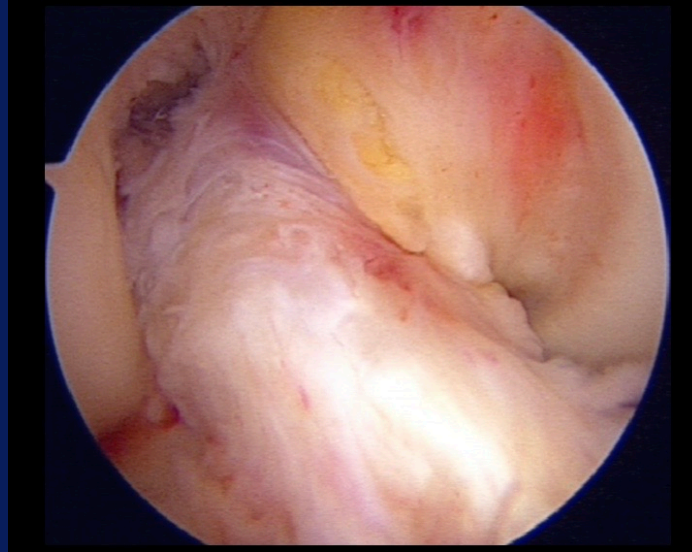


# Healing process to Ligamentization



*François Kelberine*  
*Aix en Provence & Gap*  
*France*

# Biologic process of maturation

## 3 phases

*Abe Arthroscopy 1993*

*Zaffagnini The Knee 2007*

*Menetrey KSSTA 2013*

*Chu Orthop J Sport Med 2019*

*Yao Asia Pacific J sport Med 2024*

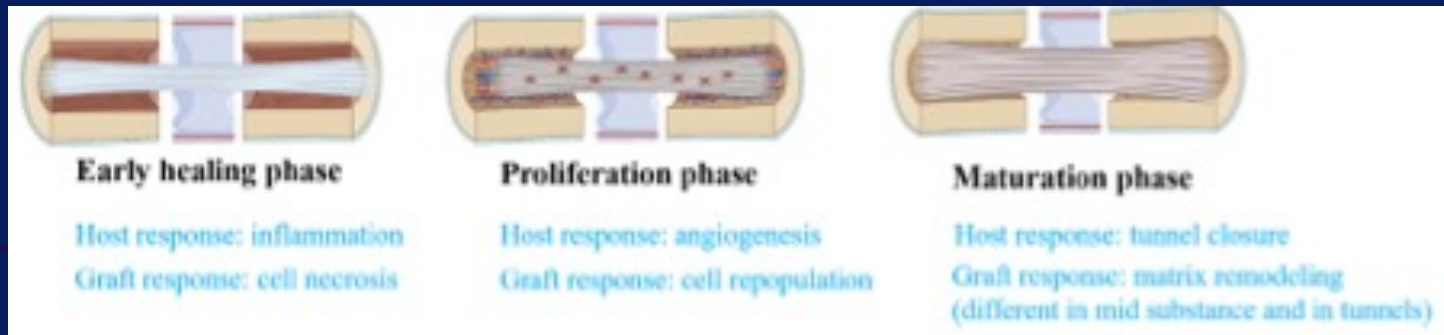
### ✓ Early healing

(Inflammatory response, necrosis, revascularization)

### ✓ Proliferation

(Cell repopulation, Collagen remodeling)

### ✓ Maturation



# Animal studies

## ✓ Graft remodeling to ACL-like structure

- ✓ 30 to 40 weeks almost native ACL
- ✓ Proteoglycan & collagen type III

*Amiel J Orthop Res 1986*

*Mayr KSSTA 2011*

## ✓ Synovial fluid nutrition

## ✓ Influences biomechanical properties

- ✓ Dog 40% @ 4 months
- ✓ Goats 50% @ 3 years
- ✓ Rhesus Monkey 80%

*Clancy JBJS 1981*

*Mac Farland Am J Sport Surg 1986*

*NG Gy J Orthop Res 1995*

## ✓ Analogy to human!!

- ✓ Much more longer

*Pauzamberg Syst Review*

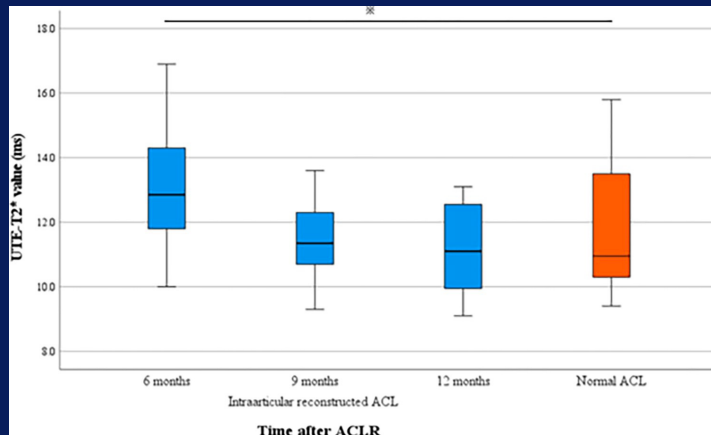
*Niki J Orthop Surg Res 2019*

*Warth Am J Sport Med 2020*

# Biologic process of maturation

✓ Timeframe from 6 month to 9 years!!

Never normal ACL



*Abe Arthroscopy 1993*

*Zaffagnini The Knee 2007*

*Claes Am J Sport Med 2011*

*Janssen KSSTA 2014*

*Chu Orthop J Sport Med 2019*

*Mayr Orthop Surg 2020*

*Yoshimitzu Plus One 2022*

✓ Consequences

✓ Graft fixation choice

✓ Optimal rehab

✓ Re rupture risk

*MARS cohort AM J Sport Med 2010*

# How to assess maturation?

Von Groningen Arthroscopy 2020

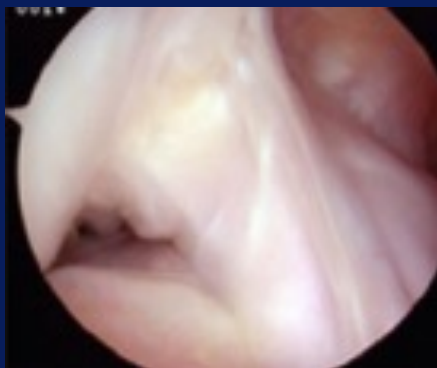
## ✓ MRI (Signal to Noise Quotient)



Howell *Am J Sport Med* 1991  
Li *Orthop J Sports Med* 2014  
Yau *Am J Sport Med* 2023

## ✓ Second look Arthro

- ✓ Synovialization
- ✓ Vascularization



Nakamae *Bone J Letter* 2014  
Lee *Arthroscopy* 2010  
Yoo *KSSTA* 2017

## ✓ Biopsy

- ✓ Stop @ 18mths
- ✓ ≠ native ACL
- ✓ No mechanoreceptors

Rouhgraf *Am J Sport Med* 1993  
Shino *Am J Sport Med* 1995  
Zaffagnini *The Knee* 2007  
Pauzamberg *Syst Review*  
Kim *Am J Sport Med* 2014

# How to assess maturation?

## ✓ Biological synovial fluid markers

- ✓ Nutrition and/or inflammation

*Chu J Orthop Res 2021*

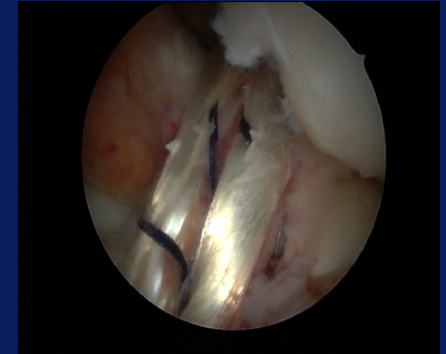
## ✓ Instrumental testings (KT 2000)

- ✓ Mechanical properties of graft
- ✓ Loss of stiffness of ACL graft
- ✓ Compliance =  $1 / \text{stiffness (mm/N)}$ 
  - Slope between 2  $\neq$  loads
  - Increase slope = insufficient graft

*Landreau Close Meeting ISAKOS 2013*

# Human / Influencing factors

✓ Smokers



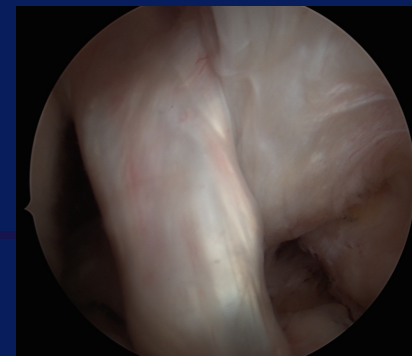
✓ Bone vascularity

✓ Type of graft : no data / timeframe of ligamentization related to autograft

✓ Allograft

*Muller Clin Sport Med 2013*

✓ Dynamic rehab +





# Remnants

✓ Experimental (rabbit)

*Lu Bone J Res 2023*

✓ Synovialization

*Adachi Arch Ortho Trauma Surg 2000*  
*Noh KSSTA 2017*

✓ Mechanoreceptors?

*Crain Arthroscopy 2005*  
*Lee KSSTA 2009*



# Adjuvants

## ✓ MSC

- ✓ Fibrin glue
- ✓ Within the graft

## ✓ PRP



*Sanchez Arthroscopy 2010*  
*Hexter Bone Joint J 2018*  
*Mifune Biomaterial 2013*

## ✓ Autologous Tissue Engineered (rabbit)

*Cai Ann Trans Med 2021*

# Conclusion = Clinical relevance

- ✓ Difficulty to assess ligamentization

- ✓ Optimization of surgical techniques

*Moretti J Clinical Med 2022*

- ✓ Improvement in rehab strategy

- ✓ Early RTS = risk of re rupture

*Salmon AJSM 2006*

*Laboute Ann Physio Rehab Med 2010*

- ✓ MRI higher signal increased risk of rerupture (7m to 9 y FU 565 cases)

*Yau Am J Sport Med 2023*