5 Nonunion

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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).

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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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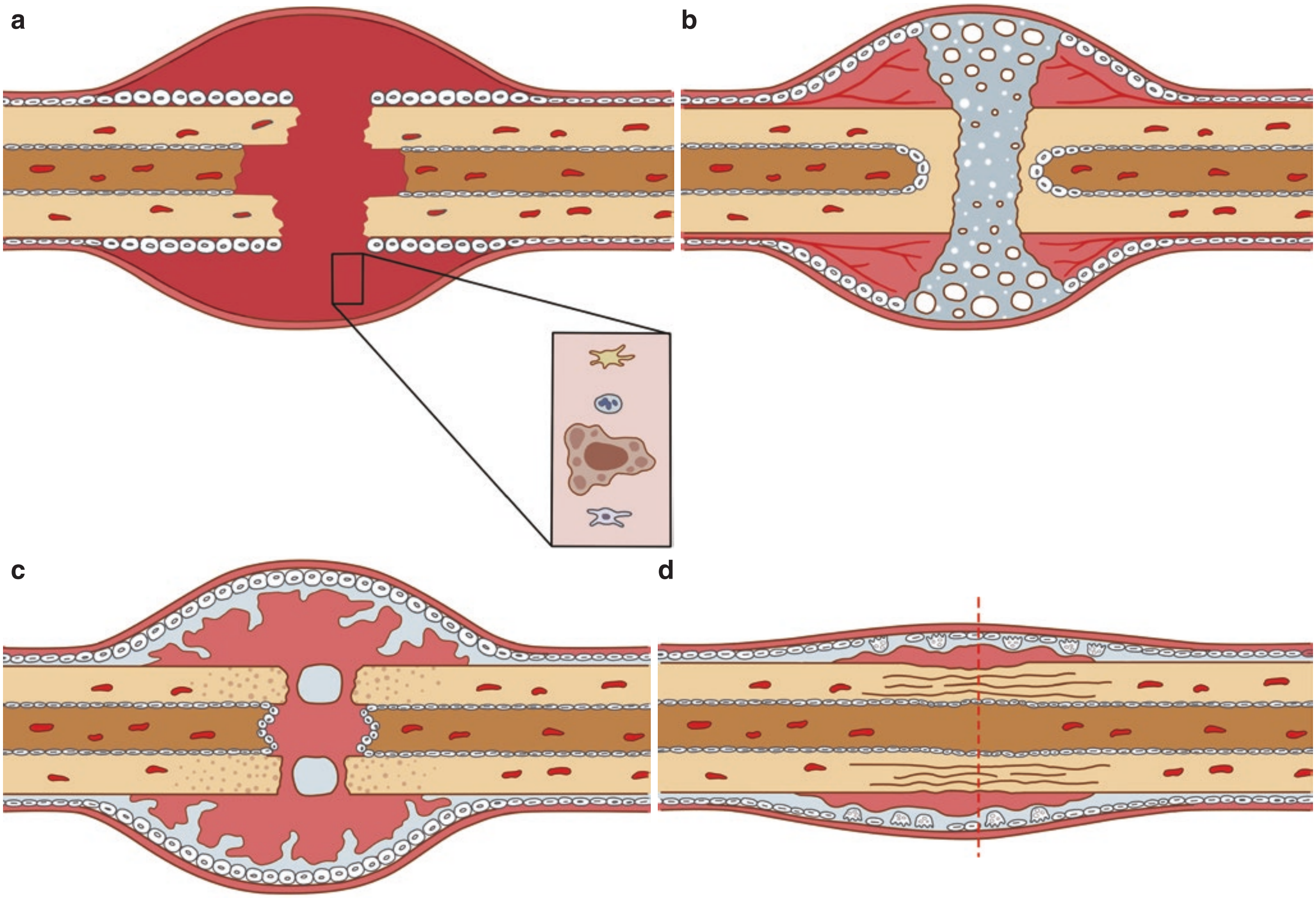

Fig. 5.1 (**a**) Inflammatory phase: The formed hematoma at the fracture ends gradually forms granulation tissue through release of inflammatory factors within the hematoma. (**b**) Cartilaginous callus formation: Cartilaginous callus is formed at the fracture site through intramembranous osteogenesis 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

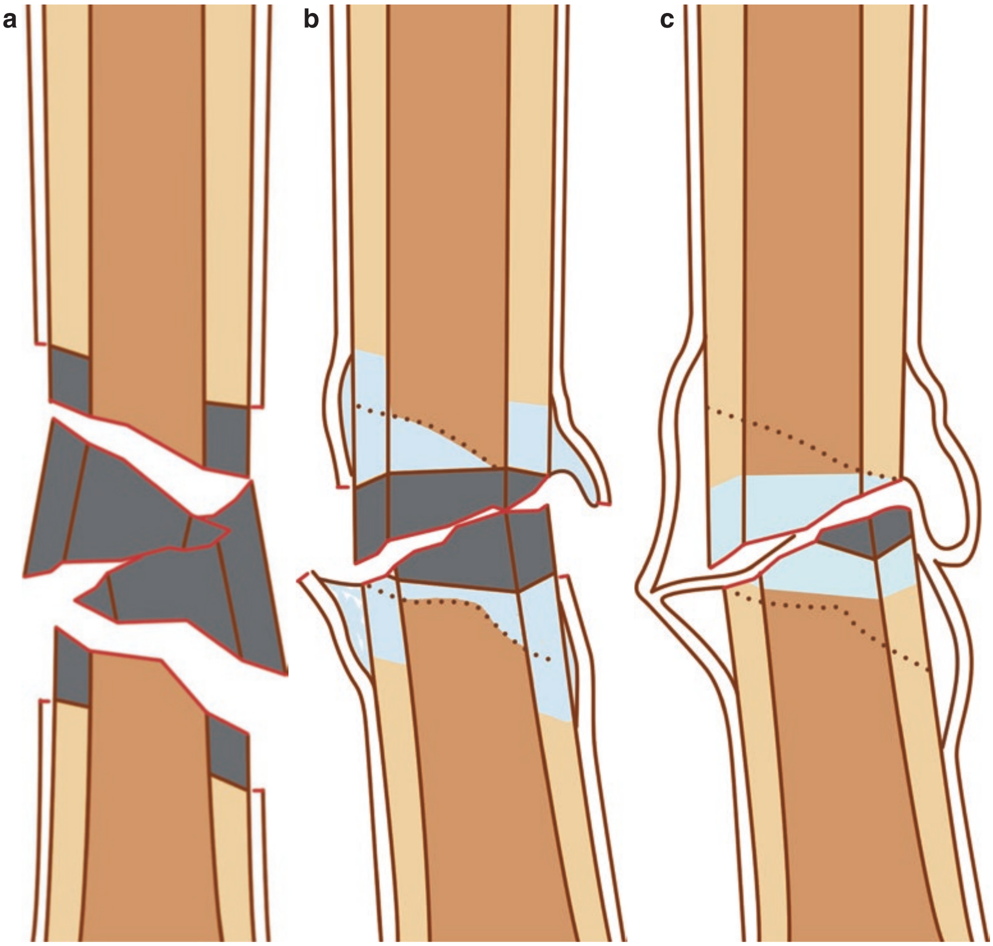

Fig. 5.3 (**a**) In the case of complex fractures, the free bone fragments at the fracture site are ischemic (dark areas in the figure). (**b**) Several months after the fracture, the two fracture fragments have united with their corresponding main bone ends via callus formation, but the central area 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.

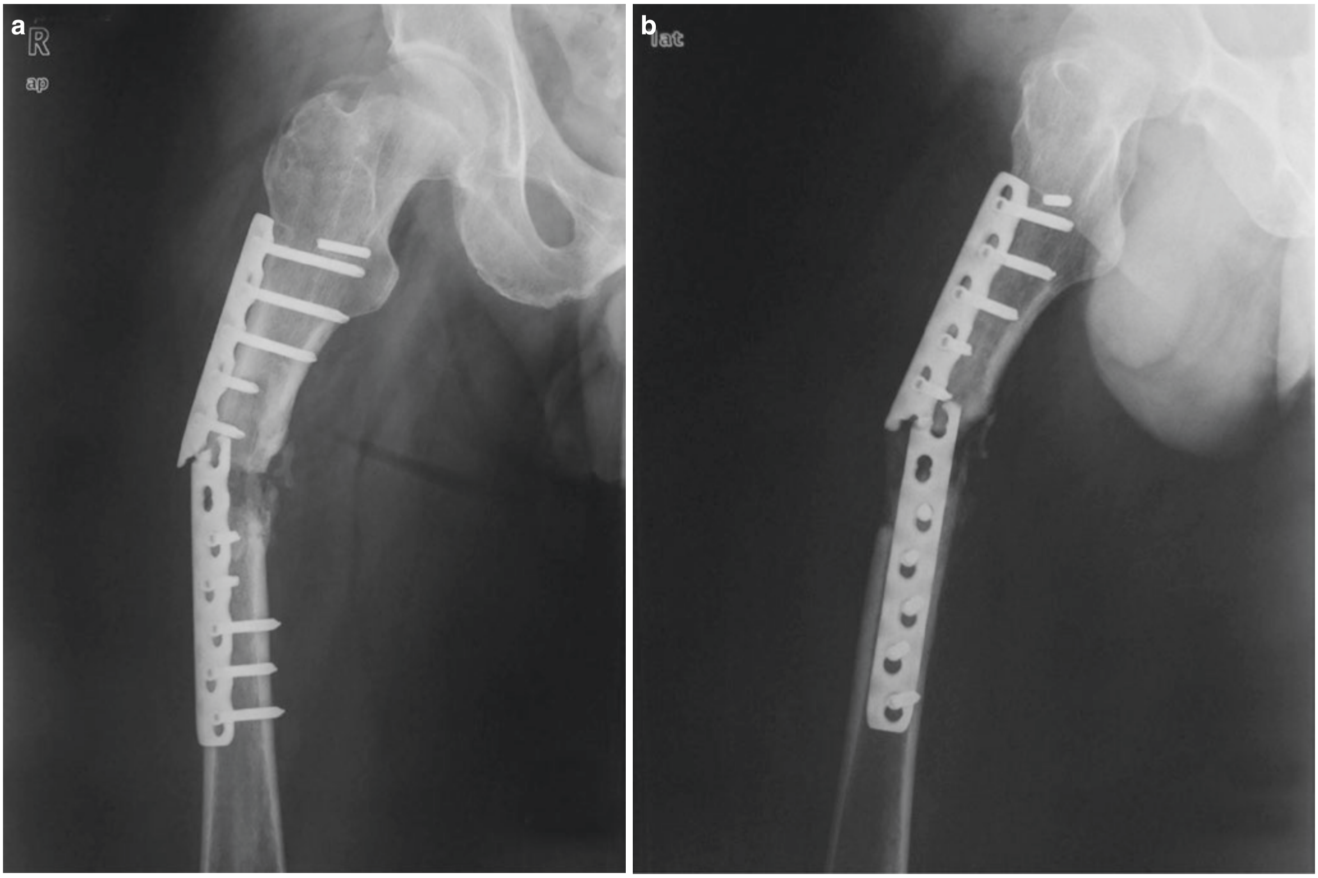

Fig. 5.4 Due to insufficient support caused by the medial bone defect of the femur, the internal fixator is severely mechanically unstable, and the plate is fatigued and broken. (**a**) AP view. (**b**) Lateral view

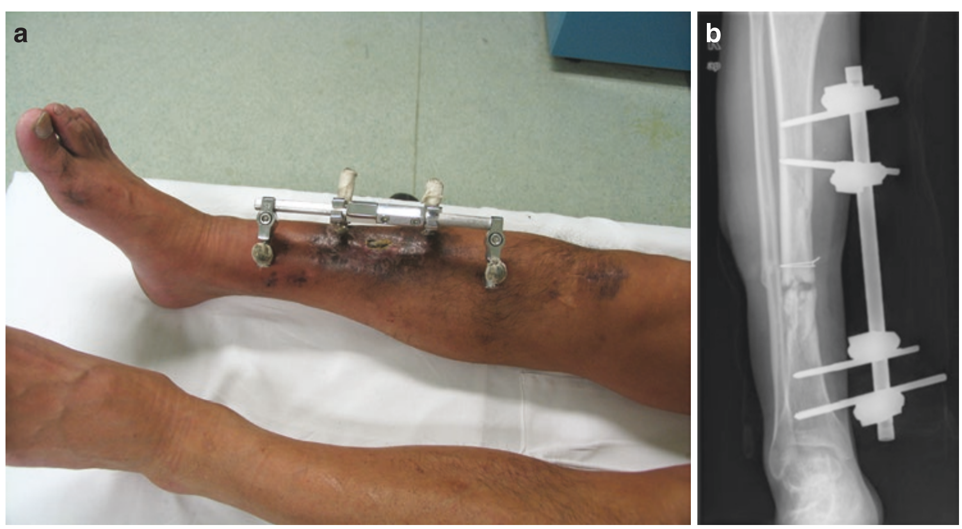

Fig. 5.5 A patient with infectious nonunion. (**a**) There is a local cutaneous sinus and purulent secretion. (**b**) A radiograph: The absorption at the fracture site is visible; a cerclage wire remains in its place; there is the formation of sequestrum and sclerosis

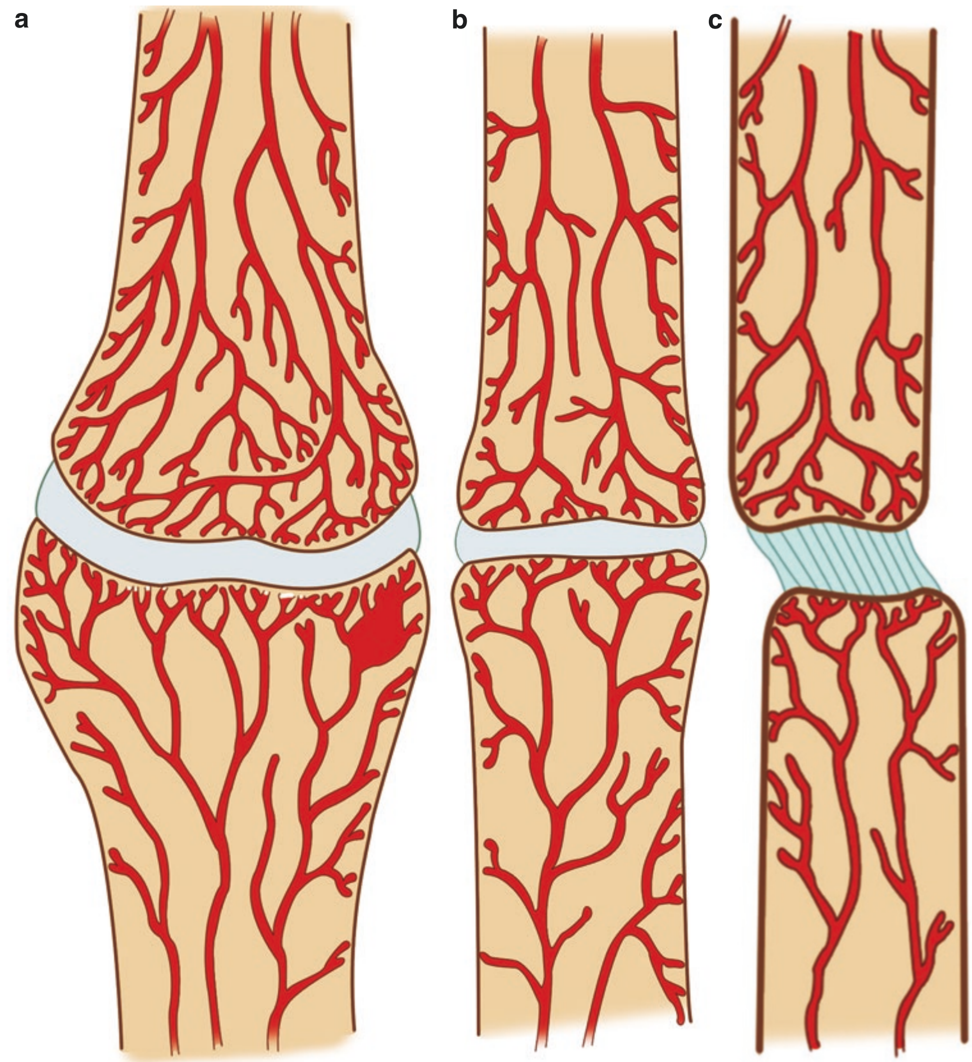

Fig. 5.6 Classification of hypervascular-vitalized nonunions. (**a**) "Elephant foot" nonunion. (**b**) "Horse hoof" nonunion. (**c**) Oligotrophic nonunion

"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.

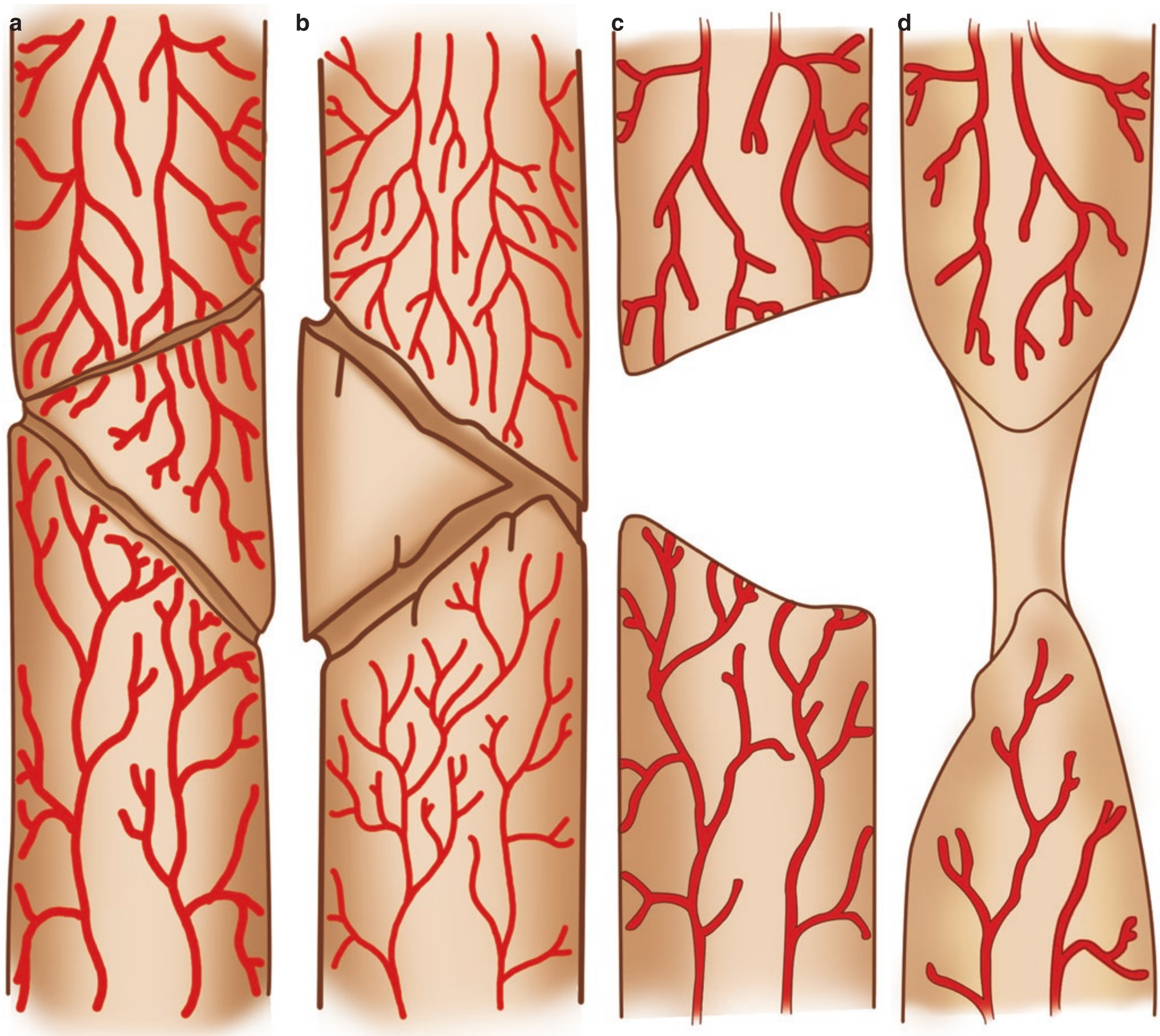

Fig. 5.7 Avascular-devitalized nonunions. (**a**) Torsion wedge nonunions. (**b**) Comminuted nonunions. (**c**) Defected nonunions. (**d**) Atrophic nonunions

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

Fig. 5.8 A radiograph showing the hypertrophic "elephant foot" or "horse hoof" nonunion

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.

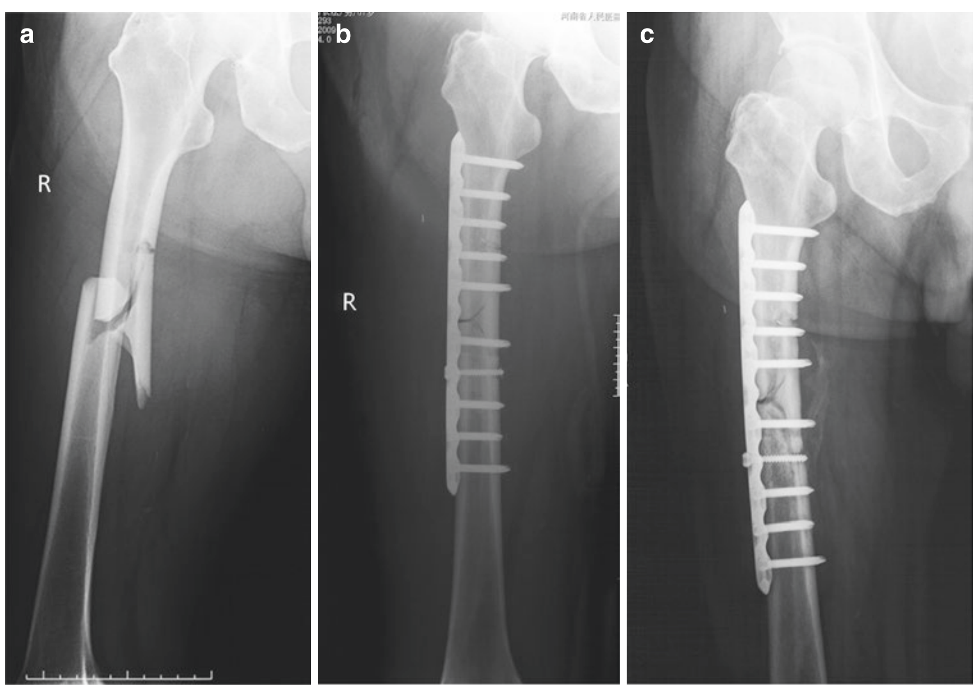

Fig. 5.9 Nonunion of the femoral shaft fracture after plate. (**a**) A preoperative radiograph showed a type B1 fracture. (**b**) Open reduction and internal fixation: The fracture was reduced anatomically. However, no compression was applied between the butterfly fragment and the main bone fragment, 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

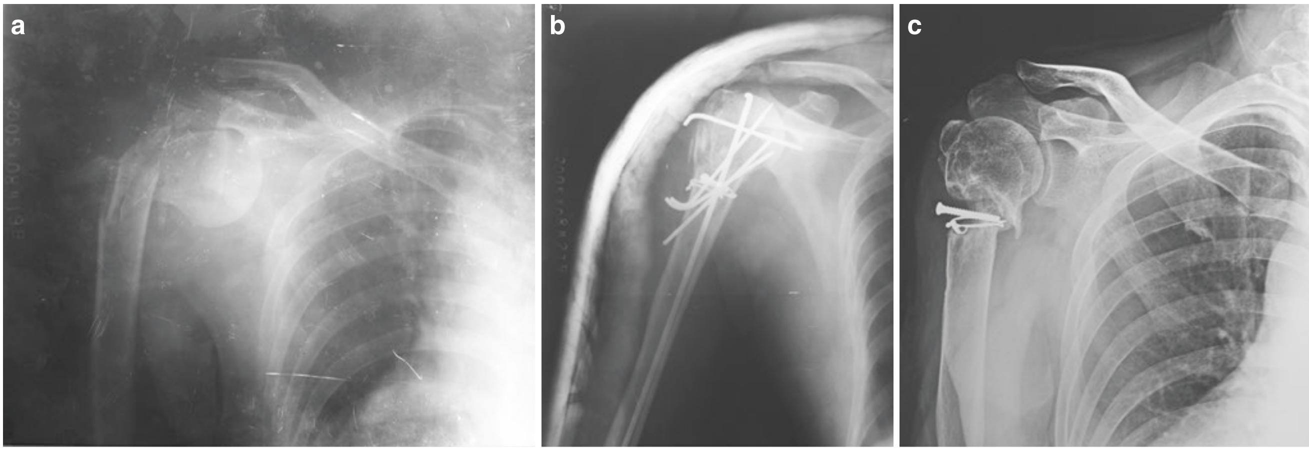

Fig. 5.10 A surgical neck fracture of the humerus. (**a**) A preoperative radiograph. (**b**) The fracture was treated with open reduction and screw fixation, wire binding, and Kirschner-wire fixation, and the affected extremity was then immobilized with a plaster cast after surgery. (**c**) The Kirshner 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

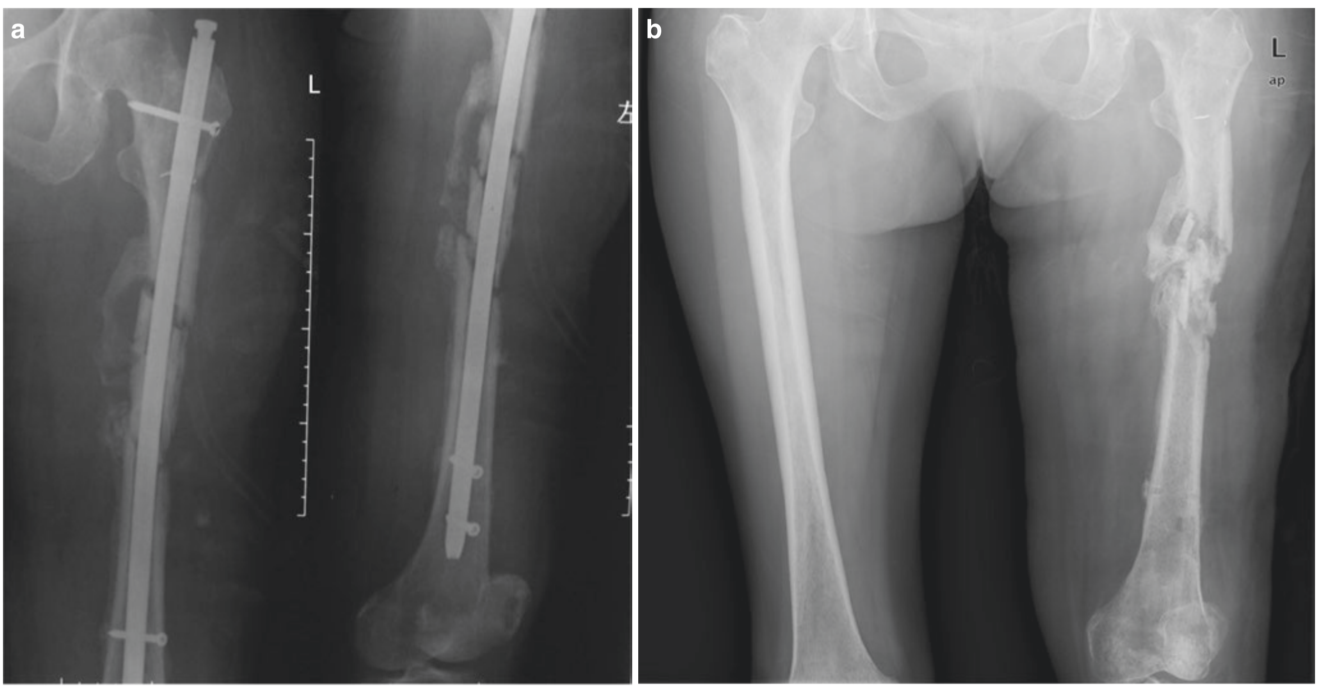

Fig. 5.11 (**a**) The patient with a left femoral shaft fracture had a postoperative infection after intramedullary nail. (**b**) The patient underwent removal of the nail, followed by catheterization and lavage for infection control; however, secondary infectious nonunion occurred. Periosteal reaction and sequestrum are present in the radiograph

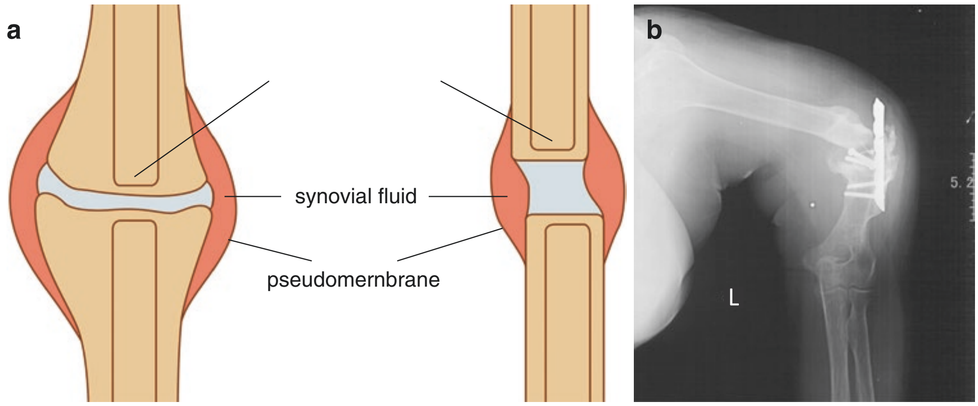

Fig. 5.12 (**a**) Schematic diagram of pseudarthrosis showing the pseudobursa, synovial fluid, and bone marrow cavity occlusion. (**b**) A radiograph of a patient with a left humeral shaft fracture who received open reduction and internal fixation but subsequently suffered pseudarthrosis due to plate 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-

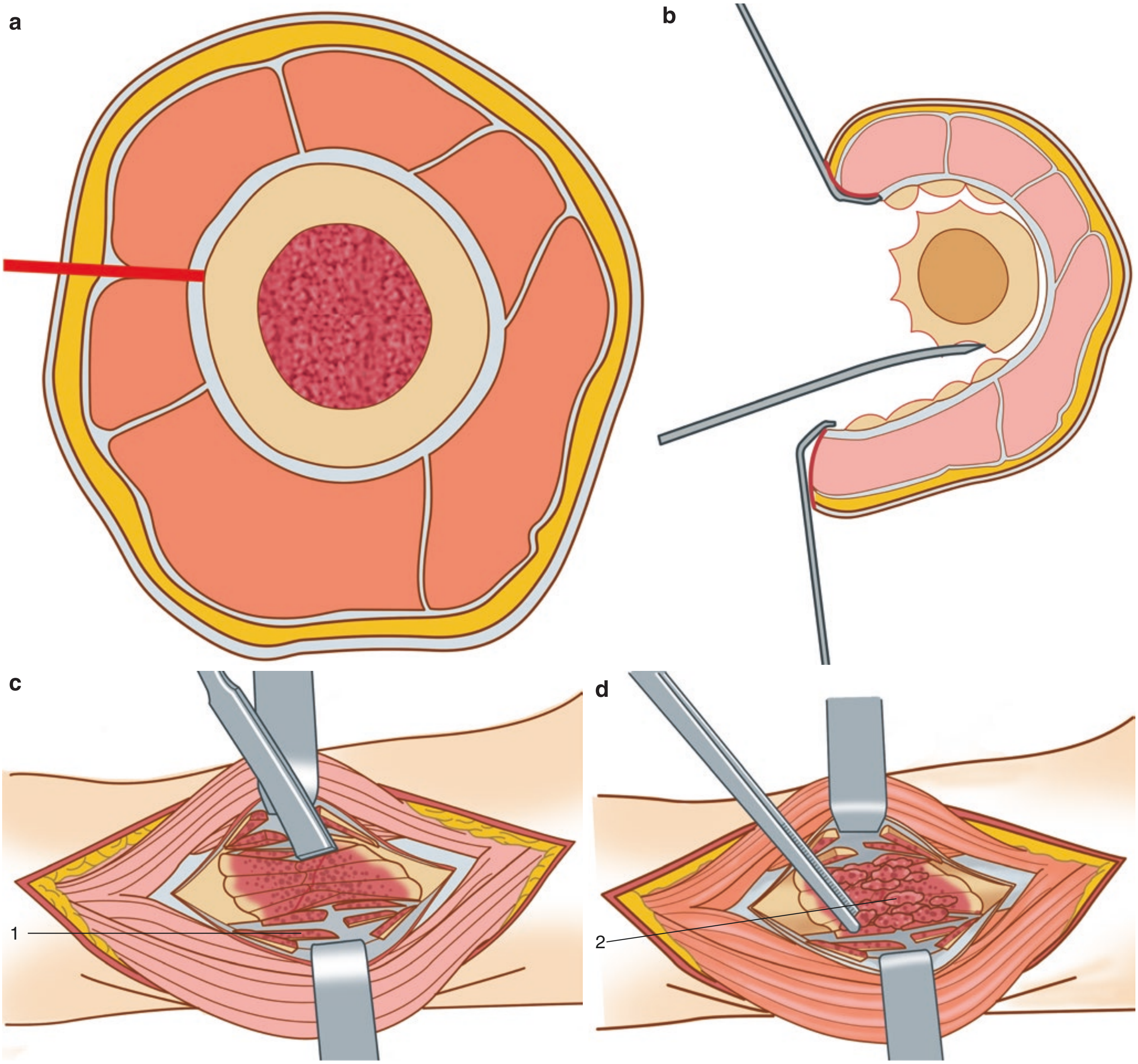

Fig. 5.14 Schematic diagram of decortication. (**a**) Most of the blood supply to the lateral cortical bone and callus is derived from the periosteum. (**b**, **c**) An osteotome is used to remove the cortical bone. It is crucial that the bone pieces should be attached to the periosteum and receive the 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

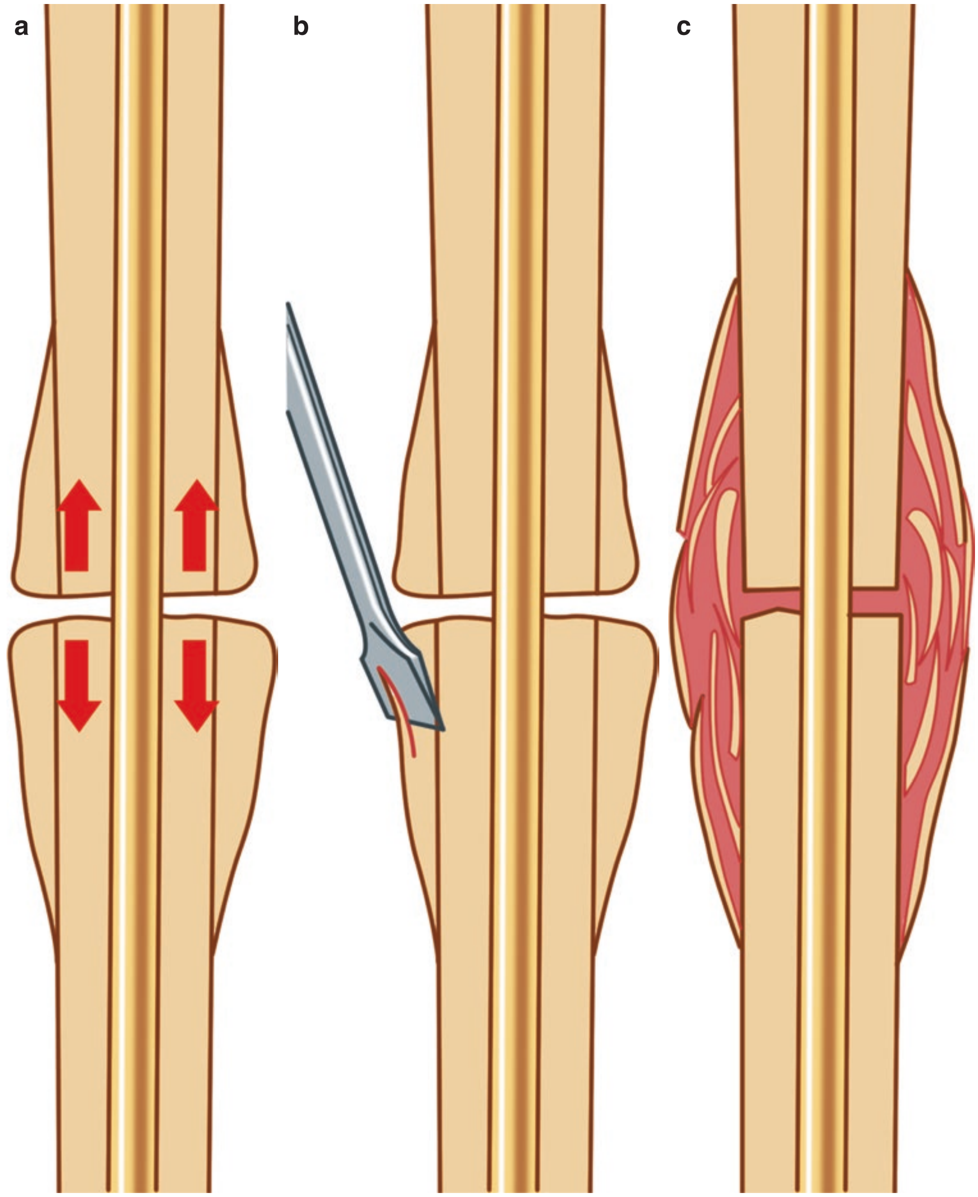

Fig. 5.15 (**a**) Hypervascular-vitalized nonunion after intramedullary nail. (**b**) Thin cortical bone pieces with an abundant blood supply are stripped off from the fracture using an osteotome. (**c**) Implant into the cancellous bone to stimulate fracture healing

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

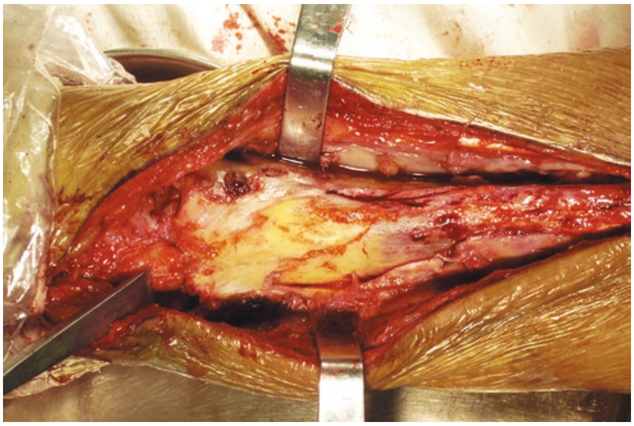

Fig. 5.16 Dead bone is waxy yellow in color and extremely hard. It is covered with scar tissue and does not bleed after stripping

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.

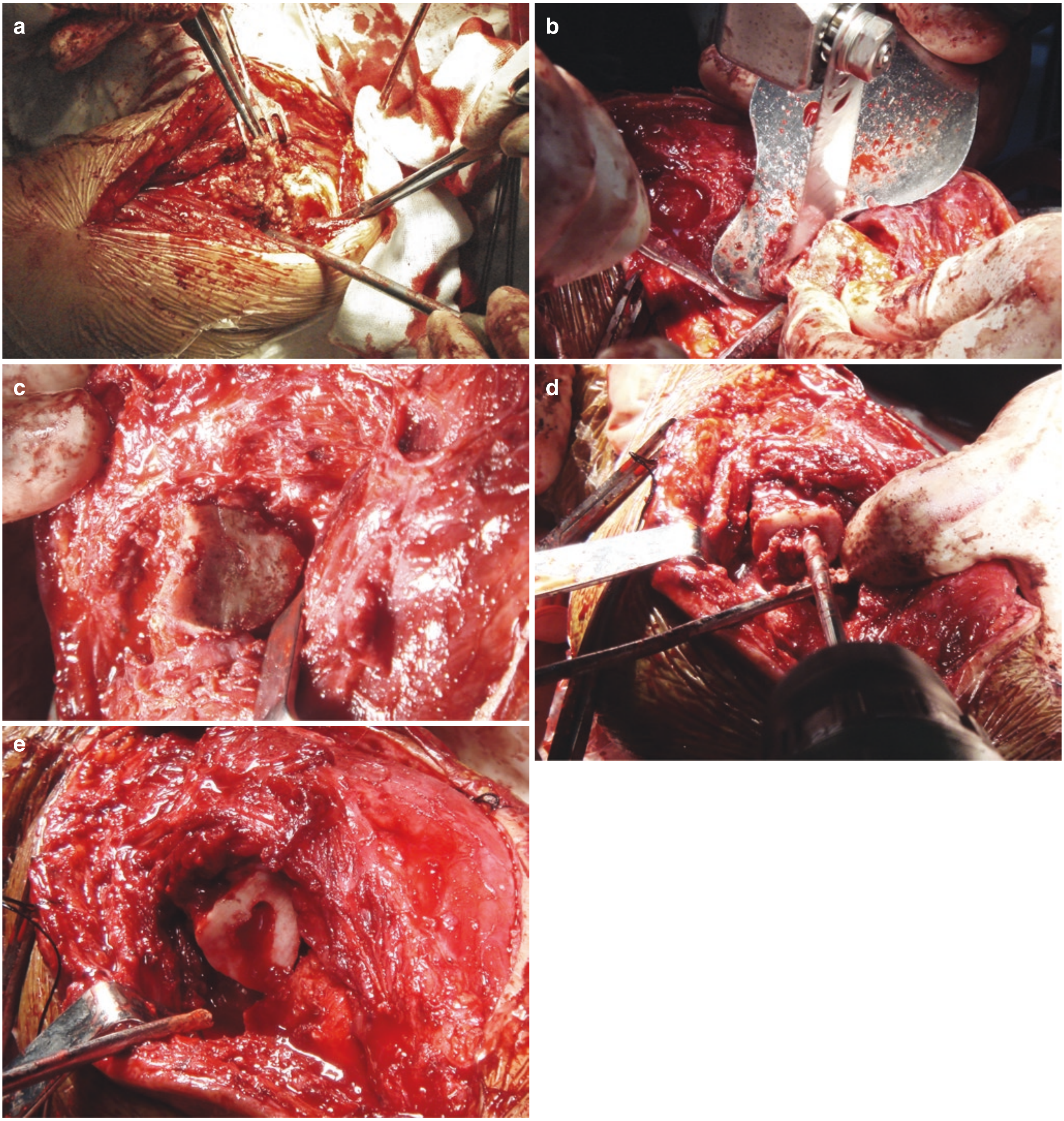

Fig. 5.17 Surgery for patients with atrophic nonunion of the humeral shaft. (**a**) The fracture site was debrided and cleaned, and the devitalized scar tissue intercalated between the fracture ends was removed. (**b**) The atrophic and hardened fracture end was removed by cutting. (**c**) The closed 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

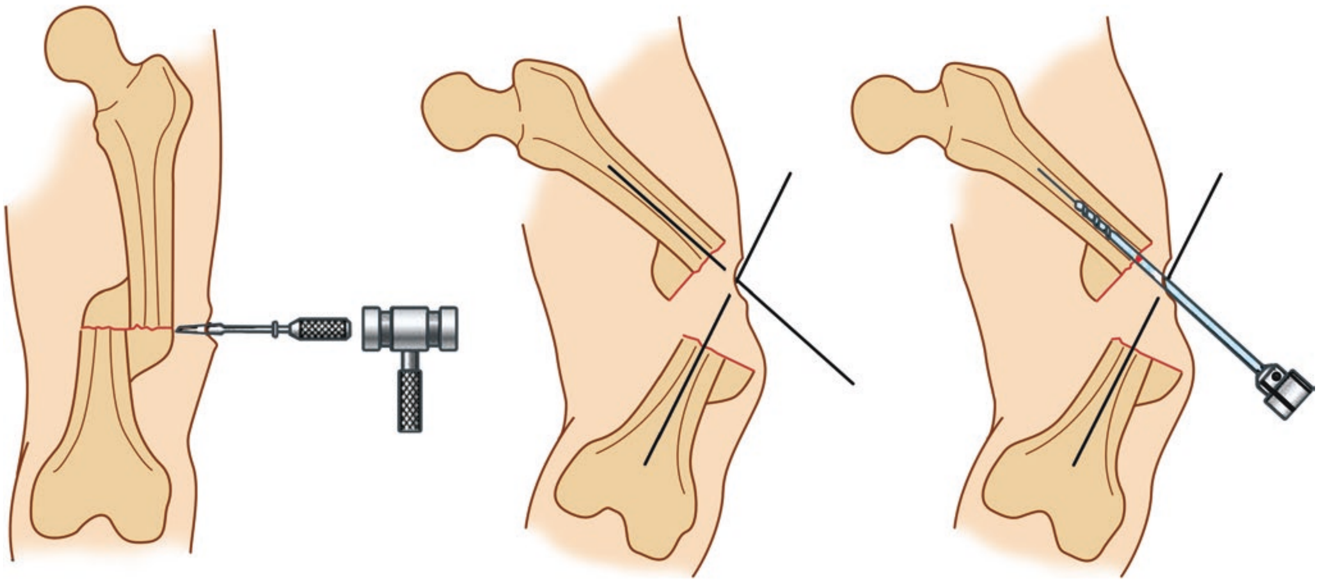

Fig. 5.18 For a displaced malunited fracture, the fracture ends are cut off first, and then the medullary cavity is recanalized after the insertion of a guide wire

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

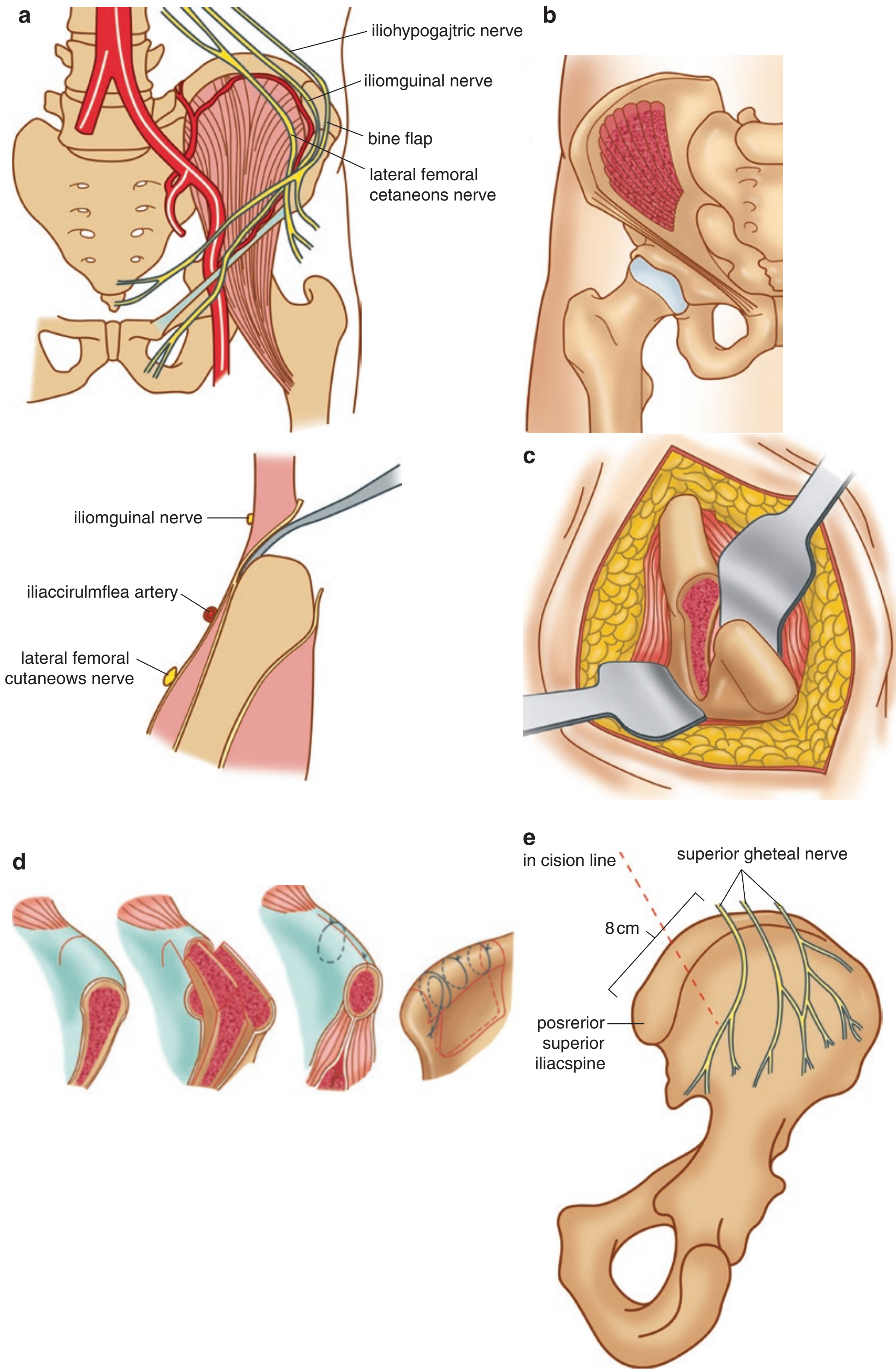

Fig. 5.19 Iliac bone graft harvest. (**a**) Because the ilioinguinal nerve, iliohypogastric nerve, and lateral femoral cutaneous nerve travel near the iliac crest and anterior superior iliac spine, the incision should not be lower than the anterior superior iliac spine. Subperiosteal stripping is performed 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

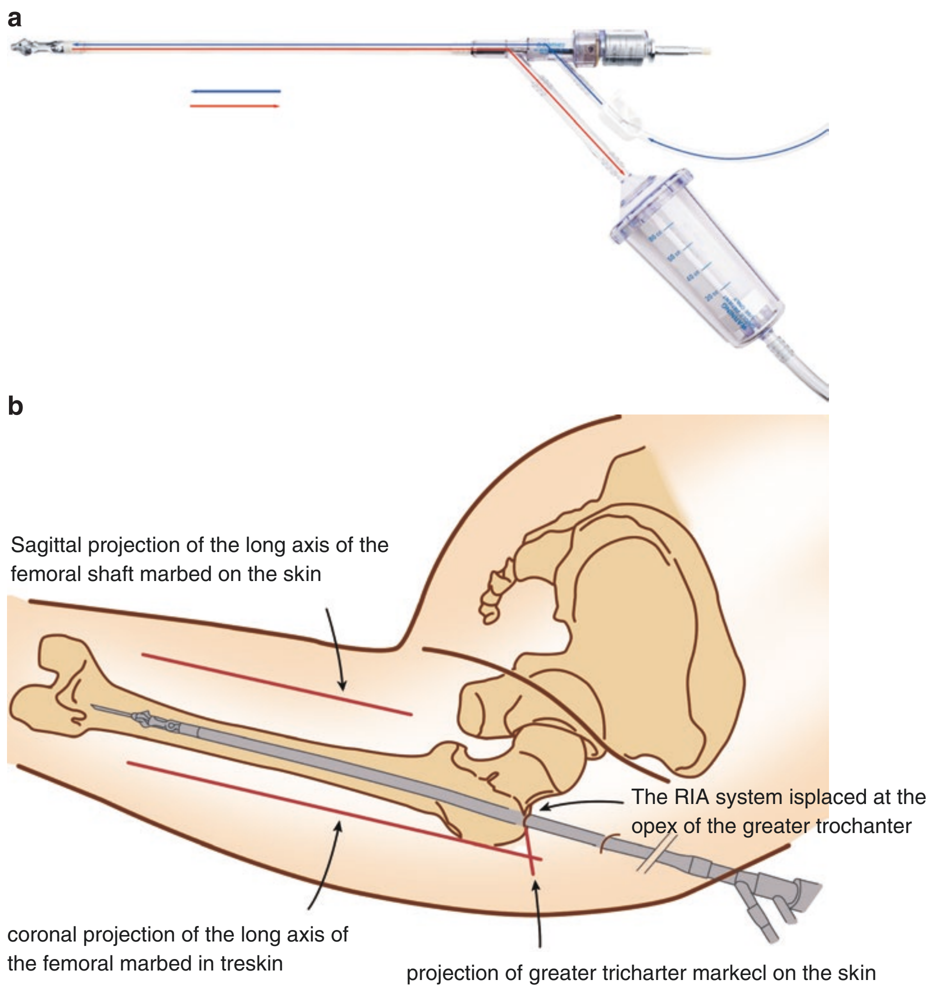

Fig. 5.20 (**a**) The reamer-irrigator-aspirator (RIA) system developed by Synthes can be used to obtain bone paste from the femoral medullary cavity. (**b**) Using this system, bone paste is obtained via intramedullary reaming similar to the technique used for intramedullary nailing of the femoral shaft

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.

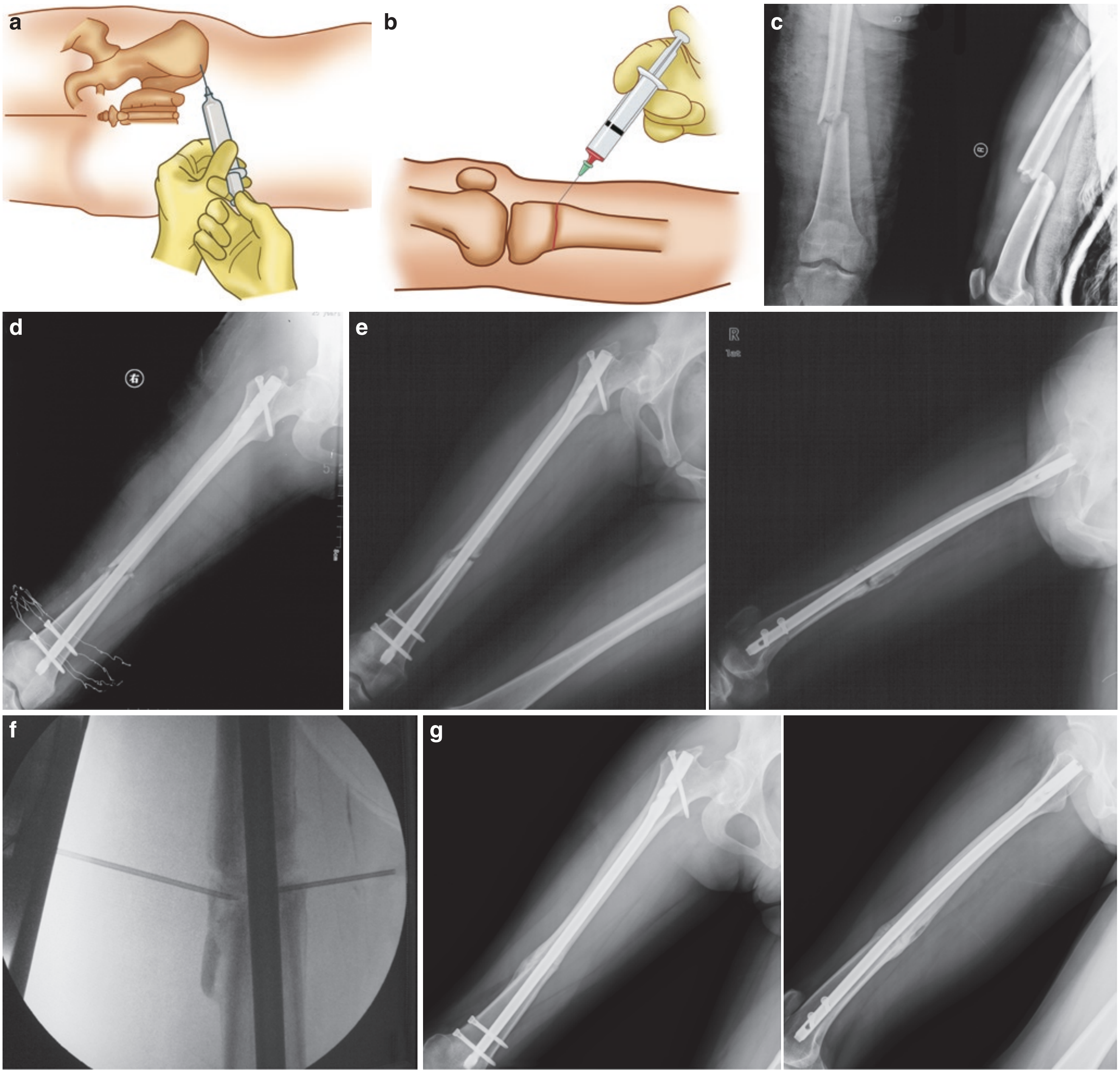

Fig. 5.21 The medullary blood is harvested by puncture and injected into the fracture site to stimulate bone regeneration and promote fracture healing. (**a**) The medullary blood is drawn from the anterior superior iliac spine or the posterior superior iliac spine. (**b**) The medullary blood is injected 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

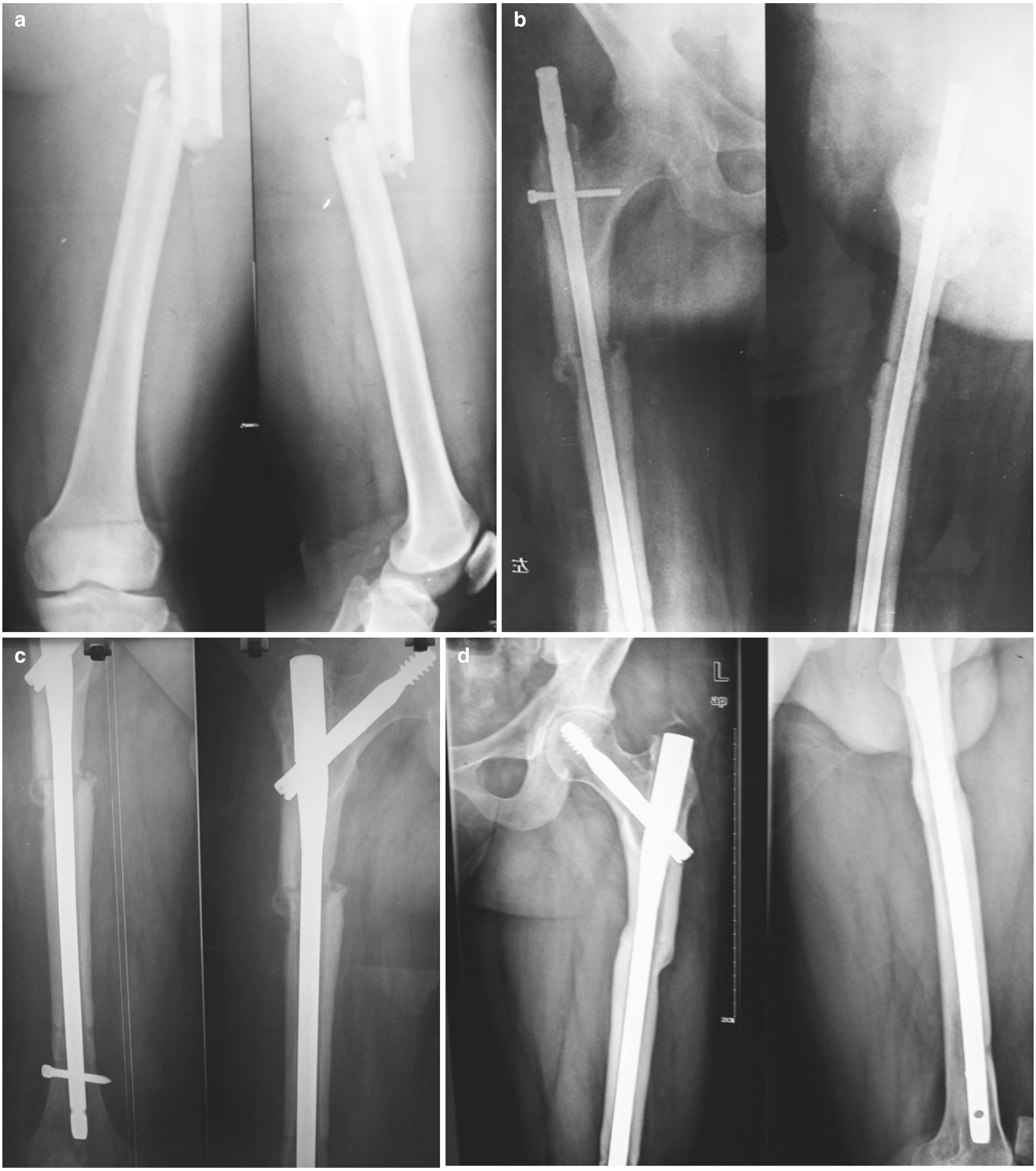

Fig. 5.22 (**a**) A type A3 fracture of the femoral shaft. (**b**) The fracture remained ununited at 10 months after surgery because the intramedullary nail used for fixation was too thin, the fracture was unstable, and the nail tail protruded from the bone surface too long. (**c**) Replacement with 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

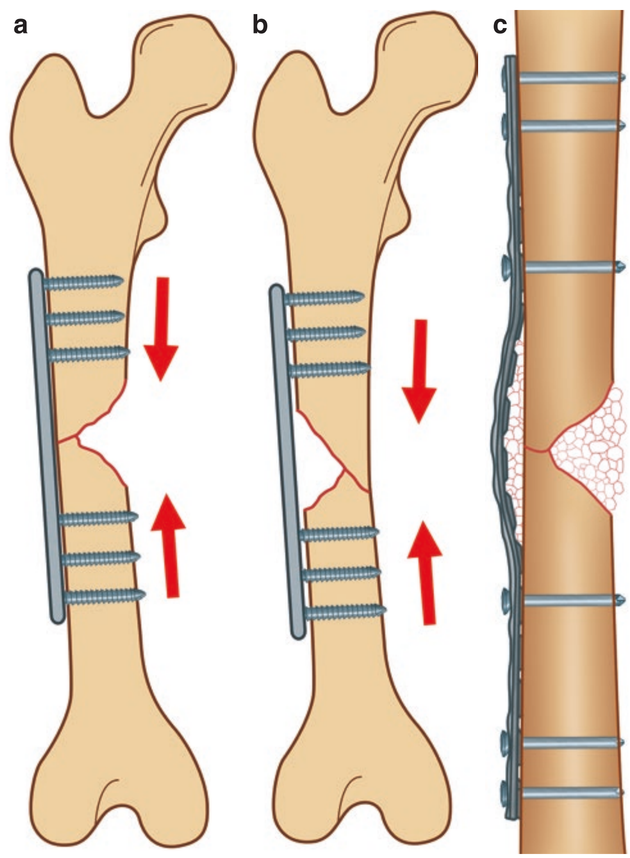

Fig. 5.23 (**a**) The bone defect is located on the opposite side of the fixation plate, causing mechanical instability under compression (similar to that of a “suspension arm”). (**b**) The bone defect is located on the same side of the fixation plate, and on the opposite side, the two bone fragments 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

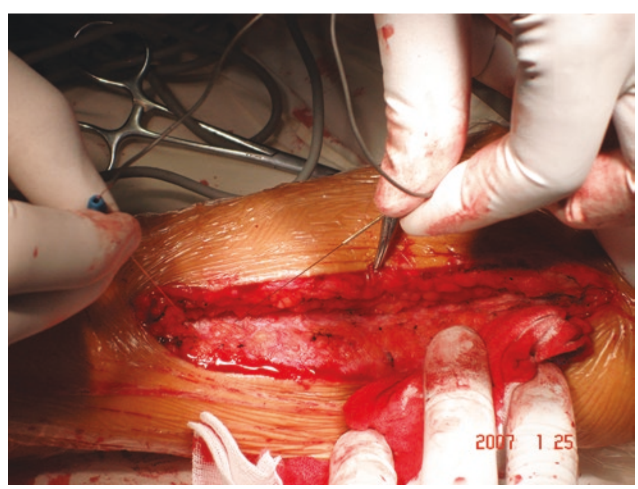

Fig. 5.24 During surgery, an electrical stimulation probe was used to locate the radial nerve, and a 1.5 cm wide muscle scar band around the radial nerve was retained

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

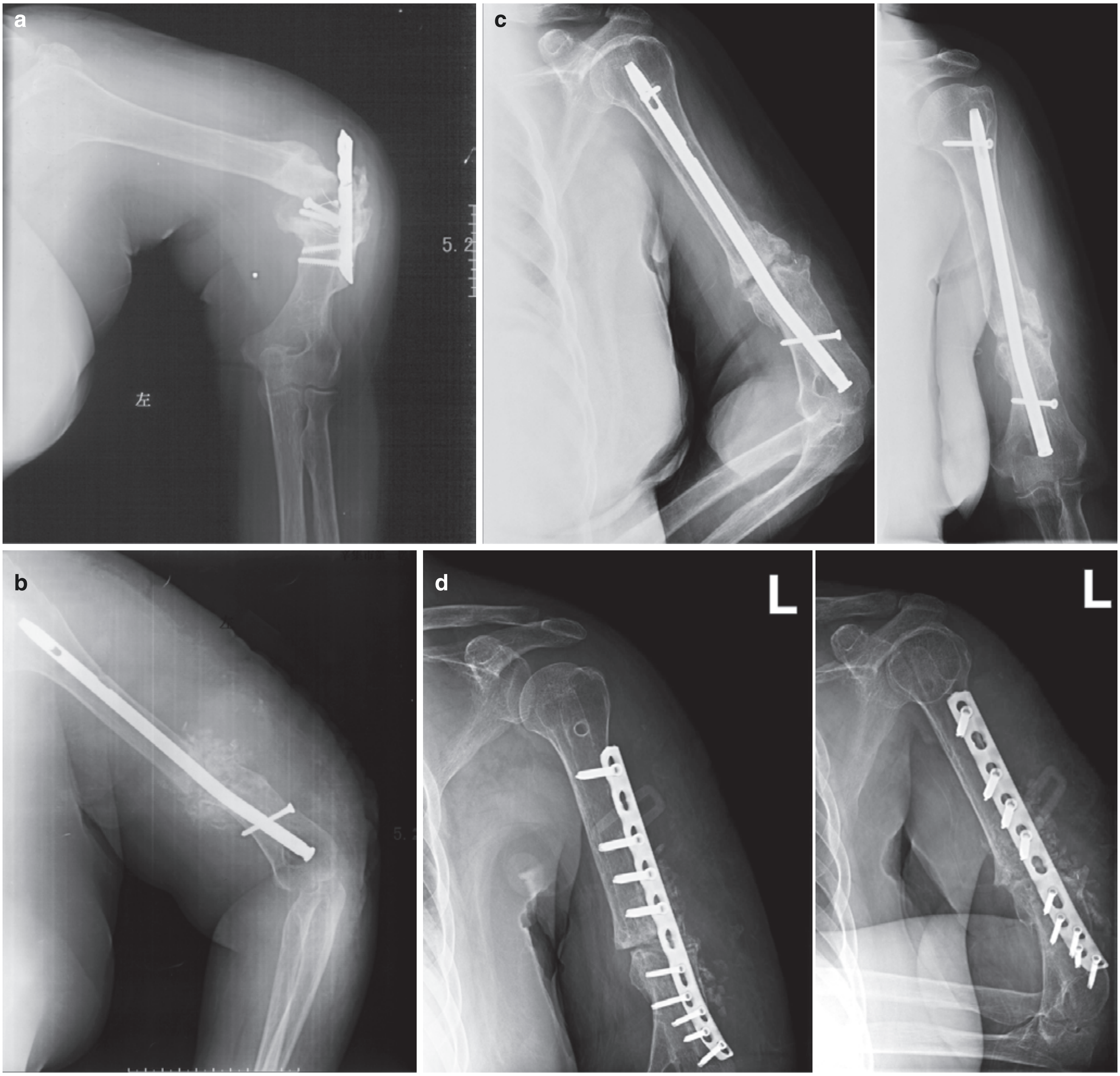

Fig. 5.25 A patient with a humeral shaft fracture (the original preoperative and postoperative radiographs were missing). (**a**) The patient received plate-screw fixation for the left humeral shaft fracture and started functional exercise at 3 months after surgery. However, left arm pain and deformity 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

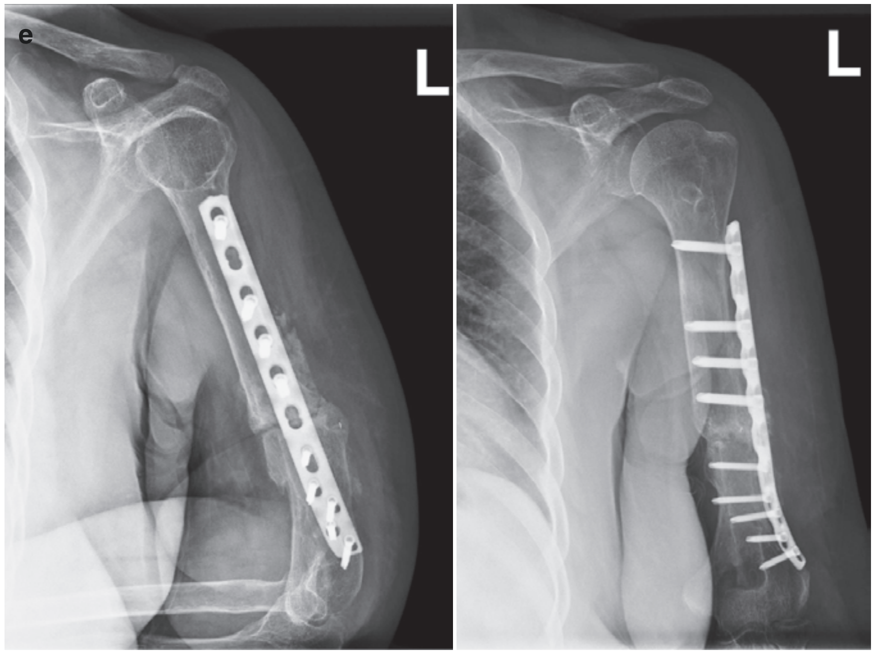

Fig. 5.25 (continued)

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

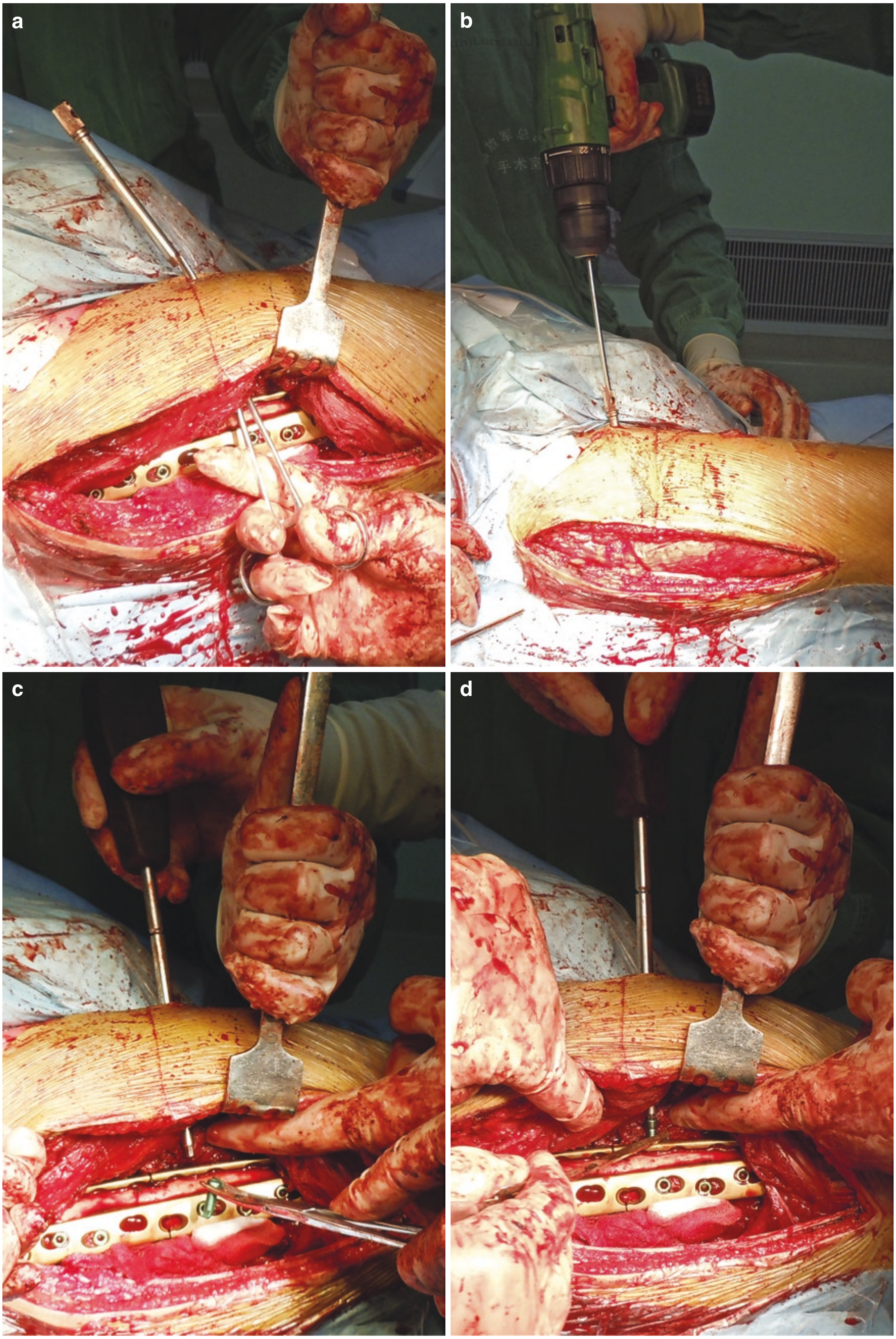

Fig. 5.26 (**a**) The muscles and subcutaneous tissue are separated outwardly using a pair of curved forceps; when the separation reaches the subcutaneous layer, a 0.5 cm skin incision is created with a small surgical blade, through which the guide apparatus is picked up. (**b**) The guide apparatus 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

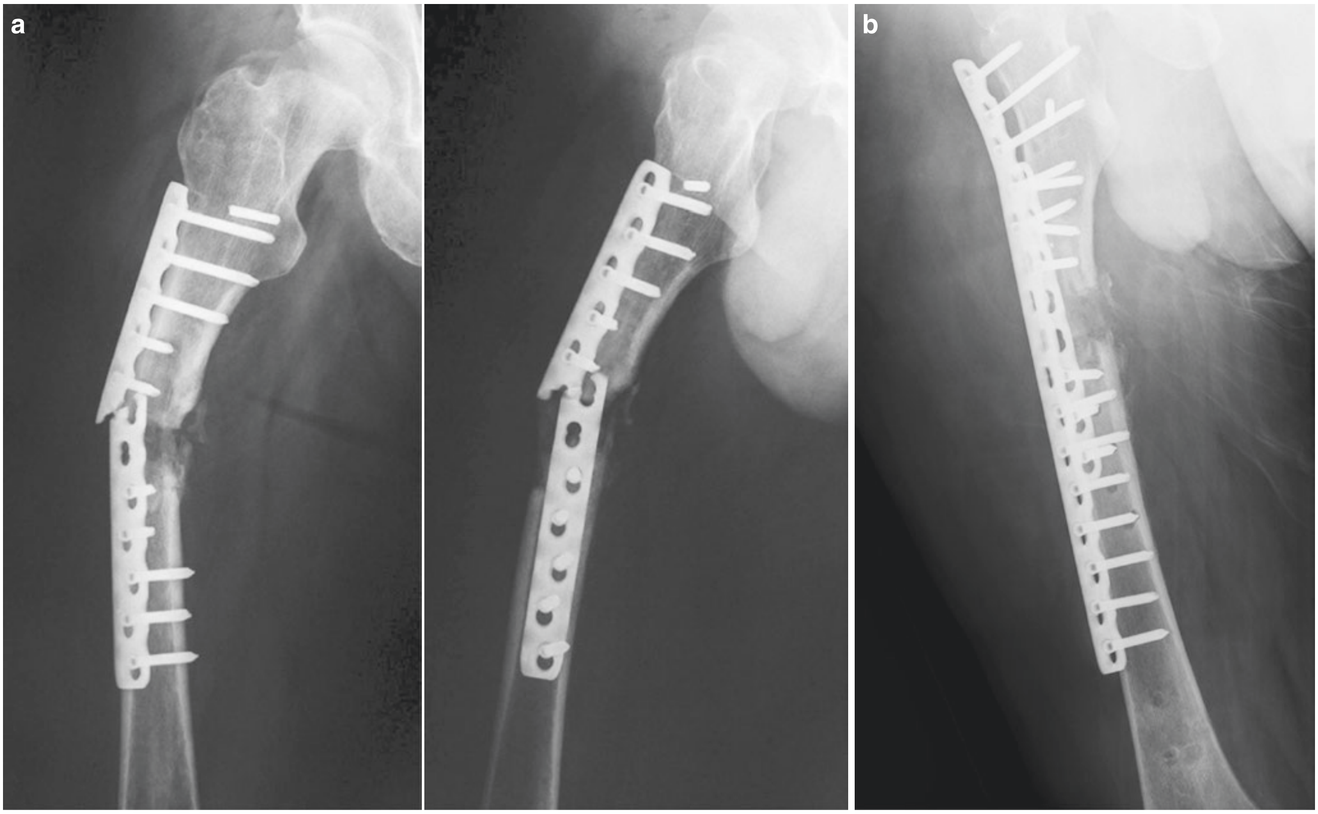

Fig. 5.27 The patient received lateral single-plate fixation for a femoral shaft fracture; however, the medial cortical defect resulted in broken of the plate and nonunion (the original preoperative and immediate postoperative radiographs were missing). (**a**) AP and lateral radiographs obtained after 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.

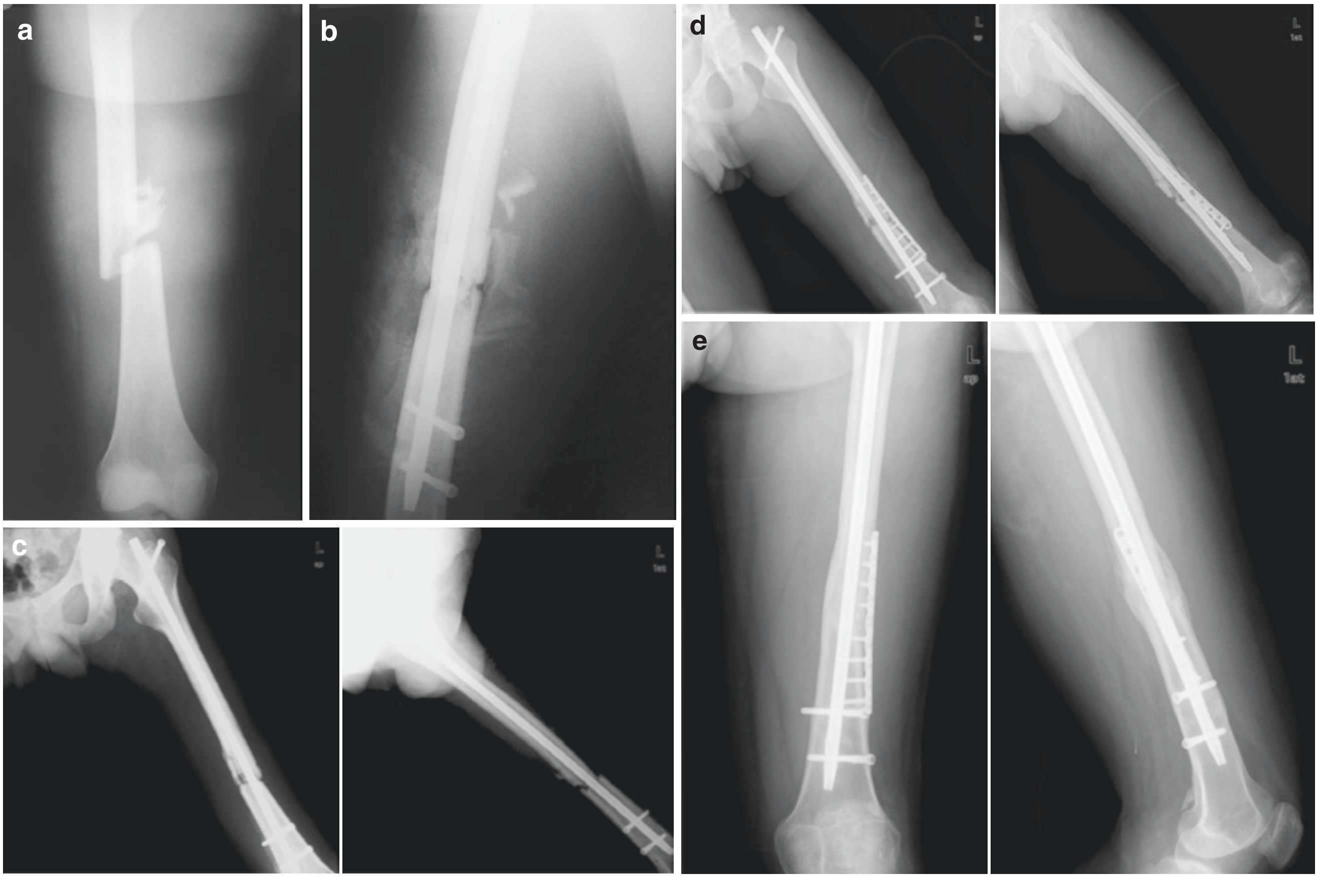

Fig. 5.28 (**a**) A preoperative radiograph of an AO type B3 open femoral shaft fracture. (**b**) A postoperative radiograph: The patient received emergency debridement, open reduction, and intramedullary nail fixation. (**c**) A radiograph at 7 months postoperatively: The fracture line was clear without 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.

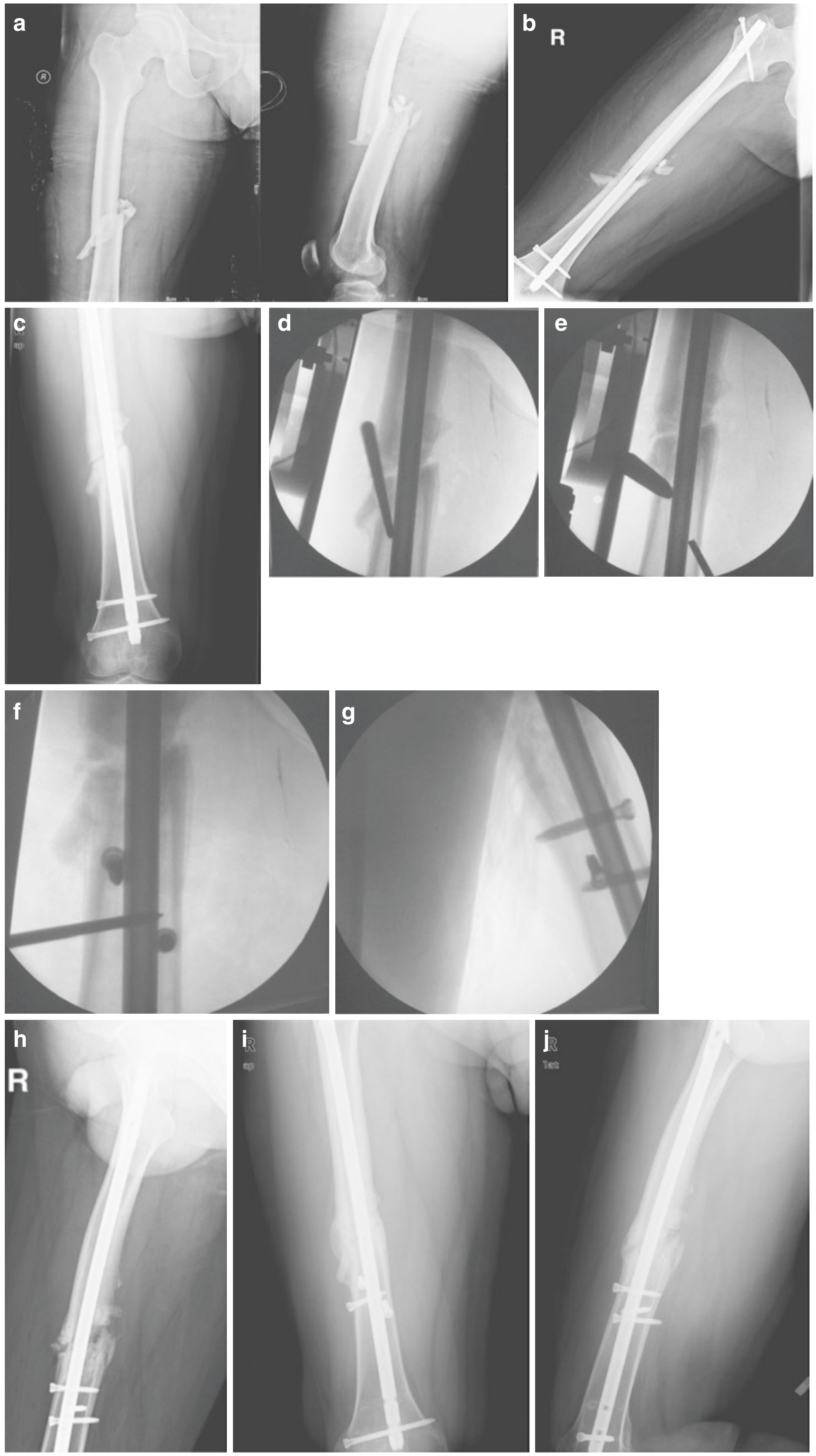

Fig. 5.29 Nonunion of an open fracture of the femoral shaft after intramedullary nail. (**a**) A preoperative radiograph showed an open comminution fracture of the femur. (**b**) A radiograph taken after intramedullary nail. (**c**) A radiograph taken at 13 months after surgery: The fracture line was 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

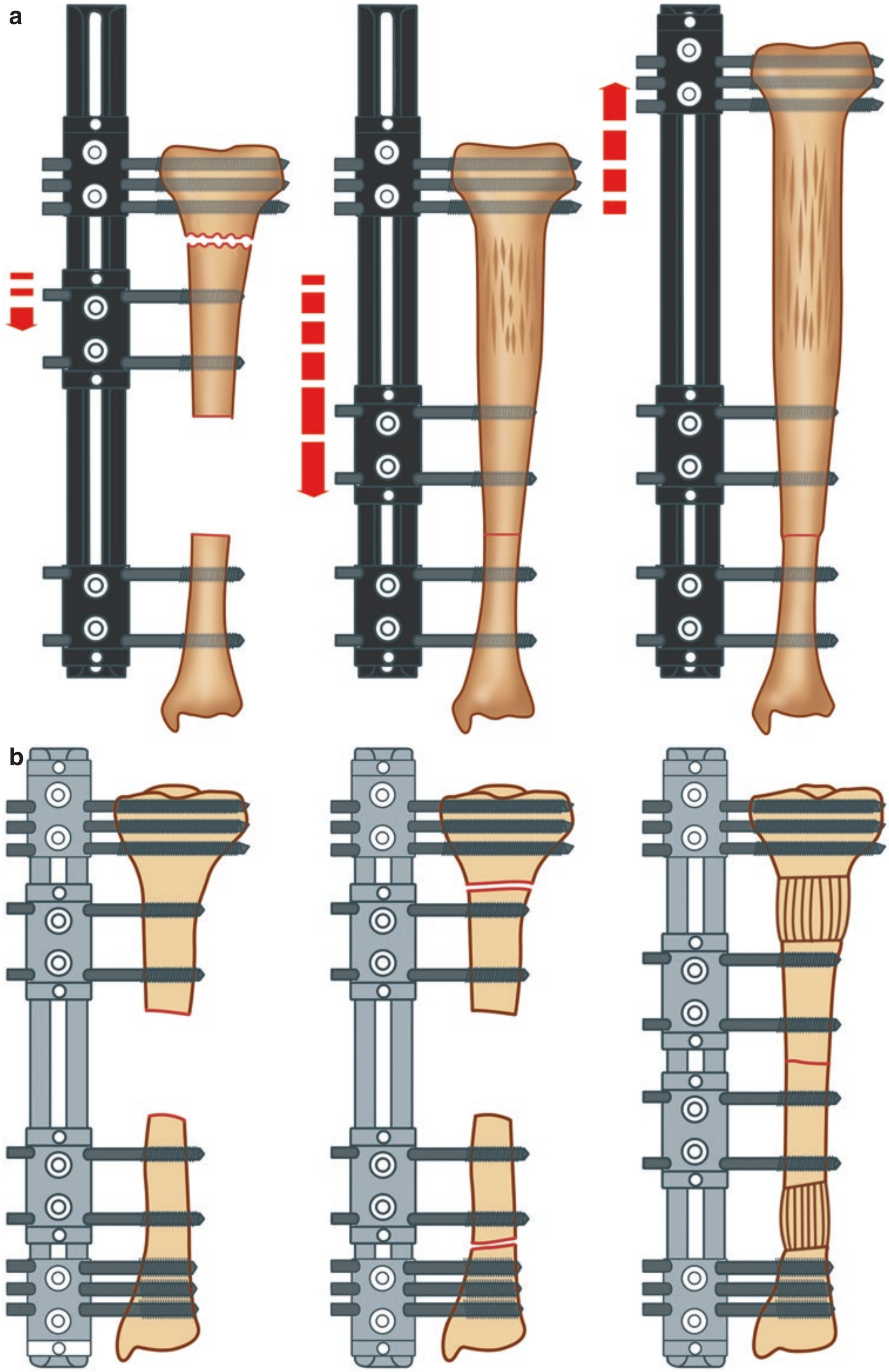

Fig. 5.30 Treatment of an infectious nonunion using a single-arm external fixator and bone lengthening technique (**a**) Unidirectional bone lengthening technique: The infected ununited bone segment was removed, followed by the creation of a fresh osteotomy plane far away from the nonunion area. After 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

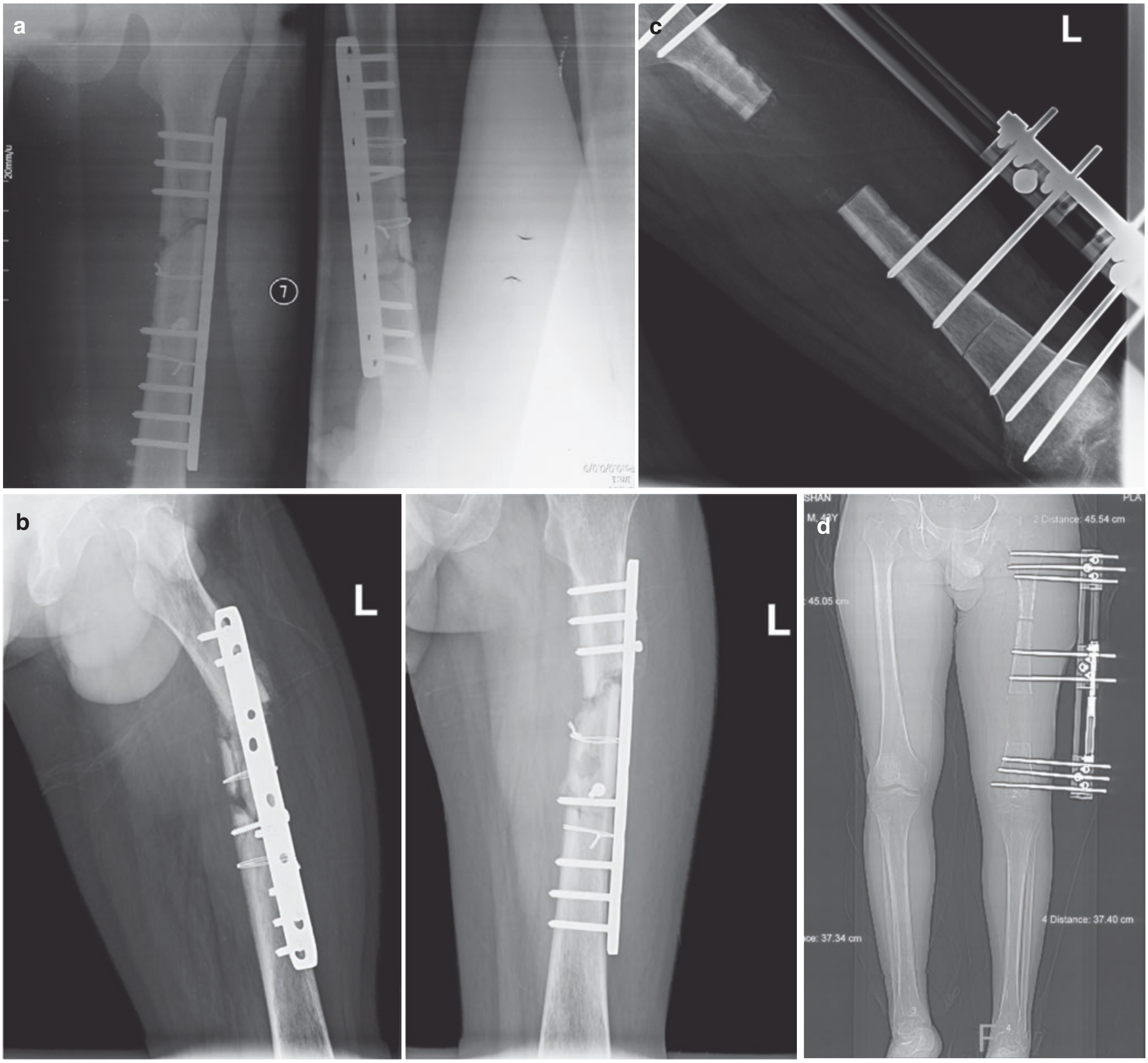

Fig. 5.32 A patient with postoperative nonunion of the femoral shaft fracture (the original radiograph was missing). (**a**) Postoperative AP and lateral radiographs of a type C3 fracture of the femoral shaft after plate: The fracture was fixed with not only a plate and screws but also wire cerclages. (**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

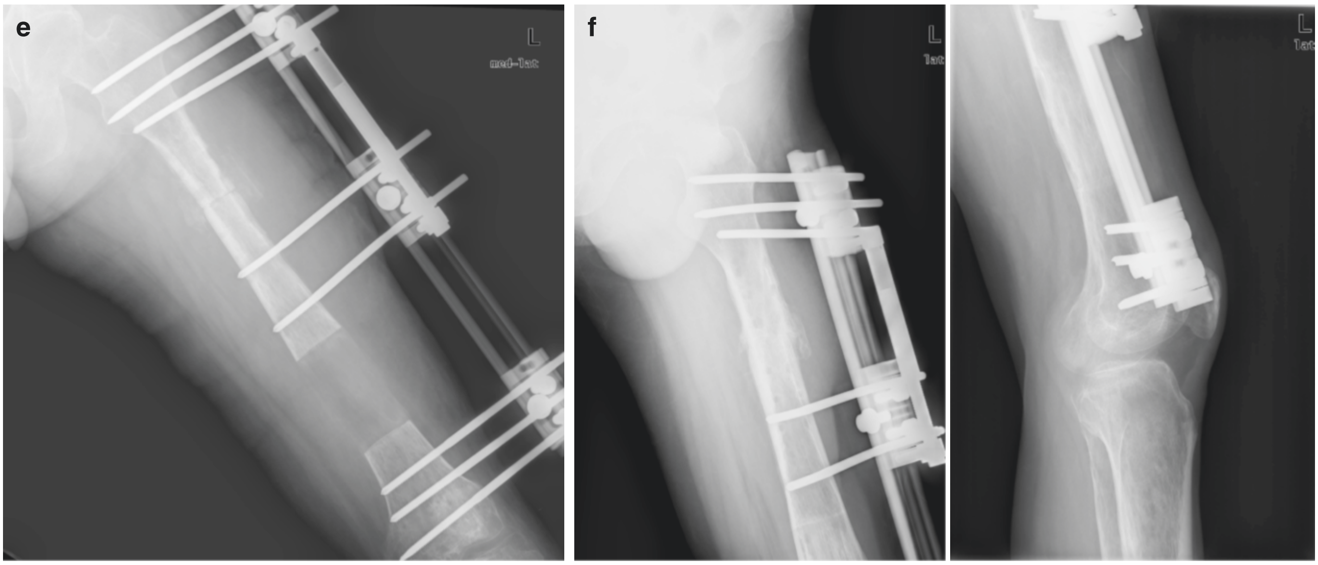

Fig. 5.32 (continued)

- 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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