The CABMM's **Brigitte von Rechenberg, Prof Dr med vet, Dipl ECVS,** and **Michael Plecko, Dr med,** on IFM in modern implants

Dynamisation of fracture healing

Since modern implants are applied to repair fractures in long bone traumatology cases, the rigidity of fracture fixation – the benefit of interfragmentary movement (IFM) – between the fracture ends is a focus of interest. There is no question that the immediate stabilisation through implants such as plates and screws has contributed considerably to the positive outcome of fracture treatment by enabling complete reconstruction of the original length and shape of the affected long bones. Furthermore, such implants have, for the first time, made it possible to reconstruct fractures close to joints or even involve articular joint surfaces without having problems with alignment of the original bone axis and/or articular surface.

Philosophy

The philosophy for long bone fixation has changed considerably in the last 60 years. At the beginning of osteosynthesis, complete reconstruction of the original bone anatomy and the reduction of fragment rigidity under primary compression were considered instrumental to primary bone healing and overall success.

Over time, however, it became evident that some IFM between fragments could stimulate and accelerate fracture healing depending on the amount of interfragmentary movement and the time at which it is applied. Amongst other factors, this new understanding of the rigidity of fracture fixation emerged through the use of different fixation systems.

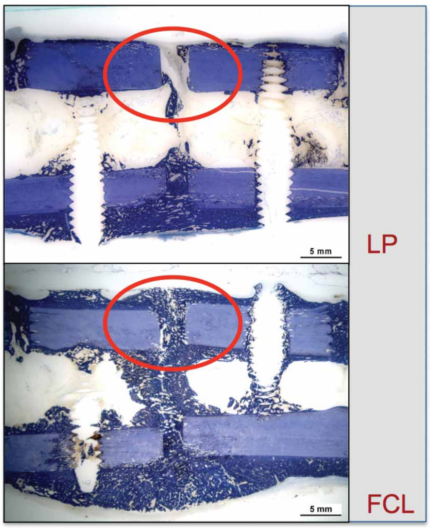
While plates and screws were certainly the implants achieving the most constant rigidity with the least IFM between fragments, other systems such as intramedullary nails or external fixators have resulted in less stable primary fixation and yet have nevertheless demonstrated excellent results. Indeed, the latter systems have been shown to be less traumatic with respect to soft tissue trauma compared to a widely open approach over the entire fracture area, in which local vascularity is additionally compromised.

Clinical

From a clinical perspective, differences were evident in the amount of callus formation. The classic rigid bone fixation under compression with plates and screws was designed to heal with primary bone healing; however, there was no callus formation.

The cortical bone fragments fused directly and histologically; this could be observed by watching osteoclasts crossing the fracture line followed by osteoblasts which deposited the new bone. The new generation of osteosynthesis plates took this into account by offering dynamic screw holes that would further enhance fragment compression when the screws were tightened.

Far locking screws ground sections of the ovine tibiae show that at nine weeks no callus formation was present at the cis-cortex using standard locking plates and screws, whereas a symmetrical callus in the cis- and transcortex was present when far locking screws were applied



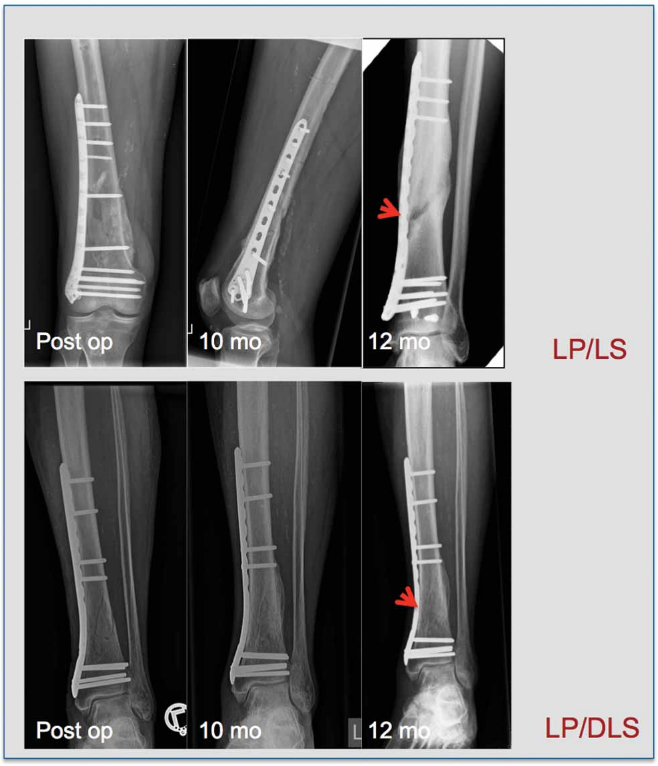
DCP

From this, the dynamic compression plate (DCP) was born. The rigidity of the fracture repair was a combination of the mechanics of the plate and the friction between the bone and implant. The DCP brought another advantage: screws could be angled within the plate, making it easier to fix the implant to the bone contour.

By contrast, the intramedullary nails and external fixators simply aligned the fracture ends without primary bone compression, often leaving a small gap that was healed by callus formation. In some situations, especially where infection or heavily affected vascular supply was present, these implants showed better results due to the fact that no additional trauma was added to the compromised fracture area.

Over time, therefore, the new concept of so-called 'biologic fracture healing' emerged; within this the key element was protection of the soft tissue in the fracture area, and only small incisions to anchor the plate further away from the fracture site were used.

The minimal invasive surgery technology for trauma cases was born from this, and a novel concept for fragment fixation was developed. With the new locking plates and screws (LP/LS)



DLS screws Differences can be seen regarding the type of callus formation. While the callus in the patient with LP/LS fixation is asymmetrical and clearly less at the cis-cortex, the fracture treated with the LP/DLS has a nice and symmetrical callus throughout the healing phase. The time frame for the asymmetric callus is 12 months

the rigidity of the fracture fixation was no longer dependent on the friction between bone surface and implant, but was relying on the interlocking of locking screws and plates. In fact, the LPs are fixed at a distance to the bone surface (up to 2mm or even more) to allow the vascularisation of the entire fracture surface.

The new concept brought many advantages for undisturbed biologic fracture healing. However, the increased rigidity also had its downside. The low IFM under the new LP, especially at the near side of the cortex (cis-cortex), resulted in less stimulation for new bone formation and fracture healing at this side. Increasing the IFM by leaving the screw holes empty close to the fracture site improved the situation slightly, but this occurred mainly at the fracture side opposite the plate (transcortex).

In addition, over-drilling the drill hole at the cis-cortex helped to improve callus formation. This asymmetric callus formation can cause a problem when the rigidity of the system warrants implant removal for further stimulation of the fracture healing, but, due to none or low callus formation at the cis-cortex, complete removal of the implant is not indicated yet. These problems lead to the concept of dynamisation of fracture healing through allowing IFM, especially at the cis-cortex.

Far cortical locking screws

Bottlang *et al.* pursued the concept of dynamisation using new designs of plate and screw systems by successfully introducing a far cortical locking screw (FLS) with only transcortical threads (Zimmer® MotionLoc™ Screw). This is a straightforward concept in that the screw does not have threads in the part inserted into the cis-cortex of the fracture fragments, similar to the classic lag screws with a smaller outer diameter at the unthreaded part of the screw.

The IFM resulting from this configuration was just enough to enhance callus formation at the cis-cortex without loosening overall strength and stiffness of the fixation. They showed in a study with human patients that the inhibition of callus formation rather than implant failure was the reason for non-unions using the classic LP system.

In biomechanical tests, they also demonstrated that, through the introduction of FLS, the stiffness of the constructs was 88% lower than the standard LP and LS system. Furthermore, they could confirm that the IFM occurring at the cis and transcortex was similar and parallel (0.51mm *versus* 0.59mm) in contrast to the classic LP/LS system, where the IFM at the cis-cortex was significantly lower (0.02mm *versus* 0.05mm).

These biomechanical tests were validated in an experimental study with tibia-osteotomies in sheep, where a 4.5mm titanium plate was either fixed with the classic LS or the FLS. A standardised 3mm gap between the fracture ends guaranteed gap healing and IFM. Weekly anteroposterior and angular mediolateral radiographs demonstrated callus formation over time until nine weeks, when sheep were sacrificed and tibiae harvested for further evaluation.

Radiographic results confirmed that the fixation with FLS showed better callus formation throughout weeks four to nine, with 36% more callus at nine weeks compared to the classic LS. Furthermore, mineral content was higher at 44% and callus distribution was more symmetrical involving the cis-cortex in the FLS compared to the LP group.

Results from biomechanics corroborated the radiographic evaluation such that the FLS was 54% stronger in response to failure on mechanical load and tolerated 156% more energy until failure occurred. Histologically, more symmetric callus formation at the cis-cortex could also be confirmed.

Dynamic locking screws

Another approach to the same problem emerged in the development of the dynamic locking screw (DLS, DePuy Synthes). The concept was similar to the FLS in that IFM was increased, particularly at the cis-cortex. Here, the DLS consisted of two parts: an inner pin-like core that was attached to the outer threaded sleeve at the bottom, leaving the core pin free near the screw head. This special design gives way to 0.2mm micromotion in each direction, whereas the pin-head-plate and the sleeve-bone interface remained locked.

Biomechanical tests revealed similar results as those with the FLS. In biomechanical tests, the construct with the DLS showed a marked reduction of stiffness in the initial phase (612.4 N/mm) compared to the classic LS (2394.9 N/mm). Due to the design of the DLS, there was a secondary stiffness measurement when the pin-head-plate exerted its free movement, touching the outer sleeve. This secondary stiffness was similar to the LS (2309.1 N/mm). What is more, the IFM was significantly higher in the cis-cortex (0.089mm ± 0.03mm *versus* 0.491mm ± 0.008mm, respectively).

Encouraged by these results, experimental studies in sheep were conducted. First, long oblique fractures in ovine tibiae with a standardised angle of 45° and proximolateral direction of the osteotomy were fixed with locking plates (3.5mm 12 hole broad LCP/159mm, stainless steel, VP4045.12).

Three groups were created: group one had the fragments completely opposed to each other at the fracture side, while groups two and three had a gap of 1mm and 3mm respectively.

Animals of each group were sacrificed at either six or 12 weeks (six animals/time point), and callus formation was compared for quantity and quality. Apart from weekly radiographs starting at week three and continuing throughout week 12, again in anteroposterior and angular mediolateral direction and histology of non-decalcified bone samples, intravital staining with fluorescence dyes was performed at weeks three, six, nine and 12 to follow calcium deposition over time (calcein green at three weeks, xylenol orange at six weeks, tetracyclin at nine weeks and calcein blue at 12 weeks).

The 1mm and 3mm gaps were standardised using a space holder while fixing the plate and thereby guaranteeing a parallel osteotomy line between fragments. After sacrifice, biomechanical non-destructive torsion tests were conducted and compared to their contralateral intact tibia. Results were reported at torsional stiffness (Nmm/°). Microradiographs of plastic sections were also used to study calcification at the fracture site.

Quantitative histomorphometry was performed such that total callus and also percentages of periosteal and interfragmentary callus were calculated for both the cis and transcortex. Results were compared to microradiograph measurements and µCT evaluation of bone samples.

Biomechanical results at six weeks showed the highest stiffness values for group two with the 1mm gap, while at 12 weeks group one, with the direct apposition of the fracture end, had the best stiffness, followed by group three (3mm) and then group two. This was confirmed radiographically and histomorphometrically at six weeks, although at 12 weeks the highest new bone deposition was found for group three, where more callus had been formed. The callus formation at the cis-cortex was rather symmetrical in all groups, and evaluation of fluorescence sections revealed that periosteal callus deposition was mainly occurring between six and nine weeks, whereas at later time points interfragmentary callus deposition was more prominent.

Differences

Differences were not always statistically significant, but then all osteotomies had been reconstructed using the DLS and only the gaps of 0, 1 and 3mm represented the difference between groups. There, the group with direct apposition of the fragment ends showed the best values for bone healing.

When results were compared with an earlier study of the same ovine animal model with 45° oblique tibia osteotomy, advantages were present for better callus formation at the cis-cortex using the DLS. Although strong tendencies were shown there, differences were not as high as expected. This was attributed to the configuration of the long oblique fracture, where the parallel fixation of the fragment ends was not always easy to achieve.

Therefore, the study was partially repeated with a comparable animal model but a transverse section of the tibia in all groups and only a 3mm gap between fracture ends. An additional difference was that 5mm LP and DLS screws were used to better resemble the human system.

In this size, the DLS screws allow micromotion in each direction of 0.45mm, and the 90° angle of the osteotomy facilitated complete parallel fixation of the fracture ends. The results confirmed our earlier studies but showed more clearly that DLS resulted in significantly higher values for biomechanical torsion test to failure, and callus formation at the cis-cortex was much improved. Overall, callus formation was much more continuous and homogenous compared to classic locking screws.

Since then, clinical results in humans have confirmed results obtained in the animal studies with sheep. However, minor problems occurred during the removal of the DLS after the healing of the fractures in humans, in that screws broke at the pin screw interface, but now a special removal device has been introduced to overcome this problem. The overall benefit of the DLS screws, especially in older patients with a more osteoporotic bone, should outweigh the small risk during screw removal.

Complex design

Due to the complex design of the DLS, the risk of corrosion between the pin core and the screw head increased. Several options were therefore tested to find which material and coating would best serve to withstand mechanical load and still show the best biocompatibility. For this, a new finish consisting of titanium-aluminium-niobium (TANNEW) for coating screws made out of cobalt chrome was produced and tested for osseointegration in a pelvic animal model in sheep. The animal model was developed in our group to screen and compare new implants in the ileac wing of sheep without posing additional mechanical challenges – particularly in the case of oral implants dealing with infections – that could jeopardise results.

The new TANNEW coating and finish was tested in standardised 2.5mm screws (diameter of 3.5mm, core of 2.5mm) of 14mm length. Removal torque tests revealed appropriate osseointegration, and histology specimens with the implant *in situ* allowed for the testing of biocompatibility and osseointegration (bone interface contact, BIC). Screws made of stainless steel or cobalt chrome alone, or coated with titanium and pure titanium, served as internal controls.

This study demonstrated that the osseointegration, biocompatibility and BIC of the new coating and finish of TANNEW screws were equally as good as those delivered by screws of pure titanium or those with a titanium coating and were significantly better values when compared to screws made of cobalt chrome or stainless steel.

Overall, the DLS and its concept of fracture dynamisation showed promising and valuable improvements for a more homogenous and symmetrical callus formation at the cis-cortex of the fracture site. The adapted design and material components will stand up to the clinical requirements in clinical cases.

Conclusions and outlook

Since the concepts of fracture dynamisation were introduced into clinics, its value has been well proven. Research is on-going to further refine the especially designed plate and screw systems to further improve standardisation and homogenisation of callus formation at the cis-cortex. These systems are also expected to improve fracture fixation in more complicated cases, such as old and brittle bone occurring in osteoporotic patients.

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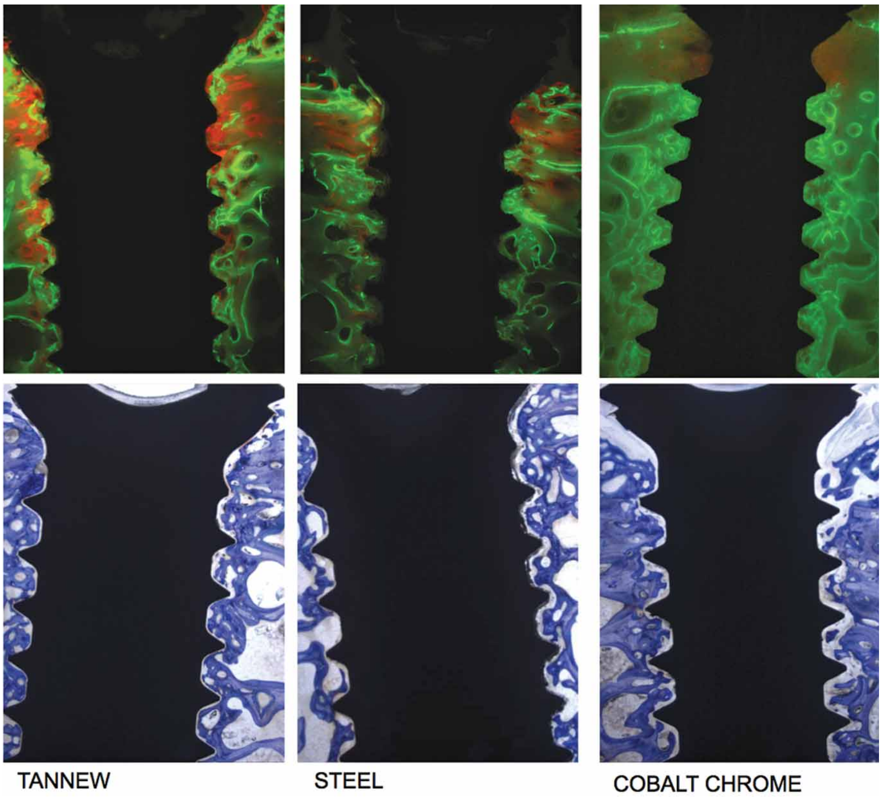

Intravital fluorescence staining shows calcium deposition at four (green) and eight (orange) weeks. TANNEW shows significantly better osseointegration and bone remodelling compared to the standard controls, steel and cobalt chrome

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