Clinical guidelines for indications, techniques, and complications of autogenous bone grafting

Autogenous bone grafts have long been considered the “gold standard” and most effective material in bone regeneration procedures. Autogenous bone is used to repair bone defects caused by nonunion, infection, and tumor resection, and in spinal and joint fusion. More than 200,000 autologous bone grafts are reportedly performed in the United States each year[1]. Although there are no specific statistics published regarding the annual number of bone grafts in China, autologous bone grafting is the most common surgical technique in orthopedics. The iliac crest remains the most common donor site, along with the fibula, ribs, tibial metaphysis, proximal humerus, distal radius, and greater trochanter. Various bone graft options provide different amounts and qualities of cortical bone, cancellous bone, and corticocancellous bone. Autogenous bone grafts are osteogenic, histocompatible, provide structural support, and carry no risk of disease transmission. The disadvantages of autogenous bone grafts are the limited supply and the increase in the magnitude of surgery owing to the need to harvest the bone graft, which increases the operative time, blood loss, and potential complications. There are no clinical guidelines or consensus focused primarily on autogenous bone grafting indications, techniques, and complication. The Trauma Orthopedic Branch of Chinese Orthopedic Association and National Clinical Research Center for Orthopedics, Sports Medicine & Rehabilitation evaluated the quality of evidence for clinical studies by referring to the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) criteria and developed these clinical practice guidelines for the indications, techniques, and complications of autogenous bone grafting. The 19 problems that Chinese orthopedic surgeons were most concerned about were selected, and 19 recommendations were finally formed through evidence retrieval, evidence quality evaluation, and the establishment of the direction and intensity of recommendations. Recommended items 1–2 involve the types of autogenous bone grafts, items 3–13 involve the indications, techniques, and complications of non-vascularized bone grafting at different sites, items 14–16 involve the most common indications, techniques, and complications of vascularized bone grafting, and items 17–19 involve the surgical techniques related to
autogenous bone grafting. The purpose of these guidelines is to standardize the surgical indications and techniques for autogenous bone grafting to reduce complications related to the donor area.

**Level of evidence and recommendation strength**

**Level of evidence**
The level of evidence grading system was developed by referring to the GRADE system combined with the findings of clinical studies conducted in China. The levels are classified by experts on the compiling committees as Category I, II, III, and IV to quantify the reliability of the evidence. To make these guidelines useful in clinical practice in China, the expert panel preferentially selected Category I and II evidence, as indicated in the guideline evaluation system [Table 1].

<table>
<thead>
<tr>
<th>Level of evidence</th>
<th>Standard</th>
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<tbody>
<tr>
<td>I</td>
<td>Based on high-level prospective randomized controlled clinical trials, observational studies or meta-analyses with large sample sizes, internationally recognized current guidelines and consensus statements, published guidelines and consensus statements from national societies or associations</td>
</tr>
<tr>
<td>II</td>
<td>Based on low-level randomized clinical trials, well-designed non-controlled trials or cohort studies, international professional association guidelines and international conference expert consensus statements, published guidelines and consensus statements from national regional societies or associations</td>
</tr>
<tr>
<td>III</td>
<td>Based on case-control studies or retrospective studies, published guidelines and consensus statements from national professional associations, and provincial societies or associations</td>
</tr>
<tr>
<td>IV</td>
<td>Based on case reports, scientific hypotheses, regional expert consensus statements and published guidelines and consensus statements from national local societies or associations</td>
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</table>
The recommendation strength of these guidelines combines the GRADE system and the characteristics of clinical practice in China with four influencing factors, namely the level of evidence, health economics, product equivalence, and accessibility. According to the weighted value of each characteristic, the experts who wrote the guidelines individually scored the recommendations using a grading system. The recommendation strength was classified as A (strong recommendation), B (weak recommendation), and C (not recommended) [Tables 2 and 3].

### Table 2: Factors influencing the recommendation strength and evaluation standard.

<table>
<thead>
<tr>
<th>Influencing factor</th>
<th>Weight/Score</th>
<th>Assignment standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level of evidence</td>
<td>60</td>
<td>I: 60; II: 45; III: 30; IV: 15</td>
</tr>
<tr>
<td>Health economics</td>
<td>10</td>
<td>Comply: 10; Do not comply: 0</td>
</tr>
<tr>
<td>Product equivalence</td>
<td>10</td>
<td>Equivalent products or measures: 10; No equivalent products or measures: 0</td>
</tr>
<tr>
<td>Accessibility</td>
<td>20</td>
<td>Good accessibility in Chinese conditions: 20; Poor accessibility in Chinese conditions: 0</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td></td>
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</tbody>
</table>

### Table 3: Recommendation strength.

<table>
<thead>
<tr>
<th></th>
<th>Average total score for the four influencing factors:</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (Strong)</td>
<td>&gt;80</td>
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<tr>
<td>B (Weak)</td>
<td>60–80</td>
</tr>
<tr>
<td>C (Not recommended)</td>
<td>&lt;60</td>
</tr>
</tbody>
</table>

### Recommendation strength review committee

These guidelines were produced by 121 voting committee members: 70 from orthopedic trauma departments (57.9%), 12 from spinal departments (9.91%), four from medical imaging departments (3.30%), one from a pathology department
(0.82%), 10 from microsurgery departments (8.26%), 17 from joint surgery departments (14.0%), two from translational medicine departments (1.65%), two from basic medicine (1.65%), and three epidemiologists (2.47%).

**Target audience**

Clinicians specializing in orthopedics in China.

**Recommendations**

**Recommendation 1: types of autogenous bone grafts**

<table>
<thead>
<tr>
<th>Types of autogenous bone grafts</th>
<th>Level of evidence</th>
<th>Recommendation strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autologous bone grafting remains the gold standard for treatment of bone defects. The limited quantities available and donor-site morbidity should be evaluated carefully.</td>
<td>I (^{[1-6]})</td>
<td>A</td>
</tr>
<tr>
<td>Autologous bone grafts are classified as nonvascular or vascularized. Bone harvesting sites and autologous bone types should be selected based on clinical needs.</td>
<td>II (^{[7-13]})</td>
<td>A</td>
</tr>
</tbody>
</table>

**Recommendation 2: indications, techniques, and complications of non-vascularized bone grafts**

<table>
<thead>
<tr>
<th>Indications, techniques, and complications of non-vascularized bone grafts</th>
<th>Level of evidence</th>
<th>Recommendation strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>The anterior iliac crest is the most common donor site for autologous bone grafting.</td>
<td>I (^{[14-22]})</td>
<td>A</td>
</tr>
<tr>
<td>Techniques for anterior iliac crest bone grafting include the curettage technique, bicortical or tricortical technique, trapdoor technique, trephine technique, and acetabular reamer technique.</td>
<td>III (^{[23-27]})</td>
<td>A</td>
</tr>
<tr>
<td>It is recommended to pay attention to the complications of anterior iliac crest grafting, namely pain, nerve injury, hematoma formation, infection, incisional hernia, vascular injury, and donor site fracture.</td>
<td>I (^{[28-36]})</td>
<td>A</td>
</tr>
<tr>
<td>The posterior superior iliac spine is the most common source of autogenous bone grafts during posterior spine fusion procedures or when a large amount of bone graft material is</td>
<td>I (^{[37-41]})</td>
<td>A</td>
</tr>
</tbody>
</table>
required.

An autologous rib bone graft is suitable for the reconstruction of spinal, maxillofacial, or limb defects. The in situ splitting approach results in a clinically significant reduction in complications.

The ipsilateral proximal and distal tibia provide adequate amounts of bone graft material in foot and ankle surgery.

The distal radius is commonly used as a bone graft donor site for surgery in the hand and wrist.

The greater trochanter of the femur is a useful autogenous bone source for surgery in the ipsilateral femoral neck or acetabulum, and in lower limb, foot, and ankle surgery.

The reamer irrigator aspirator (RIA) system is used to harvest large volumes of intramedullary bone for grafting to treat nonunion, delayed union, and bone defects.

The RIA system is recommended because of the reduction in donor site complications.

RIA bone graft harvesting provides a reliable and safe alternative source of autologous bone graft material.

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**Recommendation 3: indications, techniques, and complications of vascularized bone grafts**

<table>
<thead>
<tr>
<th>Indications, techniques, and complications of non-vascularized bone grafts</th>
<th>Level of evidence</th>
<th>Recommendation strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vascularized fibular grafting is particularly indicated for the reconstruction of massive bone defects, nonunion, and early osteonecrosis of the femoral head.</td>
<td>III [84-93]</td>
<td>B</td>
</tr>
<tr>
<td>A vascularized iliac graft based on the deep circumflex iliac vessels provides a large concave segment of bone suitable for reconstruction of the extremities and spine.</td>
<td>III [94-100]</td>
<td>B</td>
</tr>
<tr>
<td>Vascularized rib grafts are indicated for osteomyelitis, multiple-level corpectomy, tumor resection, and limb bone defects.</td>
<td>III [101-106]</td>
<td>B</td>
</tr>
</tbody>
</table>

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**Recommendation 4: surgical techniques related to autogenous bone grafts**
Surgical techniques related to autogenous bone grafts

<table>
<thead>
<tr>
<th></th>
<th>Level of evidence</th>
<th>Recommendation strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Saline or 5% glucose solution is recommended to preserve autologous bone ex vivo for as short a time as possible.</td>
<td>III[^107-108]</td>
</tr>
<tr>
<td>4.2</td>
<td>The use of antibiotic-impregnated autogenic bone grafts seems to be effective and safe for the management of infected defects.</td>
<td>I[^109-110]</td>
</tr>
<tr>
<td>4.3</td>
<td>The induced membranes technique protects the autograft from rapid resorption and promotes graft consolidation with the RIA graft to fill large bone defects.</td>
<td>III[^111-115]</td>
</tr>
</tbody>
</table>

Discussion

**Indications, techniques, and complications of autogenous bone grafting**

Autogenous bone is still considered the gold standard for most applications in orthopedics. Egol et al.[^1] reviewed the benefits of autografts, the most suitable sites for harvesting bone grafts, the timing of bone graft procedures, and the potential risks and benefits of grafting in the face of infection, and reported that the indications for autogenous bone grafts included delayed union, nonunion, acute and chronic bone defects after traumatic injury, infection, and tumor resection. Autogenous bone grafts can be harvested from various anatomic sites and express heterogeneous bone quality with a specific microstructure for each site[^2].

The most common site for bone harvesting is the anterior iliac crest, along with the posterior iliac crest, ribs, fibula, tibial metaphysis, distal radius, and greater trochanter of the femur[^3]. It is convenient to harvest bone from the anterior iliac crest because most procedures in the lower limbs are performed with the patient in the supine position. However, the posterior iliac crest has more cancellous bone and is a better option when large amounts of graft are needed, along with the ribs, fibula, tibia, distal radius, and greater trochanter of femur. The indications include delayed union or nonunion, malunion, limb salvage, arthrodesis, and reconstruction of bone defects. When selecting the graft donor area, clinicians must consider the particulars of the case, such as the location of the bone defect, the position of the patient during surgery, and the required amount of graft material. The bone harvesting techniques include...
open harvesting of cortical, cancellous, and corticocancellous bone, and the trapdoor technique, acetabular reamer technique, and RIA technique \[1, 3-6\].

Different donor areas have different indications, techniques, and complications. The most common complications are donor site pain, nerve injury, infection, and fracture, as well as an extended surgical time, increased blood loss, and limited bone graft material. Baldwin \[5\] reported that autologous bone is almost the perfect bone graft material, but the main shortcomings are its limited source and donor site complications; the incidence of complications is 20.6%, most of which are persistent pain at the donor site, incision hematoma, infection.

**Types of Autogenous Bone Grafts**

Autologous bone grafts include non-vascularized and vascularized bone grafts (VBGs). Non-vascularized autogenous bone is categorized as cortical, cancellous, and corticocancellous. Cortical bone is osteoconductive, provides functional support, and is suitable for structural defects. Cancellous bone has a viable cell and pore structure that is easy to use to reconstruct blood vessels. Cancellous bone provides an osteoinductive, osteoconductive, and osteogenic substrate, but is not suited for structural defects that require immediate mechanical stability. Cancellous bone is mainly used for surface grafting for bone defects and nonunion. Corticocancellous bone grafts offer the advantages of both cortical and cancellous bone. Segment bone grafts have the mechanical support of cortical bone and the osteoinduction and osteogenesis of cancellous bone.

After autogenous cancellous bone grafting, some of the surviving osteocytes bind to graft pores and local cytokines, promoting angiogenesis and mesenchymal stem cell recruitment. Autogenous cancellous bone can be completely vascularized in 2 days, leading to new bone formation within a few weeks, trabecular remodeling within 8 weeks, and completion of the creeping substitution process within 1 year \[7\]. Autogenous cortical bone has a high density and a stronger overall configuration than cancellous bone. The dense cortical matrix of cortical bone results in relatively slow creeping substitution and limited perfusion and donor osteocytes, making this option poorly osteogenic \[8\]. The dense structure limits the entry of osteoblasts, osteocytes,
and other progenitor cells in the cortical bone, and the grafted region regains structural strength within 12 months, especially when the size of the graft and the implantation site is large \[9\].

The VBG has traditionally been used in refractory nonunions or in areas where there is a large segmental defect. VBGs demonstrate increased perfusion, structural integrity, and ability to achieve good outcomes in challenging clinical situations compared with non-vascularized grafts. The two major categories of VBGs are pedicled grafts and free grafts. A pedicled VBG is transferred from the donor site to the recipient site with its native vasculature preserved. A free VBG has its vascular pedicle divided, permitting transfer to virtually any location. VBGs offer the most predictable incorporation and are indicated for bone defects of \(>12\) cm \[10,11\]. The most common VBGs are harvested from the iliac crest with the deep circumflex iliac artery, the fibula with branches of the peroneal artery, the ribs with the posterior intercostal artery, and the distal end of the radius with the supraretinacular artery \[12,13\].

**Indications of anterior iliac crest bone grafting**

The anterior iliac crest is the most common donor site for autologous bone grafting. Anterior iliac crest grafts are suitable for severe open fractures, bone defects, delayed union, nonunion, tumor bone defects, joint fusion, and interbody fusion. The anterior iliac crest bone graft is suitable for use with the patient in the supine or lateral position. It provides a large amount of cancellous bone, unicortical bone, bicortical bone, and tricortical bone. Ollier et al. \[14\] first found that autogenous bone graft material has osteogenic effects in certain environments. Barth et al. \[15\] named the pathophysiological process of osteogenesis after autologous bone grafting as “creeping substitution” of bone. Robinson et al. \[16\] were the first to use tricortical iliac crest grafting for anterior cervical fusion. Boucher et al. \[17\] reported the use of iliac cancellous bone grafting for spinal fusion. Since then, studies have found that the anterior iliac bone is rich in bone morphogenetic protein and osteoblasts that promote bone conduction and osteogenesis, and anterior iliac bone has been widely used in clinical practice \[18\]. Pokharel et al. \[19\] modified the conventional surgical technique
for autogenous iliac crest bone grafting in patients undergoing anterior cervical
decompression, corpectomy, and fusion surgeries. Konda et al. [20] reviewed 69 cases
of tibial nonunion treated with anterior iliac crest grafting and reported a bone healing
rate of 97.1% during an average follow-up of 7.8 ± 3.2 months, confirming anterior
iliac crest grafting as the gold standard for the treatment of complex tibial nonunion.
Carlock et al. [21] compared the treatment of limb nonunion with anterior iliac crest
bone grafting in older adults versus young patients and found no significant difference
in the healing rate and healing time between the two groups; multivariate statistics
showed that age is not a risk factor for delayed healing after autologous bone grafting.
Wang et al. [22] used anterior iliac crest bone grafting to treat wrist fusion after bone
tumor resection in the distal radius and reported average fusion times for the distal
and proximal wrist joints of 4 and 9 months, respectively, showing that anterior iliac
crest bone grafting is a simple and effective method of achieving wrist arthrodesis.

Techniques of anterior iliac crest bone grafting

The common techniques used for anterior iliac crest bone grafting include the
curettage technique, bicortical or tricortical technique, trapdoor technique, trephine
technique, iliac crest-splitting technique, and acetabular reamer technique. The
optimal technique for anterior iliac crest bone harvesting is determined by the amount
and type of bone graft material required in the recipient area.

In the supine or lateral position, an incision is started 3 cm posterior to the
anterior superior iliac spine and parallel to the iliac crest to avoid the lateral femoral
cutaneous nerve and fracture. Bone is harvested from the gluteal or iliac tubercle
region approximately 3–5 cm posterior to the anterior superior iliac spine. The
integrity of the iliac crest and iliac inner plate is preserved to avoid damage to the
ilioinguinal and iliohypogastric nerves and avoid postoperative incisional hernia. The
curettage technique allows inner or outer table harvest. Kilinc et al. [23] calculated the
amount of bone harvested from the anterior iliac crest as an average of 17.49 cm³ of
cancellous bone and 28.80 cm³ of tricortical bone.
The tricortical iliac graft has a wide range of indications, but causes the most serious injury to the iliac donor site. Engelstad et al. [24] reported that the amount of compressed cancellous bone harvested using conventional methods from the anterior iliac crest of fresh specimens was 7.0 cm³. Kim et al. [25] weighed the wet bone harvested intraoperatively and reported that the average amount of harvested cancellous bone was 27.4 g in the anterior iliac crest and 33.2 g in the proximal tibia.

The trapdoor technique is used to longitudinally split the medial and lateral edges of the iliac crest, expose the cancellous bone between the medial and lateral plates, preserve the inner plate, and harvest the cancellous and cortical bone of the outer plate of the iliac crest. Zhu et al. [26] compared the anterior iliac crest trapdoor technique with the tricortical bone harvesting technique in the treatment of tibial plateau fractures; the average amount of bone harvested was 8.35 cm³ via the trapdoor technique and 13.24 cm³ via the tricortical bone harvesting technique. Compared with traditional bone harvesting, the trapdoor technique preserves the integrity and inner plate of the iliac crest, maintains the shape of the iliac crest, and avoids complications such as incisional hernia. However, because of the small amount of bone harvested, the trapdoor technique is only suitable for the repair of small bone defects or arthrodesis of the hands and feet.

The acetabular file method is suitable for metaphyseal bone grafting, but leaves a large bone defect and cannot provide mechanical support. Westrich et al. [27] introduced a new technique of using a low-speed and high-torque acetabular file to harvest bone in the inner or outer plate of the anterior iliac crest while retaining one side of the bone plate to avoid postoperative complications such as incisional hernia. The acetabular file method harvests a large amount of bone and has the strong osteogenic effect of cancellous bone, making it suitable for irregular bone defects caused by severe injury and infection of the limbs, infectious nonunion, or a bone defect with poor blood supply in the recipient area.

Complications of anterior iliac crest bone grafting
The donor site complications of anterior iliac crest bone grafts are generally divided into major and minor complications. The major complications are those which require secondary surgical treatment or seriously affect daily life, namely deep hematoma, incisional hernia, nerve injury, vascular injury, iliac bone fracture, and deep infection. The minor complications require no or minimal treatment and result in no long-term disability, namely donor site pain, sensory nerve damage, superficial hematoma, and superficial infection. Persistent or long-term pain at the harvest site may be the most common postoperative complication. The lateral femoral cutaneous nerve is easily injured during bone extraction from the anterior iliac crest because it usually passes under the anterior superior iliac spine but will cross the iliac crest within a range of 2 cm behind the anterior superior iliac spine in 10% of patients; this variation is an important cause of nerve injury. Myeroff et al. [28] reviewed many studies on donor site selection and harvesting techniques for autogenous bone grafts and reported that the incidences of minor and major complications after anterior iliac bone extraction are 7.1%–39% and 1.8%–10%, respectively. The incidence of complications is reduced by adequate preoperative planning and standardized surgical techniques. Because of the large amount of bone harvested, tricortical bone grafting can damage the normal anatomical structure of the iliac crest and easily causes anterior superior iliac spine fracture, incisional hernia, and postoperative pain. During long-term follow-up after anterior iliac bone grafting, Singh et al. [29] found that local pain occurs in 25% of patients, scar hyperplasia in 7%, and local hematoma in 3%. Arrington et al. [30] reviewed the donor site complications of 414 patients after iliac bone grafting and found that 41 (10%) had minor complications and 24 (5.8%) had major complications.

McLain et al. [31] reported that the trephine technique for anterior iliac crest bone graft harvest provides sufficient graft material with comparable or improved perioperative complications/pain, long-term outcomes, and patient satisfaction compared with other minimally invasive approaches, and achieves significantly improved outcomes compared with traditional open techniques. Westrich et al. [32] reported that anterior iliac crest bone harvest resulted in complications in 41 of 220
patients with acetabular file bone removal and 31 of 170 patients with traditional bone removal; statistical analysis showed that high BMI and smoking were risk factors for complications. Pokharel et al. [33] used the modified surgical approach to reconstruct the bone defect after anterior iliac bone harvesting and found that the complications of iliac bone harvesting were effectively reduced by bone cement reconstruction, which was simple, safe, and easy to implement. Defino et al. [34] used rib grafts to reconstruct the iliac shape and reduce complications such as pain at the iliac donor site in patients with thoracotomy. Gil-Albarova et al. [35] used anterior iliac bone grafts to reconstruct the shape of the iliac bone and effectively relieve chronic pain at the donor site. Almaiman et al. [36] analyzed the donor site complications of 372 patients who received anterior iliac crest bone grafts (two patients with anterior superior iliac fracture, one with incisional hematoma, and three with local sensory disturbance) and concluded that standardized and minimally invasive techniques were helpful to reduce the incidence of complications.

**Indications, techniques, and complications of posterior iliac crest bone grafting**

The posterior superior iliac spine is the most common source of autogenous bone grafts during posterior spine fusion or procedures that require a large amount of bone graft material [37]. The incision is made within 8 cm lateral to the posterior superior iliac spine and perpendicular to the posterior iliac crest to avoid injury to the superior gluteal nerve. The trapdoor technique is recommended to protect the integrity of the iliac crest and internal plate, and the depth of resection is limited to 4 to 6 cm to prevent damage to the sacroiliac joint and superior gluteus artery. Kilinc et al. [38] calculated that the average amount of bone harvested from the posterior iliac crest was 27.48 cm$^3$ of cancellous bone and 36.58 cm$^3$ of corticocancellous bone; more cancellous bone and mixed bone was obtained from the posterior iliac crest compared with the anterior iliac crest. Boucree et al. [39] studied bicortical bone harvesting from 110 posterior iliac crests in 55 patients and reported an average volume of 40.6 cm$^3$.

Arrington et al. [30] reported that the incidence of common complications of posterior iliac ridge bone extraction was 7.1%–39%, with major complications (deep hematoma, nerve injury, vascular injury, sacroiliac joint injury, ureteral injury, gluteal
muscle injury leading to Trendelenburg gait, and deep infection) accounting for 1.8%–10%. The secondary complications were persistent pain at the donor site, superior gluteal nerve injury, superficial hematoma, and superficial infection. Ebraheim et al. [40] compared the complications of bone graft removal from the anterior iliac crest, posterior iliac crest, and proximal tibia. Complications of the posterior iliac crest donor site were pain, neurovascular injury, avulsion fracture, hematoma, infection, incisional hernia, gait disturbance, sacroiliac joint invasion, and ureteral injury. Injury to the sacroiliac joint and superior gluteal artery can be avoided [41].

**Indications, techniques, and complications of autologous rib bone grafting**

Rib bone is considered better than iliac bone in that it requires little additional trimming once harvested, and the outer table of rib bone is probably easier to shape to fit the curvature of the internal orbital wall and the curvature of the spine than iliac bone; furthermore, rib grafting achieves good esthetic and functional results with less surgical invasion than iliac grafting. The ratio of cortical and cancellous bone in the ribs is suitable for structural bone grafting in spinal surgery. Xu [42] used rib bone grafts to treat long bone defects of the extremities. The ribs are non-weight-bearing bones with a thin cortex and mass of cancellous bone. Thus, the bone mass of two ribs is greater than that of iliac bone and is suitable for bone grafting in the medullary cavity of long bones.

A rib bone graft is harvested through a 4–5 cm oblique incision along the anterior axillary line over the sixth or seventh rib. The outer surface of bone is chiseled with a small cutting bar, and a gentle curved osteotome is introduced by hand pressure along the cutting line. Compared with traditional rib harvesting, the technique of in situ splitting of a rib bone graft for the repair of the orbital floor and medial wall is a simple and safe procedure that causes less pain at the donor site. This technique has proved to be an optimal choice in craniofacial and spinal reconstruction. Johnson et al. [43] first introduced the in situ rib split transplantation technique in which the rib is split in the coronal plane, the deep cortex is preserved in situ, and the superficial half of the rib cortex and cancellous bone are removed. This method is technically simple,
requires a short operation time, does not damage the pleura, and reduces donor site complications.

Sawin et al. [44] compared 300 cases of rib bone grafting and 300 cases of iliac bone grafting for cervical fusion and reported similar fusion rates of 98.8% in the rib bone grafting group and 94.2% in the iliac bone grafting group (p = 0.056). The incidence of donor site complications in the rib bone grafting group was 3.7%, comprising eight cases of pneumonia, two of persistent atelectasis, and one of superficial wound dehiscence. There was no pneumothorax, intercostal neuralgia, or chronic chest wall pain. The incidence of complications in the iliac bone grafting group was 25.3%, comprising 52 cases of chronic pain, eight of wound dehiscence, seven of pneumonia, four of paresthesia femoral neuralgia, three of hematoma, and two of fracture. Even when chronic pain was excluded, the complication rate was significantly higher in the iliac bone grafting group than the rib bone grafting group.

Zhang et al. [45] reported that the rate of donor site complications was 44.44% in patients who underwent traditional total rib harvesting compared with 6.67% in those who underwent in situ rib split transplantation. Anantanarayanan et al. [46] reported that the use of catheter-based analgesia after rib harvesting provides excellent postoperative comfort, with ropivacaine providing an earlier return to normal function compared with bupivacaine.

**Indications, techniques, and complications of tibial bone grafting**

The ipsilateral proximal and distal tibia provide adequate amounts of bone graft material for use in foot and ankle surgery. The tibia is easily accessible and provides large quantities of cancellous and cortical bone. The average amount of cancellous bone obtained from the proximal tibia is approximately 25 cm³. The distal tibia is accessible via the medial or anterior approaches and provides a bone graft amount of approximately 2–3 cm³[47]. A few reports comparing the advantages and disadvantages of bone harvesting from the proximal tibia versus the anterior iliac crest have concluded that the two harvest areas provide the same amount of bone graft material and that the proximal tibial bone is a beneficial supplement to the iliac crest [48,49]. Malara et al. [50] reviewed 40 cases of proximal tibial bone harvesting with an average
cancellous bone harvest of 15.09 cm³ and concluded that the proximal tibia provides
graft quantities that are more than adequate for most foot and ankle surgeries.

Tibial bone harvesting is commonly performed using an osteotome, a curette, or
a trephine. A periosteal elevator is used to expose the underlying proximal tibia while
taking care to avoid and preserve the inferior patellar and saphenous nerves. Standard
curettes can be used to collect the graft, supplemented by curved forceps. Weight-
bearing is possible immediately after the operation. If the amount of bone harvested is
large and exceeds the tibial midline, protected weight-bearing is recommended for 6–
12 weeks to avoid stress fracture. Lukasiewicz et al. [51] obtained 27 cm³ of cancellous
bone and 16 cm³ of red bone marrow through modified negative pressure curette
extraction of proximal tibial cancellous bone. After 6 weeks, 30% of patients had mild
pain, while there were no major complications such as fracture. Distal tibial bone
harvesting is suitable for foot and ankle surgery, but the amount of bone graft material
is limited.

The most common complications after tibial bone harvest are pain at the donor
site, hematoma, deep infection, and stress fracture. Attia et al. [52] reviewed 625
patients with proximal tibial bone extraction and reported that 13 had chronic pain,
one had fracture, and three had superficial infection. Among 115 patients with distal
tibial bone harvesting, one developed a fracture and three had saphenous nerve injury.
The overall complication rate was 6.8%, which was better than that of iliac bone
harvesting. Chou et al. [53] reported that stress fracture occurred in four of 100 patients
in whom bone was harvested from the distal tibia to treat foot and ankle lesions; all
fractures healed with conservative treatment. The distal tibia is recommended as the
first site of choice for the acquirement of autologous bone during foot and ankle
surgery.

*Indications, techniques, and complications of distal radius bone grafting*

The distal radius is usually used to harvest bone for nonunions or bone defects
requiring a small amount (<3 cm³) of bone graft material for surgery on the ipsilateral
hand or wrist. The cancellous or corticocancellous bone is harvested by fenestration
through the dorsal first and second compartment approaches or the palmar approach.
McGrath et al. [54] were the first to report free bone grafting of the distal radius for the treatment of hand diseases and concluded that the distal radius had sufficient bone mass, was convenient because the harvest site was close to the surgery site, and resulted in few complications at the donor site. Kitzinger et al. [55] compared ilium and distal radius bone grafts in 180 cases of wrist arthrodesis and confirmed that the fusion rate did not significantly differ between the two groups, but the distal radius was close to the surgical site and the operation was simple and effective.

The recurrent branch of the radial artery is anatomically constant and is used as part of a vascularized free bone flap to repair scaphoid fracture nonunion and lunate osteonecrosis to obtain mechanical support and improve local blood supply. Matson et al. [56] compared the bone and bone mass at different positions of the distal radius and reported that the largest and best bone mass is attainable at 10 mm below the articular surface of the distal radius. Ross et al. [57] proposed the use of the trapdoor technique through Lister's tuberosity, in which the cancellous bone is removed through a window and then the cortical bone is reset to maintain a smooth anatomical bone surface, thereby reducing donor site complications. Smeraglia et al. [58] prospectively compared a vascularized distal radius bone flap with a free bone graft in the treatment of scaphoid nonunion and concluded that the vascularized distal radius bone flap had a shorter healing time and higher healing rate.

The main complications of distal radius bone harvest are donor site pain, tenosynovitis, infection, fracture, and nerve injury. Schuringa et al. [59] reported that approximately 5% of distal radius bone grafts are complicated by postoperative chronic pain, and recommended wrist surgery as an alternative to iliac bone grafting because of the low demand for bone grafting and the proximity of the distal radius to the surgical site. Patel et al. [60] reviewed 1670 cases of distal radius bone harvesting with an average follow-up of 4.5 years. Donor site complications were 21 cases of tenosynovitis, three of infection, two of distal radius fracture, and two of injury to the superficial branch of the radial nerve.

**Indications, techniques, and complications of greater trochanter bone grafting**
The greater trochanter of the femur is mainly composed of cancellous bone that is suitable for use in surgery of the ipsilateral lower limb, foot, and ankle, especially femoral neck nonunion and femoral head necrosis. Lindberg et al. [61] reported that the amount of cancellous bone harvested from the greater trochanter and the anterior iliac crest after cortical bone fenestration of 1.3×1.3 cm was 6.5 ml (4.2–9.6 ml) and 6.0 ml (2.7–8.8 ml), respectively, with no significant difference between the two sites. The greater trochanter is considered suitable for bone harvest for use in adjacent sites, surgeries in which the required amount of bone is not large, or in patients with a history of iliac surgery.

The greater trochanter free bone graft can be obtained using a trephine or fenestration to provide a bone volume of 5–10 cm³. The blood supply of the pedicled greater trochanter bone flap can come from muscles, fascia, or blood vessels, including the quadratus femoris muscle, deep branch of the medial femoral circumflex artery, and transverse branch of the lateral femoral circumflex artery. The pedicled greater trochanter bone flap can be locally transferred to treat femoral neck fracture, nonunion, or osteonecrosis of the femoral head. Maresca et al. [62] treated 10 cases of comminuted fracture of the posterior wall of the acetabulum in which they took bone from the greater trochanter via the incision, filled the collapsed posterior wall or acetabular roof with bone graft material, and anatomically reconstructed the acetabulum and femoral head, with no complications at the donor site.

Common complications of greater trochanter bone harvest are donor site pain and stress fracture of the femoral neck due to excessive bone harvesting. Zhao et al. [63] used the vascularized greater trochanter bone flap to treat 23 cases of osteonecrosis of the femoral head and reported that during an average follow-up of 41 months, the success rate of hip preservation was 96% with no donor site complications. Hayes et al. [64] reviewed 85 patients with foot and ankle arthrodesis with greater trochanter bone harvest who were followed up for an average of 49 months and reported that 81 patients (95%) were satisfied with the greater trochanter bone harvest, 26 (31%) had donor site discomfort, and 19 (22%) had chronic pain at the donor site, which was considered the main complication.
Indications of the reamer irrigator aspirator technique

The RIA is a relatively recent device that is placed in the femoral or tibial medullary canal to harvest bone and is supposed to be less invasive and allow the harvest of a greater graft volume compared with previous techniques. Compared with traditional iliac bone harvest, RIA harvest from the femur or tibia has the advantages of a larger bone harvest, stronger osteogenesis, and lower complication rate. The RIA technique can be used as a supplement to autologous iliac bone grafting, especially when a large amount of nonstructural autologous bone graft is required, there is infection at the conventional bone harvesting site, or there is insufficient iliac crest bone. The RIA bone graft is suitable for nonunion, osteomyelitis, bone defect, joint fusion, and other nonstructural bone grafting.

The amount of autologous bone that can be collected by the RIA technique is 30–90 cm³, with an average of 40 cm³ from the femur and 33 cm³ from the tibia[65-67]. Cell biological studies have shown that autologous bone collected by the RIA technique is rich in stem cells, osteoblast and fibroblast growth factors, platelet-derived growth factor, insulin growth factor, bone morphogenetic protein, and other growth factors, and has a similar composition to autologous iliac bone[68,69]. McCall et al. [66] performed a prospective study of 22 patients with large bone defects (average 6.6 cm) treated with RIA bone grafting and reported that 85% of patients had achieved bone union at 11 months postoperatively. However, Karger et al. [71] reported that it is not recommended to use the RIA technique alone for the treatment of long bone defects. Stafford et al. [72] compared the RIA technique with ilium bone harvesting in the treatment of limb bone defects. The average amount of bone harvested by the RIA technique was 47 cm³ without donor site complications and with a bone defect healing rate of 90% at 1 year postoperatively. However, the density of the bone graft area was too large and the central area could not be vascularized and ossified.

Reamer irrigator aspirator technique

The RIA device allows intramedullary reaming with simultaneous irrigation and aspiration to harvest large amounts of autologous bone graft from the medullary canal of long bones. The position of the patient and the site and amount of bone harvest
should be based on the recipient site surgery. The diameter of the reamer bit should be less than 2 mm greater than the diameter of the isthmus of the medullary cavity to enable the maximum amount of bone to be harvested and reduce the complications at the donor site.

A simulated single-leg standing experiment in which the apex of the greater trochanter, piriform fossa, and intercondylar fossa of the femur were each used as entry points did not destroy the mechanical stability of the femur [73]. However, most surgeons tend to prefer the apex of the greater trochanter rather than the piriform fossa as the entry point because using this entry point avoids damage to the femoral neck cortex [74-75]. The diameter of the isthmus should be determined on preoperative anteroposterior and lateral plain radiography or CT. The diameter of the drill in the RIA device is 12–16.5 mm, and the interval is 0.5 mm. When the diameter of the reamer is less than 2 mm greater than the isthmus of the medullary cavity, it has little effect on the bone strength of the femur and tibia; however, a reamer diameter of more than 2 mm greater than the isthmus may affect the bone strength and cause fracture. It has also been reported that the reamed bit should not exceed 50% of the external diameter of the shaft. When the reaming is stopped, the filtrate is collected in time to prevent the blockage of the hose around the reaming, and the flushing is suspended to prevent excessive blood loss in the pulp cavity. However, avoiding excessive irrigation of the grafted bone will weaken the osteogenic effect of the grafted bone [74-75].

Complications of the reamer irrigator aspirator technique

The RIA system carries risks of cortical perforation and clinically relevant intraoperative blood loss. Because of the continuous suction of the reamer in the RIA technique, a large amount of blood is aspirated from the medullary cavity, with an average intraoperative blood loss of 200–500 ml [76]. To minimize the risk of bleeding, RIA suction should be stopped immediately after the cessation of reaming and the RIA device should be removed [77]. If the drill moves along an eccentric path in the medullary cavity during the process of reaming, it may destroy one side of the cortex and lead to iatrogenic fracture. Osteoporosis or radiographic bone loss are also risk
factors for iatrogenic fracture using the RIA technique\textsuperscript{[78]}. To reduce the risk of iatrogenic fracture, the amount of autologous bone should be predicted preoperatively and the reaming of the distal cortex should be stopped when enough bone is obtained.

Compared with conventional iliac bone harvesting, RIA autologous bone grafting has a similar healing rate, lower pain score, and lower rates of local hematoma and deep infection\textsuperscript{[79]}. Scharfenberger et al.\textsuperscript{[80]} reported that the RIA technique results in an average of 73 cm$^3$ of autologous bone, with an average hemoglobin decrease of 44 g/L and average hematocrit decrease of 12.3%. Quintero et al.\textsuperscript{[81]} reported that the suction of the RIA device remained at the femoral isthmus for 3 minutes, resulting in hemodynamic instability and the need for acute volume resuscitation. Belthur et al.\textsuperscript{[82]} reviewed 41 cases of long bone harvesting by the RIA technique and found that eccentric reaming caused perforation of the distal anterior femoral cortex in one patient (2.4%), resulting in local pain that resolved after 4 months. There was one case of hematoma and three cases of deep infection in the iliac crest group. In contrast, the RIA group had a lower pain score and no superficial or deep hematoma, deep infection, or fat embolism. Lowe et al.\textsuperscript{[83]} evaluated iatrogenic fracture at the donor site and reported that RIA technology should be avoided in patients with osteoporosis and osteopenia. When using RIA technology, clinicians should evaluate the cortical bone thickness of the donor site preoperatively and monitor the direction of the reamer during the operation.

**Indications, techniques, and complications of vascularized fibular grafting**

Free vascularized fibular grafting (FVFG) is indicated for the reconstruction of upper extremity skeletal defects larger than 6 cm caused by oncologic resection, trauma, osteomyelitis, nonunion, or congenital malformation. FVFG is another important hip-preserving approach for the treatment of osteonecrosis. The vascularized fibular graft provides support for the articular surface, reduces intraosseous pressure, removes and replaces the necrotic tissue, and improves the biologic microenvironment of the region\textsuperscript{[84]}. Taylor et al.\textsuperscript{[85]} first used FVFG to repair bone defects in open fractures of the extremities. FVFG was then gradually applied to long bone defects of the extremities caused by infection, tumor resection, congenital...
malformation, and joint fusion \[86\]. Judet et al. \[87\] used FVFG to repair bone defects after debridement of early osteonecrosis of the femoral head. Yoshimura et al. \[88\] performed FVFG to observe the blood supply of the transplanted bone flap and opened the bone-flap composite tissue transplantation of the vascularized fibula.

The most common technique for FVFG is Wood's modified method, in which the fibula is resected between the peroneus longus and soleus muscles \[84\]. The combined application of the vascularized fibular flap and allogeneic bone for bone defect reconstruction has the advantages of loading large segments of allogeneic bone and the healing ability of the vascularized fibula, maintains good mechanical support, and promotes rapid healing of the allogeneic and host bones, which not only shortens the healing time, but also improves the healing effect \[89\]. Kanaya et al. \[90\] compared FVFG with vascularized rib grafting in the treatment of congenital pseudarthrosis of the tibia and concluded that FVFG promotes bone defect healing and is a reliable surgical method. Furthermore, the use of FVFG in the treatment of osteonecrosis of the femoral head reportedly avoids joint replacement in 92\% of patients and delays joint replacement for an average of 7 years \[90,91\]. Lutz et al. \[92\] performed prospective angiography on 120 patients and reported that preoperative angiography is needed to verify the vascular pedicle in patients with a history of lower limb trauma or abnormal vascular pulsation in the foot. Complications at the donor site include ipsilateral tibial stress fracture, flexor pollicis longus tendon contracture, peroneal nerve palsy, and compartment syndrome. Vail et al. \[93\] reported that 47 of 247 patients (19.0\%) who underwent FVFG with an average follow-up of 47 months had various donor site complications, and standardized operation was the key to reducing complications.

**Indications, techniques, and complications of vascularized iliac bone grafting**

The vascularized iliac bone graft based on the deep circumflex iliac vessels provides a large concave segment of bone suitable for reconstruction of the extremities and spine. Both pedicled iliac bone flap transfer and FVFG are effective methods for the treatment of femoral head necrosis. Moreover, with the development of small vessel anastomosis, the free vascularized iliac bone flap has also been widely used in the reconstruction of limb and maxillofacial bone defects because of the better
osteogenic ability and speed of bone healing compared with those with other bone flap graft methods. Taylor et al. [94] first reported the use of deep circumflex iliac artery and iliac bone flap transplantation to repair limb bone and composite tissue defects. Lei et al. [95] used the iliac bone flap with the deep circumflex iliac artery to treat osteonecrosis of the femoral head in young patients and found that 68.4% of patients showed improvement after 1 year of follow-up. The iliac bone flap with the deep circumflex iliac artery is effective for the treatment of osteonecrosis of the femoral head in the early stage [96].

Several donor site complications have been reported after vascularized iliac bone grafting, such as damage to the lateral cutaneous femoral nerve, gait disturbance, bowel obstruction, and herniation [97,98]. The lateral femoral cutaneous nerve may be injured and hernia may occur when the iliac flap is too large. Kearns et al. [99] compared the effects of various vascular pedicled tissue flaps and found that the complications at the donor site were delayed healing, chronic pain, loss of function, gait abnormality, scarring, secondary fracture, and incisional hernia. The delayed healing rate was 20% after forearm and radius bone flap harvest, 10% after harvest of the scapular composite tissue flap pedicled with the subscapular artery, and less than 5% after harvest of the iliac bone flap pedicled with the deep circumflex iliac artery. The vascularized forearm and radius bone flap resulted in chronic pain in 16.7% of patients and scarring in 33%. The vascularized iliac bone graft is considered suitable for bone defects less than 8 cm in length because of its hidden location, minimal adverse effects at the donor site, constant vascular anatomy, less variation, and low operation difficulty. Kim et al. [100] reported that the incidence of incisional hernia after vascularized iliac bone grafting is 2.8%–9%, and the risk factors include excessive resection of the bone flap, imprecise surgical suturing technique, obesity, COPD, and diabetes mellitus.

**Indications, techniques, and complications of vascularized rib bone grafting**

Vascularized rib graft is suitable for adjacent spinal fusion or long bone defect of extremities that require strong biomechanical support, namely when there is a large defect [101]. The advantages of rib grafting for spinal stability include increased
mechanical stability that avoids the process of creeping substitution of non-vascularized rib grafts and prevents microfracture and pseudarthrosis, which are commonly observed when a large bone graft is used. Wang et al. [103] successfully used vascularized rib grafting to repair defects of the femur or intertrochanter to increase the speed and stability of the fusion.

The vascularized rib grafting technique can be used in complex cases where there is a higher chance of nonunion, infection, or pseudoarthrosis of a bone defect. Vascularized rib grafting provides well vascularized healthy bone and is relatively low risk, with few bone graft and donor site complications such as pneumothorax and hemothorax [102]. Wilden et al. [104] used vascularized rib transplantation to treat 18 patients with spinal tumors and severe spinal deformities without donor site complications and believed that vascularized rib transplantation promoted the fusion of spinal surgery. Lin et al. [105] used vascularized rib transplantation to treat severe limb injury and reported that VBGs are also useful to treat limb bone defects after severe trauma. Yazar et al. [106] analyzed 61 patients with severe traumatic open fracture of the lower limbs, with an average limb defect of 11.7 cm. Among seven patients treated with vascularized rib grafting, one had pleural fibrosis at the donor site.

*In vitro storage of autogenous bone grafts*

Autogenous bone grafting is the most common technique used to treat bone defects. With the prolongation of in vitro preservation time, the osteoinductive and osteogenic ability of autogenous bone decreases. The common preservation methods after autologous bone harvesting include dry preservation and solvent preservation. Saline or 5% glucose solution is recommended because these solutions better preserve the osteoinduction and osteogenic ability of autologous bone compared with dry preservation [107,108].

A controlled study of cancellous bone from animal iliac crest showed that storing cancellous bone at room temperature in saline resulted in significantly more osteoblasts than dry storage of cancellous bone at room temperature [107]. Another in vitro study examined the cell metabolism and osteoblast number of cancellous bone
obtained during hip arthroplasty and stored using dry preservation, normal saline solution preservation, 5% glucose solution preservation, or saline humidified gauze preservation. After 2 hours of dry preservation, the number of osteoblasts in the sample stored using dry preservation was significantly higher than that in the samples preserved in normal saline and 5% glucose solution. The metabolism of cancellous bone cells decreased more significantly after 4 hours in dry preservation than in saline humidified gauze preservation and 5% glucose solution preservation.[108]

**Antibiotic-impregnated autogenous bone grafts**

Antibiotic-impregnated bone grafts (AIBGs) have become popular in the treatment of infected bone and joint defects. Bone defects are common in such conditions and need to be addressed before a new implant can be inserted. A major advantage of AIBGs is the possibility of impregnation with various antibiotics depending on the sensitivity profile of the causative organism. Chan et al.[109] reported that the AIBG group had significantly superior results in infection elimination than the pure cancellous bone grafting group in a randomized controlled trial of 86 patients with infected tibial nonunion. The effectiveness of AIBGs in infection elimination and bone incorporation have been reported in many retrospective studies. One study showed that the combination of tobramycin and autogenous bone grafting did not affect the fracture healing process compared with cancellous bone grafting alone according to radiographs, pathological changes, and biomechanics[110]. Chen et al.[111] observed a 100% infection eradication rate in 18 patients with small infected tibial defects at an average follow-up of 48 months after vancomycin-impregnated bone grafting.

**Autogenous cancellous bone grafting using the induced membranes treatment technique**

The induced membranes technique is a common two-stage technique that was accidentally discovered in 1986 by Masquelet in a study of 35 patients with large diaphyseal defects.[112] Cancellous bone autograft material from the anterior or posterior iliac crest has always been regarded as the gold standard in the Masquelet technique. The largest disadvantage of autologous bone grafting is the limited quantities available. The recent introduction of the RIA technique has greatly reduced
the morbidity of autologous bone graft harvesting. Compared to iliac crest bone graft harvesting, RIA bone graft harvesting has the advantages of sufficient graft quantities and low donor site morbidity. The key of the Masquelet technique in the second stage of bone grafting is to induce revascularization of the intramembranous bone graft. Cancellous bone has good porosity and osteogenesis and better revascularization potential. Therefore, autologous cancellous bone is recommended to fill bone defects \[112,113\]. The iliac crest is the most common donor site in clinical practice, and bone can be harvested from the anterior or posterior iliac crest according to the surgical position and the patient's condition. Compared to traditional techniques, the RIA technique of acquiring autologous bone obtains relatively more bone mass, reduces the time required for bone harvesting, and reduces donor site complications \[114-116\].

RIA bone graft harvesting provides an alternative source of autogenous bone grafts. However, when autologous bone obtained by the RIA system is used for the second stage of the Masquelet technique, the low bone porosity results in poor central vascularization of the transplanted bone and irregular bone healing, which affects late osteogenesis. Therefore, it is not recommended to use the RIA technique alone to obtain autogenous bone graft material for Masquelet grafting and structural bone defects. The combination of iliac cancellous bone and bone debris obtained using the RIA technique is helpful for angiogenesis and osteogenesis\[111-112\]. Alternative bone, such as allogeneic bone, xenogeneic bone, and artificial bone, can provide support and bone conduction, but an excessive amount of replacement bone affects the intramembranous revascularization after the second stage of bone grafting. The proportion of replacement bone should be less than 1/3 of the total bone volume\[111-112, 115\].

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Conflicts of interest

The expert committee for these guidelines declares no conflicts of interest. These guidelines are a reference for orthopedic specialists in clinical practice. However, the guidelines are not to be used as the basis for medical evaluation, and do not play an
arbitrating role in the handling of any medical disputes. The guidelines are not a reference for patients or non-orthopedic specialists. The Trauma Orthopedic Branch of Chinese Orthopedic Association assumes no responsibility for results involving the inappropriate application of these guidelines, and reserves the right to interpret and revise the guidelines.
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