedullary nails is more suitable for the treatment of hypervascular-vitalized but not for the treatment of atrophic nonunions.
- Surgical indications:
  - Hypertrophic nonunions of the femur and tibial shaft fracture after intramedullary nailing.
  - Caution in selecting this surgical method is necessary for nonunion after upper extremity and epiphyseal fractures.
  - Infected nonunions, atrophic nonunions, and nonunions with bone defects are not suitable for replacement of intramedullary nailing.
- Body position and preoperative preparation: Taking the replacement of the intramedullary nail of the hypervascular-vitalized nonunion in the femur as an example (refer to the surgical procedures for femoral shaft fracture in the previous subsection).
  - General anesthesia or epidural anesthesia.
  - Minimize usage or stop using the tourniquet, especially avoiding it use in reaming to prevent thermal damage to the intramedullary surface of the bone.
  - The areas of disinfection include the hip and thigh of the injured side, followed by the placement of sterile surgical drapes.
- Removing the internal fixator:
  - Under normal circumstances, the proximal end of the intramedullary nail is exposed immediately underneath the original incision.
  - After revealing the proximal end of the intramedullary nail and removing the end cap, the intramedullary nail extractor is installed to slowly knock out the intramedullary nail.
- Reaming:
  - The ball-tipped guide wire is inserted into the medullary cavity through the inlet.

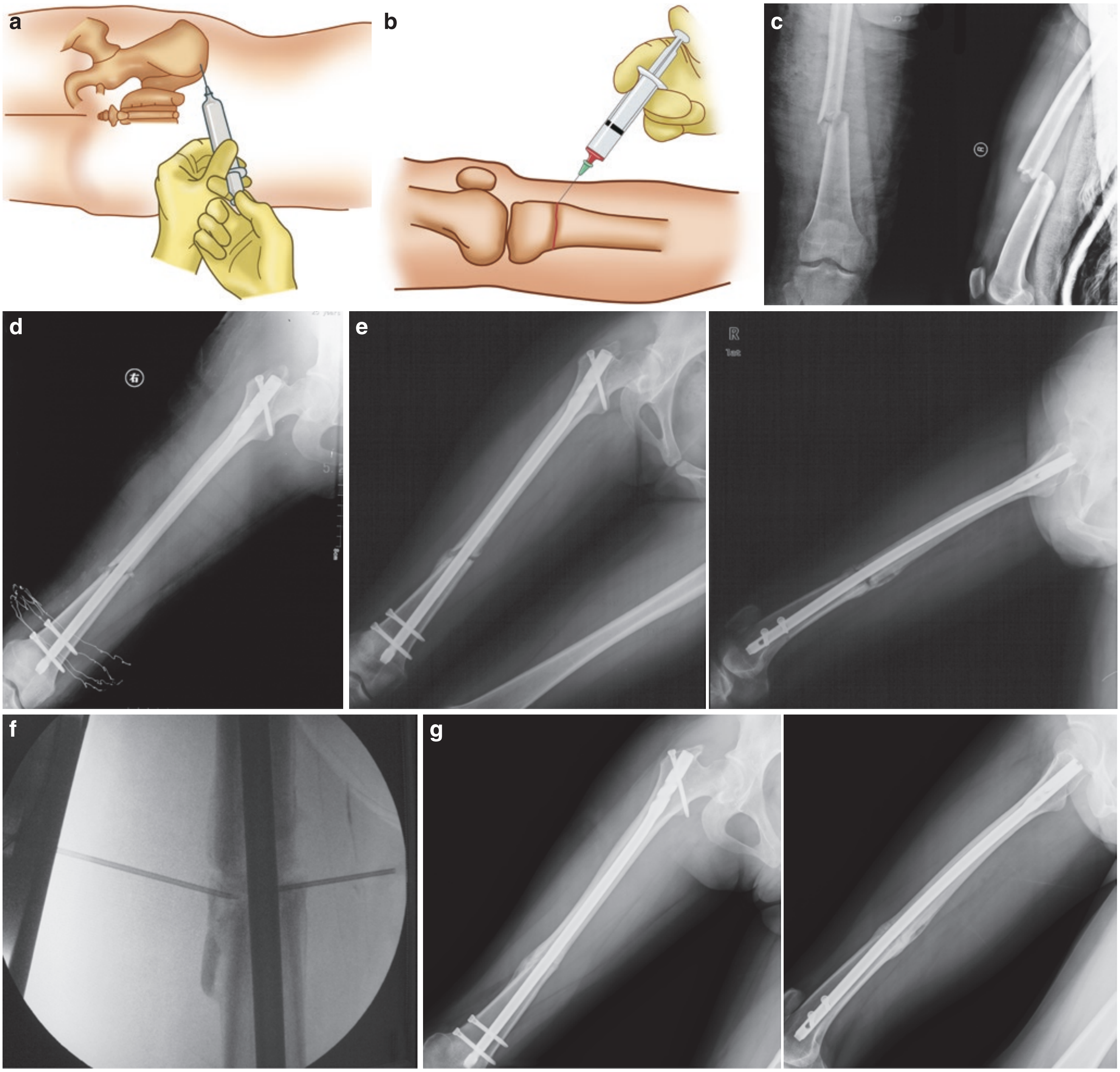


Fig. 5.21 The medullary blood is harvested by puncture and injected into the fracture site to stimulate bone regeneration and promote fracture healing. (**a**) The medullary blood is drawn from the anterior superior iliac spine or the posterior superior iliac spine. (**b**) The medullary blood is injected into the fracture site under fluoroscopic monitoring. (**c**, **g**) Case example of a patient with an AO type A3 open fracture of the femoral shaft. (**c**) Preoperative AP and lateral radiographs displayed a transverse fracture in the lower middle segment of the femoral shaft. (**d**) After thorough debridement and use of antibiotics for infection control, intramedullary nailing was performed. A postoperative radiograph showed good alignment of the fracture ends. (**e**) The fracture line was still clear at 7 months after surgery, and the bone of the fractured ends was slightly absorbed. (**f**) From three puncture points on the anterior superior iliac spine, 40 ml of autologous medullary blood was harvested and injected into the anterior, medial, lateral, and posterior sides of the fracture site with 10 mL on each side. (**g**) The fracture had healed completely at 5 months after surgery

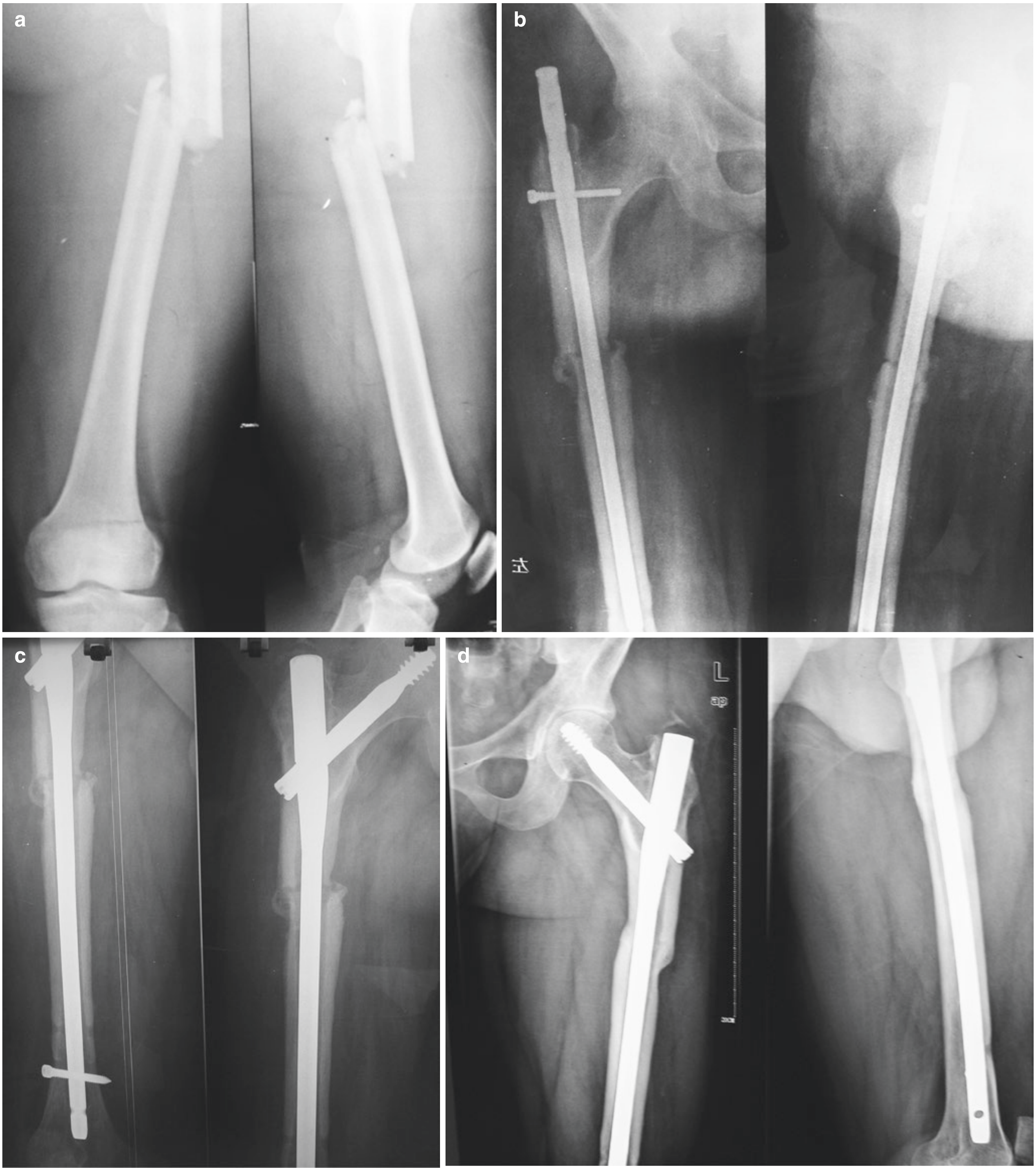


Fig. 5.22 (**a**) A type A3 fracture of the femoral shaft. (**b**) The fracture remained ununited at 10 months after surgery because the intramedullary nail used for fixation was too thin, the fracture was unstable, and the nail tail protruded from the bone surface too long. (**c**) Replacement with a larger diameter intramedullary nail: After removing the original internal fixator and reaming the medullary cavity, a thicker Gamma nail was used to re-fix the fracture. (**d**) A radiograph at the follow-up 6 months after surgery confirmed that the fracture has healed (the case was provided by Prof. Ji Fang, Department of orthopedics, Changhai Hospital)

  - Selection of the first reamer drill bit should match the diameter and model of the original intramedullary nail. The later drill bit diameter of the reamer is sequentially increased by 5 mm throughout reaming until it completely contacts the cortical bone.
  - Intraoperative application of soft tissue protector(s) is recommended, and no tourniquet is used for reaming. A sharp drill bit and low-speed reaming is recommended to reduce heat damage.
  - The posterolateral cortex of the greater trochanter should be protected during reaming.
  - Bone paste produced during the reaming process should be collected for bone grafting at the fracture ends if necessary.
- Intramedullary nail placement:
  - The ball-tipped guide wire is removed and replaced with a guide wire without a ball tip.
  - An appropriate length of the intramedullary nail is selected with reference to the conditions of the original intramedullary nail. The diameter of the intramedullary nail should be 1–1.5 mm smaller than that of the final reamer drill bit.
  - The intramedullary nail is inserted under the guidance of the guide wire.
  - The fracture ends surrounded by the scar tissues are rarely displaced. However, it is necessary to evaluate the status of fracture reduction under fluoroscopy; in particular, the lateral view should be obtained to determine the length of the intramedullary nail and the height of the proximal end of the nail. The proximal end of the nail must protrude 5 mm from the bone surface to facilitate nail withdrawal after fracture healing. The rotation shift should be carefully corrected.
  - First, the distal locking end in the intramedullary nail should be locked to facilitate the rebound of the intramedullary nail and the completion of pressurization at the fracture ends. Limited by the accuracy of the aiming device, a freehand locking technique is usually adopted for the insertion of distal locking screws in the 301 Hospital. First, the ball handle is adjusted to be perpendicular to the intramedullary nail, and then the ball handle is rotated and tilted to obtain a complete "full circle" locking hole at the distal end, with enlargement of the aperture to twice the diameter of the original nail hole. Under fluoroscopy, the screw hole is marked to correspond to the skin region to create a 1 cm incision. A Steinmann pin with a diameter equivalent to the drill bit is used to drill through the bone cortex. The screw length is measured, followed by screwing into the hole. Anteroposterior and lateral fluoroscopy are used to reconfirm the placement of the screw inside the screw hole. We also recommend using a sharp Steinmann pin instead of a drill bit for drilling because the drill bit is smooth and difficult to anchor on the bone surface, often leading to the risk of borehole deviation or drill bit breakage.
  - Fluoroscopy is used to confirm the good position of the fracture reduction. The intramedullary nail is rebounded appropriately to achieve effective pressurization at the fracture ends. The aiming arm for proximal locking is installed to guide completion of the incision, drilling, depth measurement, and screwing, in sequence.
- Incision closure: The incision is closed layer by layer, with a wound drainage or negative pressure drainage tube placed as needed.
  - Postoperative treatment:

    For patients with hypertrophic, good-contact, and non-open fracture ends, weight-bearing can be initiated with the aid of a brace 1 week after surgery to gradually increase weight on the affected bone.

    In patients with open fracture ends and bone grafting, weight-bearing is not recommended within 6–8 weeks. It should be gradually increased according to the fracture healing condition at 2–4 months postoperatively. Patients are allowed to walk without support at 4–6 months postoperatively and resume walking normally at 6–12 months postoperatively. Complete recovery of various functions after open fracture is achieved at 1.5–2 years.
- Experience and skill:
  - Decision-making regarding opening fracture ends:

    Most techniques for the replacement of intramedullary nails do not require opening the fracture ends and replacing the original intramedullary nails with larger diameter ones is sufficient.

    In fracture patients with a large fracture gap, unapparent hyperplasia at the fracture ends, or even a low level of bone defect, the fracture ends must be exposed to remove the scar tissues and a small amount of devitalized bone tissue at the fracture ends by decortication.

    After fixing the intramedullary nail, bone paste harvested from the reamed bone is implanted in and around the fracture gap. If the bone paste is insufficient, ilium bone harvesting may be required to increase the amount of bone graft.

- Decision-making regarding breaking the fibula:

  The presence of the fibula limits the contact of tibial fracture ends, which often affects the healing of tibial fractures. In special cases, the fibula is intentionally broken to enable good contact between the tibial fracture ends to promote fracture healing.

  Patients who have received intramedullary nail replacement have good fracture end contact, for whom fibula breaking is generally unnecessary.

6. Single locking plate fixation and bone grafting techniques:
   - Overview:
     - Long bone nonunion after steel plate fixation requires removal of the loosened or broken steel plate and reselection of the new steel plates or replacement of the intramedullary nails.
     - We prefer steel plate fixation because re-plating does not add more damage after removal of the original steel plate and cleanup of the fracture ends has already created a broad surgical exposure. In contrast, the replacement of intramedullary nails may damage the intramedullary blood vessels, further affecting the blood supply of the fracture ends and fracture healing.
     - The stability of steel plate fixation depends on the cortical bone contact of the fracture ends. If the cortical bone contact of the fracture ends is good, single-plate fixation will achieve mechanical stability.
     - However, the nonunion region often contains necrotic bones. Different degrees of bone defects are caused by the removal of necrotic bones. The relative position relationship between the bone defect and steel plate determines the structural stability of the fracture fixation (Fig. 5.23):

       If the bone defect is located on the same side as the fixed steel plate or if the contralateral cortical bone achieves good contact and support after steel plate fixation, single-plate fixation will be sufficient to achieve mechanical stability of the fracture site.

       If the bone defect is located on the opposite side of the fixed steel plate, the contralateral cortical bone will not achieve good contact and support after steel plate fixation and will cause instability like a suspension arm. The mechanical stability of the fracture site after steel plate fixation will be greatly reduced. Double-plate fixation can be used to secure the structure.
     - Given the reduced stress on the upper limbs, the stability of the upper limb defect is barely affected after steel plate fixation, and single-plate fixation can achieve good mechanical support. For metaphyseal fractures of the upper and lower extremities, intramedullary nailing can barely hold the large medullary cavity, even though blocking screws are applied. This operation is rather difficult, and the fixation outcomes are uncertain. Therefore, steel plate fixation is recommended for metaphyseal nonunion of the upper and lower extremities.
     - Steel plate fixation is performed according to the basic principle of internal fixation. However, nonunion bone is often osteoporotic, which affects the fixation strength of the screw hole from the original screw fixation. Therefore, the selection of a longer

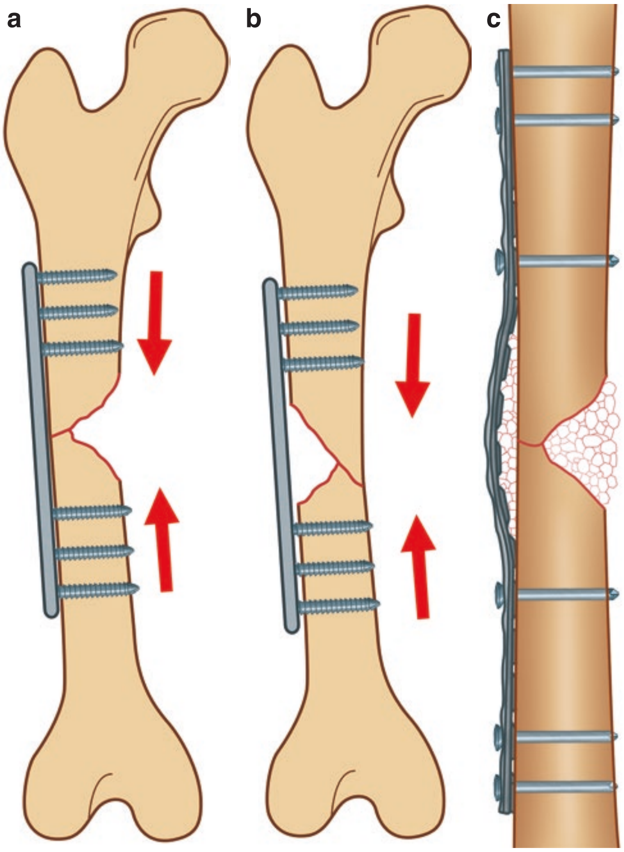


Fig. 5.23 (**a**) The bone defect is located on the opposite side of the fixation plate, causing mechanical instability under compression (similar to that of a "suspension arm"). (**b**) The bone defect is located on the same side of the fixation plate, and on the opposite side, the two bone fragments are in contact with each other under compression, making the fixed fracture mechanically stable. (**c**) The application of a wave steel plate not only increases the effective weight-bearing area, but also allows bone grafting underneath and around the nonunion, thereby facilitating fracture healing

and stronger steel plate is necessary. The locking plate has an angular stability and overall fixation effect. It can be firmly fixed to and is highly recommended for osteoporotic fractures.
  - Anatomical locking steel plates cover almost all extremity bones and provide more choices for surgeons. The corrugated steel plate allows bone grafting under the steel plate and provides significant clinical advantages.
- Surgical indications: (1) Patients with a bone nonunion in the lower extremities after initial plating fixation, in whom the bone cortexes on the opposite side of the to-be-placed plate display good contact and can provide good support; (2) metaphyseal nonunion of the upper and lower extremities; (3) nonunion of the clavicle and upper extremity fractures; and (4) nonunion secondary to pelvic and acetabular fractures.
- Surgical procedures: Taking the nonunion of the middle and the distal one-third of the humeral shaft as an example.
- Body position and preoperative preparation:
  - Preoperative radiographs are carefully evaluated to fully prepare the surgery according to the fracture type, involved area, length of the steel plate, and location of screw placement.
  - A preoperative tapping test along the travelling path of the radial nerve of the injured extremity is performed. In most cases, Tinel's sign of the radial nerve will be induced. All excitation points of Tinel's sign are connected to indicate the approximate surface projection of the radial nerve on the body surface, which is an important guide to locate the radial nerve intraoperatively.
  - The patient is placed in the supine position on a radiolucent operating table, which is adjusted to raise the head, neck, and chest position by 30–40°. The C-arm is placed on the opposite side of the surgeon.
  - The surgical area is routinely disinfected with iodine and alcohol, followed by the placement of sterile surgical drapes.
- Incision surface projection:
  - A straight incision on the lateral side of the humerus is performed with the incision starting from the deltoid tuberosity and extending distally along the longitudinal axis and stopping at the lateral epicondyle of the humerus. The incision can be preceded proximally along the gap between the pectoralis major and deltoid if necessary.
- Surgical approaches:
  - The skin, subcutaneous tissue, and deep fascia are cut open layer by layer along the incision, followed by properly dissociating the tissue toward two sides under the deep fascia and identifying the space between the biceps and triceps at the proximal end of the incision and the space between the brachioradialis and brachialis at the distal end of the incision.
- Radial nerve protection:
  - The traditional method to protect the radial nerve is the use of a pair of hemostatic forceps to carefully separate the radial nerve between the brachialis and brachioradialis from the distal region with fewer scars to the intermuscular septum of the forearm and further to the proximal end along the space between the biceps and triceps; once the whole radial nerve is isolated, it is protected using a rubber strip. In our experience, although the radial nerve is carefully protected using the above surgical procedures, the probability of its injury is still high due to the excessive scar tissue growth around the radial nerve after a previous surgery or multiple surgeries. Nerve injury is inevitable when isolating the radial nerve from the scar tissues.
  - Based on a summary of the aforementioned cases we encountered, the Department of Orthopedic Surgery of the 301 Hospital explored a series of methods to use the scar tissues adjacent to the radial nerve to protect the radial nerve. The specific procedures are as follows: With reference to the radial nerve direction marked on the body surface preoperatively, the space between brachioradialis and brachialis is distinguished and separated to locate the radial nerve. Importantly, radial nerve separation is not performed after locating the nerve, which is instead only used to guide the electrical nerve stimulation. The probe for electrical nerve stimulation (Fig. 5.24) is used to gradually detect the radial

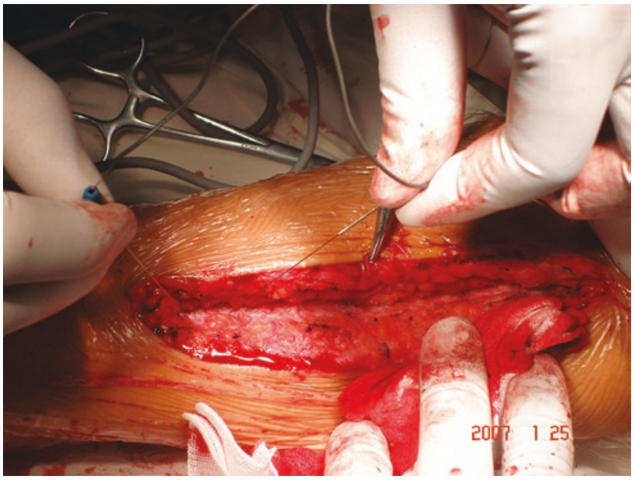


Fig. 5.24 During surgery, an electrical stimulation probe was used to locate the radial nerve, and a 1.5 cm wide muscle scar band around the radial nerve was retained

    nerve from the distal end to the proximal side. Sutures are used to mark the muscle surface along the radial nerve to clearly visualize the direction of the radial nerve. If the scar tissues grow excessively and covers the space between the brachioradialis and brachialis, i.e., the distal end of the radial nerve cannot be identified, the above suture marking step can still be used to reveal the radial nerve direction. However, for safety reasons, it is best to locate the distal end of the radial nerve to reduce intraoperative determination errors.
- Excavation and removal of the steel plate.
    - Using the radial nerve as a boundary, a 3 cm band of muscle scar tissue, with a 1.5 cm width of muscle scar tissue on each side of the radial nerve, is created to protect the radial nerve, followed by cutting the muscle tissue on both sides of the band to reveal the surface of the humerus. Importantly, the connection between the brachioradialis and the distal end of the humerus is cut, which should be performed as close as possible to the surface of the humerus to reduce the anterior radial nerve injury. The proximal humerus is exposed in front of the deltoid insertion and the space between the deltoid and pectoralis major, with the surgical instrument operating toward the front as far as possible to reduce the radial nerve injury on the posterior aspect of the humerus.
    - The tissue is carefully peeled off the bone surface or steel plate immediately adjacent to the lower side of the band of muscle scar tissue (1.5 cm away from the radial nerve) to create a tunnel space, followed by the placement of a wide gauze bandage in the tunnel space to lift the muscle band. On the one hand, this wide gauze bandage protects the soft tissue and, on the other hand, assists the operation by pulling each side separately to facilitate surgical exposure and plating.
- Placement of the new steel plate:
    - After removing the old steel plate, there is no urgency to clean the fracture ends, which are connected to the scar tissue and are relatively stable. Instead, a steel plate can first be pre-placed; otherwise, the repeated reduction will be challenging once the fracture ends are completely separated after cleaning. A relatively long new steel plate should be used for pre-placement, for which a small-diameter drill bit or Kirschner wires are used to drill through the bone cortex on one side to fix both ends of the steel plate on the sites near the fracture site. It is noteworthy that the drill holes should not be overlapped with the screw holes of the original steel plate. Through this drilling step, the long axis of the humerus is also marked on the humeral surface, which helps to prevent rotational displacement during placement of the new steel plate.
    - Decortication is used to gradually expose the fracture ends and remove the sequestra and scar tissues from the fracture fragments. A large drill bit is used to canalize the medullary cavity.
    - The fracture ends are aligned according to the marked drill holes as described previously to minimize the spacing between the two fracture ends, followed by using four unicortical screws to temporarily fix both ends of the steel plates near the fracture site.
    - The quality of the fracture reduction is evaluated under fluoroscopy.
    - The steel plate is gradually fixed with bicortical screws. All four unicortical screws are replaced with bicortical screws at each fracture end. At least three bicortical screws must be used at each fracture end to ensure reliability of the fracture fixation (Fig. 5.25).
- Bone grafting:
    - Procedures for ilium harvesting (refer to the previous subsection for details).
    - The harvested ilium is trimmed into pea-sized cancellous bone granules and matchstick-shaped bone strips. The cancellous bone granules are implanted in the voids of the fracture, and the bone strips are placed around the fracture ends, which are bundled with absorbable sutures to avoid bone displacement or loss of the implant.
- Incision closure: A drainage tube is placed, and the surgical wound closed layer by layer.

b. Double-plate fixation and bone grafting techniques.
    - Overview:
        - The key to fix an ununited bone with a steel plate concerns whether the steel plate can provide sufficient mechanical stability. In particular, large and long tubular bones, such as the humerus, femur, and tibia, are required to bear large axial and rotational stresses. When the circumference of the tubular bone cortex is incomplete, i.e., the cortical bone is defective, the comprehensive mechanical properties of the bone will be greatly reduced.
        - If the bone defect is located on the same side of the fixed plate, i.e., the cortical bone on the opposite side can achieve good contact and support after steel plate fixation, single-plate fixation will be sufficient to achieve mechanical stability at the fracture site.
        - If the bone defect is located on the opposite side of the fixed steel plate, it is better to reconstruct

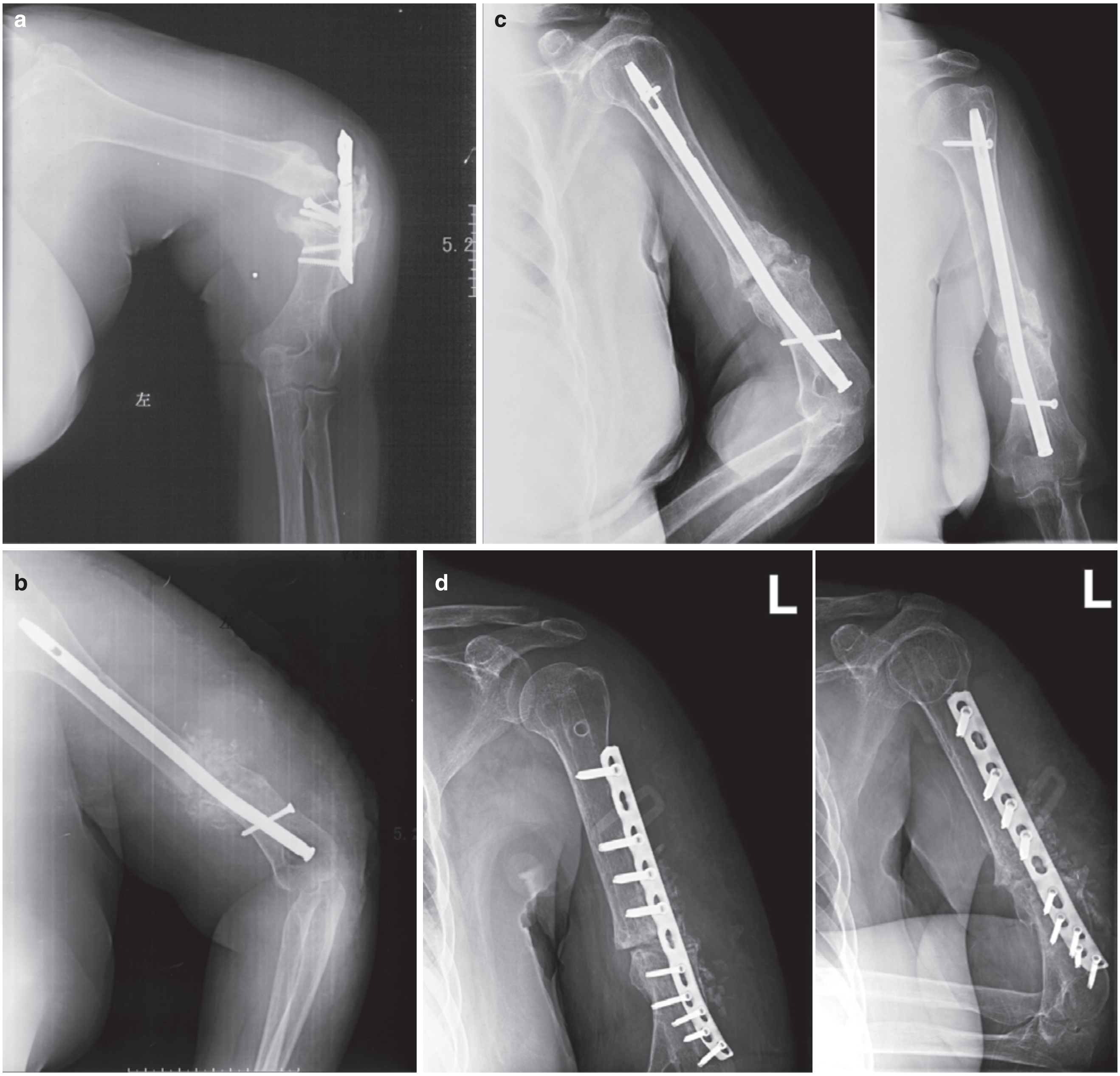


Fig. 5.25 A patient with a humeral shaft fracture (the original preoperative and postoperative radiographs were missing). (**a**) The patient received plate-screw fixation for the left humeral shaft fracture and started functional exercise at 3 months after surgery. However, left arm pain and deformity occurred repeatedly within 6 months after surgery, and the patient received only conservative treatment. At 6 years after surgery, the radiograph showed that the plate used to fix the fracture was too short and that only two screws were placed on each of the proximal and distal fragments, which had caused fracture nonunion, screw falling-off, fracture angulation deformity, and pseudarthrosis formation due to poor mechanical stability. (**b**) The patient received the second surgery for open reduction, removal of internal fixators, cleaning up of the fracture ends, retrograde intramedullary nailing, and autogenous bone grafting of the affected humeral shaft. (**c**) Because the medullary cavity of the distal humeral fragment was too wide, the stability provided by the intramedullary nail was very limited; as a result, the fracture remained unhealed at 9 months postoperatively, as displayed in both AP and lateral radiographs of the humerus. (**d**) The patient again underwent surgery for open reduction, removal of the intramedullary nail, cleaning of the fracture ends, unilateral locking plate fixation, and autogenous bone grafting at the fracture site. (**e**) At 4 months after plate-screw fixation, the AP and lateral radiographs of the humerus showed that the fracture ends became blurred and the fracture had healed

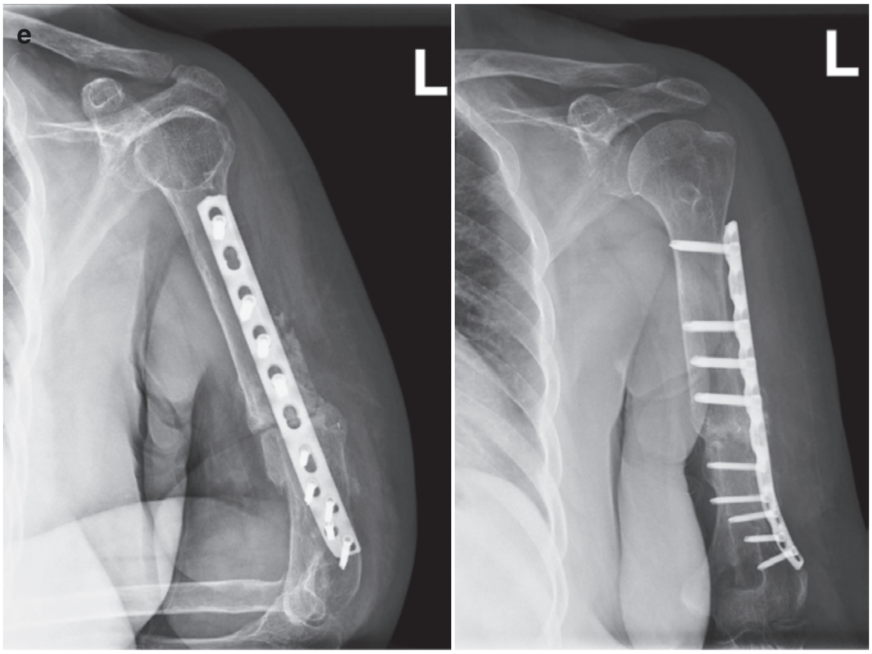


Fig. 5.25 (continued)

the mechanical stability of the bone defect; otherwise, the steel plate will be fatigued and broken again due to the excessive load caused by the loss of mechanical support on the opposite side.

  - The traditional solution to the above problem is to perform structural bone grafting with an ilium containing a three-sided bone cortex to achieve mechanical stability at the bone defect. However, the lack of strength of cancellous bone, bone resorption due to stress, and other problems, especially structural bone grafts with large defects and requiring a long time for creeping substitution, lead to a high failure rate. For this type of nonunion, double-plate fixation is usually applied in the 301 Hospital to achieve good therapeutic outcomes.
- Surgical indications: This surgical treatment is suitable in patients with long tubular bone fractures that are ununited after plate fixation and have an accompanying cortical defect on the opposite side of the pre-placed steel plate or who have a metaphyseal nonunion. However, double-plate fixation is not suitable for fractures of the clavicle and forearm bones that have a small diameter and small mechanical load capacity.
- Surgical procedures: Taking the femoral shaft nonunion as an example.
- Body position and preoperative preparation:
  - A preoperative radiograph is obtained to determine the type and extent of the bone defects. Based on this information, the length of the to-be-preset double plates and screw placement position can be planned ahead of time to ensure improved preoperative preparation.
  - The patient is placed supine on the operating table, and the hip of the injured side is raised (for convenience of operation at the back of the thigh).
  - The area of disinfection should be sufficient for harvesting the ilium and intraoperative measurement of the lower limb mechanical line, including the area around the ilium, groin, and entire lower extremity.
- Operative incision according to the projection on the body surface: The lateral approach is selected.
- Surgical approaches:
  - The skin, subcutaneous tissue, and fascia lata are cut open, followed by separation of the posterior space of the vastus lateralis muscle. The vastus lateralis muscle is excised subperiosteally and pulled forward from the surface of the femoral shaft.
- Internal fixation removal and refixation:
  - The broken steel plate is exposed and removed.
  - Before further treatment of the fracture ends, a steel plate is pre-placed with the precaution that the drill holes are not overlapping the screw holes of the original steel plate. A wide and long (as far as possible) locking plate should be selected for the lower extremity. At least four

    bicortical locking screws are used at each fracture end for fixation. The pre-placed steel plate is fixed using the same method as the above-described single-plate fixation.
  - Decortication is used to gradually expose the fracture ends and remove the sequestra and scar tissues of the fracture ends. A large drill bit or Kirschner wire is used to canalize the medullary cavity.
  - The two fracture ends are aligned according to the marked drill holes on the preset steel plate to minimize the spacing between the two fracture ends, followed by temporary fixation at both ends of the steel plate near the fracture site with four unicortical screws.
  - The quality of the fracture reduction and the position of internal fixation are evaluated under fluoroscopy.
  - If the position of the internal fixator is satisfactory, the unicortical screws will be sequentially replaced with bicortical screws to fix the steel plate. At least four bicortical screws are used at each fracture end for fracture fixation.
  - A narrow compression locking plate for the upper extremity is placed on the opposite side of the pre-placed plate as an auxiliary steel plate, fixed by two screws at each fracture end. The two plates should be placed as parallel as possible.
  - Percutaneous screw placement of the auxiliary steel plate:

    Due to the inconvenient operation, the screws for fixation of the auxiliary steel plate should be placed percutaneously on the opposite side rather than through the same surgical incision.

    Once the approximate positions of the screw holes are determined on the steel plate, a pair of curved forceps is used to separate the muscle and subcutaneous tissues outwardly, followed by the creation of a 0.5 cm skin incision with a small surgical blade to lift the guide apparatus through the skin.

    The guide apparatus is connected to the locking plate. The guide apparatus can be disconnected after hole drilling guidance.

    The screwdriver is passed through the previously generated incision to directly connect and tighten the locking screw in the operating field (Fig. 5.26).
- Bone grafting:
  - Ilium harvesting.
  - The harvested ilium bone is trimmed into pea-sized cancellous bone granules and match-shaped bone strips. The cancellous bone granules are implanted in the voids of the fracture, and the bone strips are placed around the fracture ends, which are bundled with absorbable suture to avoid bone displacement or implant loss (Fig. 5.27).
- Incision closure:
  - The vastus lateralis muscle is restored to the original position, and the drainage tube is placed underneath the vastus lateralis muscle.
  - The fascia lata is sutured and closed carefully.
  - The incision is closed layer by layer.
- Postoperative treatment:
  - The patients can sit up on the day after the surgery, and the drainage tube is removed 48–72 h postoperatively.
  - The patients are encouraged to passively perform knee exercises but not muscle exercises because the muscles of the lower extremities have very developed muscle strength and excessive stress on the lower extremity muscles can cause loosening of the internal fixation.
  - Once the radiograph shows a sufficient amount of callus formation, the patient is allowed to perform partial weight-bearing exercises and active muscle strength exercises.

c. Other techniques to stabilize the fracture ends.
   - An important cause of nonunions is excessive activity at the fracture ends. Careful analysis of the cause of nonunions and appropriate surgical interventions should be taken. Auxiliary fixation should be added based on the original internal fixation to eliminate excessive activity at the fracture ends and to re-establish a suitable biomechanical environment that is suitable for fracture healing.
   - Intramedullary nailing to assist locking plate fixation: With the continuous development of intramedullary nailing technology, the indications have gradually broadened. Some metaphyseal fractures fixed with intramedullary nailing become loose in the fracture ends because the intramedullary nails cannot hold a wide medullary cavity. This excessive activity can lead to hypertrophic nonunions. Even with the replacement of larger diameter intramedullary nails, mechanical stability is still not achieved. Supplemental steel plate fixation can be used at this point to preserve the original intramedullary nails and to eliminate the excessive activity at the fracture ends. Steel plate fixation should follow the tension band principle and be carried out on the tension side of the bone. Because the steel plate only plays a supporting role and requires less strength, the placement of a small compression

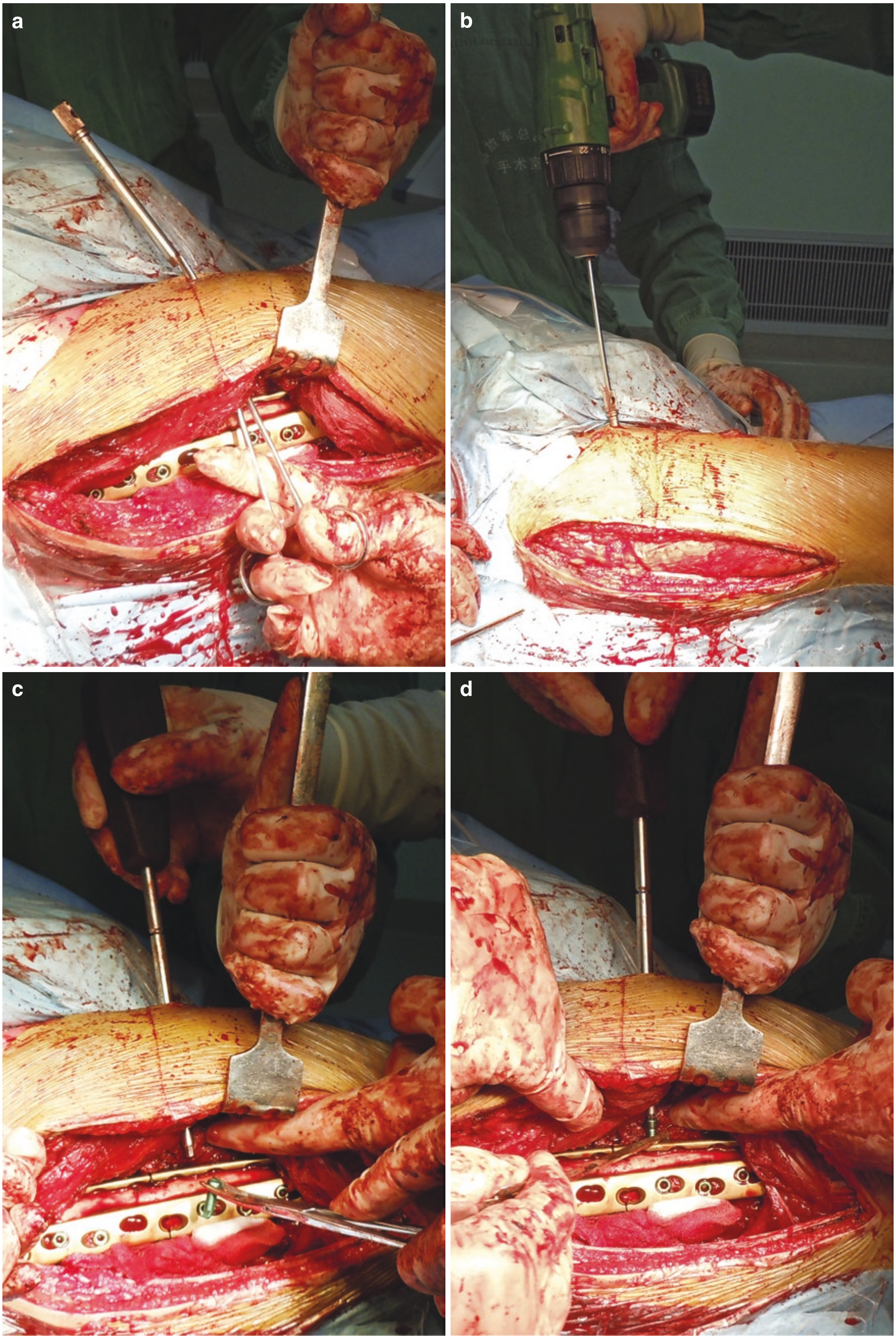


Fig. 5.26 (**a**) The muscles and subcutaneous tissue are separated outwardly using a pair of curved forceps; when the separation reaches the subcutaneous layer, a 0.5 cm skin incision is created with a small surgical blade, through which the guide apparatus is picked up. (**b**) The guide apparatus is connected to the locking plate to guide hole drilling. (**c**) The screwdriver is passed through the previously made incision and connected directly to the locking screw in the operating field. (**d**) The locking screw is inserted in percutaneously

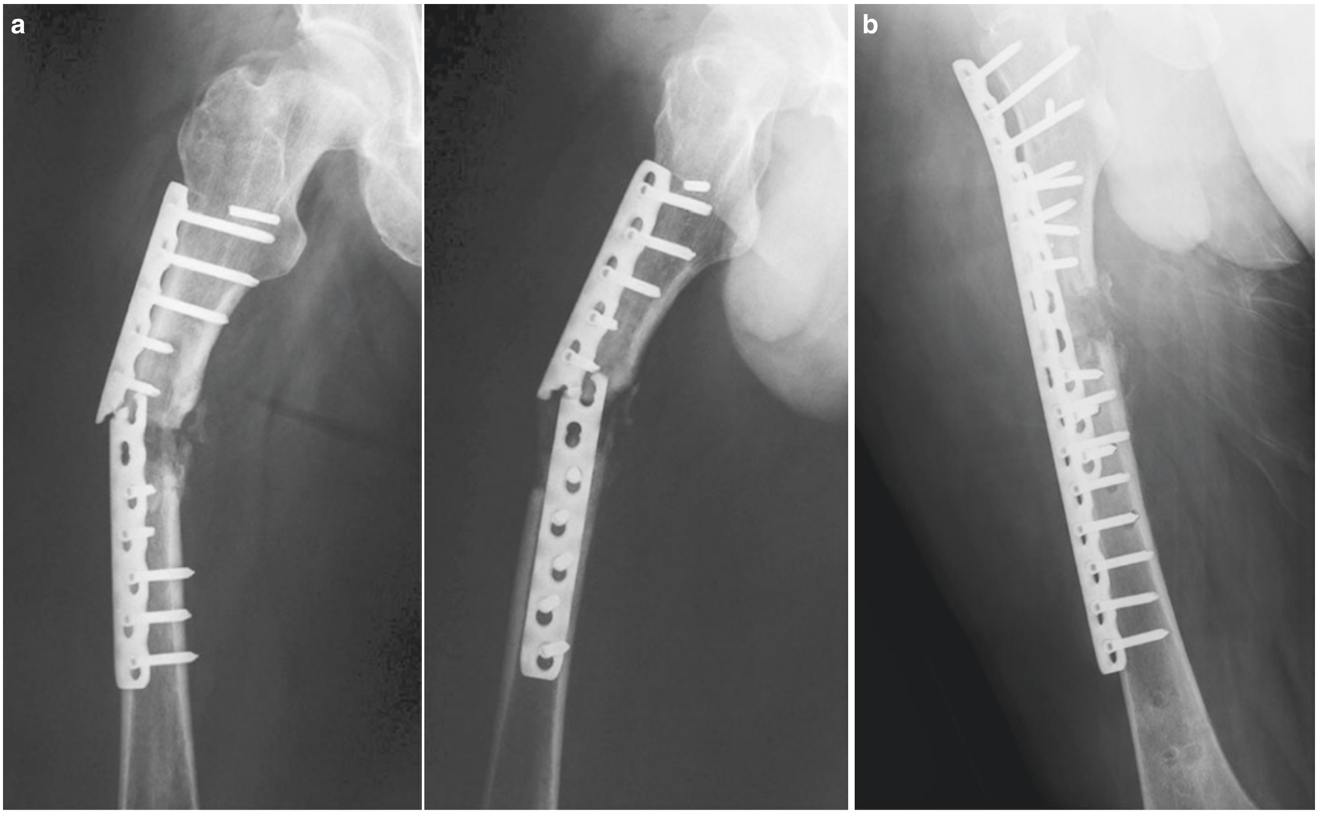


Fig. 5.27 The patient received lateral single-plate fixation for a femoral shaft fracture; however, the medial cortical defect resulted in broken of the plate and nonunion (the original preoperative and immediate postoperative radiographs were missing). (**a**) AP and lateral radiographs obtained after the plate was broken: The medial cortical bone was defective, and the plate was broken at the fracture site. (**b**) Through the lateral approach, the previous internal fixators were removed, the fracture was fixed with double plates placed at a 90° angle, and the autogenous iliac bone graft was harvested for cancellous bone grafting at the fracture site

plate in the forearm or reconstruction plate fixation is sufficient. The steel plate should not be too long, and both sides of the fracture ends are fixed with two screws. A locking plate is recommended (Fig. 5.28).

- Intramedullary nailing plus blocking-screw stabilization techniques: In the above situation, if the fracture ends exhibit unstable nail fixation and even abnormal mechanical alignment and a tendency toward nonunion in the early stage of intramedullary nailing, closed reduction and blocking-screw reinforcement can be adopted to control the excessive activity at the fracture ends in a timely manner, without affecting fracture healing (Fig. 5.29).

d. Bone transport techniques (Figs. 5.30, 5.31, and 5.32).
  - Overview:
    - The treatment for infected nonunions is the most challenging. Controlling the bone infection and repairing the large segmental bone defects are the two major challenges of this treatment.
    - Bacteria, which are responsible for the infection, are often hidden inside the bone and scars and possess strong drug resistance. Local antibiotic flushing, systemic medication, and even the application of bone cement containing antibiotics or artificial bone cannot effectively control hidden bacteria. To date, complete removal of the necrotic bone tissues, callus, and scar tissues surrounded by bacteria has generally been considered the only method to control the infection.
    - However, the resection of a large, infected bone segment can cause tremendous bone defects and therefore is another great challenge for orthopedic surgeons. Any bone defect larger than 2.5 cm requires a long time for creeping substitution and a long healing process, regardless of the use of autologous bone for structural bone grafting or vascularized fibular grafting. Even if the bone healing is barely achieved, the probability of refracture is very high.

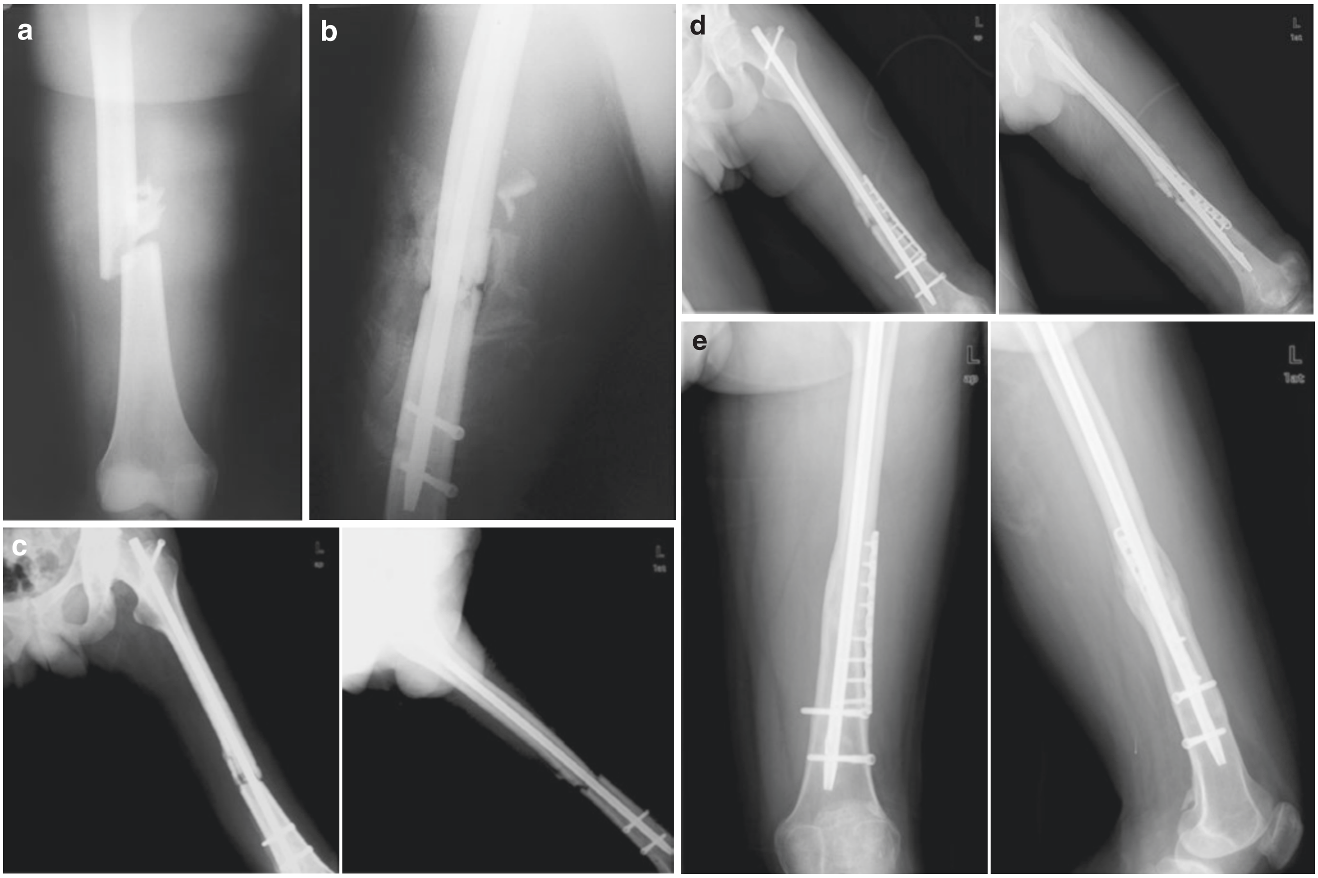


Fig. 5.28 (**a**) A preoperative radiograph of an AO type B3 open femoral shaft fracture. (**b**) A postoperative radiograph: The patient received emergency debridement, open reduction, and intramedullary nail fixation. (**c**) A radiograph at 7 months postoperatively: The fracture line was clear without obvious callus cross, which suggests nonunion. (**d**) AP and lateral radiographs obtained after augmented plating and bone grafting with preservation of the original nail. (**e**) Fracture healing was radiographically confirmed more than 1 year postoperatively

  - In recent years, Zhang et al. of the 301 Hospital adopted the Ilizarov external fixator and distraction osteogenesis to treat more than 250 patients with severe bone infection and large segmental bone defects, and they have acquired some experience. The surgical treatment procedures include the installation of an external fixator, removal of the large segmental bone and callus at the infection site, and bone lengthening via metaphyseal osteotomy.
  - The advantages of this treatment include the following. First, it completely removes the necrotic and infected bone tissues as well as the infected callus, thereby eliminating the source of infection. Second, the residual large segmental bone defects are repaired by lengthening the autologous bone with materials collected locally to avoid complications caused by bone harvesting. Third, it enables healing via the direct union of healthy bone tissue at the fracture ends, which reduces the risk of refracture. In addition, in patients with fracture exposure caused by soft tissue defects, stage-one treatment of shortening the affected extremity after removing the infected bone segment enables direct contact of the fracture ends, which allows stage-one suturing of small soft tissue defects and narrows the wound of large soft tissue defects. Furthermore, vacuum sealing drainage (VSD) auxiliary therapy promotes granulation tissue coverage, which creates conditions for skin grafting. Bone transport techniques are finally used to balance the length of the extremities.
- Surgical indications: Infected nonunions associated with the sequestrum, dead cavity, sinus tract formation, etc.; residual large segmental bone defects due to tumor resection, traumatic bone loss, etc.; and pseudarthrosis accompanied by bone defects.
- Surgical procedure: Taking the infected nonunion of the tibia as an example.

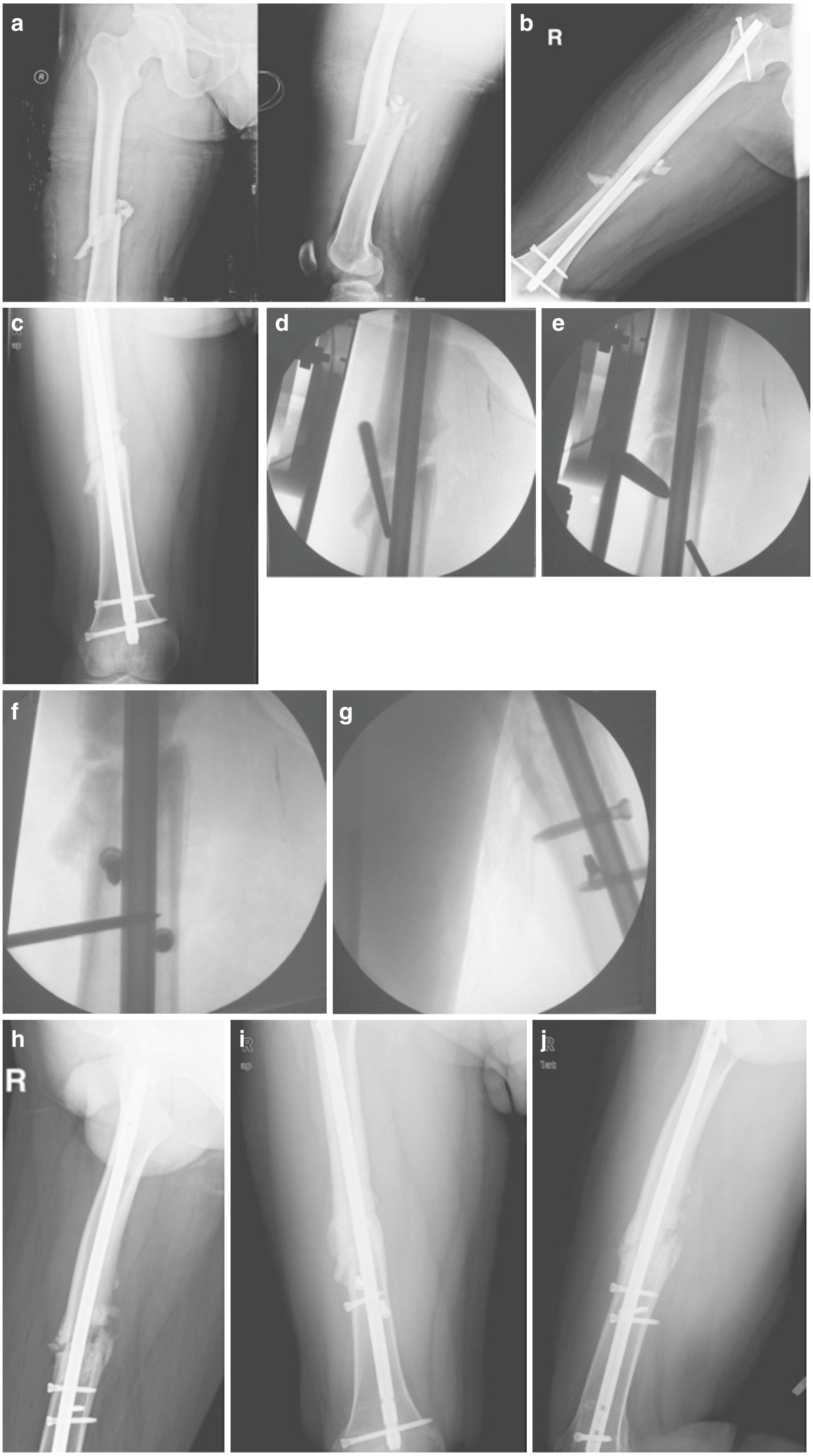


Fig. 5.29 Nonunion of an open fracture of the femoral shaft after intramedullary nail. (**a**) A preoperative radiograph showed an open comminution fracture of the femur. (**b**) A radiograph taken after intramedullary nail. (**c**) A radiograph taken at 13 months after surgery: The fracture line was still clearly visible. In addition, the distal bone fragment did not contain the isthmus, and its medullary cavity was wide, leading to poor stability after intramedullary nailing. (**d**–**g**) Three blocking screws were inserted into the proximal end of the distal fracture fragment to narrow the medullary cavity. (**h**) A postoperative radiograph. (**i**, **j**) Fracture healing was confirmed by the AP and lateral radiographs at 4 months postoperatively

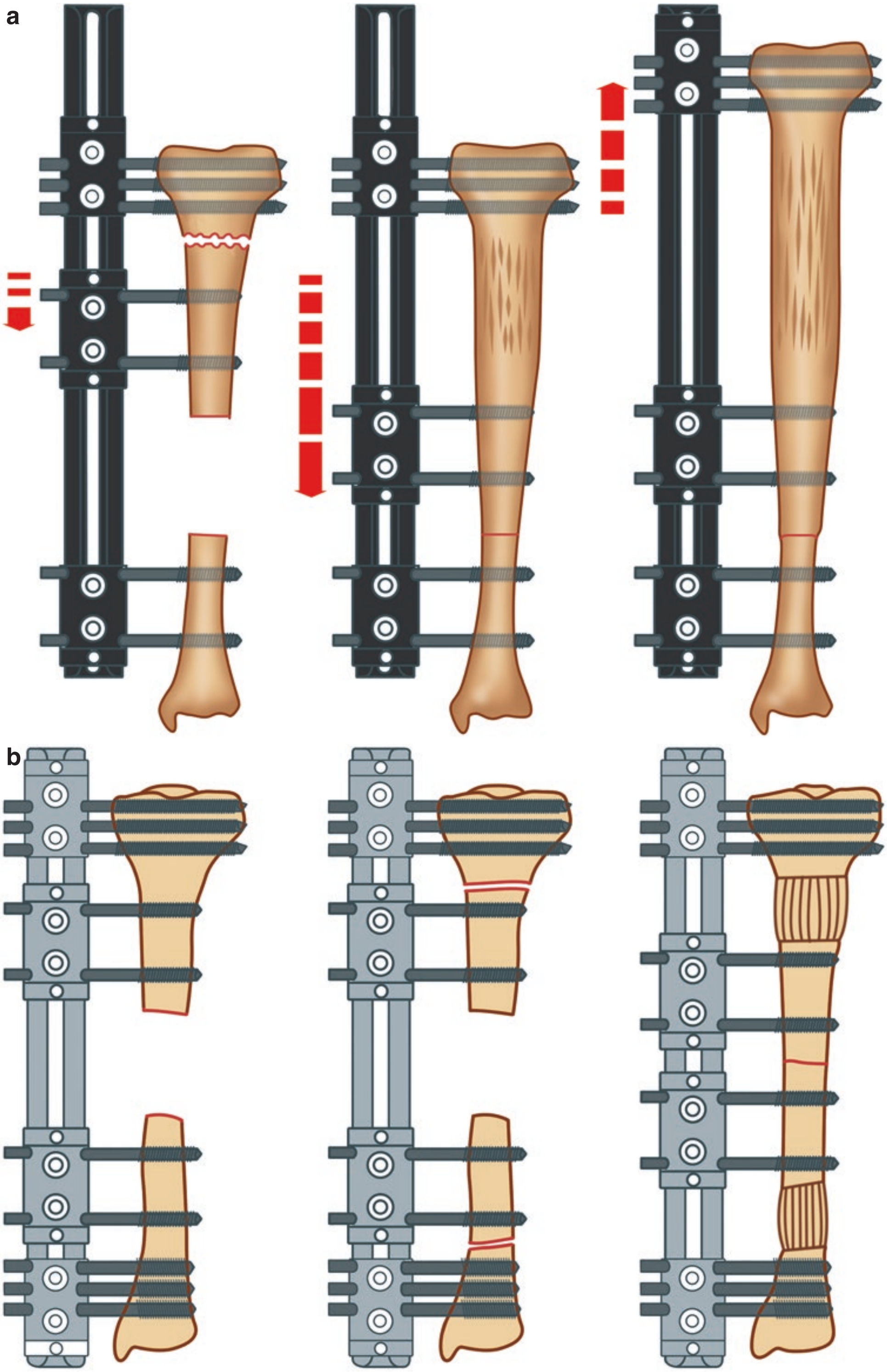


Fig. 5.30 Treatment of an infectious nonunion using a single-arm external fixator and bone lengthening technique (**a**) Unidirectional bone lengthening technique: The infected ununited bone segment was removed, followed by the creation of a fresh osteotomy plane far away from the nonunion area. After 1 week of compression, lengthening of the broker-end osteotomy was performed four times per day to lengthen it 1 mm per day. Ideally, a fresh cloud-like callus gradually forms. (**b**) If the defect segment is too long, bidirectional bone lengthening can be performed

Fig. 5.31 Open comminution fracture of the proximal tibia and fibula. (**a**) Preoperative AP and lateral radiographs: There was an open comminution fracture of the proximal tibia accompanied by a partial bone defect. (**b**) Debridement and external fixation were performed. (**c**) The patient received debridement for the second time due to postoperative soft tissue infection. After the infected bone segments at the fracture site were removed via osteotomy, the fracture was fixed with the Ilizarov ring external fixator. Additionally, osteotomy was performed at the middle-distal segment of the tibial shaft far away from the bone defect. (**d**). After 1 week of compression on the osteotomy site of the distal tibia, a bone transport toward the proximal side was conducted four times per day to transport a total of 1 mm per day. The radiographs showed osteogenesis in distraction area. (**e**) During the long-term and long-distance transport process, an orthopedic external fixator could be used to correct the talipes equinus (clubfoot) of the patient. (**f**) After bone transport, the external fixator was removed once the callus was consolidation

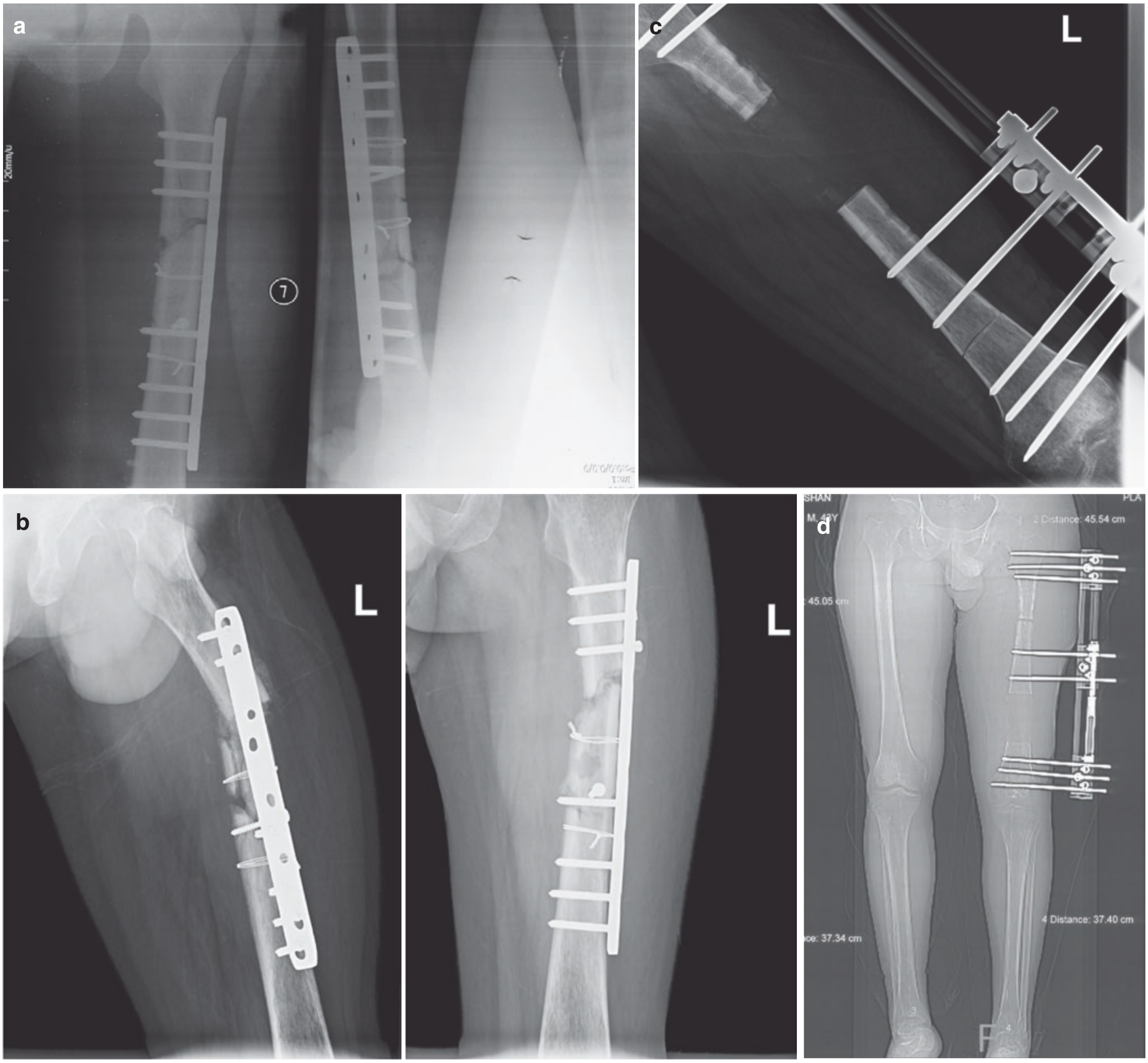


Fig. 5.32 A patient with postoperative nonunion of the femoral shaft fracture (the original radiograph was missing). (**a**) Postoperative AP and lateral radiographs of a type C3 fracture of the femoral shaft after plate: The fracture was fixed with not only a plate and screws but also wire cerclages. (**b**) AP and lateral radiographs of the femur at 7 months after the operation: The fracture did not heal, and the internal fixator was displaced and ineffective. (**c**) The patient again underwent surgery for external fixation with a single-arm frame, osteotomy at the fracture ends, and osteotomy at the distal side of the first osteotomy site for bone transport. (**d**) X-ray examination was performed regularly to monitor the bone transport process, and radiographs of full-length lower extremities were obtained when the bone transport was completed, which showed a length difference of less than 0.5 cm between the two lower extremities. (**e**) An AP radiograph of the affected extremity after completion of bone transport. (**f**) After bone transport, the fracture healed well, and the lengthened callus was fully consolidation. At this time, the external fixator was removed

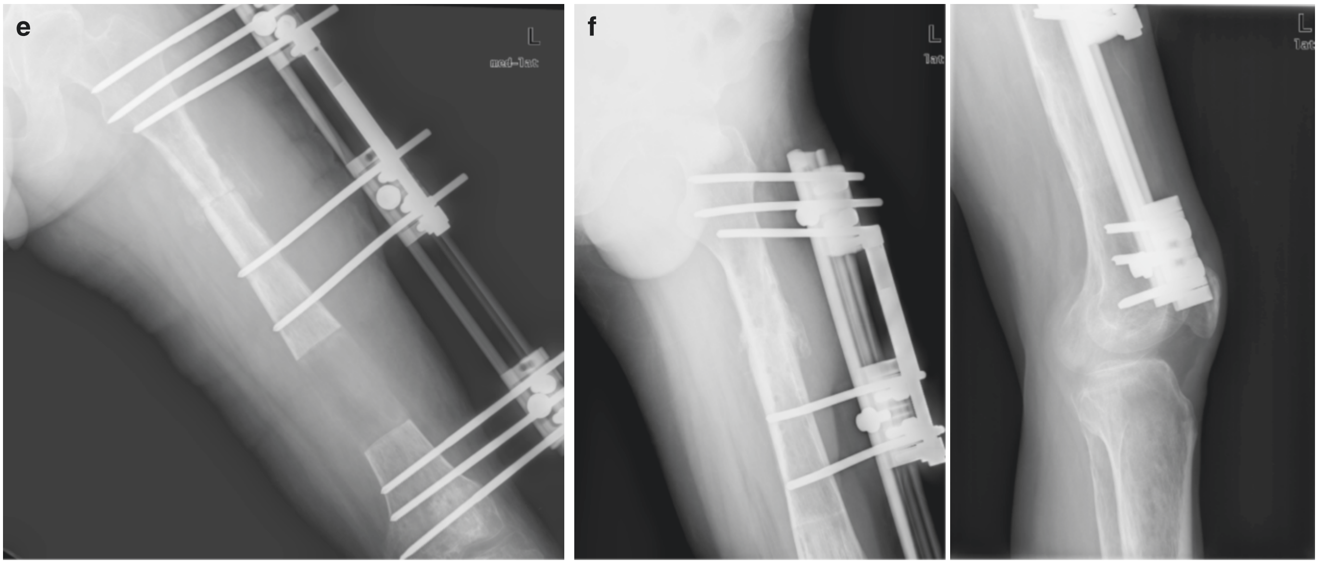


Fig. 5.32 (continued)

- Body position and preoperative preparation:
  - Preparation and installation of the external fixator: The external fixator is preoperatively prepared, and its trial installation is performed according to the length of the involved extremity, the installation location, and the functional status of the involved knee/ankle joints. The surgical incision, range of infected bone segment that must be removed, and osteotomy site should be marked preoperatively.
  - Anesthesia: Either general anesthesia or continuous epidural anesthesia.
  - A tourniquet should be strapped on the thigh.
  - Area of disinfection: From the middle of the thigh to the entire lower limb. Sterile surgical drapes should be carefully placed for proper coverage.
  - The patient's knee joint can be flexed freely without causing any contamination.
  - After slightly bending the knee joint, a sterile cushion is placed underneath the knee joint to facilitate the surgical procedures.
- Installation of the external fixator:
  - Before removing the infected bone, the external fixator should be installed and fixed to avoid difficulty in the reduction due to the loss of reference after removal of the infected bone segment(s).
- Removal of the infected tissues and osteotomy:
  - An appropriate incision is selected according to the soft tissue status of the lesion and, more importantly, the sinus formation position, the conditions of the exposed bone, and the targeted site for the osteotomy. In most cases, the original surgical incision or an incision that extends the sinus or exposed bone region is adopted.
  - The infected bone or callus surface is peeled off to expose the infected bone segment and callus, which are then gradually removed using a bone rongeur, osteotome, and other tools.
  - Intraoperative determination of living bone tissue: Living bone tissue has a reddish bone surface, accompanied by punctate hemorrhaging. The medullary cavity of living bone tissue is unobstructed and contains no inflammatory granulation tissue.
  - Removal of the infected bone segment: The interface between the infected bone and normal bone is identified. A 2.5 mm bone drill is used to create a fan-shaped hole in the normal bone, followed by the use of a sharp osteotome to directly sever the bone. Similarly, another cut is created at the other end of the bone, and then all the infected bone and callus tissues between the two cuts are completely removed.
  - The quality of the fracture reduction is evaluated under fluoroscopy, and the appropriate adjustments are made to correct the mechanical alignment, angulation, and rotational deformities, if necessary.
  - Osteotomy: The length and location of the osteotomy are determined according to the status at the resection site of the infected bone segment, i.e., residual bone at both ends of the fracture. The principle of osteotomy is to remove only one side of the metaphysis; however, both sides

    may be lengthened by metaphyseal osteotomy when the bone defect is large. The procedures are as follows. First, A 1–2 cm longitudinal incision is generated at the metaphysis and directly extended up to the subperiosteal area. After annular subperiosteal stripping, a 2.5 mm drill bit is used to vertically drill a fan-shaped hole in the long axis of the defective bone, which is then severed with retention of an intact periosteum using a sharp osteotome.

- Wound closure:
    - The small soft tissue defects can be sutured and fully drained in the first stage.
    - The large defects should be closed as much as possible. The unclosed defect can remain open for dressing changes or temporarily covered by VSD. Once the granulation tissue is fully grown, skin grafting will be performed to cover the unclosed defect.
    - In addition, shortening-lengthening techniques can be used to shorten and pressurize the defective bone segment after debridement and osteotomy to improve the local soft tissue coverage and allow simultaneous incision closure after debridement. Open dressing and skin grafting should also be avoided. At this time, another osteotomy plane should be created at a distance from the shortened osteotomy plane, and bone transport is initiated 1 week later.
- Postoperative treatment:
    - Bone lengthening is initiated a week after the surgery four times per day to achieve bone lengthening of 1 mm per day.
    - The status of external fixation should be closely monitored by X-ray examination to track the progress of bone lengthening.
    - To avoid excessive or insufficient lengthening, radiographs of the full-length lower extremities should be obtained regularly, and the bone lengthening should be terminated in time once both lower extremities have achieved the same length.
    - The accordion maneuver: If the callus grows poorly, the bone fragments can be compressed and transported in a reverse direction to stimulate callus growth, and bone fragment transport can be resumed in the normal direction after the callus growth is satisfactory.
    - After the fracture completely heals and mineralization of the lengthened new bone is good, the external fixator can be selectively removed based on the mineralization status of the fracture.

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