# SCAPHOID NONUNION-EVIDENCE BASED MANAGEMENT IN 2023

## Vascular Scaphoid nonunion
## Avascular Proximal Pole Nonunion
## Recalcitrant Scaphoid Nonunion

The title of my contribution to FESSH 2023, "The failure in scaphoid nounion surgery – Complications and how to avoid them", stimulated me to focus on the treatment of scaphoid nonunions and the still controversial issues, that is to say the current trend of treatment of a classic scaphoid nonunion without impairment of blood supply (treatment with traditional open surgery or with arthroscopic surgery), the management of the Avascular Proximal Pole Nonunions (APPN) and of the recalcitrant nonunions (Dodds 2016).
How to avoid the complications in scaphoid nonunion surgery requires a biomechanical and biological approach to the problem.

## BIOMECHANICAL CONSIDERATIONS

From the biomechanical point of view, the basic principles of fixation must be respected. Whether it is an open or an arthroscopic approach, it is essential that the fixation, however it is done, is stable for the time necessary for the bone healing, considering that most of the time this process takes place according to creeping substitution. (Dowson 2001, Schmidle 2018)

If you opt for screw fixation, you need to know, thanks to the CT scan in the sagittal plane, the spatial orientation of the nonunion and choose the most appropriate direction of fixation, whether you decide to perform it with open or arthroscopic surgery.
Investigating this aspect with a CT scan is mandatory because there are nonunions that, through the volar approach, you could never properly fix with a screw, much less from a dorsal approach, even if you are also looking for an introduction line that respects biomechanics, which is often difficult to achieve on the operating table.
Indeed, until a few years ago, applying a retrograde screw without an approach that would give you the possibility of reducing the proximal fragment, there was the risk of not correcting or accentuating the scaphoid deformity.
Although today, as we will see extensively, the reduction of the deformity of a fracture or a nonunion is part of the steps of the arthroscopic treatment, whether the fixation is retrograde or alternatively antegrade (Caloia 2020).
We can say, essentially, that the spatial approach to the scaphoid has progressively changed.

Furthermore you must still have available screws with a long or short leading thread, precisely for the purpose of stability of fixation.
Then, in retrograde fixation, we must consider the presence of the trapezium which, in some cases, can limit or even prevent, if one is not an expert, a correct application of the screw, which will inevitably lead to the failure of the fixation (Borelli 2018). Therefore always having a CT scan in the parasagittal plane is mandatory.

How to avoid the trapezium in order to introduce the screw in an appropriate way has been the subject of many proposals (Luria 2012, McCalliste 2003, Luria 2010, Borelli 2015, Bujize). Personally I use a guide with a pointed ends, which I have specifically designed for this step, which helps to dislocate the trapezium just enough for a more central placement of the screw (Borelli 2018), and it is advisable, as Zlotolow also advises (Zlotolow 2011), to perform a mini invasive approach to the tubercle for a better exposure of the ST joint and in order not to damage the palmar branch of the radial artery, aspects that I will deepen in the presentations linked to this one (see Atlas on Scaphoid Fix: https://chirurgiadellamanobrescia.it/atlas-on-scaphoid-fixation/).

However, we must consider that a transtrapezial introduction, to allow a central placement of the retrograde screw, is proposed, as an alternative in the literature (Meermans 2008, Meermans 2011, Geurts 2011).

Then we have to classify the type of deformity, which is not only in flexion, as we are used to think, but the distal fragment can also dislocate in ulnar deviation, in pronation, as well as we can have a scaphoid shortening or a translation between the 2 fragments.

We also have to know, based on the pathomechanical classification of the deformity according to Moritomo (Moritomo 2000) which pattern of associated carpal deformity we need to address to avoid residual pain.
Effectively in the volar type the pain is mostly radial, from radial-styloid impingement, a pain that can resolve itself automatically with the insertion of the graft, and if necessary, with an associated radial stylodectomy, while in the dorsal-type of deformity, DISI is less frequent, and the radial-scaphoid impingement is usually a dorsal one , and must be recognized in advance, because the pain, in this type of deformity, is not eliminated by lengthening the scaphoid, but it often gets worse.

In any case, just as we know how to correct the classic Hump Back Deformity associated with a scaphoid nonunion (Fisk 1984,

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Fernandez 1984, Fernandez 1995), we also need to know that a self-compressive cannulated screw, can initiate a series of events, such as the expulsion of the graft, the creation in fact of a malunion, and often, over the time, also cause proximal and/or distal protrusion of the screw itself, situations that can coexist and of which I will show the strategy adopted in the section of clinical cases dedicated to screw fixation failures.

In fact, the possibility of creating a malunion resulting from an initial nonunion treated with screw fixation is real even if, within certain limits, it does not seem to worsen the functional result (Putnam 2023).
Personally, to avoid these complications, I recommend using a screw with a low compression capacity, so that you can modulate the compression according to need, that is to say by making an extra turn if really needed (Borelli 2007).

But today the surgeon must also know the biomechanical features of the numerous self-compressive headless screws on the market, all born from the original Herbert screw, introduced on the market in 1984 (Herbert 1984).

Knowing the compression capacity of the screw has its rationale precisely in scaphoid nonunions, due to the obvious conditions of poor trophism of the bone tissue.
Self-compression screws have always challenged themselves to achieve the highest compressive capacity at the end of sinking into the bone (Beadel 2004, Haussman 2007, Gregory 2008) with sometimes counterproductive effects, if the fracture line is horizontal. A screw inevitably applied a little eccentric, but which compresses too much can cause a flexion deformity between the two fragments. These are undoubtedly situations that are easier to control in an open approach.

Today this problem arises in the increasingly widespread arthroscopic treatment and in particular when a self-compressive screw is used to increase the stability of fixation. An advice in this regard comes from Martin Caloia who usually uses a proximal or distal K-wire to maintain the scaphoid length during dorsal screw fixation (Caloia 2020). Or, as Nikolas Smith and Mark Ross recently advised in a discussion in World of Wrist, a self-tapping but not self-compressing screw can be used, which maintains unchanged the gap to be filled arthroscopically with cancellous graft.

Another important information comes from the CT scan which also tells us when there is a need for volar grafting, and therefore whether a retrograde screw fixation is still possible, because there is still trabecular bone in the proximal fragment in which the screw maintains its grip or if, again in the case of a volar deformity, there is the need to think of a stable fixation with Kirschner wires.
The Kirschner wires will then have to be suitably folded around the tubercle to avoid their early migration proximal or distal.
Today K-wires are often used in arthroscopic treatment, increasingly indicated in association with a graft from radius, with the intention of applying a core decompression effect, which is being talked about more and more often and which I will deal with later.

In these cases, I recommend introducing the K-wires through a mini volar approach and, once their correct introduction has been verified, folding them over the distal pole of the scaphoid and cut them close to the bending point so they can be left inside for months or even years sometimes.

Ecker also stresses the importance of aiming for a stable and solid fixation confirmed arthroscopically and of leaving the Kirschner wires in situ for 11/12 weeks. This also guarantees the bone consolidation of the proximal avascular poles in a very high percentage of cases.
And the same conclusions were reached by the French colleagues at the last GEM 2022: when Kirschner wires are used, the fixation must create situations of absolute stability for at least 3 months.

With the widening of the arthroscopic indication, the search for the stability of fixation with K-wires has stimulated the surgeon's creativity.

But let us not forget where we started from to address the problem of the stability of the fixation with K. wires: a fixation capable of healing even nonunions with associated carpal instability (Fisk 1984, Fernandez 1990).

## What is a proximal pole?

At this point we must ask ourselves the question of what is meant by proximal pole. In many of the nonunions we face, particularly those of long standing, the proximal pole is part of a complex deformity that requires a comprehensive approach to the scaphoid. Usually a proximal pole does not fall into these categories.

According to a definition of F. del Piñal we can consider that there are difficult nonunions in which there is a palmar bone deficiency to be filled after the scooping-out of the proximal fragment but which are difficult to fix by an original Herbert screw inserted through the standard volar approach: the risk of poor fixation of the proximal fragment is related to the fact that the leading thread of the screw can sink sufficiently into the bone to make a stable fixation.
The closer the nonunion gets to the junction between the middle 3rd and the proximal 3rd (Junctional nonunions), the more problems with screw fixation increase (del Piñal 2001)
Del Pinal defines them scooped-out scaphoid nonunions and junctional nonunions, both characterized by the need to have a volar gap to fill. Considering the practical difficulties of recon-

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struction and fixation, he proposed a double approach: a volar one for the reconstruction and a dorsal one for the stable screw fixation.
These nonunions differ from proximal pole nonunions proper and for which a dorsal fixation is indicated (Krimmer 1999).

We must consider that, in recent years, as already reported in the session dedicated to the biomechanical aspects, headless screws have, for the same length, long and short leading threads, precisely to better adapt to the dimensions and spatial orientation of the proximal fragment, when this must be fixed through the volar approach.

In the clinical practice we can consider 2 categories of proximal Poles, with intact or deformed external envelope. Both categories can be avascular or with vascular impairment. However, the CT always provides us with all the essential informations on how to deal with them.
But we are more frequently faced with proximal fragments/poles which have an external envelope with a normal morphology and with consequent reconstructive and fixation logics, as we have seen previously with Kierschner wires or screws.

In my opinion, if the CT shows that there is a need for a volar graft, the volar approach (saving the superficial branch of radial artery and RSC and RLT ligaments !) is a correct indication, and in any case consists in the emptying of the proximal pole, sometimes almost complete, until bleeding is evident, and in an adequate stable fixation, with Kierschner wires or screws after cancellous or corticocancellous graft from radius (For technical details: https://chirurgiadellamanobrescia.it/atlas-on-scaphoid-fixation/).

The arthroscopic approach is conceptually the same: that is to say emptying the proximal pole until bleeding become evident and performing a cancellous bone graft harvested from the radius or iliac crest. Sometimes the emptying is almost complete, but in these cases Ecker recommends always leaving a certain amount of trabecular bone useful for fixation (Ecker 2022). Today the precision achieved by the arthroscopic technique allows the fixation of even very small proximal pole. The revascularization of the graft and of what remains in the proximal pole, thanks to a stable fixation even with K wires, occurs through creeping substitution (Ecker 2022).
Of course, if there is no need for a volar graft, an open dorsal fixation and a possible bone graft from the radius certainly represents, for most surgeons, the first indication for treatment, and in any case, given the possibility of minimally invasive dorsal approaches, a correct alternative to the increasingly widespread arthroscopic approach.

I also emphasize that there are other methods, such as the scaphoid plate, well supported by the literature, to perform a stable fixation in a non-deformed proximal pole, rigorously using a non-vascularized graft (The Derby on line Teaching Pulvertaft Hand Center Webinars: Update scaphoid fractures and nonunions. Dr Pascal Hannemann, 13-6-2022 https://www.youtube.com/watch?v=uHs9S7dPBwc).

I therefore suggest to consider, in recent classifications, as regards the proximal pole also situations, which are the most frequent, in which the morphology of the proximal pole is normal, the bone tissue is not sclerotic, it is like a shell which must be filled. They are different from situations in which the proximal fragments have the morphology altered by the time elapsed.
Finally, there are very small proximal poles nonunions (basically it is a " SL intralegamentous injury"), where reconstruction does not seem possible, and the technique proposed by Marc Garcia Elias is an option that have to be considered. A sort of ligament refixation has to be performed, using a FRC tendon graft as a spacer to be inserted into the residual space. (Garcia 1998)

## The Avascular Proximal Pole. How to manage it?

When we speak of the proximal pole, the reference to its particular vascular anatomy is immediate, because the result of any treatment strategy often depends on this aspect. Studies on vascular anatomy consider a potential distribution of the intraosseous circulation also from the RSL leg (Kauer 1984, Gelberman 1980) , and fortunately quite constant, as I myself was able to verify in dissection studies of fresh cadaver limbs that I made in 1990 in the Department of Anatomy of the University of Paris. That the presence of vessels at the level of the ligamentous insertion of the RSC and RSL and volar and dorsal portions of the SL interosseous ligaments, meant a potential contribution to the intraosseous circulation had already been the subject of studies by Gelberman and Menon in 1980. This became an important factor for the potential healing of a proximal pole.
The demonstration of a proximal vascular anatomy and that this corresponds to an intraosseous blood supply has also been the subject of other studies, which those who deal with the Scaphoid are well aware of (Kuhlmann 1981, Travaglini 1959, Mestadg 1993, Buchler 1995)

In fact, recently Schmidel has proposed a so-called "anatomical" classification of the proximal pole, considering the dorsal insertion of the SL ligament to identify proximal poles that are more critical than others, just because they are supposed to lack vascularization, but this classification does not take into account the potential source from the proximal volar vessels just mentioned.

The presence of vascular supply also from the RSL ligament, provided it is small, may have its importance in the treatment strategy of fractures and nonunions of the proximal pole (Borelli 2007) because even a conservative treatment, even if obsolete

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today, could lead to the radiological healing of a proximal pole thanks to this possible source of vascular supply.
However, I believe that this "anatomical/vascular" approach can justify those MRI findings with the presence of perfused tissue in the vertex in the proximal pole which would be appropriate to identify in a preoperative MRI.
This minimal residual vascularization, which the radiographic examination does not reveal, obviously assumes great importance in the strategy of fixation.

Although there is agreement that the only reliable way to evaluate the presence of vascularization in the proximal pole is MRI with Gadolinium (Cerezal 2000, Megerle 2011), the verification of the presence of vascular supply through bleeding points is a parameter that is inevitably simply obtained at the operating table.

The importance of vascular anatomy is also confirmed by a recent work (Morsy 2019) in which, in addition to the conventional distribution of the intraosseous circulation, vessels that penetrate the scaphoid along the ligament attachments are described, studies that do nothing but corroborate the studies described regarding the possible proximal intraosseous vascularization through the RSC ligament attachment.

Obviously, it is not only this anatomical aspect that determines the primum movens of ischemia. There are other factors such as the energy and mechanism of the trauma, the degree of initial displacement and associated ligament injuries, considering that ligament injuries of a certain importance can also be associated with a non-displaced fracture of the carpal scaphoid (Loisel 2021).
Of course, what makes the treatment of a proximal fragment even more difficult is when it is part of a nonunion that does not heal (recalcitrant nonunion) and with evidently precarious vascular supply. In these cases we need to consider the biological aspect, as well as the mechanical one, if we want to save the scaphoid, as we will see in the session of clinical cases of failed fixation.
From 2000 to 2010 there was certainly a rationale in these recalcitrant proximal poles to recommend free iliac crest vascular grafts as the 1st treatment option (Doi 2000, Gabl 1999, Gabl 2009, Arora 2010, Arora 2018).

We then saw how the treatment options, particularly for avascular proximal poles and failures fixation, have widened to include pedicled vascularized grafts as well (Zaidenberg 1991, Kuhlman 1987, Mathoulin 1998, Hearle 2003, Gras 2011) among free vascularized Bone grafts (Higgins 2013, Burger 2009, Burger 2013, Shin 2001, Giele 2016), so much so as to question the use of non-vascularized grafts: for many experts on scaphoid surgery the choice of the 1st indication in case of avascular necrosis of the proximal pole nonunion was almost homogeneous (Amadio 2002, Dias 2002, Herbert 2002, Krimmer 2002, Inoue 2002).

Here are some of their opinions. "It is possible to achieve union in an avascular proximal fragment through creeping substitution and revascularization of the proximal pole, provided stable internal fixation and iliac bone graft (non vascularized) are performed (Inoue 2002)". "The presence of avascular necrosis does not affect the choice of initial treatment, but would influence the choice for re-operation (Amadio 2002)". "At first operation, the presence of Avascular does not alter our management of bone grafting and screw fixation, as we have found even in these a healing rate of 70%. However if it is the second operation we use a vascularized bone graft, preferably from the dorsum of the radius (Krimmer 2002)".

In this variegated field of options, the Innsbruk's group correlated CT and histological parameters and identified a variable intrinsic healing capacity in the bone structure of the proximal fragment which, associated with the localization of the nonunion led to the proposal of an algorithm, in order to properly choose between vascularized graft and non-vascularized graft (Schmidle 2018).

In fact what emerged at the same time from other works is that the bone can be ischemic but not completely devitalized and observing the *bleeding points* directly is certainly safer, and that the sclerotic and necrotic tissue can be replaced by cancellous bone *non-vascularized*, provided it is associated with rigid fixation. Vascularized Bone grafting therefore rarely became indicated (Rancy 2018).
In practice, the evidence is once again moving towards a treatment with *non vascularized grafts*, provided they are associated with a stable fixation. The indication for the Vascularised graft obviously remains, but is no longer absolute (Rancy 2019).

In this very recent meta-analysis on *vascularized* and *non-vascularized* bone grafts the failure rates are comparable, and the conclusion is that the non-vascularized graft could be the first choice of treatment in scaphoid nonunion, above all for the less surgical invasiveness. (Fujiara 2023)

My personal view on this topic is as follows: just as it is important to recognize that vascularized bone grafts apply valid biological principles to achieve bone union, it is equally important to understand the biomechanics of a nonunion and how to perform a stable fixation after have performed a simple cancellous bone graft, or after have corrected a deformity with a cortico-cancellous graft.
That is, the deformity of the nonunion comes into play in the choice of the type of graft: We must actually ask ourselves if we only have to fill the nonunion with a cancellous bone graft, or do we also need to correct the deformity, and with which graft: a non-vascularized bone graft? A pedicled vascularized graft ? A free vascularized graft? Everyone has a rationale for correcting an anterior deformity. Would a Zaidenberg make sense in case of a scaphoid flexion deformity? Personally in a classic intras-

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caphoid flexion deformity, that is to say an Hump Bach Ddeformity to be corrected , I would not use it.

In fact, we cannot continue to see work on the use of a single type of vascularized bone graft, the Zaidenberg in this case, reporting healing rates and functional improvement in disomogeneous groups of nonunions (Çolak 2022).

Recently the predictors of failure in scaphoid nonunion surgery with vascularized and non-vascularized grafts have been analysed: Hump Back Deformity and DISI represents a risk of failure for vascularized grafts, while avascular necrosis increases the risk of failure for both type of grafts (Rancy 2022).

We must recognize that the correction of the Hump Back Deformity and DISI is more complicated in a free VBG, for obvious reasons, while, even in the presence of HBD and avascular necrosis, thanks to a stable fixation, the conditions for a consolidation can be created.

Since some years, we have noticed that the need for a preoperative diagnosis of avascular necrosis with MRI has decreased with the diffusion of the arthroscopic technique: as already mentioned, a proximal pole is often almost completely emptied, up to the onset of bleeding and therefore, a preoperative diagnosis of vascular or avascular pole what difference does it make ? (Jeff Ecker, FESSH 2016 Santander)

In arthroscopy the steps are now codified, regardless of the preoperative imaging, and are: localization of the nonunion, the debridment of both fragments, until a bleeding tissue become evident, of particular importance obviously in the proximal fragment. We must underline that the intraoperative verification of the presence of bleeding in the proximal pole is recommended by some, even without a tourniquet to be sure that there is really no bleeding (Mikko, World of Wrist, July 9th, 2023).

Regarding the current management of waist and proximal pole nonunions, on how to evaluate the deformity and residual vascular supply, and what type of bone graft is indicated in the daily practice of wrist surgeons, there was an interesting discussion on the World of Wrist chat, which I will repost separately.

After all, these concepts had been known since 2011 thanks to the paper of Clara Wong and PcHo (Wong 2011).
PcHo and Wong at the IFSSH 2019 in Berlin reiterated that avascular necrosis of the proximal pole is no longer a contraindication for arthroscopic treatment and that K-wires do not compromise the result. Moreover, the procedure can be repeated several times if it fails, and just in failures it represents a valid alternative to vascularized grafts (PcHo 2019).

But there was also a turning point in open surgery: Scott Wolfe argued that bone healing can also be achieved in practice with non-vascularized grafts, even taken from the radius provided, as I have already underlined, it is associated with a rigid fixation. A vascular graft becomes rarer as an indication. Certainly remains a prerogative of the Surgeon, with its obvious rationale, but the NVBG graft from radius also begins to have another potential role: it also allows the application of a biological principle: the Illarramendi effect, as defined by Scott Wolf (Wolf FESSH 2016, Wolf FESSH 2018)

## BIOLOGICAL CONSIDERATIONS

I presented my experience on Core Decompression at FESSH 2018, in 13 patients, all with the need for a volar graft, but above all with a proximal pole considered avascular by the absence of bleeding on the operating table. I had emphasized that, with a precise technique, a good structured bone graft can also be obtained from the distal radius.
In that congress context I presented cases with evident vascular impairment and where screw fixation was still biomechanically possible, but only using a screw with a short leading thread. Bone healing was obtained in practice by associating the stability of fixation with a double biological contribution: Core Decompression and Bone Growth Factors Stimulation, which I routinely use in such cases.
In that congress context I presented also cases where the lack of bleeding seen at the operating table required complete emptying of the proximal pole. In such a situations the outer envelope remains intact and must be filled with cancellous graft taken from the radius. In these cases, bone consolidation is obtained by also relying on the biological contribution of Core decompression and Bone Growth Factors Stimulation and on stabilization with Kirschner wires, applied with the particular care not to create any functional limitation or discomfort, even for years. For the technical details of the fixation with K-wires refer to this link https://chirurgiadellamanobrescia.it/atlas-on-scaphoid-fixation/.
In my conclusions I underlined that the fixation with K-wires made the open procedure correlated to the arthroscopic one, but with the particularity that taking the graft from the radius (unlike ABG in which the iliac crest, at that time, was used as the source of the graft), we could also have a further stimulus to bone regeneration thanks to Core Decompression. Moreover using Medical Devices able to induce Bone Growth Factors through non-ionising Electric Fields utilized for therapeutic purposes, called biophysical stimulation, would seem to trigger a further biological input (Borelli 2018).

We also have to consider that we are not always faced with a proximal pole but with a proximal fragment, with its deformity well known, and to be corrected. Also in these proximal fragments the problem of the residual blood supply is of vital importance. The radiological parameter certainly has its rationale (Keller 2020), but I believe that even in these cases the parameter

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of direct bleeding from the bone tissue being treated, could give more practical information to the reconstruction strategy.
In fact, as already mentioned earlier, there is still no consensus on the methods that allow us to make a certain diagnosis of avascular necrosis, and therefore to support the use of a vascularized or non-vascularized graft to improve an outcome for which, we know, there are many other risk factors of failure (Higgins 2021)

There is also another aspect to consider: a vascularised bone graft from the femoral condyle can also be proposed with the intention of removing the nonunion "en bloc", in order to eliminate other problems of bone conflict as well, with its own rationale, but still addressing the problems of the challenging surgical approach (Jones and Shin 2010).

However, in this regard, we must also consider the level of skill achieved in reconstructions with the free vascularized osteochondral graft: conceptually the whole nonunion and the proximal portion of the scaphoid is replaced with the aim that the subchondral perfusion of the VBG graft offers a better condition to the cartilage which is exposed to the intrasynovial environment (Higgins 2020).
Or with the aim of replacing that part of the body of the scaphoid before it occurs, if not replaced by the vascularized osteochondral graft, arthritic degeneration, associating if necessary also radial styloidectomy to also eliminate bone impingement origin of pain (Crepaldi 2022).
Basically, the literature teaches us that there is always a rationale in support of a reconstructive strategy in the carpal scaphoid, especially regarding the biological aspect.

So what is the evidence up to 2023 on the biological strategies which, in carpal scaphoid nonunions with critical or absent vascular supply, can implement the bone healing process? Lets deal with them one by one.

## Is there a Role for Core Decompression in Scaphoid Nonunion surgery?
## Is there a role for Bone Growth Factors Stimulation?
## Is there a role for synthetic rhBMP2?

The first aspect to consider and also to understand, precisely because of the growing use of *Core Decompression* in scaphoid surgery is what role there really can be. In fact, even if we have known for some time the effect of *Core Decompression* on local hyperemia (Illarramendi 2001), what really is the basis of the good and lasting clinical results has stimulated the interest of the literature also on the biomechanical aspect of *CD*, because a real decompression effect on the lunate could not be demonstrated (Sherman 2008).

In the past, *Core Decompression* has been compared to other techniques indicated for the same stages of Kiembock's disease and with the same pain relief effect. The only common mechanical aspect was the violation of the bone cortex (Lindsay 2010, Blanco 2012).
According to De carli, however, there is a biological effect which depends on a vascular response on the carpus which can last for many months, as demonstrated by scintigraphy (De Carli 2017).

On the cascade of events that this vascular response triggers at the cellular level and on the endogenous growth factors involved in the whole process, including the BMP2 morphoprotein, he had already spoken at the FESSH Congress 2016 in Santander, with a rich supporting literature which originated from Urist's studies (Urist 1965) of bone formation by self-induction, and on the stimulation of *endogenous bone regeneration growth factors*, such as the rhBMP2 morphoprotein.

Osteonecrosis of the femoral head has been a field in which to evaluate the role and potential of growth factors, triggered by the process of bone necrosis itself (Mont 1998). Anything that stimulates local angiogenesis, such as hyperemia for example, triggers the action of *endothelial growth factors* which have a direct effect on *osteoprogenitor cells* (Keramaris 2008). The *morphoproteins BMP2 and BMP7* have also been shown to have a beneficial effect on the bone healing process (Simpson 2006).

There is increasing evidence that angiogenesis is a vital component of the bone healing process. Formation of new blood vessels facilitates osteogenesis thanks to the activity of progenitor cells. At the cellular level, many growth factors are involved in the physiological process of forming new blood vessels (Pountos 2014), and therefore *a dual approach* with *endothelial and bone growth factors* could be ideal for bone regeneration.

Greg Bain returned to the topic with the rationale of his algorithm on the Kiembock but also with an intriguing philosophical approach to *Core Decompression*, better definable today as "*radial forage*" which leads us to consider a softer and more multimodal approach of which we will have more details soon (Bain 2023).
In his report on the subject at FESSH 2023, De Carli tried to give an explanation to the mechanism of action of the "*radial forage*" with a term that reinforces the original explanation, i.e. a real *"vascular storm"* takes place which activates, in turn, a biological cascade, which will lead to the activation of those growth factors, including BMP2, he was talking about at the FESSH 2016 in Santander.

But we must emphasize that even the *biophysical stimulation*, which I have routinely associated for years with scaphoid reconstruction surgery, in addition to the well-known *local anabolic factors* (osteogenetic, chondrogenetic, angiogenetic),

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activates the production of *endogenous growth factors*. (Aaron R. 2004). Biophysical stimulation is known to play a key role in the production of local growth factors, including BMP2 (Martini F. 2020, Bloise N. 2020). Indeed, the use of physical energy to modulate the osteogenetic response and ultimately to improve fracture healing has been a widely studied topic worldwide for several years (Massari L 2019).

It is certainly interesting to note how both *Core Decompression*, or rather *Radial Forage*, and *biophysical stimulation* activate the same biological cascade which leads to the production of endogenous growth factors.

Biophysical stimulation has long been considered a useful therapy in all situations where bone induction is required to stimulate the biologic processes of bone healing (delay or failure of union) or to improve autologous cell-based regeneration of bone defects. It has been shown that it is able to stimulate an early osteogenic induction in both BMSCs and ASCs (mesenchymal stem cells isolated from bone marrow and from adipose tissue) (Ongaro A. 2014). It can be applied repeatedly and easily in anatomical sites where a controlled synthesis of endogenous growth factors, such as the bone morphoprotein BMP2, is a desirable biological contribution. (Wang Z. 2006)

But are there other factors that can participate in promoting the bone healing process in scaphoid surgery? We know that *biotechnology* has consolidated its role in the orthopedic field, precisely in the problems of bone tissue healing, in the *synthesis of growth factors*, *such as BMP2*, in the production of growth factors such as enriched plasma, or mesenchymal cells or various types of scaffolds (Calori 2010).
Thus, in parallel with biophysical stimulation, we can also consider the world of biotechnology and tissue engineering. Since 1965, *synthetic growth factors* have been studied, which can act directly in the sites where a healing process is particularly difficult. For now, however, there is FDA approval for clinical use in a specific orthopedic field (Mumcuoglu 2017).

A recent review clarifies the process of local bioactivity linked to the in vivo ectopic application, at the site of the lesion, of the morphoprotein BMP2. It is still object of study in the orthopedic field, but of great interest (Mumcuoglu 2017).
But, if we remain in the field of carpal scaphoid nonunion, we have known for some time that the nonunion tissue cells maintain an intrinsic osteogenetic capacity and that this capacity can be stimulated by *synthetic growth factors* such as the "recombinant human" morphoproteins BMP2, which potentially further enhance this intrinsic healing ability (QU 2008), and based on this action the implantation of rhBMP2 had been proposed in the arthroscopic treatment of scaphoid pseudoarthropsis by PC HO at 14th IFSSH 2019, in Berlin (Ho 2019).
Precisely thanks to the clinical experience gained in the orthopedic field (Polmear 2021), the use of *synthetic BMPs* has also extended to scaphoid surgery and the related literature has recently been the subject of a recent systematic review. In addition to the literature review, in the same work 21 patients with primary nonunion or review of failures were treated with *synthetic BMP2* and the healing rates and also the complications were analysed, in particular the dreaded heteroptopic ossification, which occurred in a very low percentage (Polmear 2021).

Moreover the interest on the role of *synthetic BMP2* in compartment regeneration is undoubtedly growing exponentially also in other fields, such as the repair of the SL ligament complex (Lui 2023).

*BIOPHYSICAL METHODS* was approved for clinical use by the U.S. Food and Drug Administration in 1979 and are employed in many countries to promote and reactivate the formation of bone tissue (Basset CA Jama 1982). The medical devices, called *BONE GROWTH STIMULATORS*, have been shown to be effective by international consensus, in critical cases of bone healing. (Fig.1,


Fig.2, Fig.3, Fig.4)

The international orthopedic community has played a central role in understanding the mechanism of action and the clinical importance of the biophysical stimulation, precisely with the clear advantage of being able to be applied locally, where needed, simply and without side effects (Massari 2019).
It should also be reported that a recent systematic review and meta-analysis underlined a particular role of biophysical stimulation on stem cell activation and therefore also a possible support for tissue engineering while concluding that further research is needed necessary to evaluate the effective efficacy in the clinical setting (Mansourian 2021). This study underlines the role of cell type and signal characteristic parameters, which were of high importance for targeted therapies using physical stimuli. In this regard, the Italian orthopedic community has teamed up to create a focus group on the clinical use of electrical stimulation

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in orthopedics and traumatology (Massari L 2017). An article was published from the meeting that states that "Therapy with a medical device for the electrical stimulation of osteogenesis and chondroprotection must ensure:

- the electrical safety of the device;
- biological safety, understood as the absence of side effects;
- the effectiveness of the device in the specific pathology, demonstrated by clinical studies;
- the absence of specific contraindications for the patient who will have to use the medical device".

The early use of *Bone Growth Factors stimulators* in the post-operative period of complex wrist fractures is increasingly widespread in clinical practice to avoid delayed union TO lead to a shorter immobilization, thus allowing an earlier return to daily life activities and work (Factor S. 2023).
It is widely used to treat bone marrow edema or Complex Regional Pain Syndrome (CRPS-1)(Notarnicola A. 2021) when it appears inexorable (Borelli 2017), so much so that today the early clinical application of Bone Growth Factors *stimulators* is considered, more and more often as a biological contribution in the presence of nonunions or delayed consolidation of difficult fractures (De Francesco F. 2022). Its efficacy has been proven in prospective, randomized, double-blind, placebo-controlled trials (Peng L. 2020), sometimes coming, in particular situations, to be considered a possible alternative to surgery (Pfanner 2022).

However, to return to the carpal scaphoid, systems that stimulate the production of bone growth factors can be a further substantial biological contribution, in addition to core decompression, in the treatment of scaphoid vascular nonunions or nonunions with poor blood supply and above all, in my experience, also in avascular nonunions of the proximal pole (Borelli 2018). Indeed, it has been reported by some authors that hip survival is significantly higher in patients who are managed with core decompression plus biophysical stimulation compared with patients who are managed with core decompression alone ($p = 0.01$) (Steinberg ME 1989, Aaron RK 1898, Massari L. 2006). Thus, biophysical stimulation should be considered as an ancillary adjunctive treatment to surgical treatment for both early and later stages of osteonecrosis or nonunions, not only of the femoral head, but also of carpal scaphoid.

We can therefore arrive at the following considerations: the biological phenomena activated by hyperemia in conditions in which the bone cortex is violated, as precisely the "*radial forage*" of De Carli, or activated by *biophysical stimulation*, together with the *osteogenic capacity* of the cells of the nonunion itself, in turn enhanced both by the biophysical stimulus and by ectopic growth factors, all this in addition to the possible sparing of the blood supply thanks to increasingly less invasive surgical approaches or thanks to the arthroscopic approach, *associating a stable fixation*, create conditions more and more favorable to bone healing, even when the blood supply in the proximal pole is critical.

## CURRENT METHODS OF CARPAL SCAPHOID NONUNIONS TREATMENT

### What is the current trend for Radial Forage, Arthroscopic Bone Grafting, Open Bone Grafting in the treatment of carpal scaphoid nonunions?

Today, applying the concept of *Core Decompression* to scaphoid nonunion is frequently found (Dedeoglu 2017), even when the bone graft harvesting site is dorsal (Schriber 2018).
Even if it should still be considered empirical, as underlined by De Carli himself (Rellan 2019), resorting to this method is increasingly widespread in scaphoid surgery.
It must also be said that, precisely thanks to the affirmation of wrist arthroscopy, considering the potential role of *Core Decompression* has become almost automatic, even in particularly unstable nonunions (Caloia 2020). Whether it is the cortical violation that triggers the " vascular storm" on the carpus, as De Carli hypothesizes, we have to agree that today it is to be considered a biological concept that applies perfectly in cases of unstable nonunions and failed Scaphoid nonunion surgery (Caloia 2020).

The arthroscopic approach has also changed the spatial approach to carpal scaphoid nonunion. Today, in expert hands, HBD is no longer a contraindication. The reduction maneuvers of arthroscopic treatment are now codified steps, not always easy to perform, even if we have to recognize with positive functional effects (Delgado 2022), but we have to admit that this is the limit of arthroscopic treatment compared to the "open" technique as regards the recovery of the anatomical reduction. The Delgado's approach represents for me the perfect conjugation between 2 different ways of tackling the same problem with evident rationality: the approach of the Innsbruk's group is conjugated to the present that is advancing more and more, the arthroscopic approach, whether it is a nonunion of the waist where the screw fixation is retrograde and the biological input comes from *radial forage*, or whether we are dealing with a proximal pole with the most critical of the vascular conditions, according to Schmidle's classification, where the screw fixation will be anterograde, and the biological input can in any come from *radial forage*.

Let's say that faced with a complex scaphoid nonunion, where we all have one goal, that is of aiming at bone consolidation, the parameters for setting up the correct reconstruction strategy are always the same: aim at anatomical reduction, at stability of the fixation , at choosing *the most appropriate bone graft* and then

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at implementing all that the evidence can provide us in terms of *biological contribution*.
To achieve consolidation, the ingredients are always the same, the doses change according to the case we are facing, which perhaps sometimes requires more biological stimulus than in other situations.

Choosing between the open or arthroscopic technique remains a surgeon's choice, the objective is in any case to achieve bone consolidation. Certainly the open technique, in which the interpositional graft is modeled as needed, allows, in my opinion, an easier anatomical reduction of the deformity.

In this regard, however, we must acknowledge Gublev, an expert arthroscopist, for an interesting critical observation on the Linsheid maneuver, which in any case presupposes an intact ligament complex. In fact, a corrected lunate position does not necessarily mean the correction of the scaphoid deformity, this is because an associated ligament injury is always to be considered (Gublev, Wrist academy 2022).
And another trick of surgical technique can be attributed to Gublev: namely that of practicing a *direct volar portal*, thanks to which to work directly inside the nonunion. Through this *direct volar portal* it is possible to introduce a Mosquito with which to lengthen the scaphoid by opening the branches of a mosquito, then checking the insertion of 3 K-wires, which serve to keep the scaphoid lengthened and stable during the insertion of the cancellous bone graft taken from the iliac crest (Gublev, Wrist academy 2022).

## What is the opinion of World of Wrist on these issues?

The discussion on a case of failed screw fixation (WoW April 16th 2023) was really very interesting due to the patient's age, his functional needs and because according to Literature Evidence there were all the parameters to indicate a Vascularized Bone Graft.

Let's look at the options considered and reported individually in the presentation.
For the most part the indication was ABG relying on the Core Decompression, on stable fixation with K-wires or with a screw, as an alternative to open fixation with a dedicated plate.
In any case, apart from one indication for a volar pedicled vascularized graft, there were no indications for free vascularized bone grafts.
In practice it was interesting to note that in a condition in which vascularised bone grafts were the first indication up until a few years ago, now the strategy is divided between arthroscopic and open surgery, the bleeding points and areas of bleeding are always looked for, the DISI is obviously corrected with arthroscopic manouvres, the maximum stability of the fixation is sought, and the concept of *core decompression* or, better defined today, *radial forage* is applied to increase the percentage of consolidation.

Basically in a *difficult proximal nonunion* (such as a failed screw fixation, the subject of the WoW discussion) the current trend is: mostly arthroscopic bone graft from the radius, *radial forage* and stable fixation with K-wires or screws or alternatively non-vascularized cancellous bone graft and plate fixation.

## Which news or tips on the choice between vascularized and non-vascularized bone grafts did we receive from FESSH 2023?

From Lucian Marcovici, whether it is a non-union of the proximal pole without deformity but with poor blood supply or a waist non-union with deformity, today arthroscopy associated with *radial forage* is a valid treatment option.

From Mireia Esplugas an anatomical study and some recommendations relating to the *direct volar portal* to the scaphoid, as we have seen now widespread among arthroscopy experts in the chat of World of Wrist, because it allows a good view of the condition of the proximal pole bone tissue, of the condition of the cartilage and a good control of the bone graft. In order to avoid iatrogenic injury she recommends a small longitudinal incision on the distal wrist crease.

From Fernando Corella the usefulness of the *direct volar portal* with which arthroscopy has gained a complete spatial approach towards the scaphoid. With a necessary learning curve it is possible to performe a more accurate debridment and to introduce a graft from the volar side, as occurs in the open approach.

Again from Fernando Corella the message that, in the indications in which the literature still proposes a vascularized bone graft, with its own rationale, i.e. in an avascular nonunion of the proximal pole, today one can opt for an arthroscopic graft and dorsal fixation, as an alternative to vascularized bone graft.
As well as in recalcitrant nonunions, where the literature indicates a vascularized bone graft, as the 1st treatment option today, the arthroscopic assistance can cover all the stages of treatment, from screw removal, reconstruction with non-vascularized cancellous bone graft, to a stable fixation, even retrograde. Even in these cases, arthroscopic bone grafting may, in practice, be an alternative option to vascularized bone graft.

We also got from Jeff Ecker the message that in failures of screw fixation, through 1 single operation you can perform any steps: arthroscopic confirmation of nonunion, removal screws or K wires, arthroscopic bone graft and new fixation. According to Ecker, arthroscopically treated proximal poles almost always heal

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In particular from Ecker came the message that the arthroscopic technique allows an accurate and complete diagnosis of nonunion in all its spatial aspects, in one shot, so as to perform diagnosis and treatment in a single operation.

From Delgado the message that we have to face the biomechanical problem of the stable fixation also with K wires.

From Rohit Arora that we must always remember that there is also a biological aspect to consider when deciding on the type of graft. Rohit deems it preferable to follow the indications for the vascularised bone graft from the femoral condyle, according to the classic indications: a Proximal Pole with Avascular Necrosis (AVNPP) , even without HBD, a long-standing AVNPP with HBD, a long-standing Nonunion with previous failed surgery and in long-standing nonunion with bone loss and fragmentation.

Basically, there is no doubt that vascularized bone grafts are based on a biological principle, but we must recognize that often the fixation in a VBG must pay a price, that is, fixation must adapt to the biological aspect, it must respect the vitality of the graft, and often, without being able to follow the biomechanical stability parameters of the fixation without endangering the vascular supply of the graft itself.

In my opinion, non-vascularized grafts, with open or arthroscopic surgery, more easily allow a stable reconstruction, based on biomechanical principles, to achieve bone healing in difficult nonunions (unstable, avascular, recalcitrant or failed surgery). In these cases, certainly, a *biological contribution*, whether it is Core Decompression/*radial forage* or *Bone Growth Factors stimulators*, can undoubtedly be of great help.

In this regard, an important message came from Corella in the last session of the FESSH 2023 Congress, when he presented the last frontier: his experience in the reconstruction of a nonunion with a *free vascularized bone graft and arthroscopic assistance*. Why ? According to Corella, in general, reconstruction with a free vascularised bone graft has 5 disadvantages: 1 the donor site morbidity, 2 the need for a big approach in the wrist, 3 the difficulty, in long-standing nonunions, in reducing the deformity, 4, probably the major limitation for the comparison with other types of graft, is precisely the thickness of the soft tissues covering at least one side of the bone graft. This makes it very difficult, in the step of inserting the graft in the volar gap, to understand how the volar bone defect is actually corrected.
Lastly, the difficulty of performing a microvascular anastomosis of artery and vein, a technique only for super experts.

Corella shows, with 2 cases, these difficulties in a reconstruction with a classic microvascular vascularized bone graft from the femoral condyle: the reconstruction pays an important price to the morphology of the proximal portion of the scaphoid, as can be seen from the 2 cases of his presentation. The problem is precisely the proximal reconstruction, in terms of both stability of fixation and respect for the morphology: of course, the biological contribution is certainly important, but we have to deal with reality. From the 2 cases given as examples it can be seen that microsurgical needs require a price to pay.
That's why Corella wonders if we can improve these technical difficulties with arthroscopic assistance showing us 2 more cases of failed fixation, treated precisely with free medial femoral condyle graft and arthroscopic assistance in which, saving the scaphoid was undoubtedly difficult, as evident from the related images, but it was an absolute must. I totally agree on this aspect: in young patients with functional needs let's save the scaphoid, we are always in time to sacrifice it.

I would like to finish this review with this consideration by Greg Bain: " *we are in a moment of revolution with so many proposals that the most important aspect is to reflect "*.

## CONCLUSION

Essentially from this analysis of the literature and of scientific contexts there is no evidence that vascularised grafts give better results than non-vascularised ones. My advice:
-Use the graft and the surgical technique with which you feel most familiar,
-Use the CT scan (Cone Beam if possible) to identify the best approach and whether to perform a cancellous graft alone or a cortico-cancellous graft.
-It is Important that fixation and reconstruction are stable for at least 3 months to have revascularization according to creeping substitution of a possible proximal avascular pole and of the avascular bone graft itself.
-Associating a biological input is highly recommended (*Core Decompression/radial Forage ? Biophysical stimulation* ? *Both, why not* ?)

In conclusion, in the light of the current Evidence, I believe that in even difficult scaphoid nonunions (Avascular proximal fragment/pole or failed fixation) a stable fixation and a non-vascularized graft represents a correct indication. The biological contribution thanks to *radial forage* and *biophysical stimulation*, intended as Bone Growth Factors stimulation, is certainly of great benefit.

Thank you for your attention, hoping that this review of the evidence on a topic that is still much debated will be useful.

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