

Fracture Healing: Fracture Healing Understood as the Result of a Fascinating Cascade of Physical and Biological Interactions. Part I. An Attempt to Integrate Observations from 30 Years AO Research, Davos

Hojení zlomenin: kostní hojení jako výsledek fascinující kaskády fyzikálních a biologických interakcí. Pokus o integraci pozorování z 30letého výzkumu AO v Davosu. Část I.

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SUMMARY

The choice of best procedure in fracture treatment relies on a proper understanding of tissue reactions to the prevailing mechanical and biological conditions. Investing time and effort is rewarding as it opens up access to a fascinating world and improves fracture treatment based on logical decision making.

An intact bony skeleton enables mechanical functions of the human body such as locomotion. This function of the bone is made possible by its stiffness and strength, which allows bone to carry load without undergoing major deformation while remaining intact even under heavy loads. The shortcoming of bone as a strong and stiff material is its brittleness. Its brittleness prevents bone from bridging a fracture under unstable conditions. In spontaneous healing or healing under flexible fixation, a cascade of repair tissues stabilizes the fracture and allows for solid bony union.

Excessive load fractures the bone. Disrupted bone loses its stiffness. Loss of stiffness and, consequently, loss of skeletal support disables the function of the limb. Fracture healing is a ubiquitous and spontaneous process which restores stiffness as a prerequisite for mechanical function. Restoration of mechanical integrity requires that bone bridges and/or remodels the fracture site. If there is high initial tissue deformation (strain) at the fracture site, bone as a brittle material cannot bridge the gap. In spontaneous healing or healing under flexible fixation a cascade of consecutive phases of tissue differentiation are required to overcome this shortcoming of bone. The cascade increases tissue stiffness at the expense of tolerance to deformation until a low value of interfragmental strain is reached that then allows bone to form a solid bridge.

The cascade of differentiation is impressive as a “reasonable” process with a goal. Therefore, bone healing is often considered as a rational process where the repair tissues are expected “to think and to act in order to achieve”. We propose the observation of bone reactions without assuming that these reactions are guided by goal-oriented intelligence because the latter is non-existent. Observing the unexpected without having a preconceived opinion is a precondition for new insight. This approach avoids being misled into projecting one’s own thinking into tissues that react without goal orientation.

Fracture healing is a repair process which requires induction and must be enabled. To get a feel for the problem we will first address the mechanical properties of bone as the prerequisites for its mechanical functions. Then we will discuss which conditions induce and which enable the repair process. The following paper addresses a fascinating interplay between physical and biological processes that enable fractured bone to bridge solidly and remodel to regain its “pre-fracture” function and structure.

No one of the different treatment modalities or healing patterns is best on its own. For a given situation the goal is to recover the function of the bone, limb and patient early and permanently by choosing the optimal procedure and implant. Understanding bone reactions permits a rational choice and replaces subjective predilection and monomania. The stability of the fixation and the blood supply are priority considerations, which must often be weighed against each other.

PREAMBLE

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An intact bony skeleton enables mechanical functions of the human body such as locomotion. This function of the bone is made possible by its stiffness and strength, which allows bone to carry load without undergoing major deformation while remaining intact even under heavy loads. The shortcoming of bone as a strong and stiff material is its brittleness. Its brittleness prevents bone from bridging a fracture under unstable conditions. In spontaneous healing or healing under flexible fixation, a cascade of repair tissues stabilizes the fracture and allows for solid bony union.

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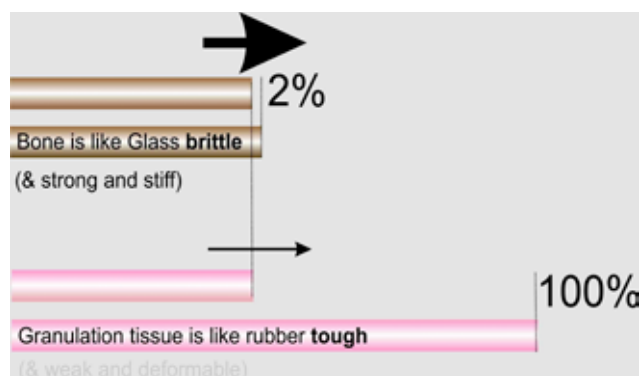


Fig. 1. Elongation at rupture defines the tolerance of a tissue to deformation. At onset of fracture healing tolerant tissues are required. Later stiffer but less tolerant tissues help achieve solid union. The elongation at rupture of the repair tissue is a critical characteristic.

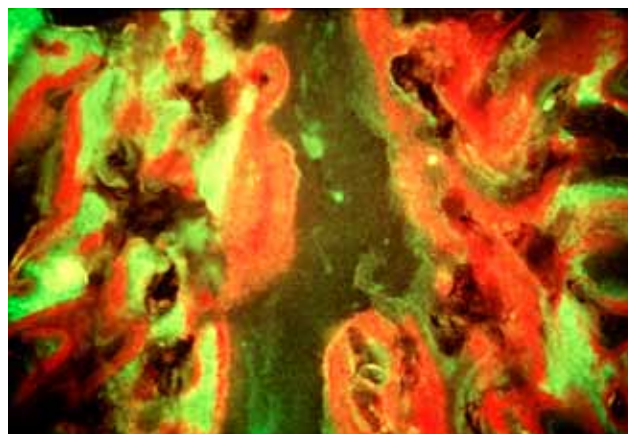


Fig. 2. Later stage of solid bridging by callus. Onset of internal remodeling of callus.

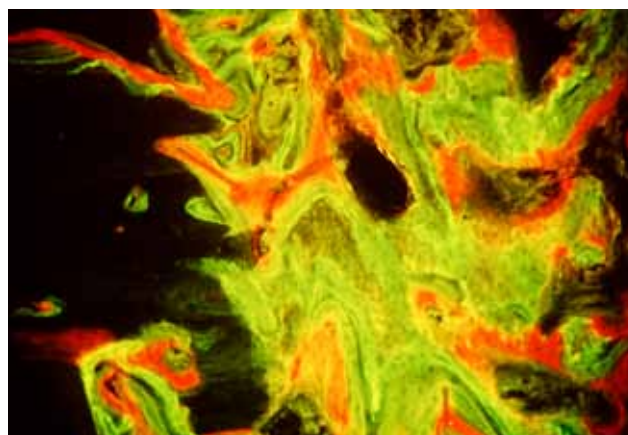


Fig. 3. Sheep tibia, flexible plate splinting, fracture gap filled with woven bone. The fluorescent markings (green then yellow then red) show the advancement of the callus fronts towards each other. No bridging at this time.

patient early and permanently by choosing the optimal procedure and implant. Understanding bone reactions permits a rational choice and replaces subjective predilection and monomania. The stability of the fixation and the blood supply are priority considerations, which must often be weighed against each other.

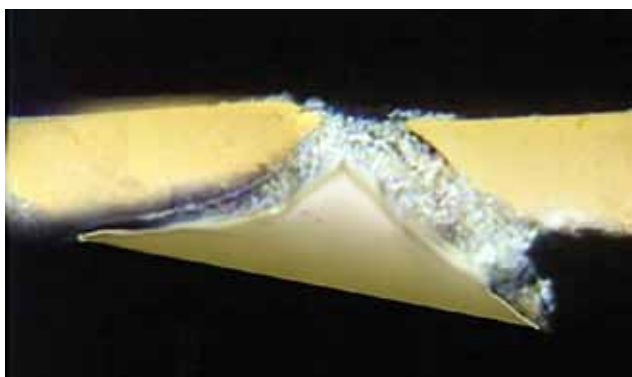


Fig. 4. High speed video recording of a fracture of plastic bone. The recording was taken under water. This image from a movie shows the effect of the implosion and distinct cavitation, which produces relevant tissue damage. (Courtesy R. Moor; ARI).

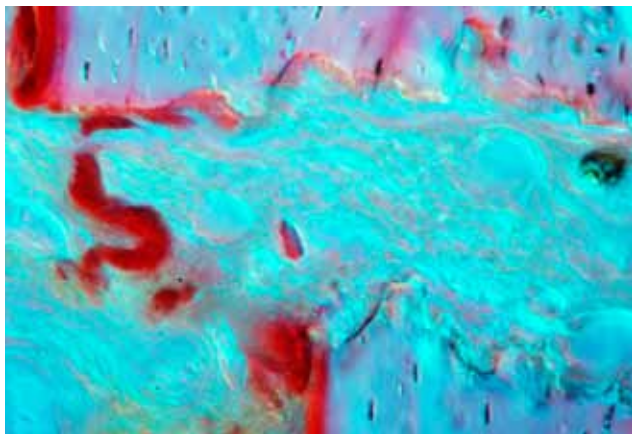


Fig. 6. Two flexibly fixed fracture fragments. Where the surfaces are opposed surface resorption occurs. The lower surface does not show resorption where no opposing fragment allows for lower strain. In this area a folded callus bridge forms first.

MECHANICAL ASPECTS

a) The mechanical functions and characteristics of bone

The mechanical functions of the skeleton require a rigid supporting structure for the muscles and articulations. If the tibia was likely to bend or buckle when bearing weight the muscles bridging the fracture could not maintain a given position of the fracture fragments in relation to each other: Stiffness of bone is a prerequisite for the function of the limb. Strength of bone allows for resistance to load without failure. Apart from stiffness and strength a third mechanical characteristic is essential. It is the amount of deformation that a material undergoes before rupturing under increasing load. This is usually called "elongation at rupture" expressed as a relative unit such as percent (Fig. 1). A material with small elongation at rupture behaves like glass while rubber exhibits a large deformation at rupture. In turn glass breaks when a small deformation is imposed while rubber breaks after large deformation, bone is brittle

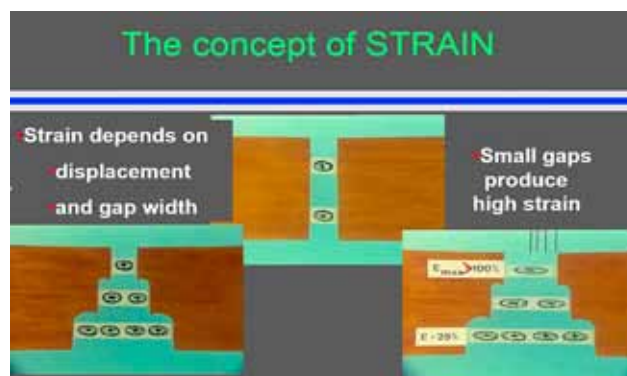


Fig. 5. The effect of width of the gap on tissue deformation (strain) within the gap. For the same amount of displacement in the narrow gap the strain is much larger than in the wide gap.



Fig. 7. Schematic representation of resorption of the two surfaces corresponds and installs a similar amount of strain. The folding of the callus bridge reduces the strain of the bridging element.

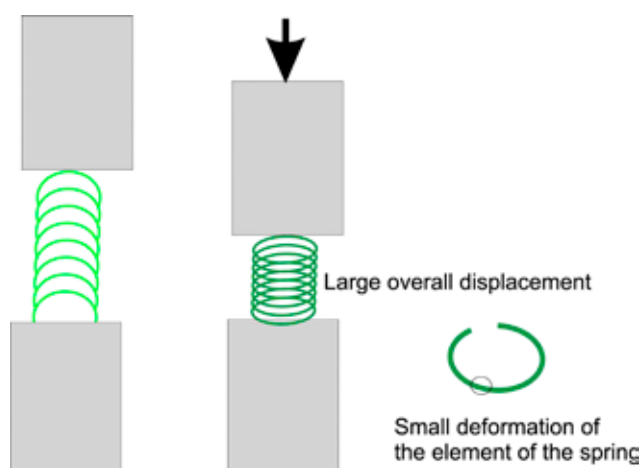


Fig. 8. When a spring is deformed it may undergo large overall displacement while the elements of the spring experience only little deformation.

like glass and connective tissue is tough like rubber. The element of bone (cortical and cancellous) breaks at an elongation of only 2% (17). As we will see the brittleness of bone is an essential characteristic that

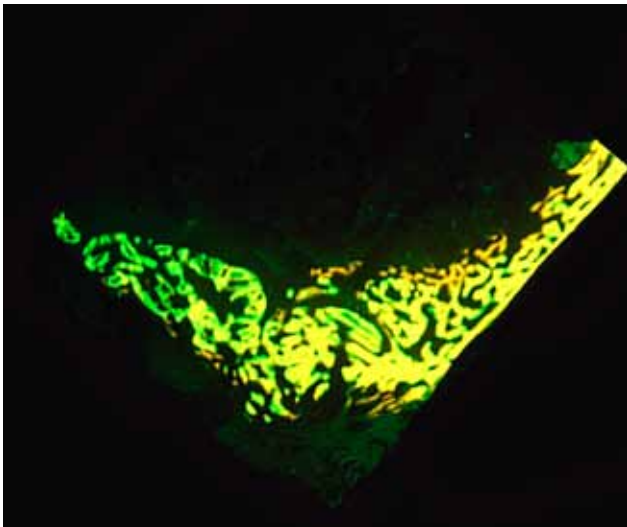


Fig. 9. The structure of the 3-D woven callus acts like a spring reducing the strain of the element in relation to the overall strain. This explains why the woven callus can tolerate up to about 10% deformation.

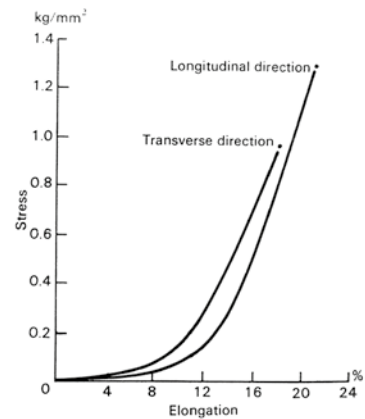


Fig. 80. Stress-strain curves in tension of aponeurotic tissue from the central tendon of the diaphragm of rabbits.

Fig. 10. Stiffness increases with elongation in a nonlinear way (Yamada). This favors reduction of mobility.

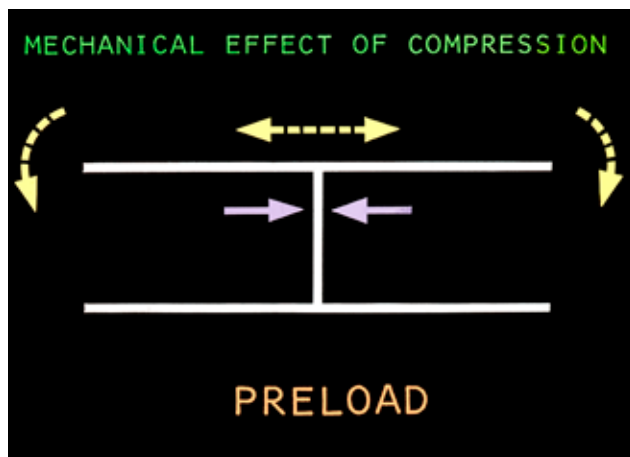


Fig. 11. Compression eliminates mobility of the fracture fragments in relation to each other by preloading as long as the compression exceeds the traction produced, e.g. by bending.

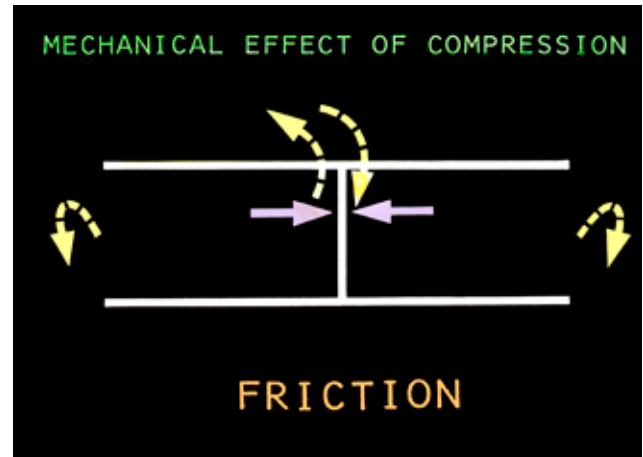


Fig. 12. Compression also produces friction. Shear displacement, e.g. by torque is suppressed as long as the friction exceeds the shear load.

limits the contribution of bone to spontaneous healing and healing under non operative or flexible surgical fixation.

Here the issue is to understand how fracture healing is enabled through a cascade of differentiating repair tissue and induction as well as bone resorption at the opposing surfaces of the fracture fragments (Figs 2 and 3).

b) Mechanical characteristics of the fracture site during and after fracture

As high speed video recordings have demonstrated an explosive opening of the fracture site produces a void into which the soft tissues implode (Fig. 4). This is a process which results in a tissue-traumatizing implosion similar to cavitation. After the fracture has occurred the stiffness of the bone is disrupted locally and even small loading results in large displacement of the fracture fragments in relation to each other. After fracture

and before treatment any repair tissue within the fracture gap is likely to undergo large deformation. Such large deformation is tolerated only by tissues that are tough. Prevailing conditions and characteristics of the tissue may be incompatible. Let's consider which procedures are required to enable final strong and stiff bridging of the fracture.

c) Two different pathways that allow bony bridging

As mentioned bridging by any tissue can only occur when the tissue deformation in the fracture gap is below a given level, which depends on the elongation at rupture of the material and structure of the bridging tissue. Tissue deformation (strain) depends on the amount of displacement (mobility of the fracture) and, even more importantly, inversely on the width of the fracture gap (9).

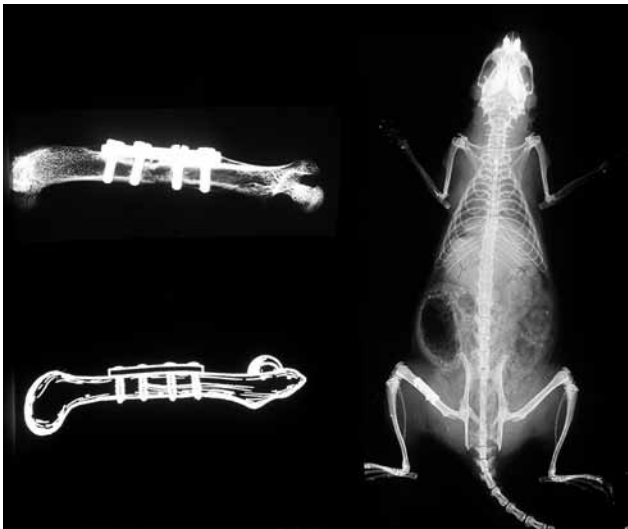


Fig. 13. Plate fixation of a transverse osteotomy in a mouse femur. This is an experimental technique that permits the study of compressed as well as splinted plate fixation in the tibia of mice. (Courtesy R. Matthys).

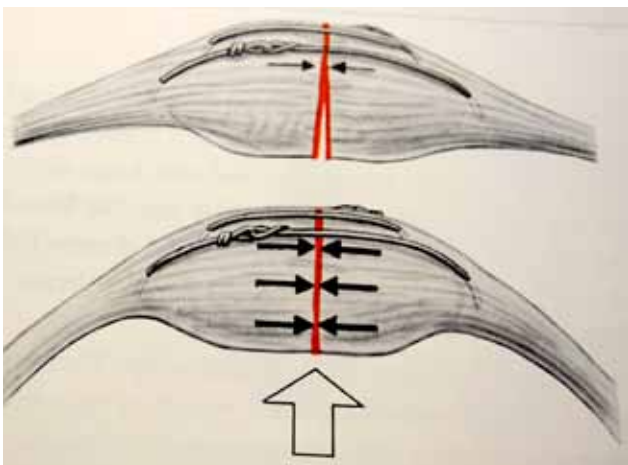


Fig. 14. Example of tension band fixation. Upon application of bending the wire takes up traction and therefore the fragments remote to the wire are compressed (8).

Reducing fracture mobility

Immediately after fracture the following elements contribute to some reduction of the mobility of the fracture site:

- To minimize pain the body avoids loading of the fracture site.
- Pain-induced active tensioning of the muscles bridging the fracture. The tensioned muscles act as a sort of soft splint.
- The fracture hematoma and edema passively pre-tension the tissues bridging the fracture gap
- The hematoma displaces the soft tissue cuff and thus increases leverage of all tissues bridging the fracture.
- Under conditions of minimized loading even soft splints have an appreciable effect.

In the weeks after fracture the following tissue modifications essentially reduce fracture mobility:

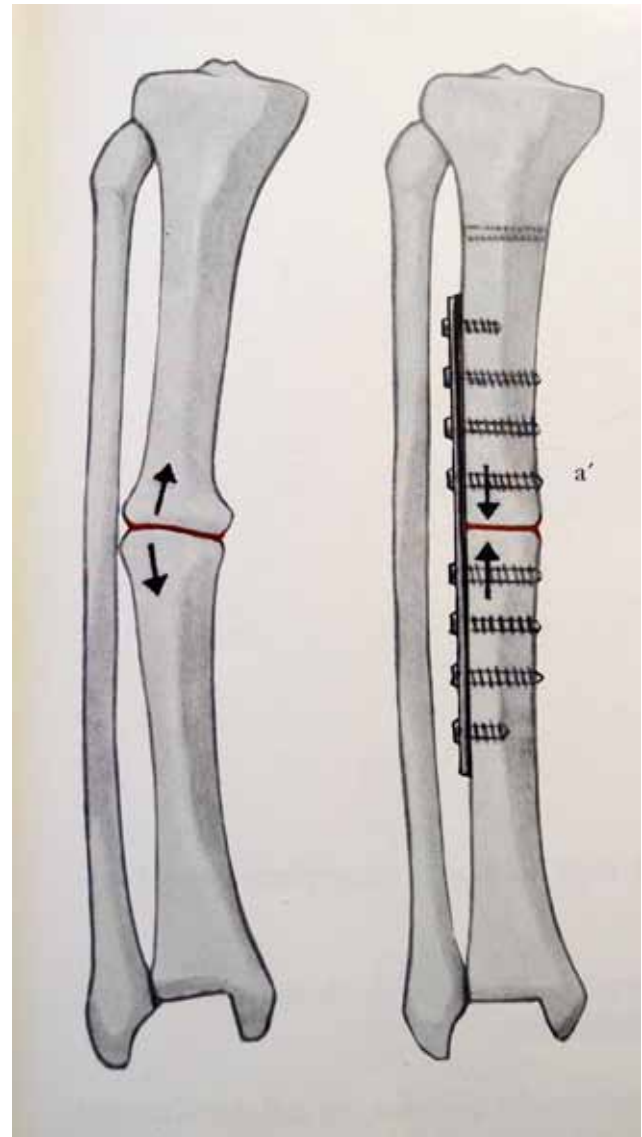


Fig. 15. Early example of tension band function of a plate. Here the same forces acts as in the tension band wiring of Fig. 14 (8).

- The soft cuff bridging the fracture undergoes differentiation to stiffer and stronger dense fibrous and/or fibro-cartilaginous tissue. The tissue stiffness from granulation tissue to cartilage increases by a factor to the power of ten.
- The diameter of the cuff increases and often reaches twice or more the diameter of the original bone. The resulting increase in stiffness may exceed physiological stiffness by ten times due to better leverage.

Reducing tissue deformation within the fracture gap

The effect of the width of the gap on tissue deformation within the gap is as a rule not taken into account when the effect of stability or instability of the fracture is considered (10, 11, 12, 13). Let's look at reducing the mobility of the fracture and concomitantly at reducing tissue deformation further due to an increase in

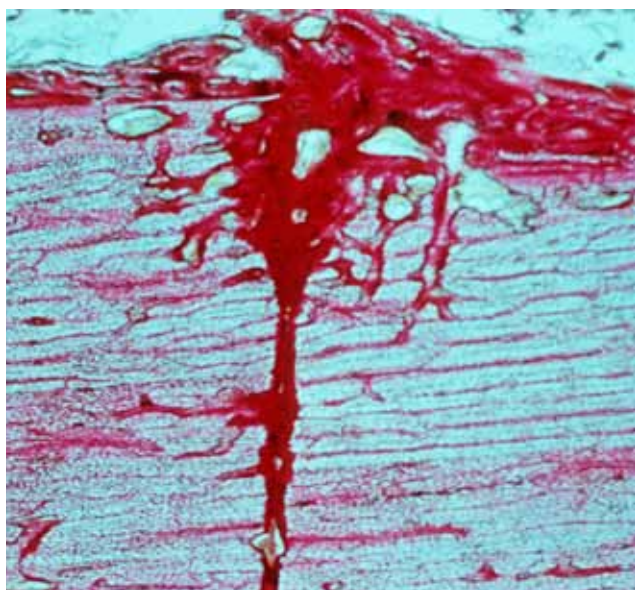


Fig. 16. At the outer surface of the compressed contact functional load produces a small area of bone resorption that re-fills with callus. This phenomenon has been called "gocce di cere" (B.A. Rahn et al. 1971).



Fig. 17. Spontaneous healing, femur of a mountain goat. Strong mobility of fragments, wide gap, moderate strain. Solid union but malalignment. (Courtesy U. Geret).



Fig. 18. Healing after conservative treatment. Moderate mobility, moderate gap width, moderate strain. (Courtesy H. Wilenegger).

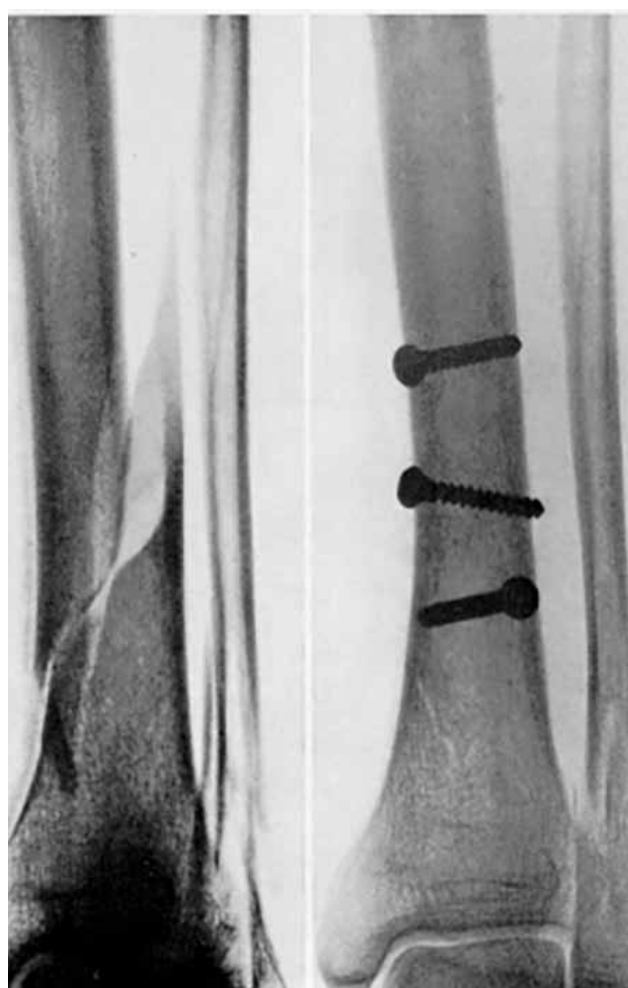


Fig. 19. Spiral fracture fixed with three lag screws. Absolute stability, no displacement between contacting compressed surfaces, primary healing, limited strength.



Fig. 20. Flexible fixation, prompt healing provided gap width and mobility produce a strain within the bandwidth that induces bone repair and tolerates existing mobility (Courtesy C. Ryf).



Fig. 22. External fixator, here an experimental setup which allowed a study of the effects of dynamic compression and traction (Courtesy B. Füchtmeier).

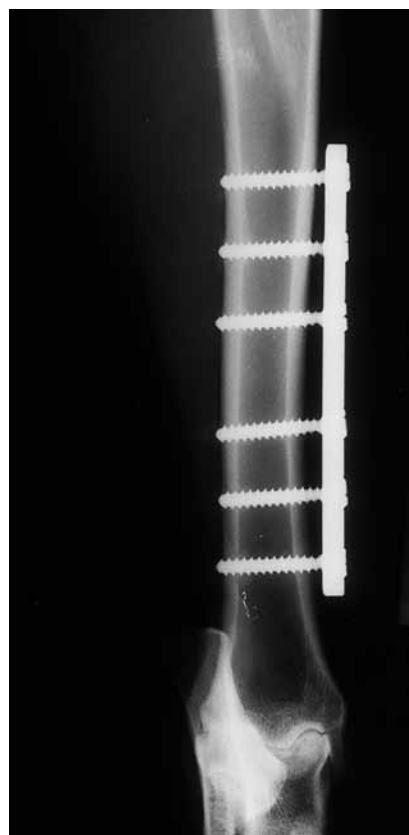


Fig. 23. Plate used as an internal fixator for flexible splinting to avoid contact necrosis, no contact damage to blood supply.



Fig. 21. Flexible fixation of bilateral multi-fragmentary fractures with nail and plate splinting, prompt healing by callus formation (Courtesy R. Ganz).

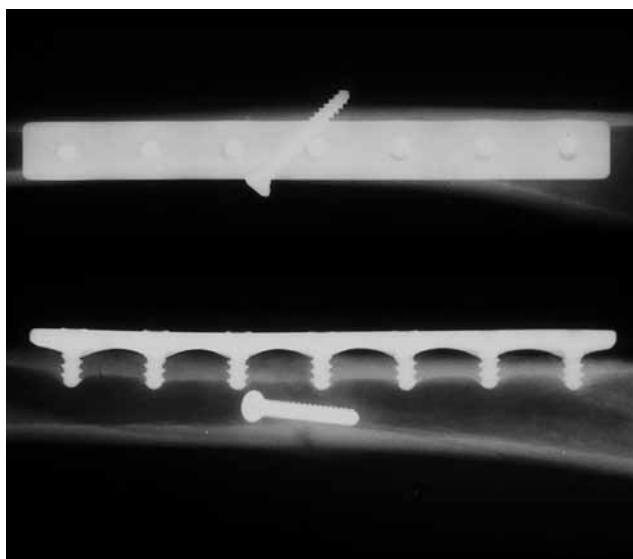


Fig. 24. Compression fixation by insertion of a lag screw protected by a plate splint. The PC-Fix allows optimal blood supply and avoidance of stress risers through undercuts; only isolated point contact. Solid healing at 10 weeks (S. Tepic).

the width of the fracture gap due to surface resorption (Fig. 5).

As outlined earlier tissue deformation within the fracture gap for a given amount of fracture mobility depends on the distance of the moving fracture surfaces whereby the mobility has a proportional effect and the width of the gap has an inverse effect. Large strain may result in minimal fracture mobility if the gap is very small. As an example, a displacement of the fracture fragments of barely visible 0.1 mm results in 100% strain when the gap is only 0.1 mm wide. One would not expect such high amounts of strain in a fracture situation where both displacement and gap width are barely visible.

Especially for a small fracture gap tissue deformation can be lowered by increasing gap width. The opposing fracture surfaces show a ragged structure of surface resorption that results in achieving a more or less equal distance between the surfaces. It has been shown that high strain at bone interfaces induces bone surface resorption that lowers strain (4).

Increasing the length of the bridging connection between two surfaces moving in relation to each other

A tissue bridge which spans a gap straight across, i.e. at the shortest distance from point to point between two moving surfaces undergoes the highest tissue deformation. If the bridge is structured in a three-dimensional way like a spring, the element of the spring undergoes small deformation in spite of the large overall displacement of the spring (Fig. 8). This is exactly what happens with the structure of callus which is appropriately called "woven" bone (Fig. 9). Callus acts like a spring. Once a small bridge is installed the increase in thickness and number of spanning elements immobilizes the bridge ultimately providing a solid connection.



Fig. 25. Double plating with a helical plate. This is an extremely rigid fixation whereby the additional elevated helical plate is applied without damage to the blood supply. This type of double plating is acceptable because blood supply is maintained. Healing is slow but a desperate situation was resolved (11).

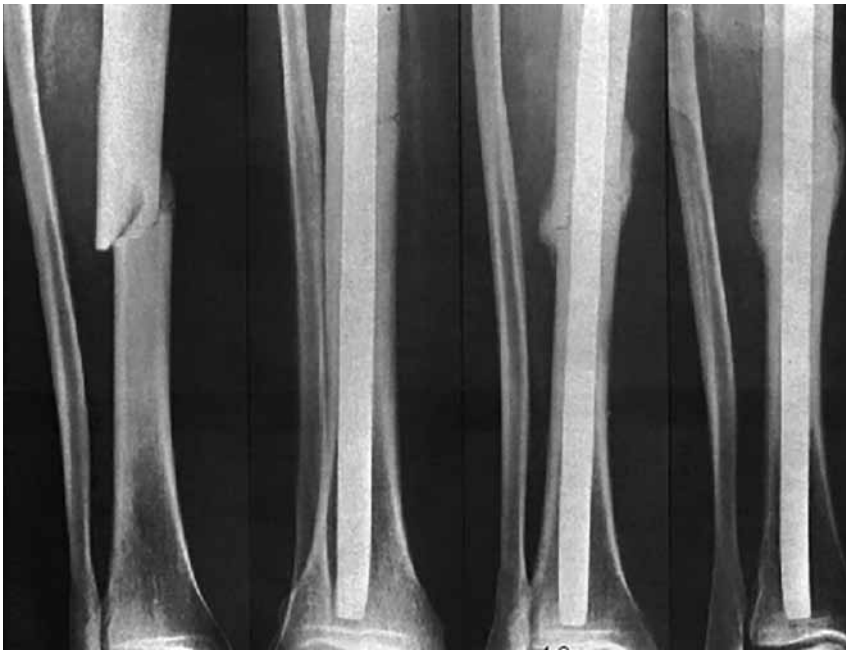


Fig. 26. Simple transverse fracture non locked nail, flexible fixation with functionally compressed close contact.



Fig. 27. Locked plate and locked nail, late stage of healing. The locked nail prevents shortening and also twisting of the main fragments in relation to each other. (Courtesy R. Ganz.).

Nonlinear stiffness as a function of tension in the initial repair tissues

Of special interest is the fact that with increasing elongation the stiffness of connective tissue, for example, increases in a nonlinear way (17) (Fig. 10). Straightening of the ringlets of collagenous tissue seems to be the underlying mechanism. The effect of the nonlinear behavior of the material's stiffness is that a soft tissue that can tolerate the initial large deformation (strain) is able to limit the amount of movement. In this way a gradual transition through the consecutive steps of differentiation is stimulated and enabled.

“Complete” elimination of fracture mobility by maintaining the fracture surfaces in close contact: compression fixation

The mobility of a fracture can be eliminated by compressing the adapted opposing surfaces of the fracture. Compression keeps fragments immobilized through preload and/or by producing friction. When a fracture is exposed to a bending load the surfaces of the fracture are compressed while surfaces on the opposed side of the fracture are unloaded and distracted. When the fracture surfaces are pushed together by application of compressive preload the surfaces remain in close contact for as long as the compressive preload exceeds the functional traction (Figs 11–13).

A classic example of transforming dynamic traction into compressive preload is the application of one or more wire loops, for example, in the application of a plate as a tension band on the traction side (Figs 14 and 15). When such implants are applied under some pretension traction produces bending. The distraction side of bending is protected by the wire while on the compression side the preload increases with traction.

The above statements consider the situation within the compressed surfaces. At the outer edge of such compressed surfaces one can expect that within a narrow zone from the outer bone surface inwards there is dynamic micro displacement with

induced bone resorption and refilling (13) (Fig. 16 “gocce di cere”, tear drop phenomenon).

Two side issues are worth mentioning here:

Precise reduction has often been advocated as a precondition for compression osteosynthesis. Precise reduction of the fracture is not a precondition for stabilization as such but facilitates tolerance of higher compressive load by distributing it over a larger contact surface thus reducing the critical load per unit area (stress). However, when ragged surfaces without precise reduction are compressed the contact peaks are squeezed until what is now a larger contact surface reduces the stress (force/area) below the strength (expressed as units of stress) of the bone.

As we will discuss later, rigid stabilization of a fracture using compression eliminates the fracture mobility that is a precondition for induction of fracture healing on the basis of callus. Under complete immobilization fracture healing by triggering callus formation is absent and fracture union depends entirely on internal remodeling. Such internal remodeling is similar or identical to the process we observe as the internal creeping substitution of necrotic bone as in contact necrosis. With this in mind we understand “primary” healing as a side effect of internal creeping substitution (osteonal remodeling) induced by and replacing necrotic bone. This statement relies on the observation of remodeling of dead bone.

MECHANICS AND BIOLOGY OF DIFFERENT TREATMENTS AND HEALING

The following examples (Figure 17–Figure 25) demonstrate the different treatment modalities and their advantages and disadvantages based on different conditions of blood supply and mechanics of fixation.

Part 2 of the article will follow in the issue 1/2015.

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¹ We use the term “internal creeping substitution” for a process of internal remodeling of the osteonal structure that keeps the overall stiffness and strength of the bone intact.

² These references mainly concern the activity at the AO Research Institute. For an extensive List of Literature see Perren 2002