Bone healing: radiology of normal and diseased bone

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Learning objectives

The aim is to describe physiological mechanisms of bone healing and their correlation to multimodality imaging findings in different stage (from the acute phase to the outcome) and to review principal causes of failure/delayed repair and related imaging signs.
**Background**

**INTRODUCTION**

The skeleton is frequently exposed to accidental insults, traumatic and non-traumatic (eg trauma, tumors, osteitis, delayed unions, non-unions, osteotomies, arthrodesis) resulting in bone disruption.

A bone fracture or osteotomy is a complete or incomplete break of the continuity of bone, ending in mechanical instability: the fracture usually occurs with injury of the surrounding soft tissues, disruption of blood supply to the bone and results in damage of the musculo-skeletal function.

Fractures of normal bone usually occur due to violent traumatic injuries; other specific pre-existing factors such as osteoporosis or focal latent lesions increase the risk of fracture even in minor traumas.

**BONE HEALING PHYSIOPATHOLOGY**

**PRIMARY AND SECONDARY MECHANISM**

Skeletal tissue has a great regenerative potential; it is able to heal without forming fibrotic scar tissue and develop again its mechanical pre-injury properties.

Skeletal injury actually begins a complex healing process, involving molecular pathways and mechanical factors, leading to complete restoration of osseous function and anatomy.

Definition of the patterns of bone healing is based on a variety of factors that influence the repair process, based on differences in local motion and gap between fracture fragments:

- **Primary Healing**: it is a direct attempt by the cortex to develop a new continuity between fracture edges. It occurs in fractures when alignment stability and lack of excessive inter-fragmentary motion is obtained by rigid internal fixation. This repair process is considered as healing in primary intention, with a minimal replacement of the injured bone and without cartilaginous or woven bone formation.
Secondary Healing: it is a periosteum and endosteum reaction to bone injury. It occurs in fractures with significant gap between bone fragments, with an extent of less than the diameter of the bone; it is enhanced by limited fragment motion and inhibited by rigid fixation. This repair process is considered as healing in secondary intention, with intramembranous ossification and endo-chondral bone formation.

At the periphery of the site of fracture, intramembranous ossification forms new bone tissue from the inner layer of periosteum on fracture edges without forming cartilage, thus not bridging the bone margins.

Within the site of fracture, endo-chondral ossification develops a cartilage callus in response to local hypoxia due to lack of blood supply.

In this repair process fractures heal with a combination of intra-membranous and endo-chondral ossification, forming woven bone which progressively calcifies; the woven bone will be later remodeled by osteoclasts to form lamellar bone.

STAGES OF FRACTURE REPAIR

Indirect healing is a continuous process and has been divided in different stages (Table 1).

When a fracture occurs, the vascular injury to periosteum, endosteum, and the surrounding soft tissue causes hypo-perfusion in the area.

In Inflammatory Stage, hemorrhage begins at the site of fracture, coagulation process is activated developing a hematoma that fills the gap between bone edges; necrotic material in the hematoma (bone marrow, periosteal and soft tissue cells) stimulates an acute inflammatory response; in addition blood clot serves as medium for fibroblast proliferation and vascular budding.

In Reparative Stage fibroblasts settle in the hematoma converting it in granulation tissue; in addition mesenchymal cells differentiate in cells producing collagen, cartilage and bone, depending on local factors like oxygen supply and pH: in this way new immature bone tissue is produced (bone induction). The tissue developed so far (made of fibrous tissue, cartilage and immature bone) is called primary callus: it immobilizes the site of fracture forming a periosteal and endosteal bridge between the fragments; it corresponds to the stage of clinical union.

In Re-modelling Stage immature bone tissue is progressively replaced by adult lamellar calcified bone tissue, able to withstand normal stresses.
ABNORMAL FRACTURE REPAIR PROCESS

Fracture healing process may be prone to pathologic changes, ending in delayed repair or abnormal repair processes (Table 2).

- DELAYED UNION

In normal fractures a time period is required to elapse before bone repair process may be expected to occur. This time varies according to different factors like fracture configuration, patient characteristics (i.e. age, habits like smoking or alcohol) inter-current pathologies (i.e. diabetes, hypothyroidism, post-menopausal osteoporosis) or medications (i.e. NSAID drugs, corticosteroids).

Delayed union occurs when there is not bone union achieving within the expected time since initial injury, even considering eventual inhibiting factors (16-18 weeks). If a bone is delayed in its union, it does not mean that it will become a non-union; the diagnosis between the two is sometimes difficult.

Generally the causes for delayed union are inadequate fixation and or immobilization, distraction, lack of blood supply, and infection.

Inadequate reduction of a fracture, regardless of its cause, may be a major reason for delayed union or non-union. It leads to instability and or poor immobilization. In addition soft tissue disruption usually leads to vascular supply lack at the fracture site.

Inadequate immobilization may lead to biomechanical and physiologic problems associated with fracture healing.

The fact that fracture healing is delayed and may eventually go on to union is often a good reason to dismiss the original treatment: instead it may be beneficial to change the form of treatment to achieve a rapid progression of fracture healing.

- NON-UNION

According to the definition provided by the American Food and Drug Administration (FDA, 1988) a minimum of at least 9 months has to elapse since the initial injury and there should be no signs of healing for the final 3 months for diagnosis of fracture non-union. The final status of a non-united fracture is the formation of a synovial pseudo-arthrosis.
Since all of the factors leading to delayed union usually occur to a more severe degree in non-union, the differentiation between delayed and non-union is often based on imaging criteria and time.

There are a few different classification systems, but non-unions are most commonly divided into two categories of hypertrophic non-union and atrophic non-union.

In hypertrophic non-union, also known as hyper-vascular non-union, fracture margins are vascularized and have a potential for biological activity. There is evidence of callus formation around the fracture area, which is thought to be in response to excessive micro-motion at the fracture site.

In atrophic non-union, also known as avascular non-union, fracture edges are avascular or have a poor blood supply; thus there is no or minimal callus formation and fracture lines remains evident. This type of non-union requires biological enhancement with bone grafting, in addition to adequate immobilization to achieve healing.

The changes in radiographic appearance may be slight, and therefore radiographic monthly monitoring should be evaluated to demonstrate eventual progression.

- MAL-UNION

Mal-union is defined as bone healing in an abnormal position; Mal-unions can be classified as functional or non-functional. Functional mal-unions are usually those that heal with small deviations from normal axes and do not incapacitate the patient. Non-functional mal-unions can occur with both axial deviations and rotational deformities. Bone deformities (rotational, varus / valgus, recurvatum / procurvatum) may cause secondary osteoarthritis of the joints proximal to the fracture area.

Treatment of mal-unions may involve osteotomies, which can have the same complications of bone fractures such as delayed union, non-union, and infection. Most mal-alignments should be detected before healing occurs. In these cases adequate treatment is resolving the axis or rotational deformity, thus allowing normal union to take place. Adequate follow-up after internal fixation or splinting should make the occurrence of mal-union very infrequent.
### NORMAL FRACTURE REPAIR STAGES

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### ABNORMAL REPARATIVE FRACTURE PROCESS

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### Table 1

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### Table 2

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Findings and procedure details

DIAGNOSTIC IMAGING IN TRAUMA

Diagnostic imaging provides detailed pictures of bone and soft tissues and is essential in appropriate clinical management of Patient injury and follow-up, in order to recognize the normal healing process or its abnormalities and hence to arrange adequate treatment, either medical or surgical.

Diagnostic imaging may include X-Rays (Digital Radiography), Multi Detector Computer Tomography (MDCT) scans, Magnetic Resonance Imaging (MRI) and Positron Emission Tomography (PET).

RADIOGRAPHY

Despite their limitations, radiographic assessment is still a crucial imaging modality in evaluating progression in fracture healing. Radiography is obtained in two views, with oblique accessory views if necessary. Radiological findings include callus evidence and size, cortical bridging and progressive loss of fracture line at the site of fracture (Fig.1, 2, 14). X-ray follow-up may also detect insufficiency fractures (fig. 12). Despite progresses in advanced imaging techniques to evaluate bone healing, both quantitatively and qualitatively, plain radiography is the most widespread used diagnostic imaging tool for this goal. This is due to lower cost, wider availability, and lower patient radiation exposure of radiography in comparison with other imaging modalities. There are few studies evaluating reliability of radiography in detecting bone repairing; they conclude that radiography has only minor accuracy in determining the stage of union. Recent studies attempted to standardize radiographic healing criteria for tibia and femur fractures with promising initial results.

The teams at the University of Toronto and McMaster University have proposed two radiographic scoring systems, Radiographic Union Score for Hip (RUSH) and Radiographic Union Score for Tibia (RUST): they show an increase in agreement among orthopedist surgeons and radiologists in assessing bone healing. They showed that assessment of the number of callus bridged cortices had higher reliability in determining healing; thus they developed scaling systems mainly based on the appearance of the cortex on plain films. In fact the RUST and RUSH scores are based on callus formation and visibility of fracture line at 4 cortices observed on AP and lateral radiographic views.
Both the RUST and RUSH are promising scores in research medicine, however they require larger clinical studies to compare their data with other outcome measures of healing such as physical exam findings, other imaging modalities, and bio-mechanical data.

**COMPUTER TOMOGRAPHY**

Multi Detector Computed tomography (MDCT) is superior to radiography both in assessment of healing and in demonstrating fracture in presence of abundant calcified periosteal callus or overlaying cast.

In MDCT the X-ray beam passes through the whole volume of the object of interest, and, using isotropic resolution, allows volumetric imaging with Multi-Planar Reconstruction (MPR) on arbitrary spatial planes (Fig.3).

Radiography is often an unreliable diagnostic modality, and is not sufficient as the exclusive radiologic technique for the clinical management of patients with suspected abnormalities in bone healing process. On the contrary MDCT provides valuable data in assessing bone healing in patients with a clinical suspicion of delayed union or non-union, especially when the radiography is equivocal (Fig.4, 13).

There are multiple studies to test accuracy and efficacy of computed tomography in assessment of fracture union in clinical settings.

When testing normal healing, these studies show that early signs of normal healing, such as blurring of fracture edges and periosteal callus formation are evident earlier with CT scan than with plain radiography.

When testing non-union these studies show that CT has very high sensitivity (100%) but is limited by a low specificity of 62%.

A limitation of CT is beam-hardening artifact due to internal and external fixation hardware. Despite progress in image quality using modern software, resolution is still affected when evaluating bone tissue adjacent to metal surgical hardware. Another limitation of CT scan is cost and radiation dose, significantly higher than radiography: despite CT is superior in diagnostic accuracy and correlation with other clinical markers, radiography remains the first imaging tool when monitoring bone healing.

**MAGNETIC RESONANCE IMAGING**
Magnetic Resonance Imaging (MRI) is comparable or even better than MDCT in evaluating bone fractures, and in particular in detection of radiographically occult (i.e. insufficiency and stress fractures) and subtle fractures. Indeed CT and MRI show specificity in the diagnosis of fracture as high as 100%, while MRI has a higher sensitivity than MDCT. The superior performance of MRI over any other imaging modality in the detection of occult fractures is now widely recognized.

MRI is also very sensitive and specific in detecting fracture associated soft tissue abnormalities (i.e. ligamentous lesions). However, because of its relative unavailability in emergency units and high costs, MRI may only be performed as second level imaging modality in Patients with negative X-rays. MRI signs of occult fractures become evident several weeks before X-ray signs appear. Typically occult fracture is shown as a linear hypo-intensity on T1 W images; MRI also depicts marrow abnormalities surrounding the fracture line, such as bone marrow edema, intra-osseous hemorrhage or granulation tissue, shown as hypo-intensity on T1 W images and hyper-intensity on fluid-sensitive sequences (Fig.5, 15, 16).

Because of cost concerns and availability, current MRI use should be re-served for excluding a fracture in the setting of negative plain radiographs and CT scan, and positive clinical exam findings.

MRI is very sensitive in detection of bone fracture healing process, as it is sensitive to marrow changes. Typically the appearance of healing on MRI is seen as a the fracture line surrounded by linear bands representing the revascularization front. A failure in the progress of revascularization front is almost always associated with eventual non-union. MRI is also useful as it can confirm bony union in a high percentage of patients deemed to be clinically non-united. MRI usually continues to show an abnormal signal around a stable fracture even if healing progresses; the only sign of union is the return of normal marrow sign and continuity across the fracture rim.

Although 1.5 T and 3 T MRI are considered as the current gold standard for the detection of radiographically occult fractures, ultra-high field MRI provide higher signal-to-noise ratio and, therefore, is expected to be superior to 1.5 T and 3 T.

Ultra-high field MR seems to be promising in the diagnosis of a variety of musculo-skeletal conditions including trauma, but it is not used in daily routine yet.

DIAGNOSTIC IMAGING IN INFECTIONS
Skeletal segments, usually resistant to infections, may be prone to developing osteomyelitis due to trauma, bacteremia, surgery, or foreign bodies. Osteomyelitis is characterized by progressive flogistic destruction and apposition of bone, most commonly caused by pyogenic bacteria and mycobacteria. Osteomyelitis clinical features depend on the age of the patient, specific microorganism, anatomic area of involvement, affected skeletal segment, route of contamination, systemic and local host factors, eventual comorbidities.

Imaging techniques are essential in the early diagnosis and follow-up to provide adequate therapy.

There are different classification systems to categorize osteomyelitis.

Previous classification, focused on clinical course and labeled different stages (acute, subacute or chronic).

More detailed classification systems for osteomyelitis classifications were proposed.

A staging system (Waldvogel et al.) based on the infection’s pathogenesis, labeling three different groups: hematogenous; secondary to a contiguous focus of infection; associated with vascular insufficiency.

Another classification system (Cierny et. al.) focuses on the anatomic area of bone involvement and the host status and comorbidities, providing a useful way for evaluation of a patient and treatment planning.

Microorganisms can reach the skeletal segments by the hematogenous route, from a contiguous focus of infection, or by a penetrating wound. As the infection spreads into the medullary cavity, it may also extend into the cortex, into the sub-periosteal space and finally to the periosteum and adjacent soft tissues.

Early diagnosis of acute osteomyelitis is critical because prompt antibiotic therapy may prevent necrosis of bone.

Osteomyelitis is primarily a clinical diagnosis, although the clinical features may be confusing. An inadequate or late diagnosis significantly increases the degree of complications and morbidity; thus imaging modalities are essential to confirm the clinical diagnostic hypothesis and to provide information regarding the anatomic extent of the
infectious process. Imaging information can be extremely helpful to the therapeutic planning, whether medical or surgical treatment.

Several imaging modalities are useful in the evaluation of suspected osteomyelitis, but no one can definitively confirm or exclude the presence infection; thus a combination of imaging techniques is necessary.

Cross-sectional imaging techniques (CT, MRI) are now considered standard in the diagnosis of osteomyelitis: they have very high sensitivity and specificity. These imaging modalities give excellent information of the infected area (skeletal segment and the surrounding soft tissues). Nuclear medicine techniques, although highly sensitive, are sometimes non-specific.

**RADIOGRAPHY**

The evaluation usually starts with conventional radiography when osteomyelitis is clinically suspected; plain radiographs may suggest the correct diagnosis, exclude other diagnostic chances, or provide clues for co-existing pathologic conditions.

Radiographic features confirming the suspect of osteomyelitis may be soft tissue changes, muscle swelling, and blurring of the soft tissue planes.

In pyogenic infections, bone abnormalities indicate that the infectious process has been present for at least 2 to 3 weeks. In general, osteomyelitis must compromise 30 to 50% of bone mineral content to produce evident changes in plain radiographs. Early findings may be subtle and may not evident until 1 or 2 weeks. Typical early bone abnormalities are: periosteal thickening, lytic lesions, endosteal scalloping, osteopenia, and new bone apposition. Plain radiographs in the detection of osteomyelitis have a higher specificity than sensitivity: thus alternative imaging modalities such as scintigraphy and MRI are mandatory.

Single or multiple radiolucent abscesses can be evident in osteomyelitis (Fig.6). These abscesses are defined as circumscribed lesions, usually localized in the extremes of long bones; they are characteristically found in sub-acute pyogenic osteomyelitis. Brodie’s abscesses are common in male children, particularly in the metaphyses of the tibia.

The typical finding in chronic osteomyelitis is necrotic bone, which is formed in an average of 10 days; nevertheless conventional radiography may be unable to detect sequestra for many weeks.
Other features in chronic osteomyelitis are: periostitis, involucrum formation, and fistulae; they are due to sub-periosteal abscess with lifting of the periosteum, new bone formation, and soft tissue fistulas.

**COMPUTER TOMOGRAPHY**

In CT imaging, post processing techniques provide excellent multi-planar reconstructions of the axial images, thus detecting even the most subtle bone abnormalities. In chronic osteomyelitis, CT shows abnormal thickening of the bony cortices, with sclerotic changes, extension in the medullary cavity, and chronic draining fistulae. CT is superior to conventional radiography as it may show these changes earlier than plain radiographs (Fig.7).

In chronic osteomyelitis CT imaging plays a major role in detection of bone sequestra, as the necrotic bone may be masked by the surrounding osseous abnormalities on conventional radiography: in fact the detection of sequestra is helpful to guide the therapeutic options.

CT is superior to MRI for the detection of sequestra, involucra, or intra-osseous gas and can help in the imaging guidance of needle biopsies and joint aspiration.

In different studies for the evaluation of chronic osteomyelitis, CT imaging technique shows a sensitivity of 0.67 with a 95% confidence interval (0.24 to 0.94), and specificity of 0.50 (0.03 to 0.97).

In CT imaging the presence of metal (i.e. joint replacement implants) in or near the area of osteomyelitis, produces a substantial loss of image resolution due to a beam-hardening artifact, thus reducing the diagnostic accuracy.

**MAGNETIC RESONANCE IMAGING**

MRI is very helpful in osteomyelitis diagnosis; it detects early signs of infection in acute osteomyelitis; it assesses the extent of involvement and the activity of the disease in every stage of bone infection and surrounding soft tissues.

MRI is considered the most useful imaging technique in osteomyelitis because of its ability to detect bone marrow abnormalities with an excellent structural definition and spatial resolution. MRI is highly sensitive for detecting osteomyelitis as early as 3 to 5 days after the onset of infection.
MRI helps the surgery planning by assessing the extent of necrotic tissues and defining the critical adjacent structures involved that would require different surgical management to avoid morbidity and complications.

In MRI the presence of metal (i.e. joint replacement implants) may produce local artifacts that decrease diagnostic quality.

The MRI findings are variable, depending on the pulse sequences (T1-weighted or T2-weighted) and on the disease stage.

Different pulse sequences and imaging protocols can be used in the evaluation of the musculoskeletal system. The combination of short-tau inversion-recovery (STIR) and T1 spin echo sequences shows a high sensitivity and specificity for the detection of osteomyelitis.

The earliest feature of acute osteomyelitis on MRI is an abnormal marrow signal intensity, that can be detected as early as 1 to 2 days after the onset of infection; the edema and exudates in the medullary space produce an ill-defined low-signal intensity on the T1-weighted images and a high signal on STIR sequences.

On MRI, a sequestrum is detected as a low signal intensity area on T1-weighted and STIR sequences; the surrounding granulation tissue is characterized by intermediate to low signal intensity on T1-weighted images and high signal intensity with STIR or T2-weighted sequences. With intravenous contrast medium (gadolinium), the granulation tissue is enhanced, whereas the sequestrum is characterized by low signal intensity.

The ossified periosteal tissue and the necrotic cortical bone of an involucrum have low signal intensity on all sequences; periosteal reaction and cortical bone are separated by linear intermediate to high signal intensity on STIR sequences.

A cloaca is detected by a linear low signal intensity periosteum that is risen from the normal or thickened cortex. This high signal intensity can be seen extending into the soft tissues from the cloaca and may form a fistula or abscess (Fig.8).

Detection of increased signal intensity of the bone marrow on STIR sequences may represent post-surgical or post-infectious granulation tissue and not necessarily persistent infection. However, if progression of this marrow abnormality is present in serial MRI studies, the finding indicates osteomyelitis activity.
MRI may be occasionally unable to distinguish infectious from reactive inflammation; its diagnostic accuracy may be decreased by metallic implants, such as joint prostheses or fixation devices in the site of infection.

**DIAGNOSTIC IMAGING IN BONE GRAFTS, SCAFFOLDS, BONE SUBSTITUTES AND BONE TRANSPORT**

Bone graft materials are widely used in orthopedic surgery to promote new bone formation and healing and function as a means for antibiotic in site-delivery.

The goal of bone graft material is to promote the healing of bone defects through new bone formation. Thus bone graft material provides a scaffolding on which new bone can grow through process of osteogenesis, osteo-induction, and osteo-conduction.

Graft osteogenesis results from the transplantation of osteogenic precursor cells from the graft or the host site. The cells within the graft must be transplanted, remain viable and thus produce new bone at the host site. Types of grafts capable of osteogenesis at the transplantation site are cancellous and cortical bone and vascularized bone segments.

In osteo-induction pluri-potential mesenchymal cells are recruited from the surrounding tissue and differentiate into osteoblasts; this transformation is mediated by growth factors within the graft.

In osteo-conduction the resorbable or permanent implant works as a scaffold to facilitate the ingrowth of vascularization and the migration of host osteo-genetic cells. As new bone tissue is formed, the graft may undergo progressive resorption, either partially or completely.

Incorporation of bone graft material depends on new bone formation and remodeling of the host skeletal tissue in response to mechanical stress: these processes progress in sequential phases similar to those in fracture healing.

There are three main types of bone graft materials: auto-grafts (grafts from the host bone stock), allografts (grafts from cadaveric bone stock), and synthetic bone graft substitutes.

In **auto-grafts** cancellous, cortical, and cortico-cancellous bone particles and bone marrow are taken from patient own bone stock; they supply not only bone volume but also osteo-genic cells capable of new bone formation through process of osteo-genesis, osteo-induction, and osteo-conduction. The primary sites of bone auto-grafts are the iliac
crest and the fibula, but graft materials also may be taken from the other long bones. Physical forms vary from paste and chips to blocks, and segments.

**Allografts** (cadaveric bone transplants) provide an osteo-conductive matrix lacking osteo-inductive properties. The graft is surrounded by granulation tissue and undergoes vascular and osteo-genic cell invasion. The interface between allograft transplant and host granulation tissue is the site of osteo-clastic activity. When balance between osteolysis and osteogenesis is maintained, graft successful incorporation may progress. Bone allografts have specific limitations, like host immune response and graft rejection, unsuccessful incorporation, economic cost.

Allograft works as a bone void filler, an antibiotic delivery system, a composite graft, and an onlay graft.

Onlay allografts are utilized as bone scaffolds in peri-prosthetic fracture or large bone resections. Complications may include fracture nonunion or graft fracture. In orthopedic reconstructions, bone allografts are often placed together with fixation devices; however, graft failure may produce excessive mechanical load on the hardware, thus resulting in hardware failure.

Graft combinations are often used to obtain both osteo-conductive and osteo-inductive processes. Allografts may be mixed with autologous platelet-rich plasma (PRP), a concentration of human platelets in a small volume of plasma, which enhances osteo-induction by supplying growth proteins.

**Synthetic substitutes** may be classified into three groups: demineralized bone matrix, and composite materials (ceramics).

Demineralized bone matrix is produced from bone through a demineralizing acid process to form a composite of bone growth factors, non-collagenous and collagenous proteins. Demineralized bone matrix has osteo-inductive properties but lacks in structural rigidity because of loss of mineral component.

Ceramics are composed of calcium sulfate, hydroxyapatite, tri-calcium phosphate, or a combination; they are available in a variety of forms, like pellets, cement, and paste.

Ceramics provide an osteo-conductive framework but lack in osteo-inductive properties. These products are designed to allow progressive substitution, which involves replacement of the ceramic by bone during the healing process.
**RADIOGRAPHY**

The imaging features of a bone auto-graft depend on the type, composition, and age of the graft; chip auto-grafts initially look like osseous fragments on radiographs; vascularized fibular auto-grafts show the characteristics of long bones, with defined cortices and medullary canal.

Allografts show radio-opacity similar to that of cortices, appearing as high-attenuating conglomerates within the bone defects; when used in combination with PRP, only the allograft material is evident on radiographs, because platelet-rich plasma is radiolucent.

Demineralized bone matrix is radiolucent in conventional radiographs due to its intrinsic absence of mineral component.

On radiographs, ceramics appear denser than the adjacent native bone (Fig.10). In the post-operative period, a radiolucent area is evident at the graft-host interface, and the margins and internal architecture of the graft are well defined. With progression of bone ingrowth radiographs show obliteration of the radiolucent area around the implant and with loss of definition of the implant margins. These changes are the result of osteoclastic activity and osseous ingrowth.

**COMPUTER TOMOGRAPHY**

On MDCT scans, the attenuation of an auto-grafts is similar to that of the adjacent cortical bone; as in radiography vascularized fibular auto-grafts show the anatomical structure of tubular bones, with defined cortex and medullary canal.

Allografts have attenuation similar to that of cortex on MDCT scans. After placement, en bloc allografts initially appear as long bones with a defined cortex and medullary canal. Grafts in the form of chips are evident as high-attenuating conglomerates within the bone defects. At the beginning discrete radiolucent interface between host and graft is identifiable; however, as healing progresses, the graft-host junction is obliterated because of bone ingrowth.

On MDCT scans obtained immediately after placement, the calcium sulfate ceramics have attenuation similar to that of bone cortex; however, follow-up scans demonstrate progressive resorption in 30-60 days.
On MR imaging auto-grafts have a variable post-operative appearance. On T1-weighted MR images, solid fusion of the auto-graft with native bone may be evidenced by normal marrow signal intensity extending through the surgical site and by an intact cortical margin. The signal in the auto-graft may be hyper-intense on T1-weighted MR images and hypo-intense on T2-weighted MR images. The MR imaging appearance of auto-grafts is consequent to the viable marrow inside them, a characteristic not present in other graft materials. Low signal intensity on T1-weighted images and iso-intensity to hyper-intensity on T2-weighted images, may be evident in auto-grafts, due to necrosis and ingrowth of granulation tissue. Vascularized fibular auto-grafts should maintain T1- and T2-weighted signal intensity similar to that of bone marrow; in the absence of these characteristics, vascular and graft compromise may be suspected.

In the immediate post-operative period, allografts have signal hypo-intensity on both T1- and T2-weighted MR images. MR imaging is also useful for evaluating the presence or absence of marrow signal intensity, which may be evidence of graft incorporation or failure. The replacement of normal fatty marrow by hematopoietic tissue in the later phases of graft incorporation is evidenced by the presence of a red-marrow signal.

When ceramics pellets are used in orthopedic surgery, on MR images obtained in the post-operative scans, a diffuse enhancement of signal intensity in the post-operative site is an expected finding: this is presumably caused by the ingrowth of vascularized granulation tissue. Calcium sulfate pellets, regardless of the MR sequences, appear hypo-intense and mass-like (Fig.11).
**Images for this section:**

![Radiographs](image)

**Fig. 1:** Simple diaphyseal fracture of the Tibia with a spiral fracture line: plain radiographs: 
a) at the time of trauma, demonstrating the fracture; b) post-operative control in 
orthopedic casting; c) and d) control at 3 and 6 months, showing callus evidence and 
size, cortical bridging and progressive loss of fracture line at the site of fracture.

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Fig. 2: Spiral wedge fracture of the middle diaphysis of Femur: plain radiographs: a) post-operative control; b) and c) control at 3 and 6 months, showing progression of bone healing process ending in hypertrophic periosteal callus.

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Fig. 3: Multifragmentary diaphyseal fracture of the Femur: a) plain radiograph at the time of trauma; b) MDCT scan, axial and multiplanar reconstruction images showing the dislocation of this complex fracture; c) 3D VRT reconstruction showing a panoramic view of the focus of fracture.

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Fig. 4: Multifragmentary distal diaphyseal fracture of the Femur: a) plain radiograph, control at 3 months since surgery; b) and c) MDCT scan, multiplanar reconstruction and axial images showing delay in bone healing with incomplete trans-fragmentary bridges and focal loss of bone tissue.

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**Fig. 5:** Occult diaphyseal fracture of 5th metatarsal bone: a) plain radiograph, not showing a fracture line; b) T1-w MR sequence showing subtle hypo-intense diaphyseal spiral line of fracture; c) TIRM MR sequence showing bone marrow edema surrounding the fracture line.

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Fig. 6: Osteomyelitis of the Calcaneum: plain radiograph showing radiolucent abscess partially masked by surrounding sclerotic bone reaction.

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Fig. 7: Osteomyelitis of the Calcaneum: same Patient as in fig.6: MDCT multi-planar reconstruction demonstrating sclerotic changes, extension in the calcaneal body, and chronic draining fistula in plantar aspect of Calcaneum.

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Fig. 8: Osteomyelitis of the Calcaneum: same Patient as in fig.6: MRI scan: a) T1-w sagittal image showing bone abscess in calcaneal body; b) and c) TIRM axial and coronal images showing marrow edema surrounding bone abscess and a fistula opening in the soft tissue on the plantar aspect.

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Fig. 9: Osteomyelitis of the Femur: MRI scan: a) TIRM axial image showing marrow edema and a fluid abscess in the quadriceps muscle; b) T1-w axial image demonstrating periosteal reaction and a cloaca on posterior aspect of the femoral shaft; c) T1-w coronal Image demonstrating periosteal reaction of the femoral shaft and a fluid abscess in the quadriceps muscle.

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Fig. 10: Chronic Osteomyelitis treated with syntetic bone graft substitute (ceramics pellets): on plain radiograph ceramics pellets are dense as native bone tissue.

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Fig. 11: Chronic Osteomyelitis treated with syntetic bone graft substitute (ceramics pellets): same Patient as in Fig.10: MRI scan: T1-w coronal image: Ceramics pellets appear hypointense.

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**Fig. 12:** FEMURAL HEAD COLLAPSE: post-operative X-ray shows acetabular fracture fixation; follow-up X-ray evaluation (b,c) show progressive progressive femoral deformity with collapse of its head due to vascular insufficiency fracture.

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**Fig. 13:** FEMURAL HEAD COLLAPSE: coronal (a) MPR CT image (bone window) shows confirms left femoral head collapse with deformity and sclerosis of the superior aspect and acetabular post-traumatic degenerative changes. VRT images (b,c) offer a panoramic view of the injured left coxo-femoral joint and the position of orthopedic hardware in left acetabulum. (same patient in fig.12)

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Fig. 14: HYPERTROPHIC CALLUS AND PSEUDOARTHROSIS: AP (a) and LL (b) x-ray views show radius and ulna diaphyseal fracture. Post-operative AP (c) and LL (d) x-ray views show regular fracture fixation. 6 month follow-up AP (e) and LL (f) x-ray views show hypertrophic callus at fracture site due to pseudoarthrosis.

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Fig. 15: NAVICULAR FRACTURE: patient with right wrist trauma and pain at navicular site: tomo-synthesis (a) and coronal CT MPR image(b) show no sign of fracture. MR T1w (c) and TIRM (d) coronal images show non-displaced navicular fracture with marrow edema due to bone hemorrhage, and post-traumatic articular fluid collection.

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Fig. 16: NAVICULAR FRACTURE MRI FOLLOW UP: Coronal PD (a) and T1w (b) images at time of fracture. 3-month follow up (c,d) show increase of bone marrow edema due to
regular bone reparative reaction. 6-month follow up (e,f) show almost complete resolution of reactive marrow edema, without osteonecrosis, due to progression of healing. (same patient in fig. 15)
Conclusion

Diagnostic imaging offers many modalities to evaluate progresses in normal bone healing or its abnormalities, in order to settle the right treatment.
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