

# Modélisation & simulation du comportement du complexe peau / tissu sous-cutané en chirurgie plastique d'augmentation tissulaire

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*Thèse de Sciences*

*EA2415 - I2S - Biostatistique*

*16 décembre 2014*

# Pourquoi l'augmentation tissulaire ?

L'augmentation ou la restitution des volumes corporels représente une activité importante et en **constante progression**

en chirurgie reconstructrice

en chirurgie esthétique



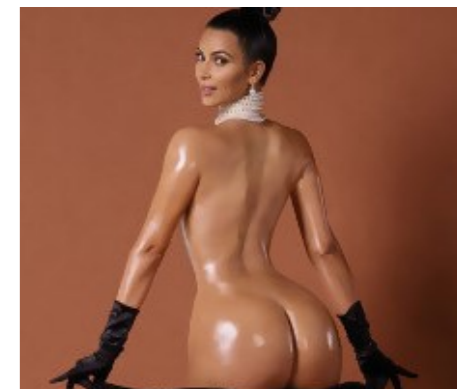
Cas Pr Sinna



Rohrich RJ 2013



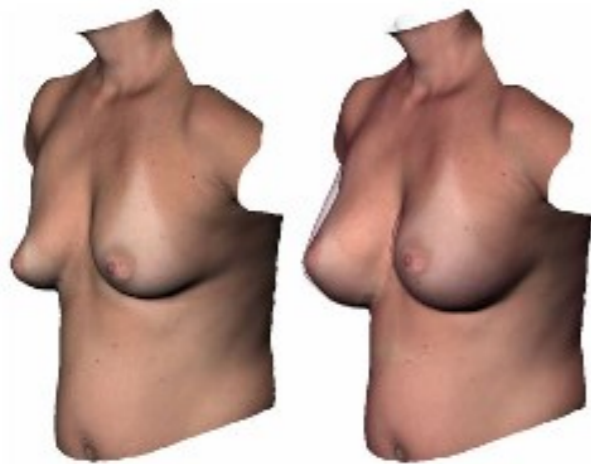
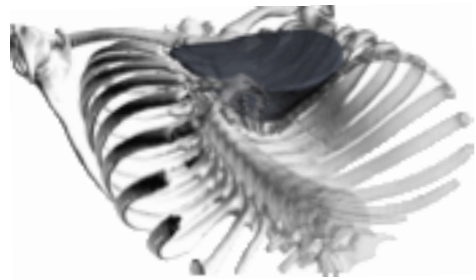
Nelligan P. 2013



# Qu'entend-on par augmentation tissulaire ?



**Implants**



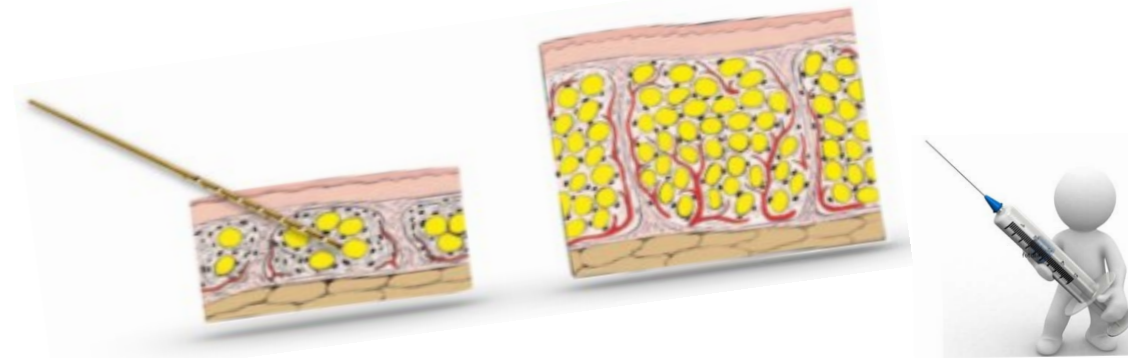
Jacono et al. 2015



Cas personnel



Cas Pr. Sinna



**Autogreffe adipocytaire**



Source net



Cas personnel

# Pourquoi un outil de simulation ?



# Pourquoi un outil de simulation ?



**1 séance, 15 cc de graisse**



Palua N. et al. 2014

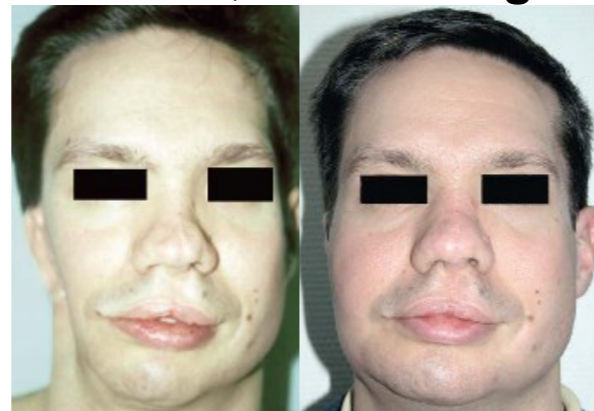


**1 séance, 25 cc de graisse**



Mojallal et al. 2012

**3 séances, 110 cc de graisse**



Mojallal et al. 2012

**Expansion puis prothèse, 500 cc environ**



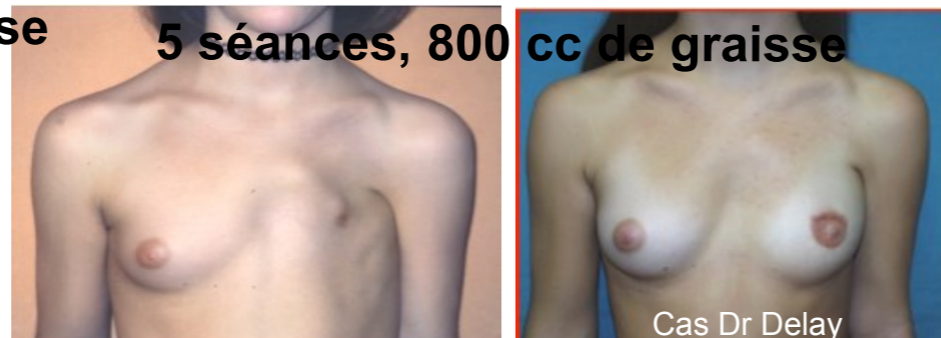
Masson J. et al 2007

**2 séances, 220 cc de graisse**



Cas personnel

**5 séances, 800 cc de graisse**



Cas Dr Delay

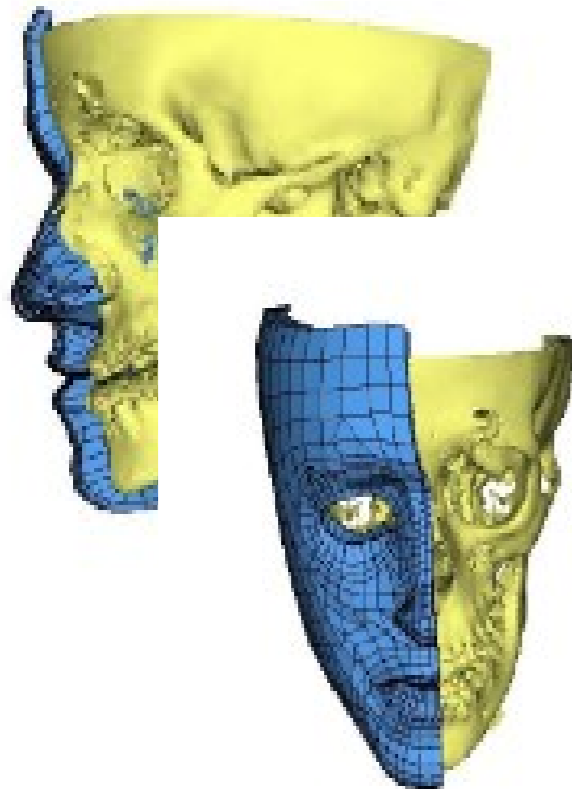
**Prothèse, 250 cc environ**



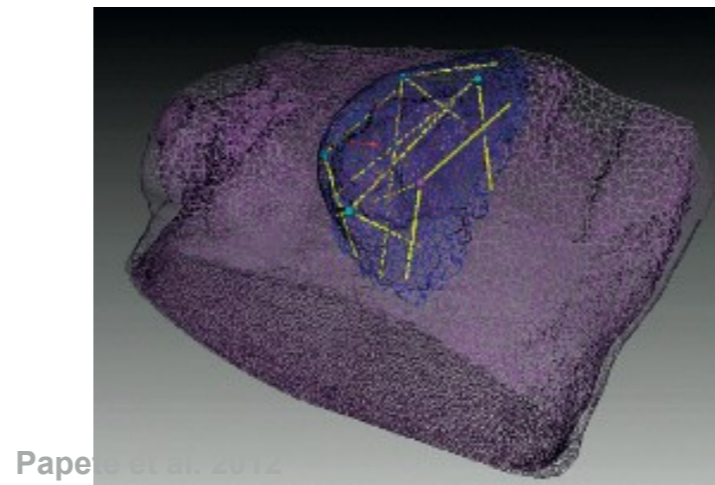
Cas Pr Chavoïn



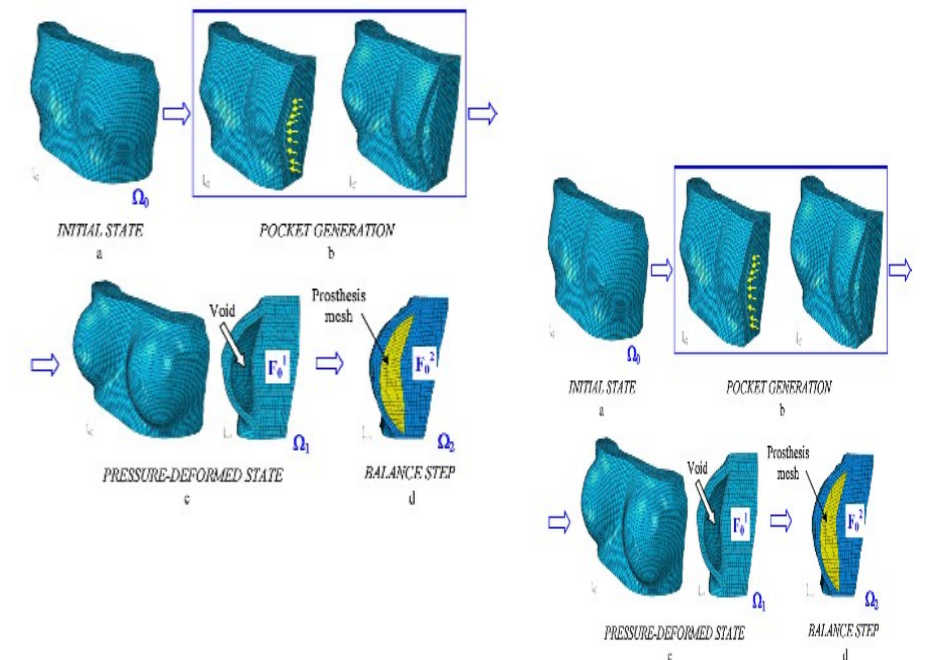
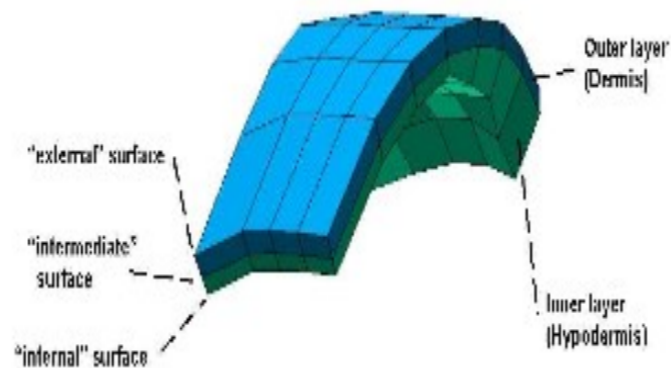
# Comment simuler une augmentation tissulaire ?



Chabanas et al. 2003.



Pape et al. 2012

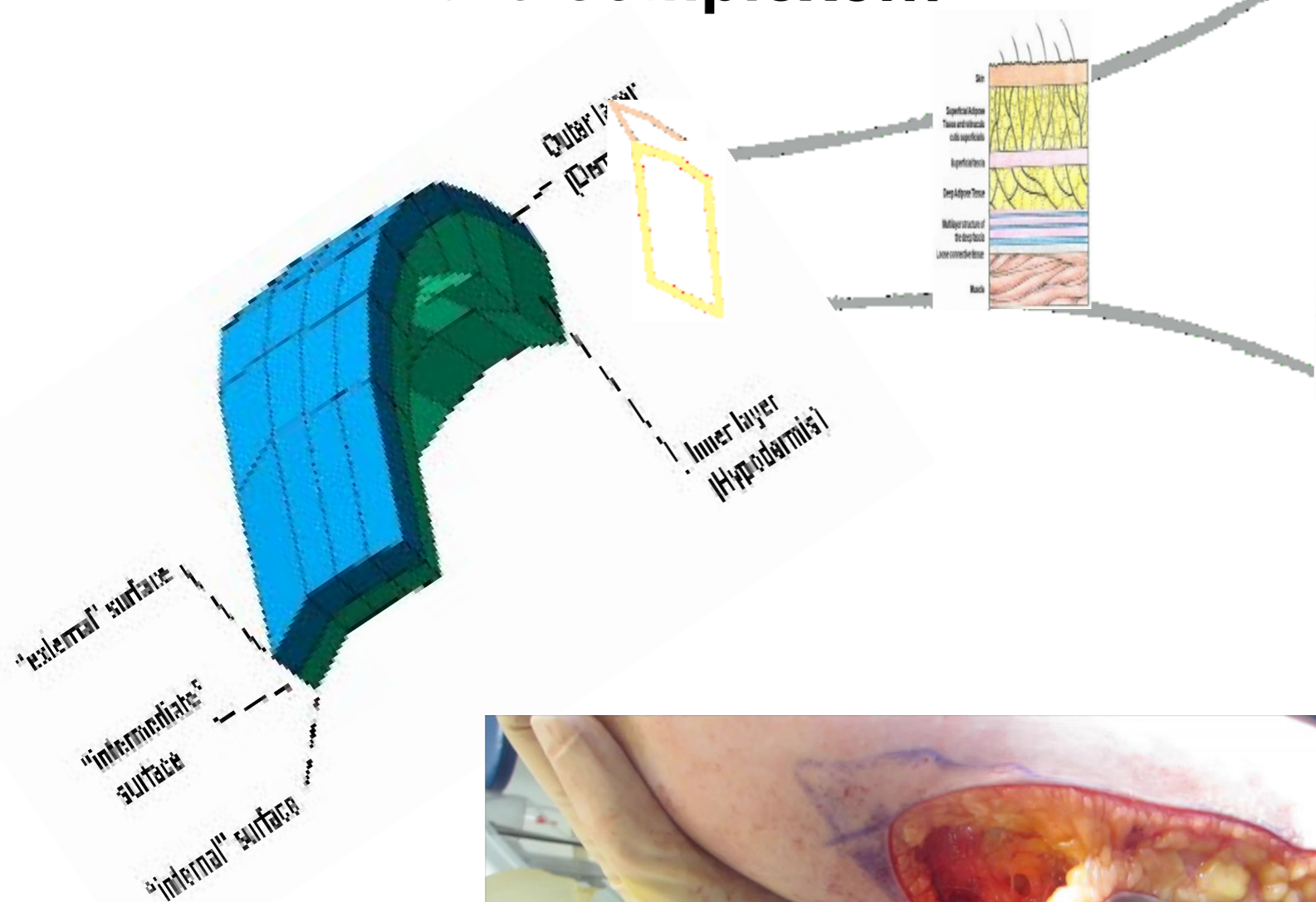


Lapuebla-Ferri et al. 2011

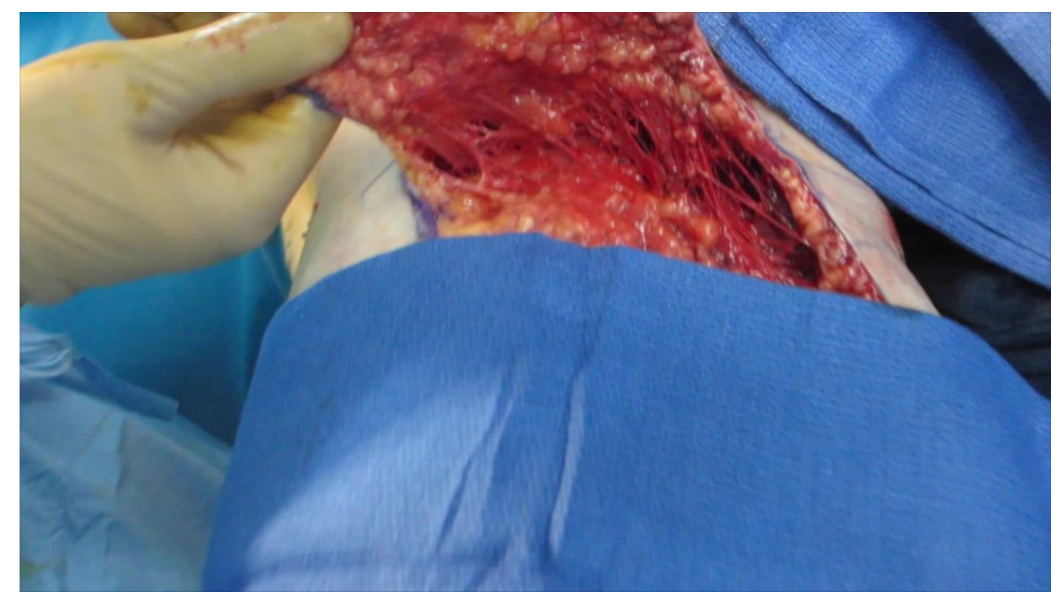
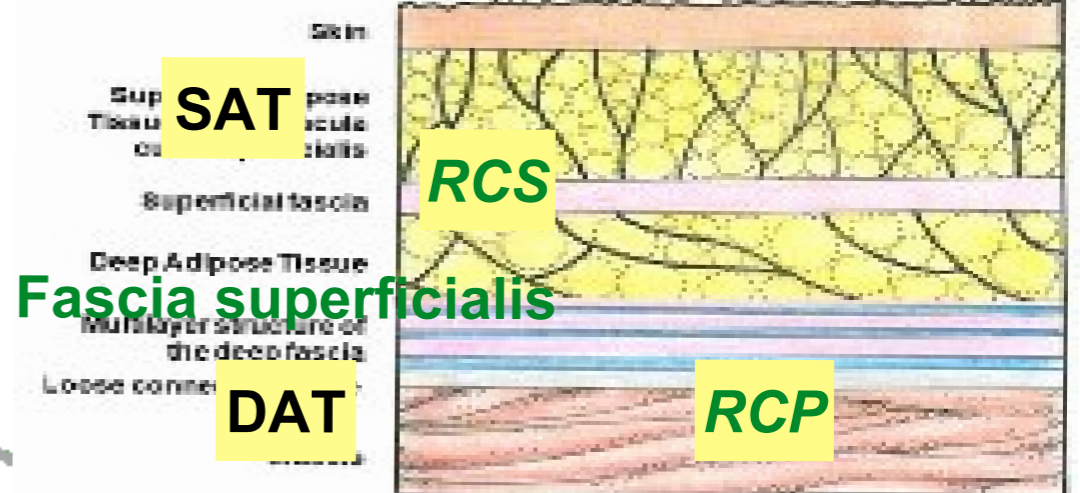
## Modèle numérique biomécanique 3D du complexe peau tissu sous-cutané (CPTSC)

# Le CPTSC

## Architecture complexe...

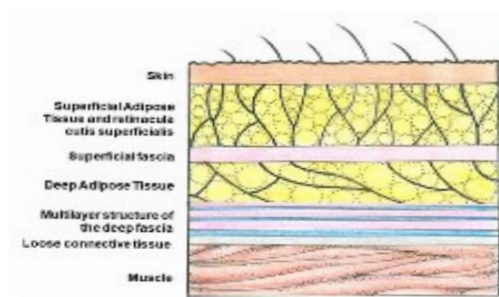


## Peau



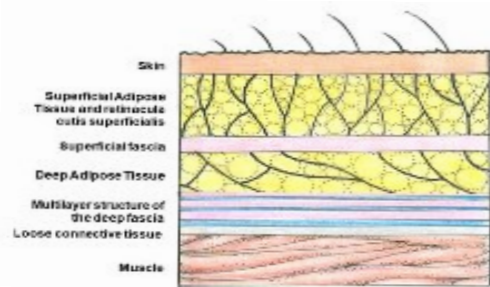
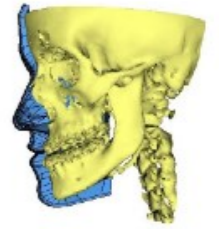


# PLAN



# PLAN

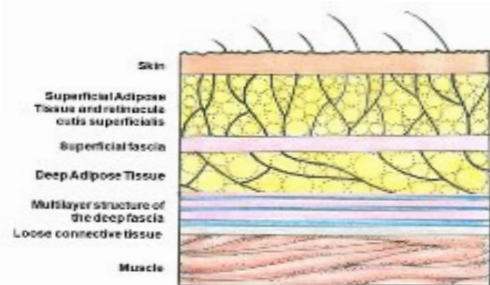
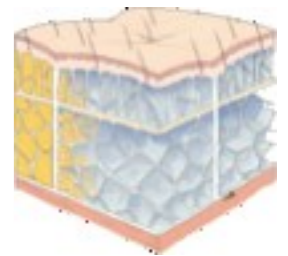
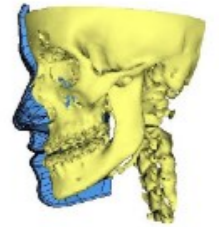
Etat de l'art



# PLAN

Etat de l'art

Modélisation anatomique

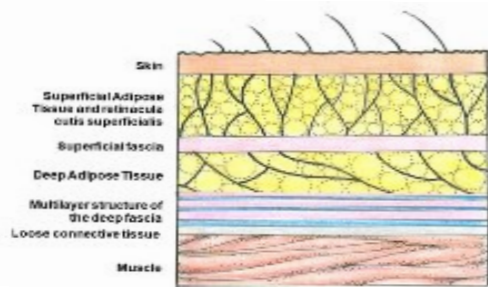
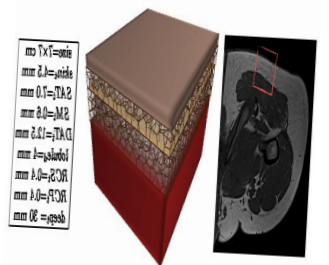
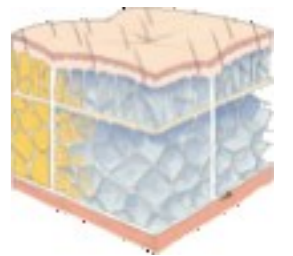
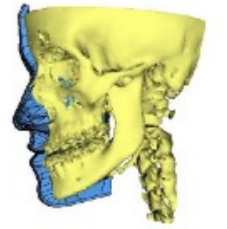


# PLAN

Etat de l'art

Modélisation anatomique

Modélisation géométrique  
paramétrique et procédurale



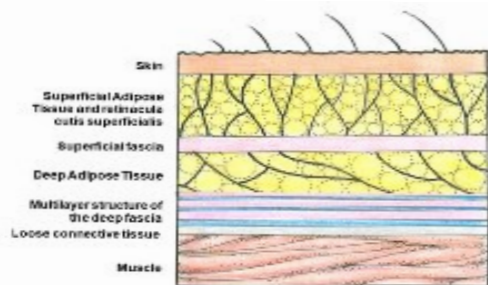
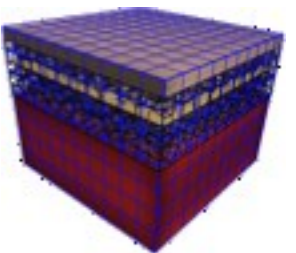
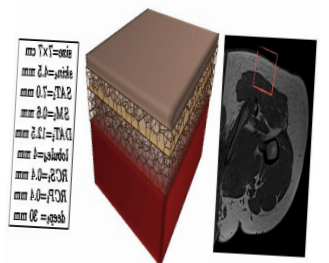
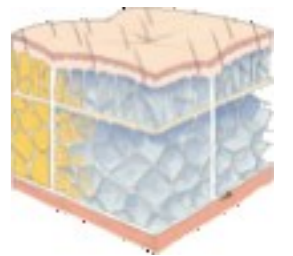
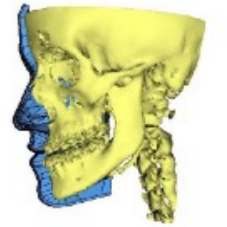
# PLAN

Etat de l'art

Modélisation anatomique

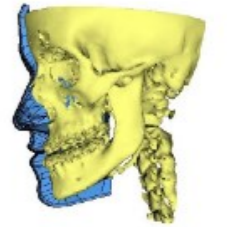
Modélisation géométrique  
paramétrique et procédurale

Modélisation biomécanique hybride

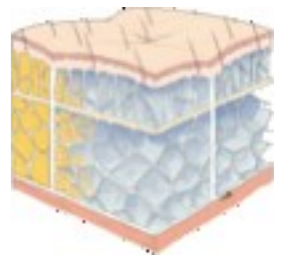


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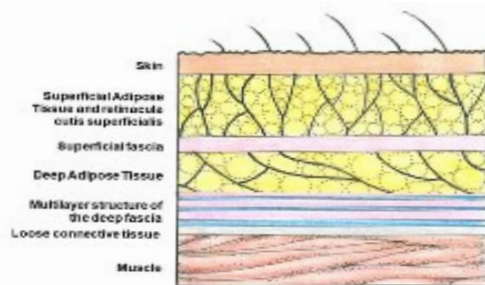
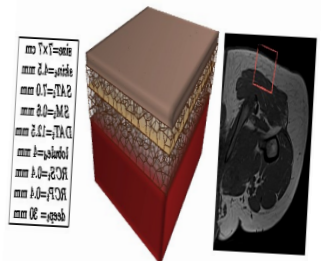
Etat de l'art



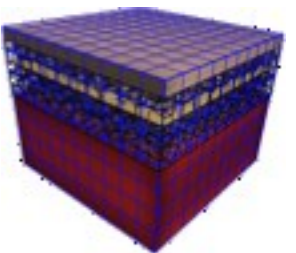
Modélisation anatomique



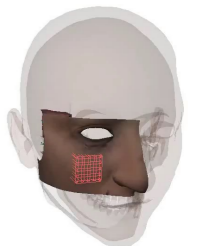
Modélisation géométrique paramétrique et procédurale



Modélisation biomécanique hybride

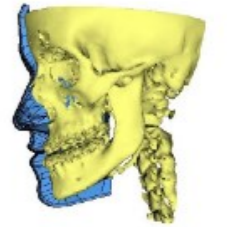


Simulations

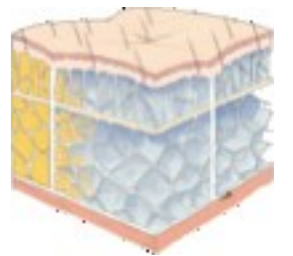


# PLAN

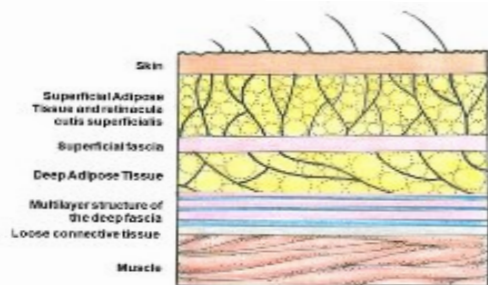
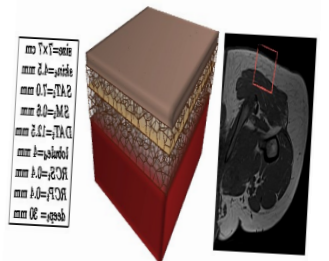
Etat de l'art



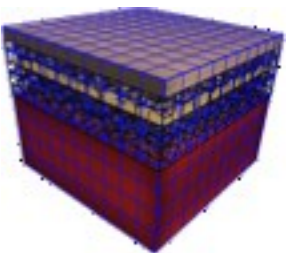
Modélisation anatomique



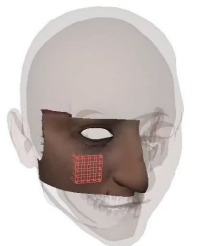
Modélisation géométrique paramétrique et procédurale



Modélisation biomécanique hybride



Simulations

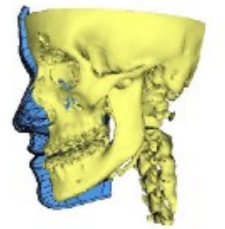


Perspectives

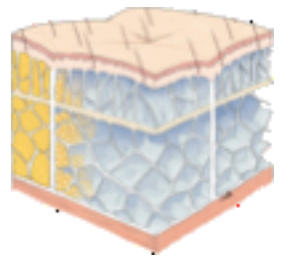


# PLAN

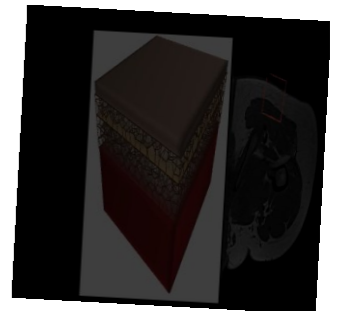
Etat de l'art



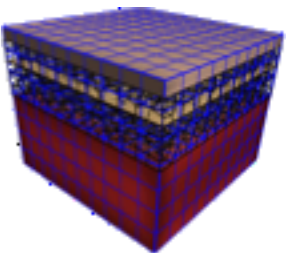
Modélisation anatomique



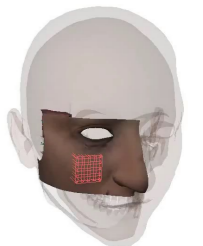
Modélisation géométrique  
paramétrique et procédurale



Modélisation biomécanique hybride



Simulations

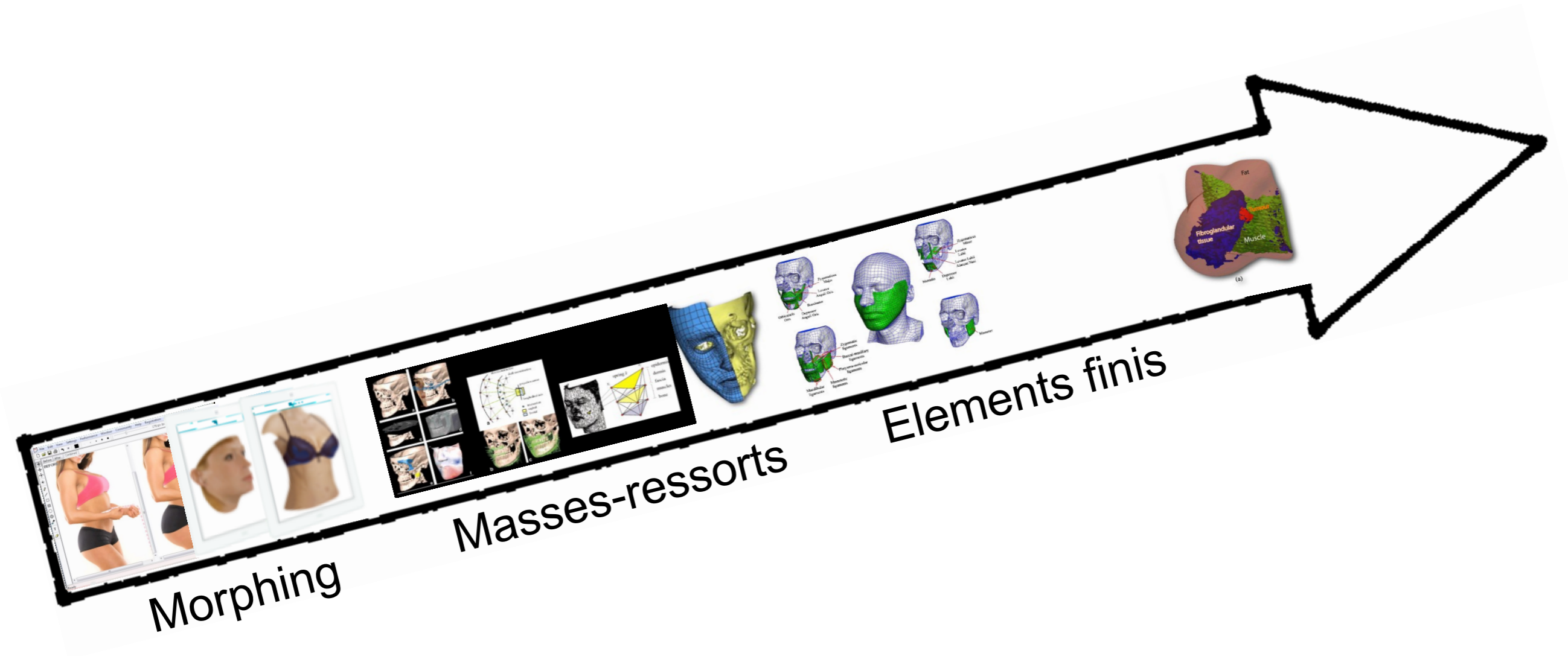


Perspectives





# Modélisations existantes



# Modélisations existantes



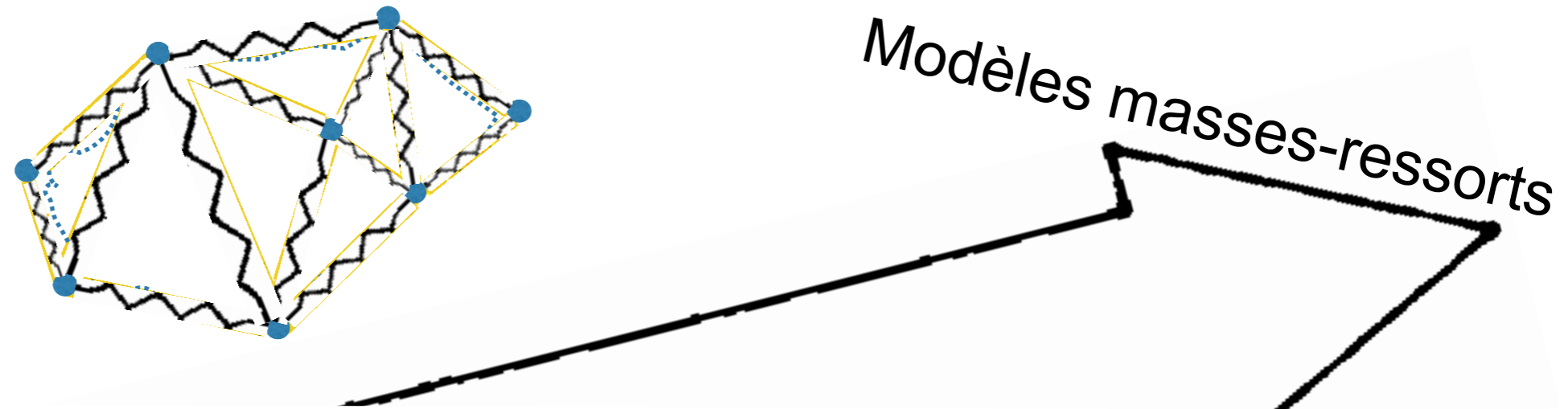
Morphing



**Plastic Surgery Simulator** Beauty is a right

Basées sur la déformation d'images  
Acquisition des patients au smartphone  
Plus illustratif qu'un outil médical

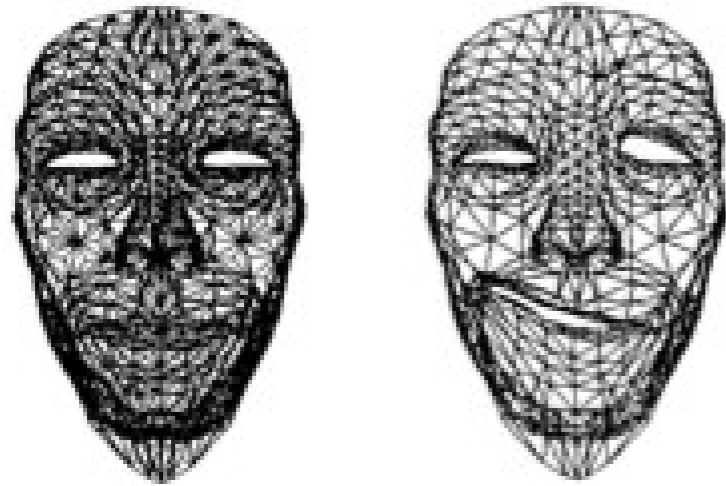
## Modélisations existantes



L'objet à modéliser est maillé en 3D :

- La masse est concentrée sur les **noeuds**.
- La raideur du matériau est rassemblée sur les **arêtes** (ressorts)

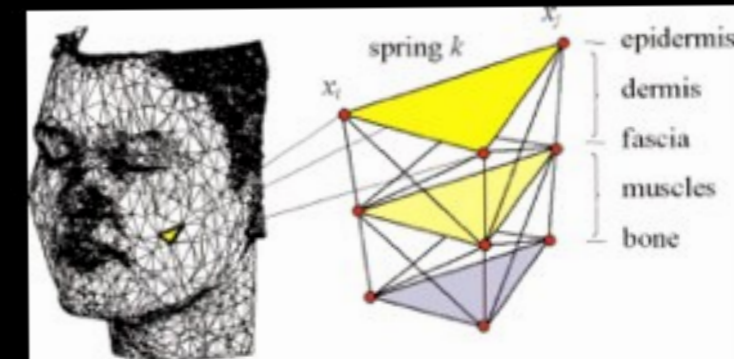
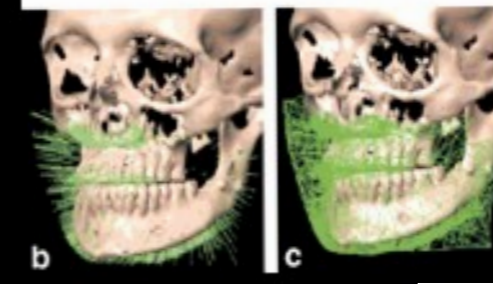
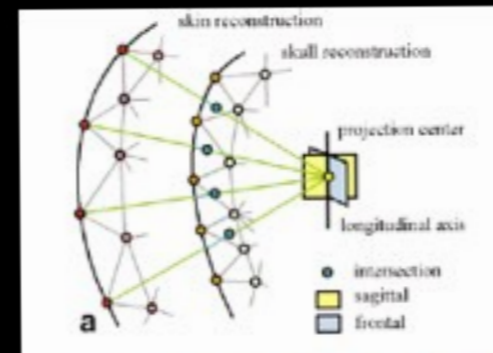
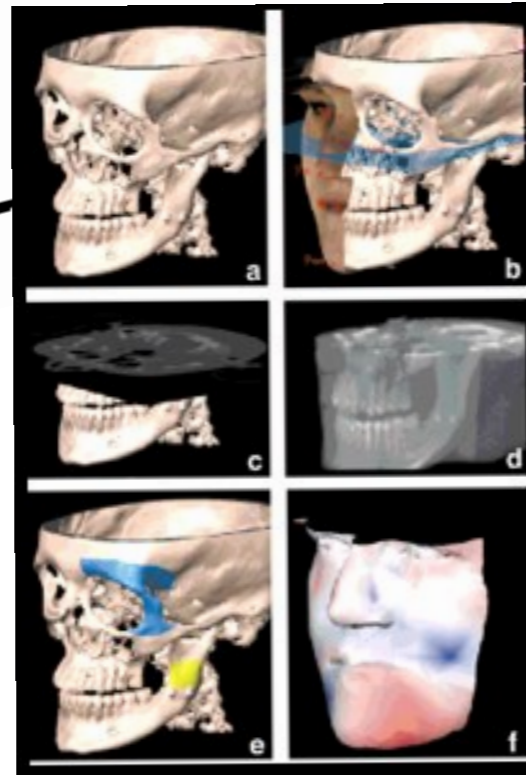
# Modélisations existantes



Modèles masses-ressorts

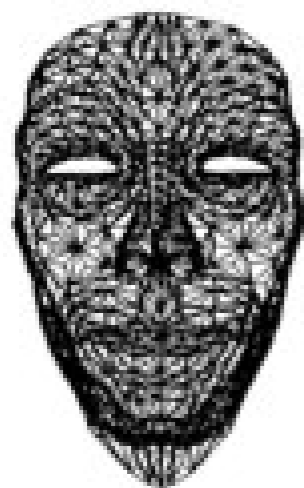


Waters K et al. 1990



Keeve E et al. 1998

# Modélisations existantes



## AVANTAGE

Rapide

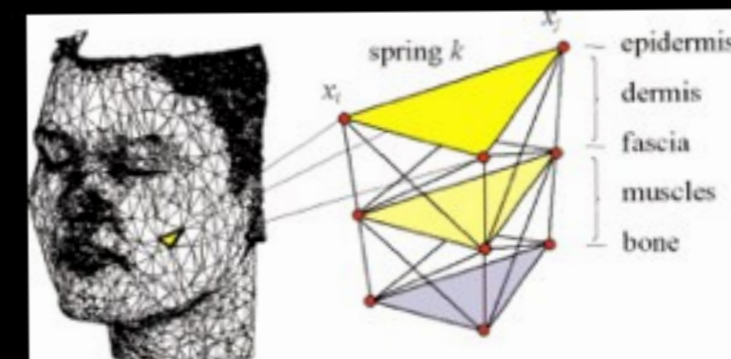
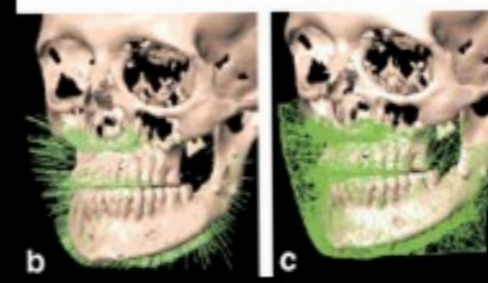
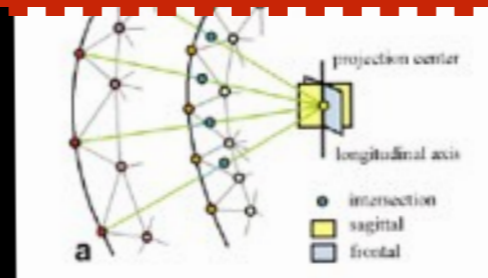
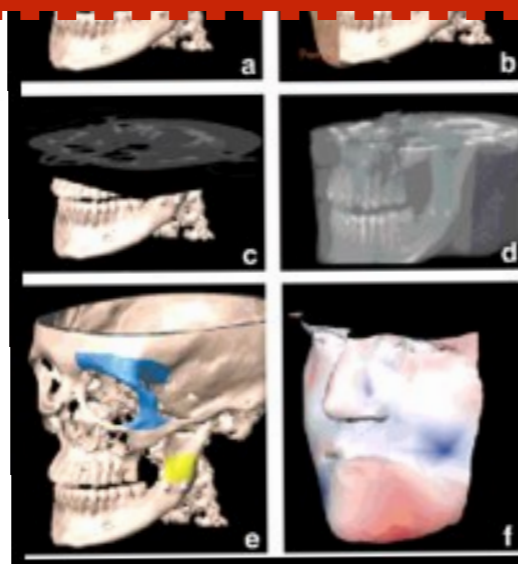
Modèles masses-ressorts



Waters K et al. 1995

## LIMITES

N'intègre pas les lois de la physique des milieux continus  
Difficile d'agencer & de paramétrer les ressorts en 3D



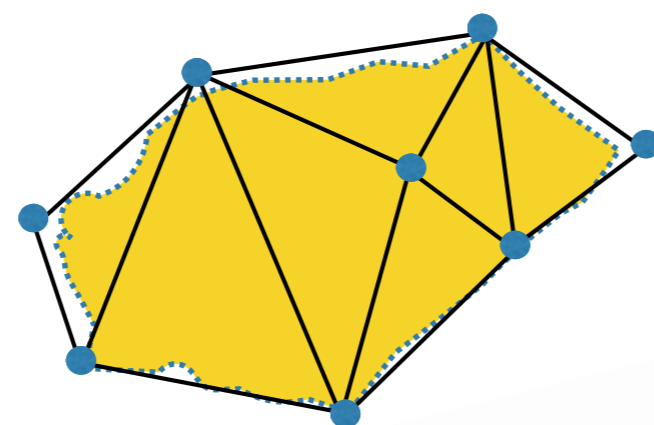
Keeve E et al. 1998

# Modélisations existantes



Modèles masses-ressorts

## Modélisations existantes



Modèles Eléments Finis

L'objet à modéliser est maillé en 3D :

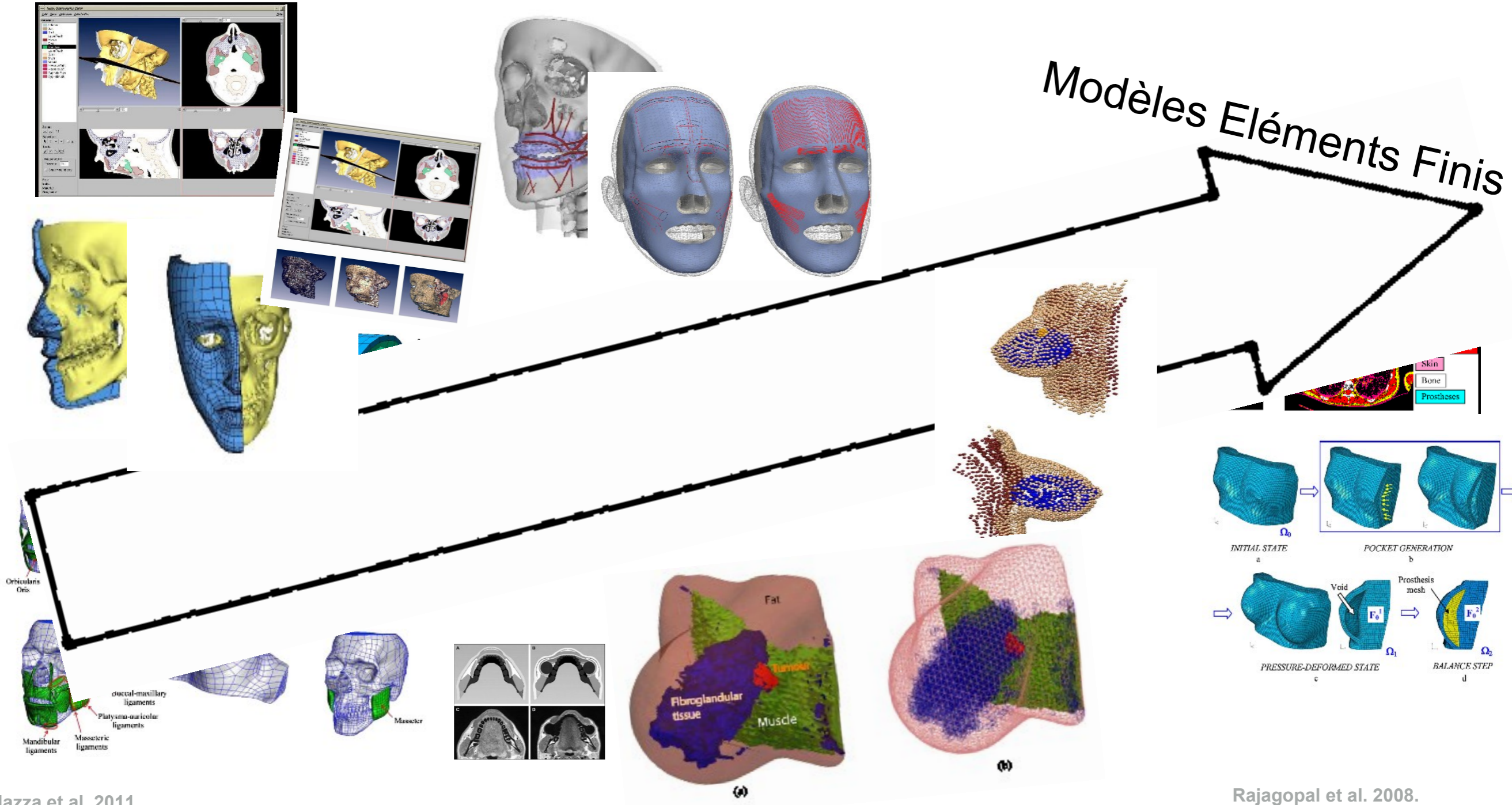
1 élément = 1 cellule du maillage

- La masse est intégrée dans les éléments

- La raideur du matériau est intégrée (et moyennée) dans les éléments

*Interpolation des champs physiques en tout point en fonction de leur valeur aux nœuds ce qui permet d'écrire les équations physiques pour le milieu continu au niveau du maillage discret.*

# Modélisations existantes



Mazza et al. 2011

Chabanas et al. 2003

Nazari et al. 2010.

Westermarck et al. 2005

Majorczyk et al. 2013

Rajagopal et al. 2008.

Han L et al. 2011

Lapuebla-Ferri et al. 2011



# Modélisations existantes

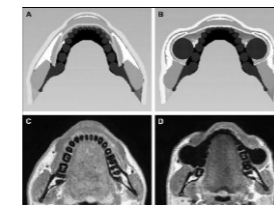
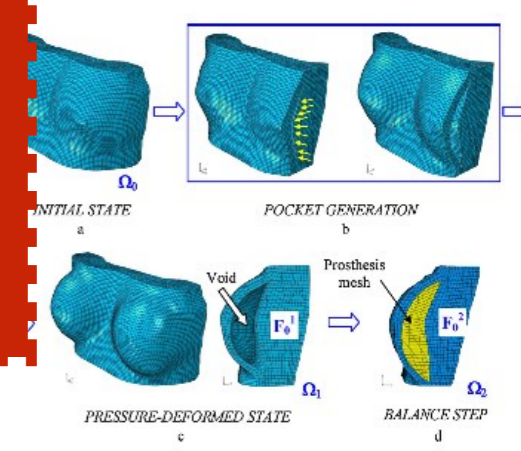
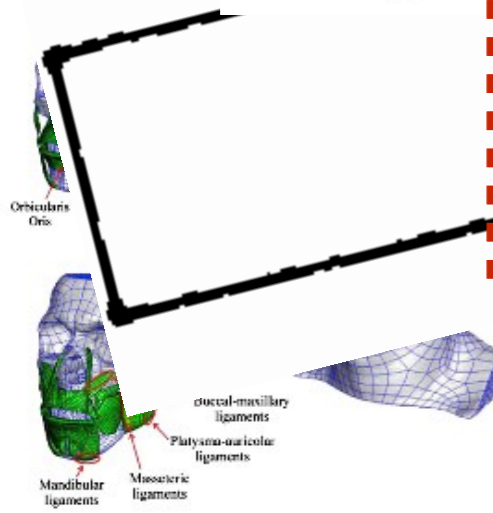
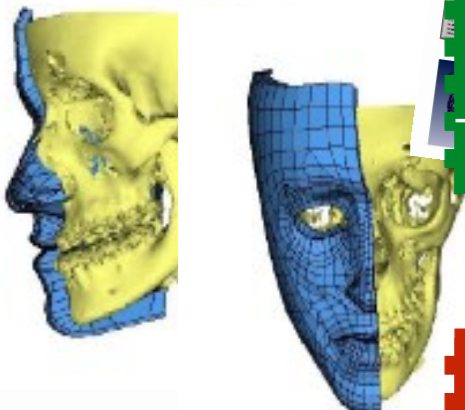
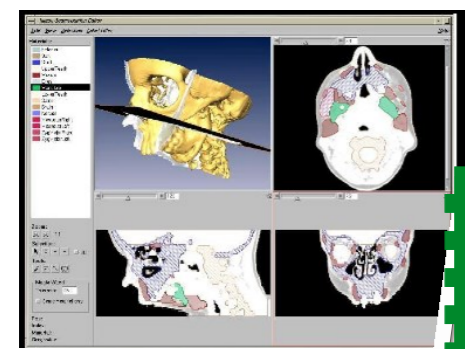
## AVANTAGES

- Prise en charge de lois de comportements réalistes et complexes
- Solution convergente vers la solution continue

## LIMITES

- Parfois lourde d'un point de vue calculatoire
- Problèmes de choix de la forme des éléments dans les géométries complexes

Modèle à Éléments Finis



Mazza et al. 2011

Chabanas et al. 2003

Nazari et al. 2010.

Westermarck et al. 2005

Majorczyk et al. 2013

Rajagopal et al. 2008.

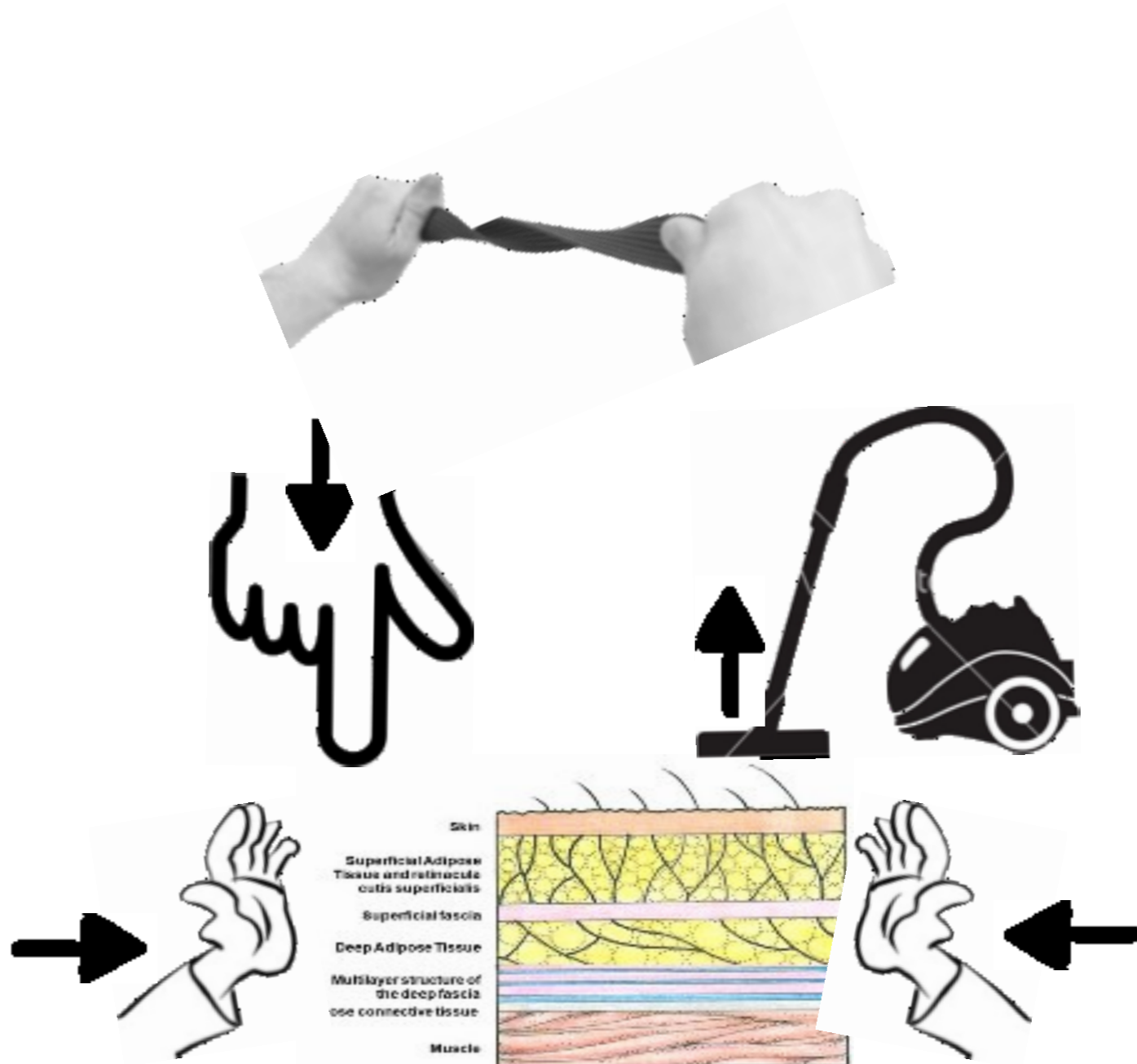
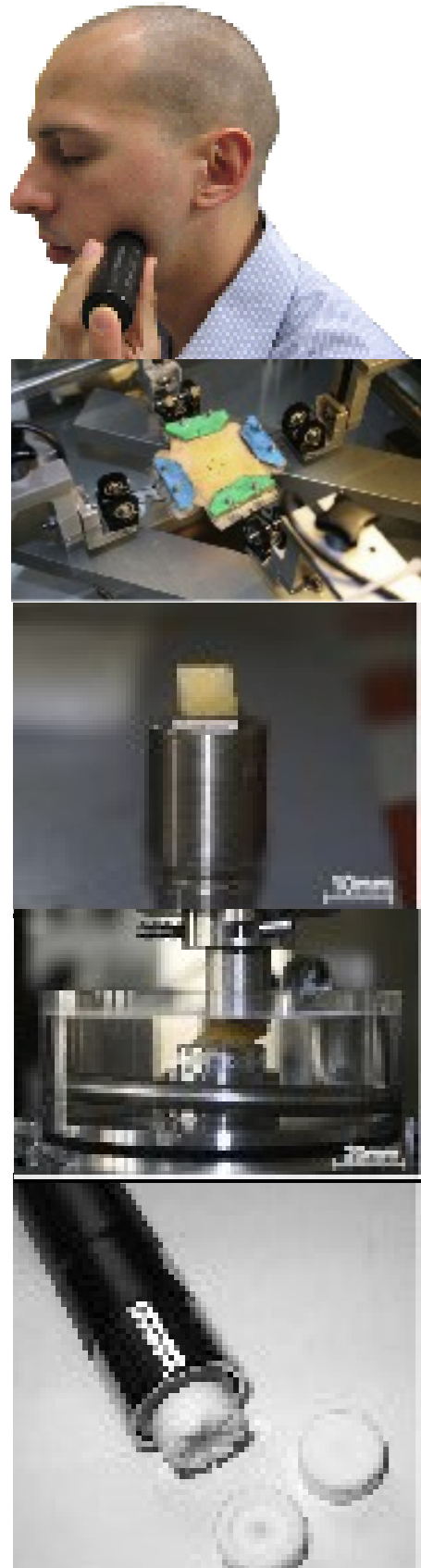
Han L et al. 2011

Lapuebla-Ferri et al. 2011

## **BILAN des modèles du CPTSC existants**

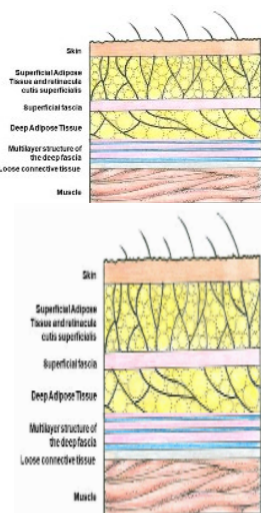
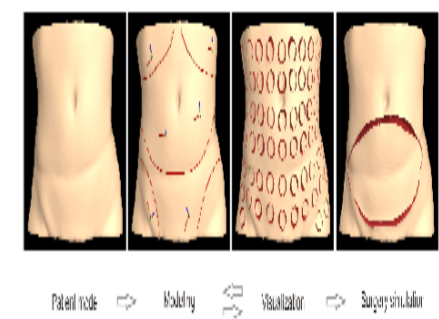
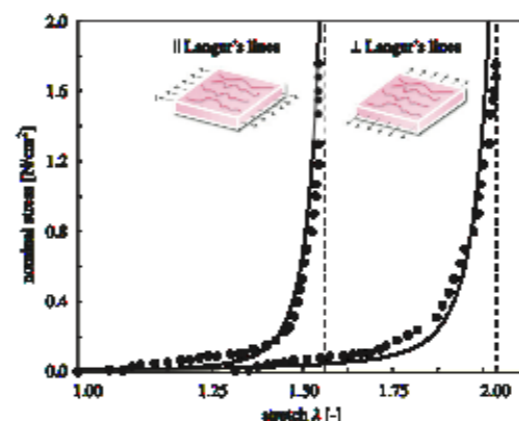
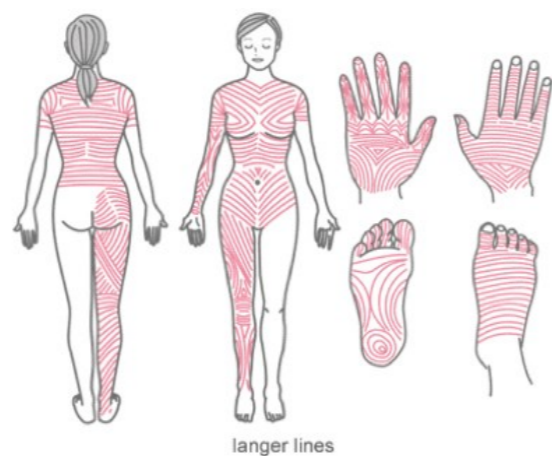
- modèles le plus souvent **géométriquement simplifiés**
- de **comportement mécanique moyenné**
- utilisant des **lois de comportements parfois complexes**
  
- modèles **non personnalisables** à d'autres patients
- **non paramétrables** à d'autres régions anatomiques
- peu appropriés à l'**utilisation clinique** car difficile à programmer

# Biomécanique expérimentale du CPTSC



# Biomécanique expérimentale du CPTSC

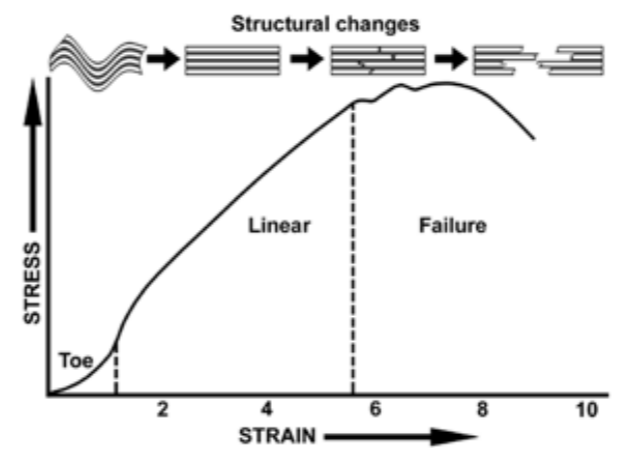
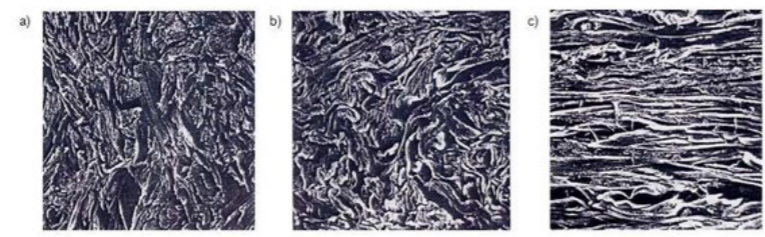
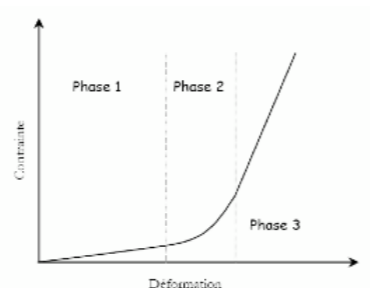
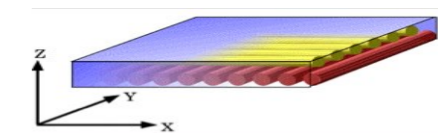
## Comportement mécanique de la peau sous contraintes externes



### Peau

Non linéaire

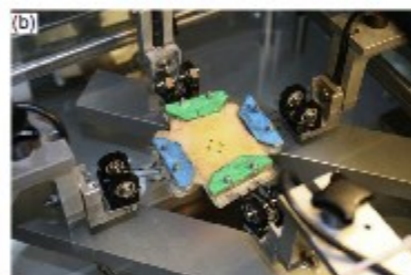
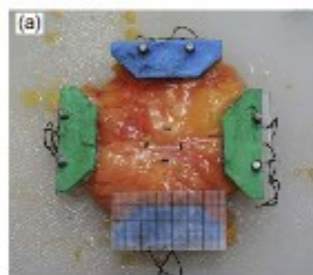
Anisotrope



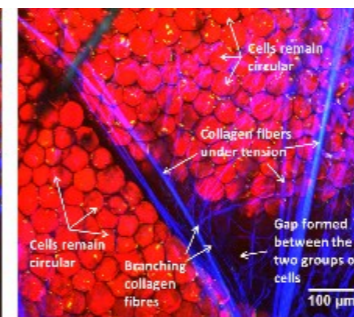
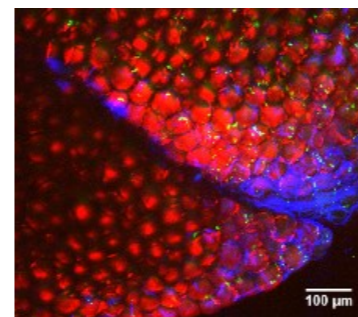
Tepole et al. 2012  
Kendall et al. 2010

# Biomécanique expérimentale du CPTSC

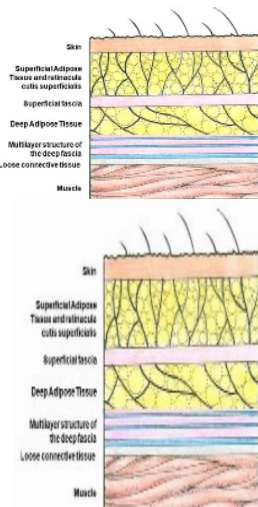
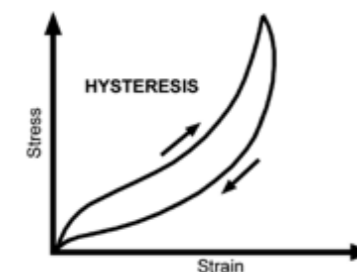
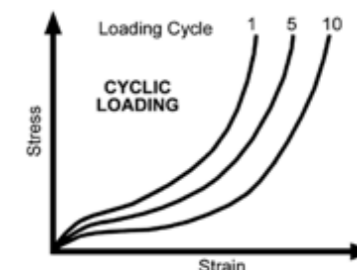
## Comportement mécanique du **tissu sous-cutané** sous contraintes externes



Sommet et al. 2013



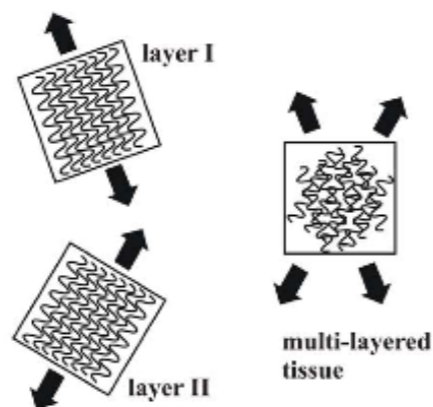
Dirillou et al. 2000



**Tissu sous-cutané**

**Visco-élastique**

**Anisotrope**



Abu-Hijleh et al. 2006

# Biomécanique expérimentale du CPTSC

Type de tissu	Méthode de mesure	Module de Young (Pa)	Localisation	Couches intéressées	Référence bibliographique
PEAU					
	Indentation / Suction	7200 (vieux) à 10 700 (jeune)	Avant Bras	Global	128
	Indentation	6 C10 = 660 à 96 000	Avant Bras	Epiderme + Derme moyen	121

Type de tissu	Méthode de mesure	Module de Young (Pa)	Localisation	Couches intéressées	Référence bibliographique
GRAISSE					
	Indentation //FEM//IRM	600	Avant Bras	Global	20
	Elastographie	3 100 à 9 680	Multiples	Hypoderme	126

## BILAN des mesures expérimentales

- Mesures **exactes** et lois de comportement **simples** pour les tests **uni-tissulaires**
- Mesures **variables** (facteur  $10^5$ ) et lois de comportement **complexes** pour les tests **pluri-tissulaires**

Type de tissu	Méthode de mesure	Module de Young (Pa)	Localisation	Couches intéressées	Référence bibliographique
ELASTINE					
	Revue de la littérature	600000	Indéterminé		216
COLLAGENE					
	Revue de la littérature	100000000	Indéterminé		216
		3000000	Rétine (collagène type IV)		222

Type de tissu	Méthode de mesure	Module de Young (Pa)	Localisation	Couches intéressées	Référence bibliographique
	preC			tibroglandulaire	
	Compression 20% preC	50000	Sein	Tissu fibroglandulaire	218
	Elastographie	35000	Sein	Tissu fibroglandulaire	213

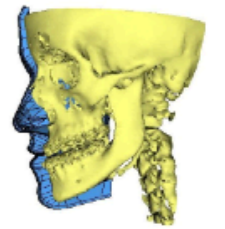
Type de tissu	Méthode de mesure	Module de Young (Pa)	Localisation	Couches intéressées	Référence bibliographique
LIGAMENT DE COOPER					
	Extrapolé des mesures sur le genou	80 000 000 à 400 000 000		Extrapolé des mesures sur le genou	141

## Conclusion de l'état de l'art

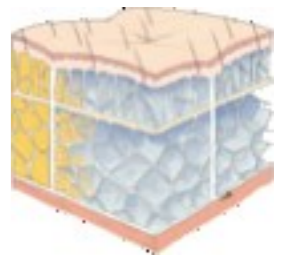
- Intérêt de construire un modèle anatomiquement exact
- paramétré avec une loi de comportement simple
- et une constante d'élasticité la plus proche de la réalité

# PLAN

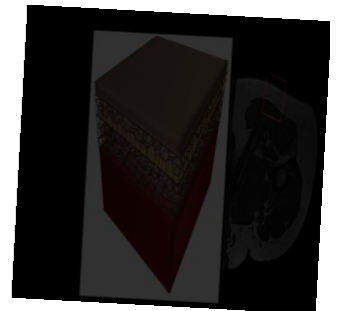
Etat de l'art



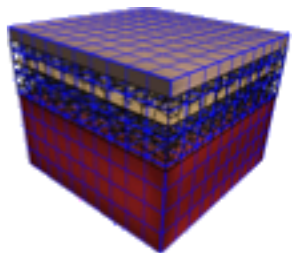
Modélisation anatomique



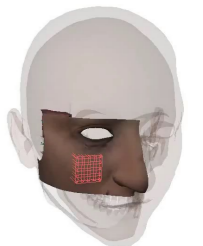
Modélisation géométrique paramétrique et procédurale



Modélisation biomécanique hybride



Simulations



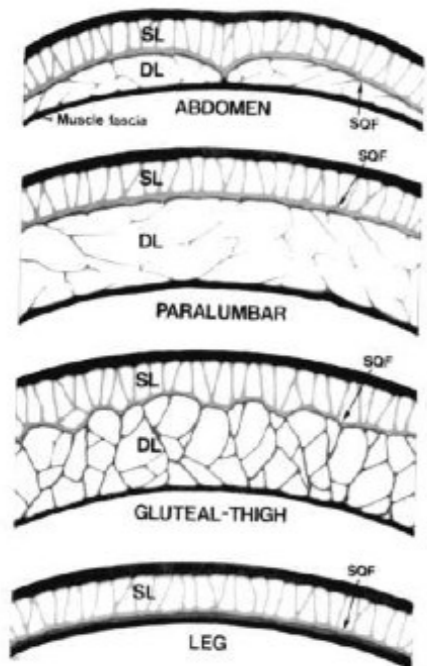
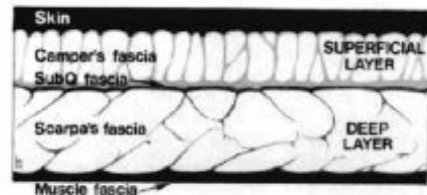
Perspectives



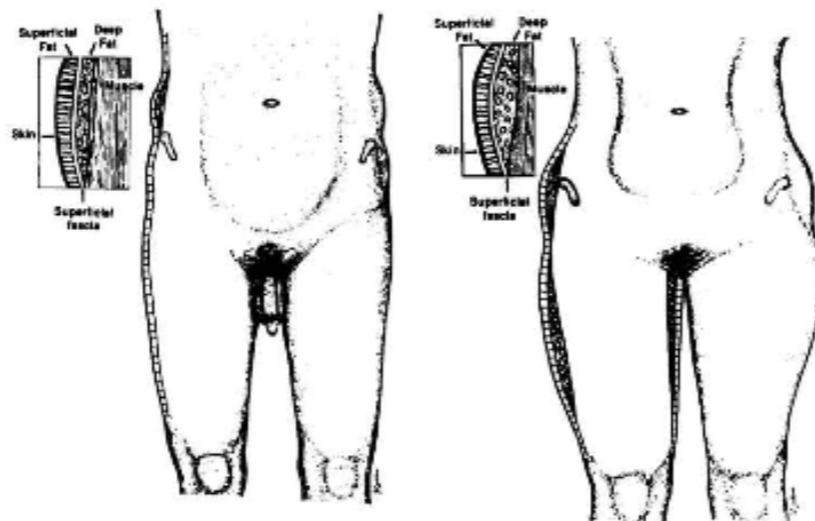


# Etude radio-anatomique

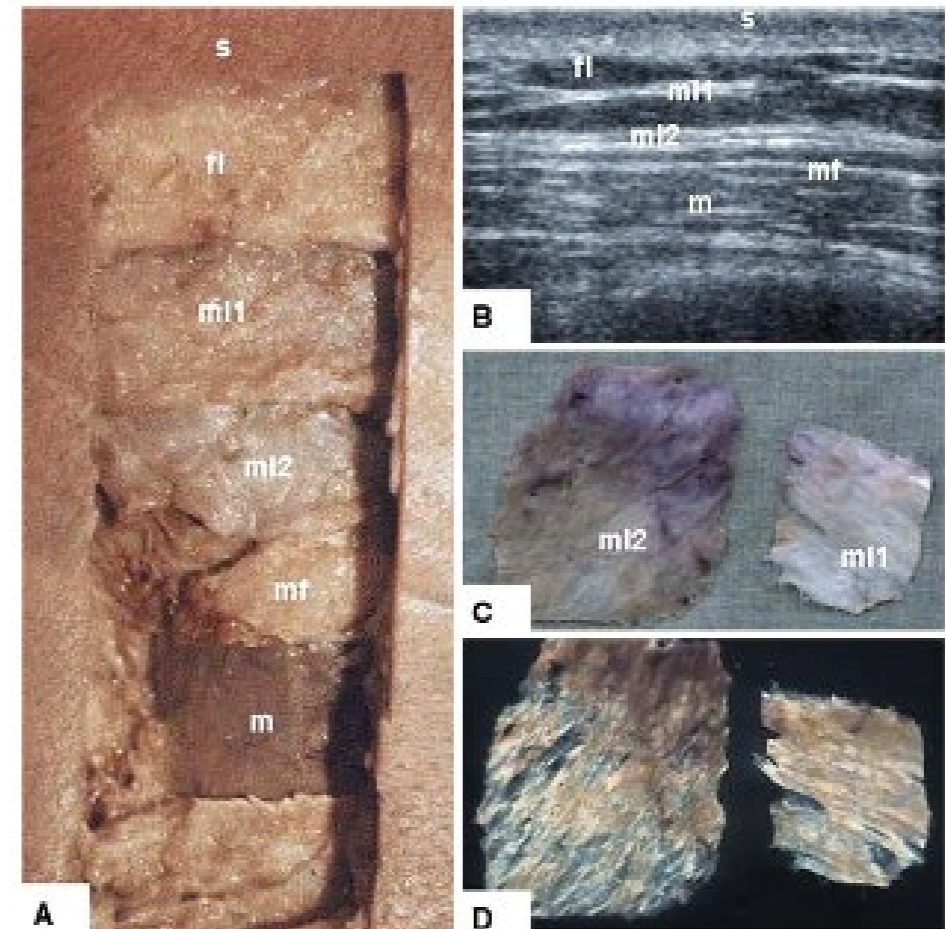
*Notion d'une organisation commune mais données parcellaires*



Markman et al. 1986



Lockwood 1990



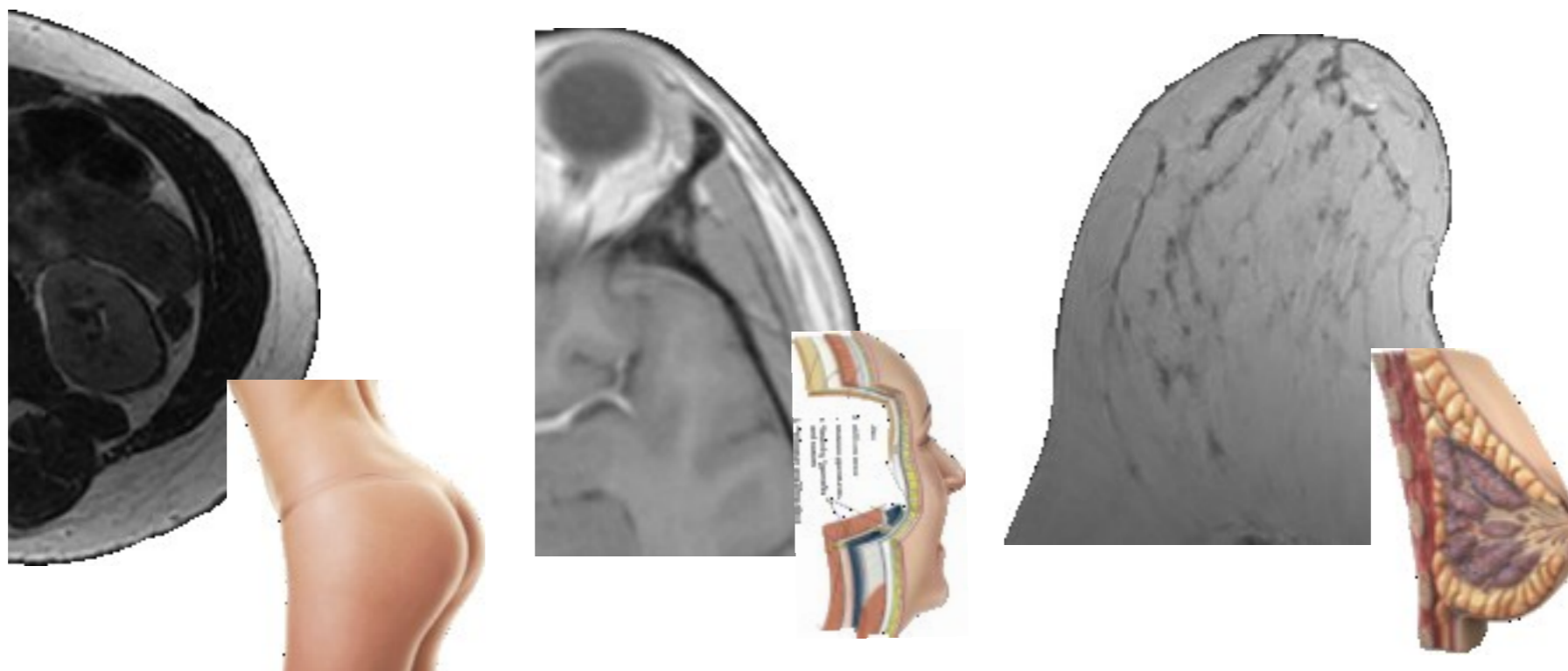
Abu-Hijleh et al. 2006

# Etude radio-anatomique

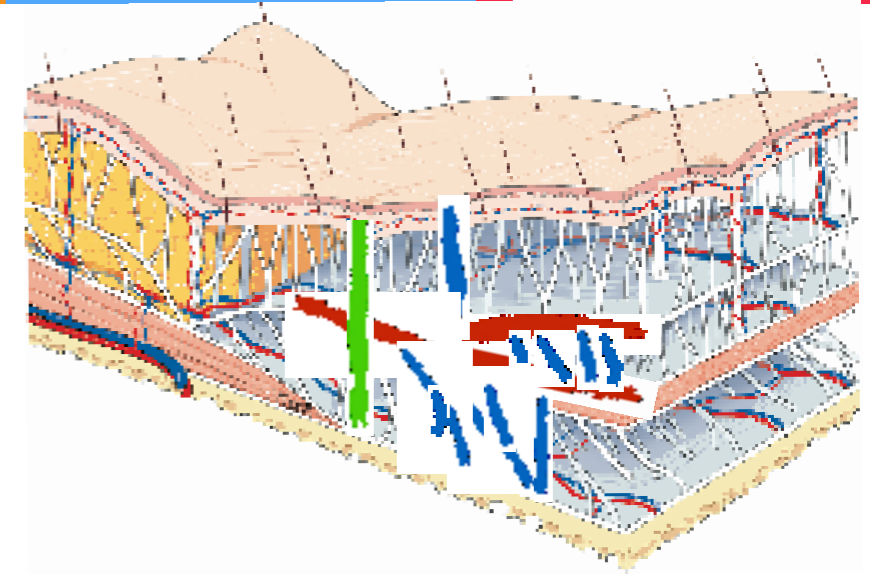


8 acquisitions IRM 3T  
sur 6 sujets

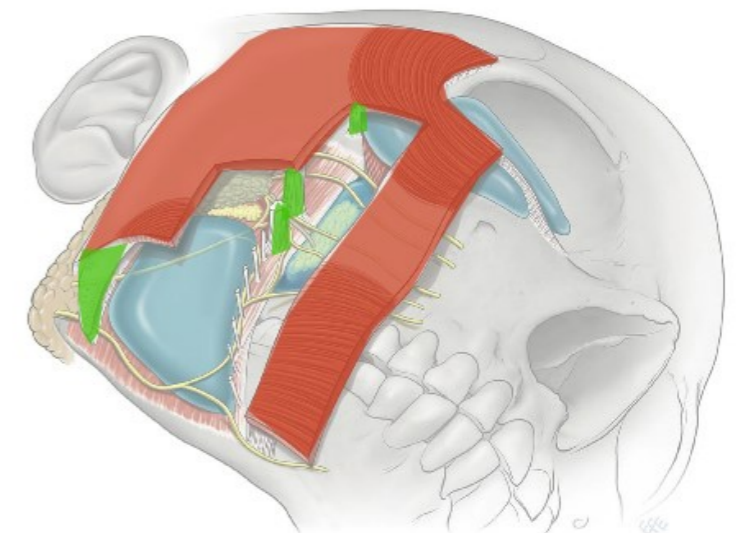
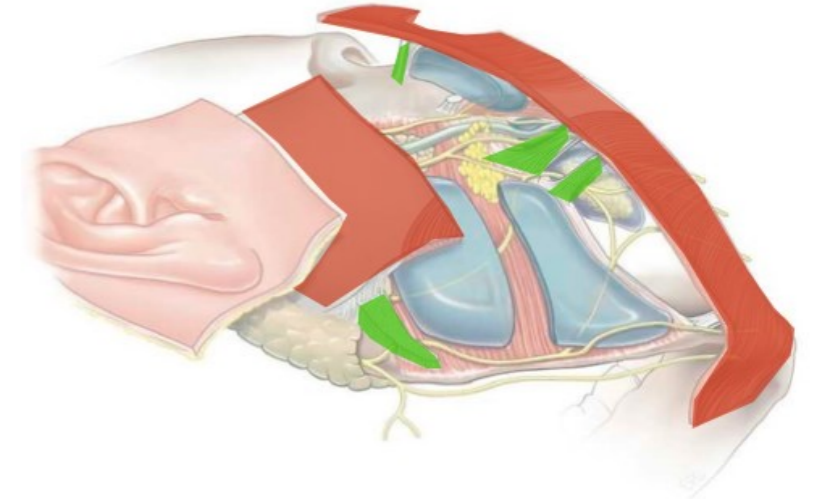
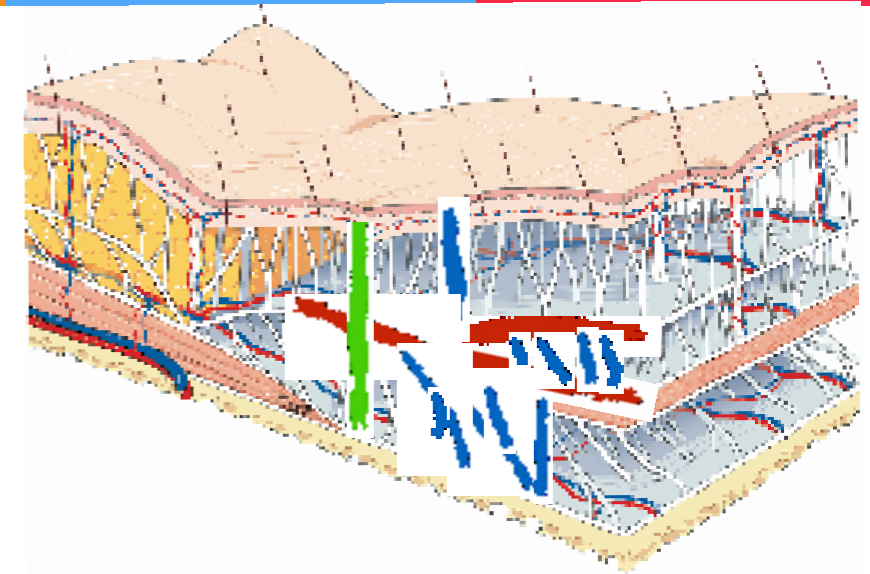
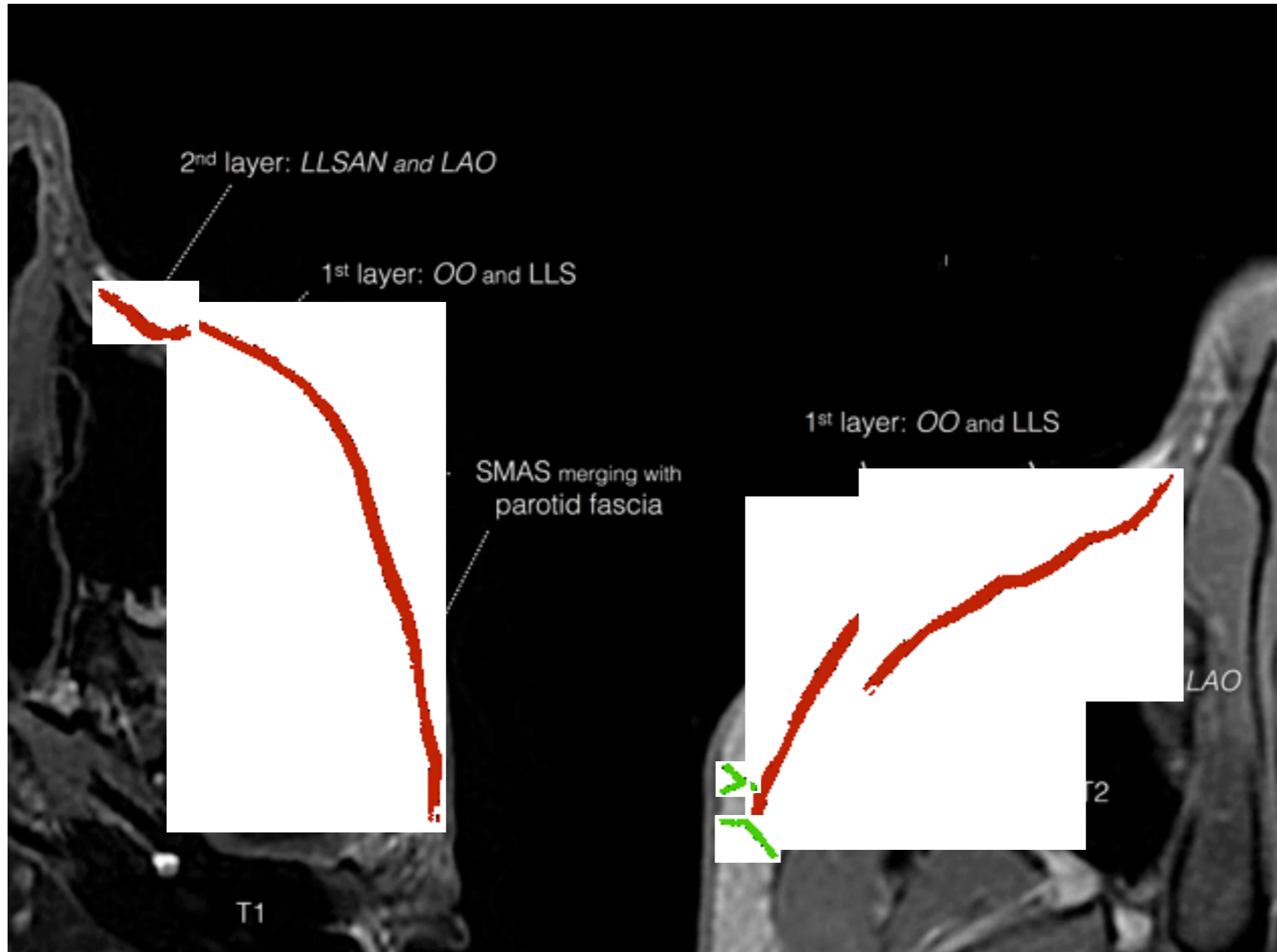
Face, Seins, Thorax, Abdomen, Membres



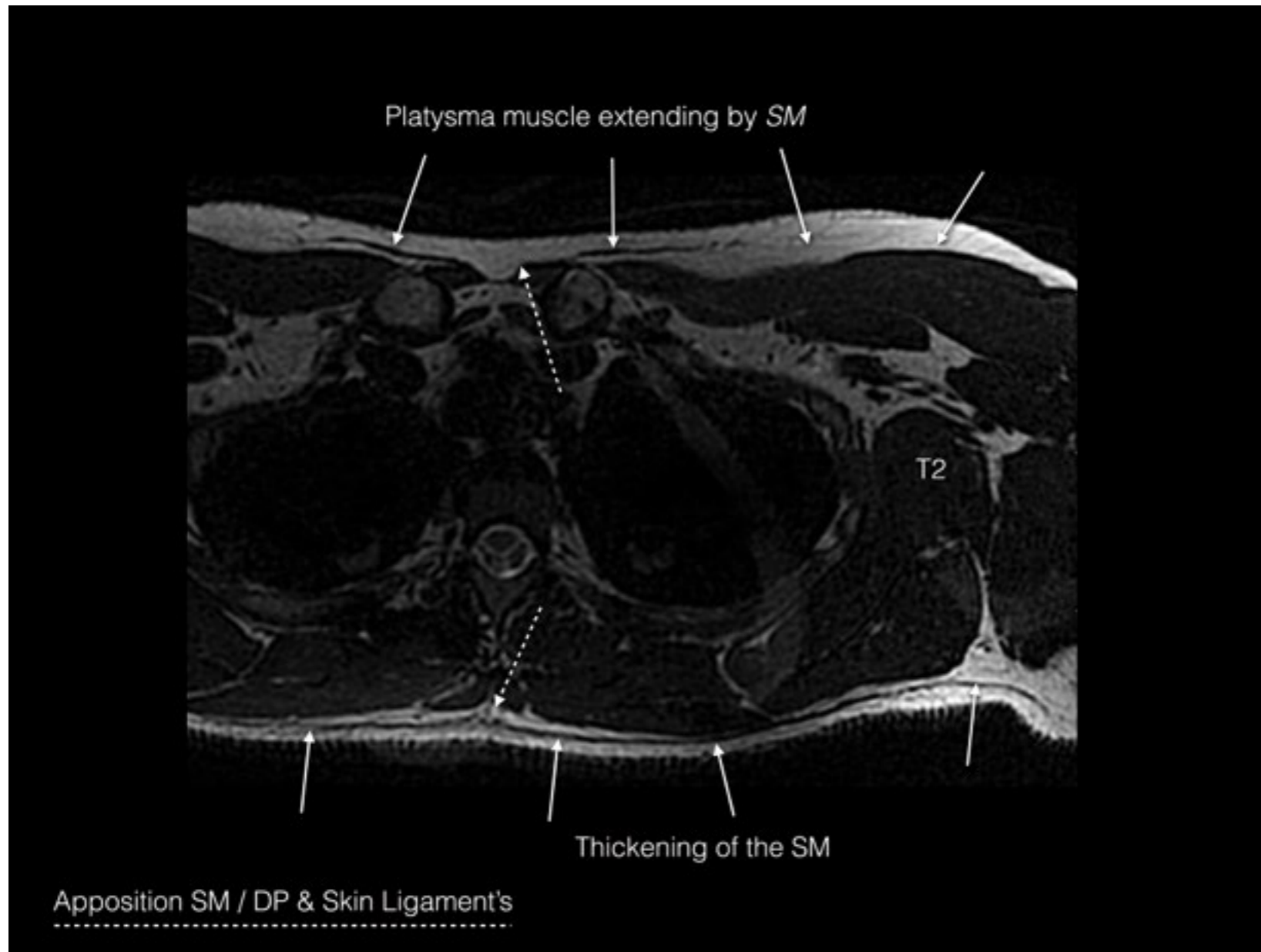
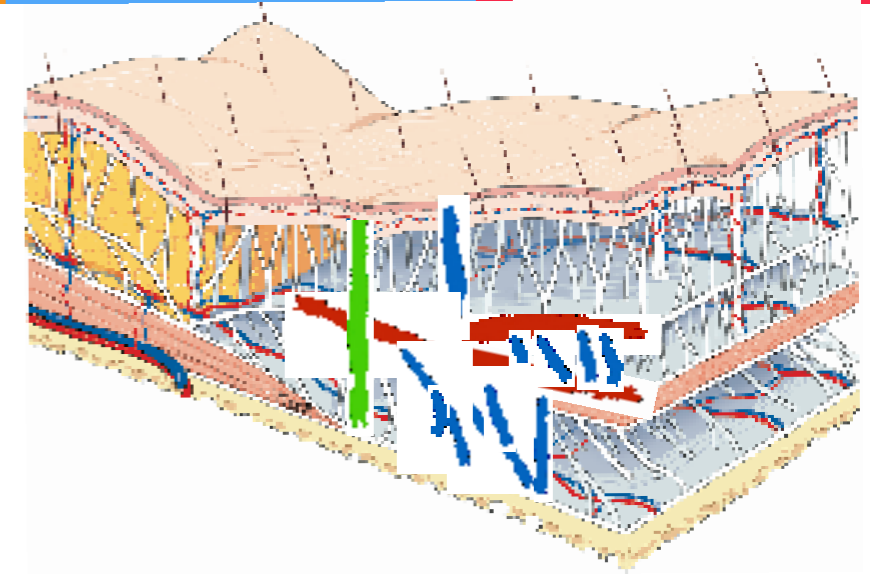
2D



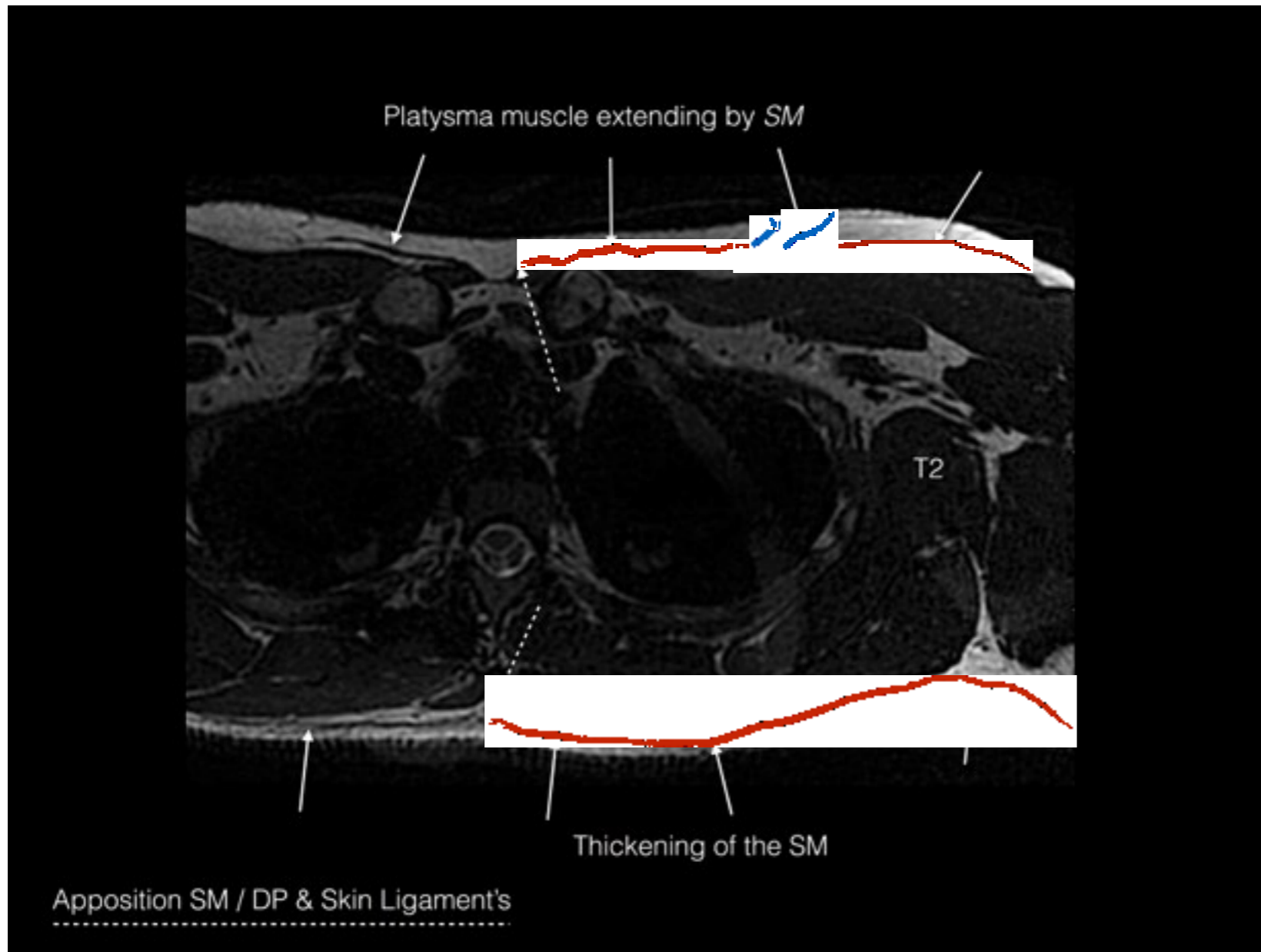
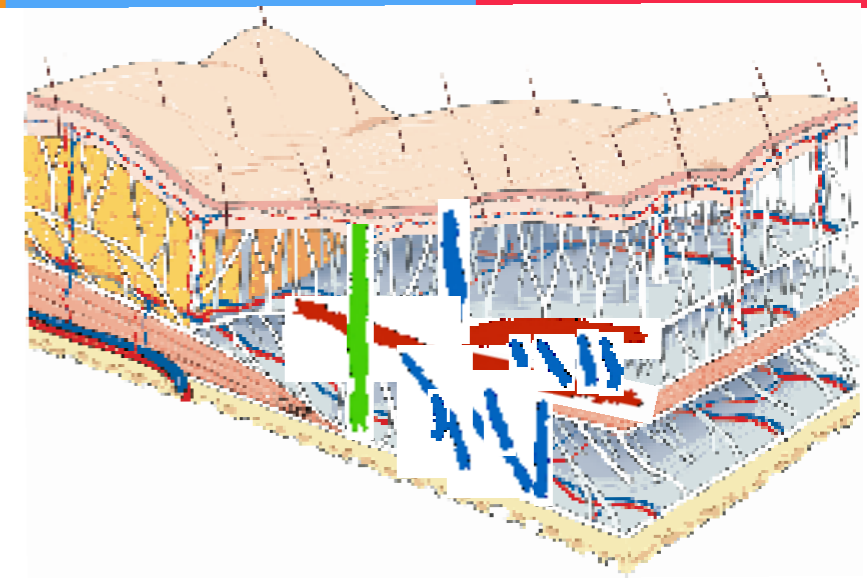
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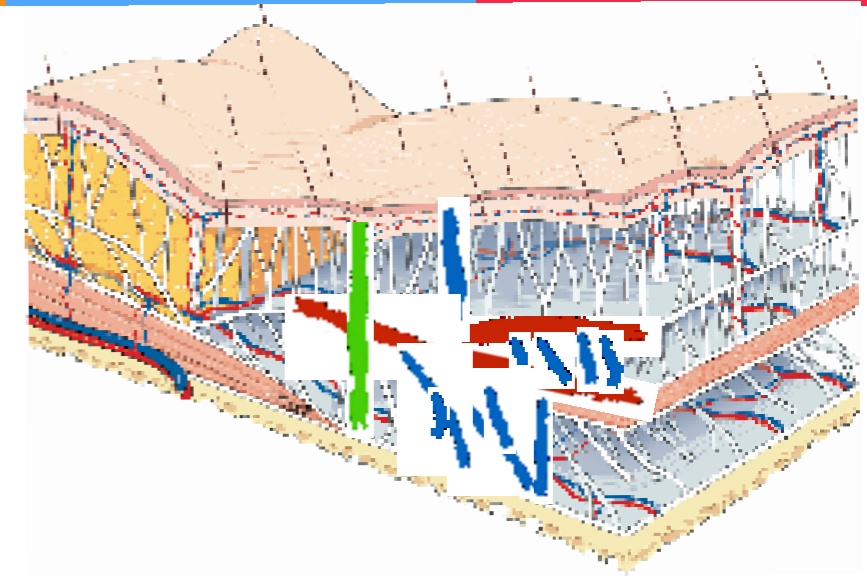
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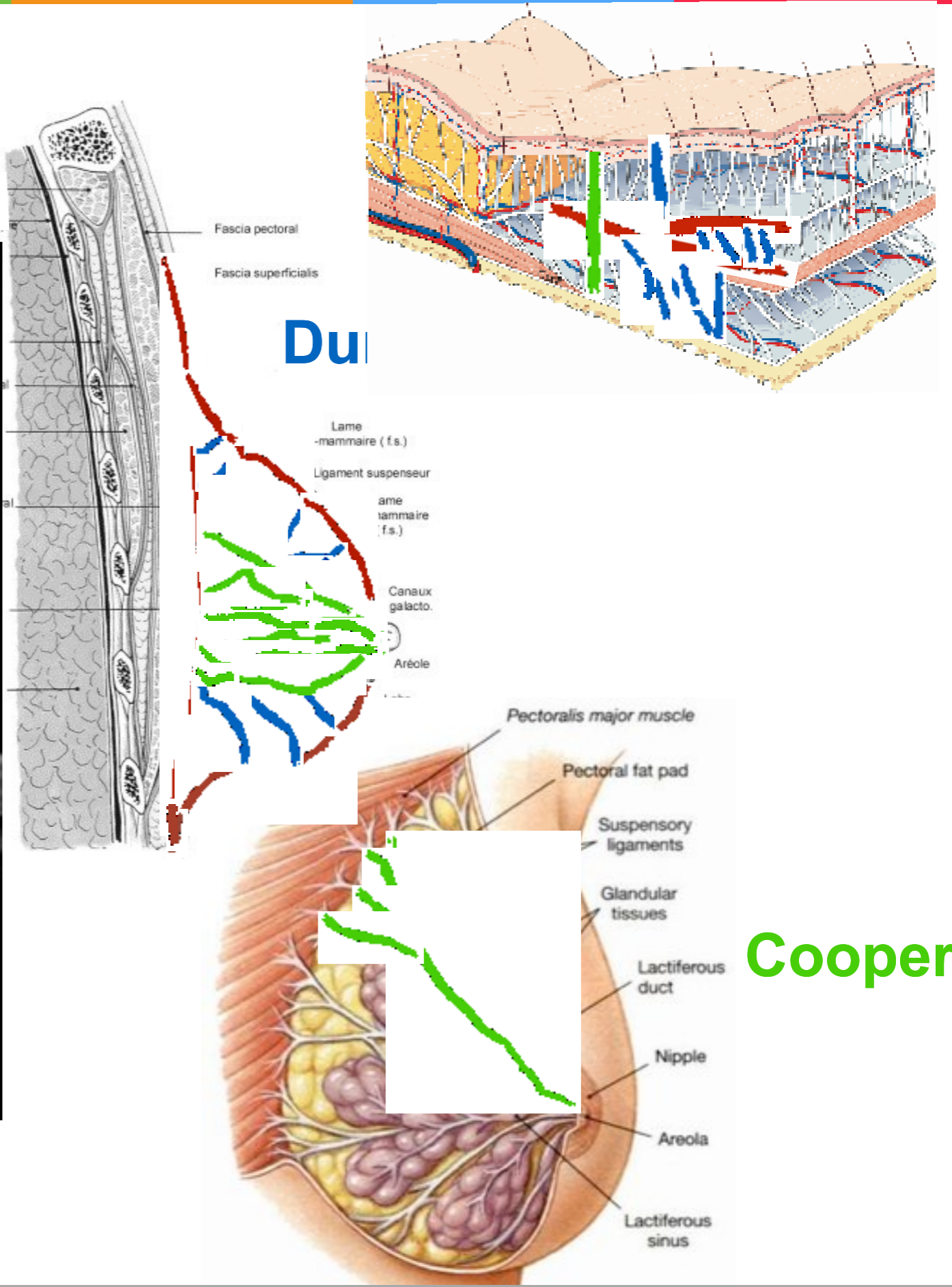
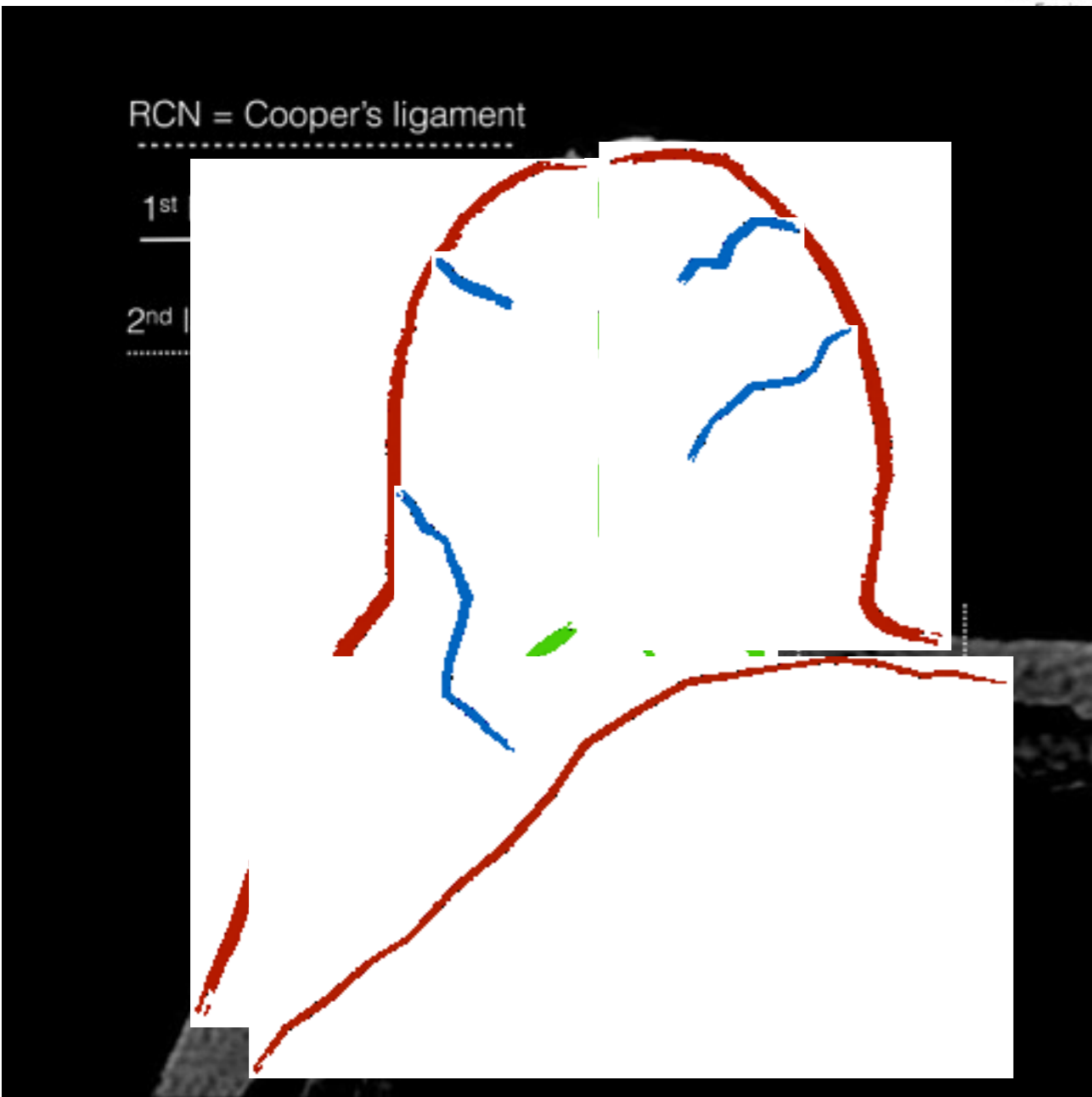
2D



2D

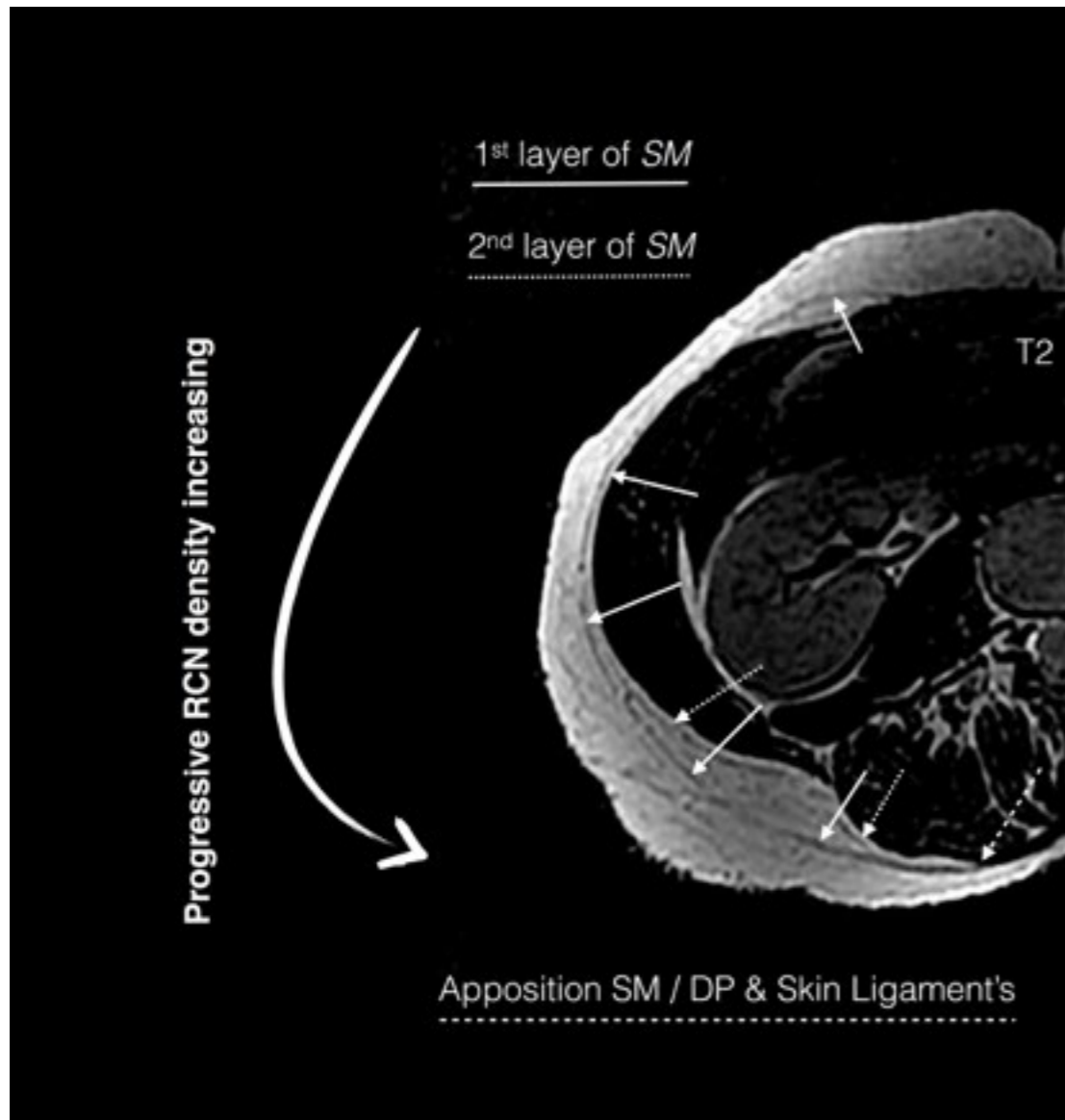
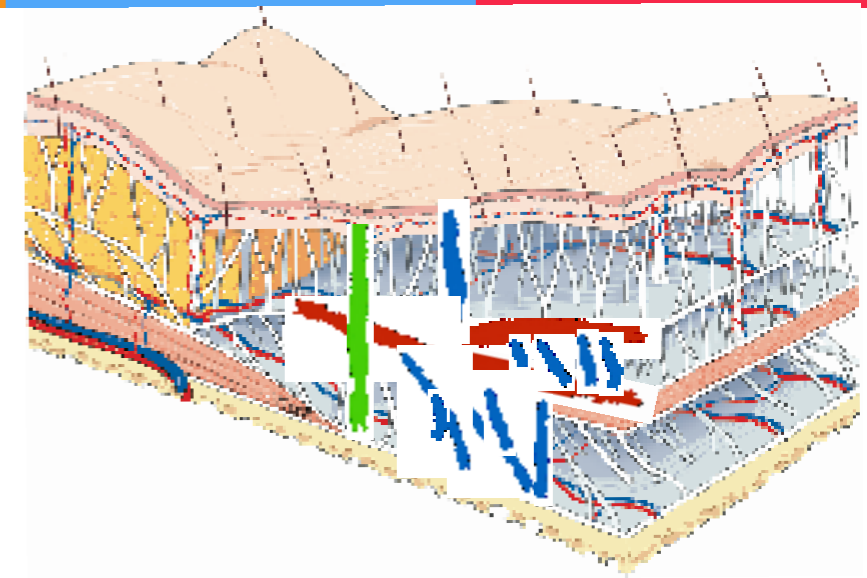


2D

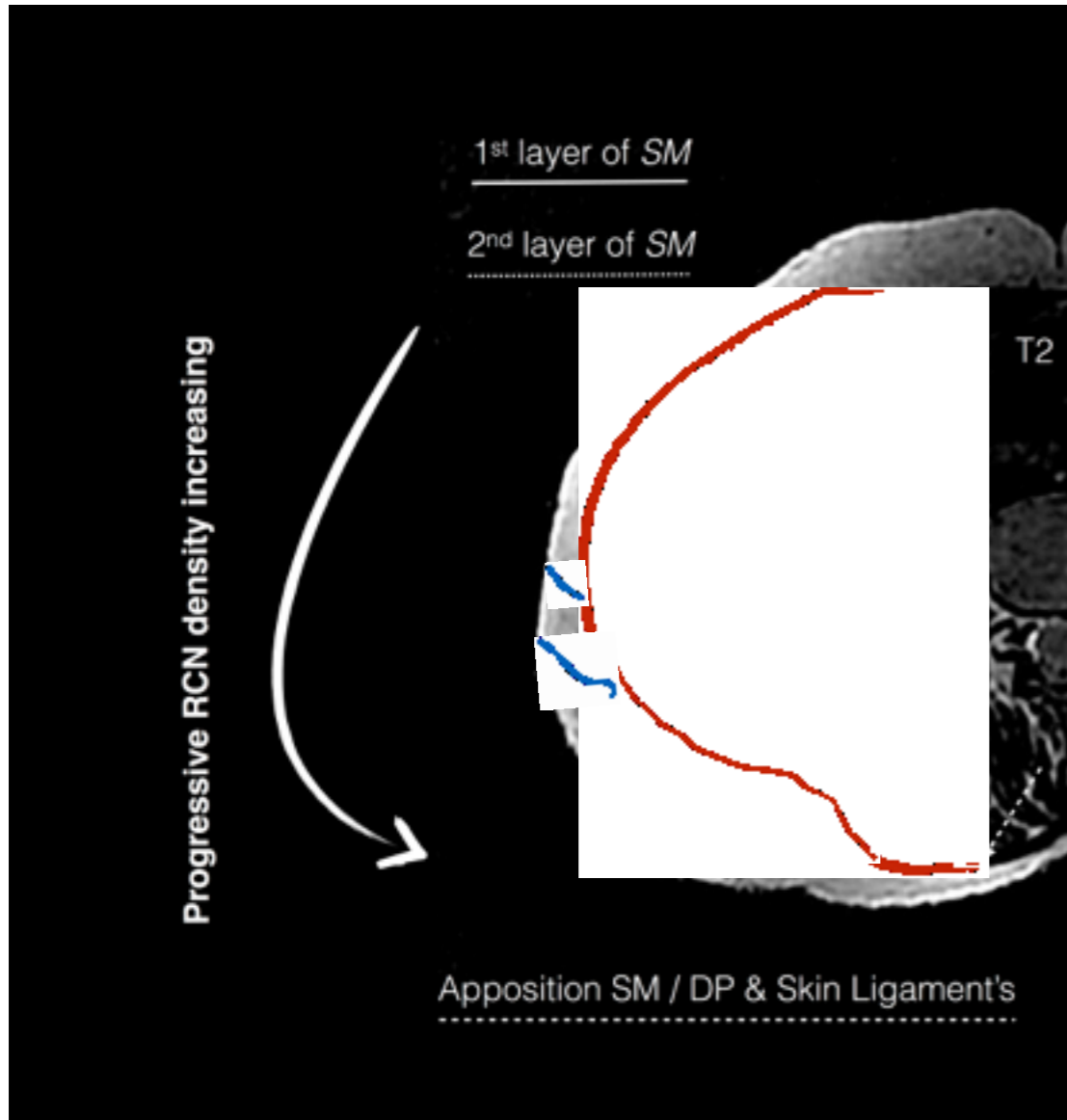
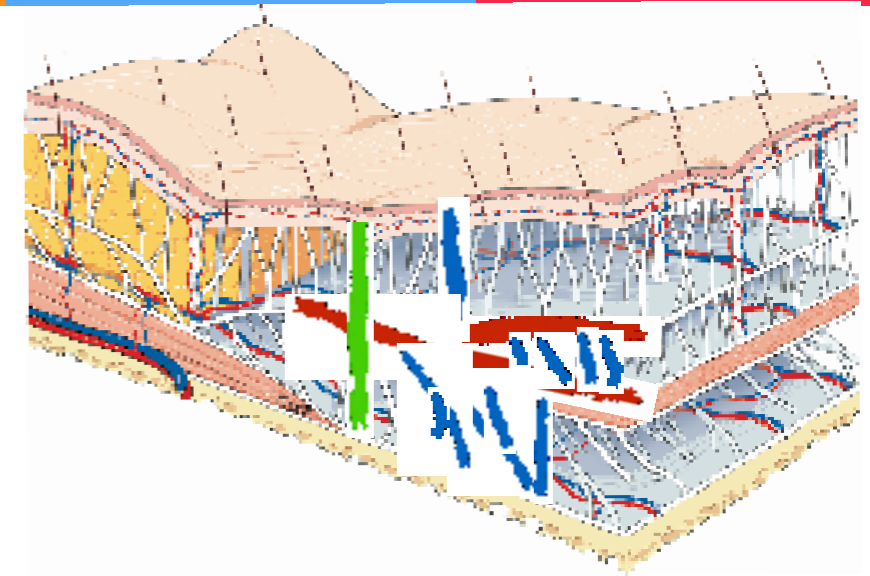




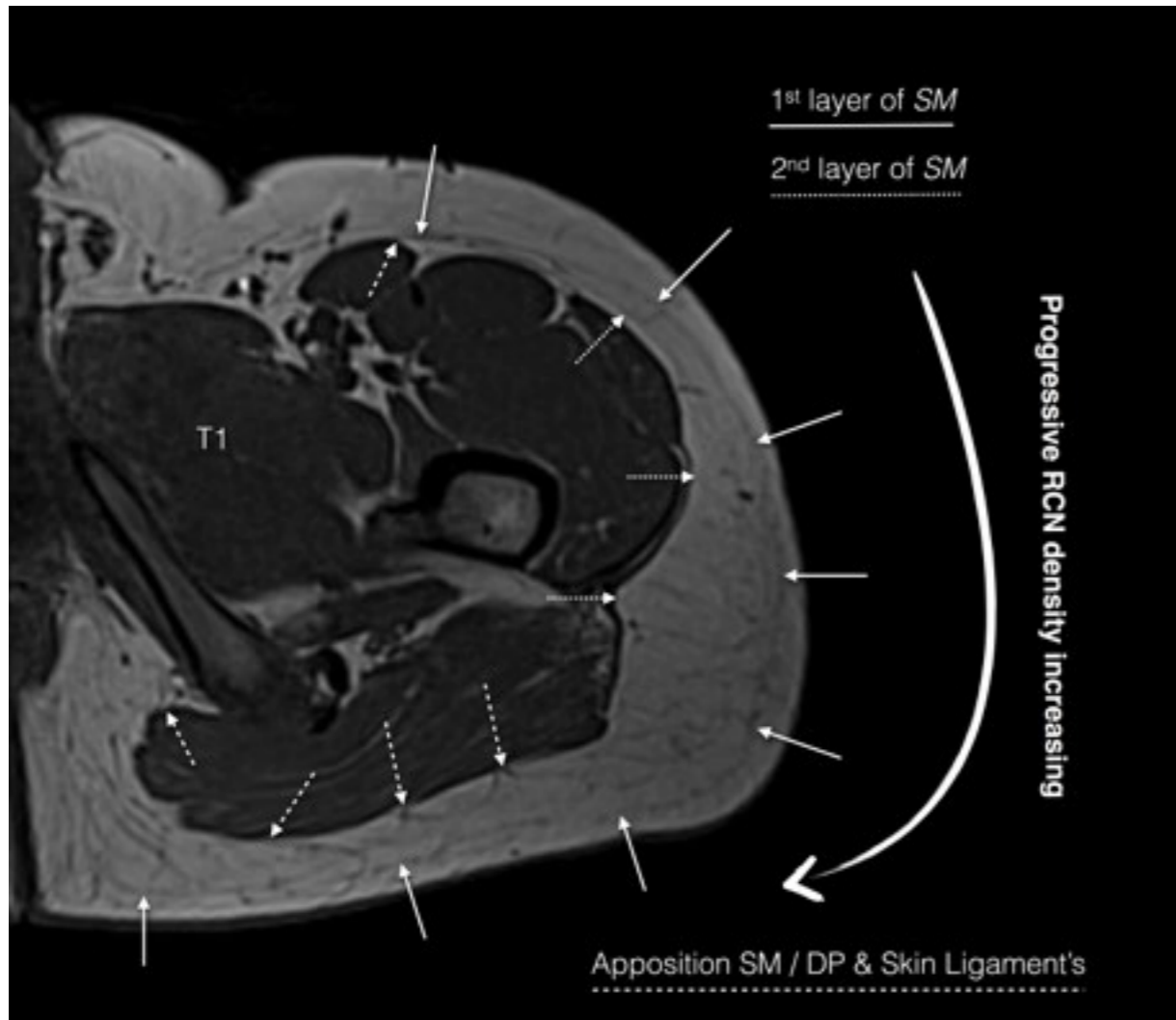
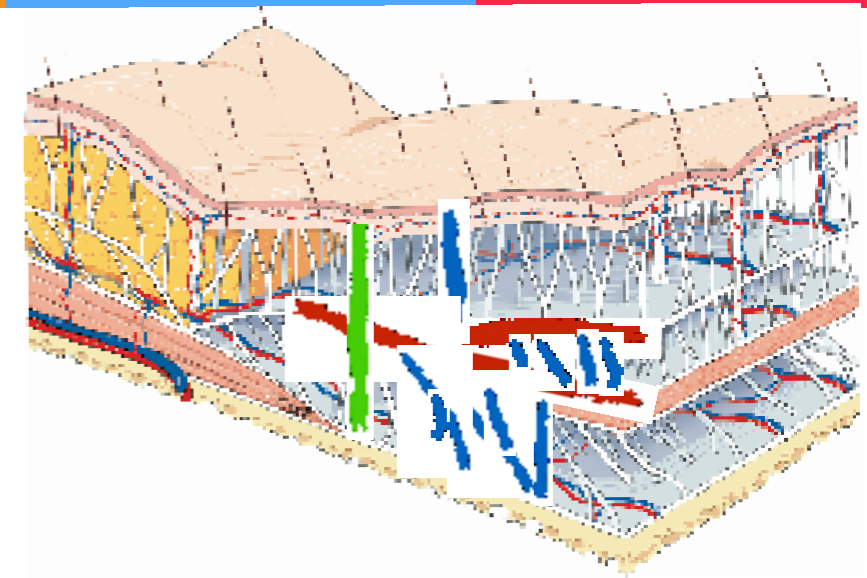
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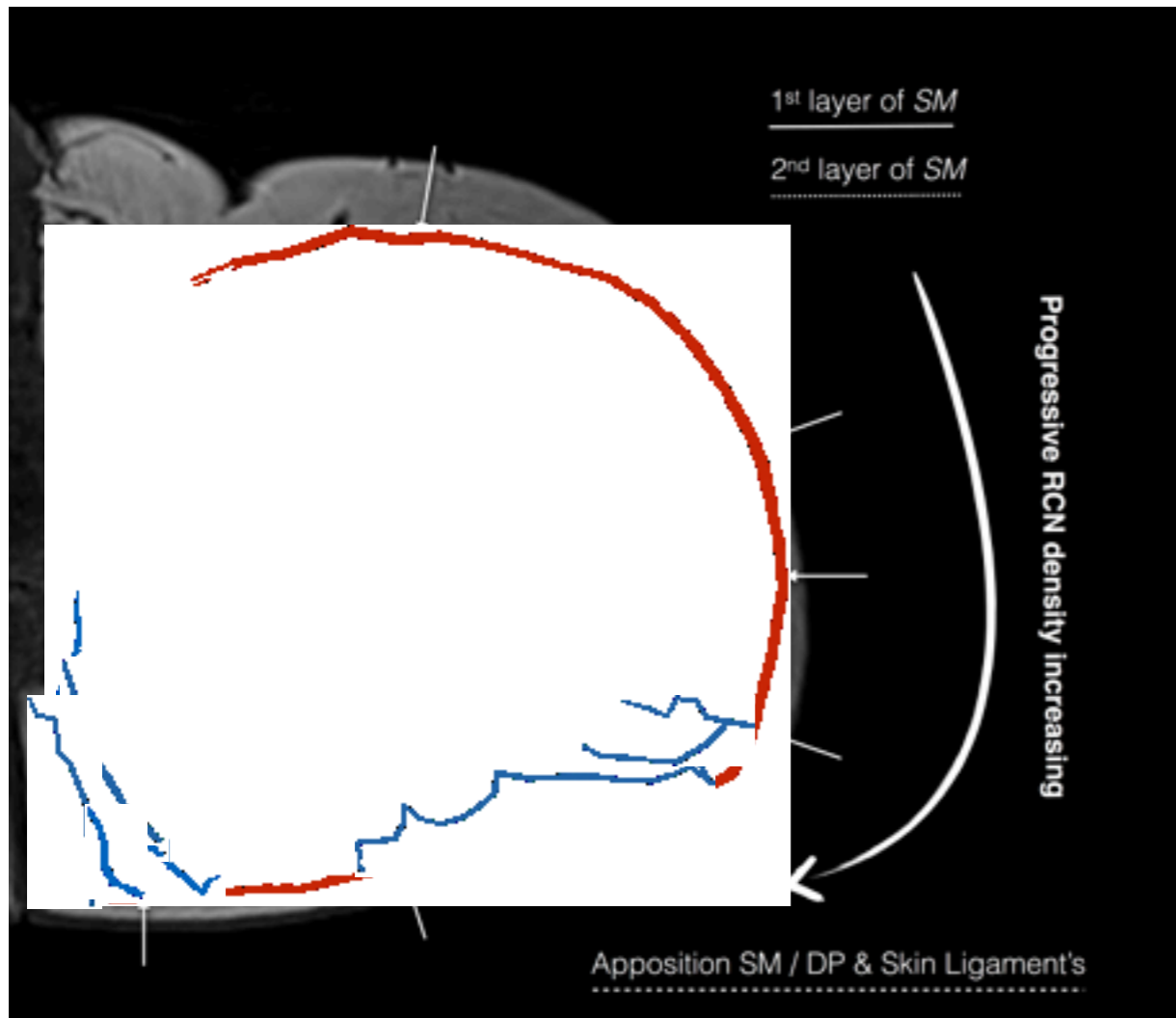
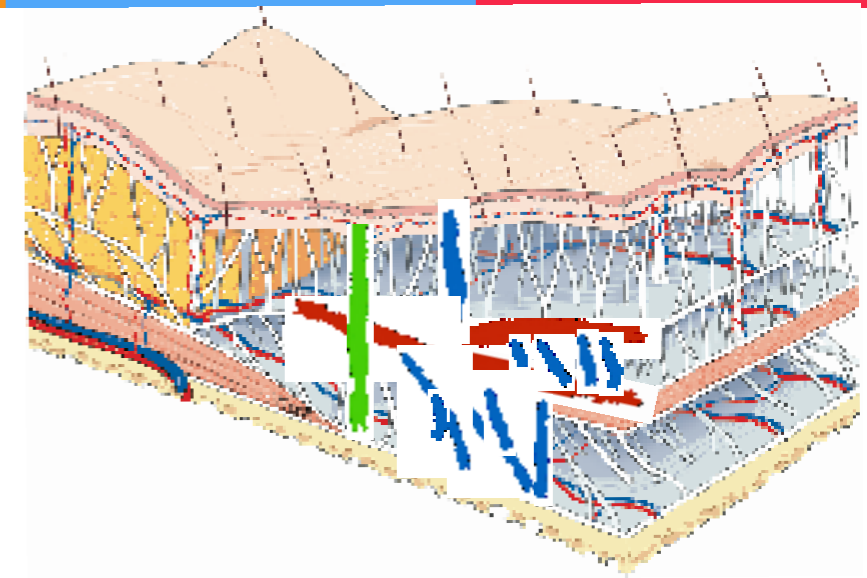
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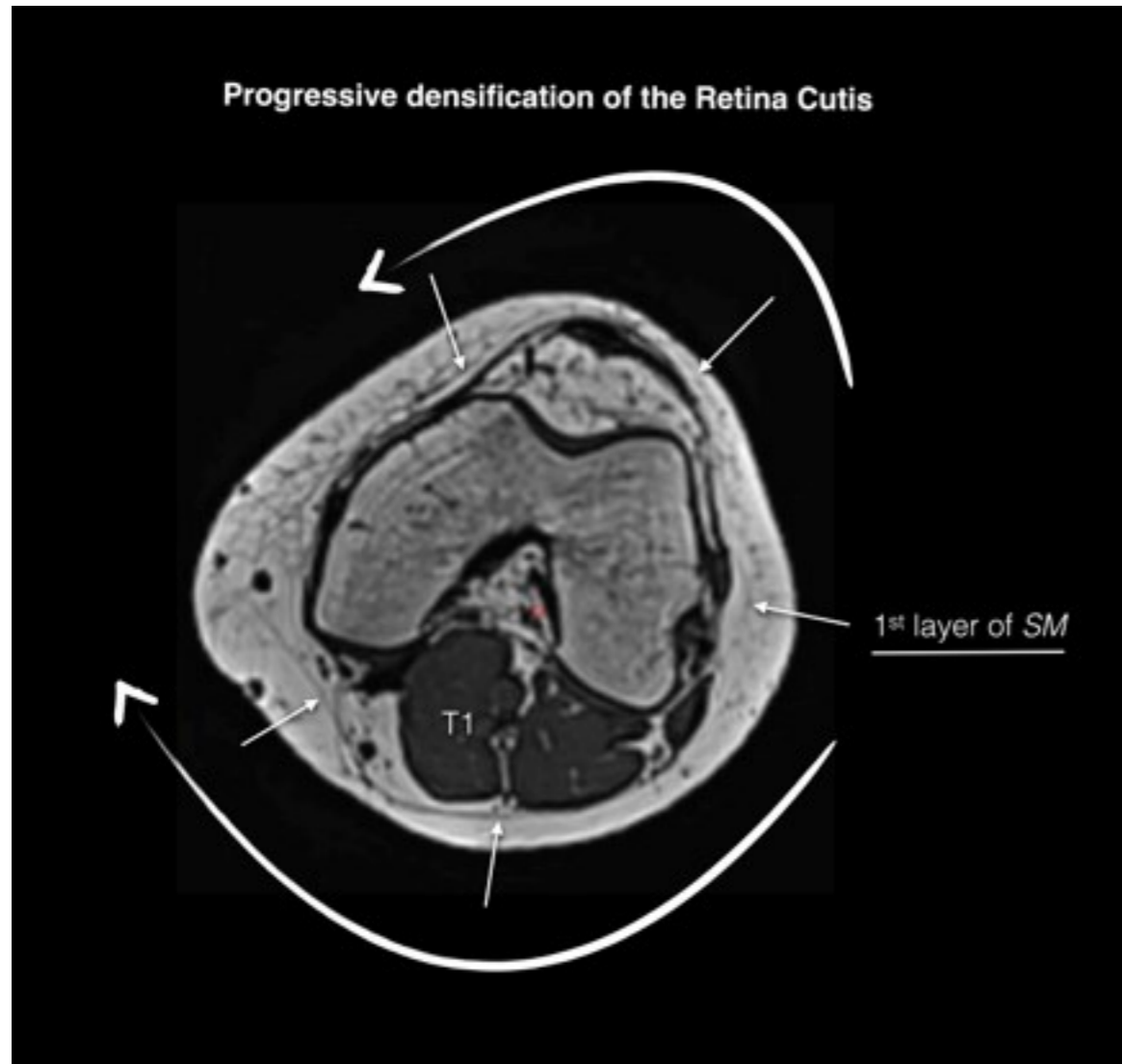
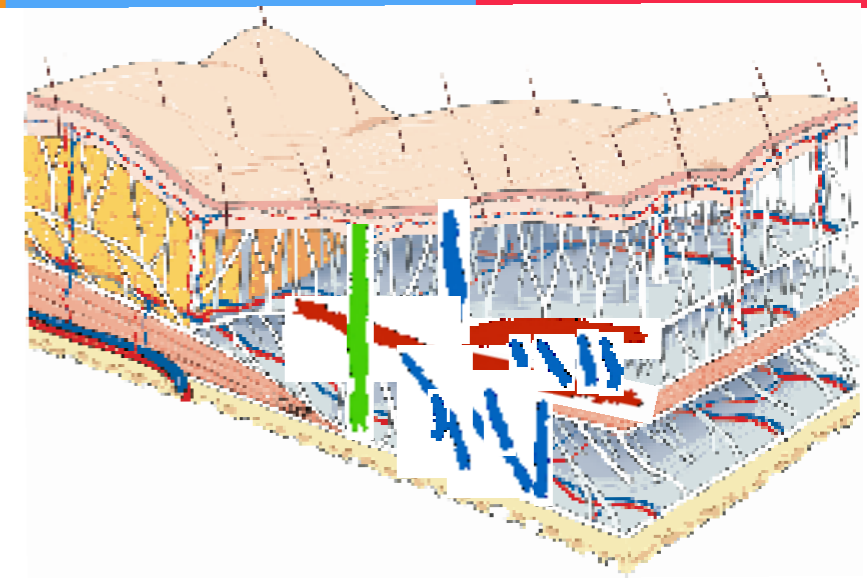
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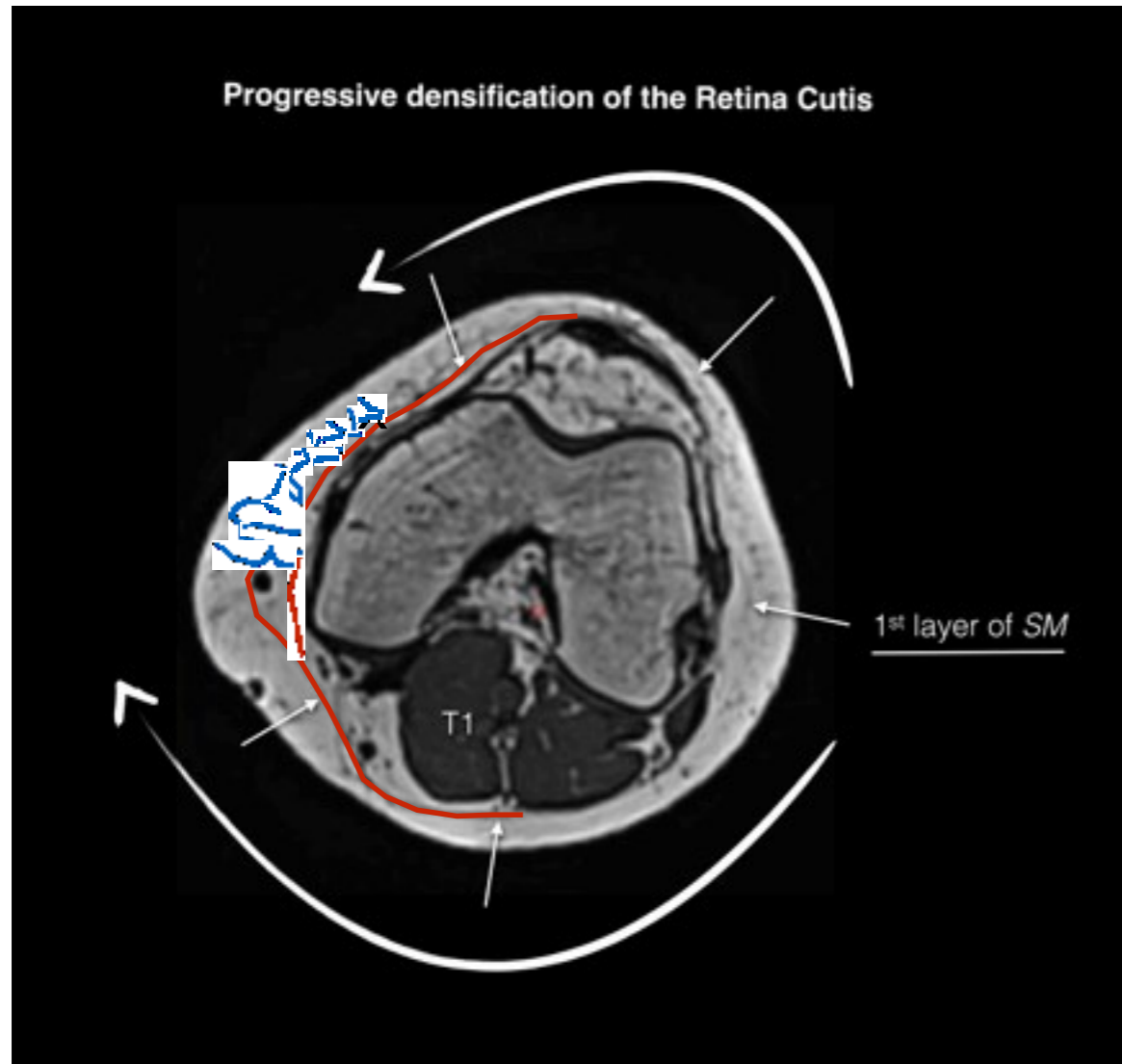
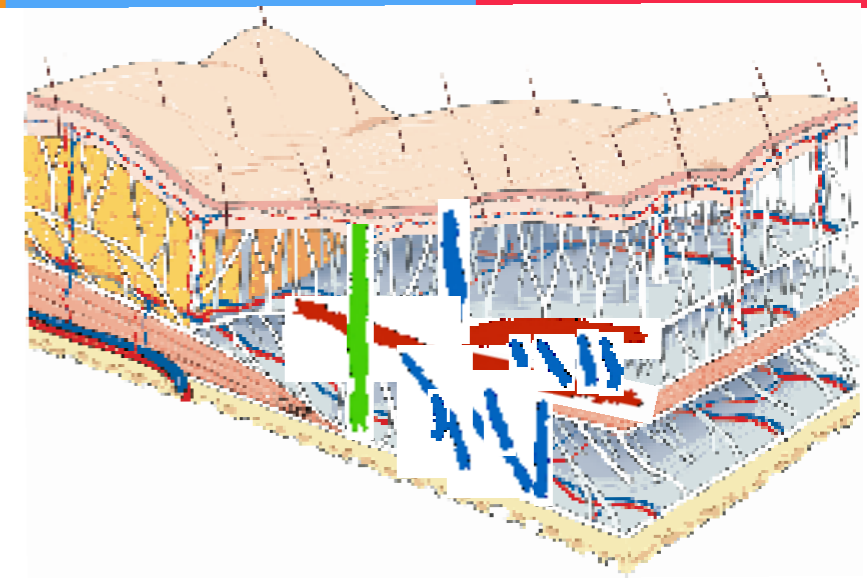
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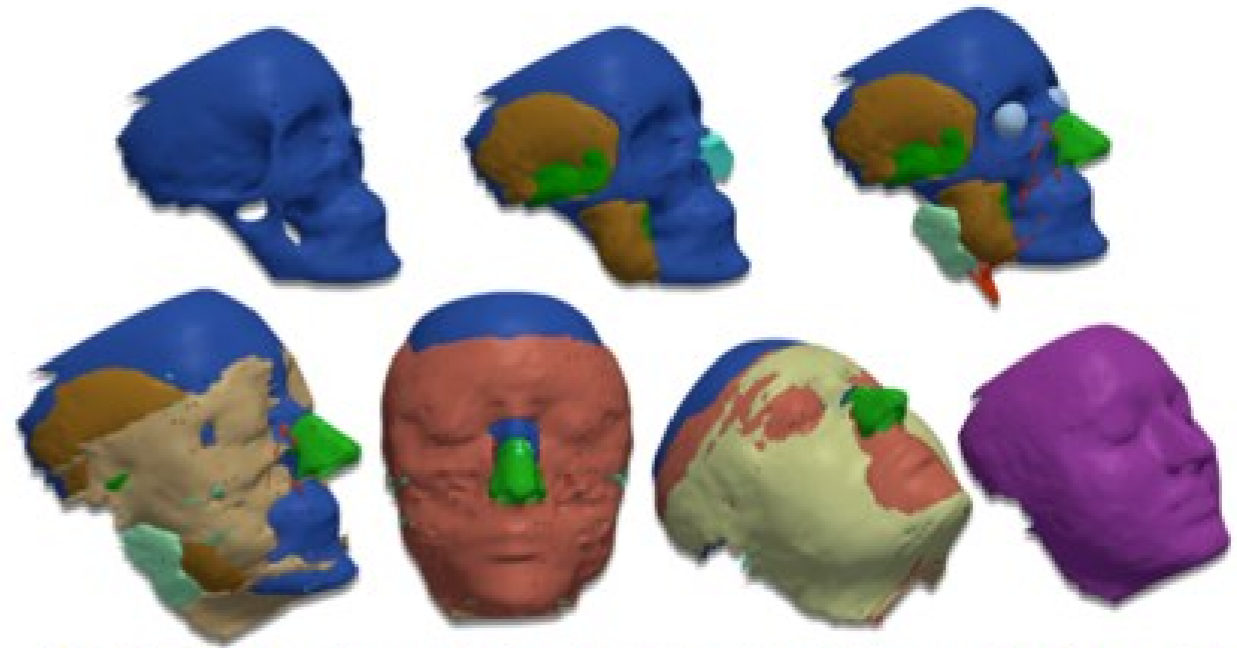
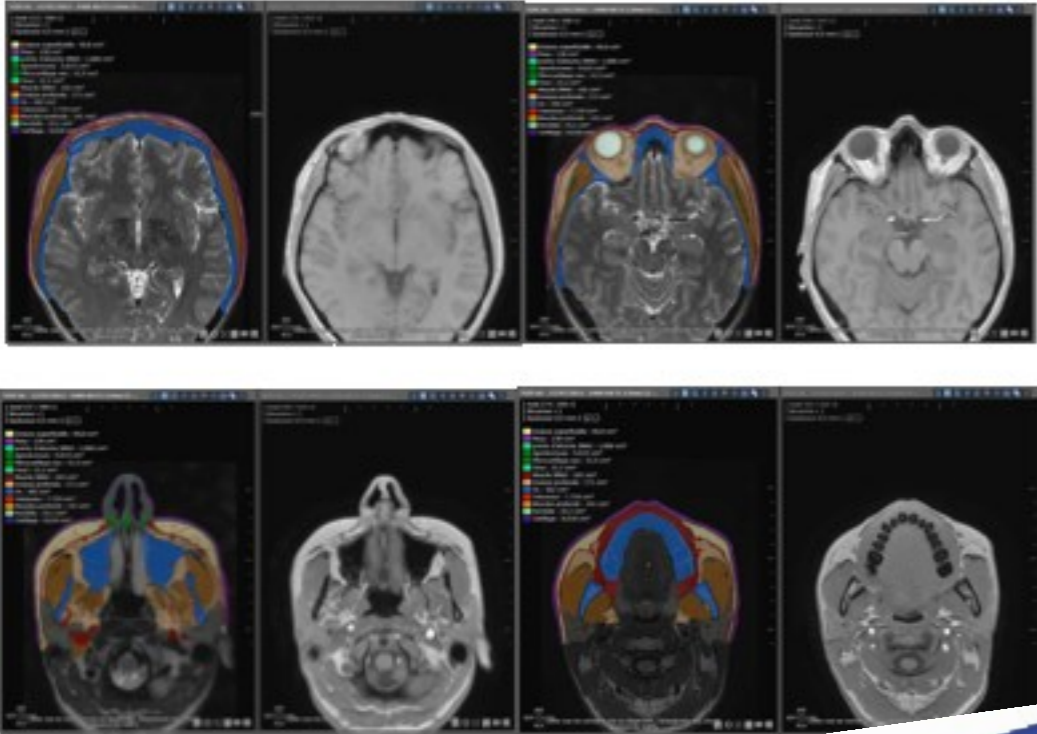
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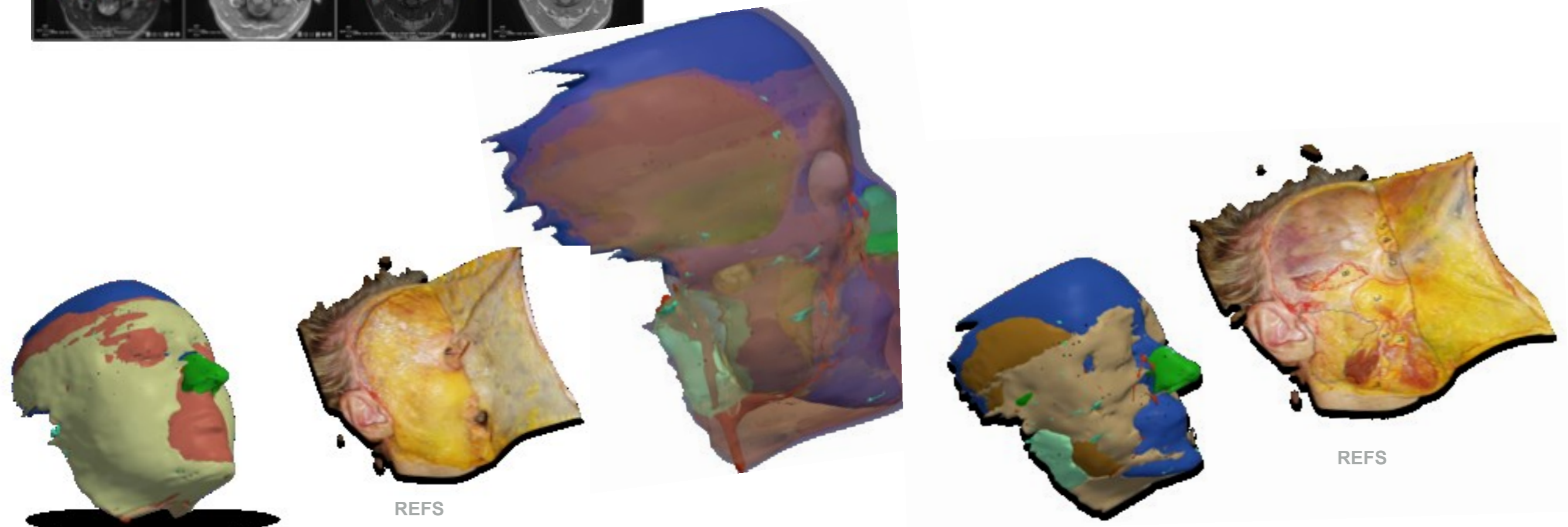
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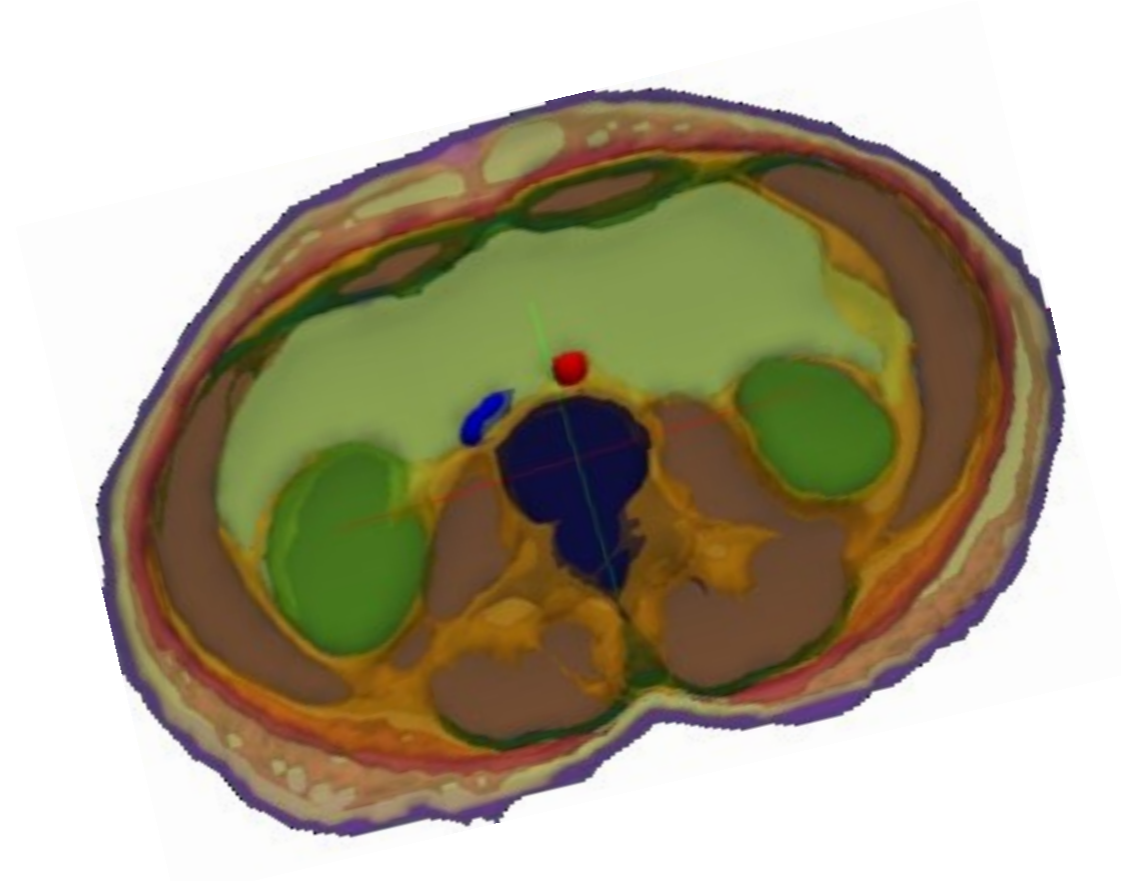
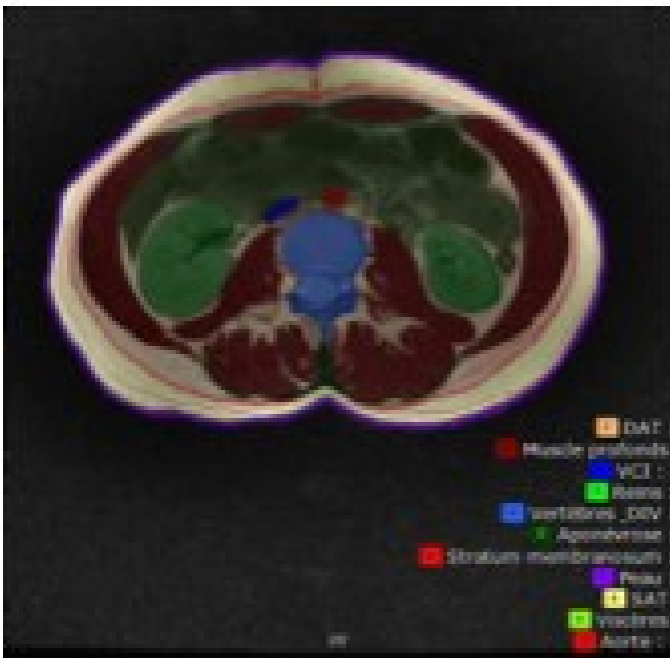
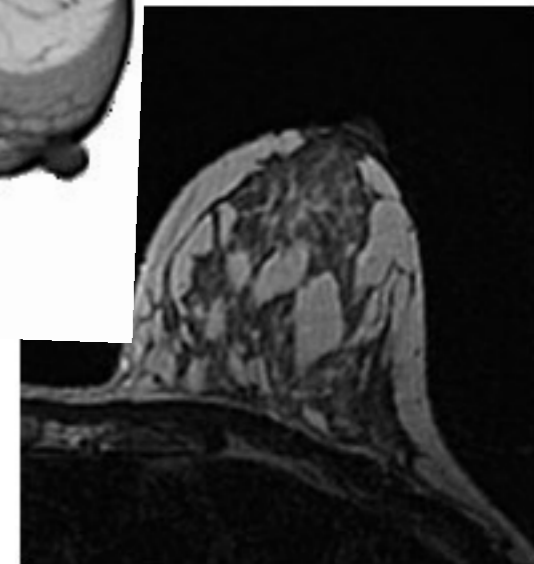
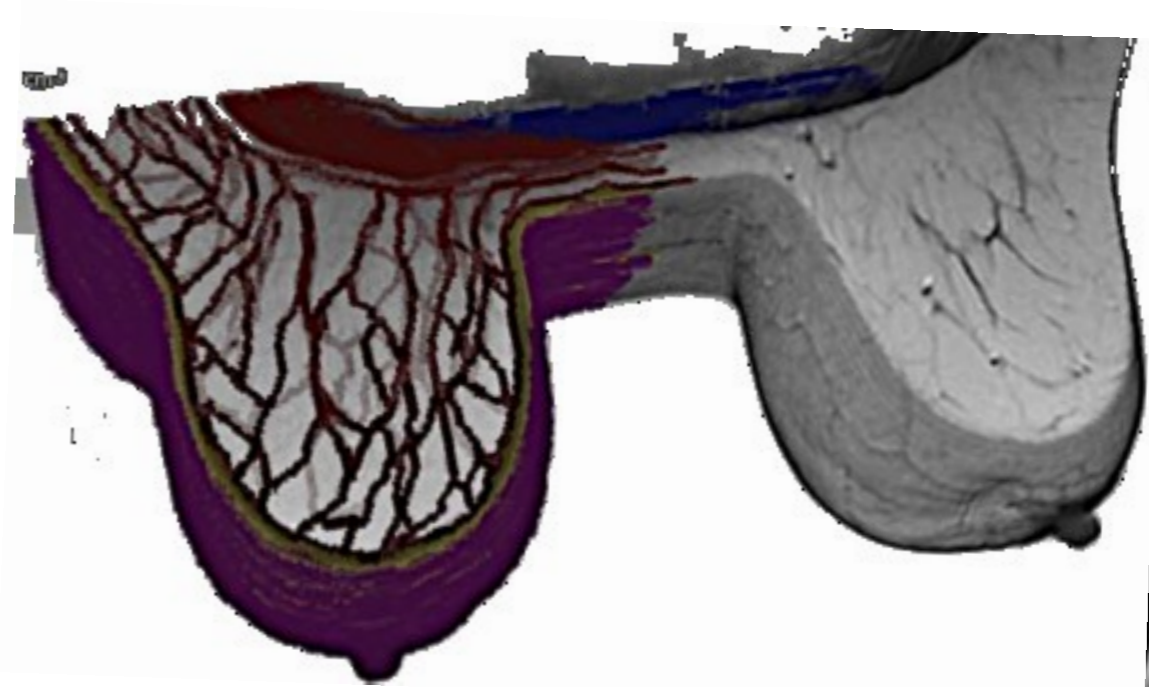
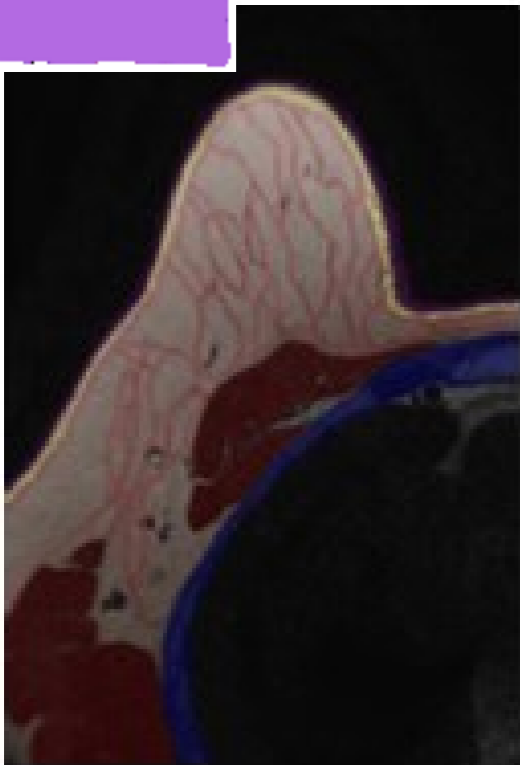
3D



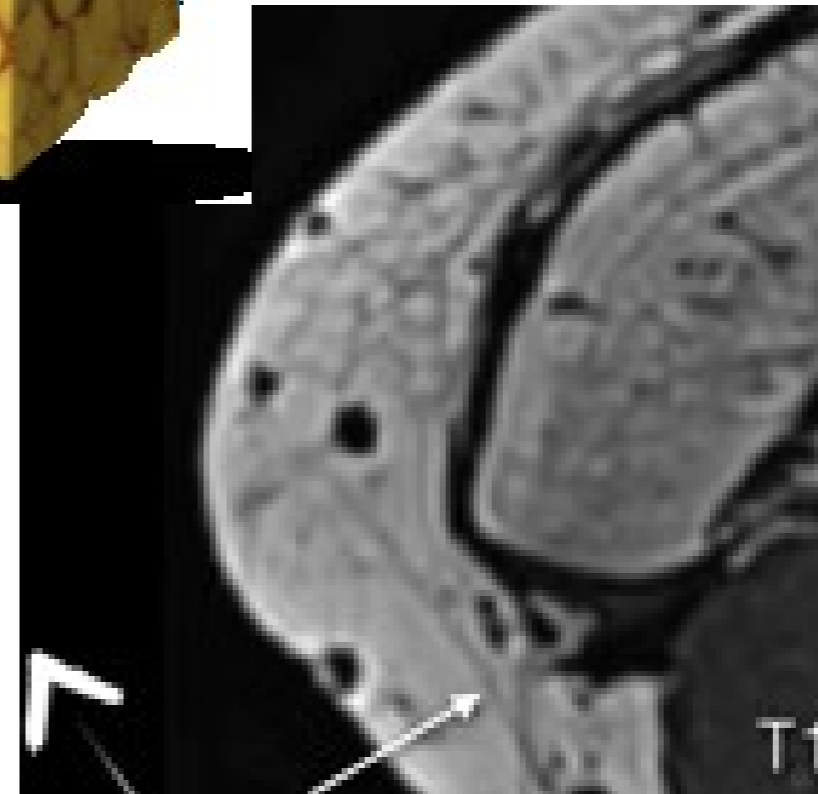
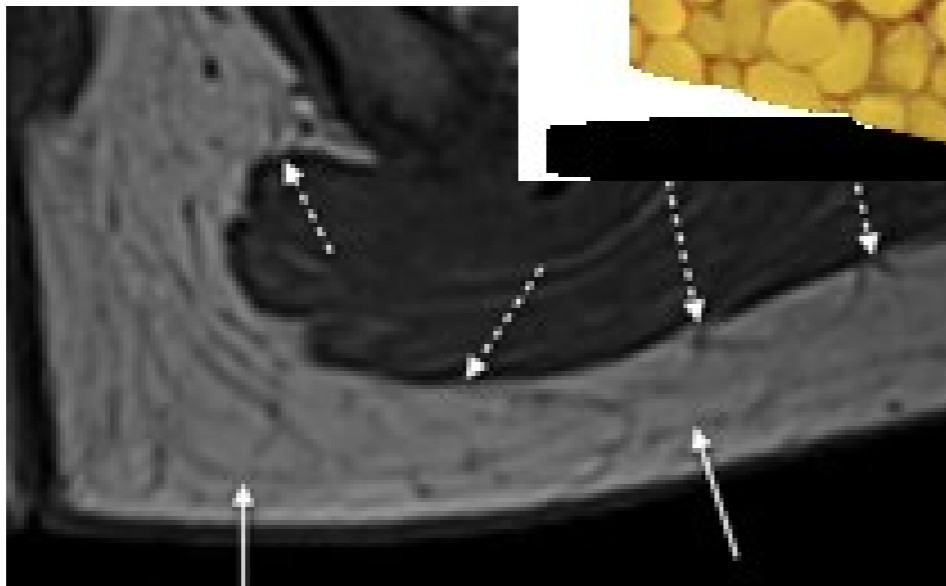
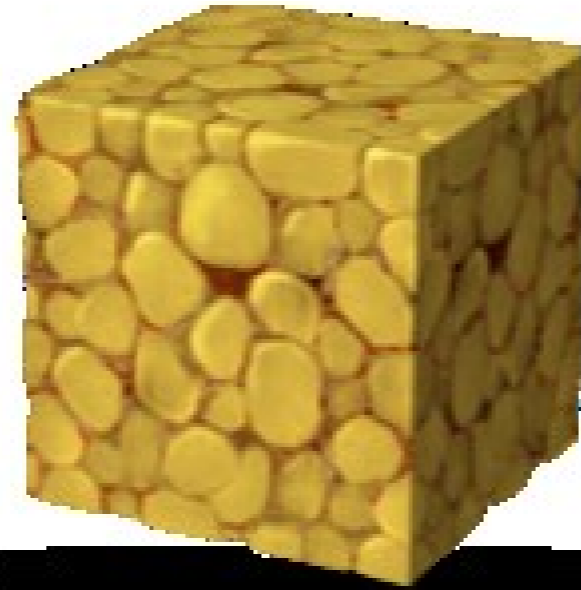
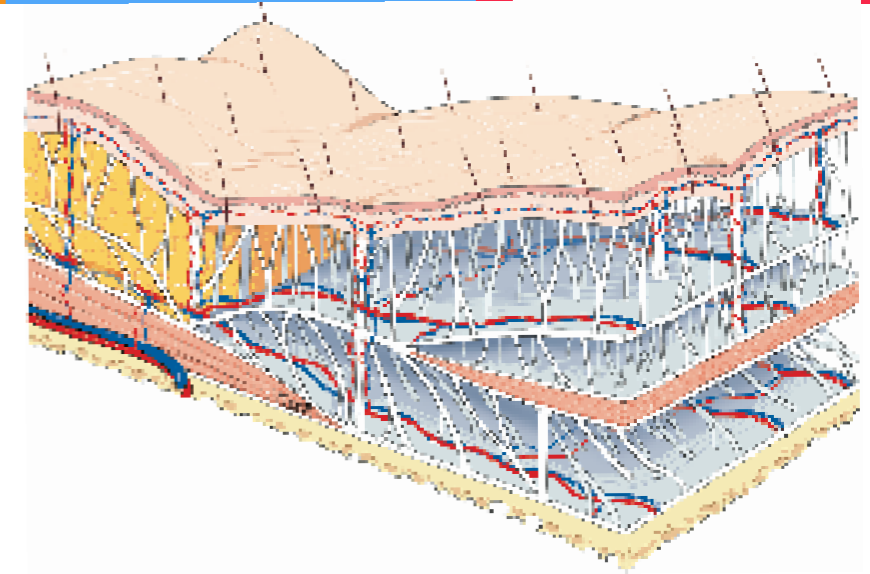
Os + Muscles + Aponévroses + Septum Nasal + Parotides + Vaisseaux + Cartilage nasal  
 + Skin ligaments + Graisse Profonde + SMAS + Graisse Superficielle + Peau



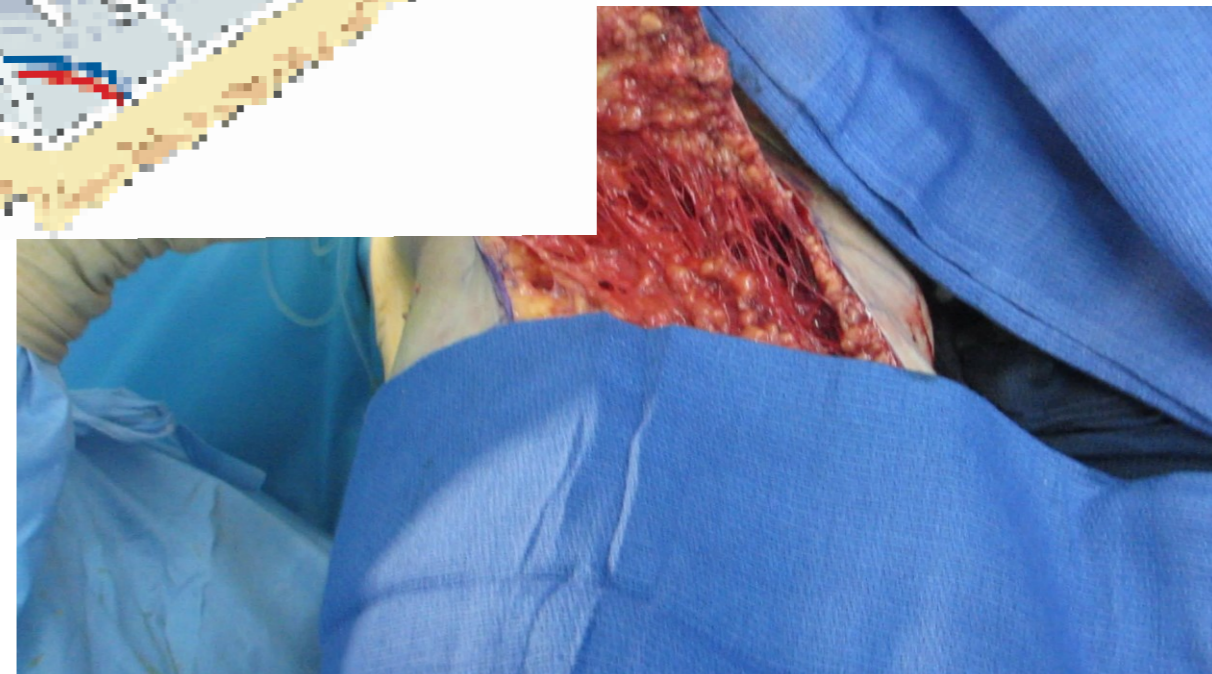
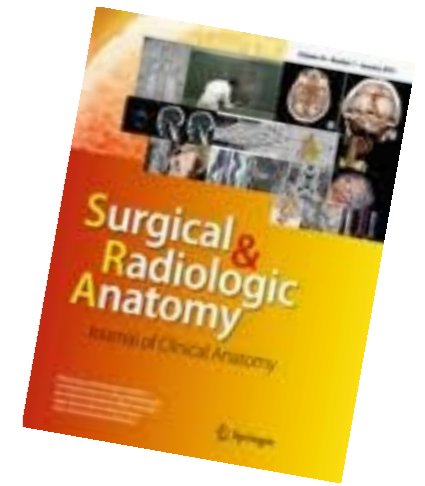
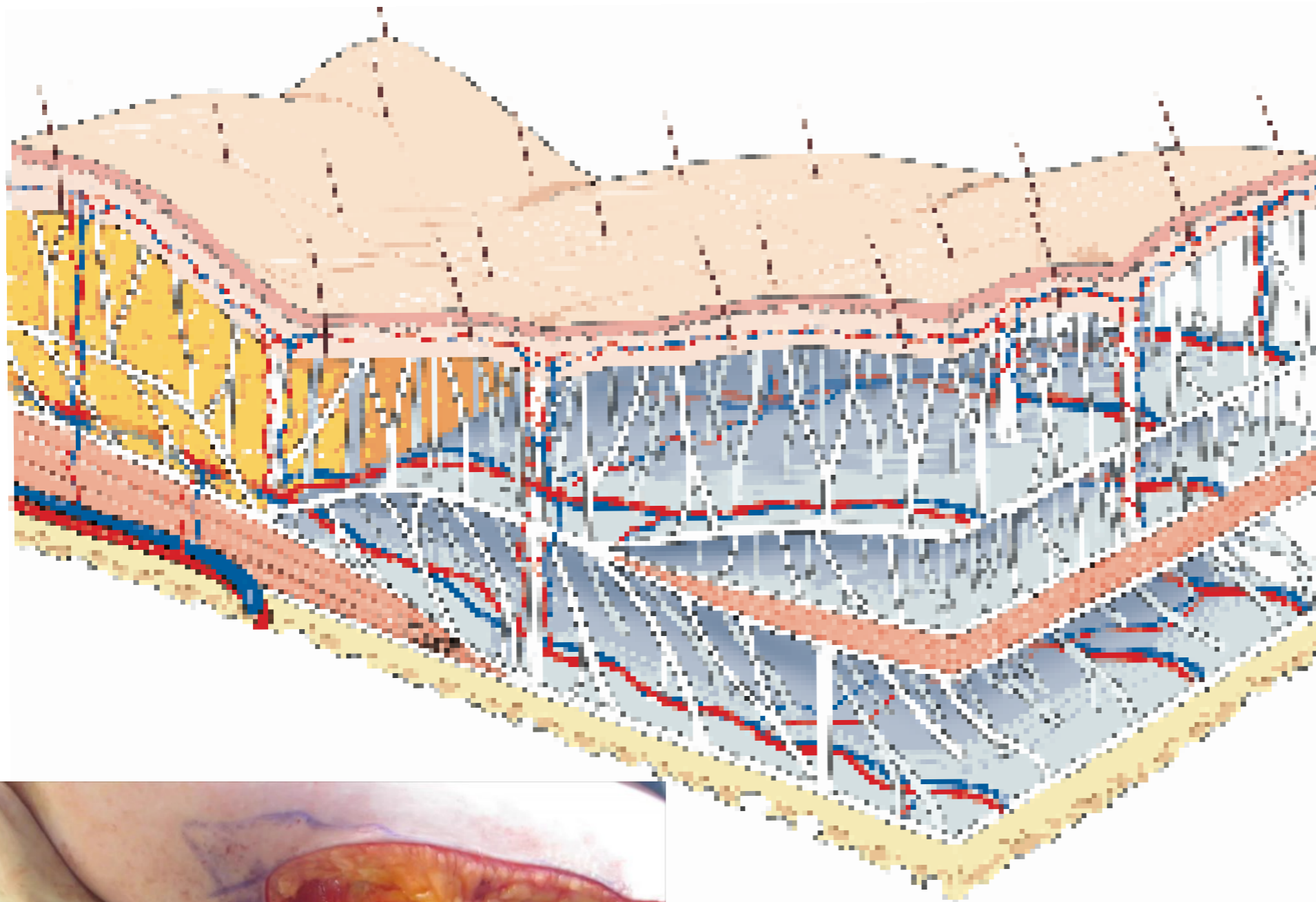
3D





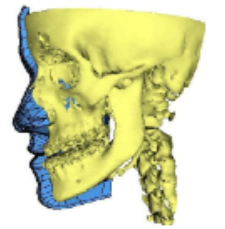


Impossible de segmenter l'architecture lobulaire

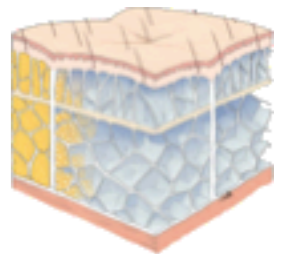


# PLAN

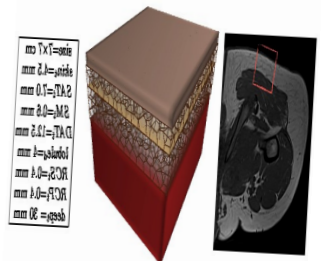
Etat de l'art



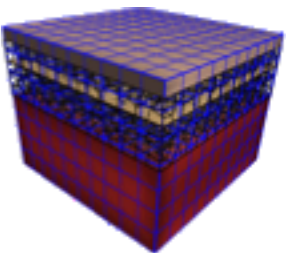
Modélisation anatomique



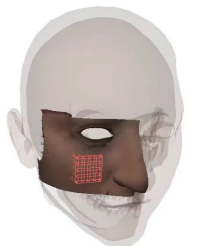
Modélisation géométrique paramétrique et procédurale



Modélisation biomécanique hybride



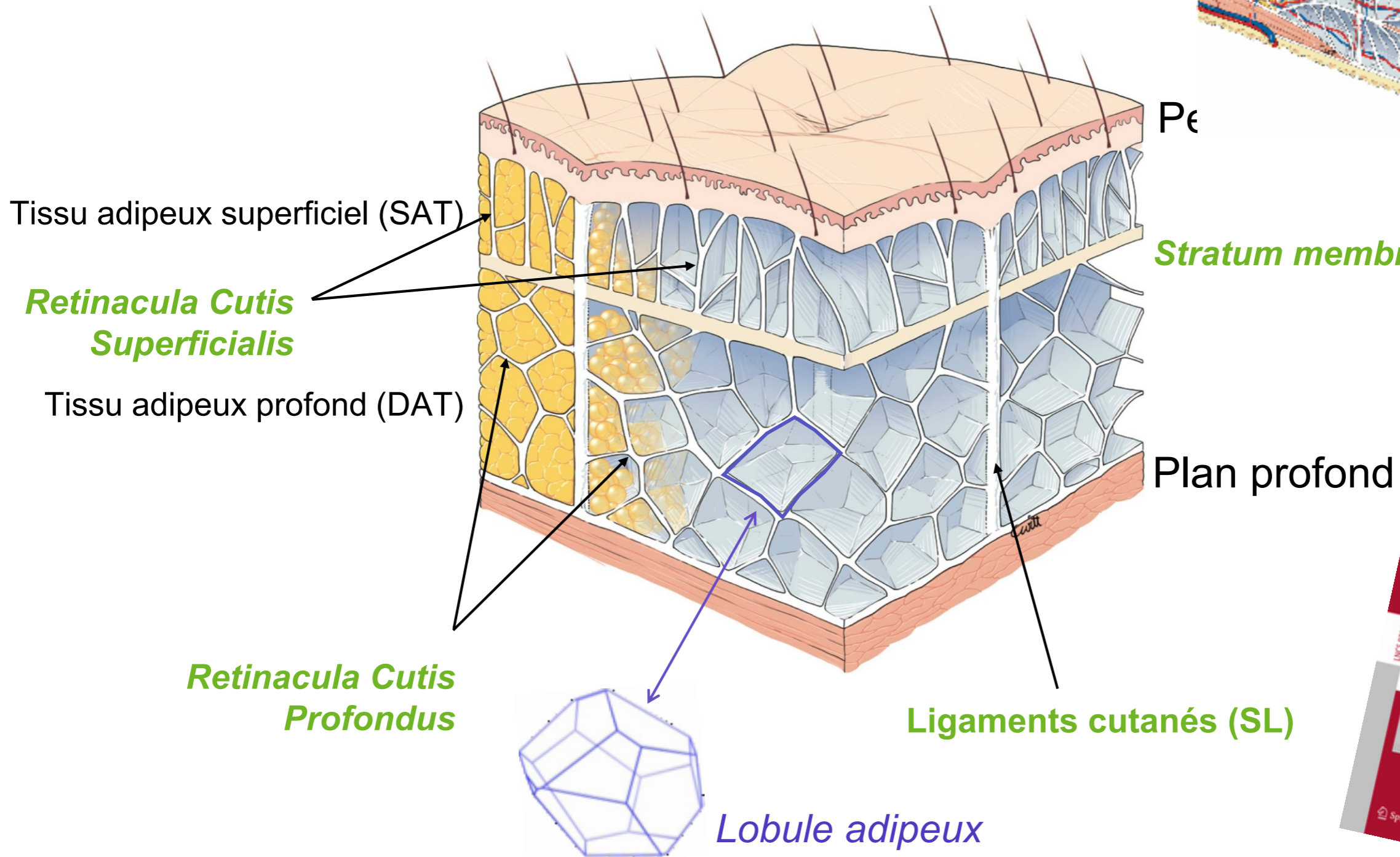
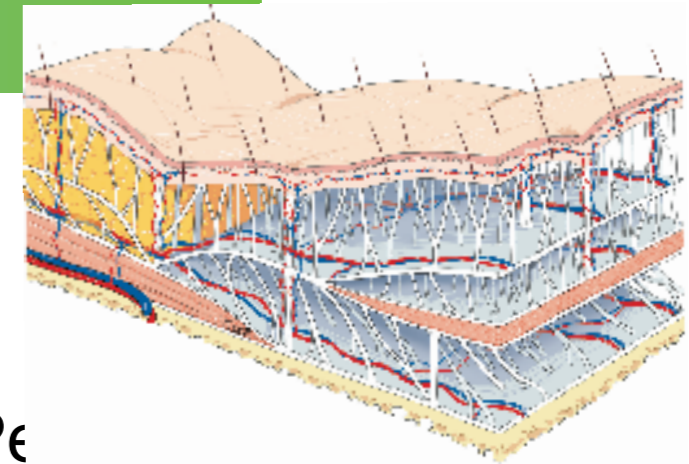
Simulations



Perspectives



# Modélisation géométrique

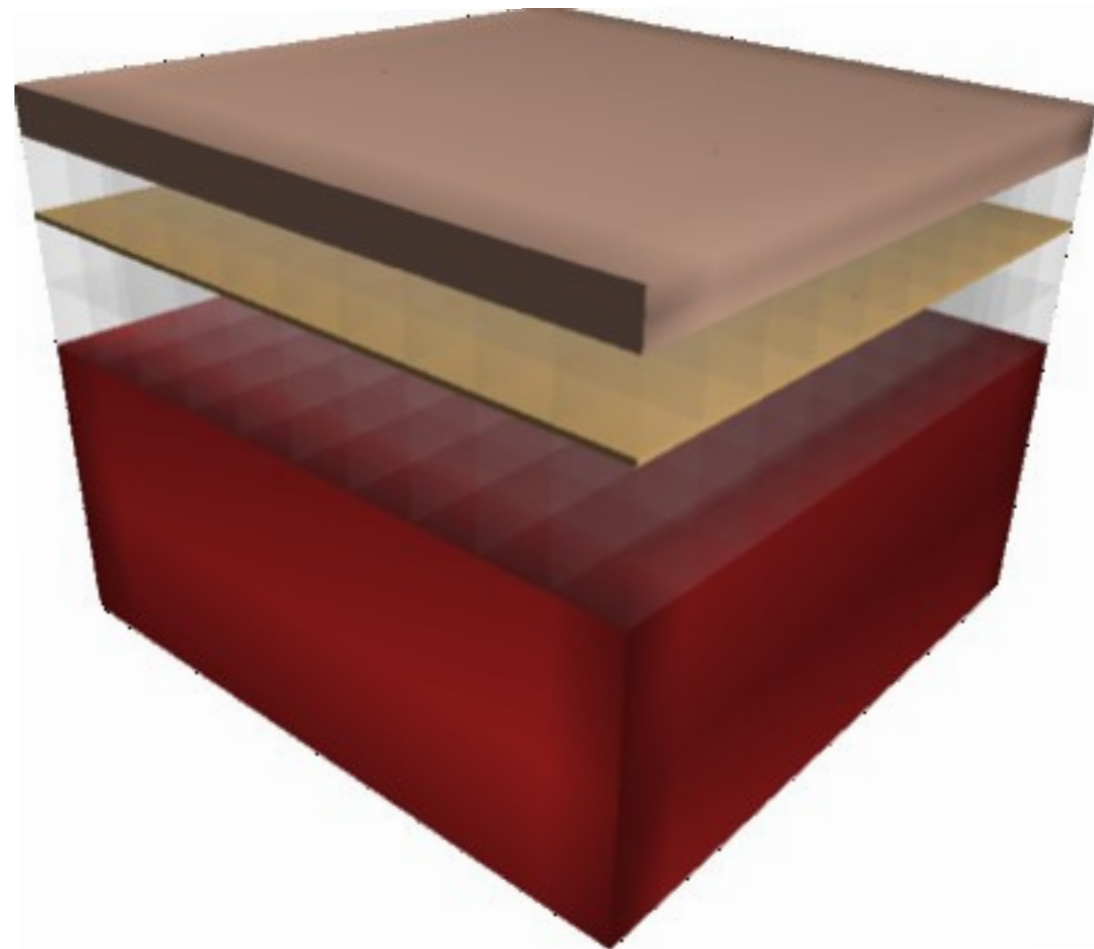
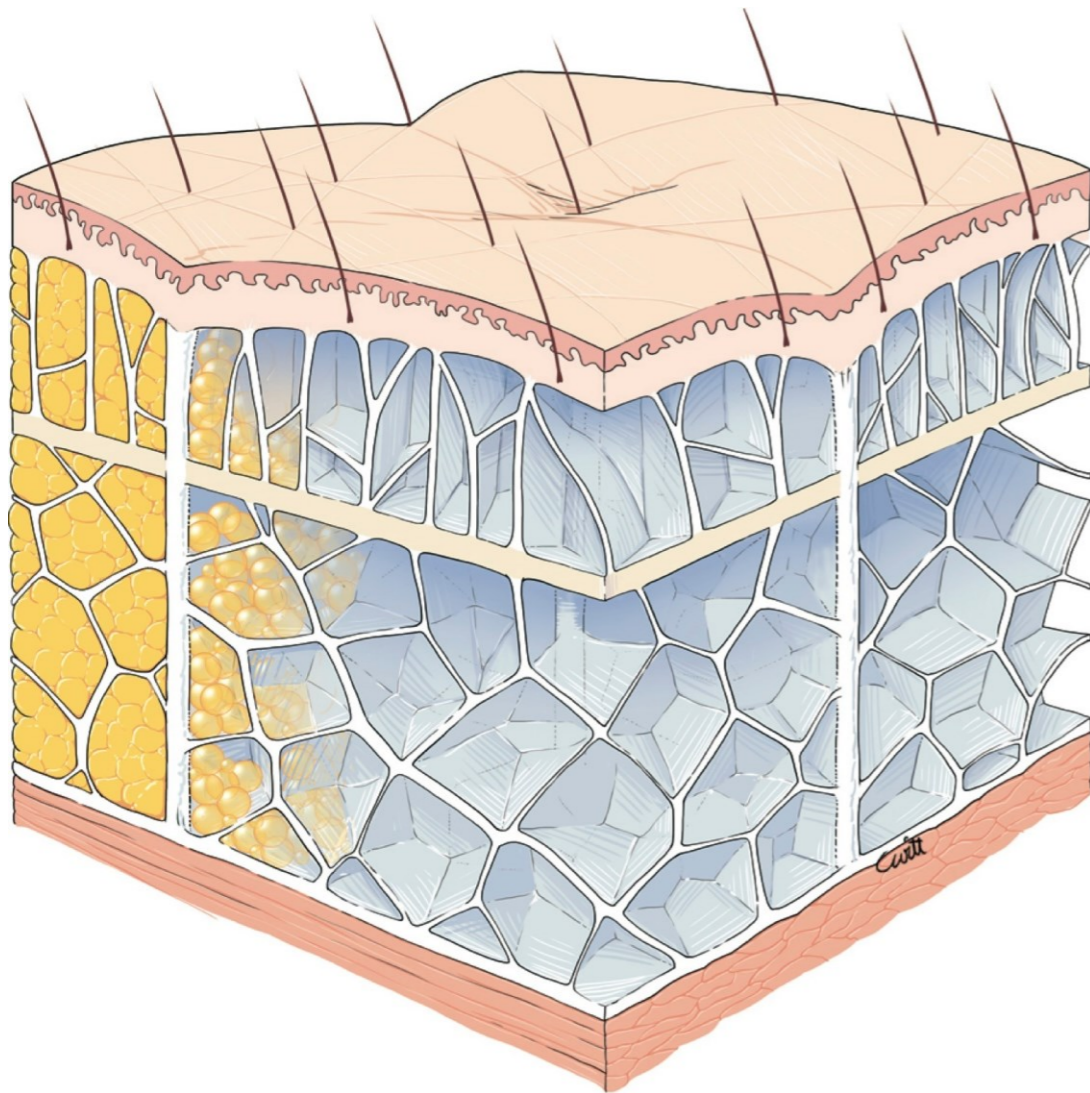


Pe

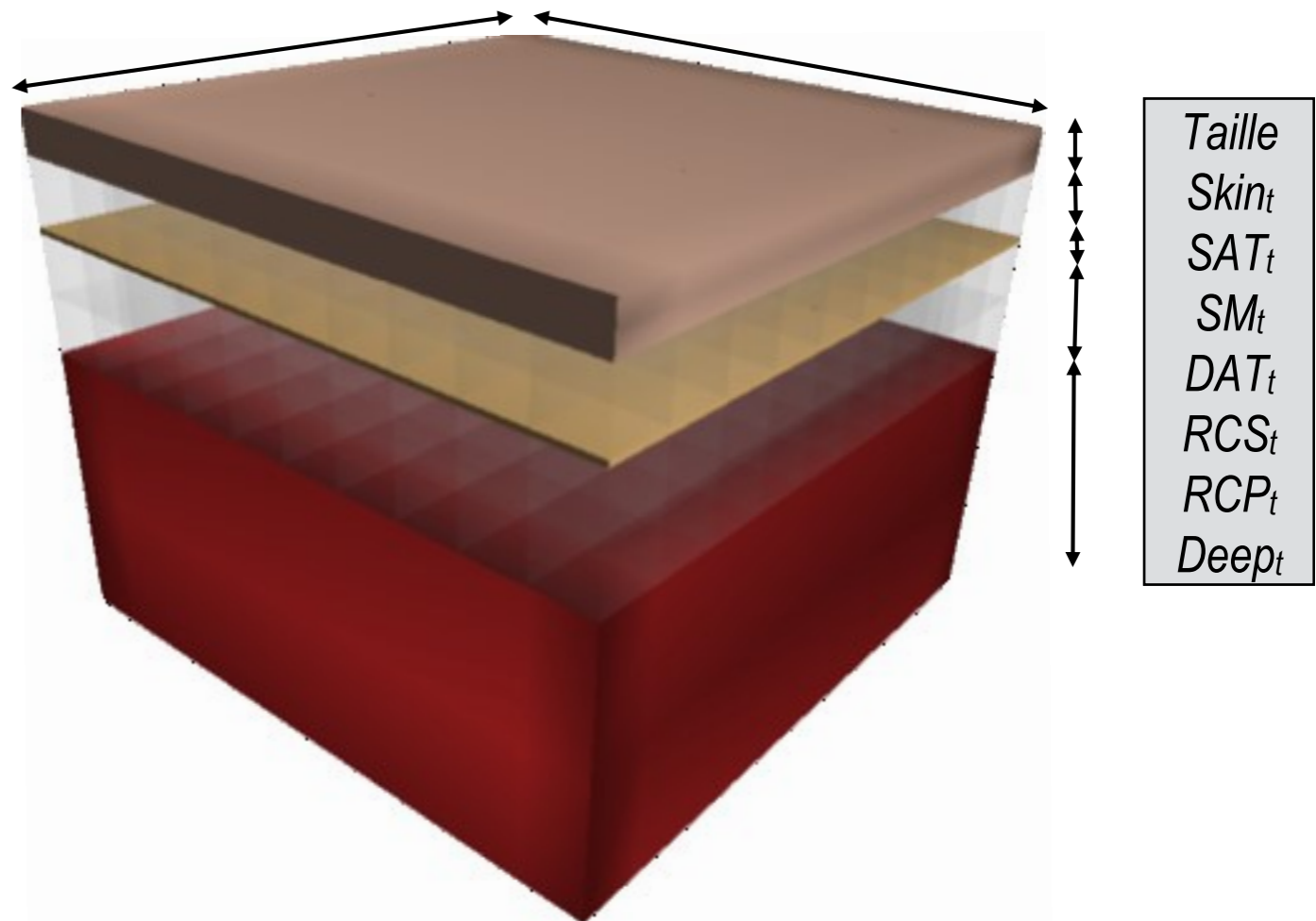
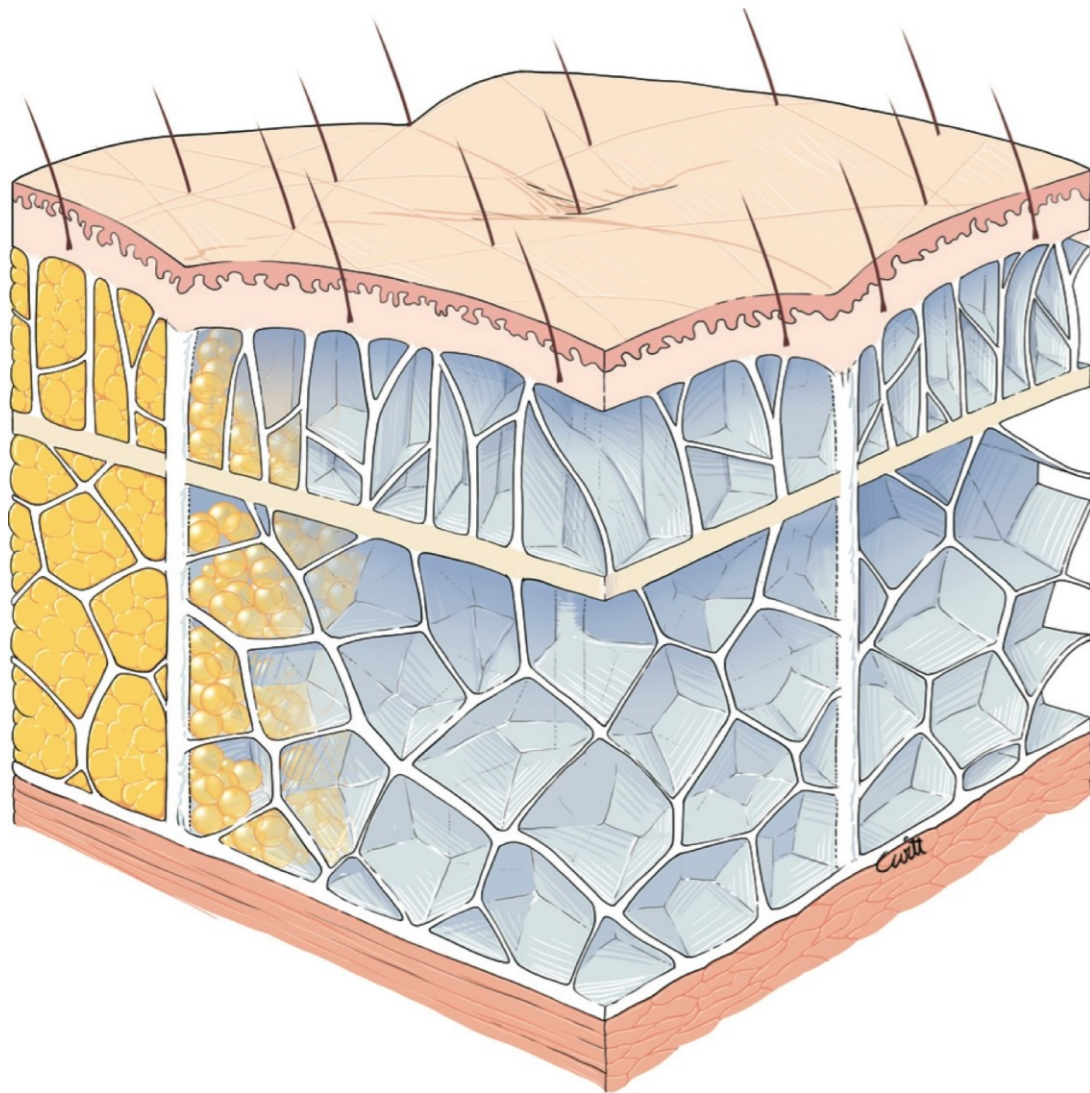
*Stratum membranosum*



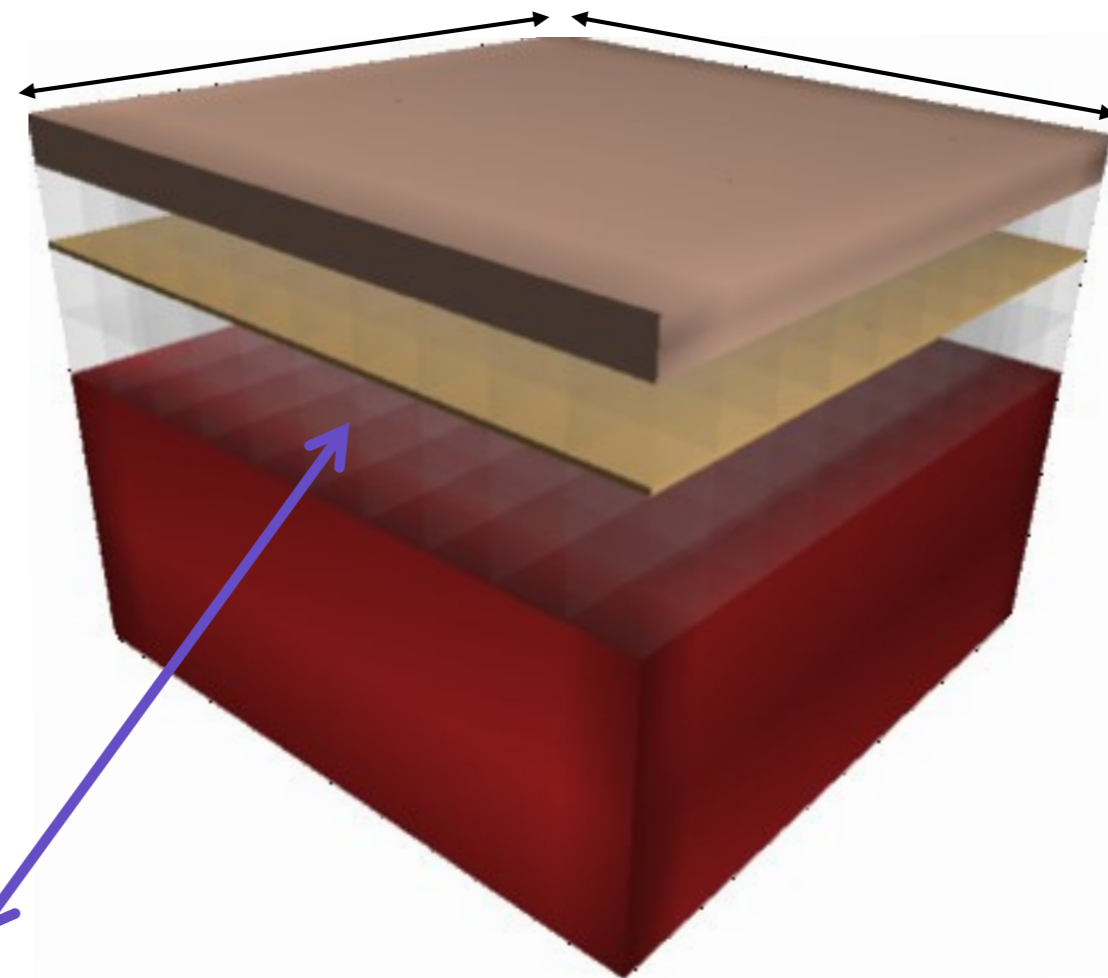
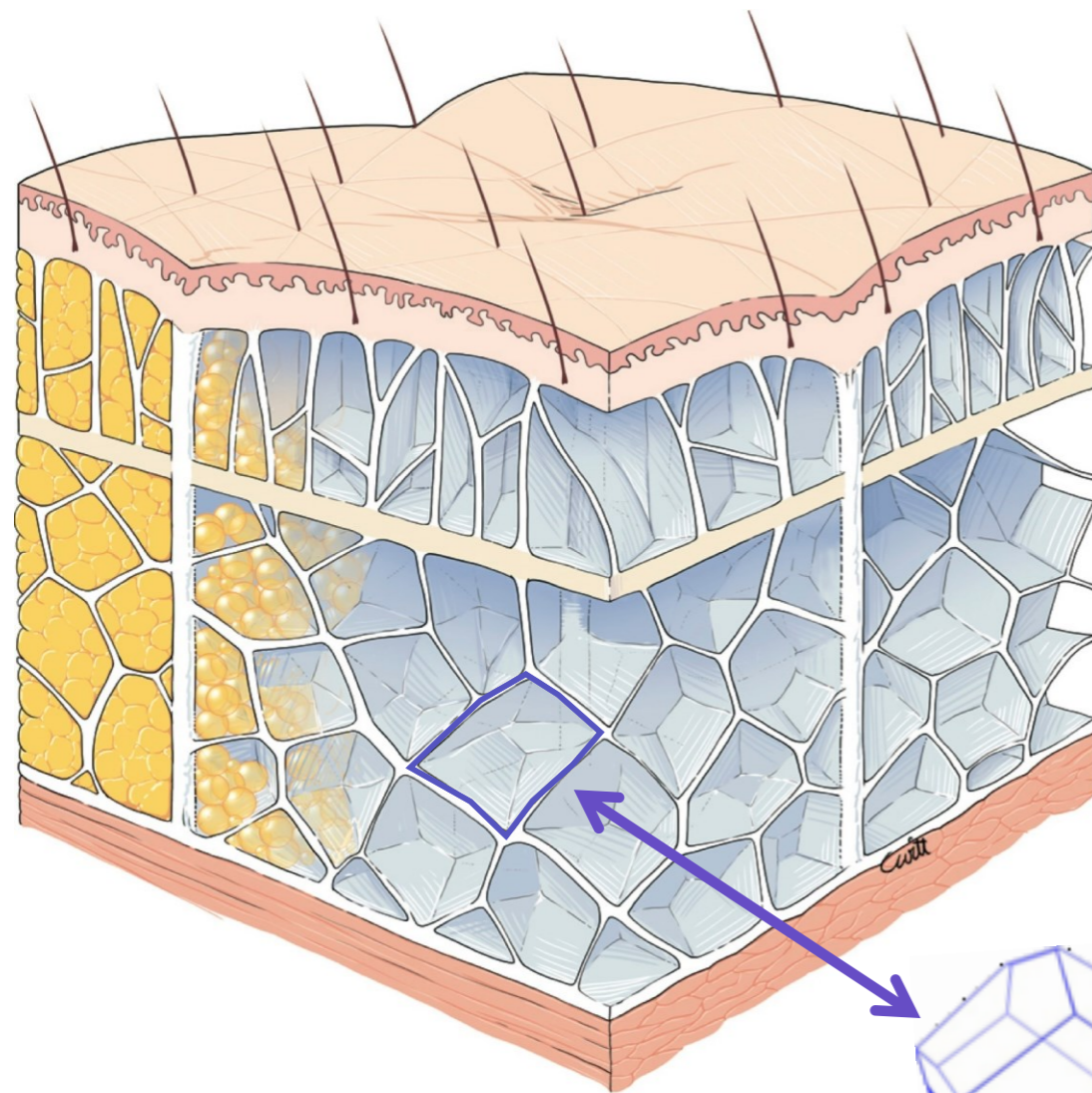
# Modélisation géométrique



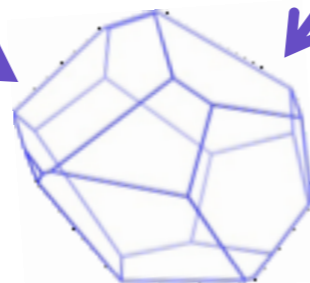
# Modélisation paramétrique



# Modélisation paramétrique

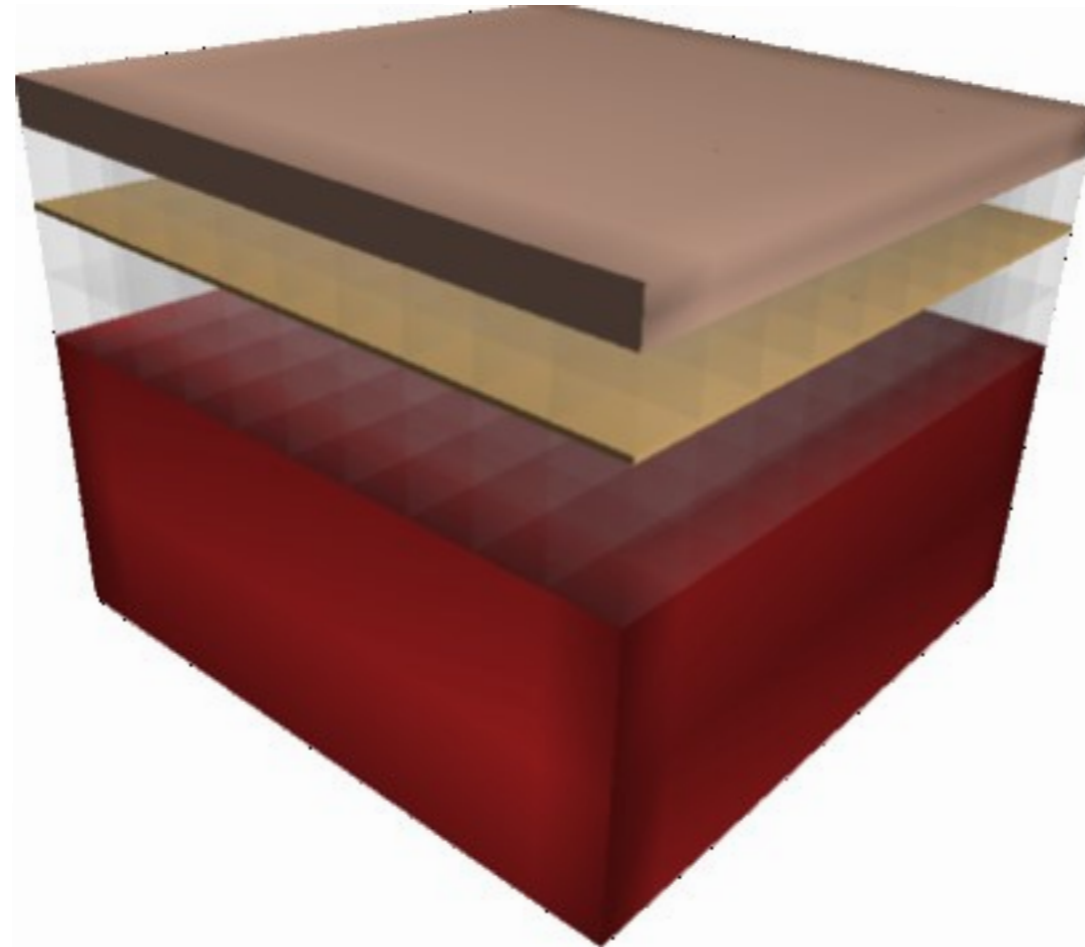
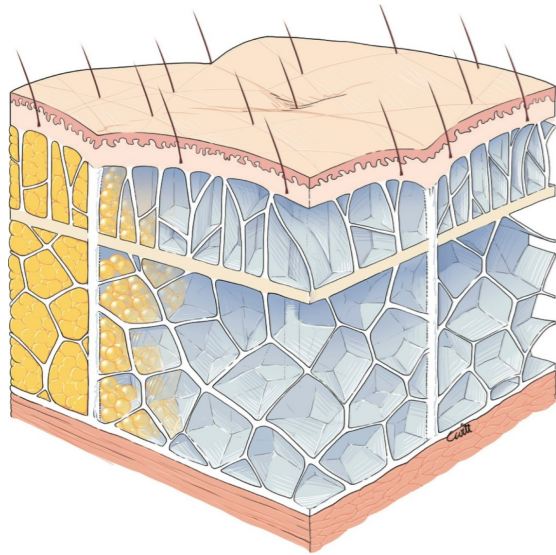


Taille  
 $Skin_t$   
 $SAT_t$   
 $SM_t$   
 $DAT_t$   
 $RCS_t$   
 $RCP_t$   
 $Deep_t$



*Lobule adipeux*

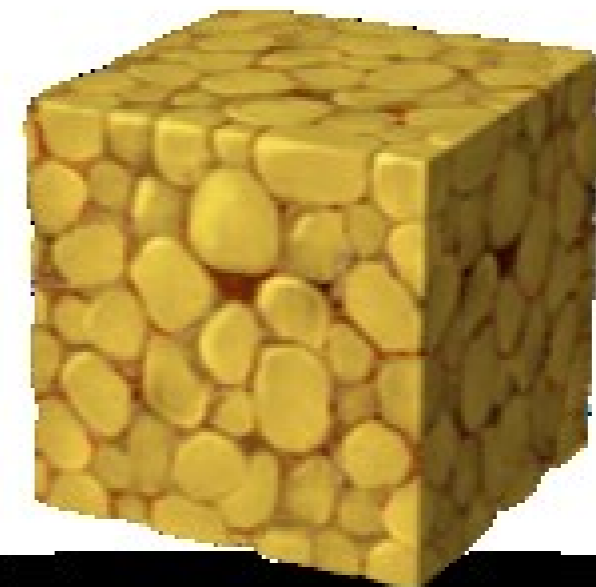
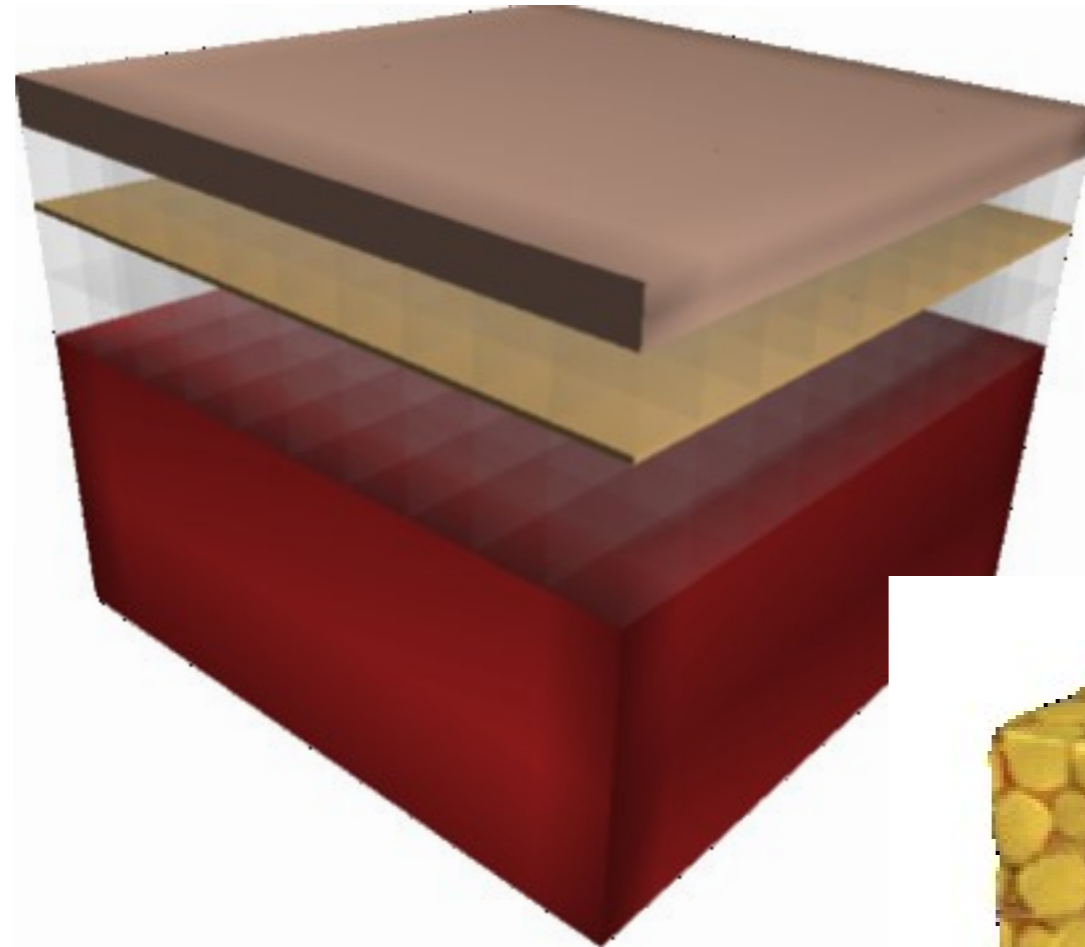
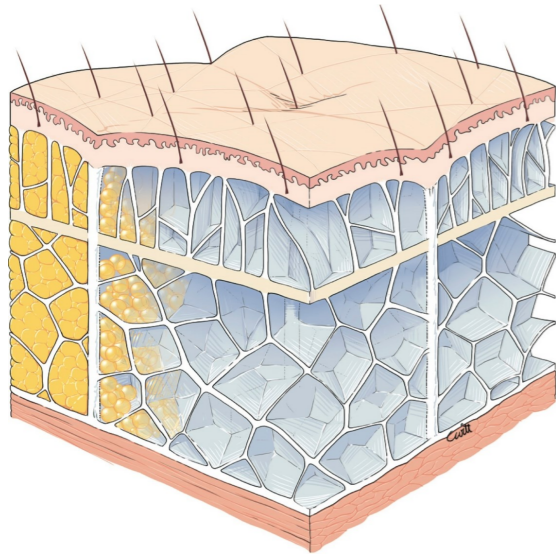
# Modélisation paramétrique



Taille  
 $Skin_t$   
 $SAT_t$   
 $SM_t$   
 $DAT_t$   
 $RCS_t$   
 $RCP_t$   
 $Deept$

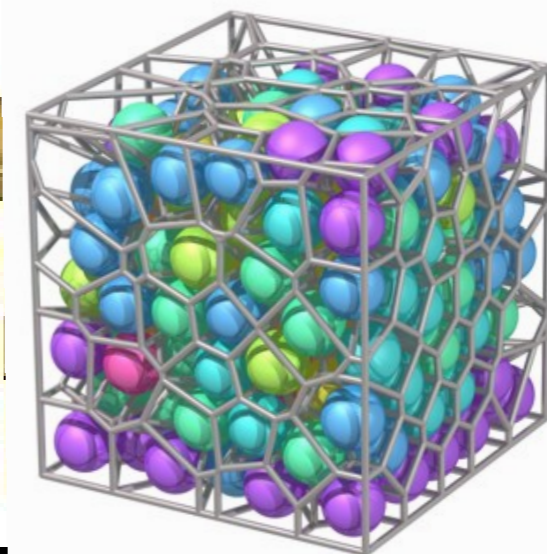
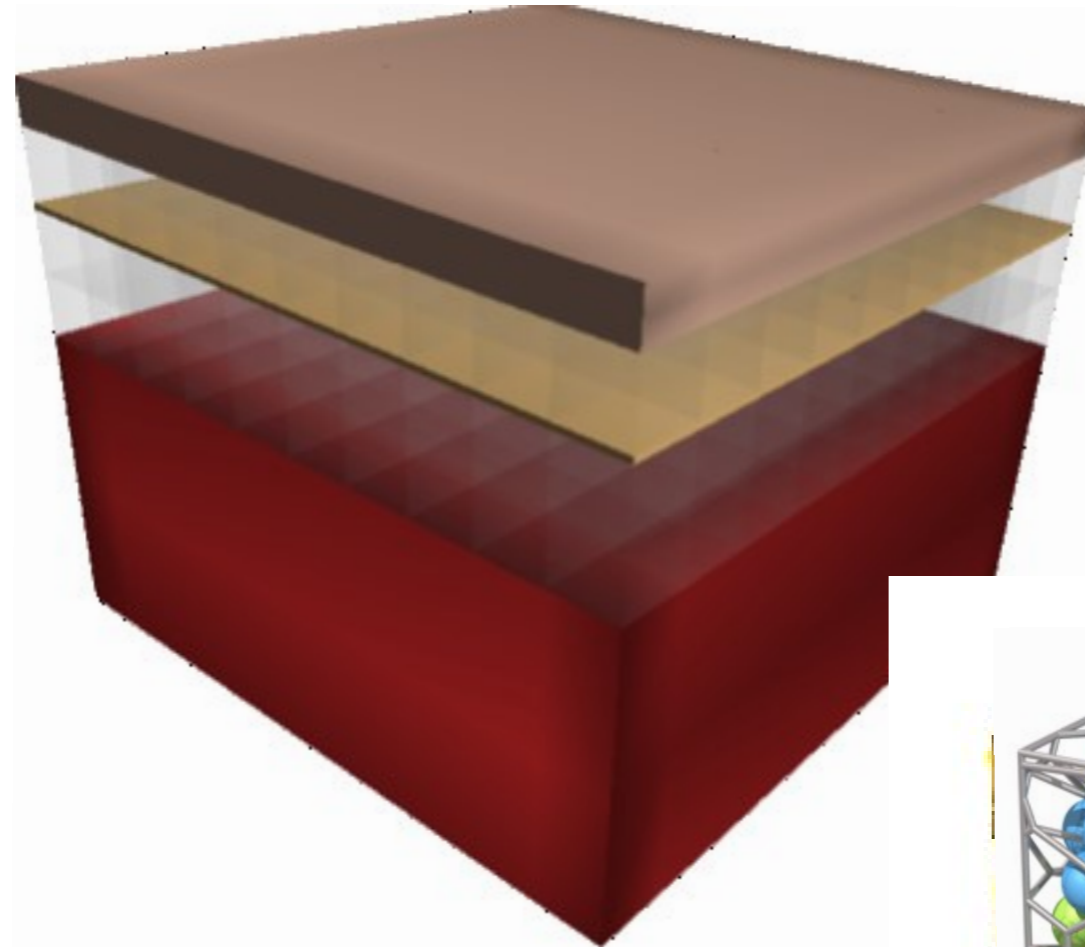
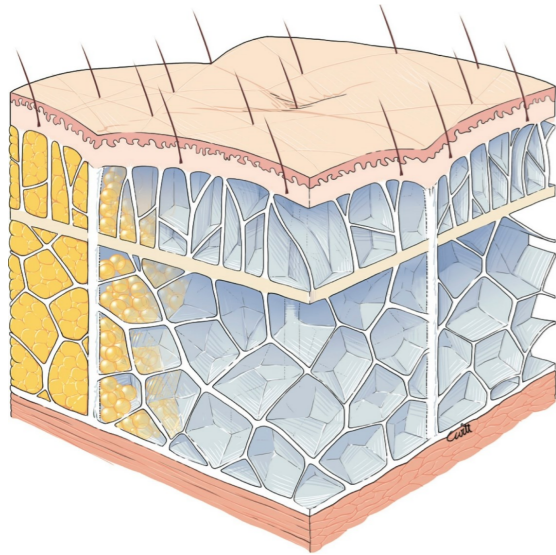


# Modélisation procédurale



Taille  
 $Skin_t$   
 $SAT_t$   
 $SM_t$   
 $DAT_t$   
 $RCS_t$   
 $RCP_t$   
 $Deept$

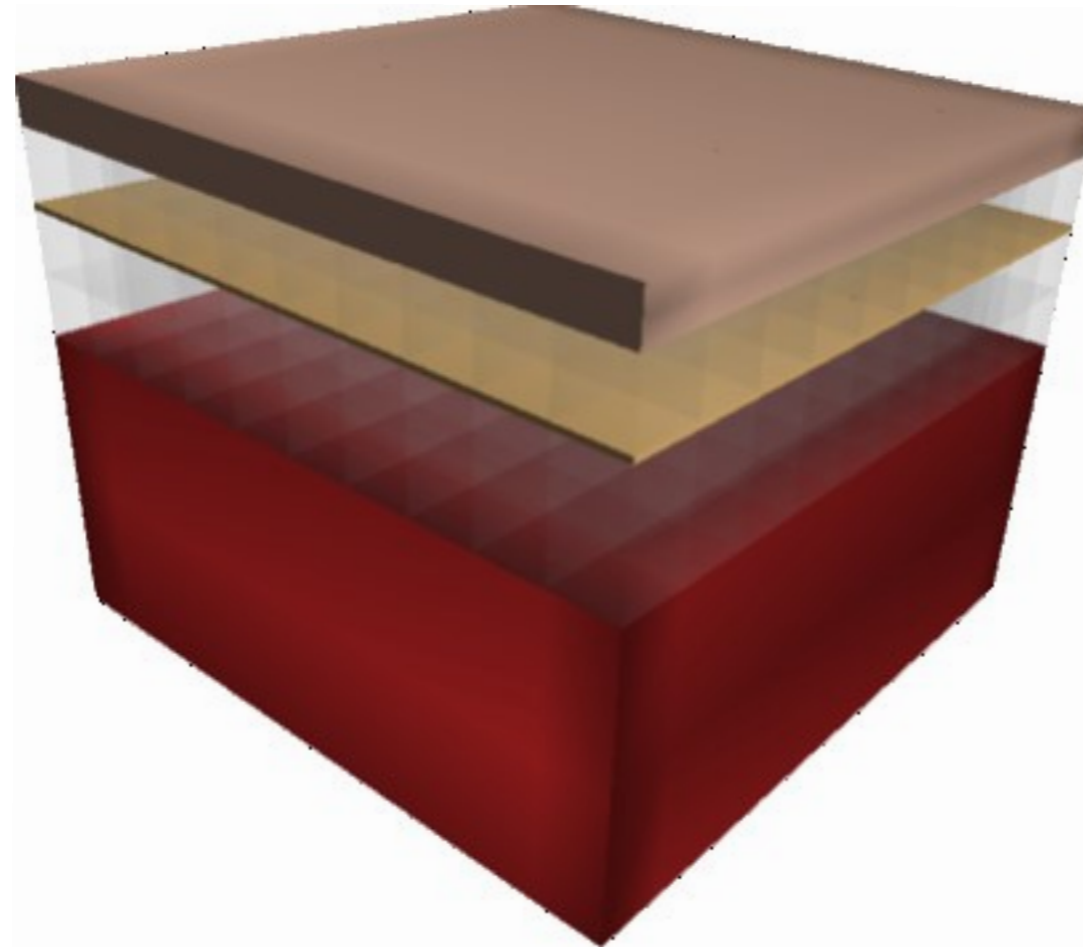
# Modélisation procédurale



Taille  
 $Skin_t$   
 $SAT_t$   
 $SM_t$   
 $DAT_t$   
 $RCS_t$   
 $RCP_t$   
 $Deept$

Hypothèse: lobules de tailles uniformes

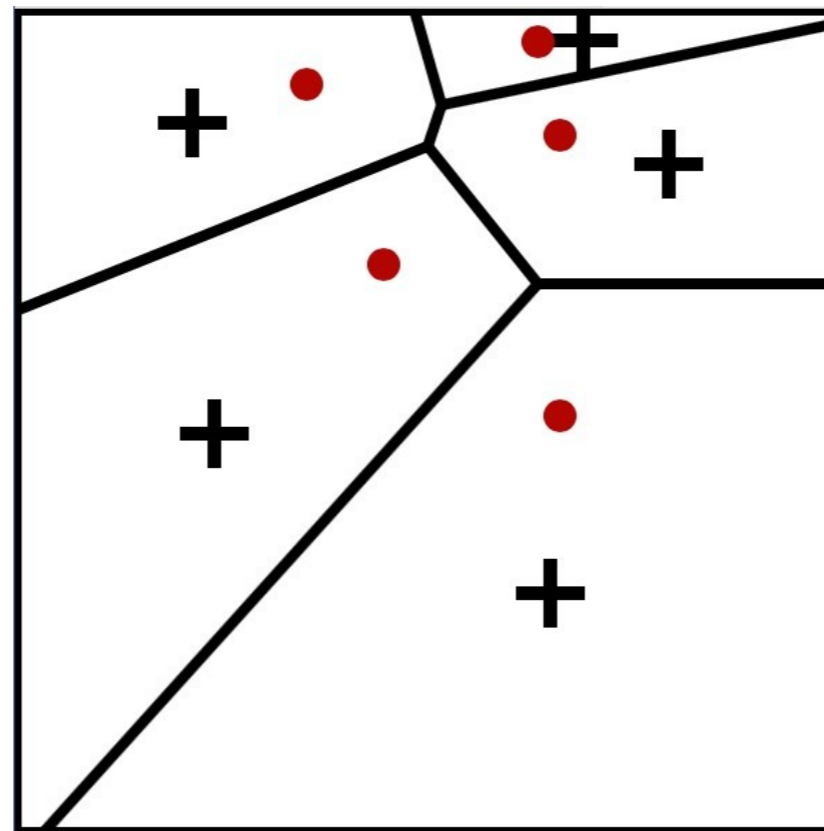
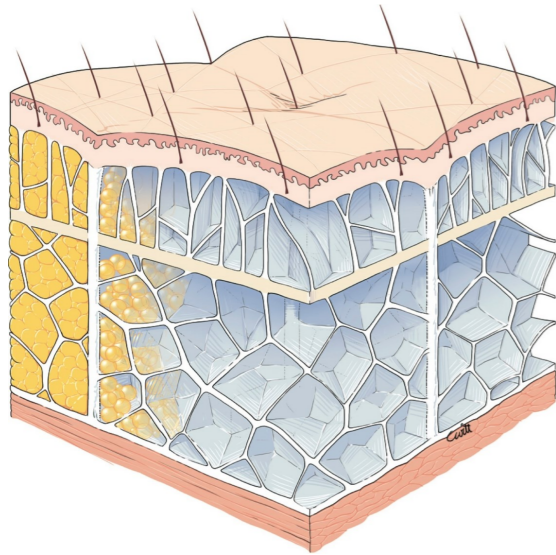
# Modélisation procédurale



Taille  
 $Skin_t$   
 $SAT_t$   
 $SM_t$   
 $DAT_t$   
 $RCS_t$   
 $RCP_t$   
 $Deep_t$

*Tessellation 3D de Voronoï permet de reconstituer les lobules et les septas interlobulaires*  
*Mise en place des centroïdes des cellules par relaxation de Lloyd*

# Modélisation procédurale

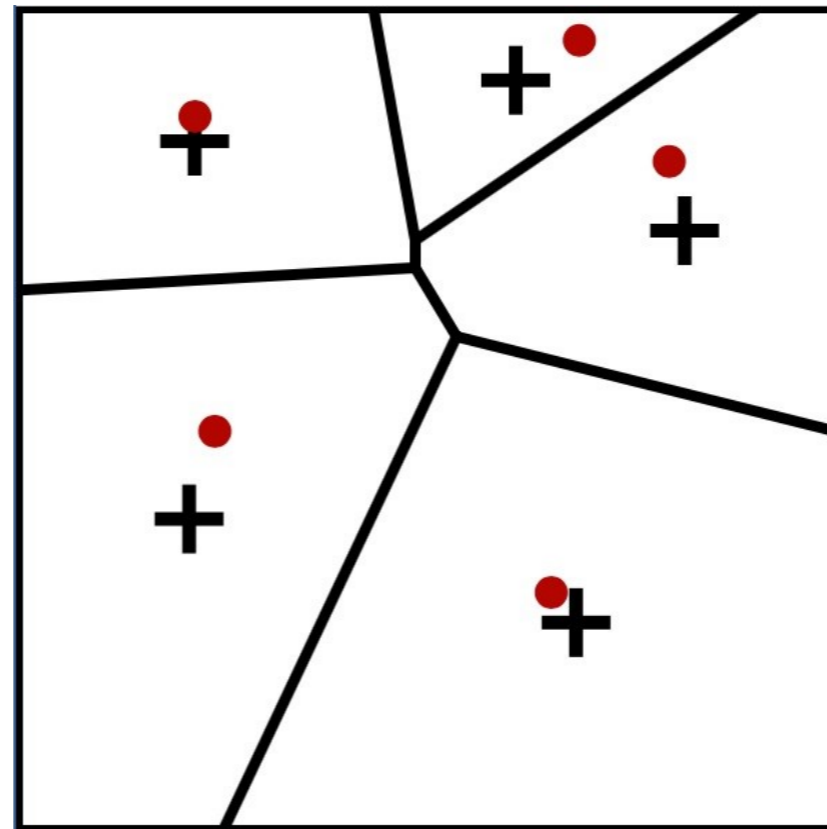
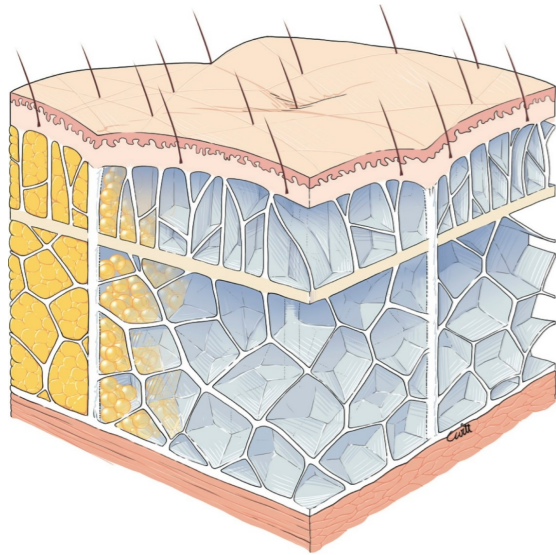


relaxation de Lloyd

*Centre* définit le sous espace le plus proche

*Itérations visent à placer les centres des cellules au niveau de leurs barycentres*

# Modélisation procédurale

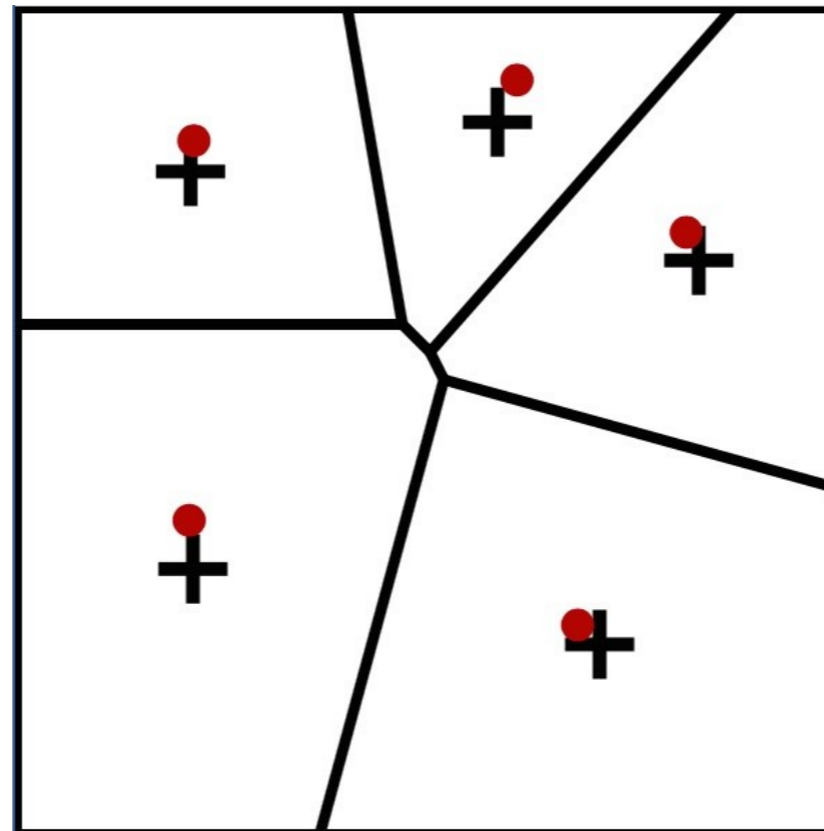
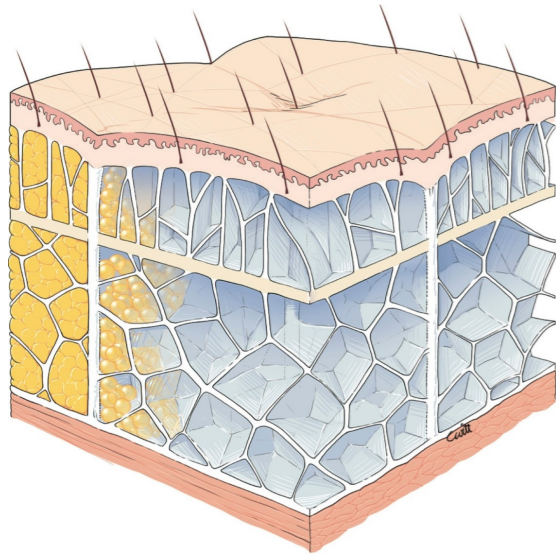


relaxation de Lloyd

*Centre* définit le sous espace le plus proche

*Itérations visent à placer les centres des cellules au niveau de leurs barycentres*

# Modélisation procédurale

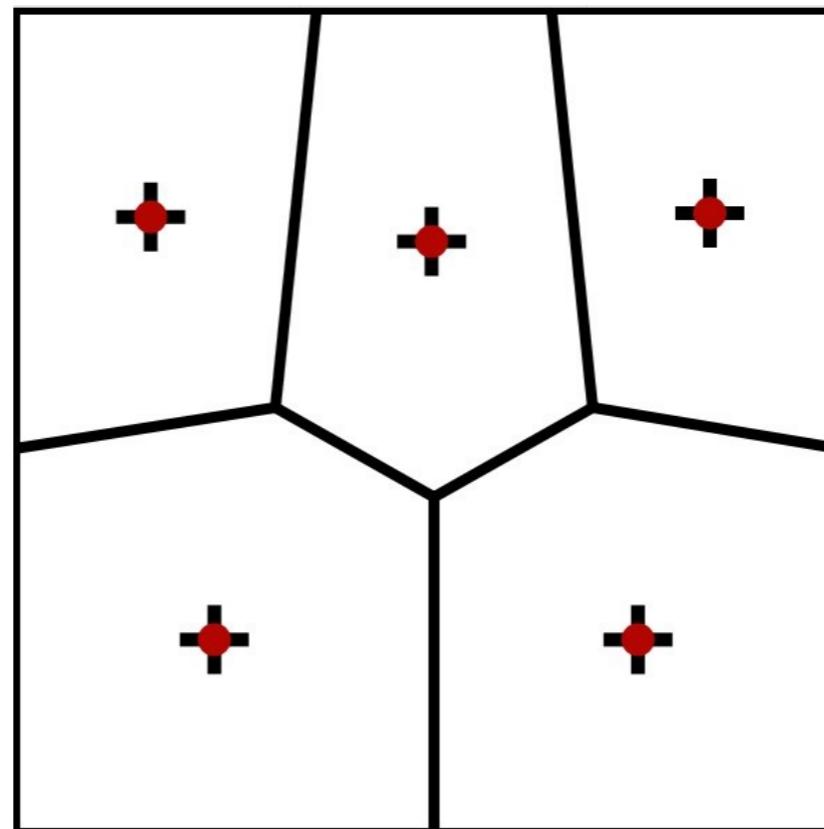
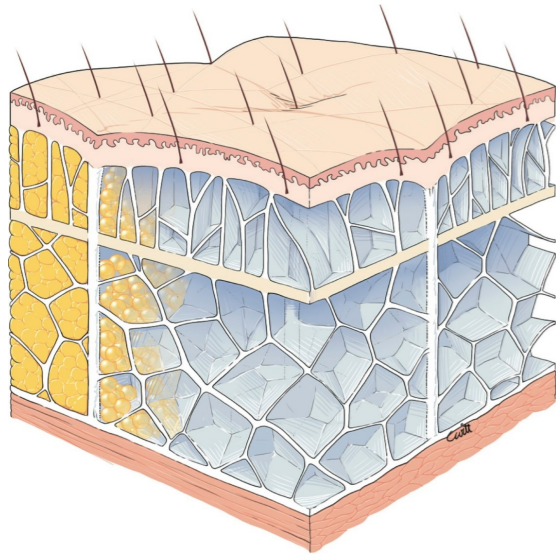


relaxation de Lloyd

*Centre* définit le sous espace le plus proche

*Itérations visent à placer les centres des cellules au niveau de leurs barycentres*

# Modélisation procédurale

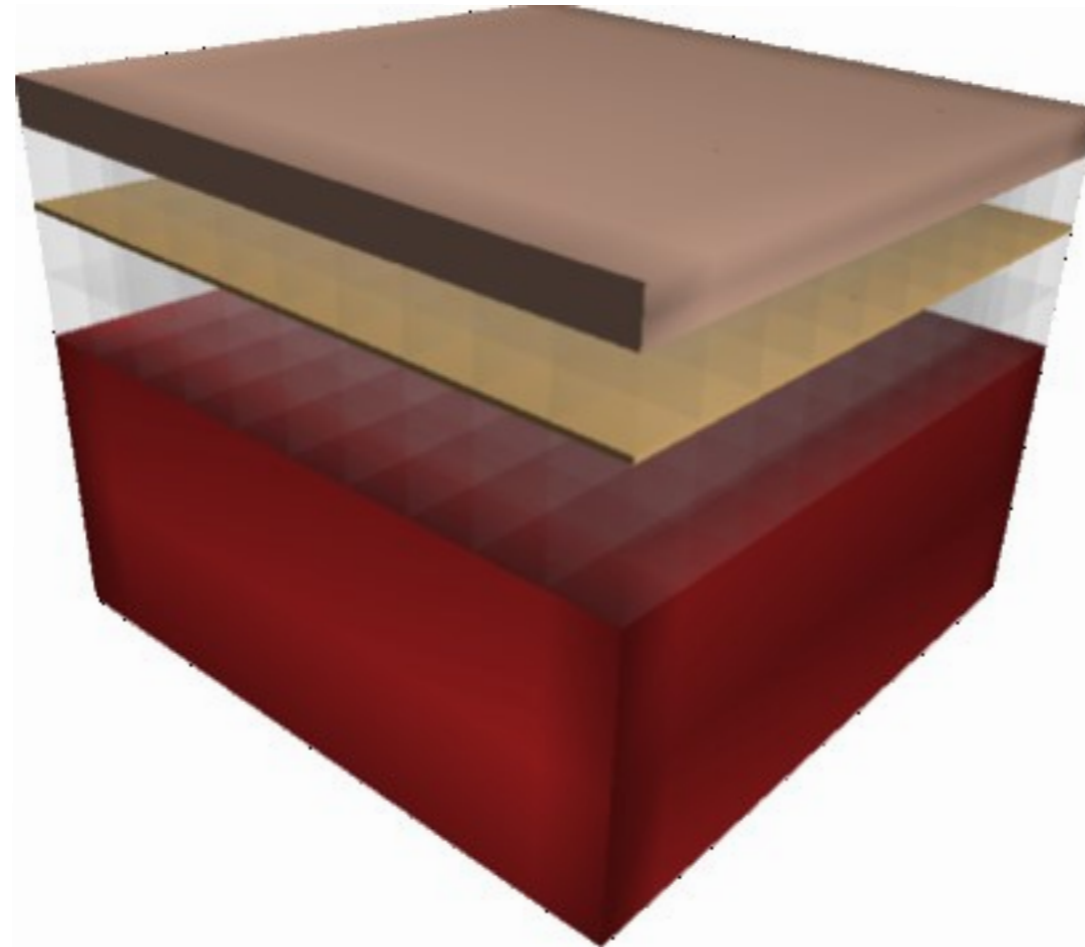
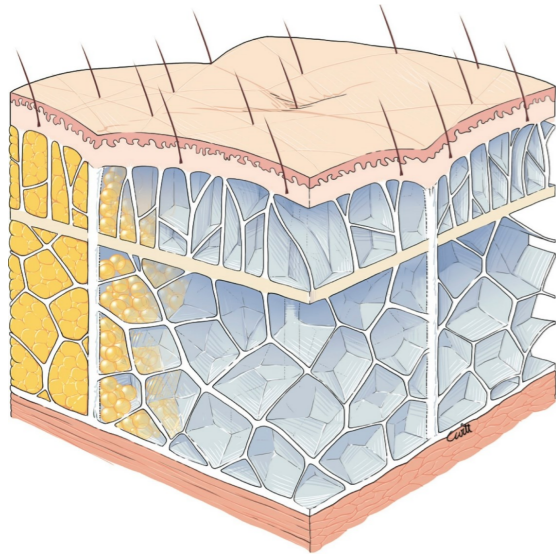


relaxation de Lloyd

*Centre* définit le sous espace le plus proche

*Itérations visent à placer les centres des cellules au niveau de leurs barycentres*

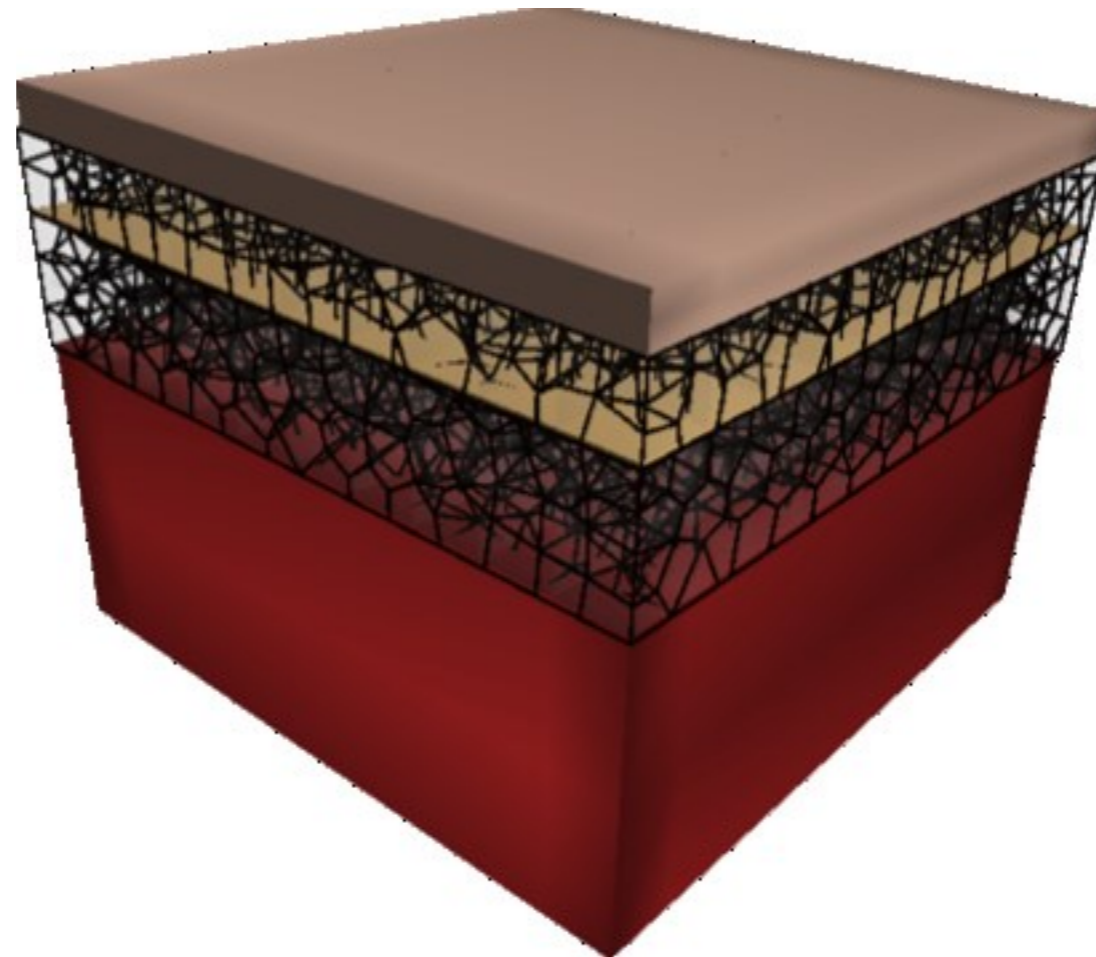
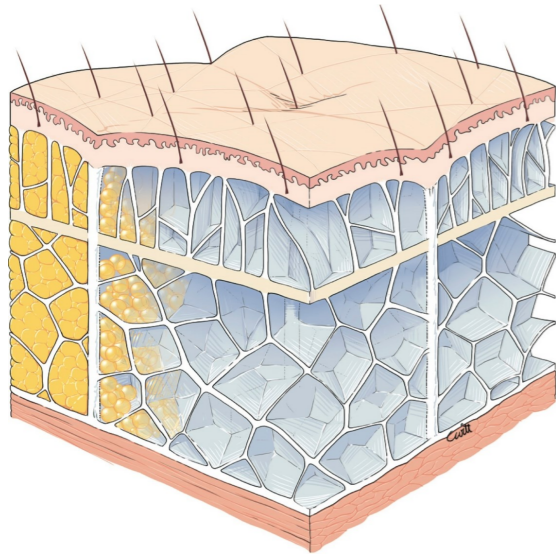
# Modélisation procédurale



*Taille*  
*Skin<sub>t</sub>*  
*SAT<sub>t</sub>*  
*SM<sub>t</sub>*  
*DAT<sub>t</sub>*  
*RCS<sub>t</sub>*  
*RCP<sub>t</sub>*  
*Deep<sub>t</sub>*



# Modélisation procédurale

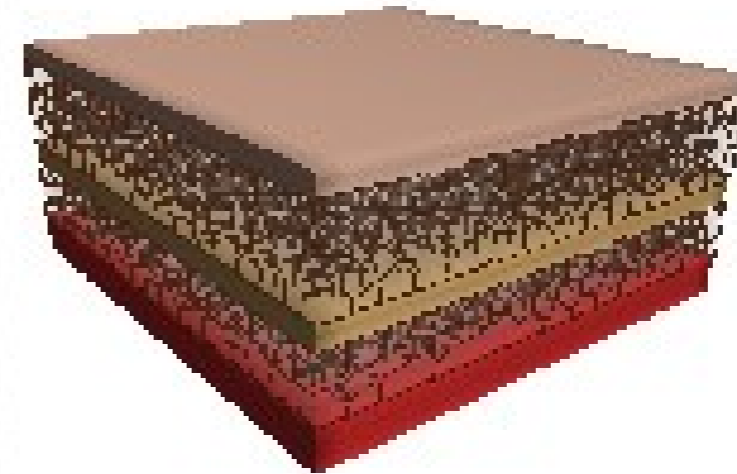
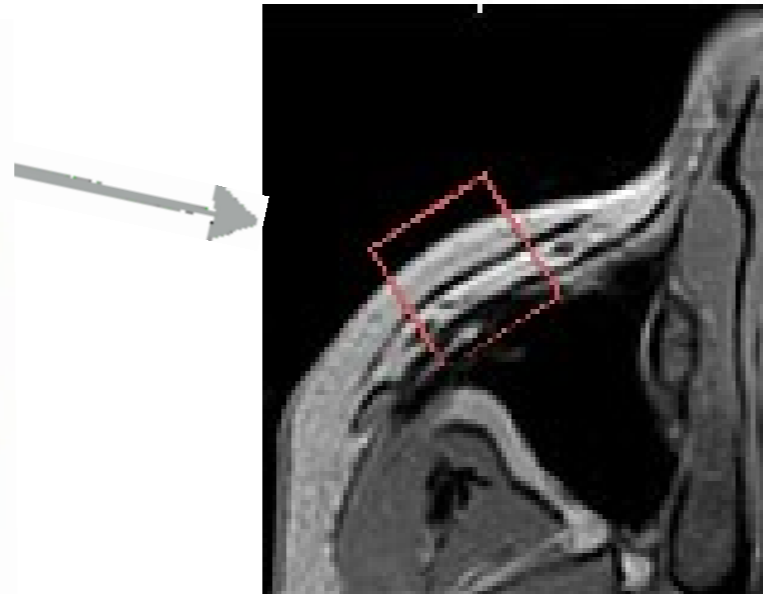


*Taille*  
*Skin<sub>t</sub>*  
*SAT<sub>t</sub>*  
*SM<sub>t</sub>*  
*DAT<sub>t</sub>*  
*RCS<sub>t</sub>*  
*RCP<sub>t</sub>*  
*Deept*

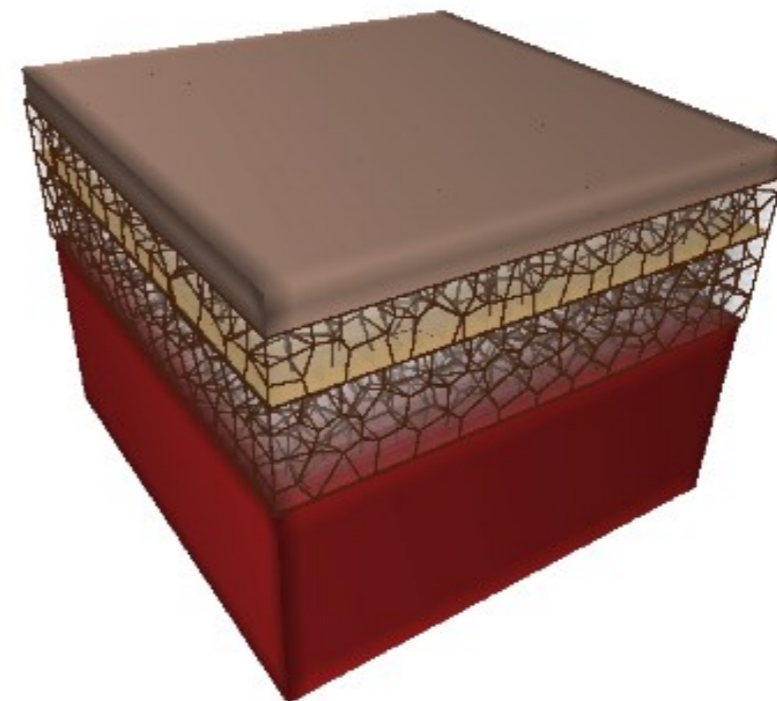
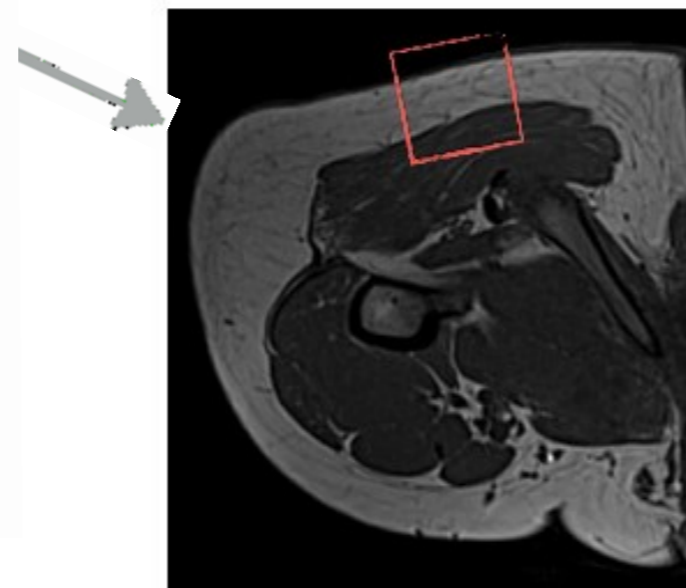
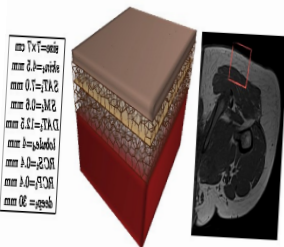
**+ lobule<sub>d</sub>**



# Spécialisation topographique



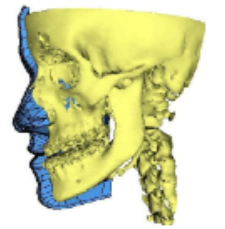
$size = 9 \times 9 \text{ cm}$   
 $skin_t = 1.2 \text{ mm}$   
 $SAT_t = 6.0 \text{ mm}$   
 $SM_t = 1.2 \text{ mm}$   
 $DAT_t = 3.4 \text{ mm}$   
 $lobule_d = 1.5 \text{ mm}$   
 $RCS_t = 0.2 \text{ mm}$   
 $RCP_t = 0.1 \text{ mm}$   
 $deep_t = 2.5 \text{ mm}$



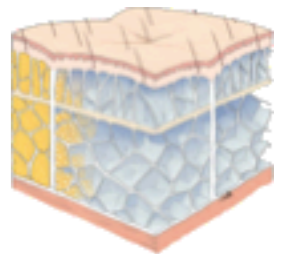
$size = 7 \times 7 \text{ cm}$   
 $skin_t = 4.5 \text{ mm}$   
 $SAT_t = 7.0 \text{ mm}$   
 $SM_t = 0.6 \text{ mm}$   
 $DAT_t = 12.5 \text{ mm}$   
 $lobule_d = 4 \text{ mm}$   
 $RCS_t = 0.4 \text{ mm}$   
 $RCP_t = 0.4 \text{ mm}$   
 $deep_t = 30 \text{ mm}$

# PLAN

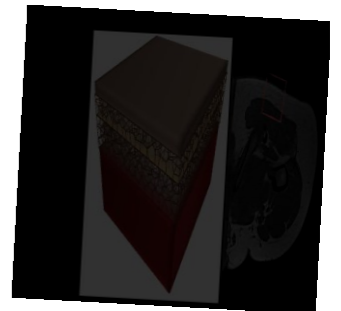
Etat de l'art



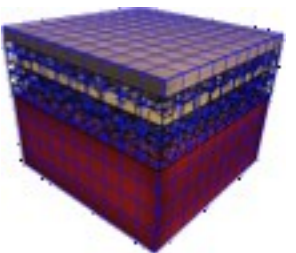
Modélisation anatomique



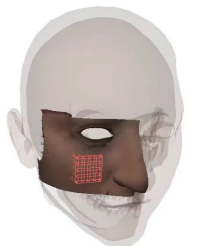
Modélisation géométrique paramétrique et procédurale



Modélisation biomécanique hybride



Simulations



Perspectives

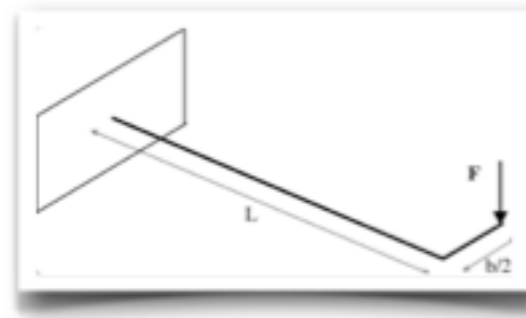
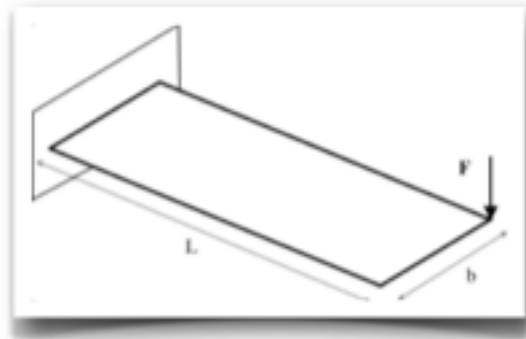
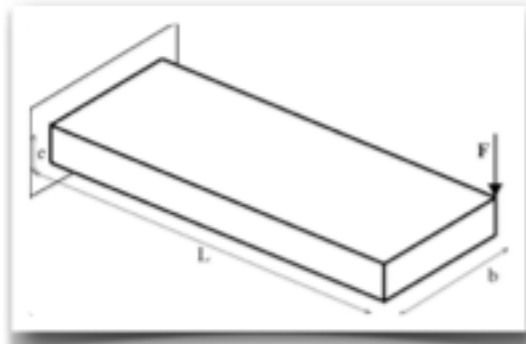


# Modélisation biomécanique hybride



## Éléments adaptés à la forme des constituants du CPTSC

### Loi de comportement simple (Hooke)



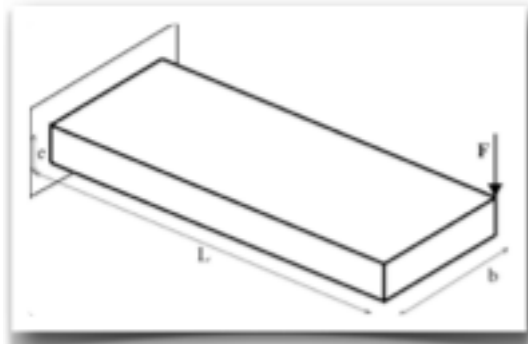
# Modélisation biomécanique hybride



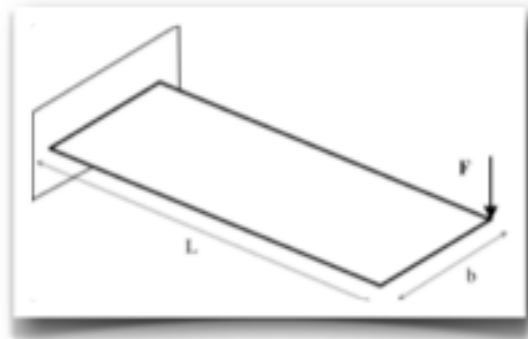
## Éléments adaptés à la forme des constituants du CPTSC

### Loi de comportement simple (Hooke)

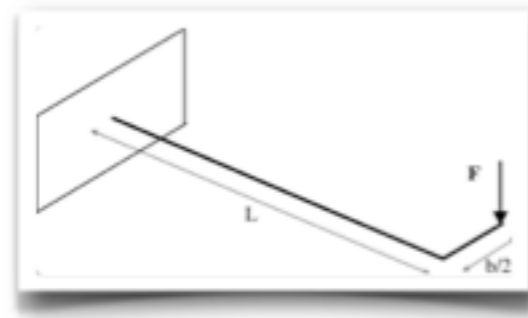
**Volumique**  
(Hexaèdre fin)



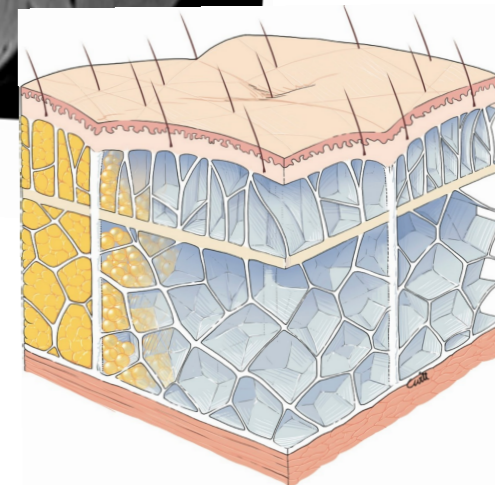
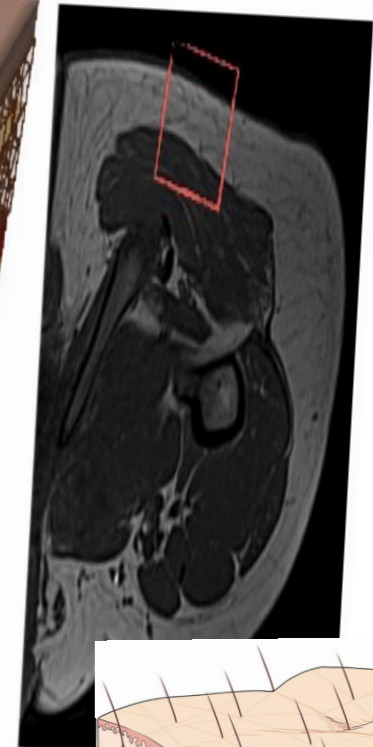
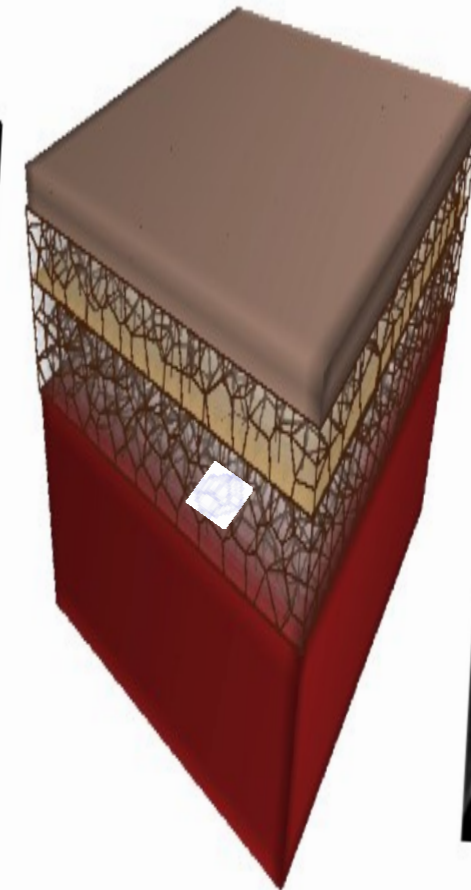
**Surfacique**  
(Triangle)



**Linéique**  
(ligne)



mm 1.0 = TA 2  
mm 0.7 = TA 2  
mm 0.6 = M 2  
mm 1.2 = TA 1  
mm 1.0 = TA 1  
mm 0.4 = RC 2  
mm 0.4 = RC 2  
mm 0.4 = RC 2  
mm 0.3 = RC 2

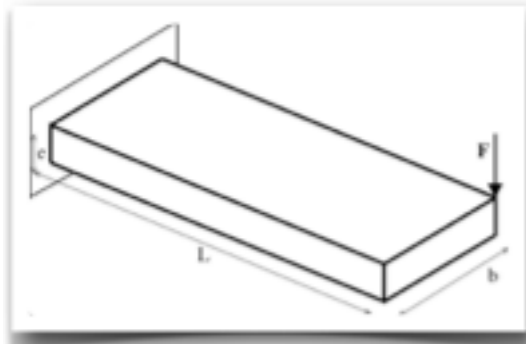


# Modélisation biomécanique hybride

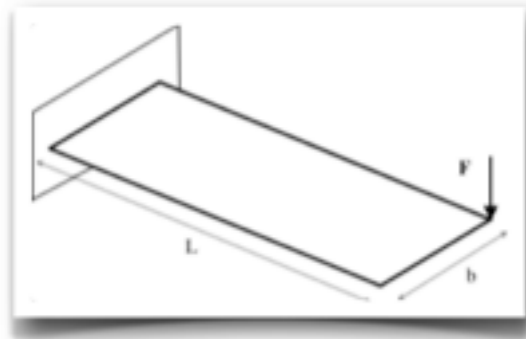


## Éléments adaptés à la forme des constituants du CPTSC

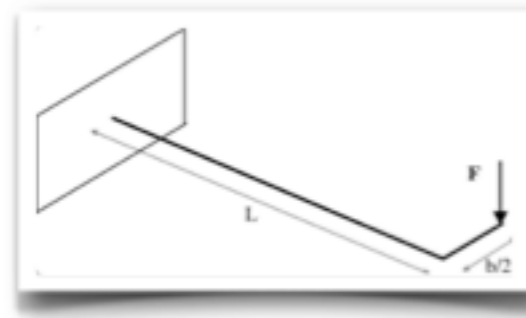
### Loi de comportement simple (Hooke)



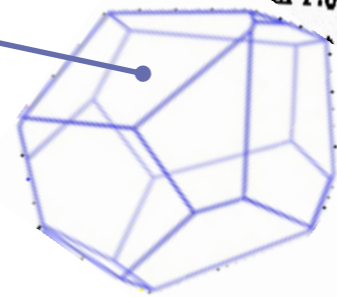
**Volumique**  
(Hexaèdre fin)



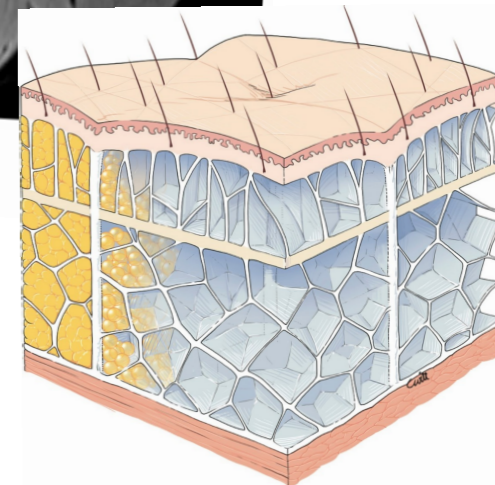
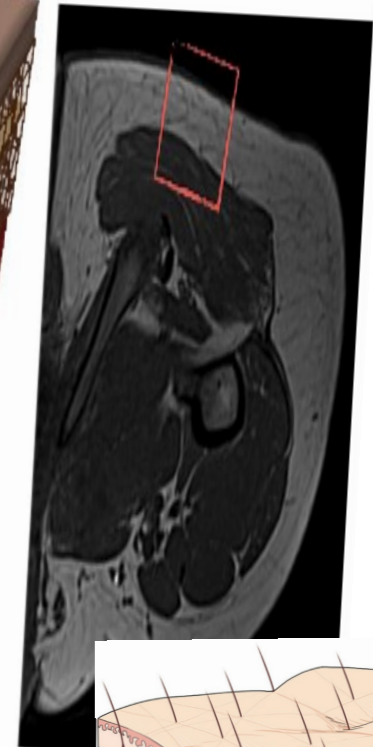
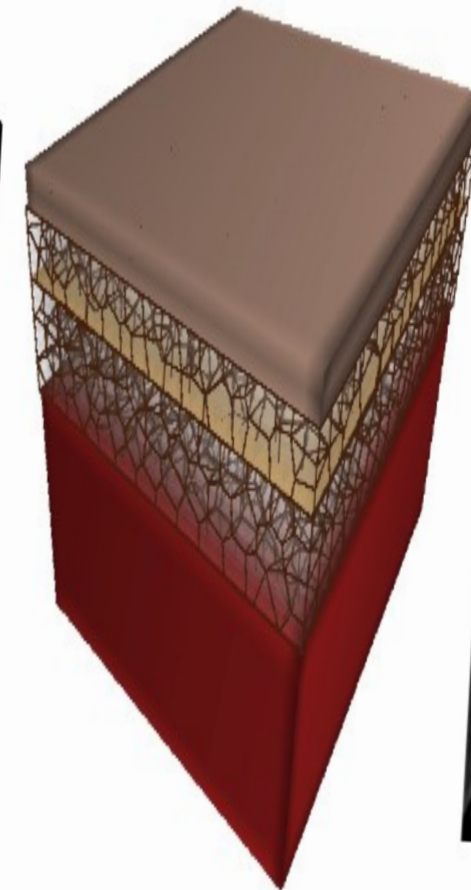
**Surfacique**  
(Triangle)



**Linéaire**  
(ligne)



mm 7x7=9318  
mm 2.1=,31818  
mm 0.7=,7182  
mm 2.0=,8182  
mm 2.2=,9182  
mm 4=,4182  
mm 4.0=,4182  
RCP=0.4  
RCP  
RCP

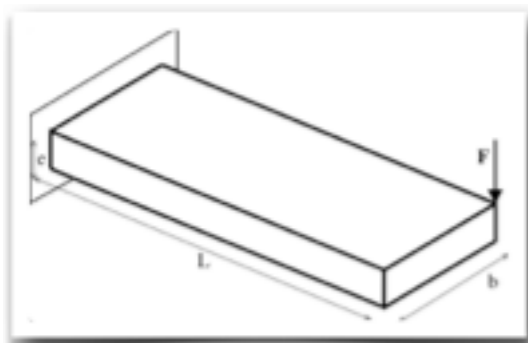


# Modélisation biomécanique hybride

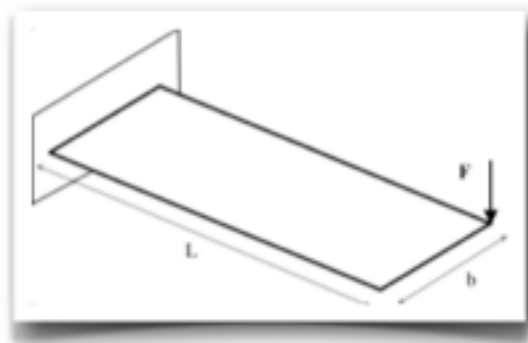


## Éléments adaptés à la forme des constituants du CPTSC

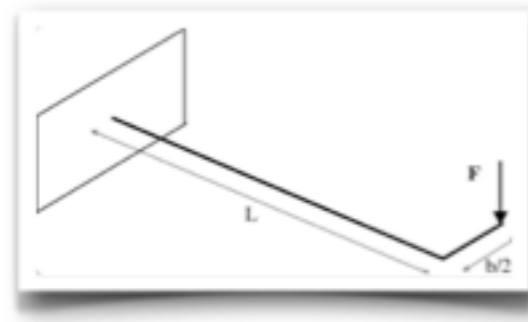
### Loi de comportement simple (Hooke)



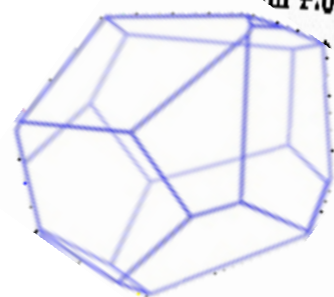
**Volumique**  
(Hexaèdre fin)



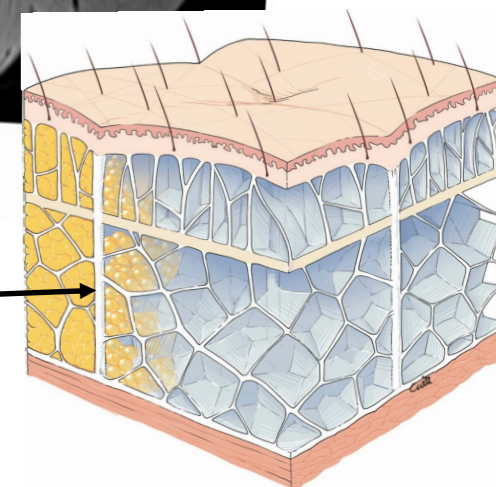
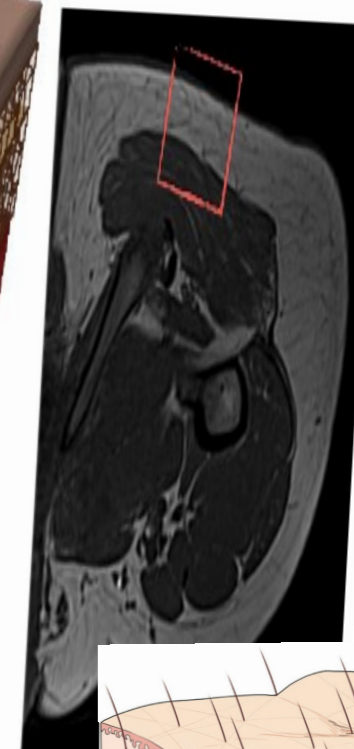
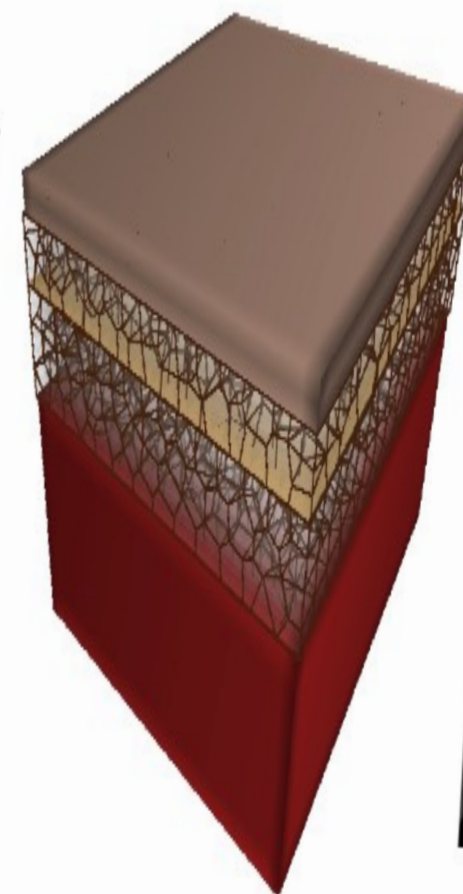
**Surfacique**  
(Triangle)



**Linéaire**  
(arête)



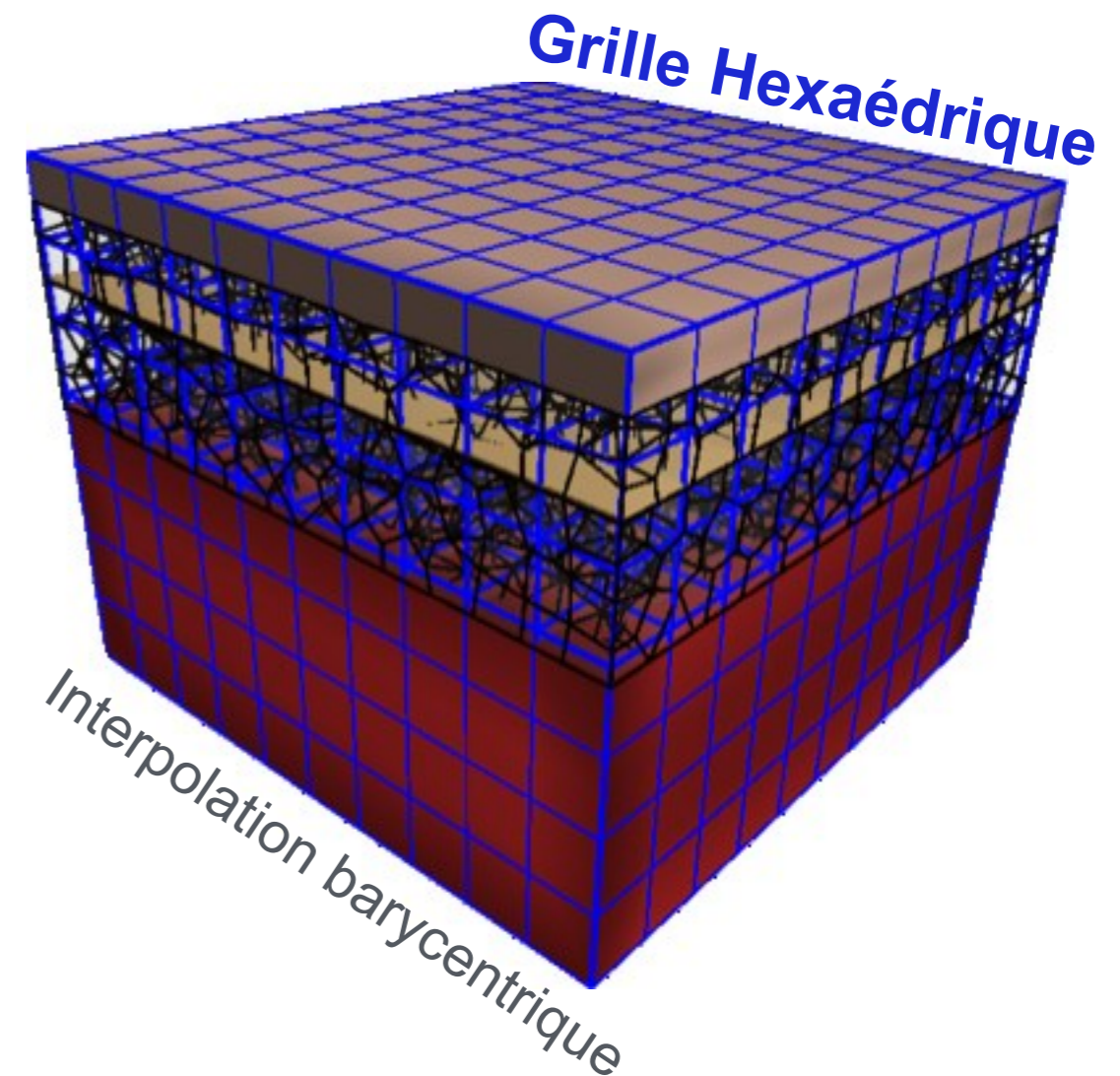
mm  $\delta = 0.5$   
mm  $\delta = 1.0$   
mm  $\delta = 1.5$   
mm  $\delta = 2.0$   
mm  $\delta = 2.5$   
mm  $\delta = 3.0$   
mm  $\delta = 3.5$   
mm  $\delta = 4.0$   
mm  $\delta = 4.5$   
mm  $\delta = 5.0$   
mm  $\delta = 5.5$   
mm  $\delta = 6.0$   
mm  $\delta = 6.5$   
mm  $\delta = 7.0$   
mm  $\delta = 7.5$   
mm  $\delta = 8.0$   
mm  $\delta = 8.5$   
mm  $\delta = 9.0$   
mm  $\delta = 9.5$   
mm  $\delta = 10.0$



# Modélisation biomécanique hybride



**COUPLAGE MECANIQUE** en utilisant une **Grille Hexaédrique**

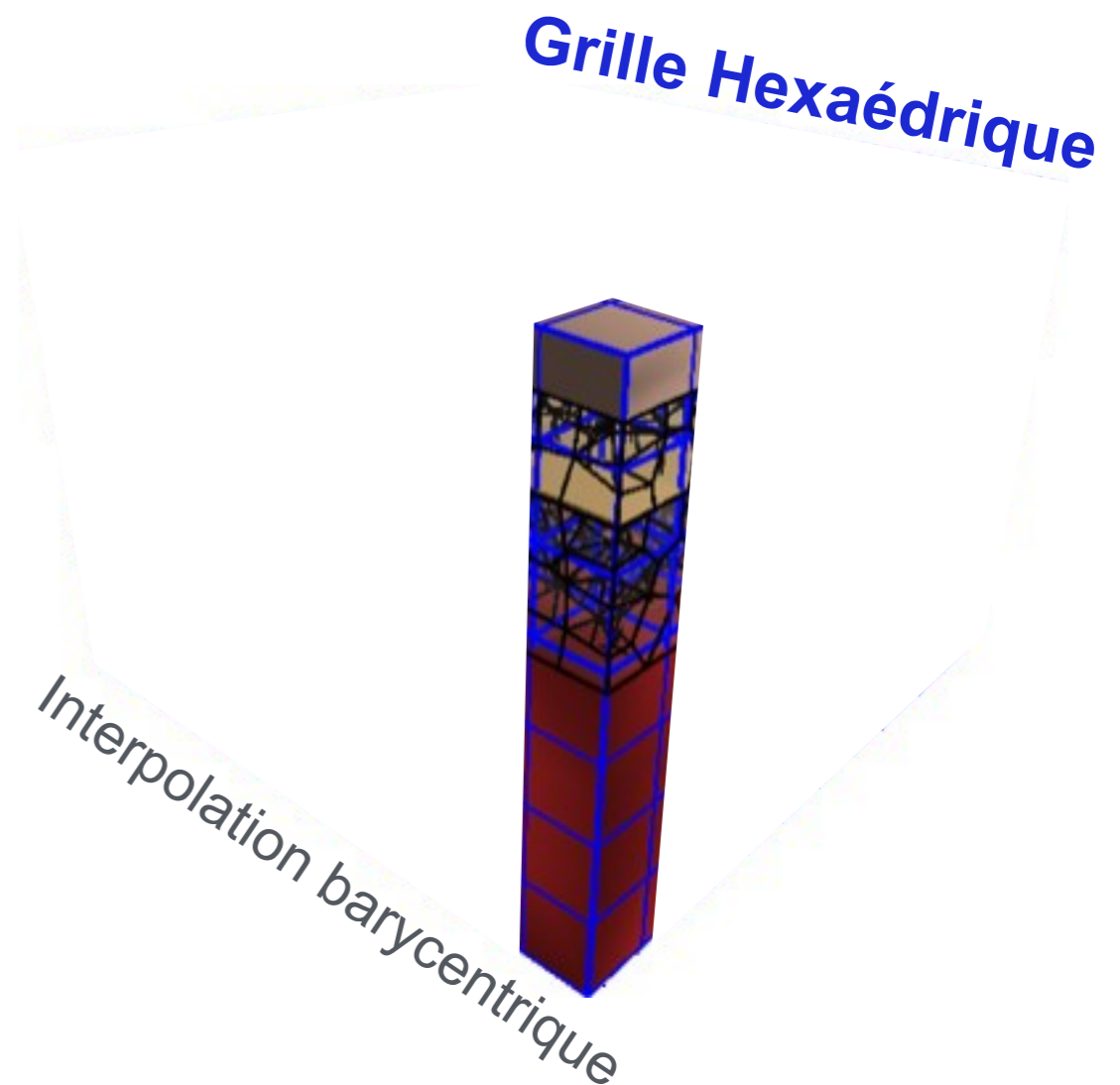
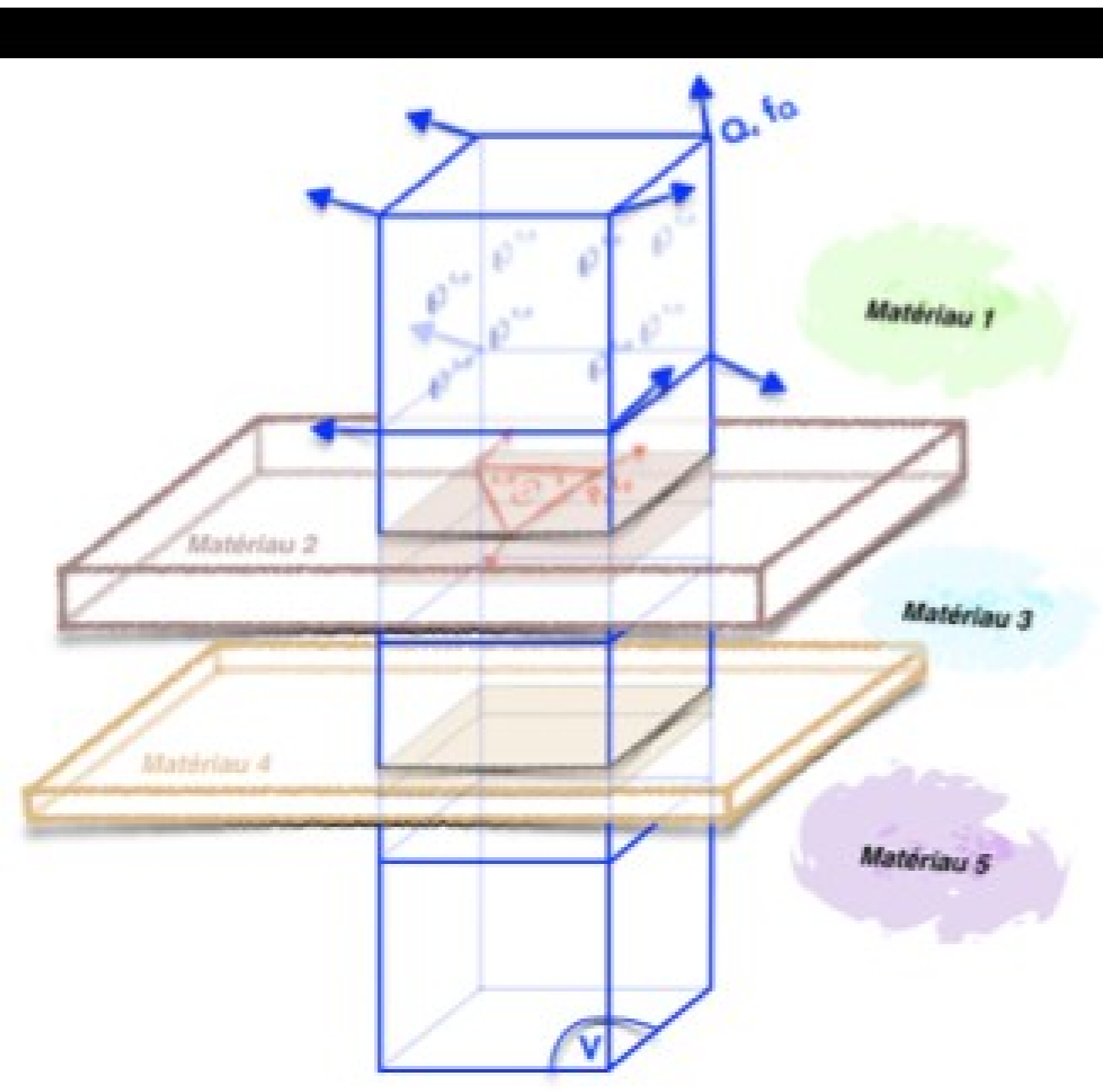




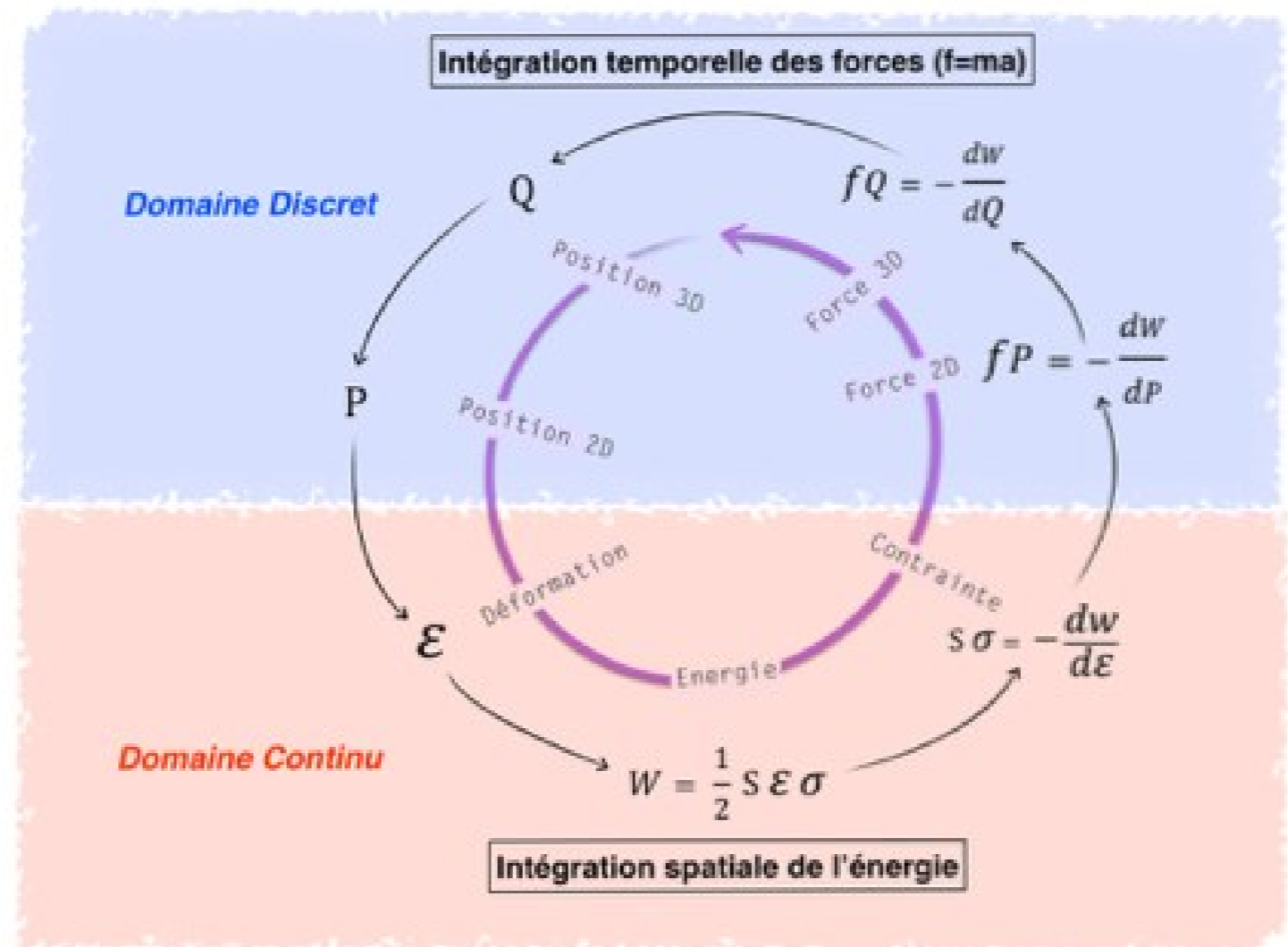
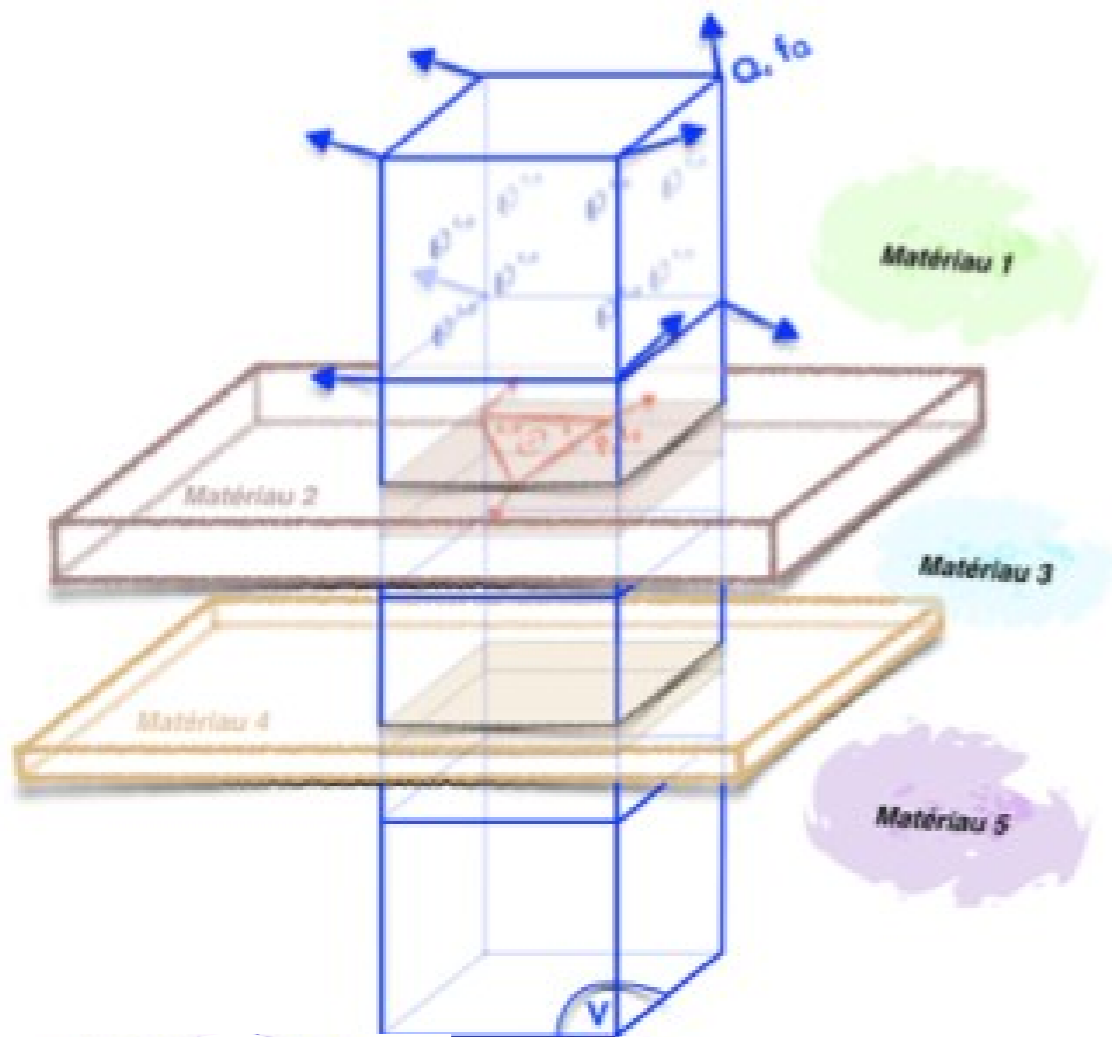
# Modélisation biomécanique hybride



## COUPLAGE MECANIQUE en utilisant une Grille Hexaédrique



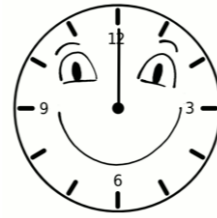
# Modélisation biomécanique hybride



# Modélisation biomécanique hybride



## SIMULATION RAPIDE



2000 hexaèdres (peau, SAT, SM, DAT et

13000 triangles pour les septas du SAT

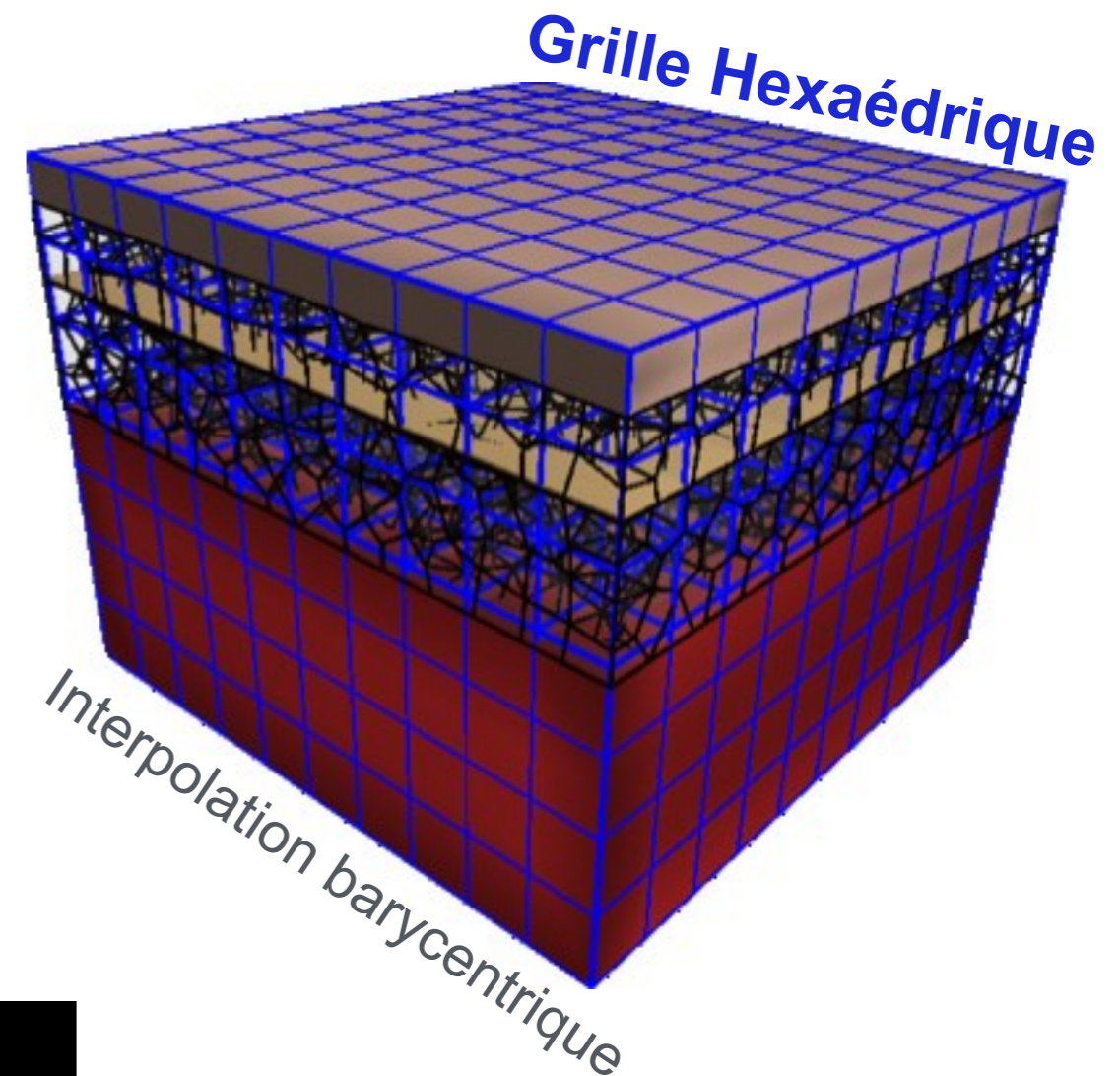
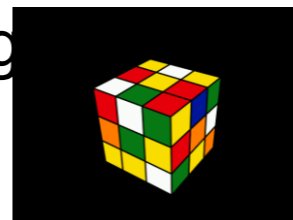
23000 triangles pour les septas du DAT

**700 hexaèdres**

**Loi de comportement simple (Hooke)**

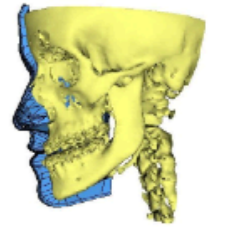
Déformations mesurées par une  
**méthode corotationnelle**

Intégration temporelle des noeuds de la g  
par un **schéma d'Euler implicite**

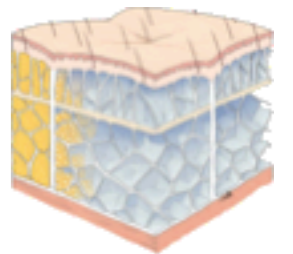


# PLAN

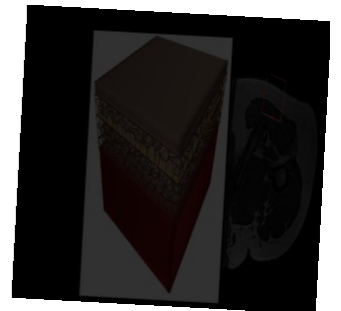
Etat de l'art



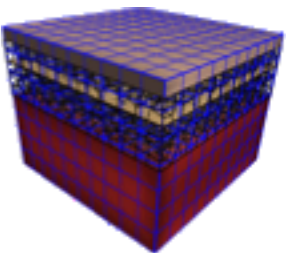
Modélisation anatomique



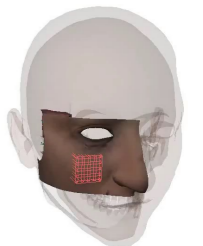
Modélisation géométrique paramétrique et procédurale



Modélisation biomécanique hybride



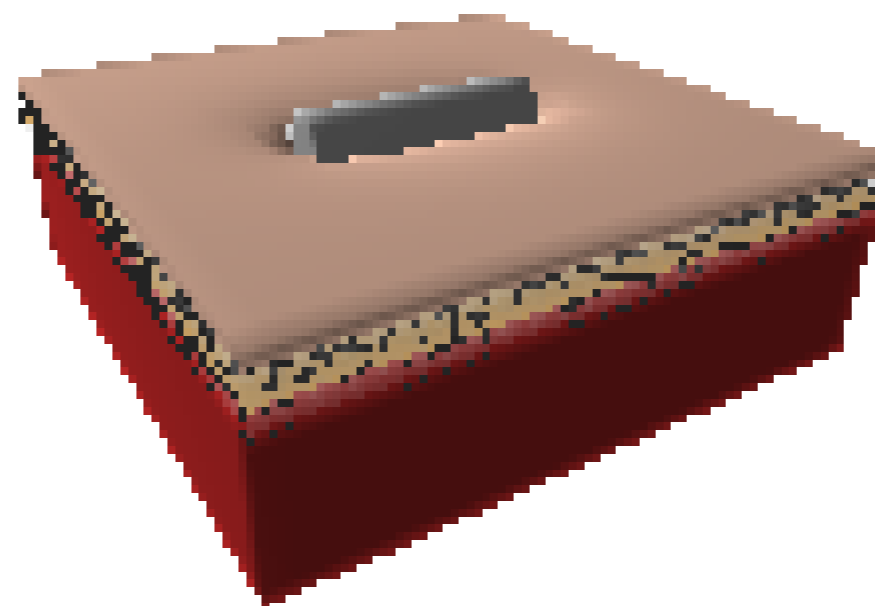
Simulations



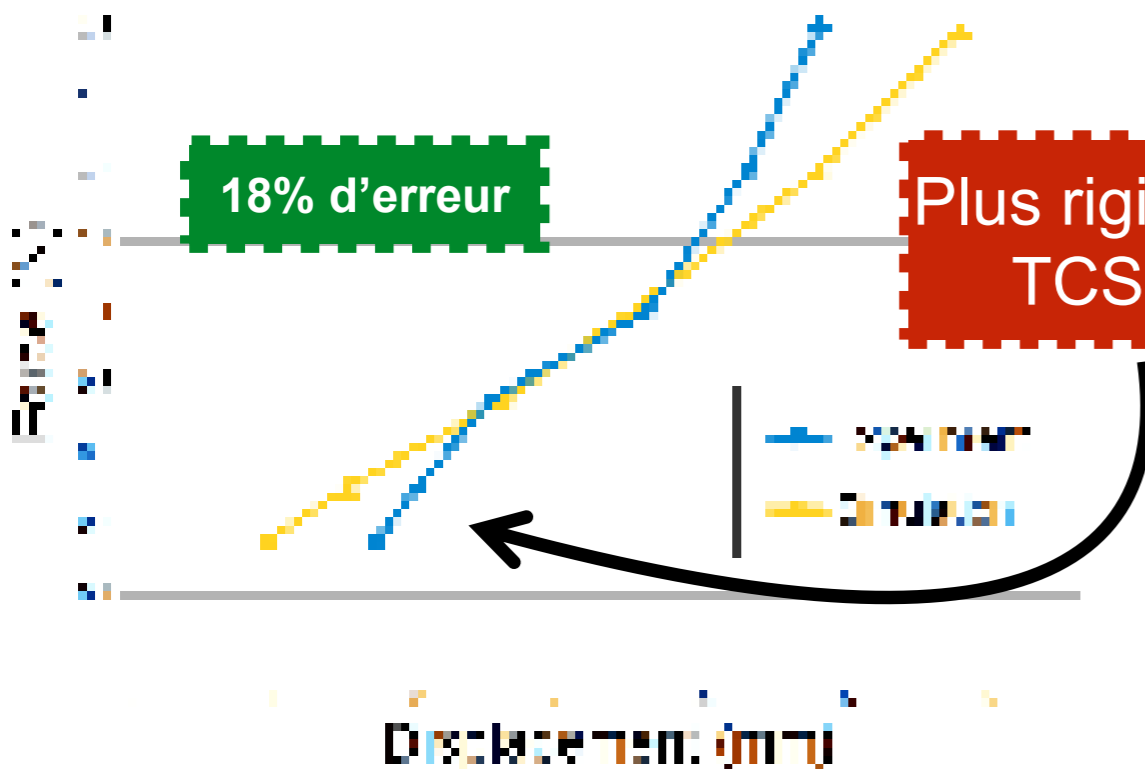
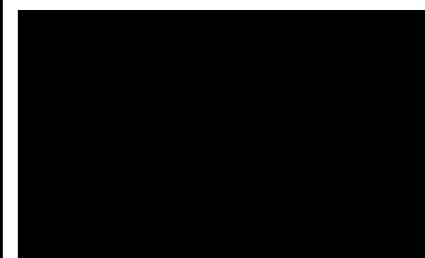
Perspectives



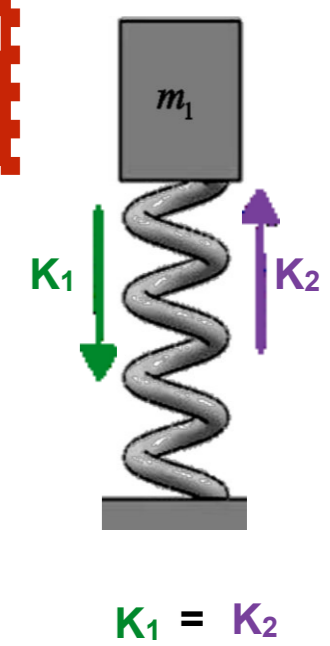
# Simulation



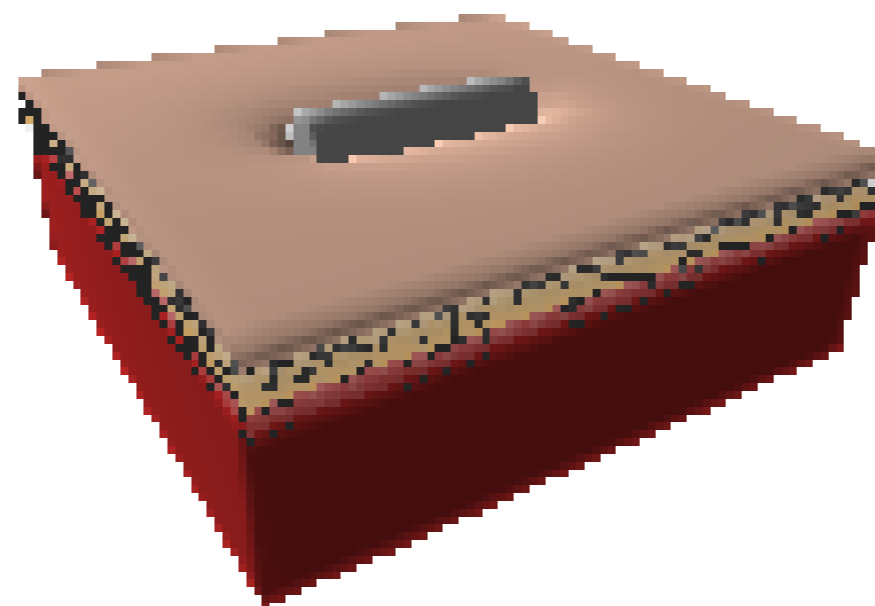
$size_x = 5 \times 5 \text{ cm}$   
 $size_y = 1.48 \text{ mm}$   
 $SAT_x = 1.8 \text{ mm}$   
 $SAT_y = 0.8 \text{ mm}$   
 $DAT_x = 0.68 \text{ mm}$   
 $lobule_x = 1.8 \text{ mm}$   
 $RCS_x = 0.1 \text{ mm}$   
 $RCP_x = 0.1 \text{ mm}$   
 $depth = 12 \text{ mm}$



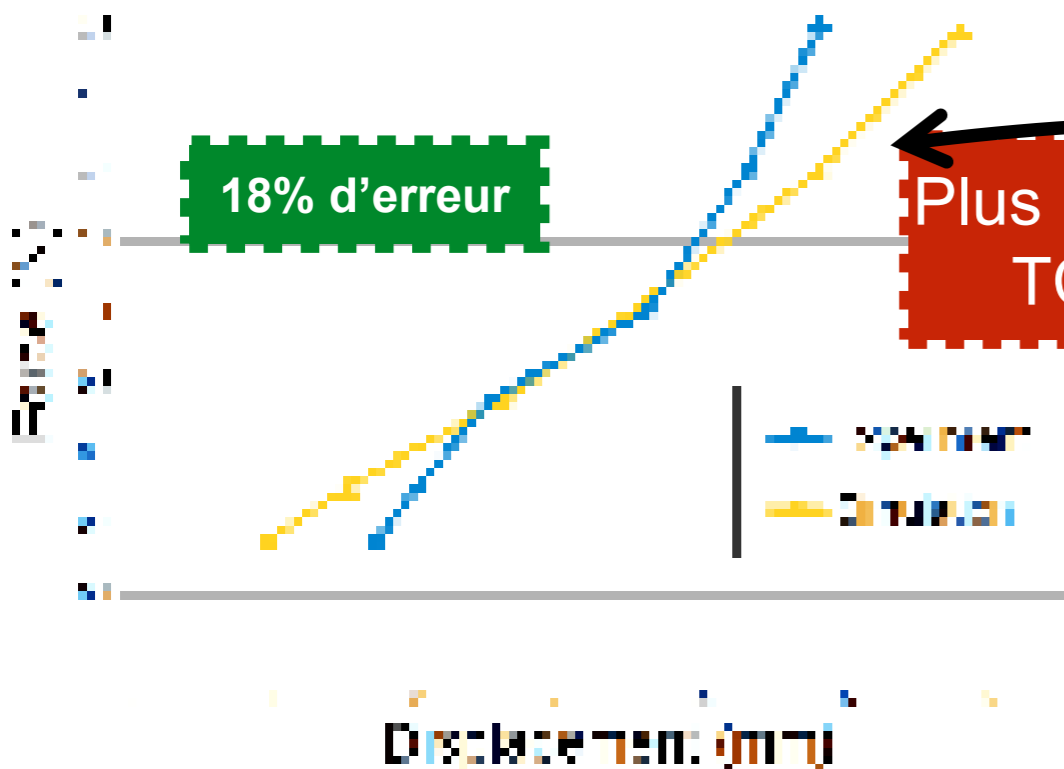
Plus rigide à bas régime car prise en compte du TCSC dont la rigidité était monophasique



# Simulation

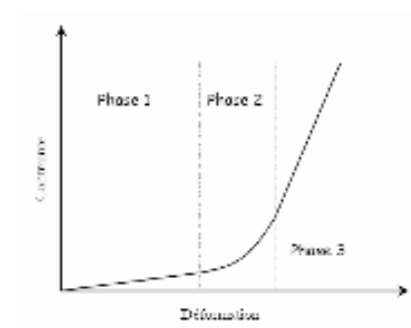


$size_x = 5 \times 5 \text{ cm}$   
 $size_y = 1.45 \text{ mm}$   
 $SAT_z = 1.8 \text{ mm}$   
 $SAT_x = 0.8 \text{ mm}$   
 $DAT_z = 0.68 \text{ mm}$   
 $lobule_x = 1.8 \text{ mm}$   
 $RCS_z = 0.1 \text{ mm}$   
 $RCP_z = 0.1 \text{ mm}$   
 $depth_z = 12 \text{ mm}$



Plus rigide à bas régime car prise en compte du TCSC dont la rigidité était monophasique

Moins rigide à haut régime car utilisation de lois élastiques linéaires

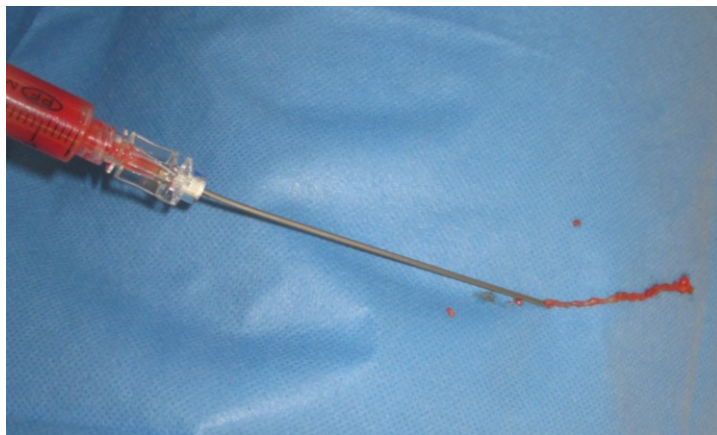
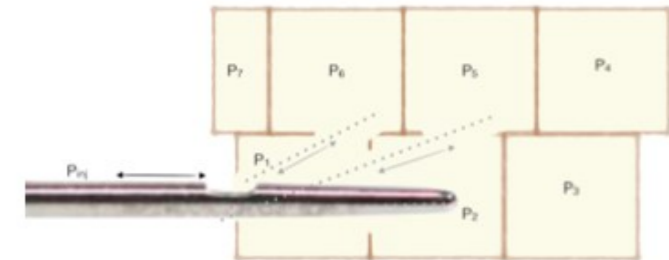


# Simulation d'augmentations tissulaires

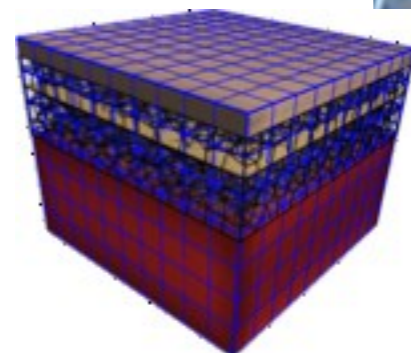
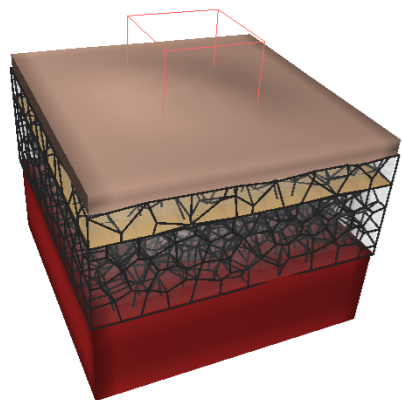


Injection du tissu adipeux dégradé  
difficile à simuler de part sa composition  
 nature de son introduction

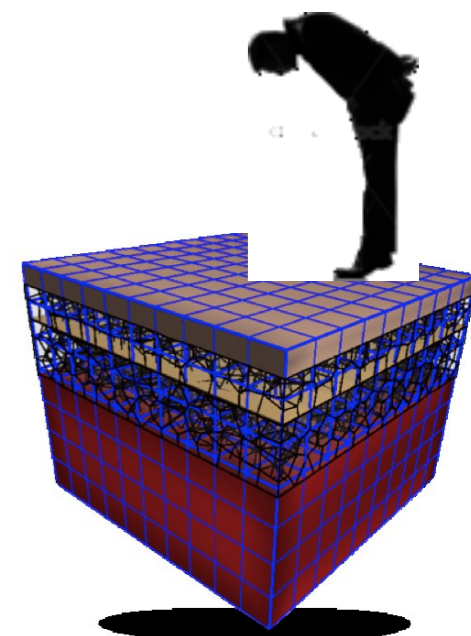
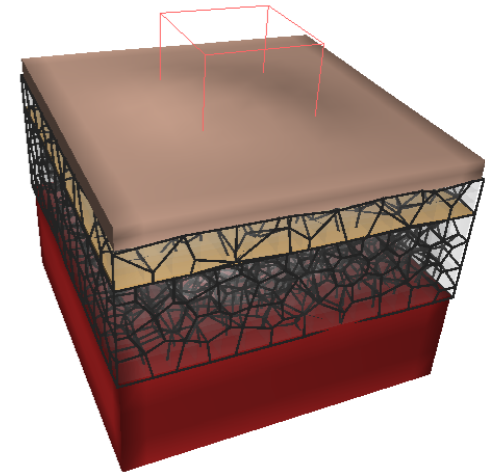
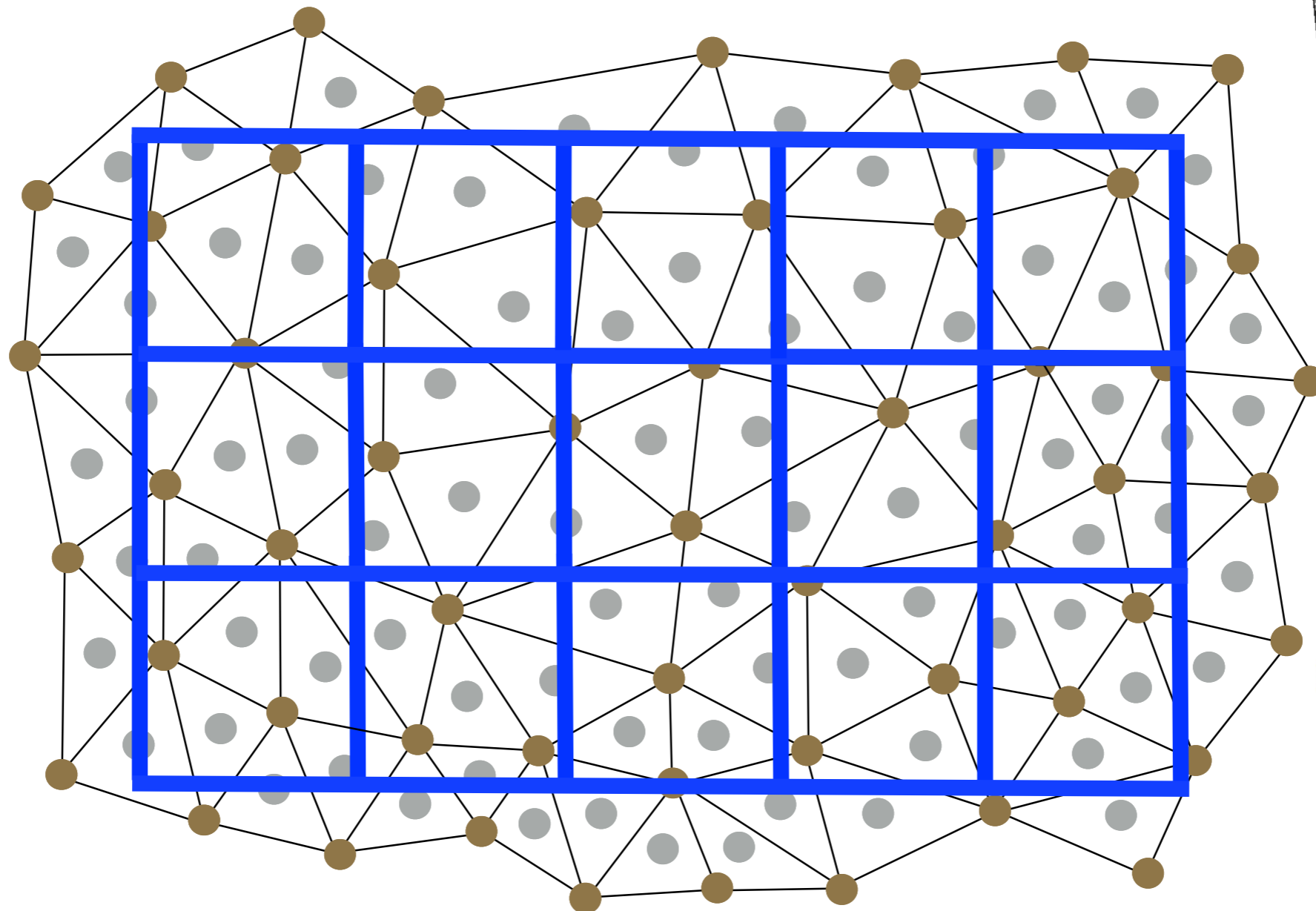
très  
 et la



Offset  $\oplus$  isotrope

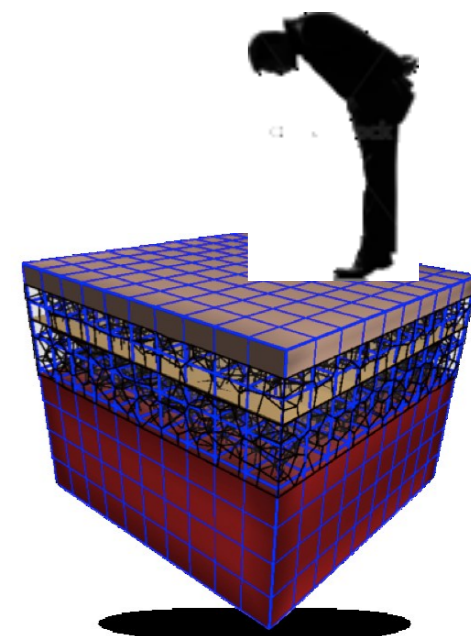
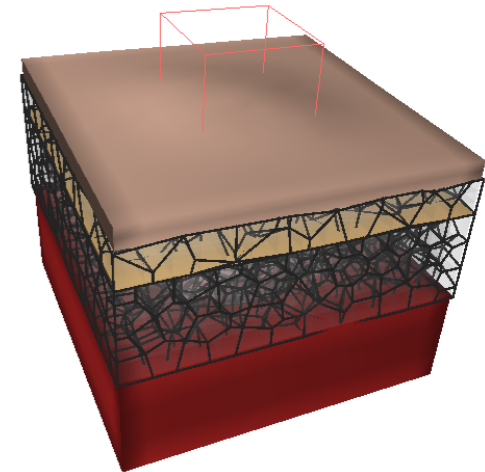
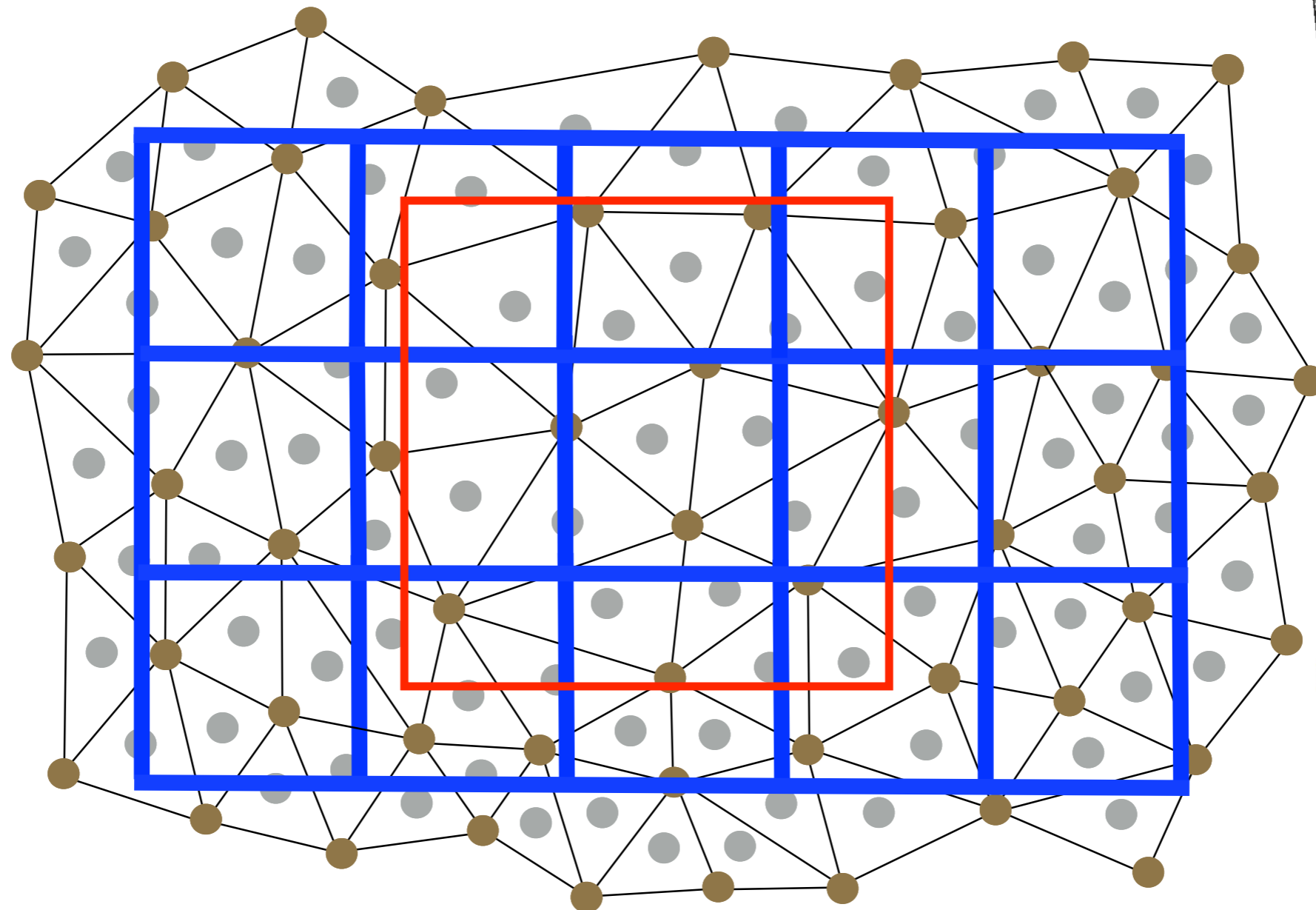


# Simulation d'augmentations tissulaires

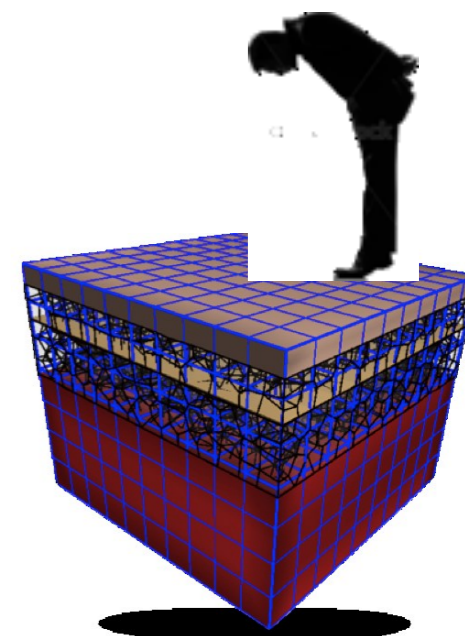
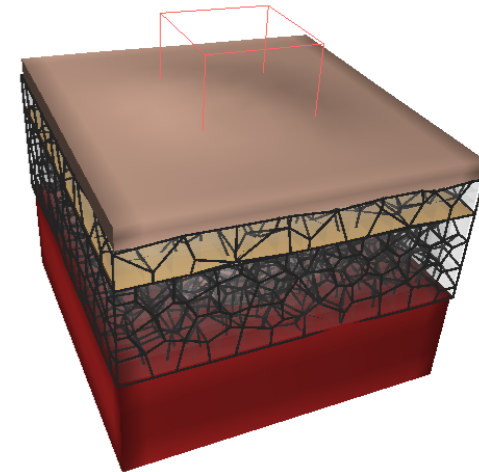
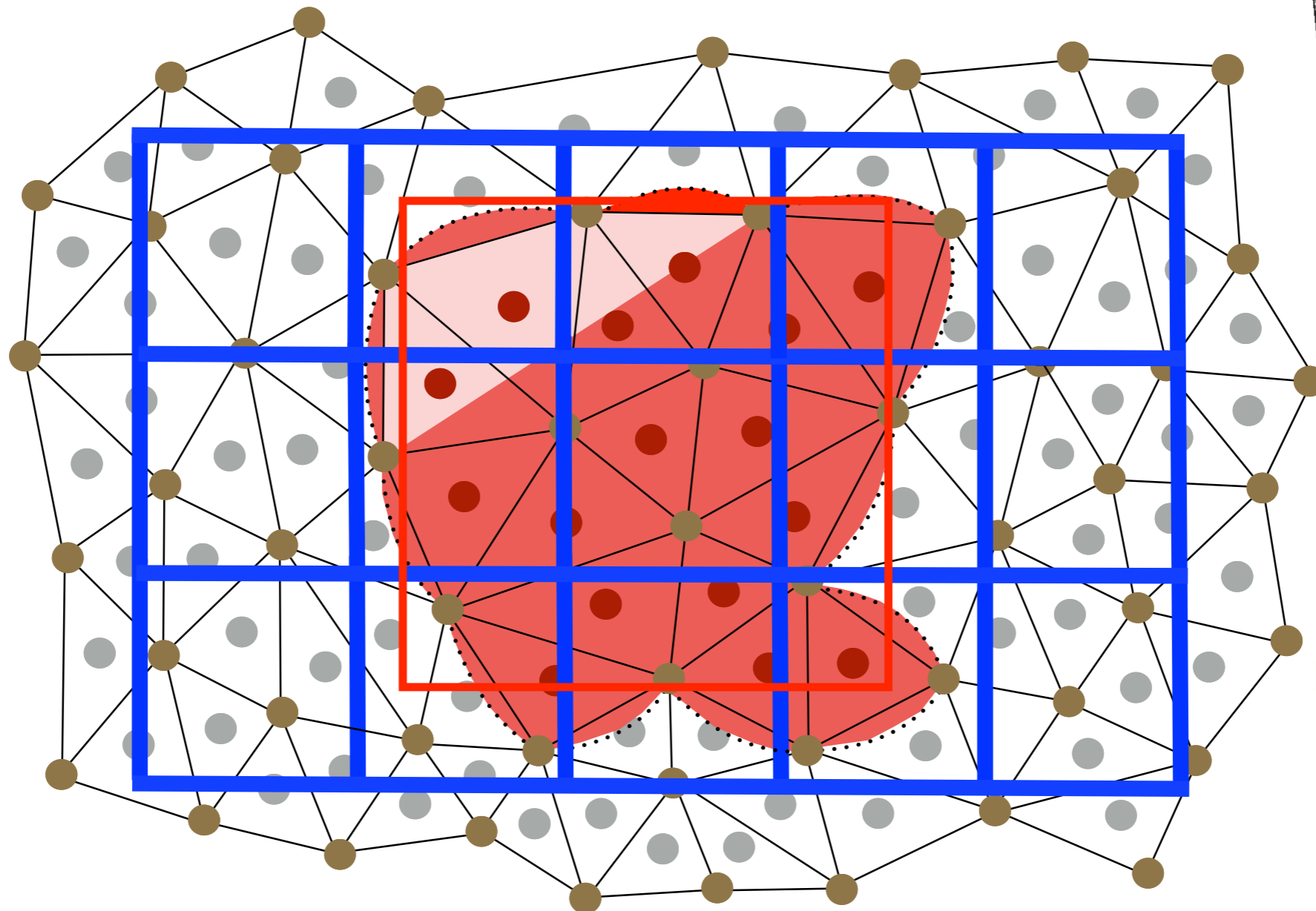




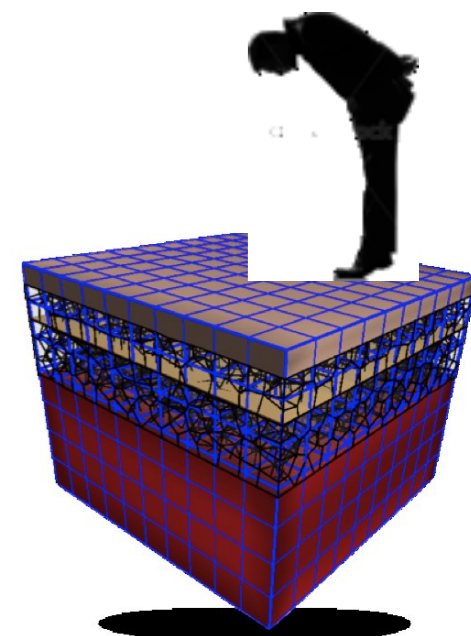
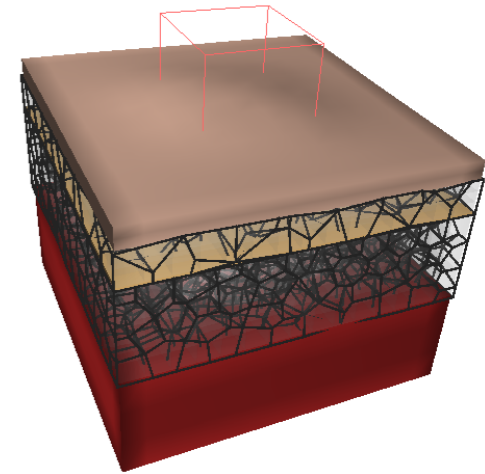
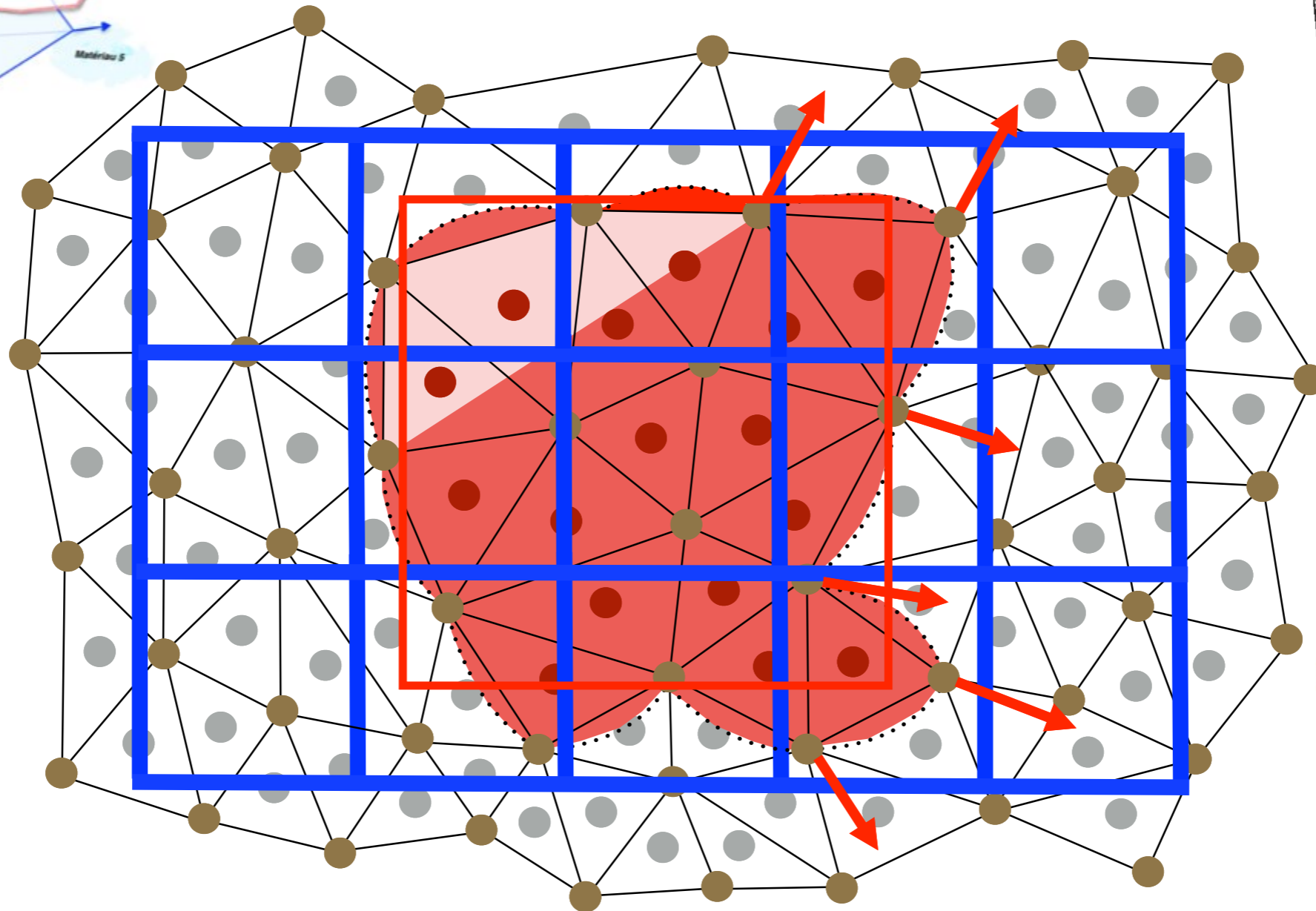
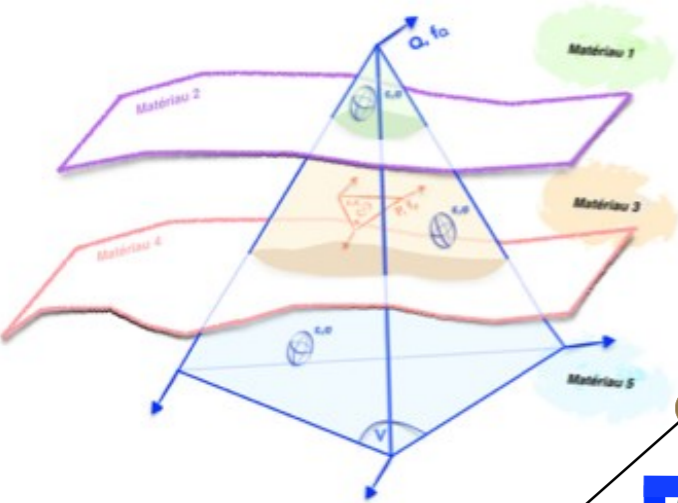
# Simulation d'augmentations tissulaires



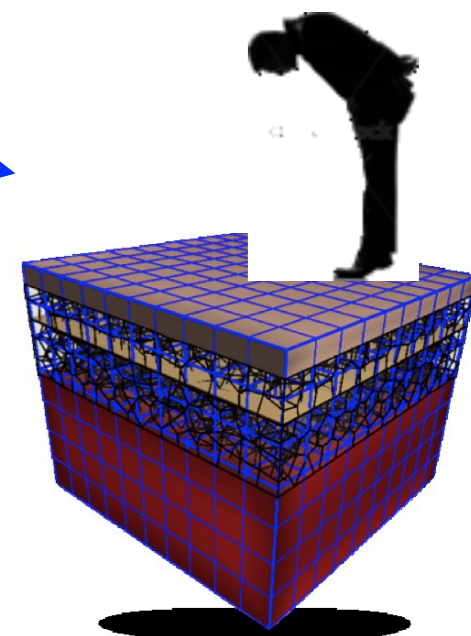
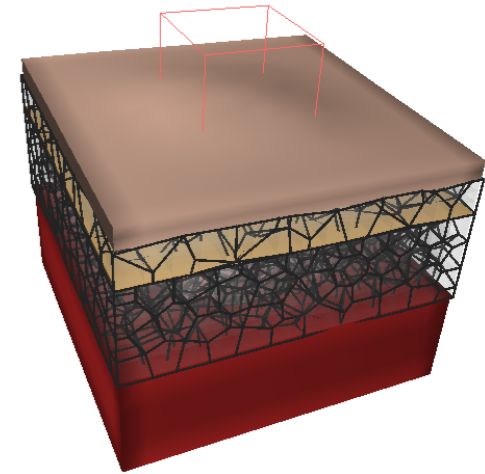
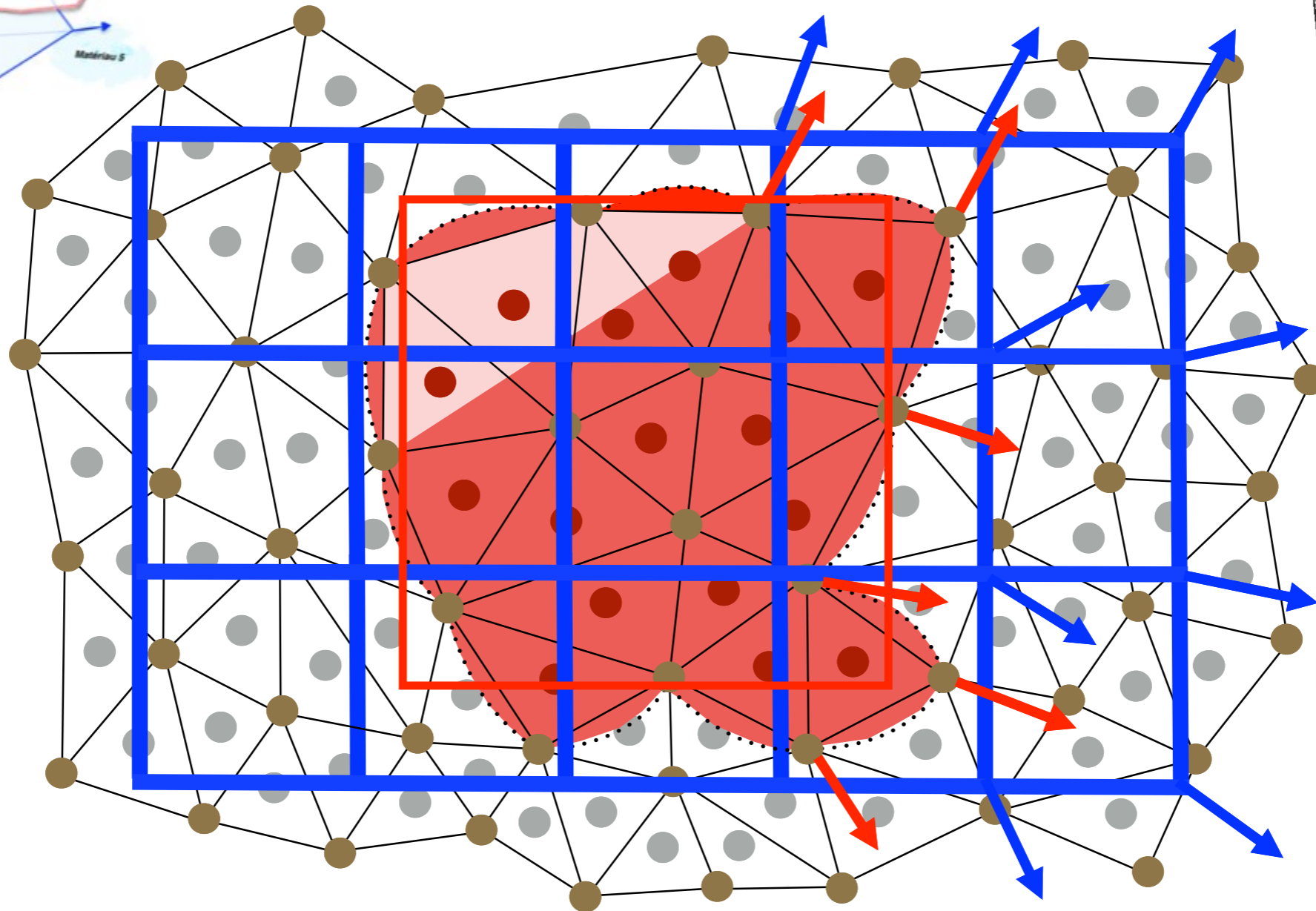
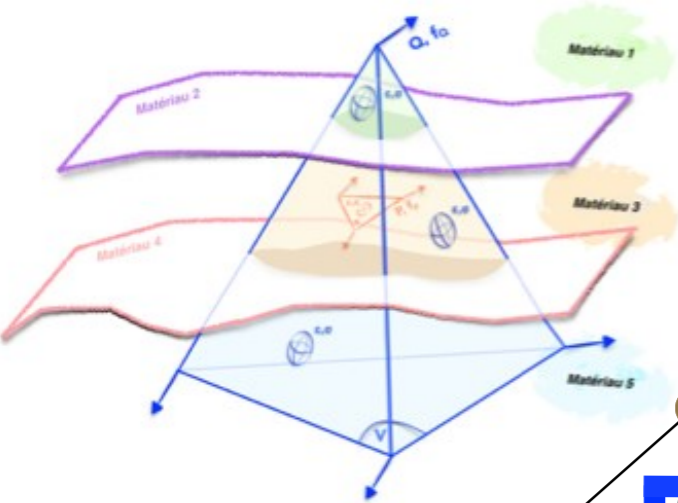
# Simulation d'augmentations tissulaires



# Simulation d'augmentations tissulaires



# Simulation d'augmentations tissulaires

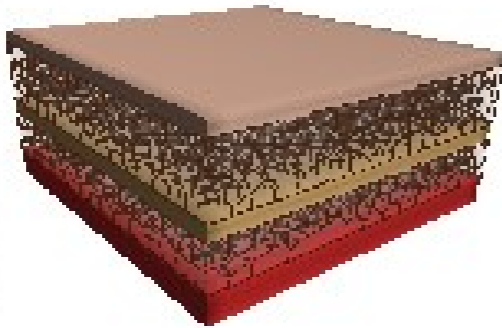
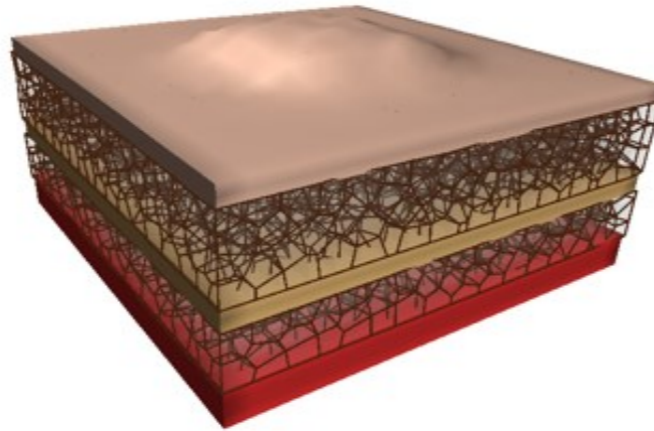


# Effet de la profondeur d'injection



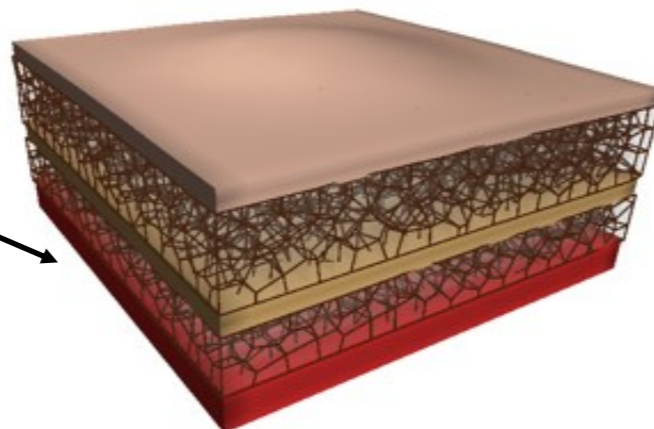
**0,5 cm<sup>3</sup>**

dans le SAT



size	= 3x3 cm
skin	= 1.2 mm
SAT	= 5.0 mm
SM	= 1.8 mm
DAT	= 3.4 mm
lobules	= 1.5 mm
RCS	= 0.2 mm
RCP	= 0.1 mm
depth	= 9.5 mm

dans le DAT

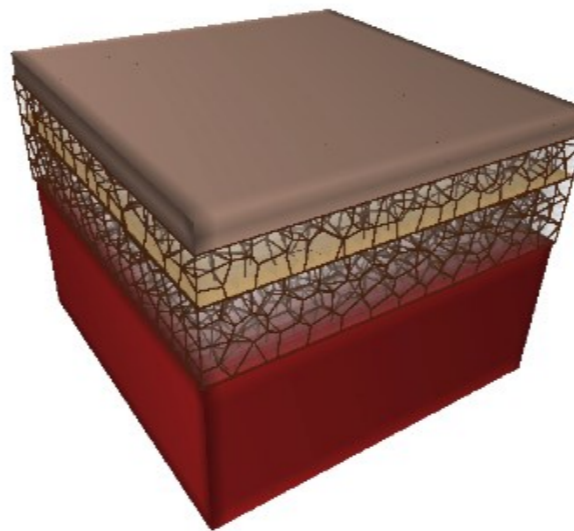
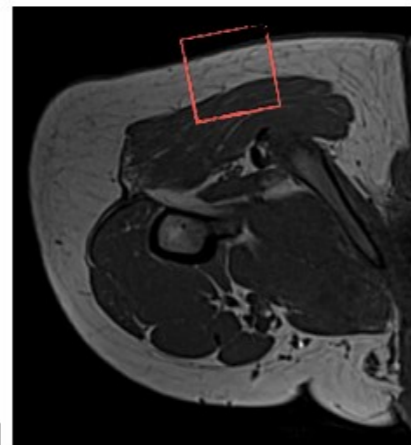


# Simulation de l'effet peau d'orange



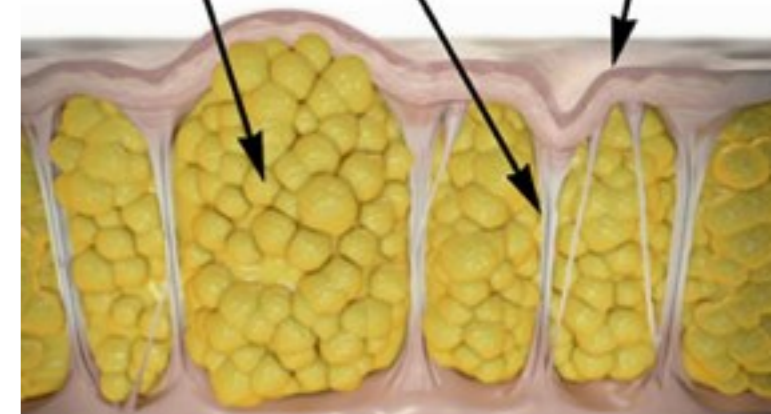
## Simulation des origines supposées de la cellulite

- *Augmentation du contenu graisseux*
- *Dégradation des propriétés élastiques de la peau*
- *Fibrosclérose du TCSC*



$size=7 \times 7 \text{ cm}$   
 $skin_t=4.5 \text{ mm}$   
 $SAT_t=7.0 \text{ mm}$   
 $SM_t=0.6 \text{ mm}$   
 $DAT_t=12.5 \text{ mm}$   
 $lobule_d=4 \text{ mm}$   
 $RCS_t=0.4 \text{ mm}$   
 $RCP_t=0.4 \text{ mm}$   
 $deep_t=30 \text{ mm}$

Excess fat causing a bulge  
 Fibrous septae causing dimpling  
 Thin, inelastic skin



Luebberding et al. 2014

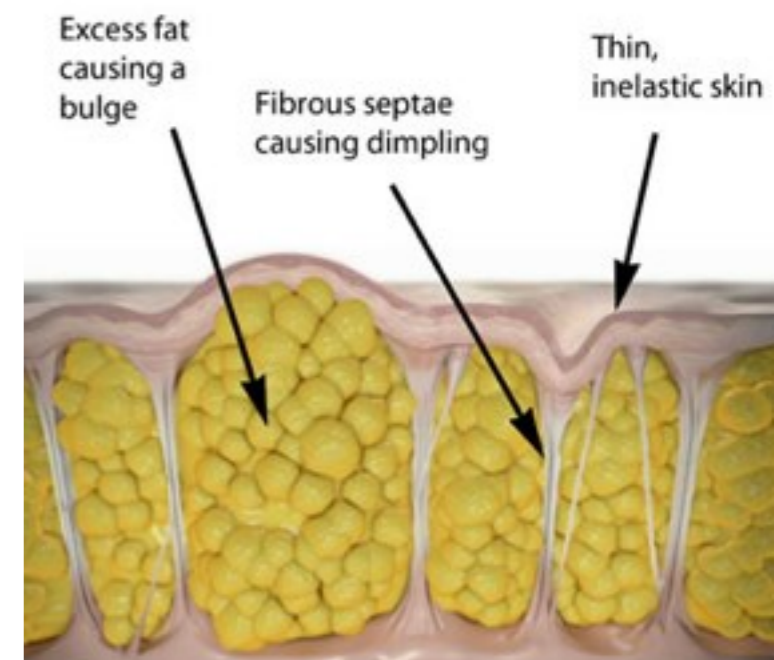
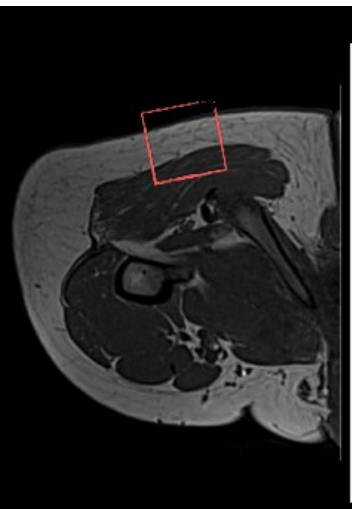
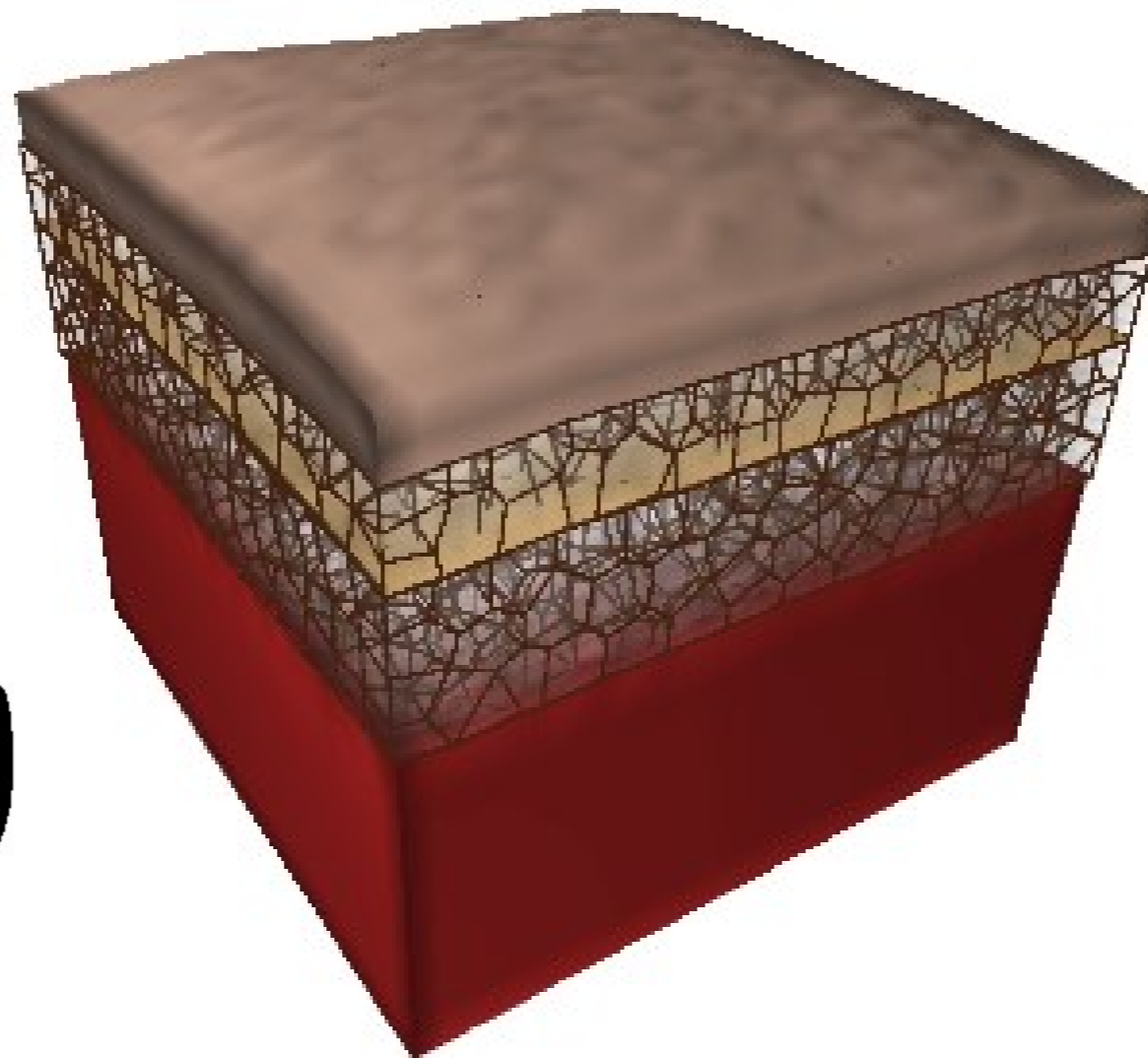
Hexsel et al. 2013



# Simulation de l'effet peau d'orange



## Augmentation du contenu graisseux

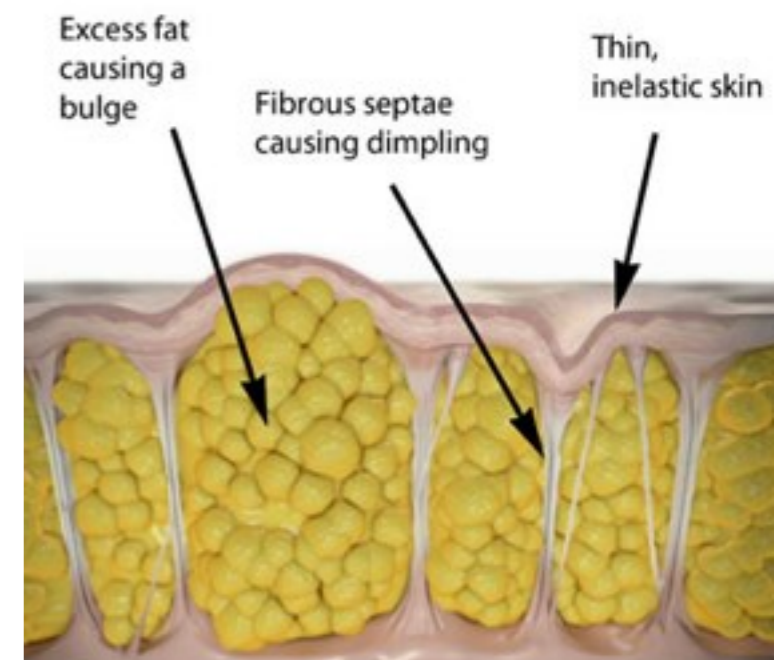
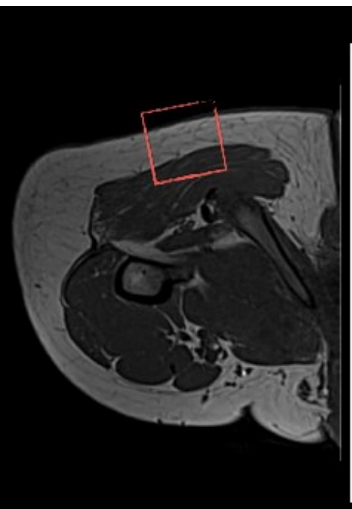
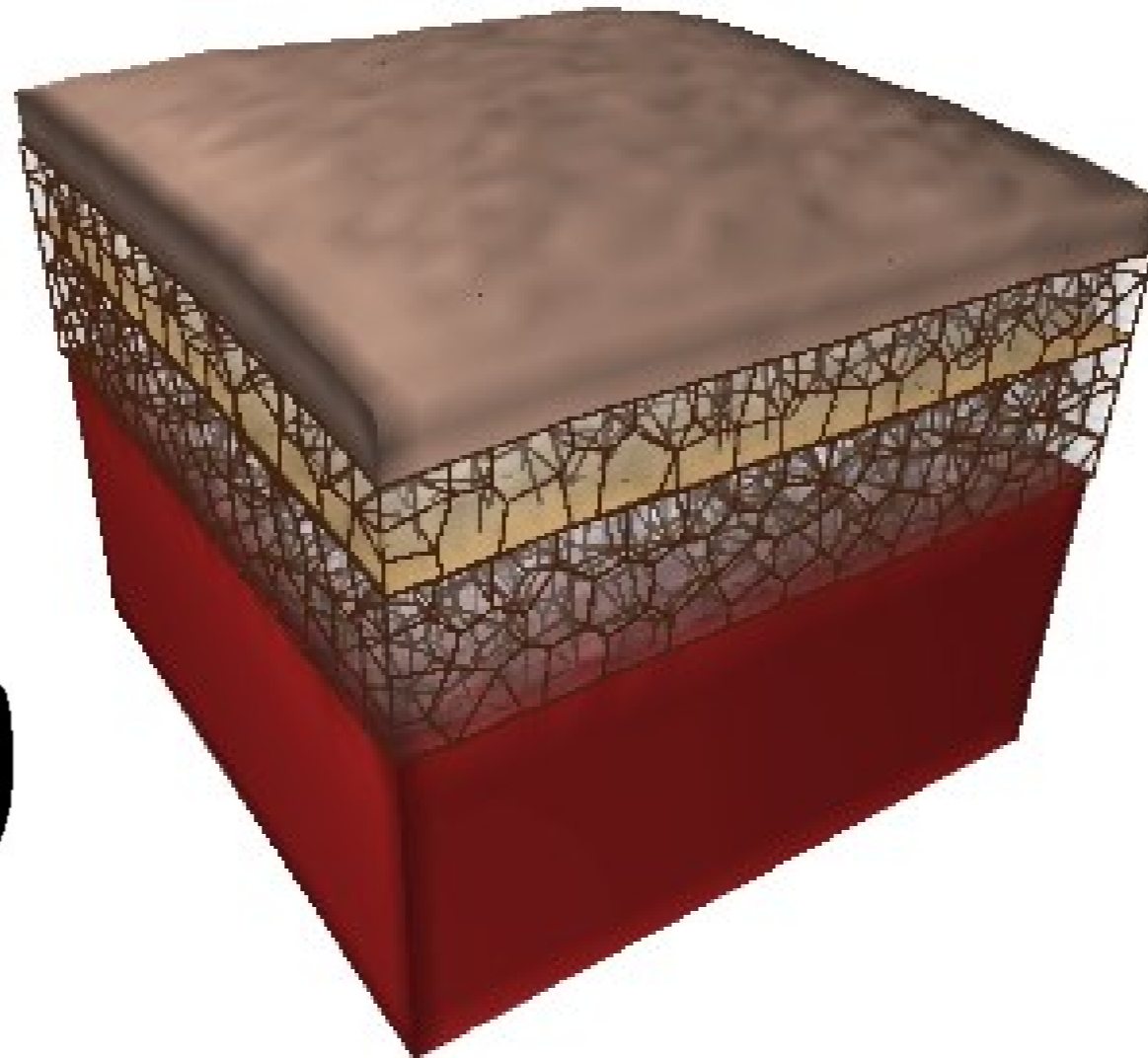


# Simulation de l'effet peau d'orange



Augmentation du contenu graisseux

- + Diminution des paramètres d'élasticité de la peau
- + Augmentation des paramètres d'élasticité du TCSC





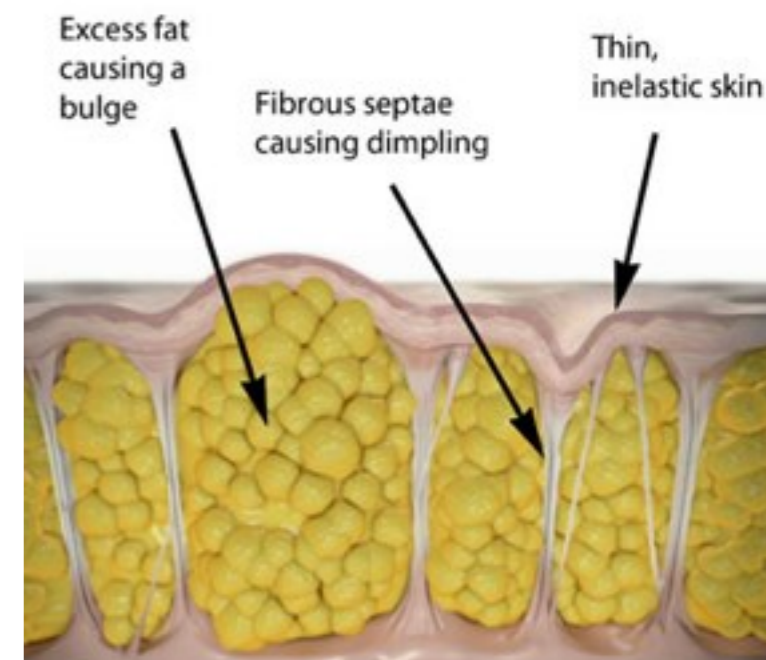
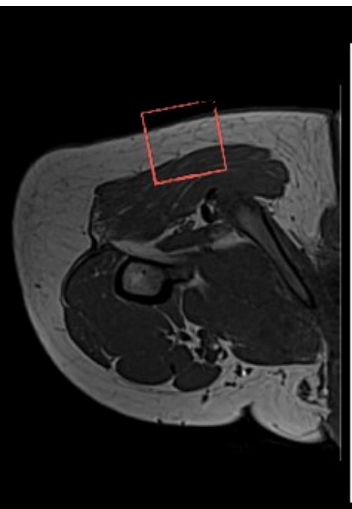
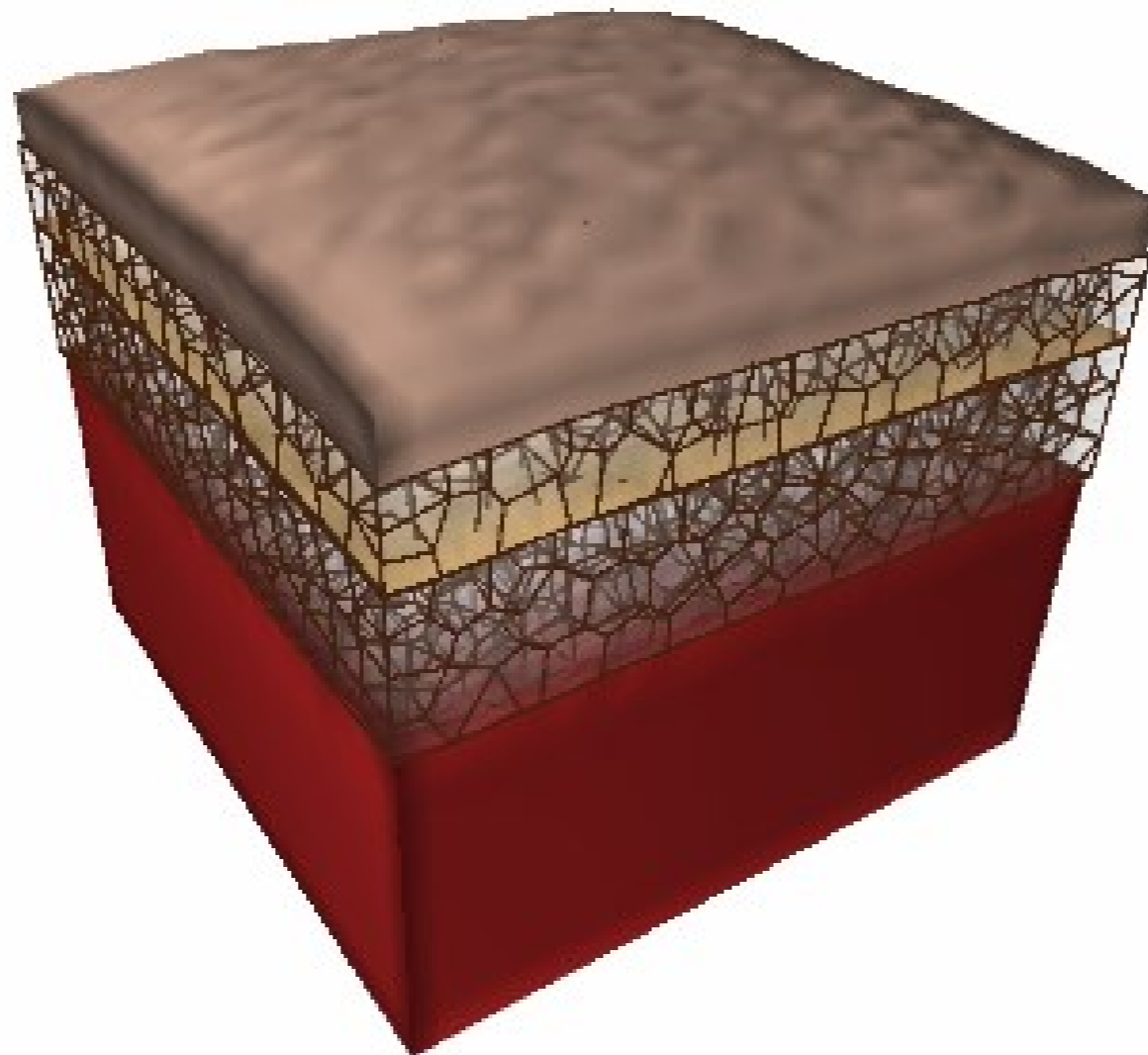
# Simulation de l'effet peau d'orange



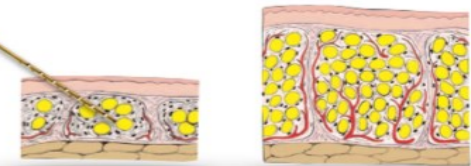
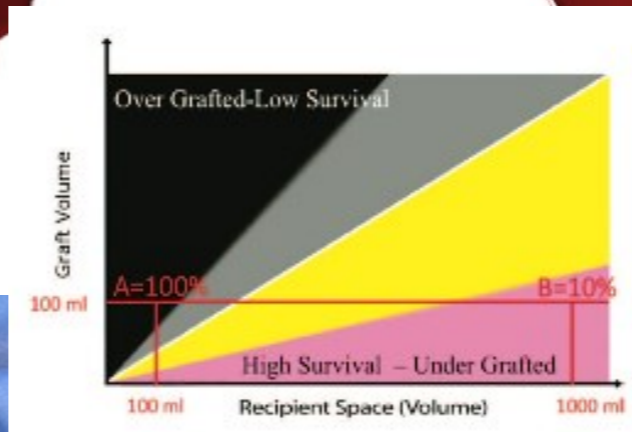
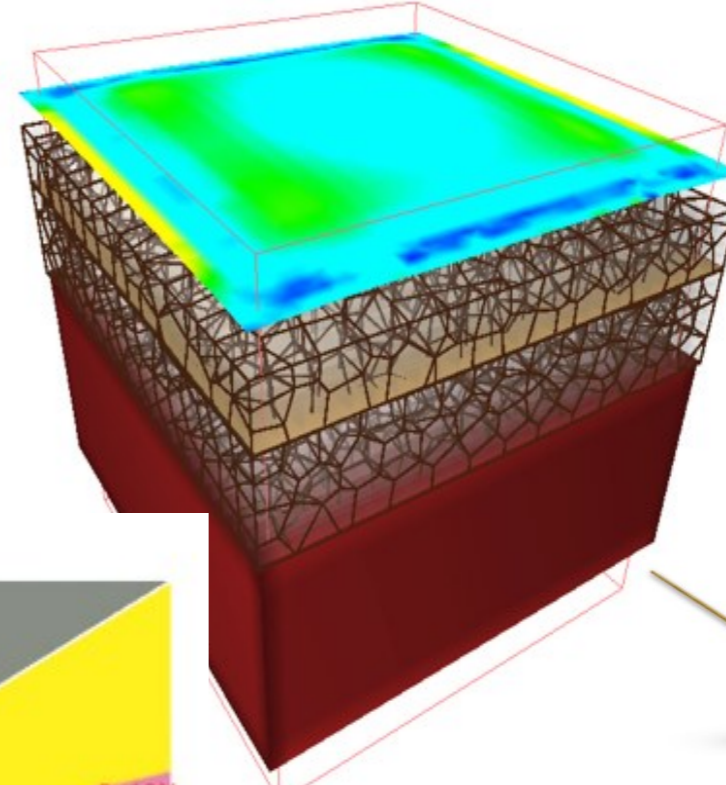
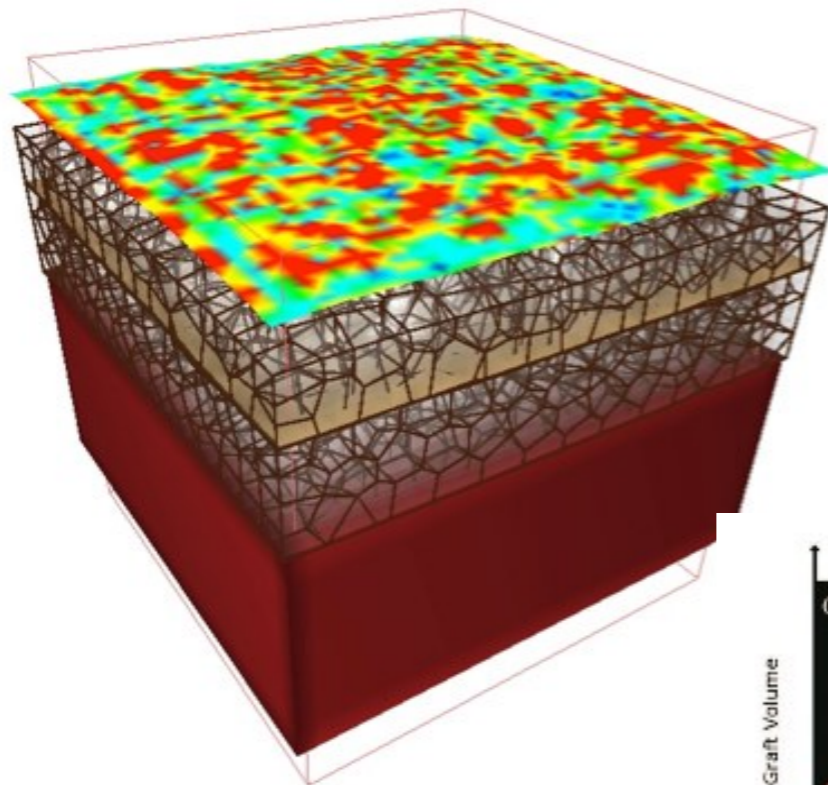
Augmentation du contenu graisseux

+ Diminution des paramètres d'élasticité de la peau

+ Augmentation des paramètres d'élasticité du TCSC



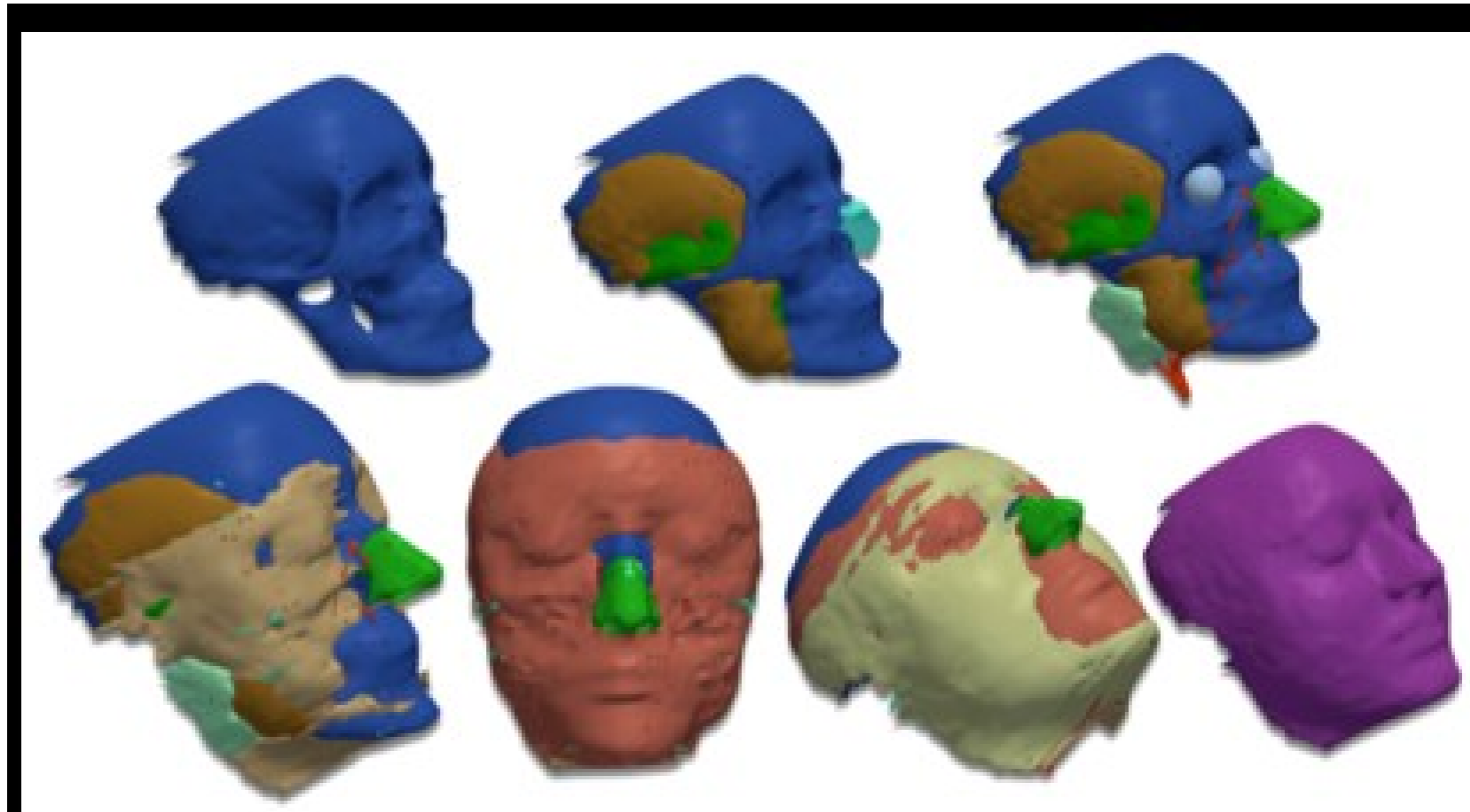
# Simulation des fasciotomies



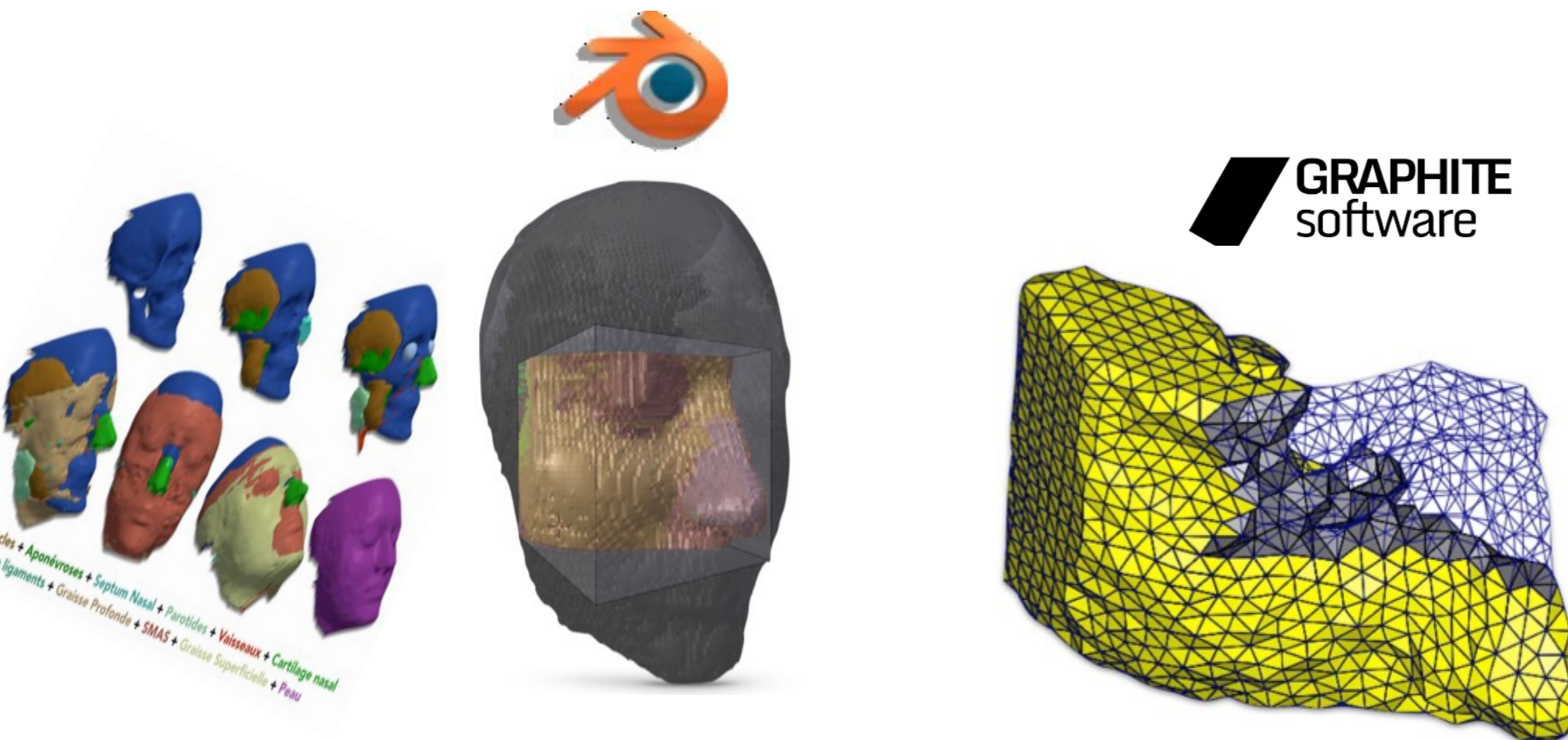
Khouri et al. 2014  
Cheriyann et al. 2014



# Simulation d'une AGA de la joue

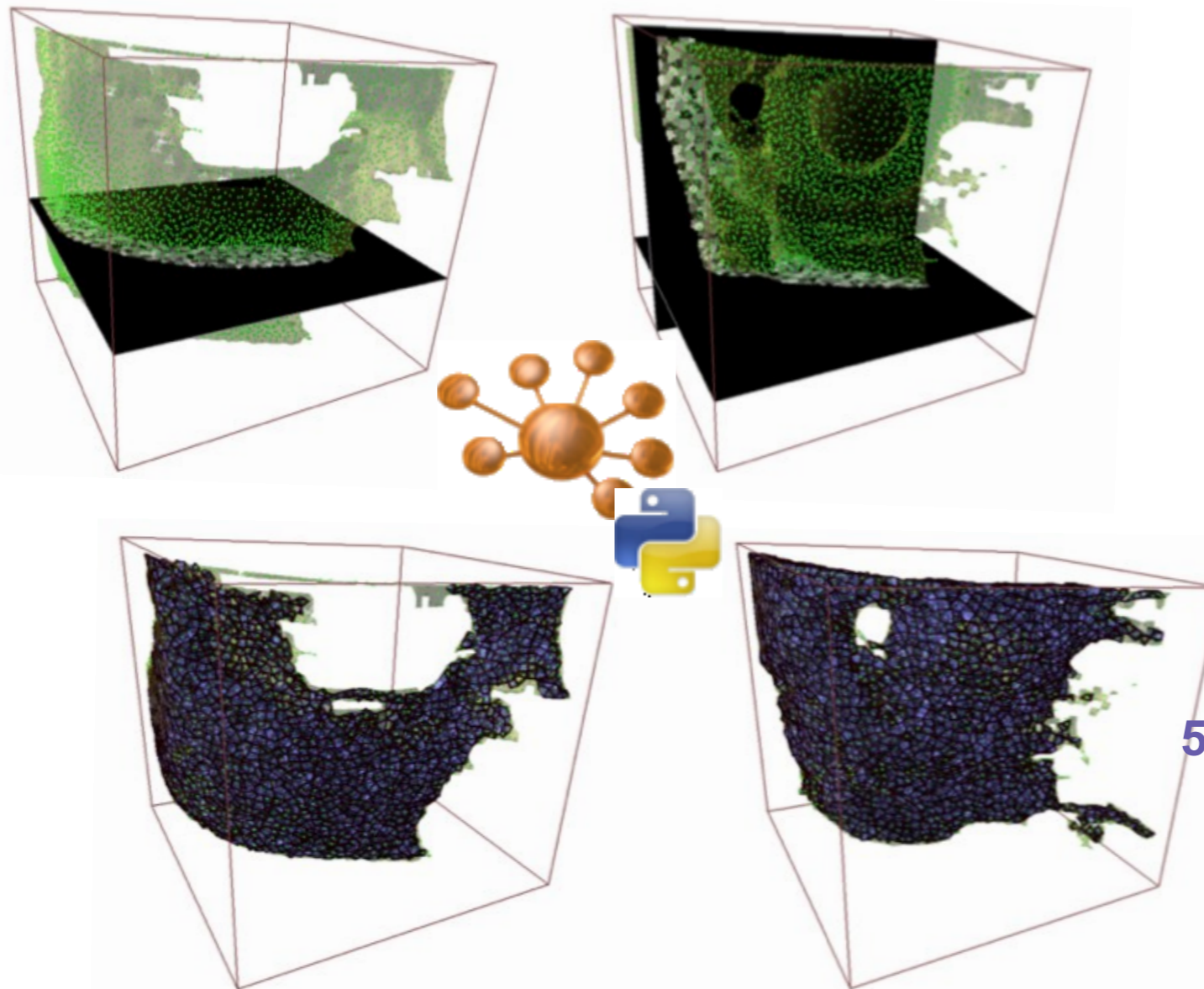


# Simulation d'une AGA de la joue



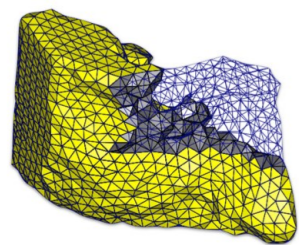
- ▶ Sélection de la **zone d'intérêt** jugale
- ▶ Création d'une **maillage tétraédrique** (peau, SAT, DAT, SM, muscle, os)  
(9900 *t* et 2305 *n*)

# Simulation d'une AGA de la joue



4000 cellules / SAT  
6000 cellules / DAT

58 441 triangles / SAT  
100 000 triangles / DAT



- ▶ Remplissage des maillages du SAT et du DAT par le modèle lobulaire
- ▶ Lobule<sub>d</sub> (IRM 3T) de 1,44 mm (SAT) et 1,56 mm (DAT)

# Simulation d'une AGA de la joue



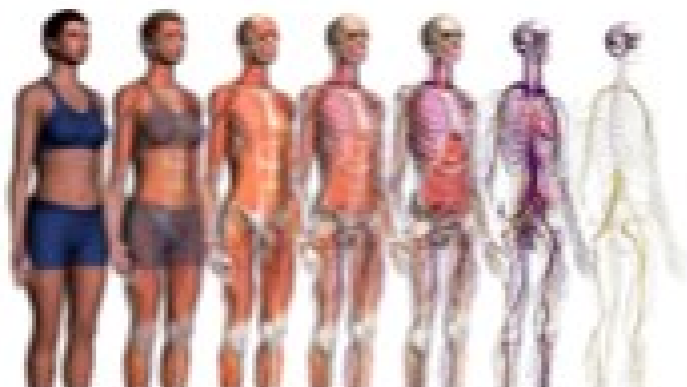
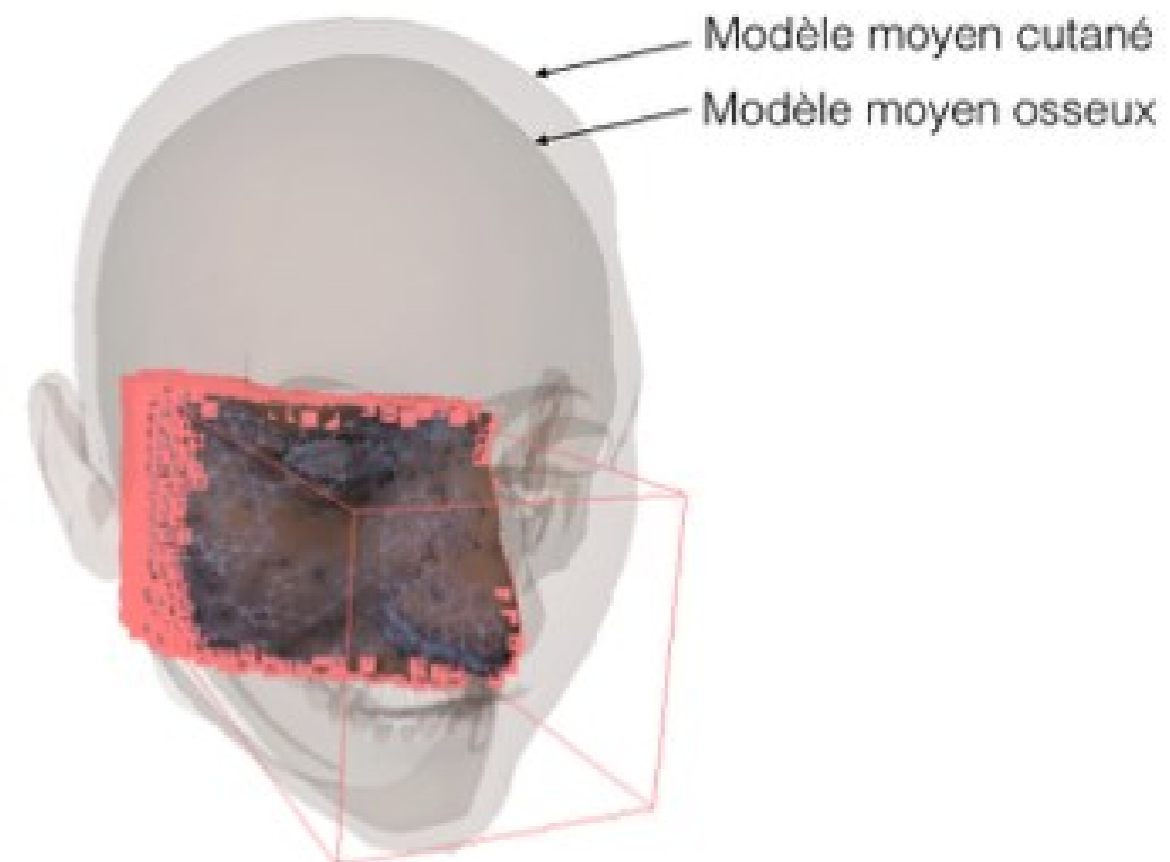
## Recalage Elastique

Modèles squelettique et surfacique Zygote®



## Fixation des bords

VOI + plan profond

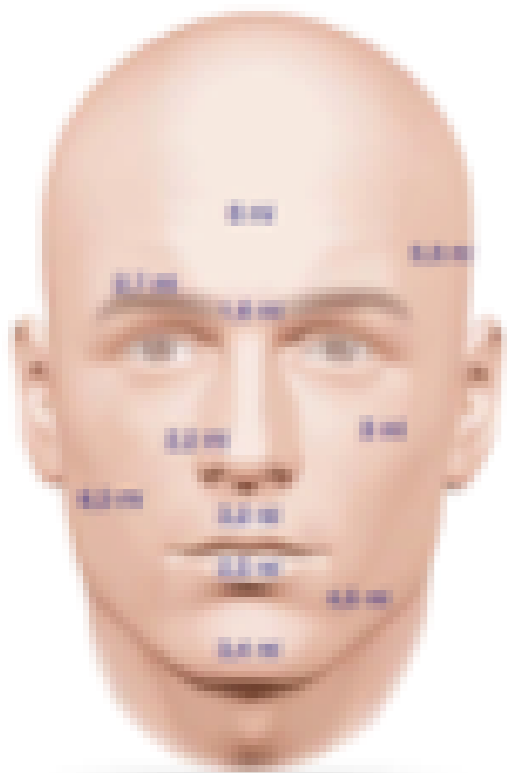


# Simulation d'une AGA de la joue



Volume

Géométrie de la zone d'offset



3 - 6 cm<sup>3</sup>



Boîte carrée



Boîte 2mm



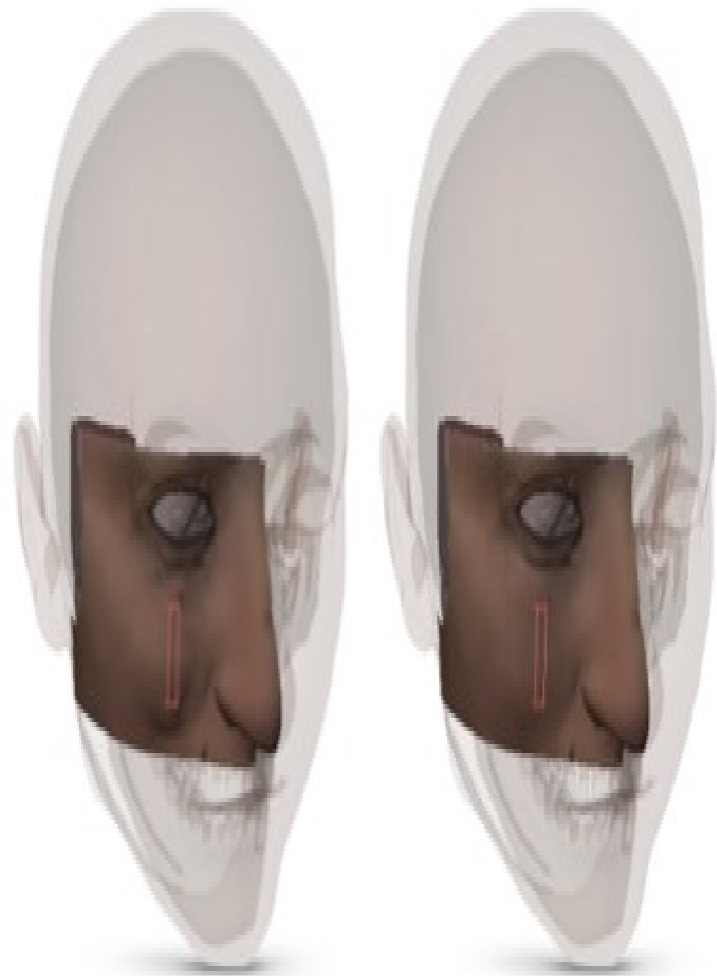
Trajets de 2 mm



# Simulation d'une AGA de la joue

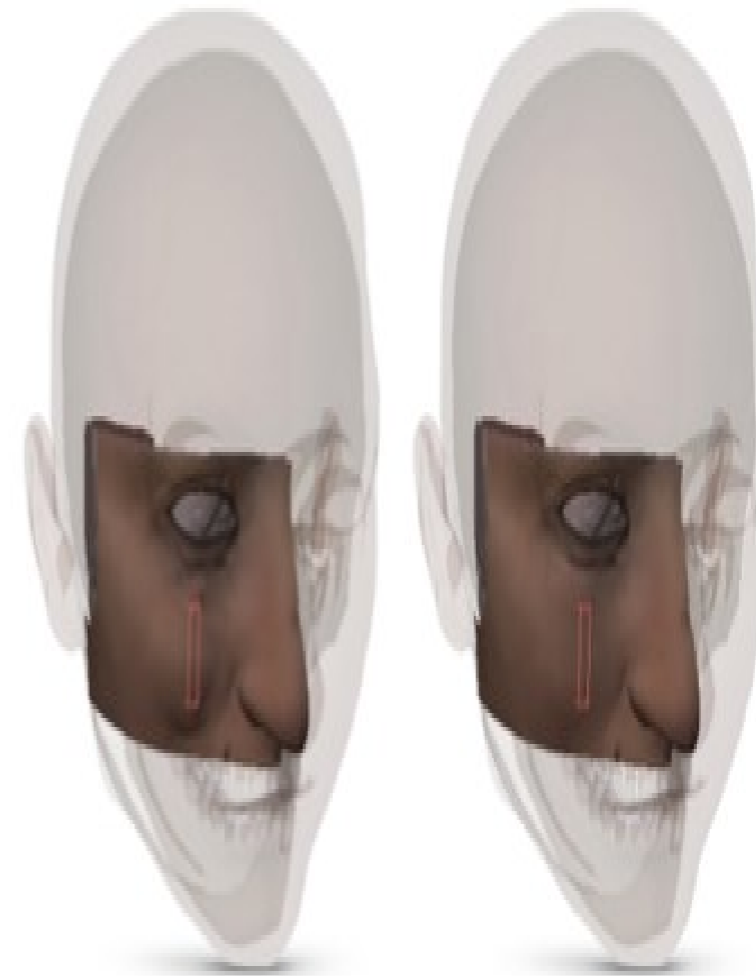


2 cm<sup>3</sup> de le SAT



2 cm<sup>3</sup> de

SAT

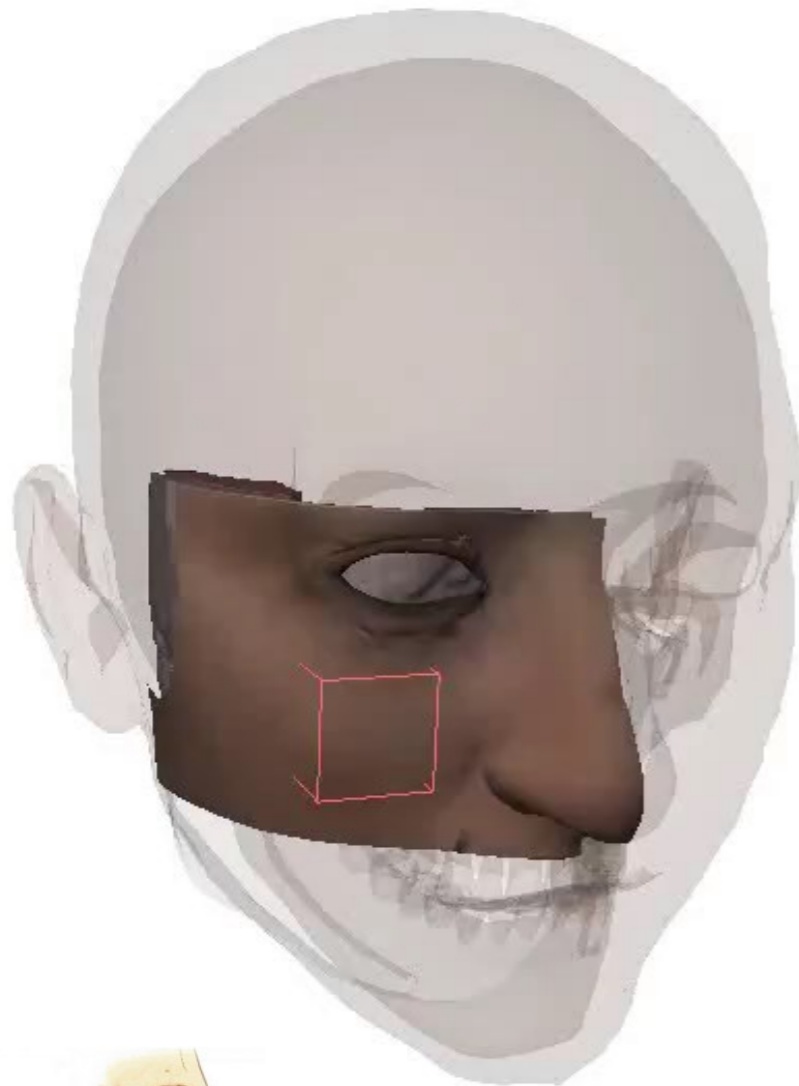




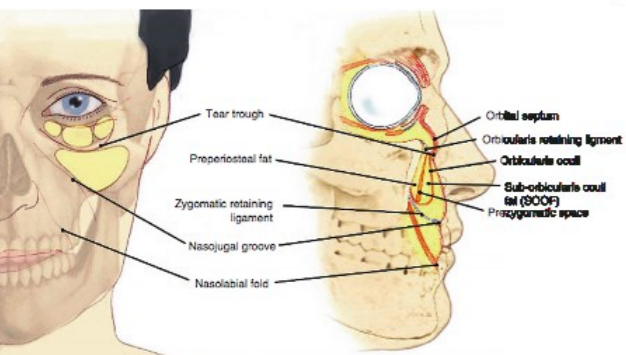
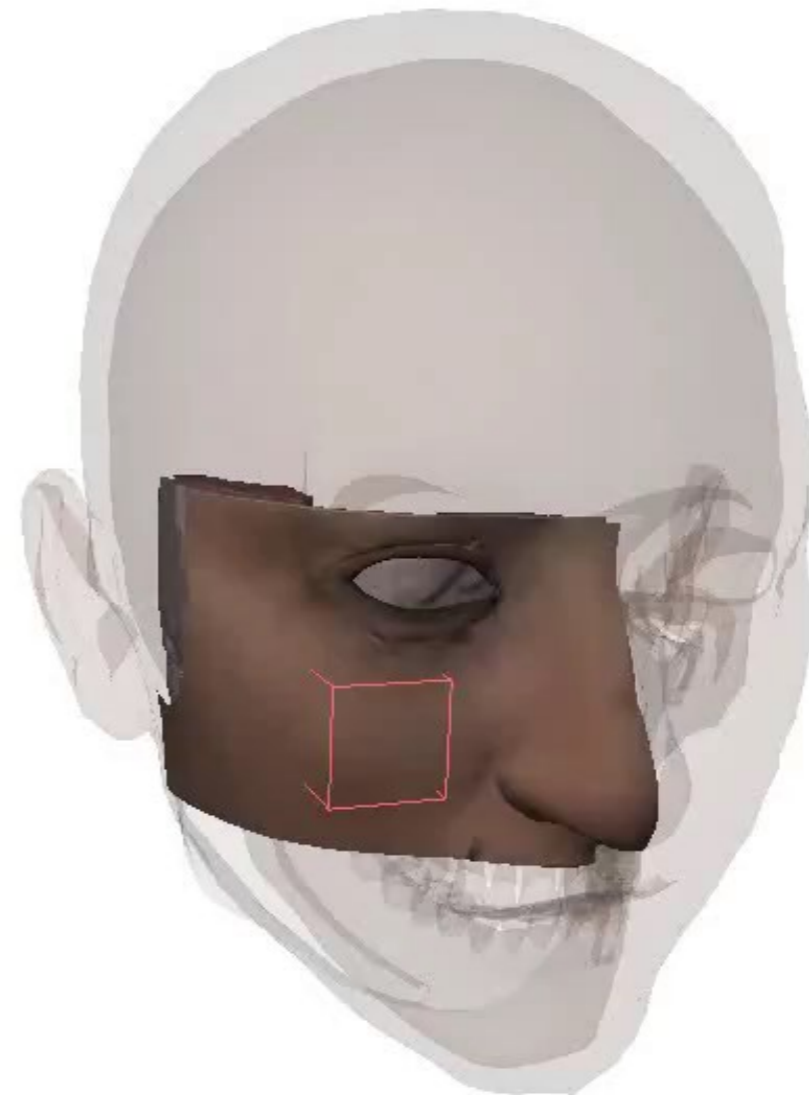
# Simulation d'une AGA de la joue



5 cm<sup>3</sup> dans le SAT



5 cm<sup>3</sup> dans le DAT



# Simulation d'une AGA de la joue



5 cm<sup>3</sup> dans le SAT



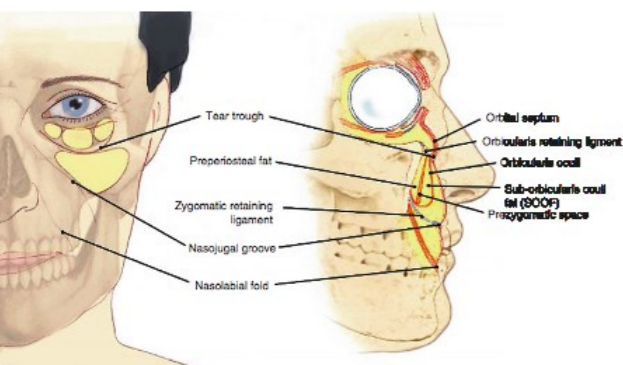
5 cm<sup>3</sup> dans le SAT+DAT



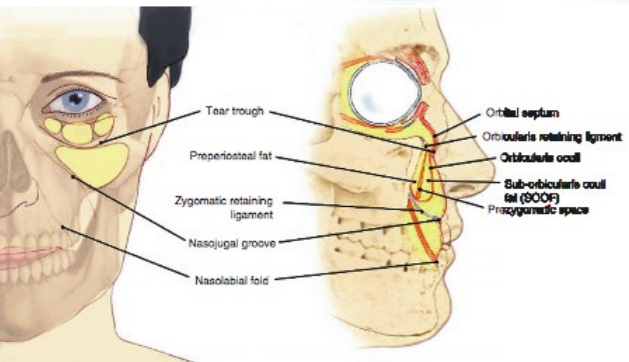
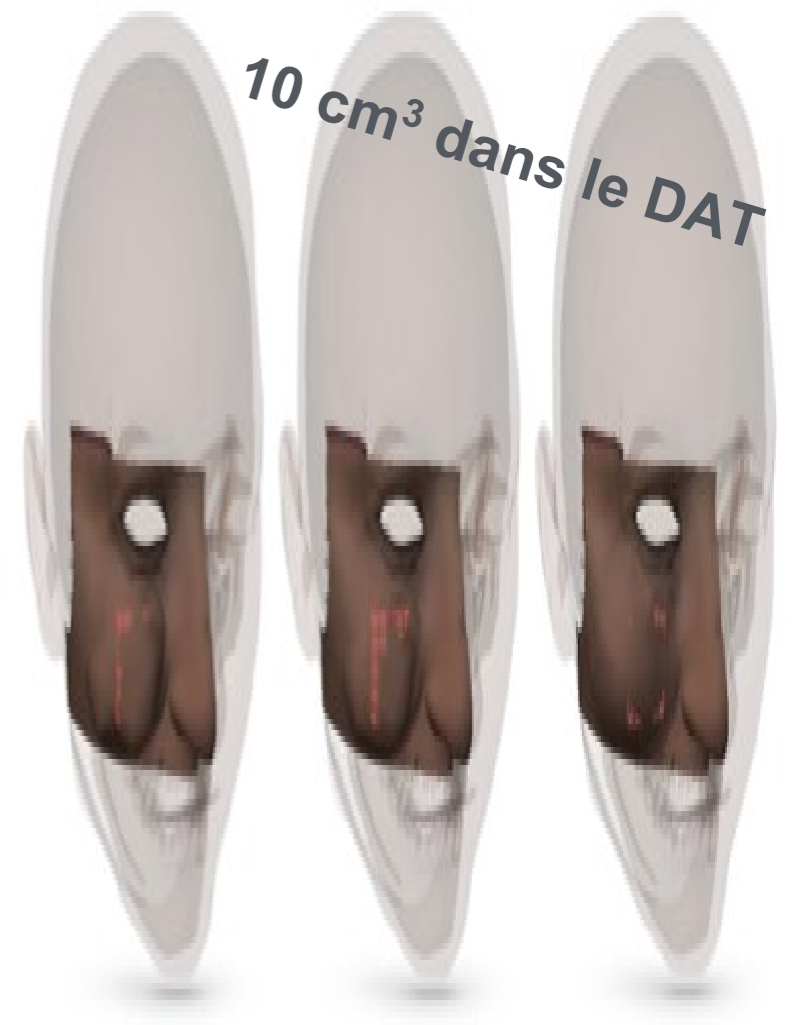
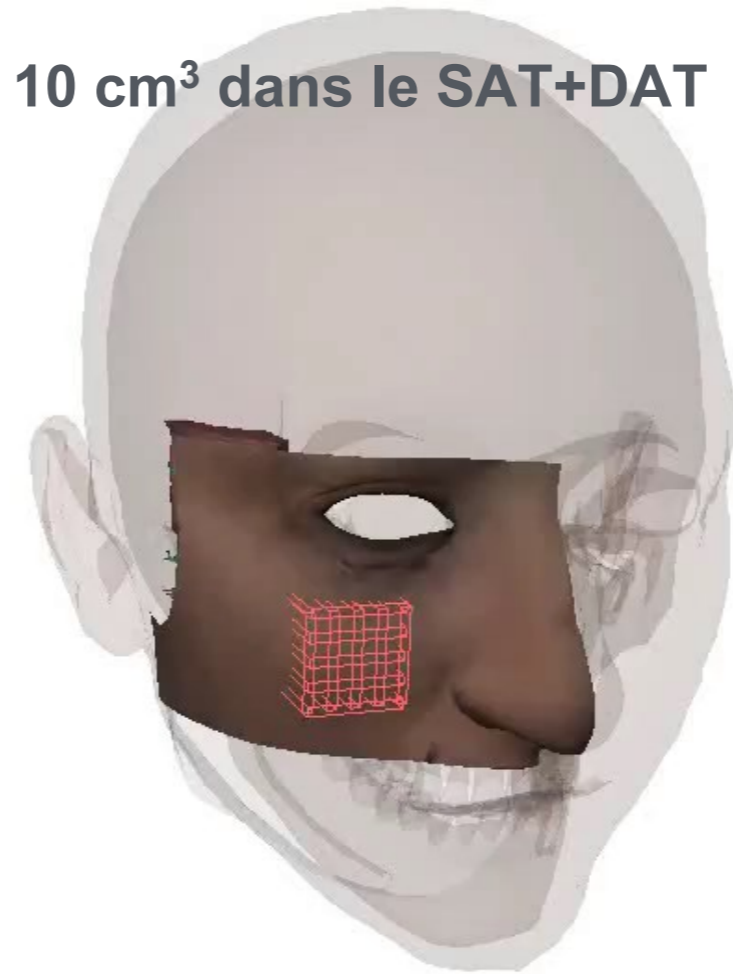
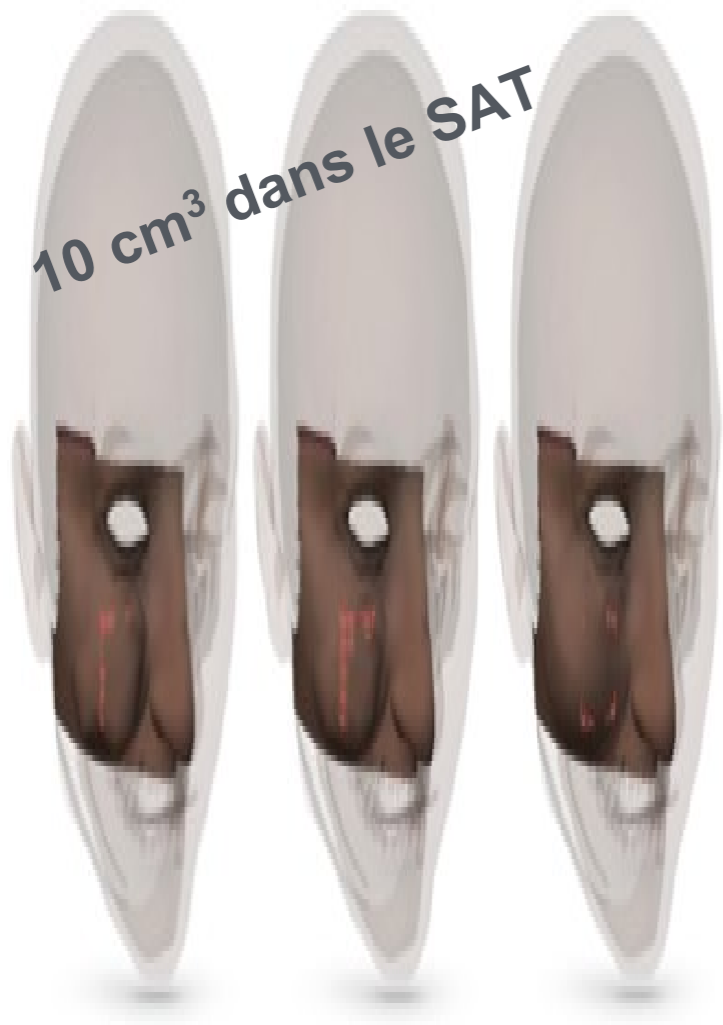
5 cm<sup>3</sup> dans le DAT



**Figure 4.20: Simulation d'une injection jugale de 5 cm<sup>3</sup> dans le SAT (figure de gauche), répartie dans le SAT et le DAT (figure du milieu) et dans le DAT (figure de droite).**

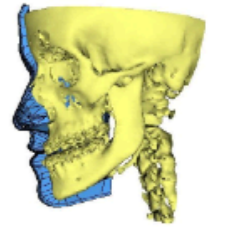


# Simulation d'une AGA de la joue

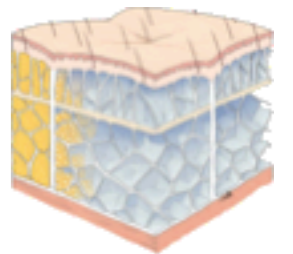


# PLAN

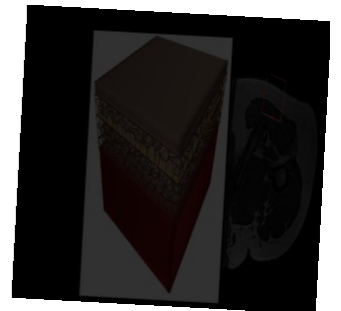
Etat de l'art



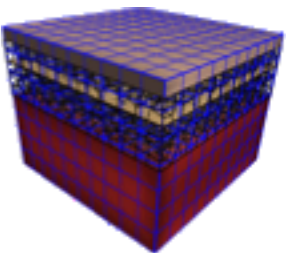
Modélisation anatomique



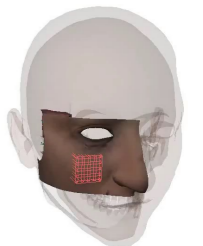
Modélisation géométrique paramétrique et procédurale



Modélisation biomécanique hybride



Simulations

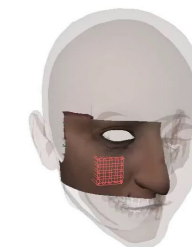
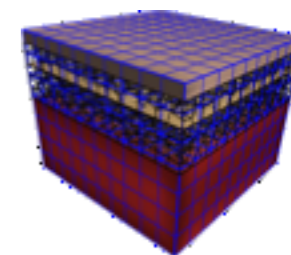
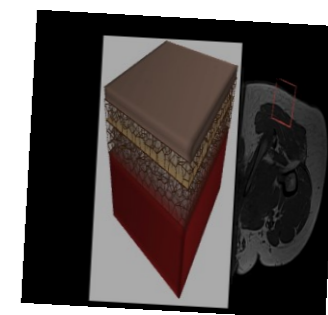
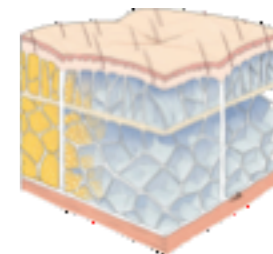


Perspectives



# Bilan des contributions

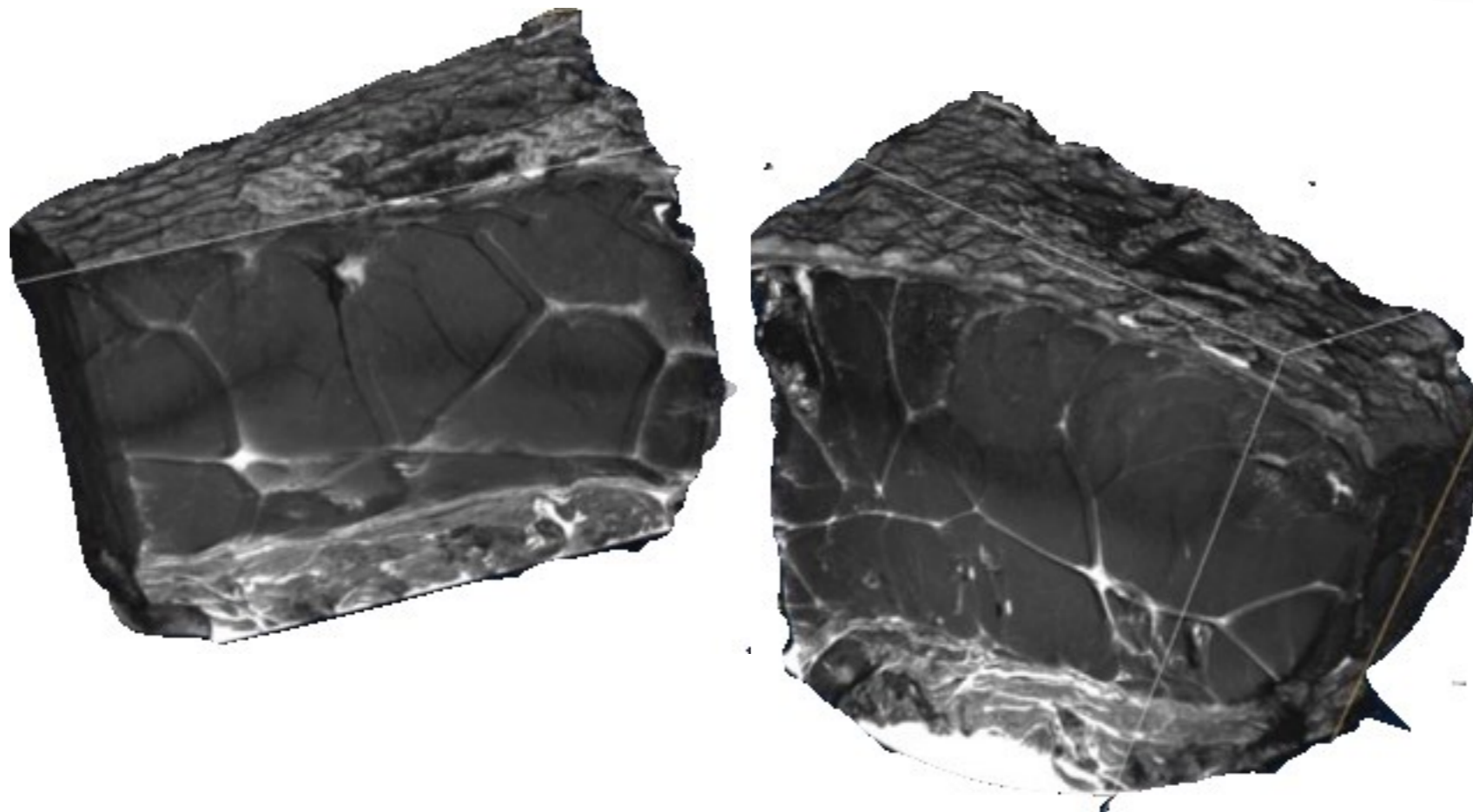
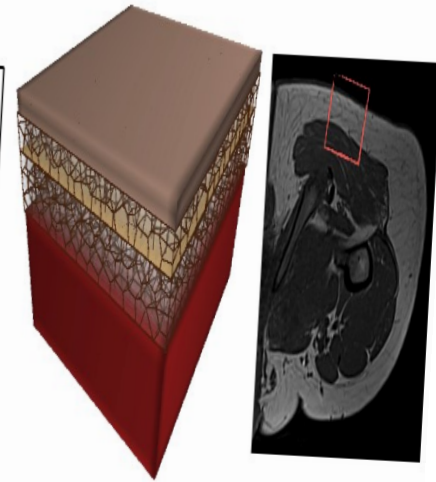
- Préciser l'**organisation anatomique générique** du CPTSC grâce à l'imagerie *invivo*
- Elaborer un **modèle géométrique générique** du CPTSC déclinable à plusieurs sous-parties du corps
- Construire d'un **modèle biomécanique hybride** du CPTSC capable de retranscrire la complexité du comportement du CPTSC en une somme de comportements élémentaires
- **Simuler des injections de tissu adipeux** sous la peau à différentes localisations



# Améliorations géométriques

## Précision du modèle lobulaire

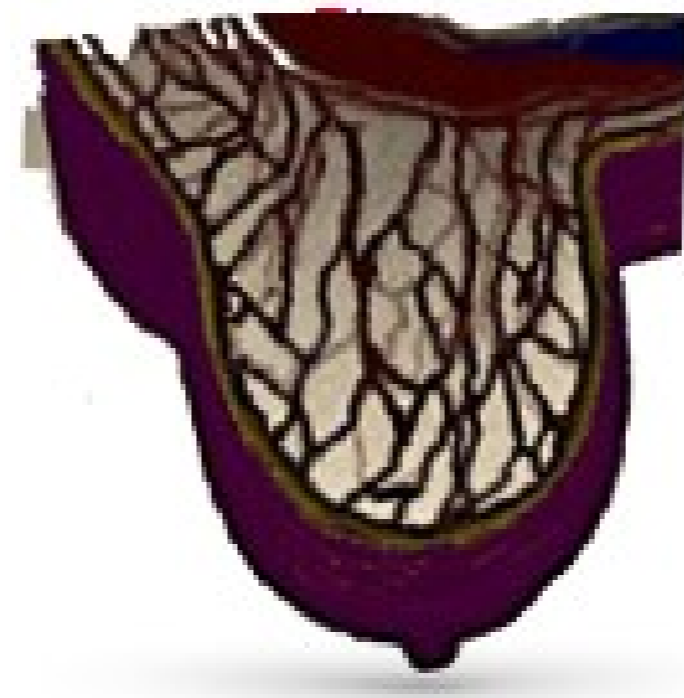
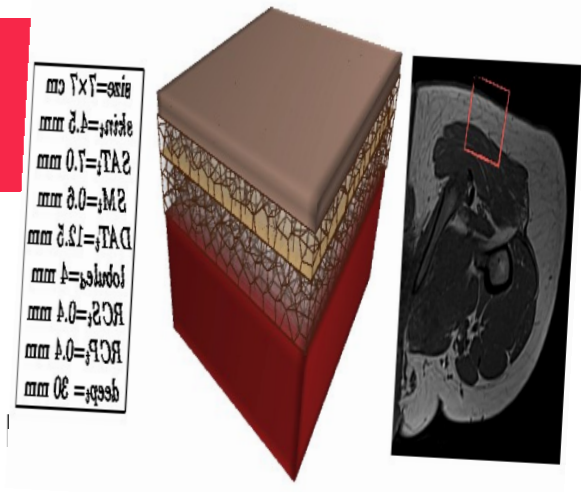
mm 1.7 = TA2  
mm 2.4 = TA2  
mm 0.7 = TA2  
mm 2.0 = M2  
mm 2.5 = TA2  
mm 1.4 = M2  
mm 1.0 = TA2  
mm 1.0 = TA2  
mm 0.8 = M2



*Acquisition en nano IRM (protocole en cours avec UM2)*

# Améliorations géométriques

## Modèle procédural spécifique du sein



*Systeme-L*  
Lindenmayer A. 1968

# Améliorations mécaniques

## Changement de la loi de comportement

$$\sigma = \mathbf{K} \varepsilon$$

*Hooke*

élasticité linéaire

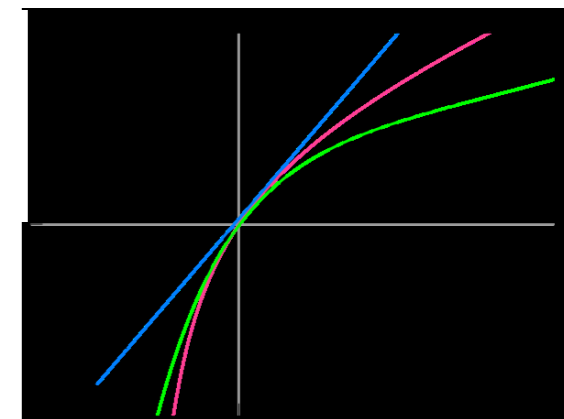
$$\psi = C_{10} (I_1 - 3) + \frac{k}{2} (J - 1)^2$$

*Néo-Hookéenne*

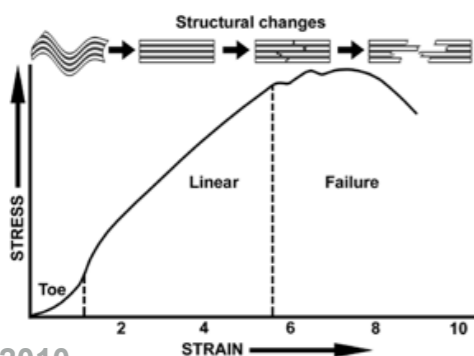
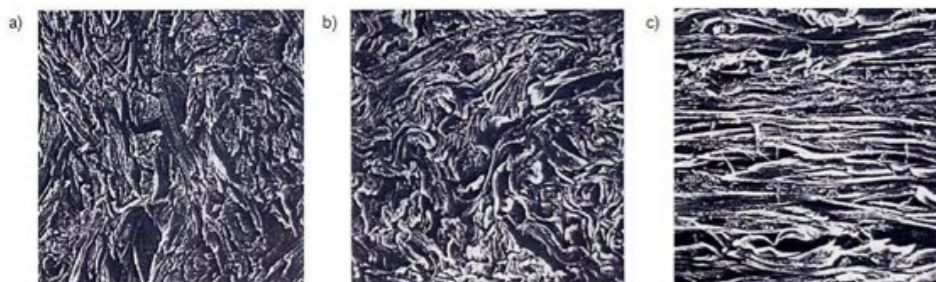
.....→ hyperélasticité

$$\Psi = \sum_{\alpha=1}^N C_{\alpha} (I_{\alpha} - 3)^{\alpha}$$

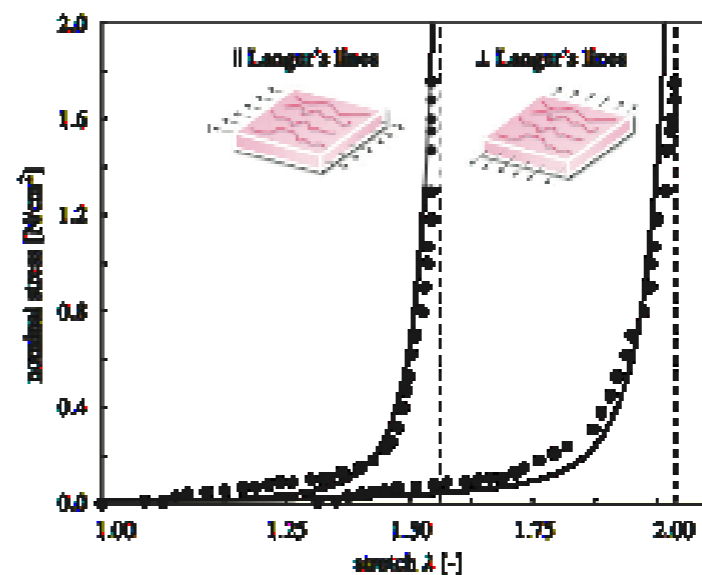
*MOONEY-RIVLIN*



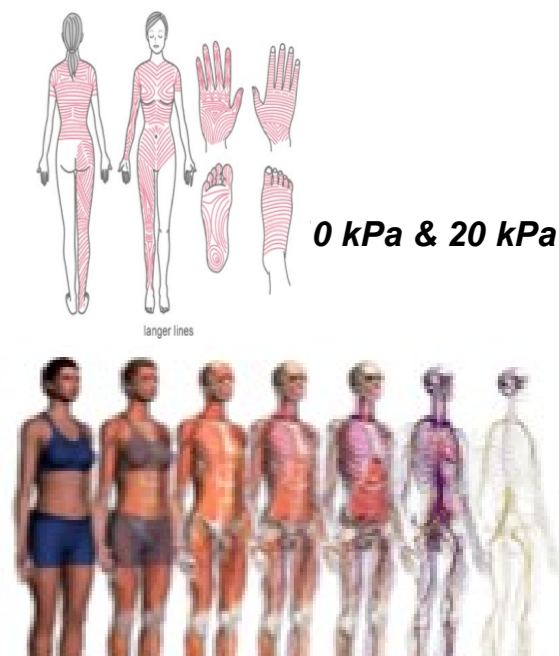
## Prise en charge des anisotropies



Kendall et al. 2010



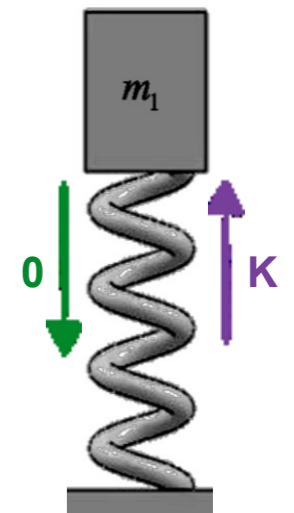
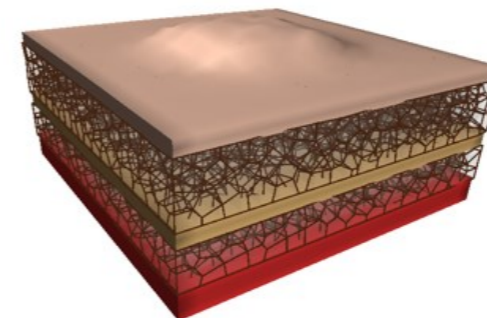
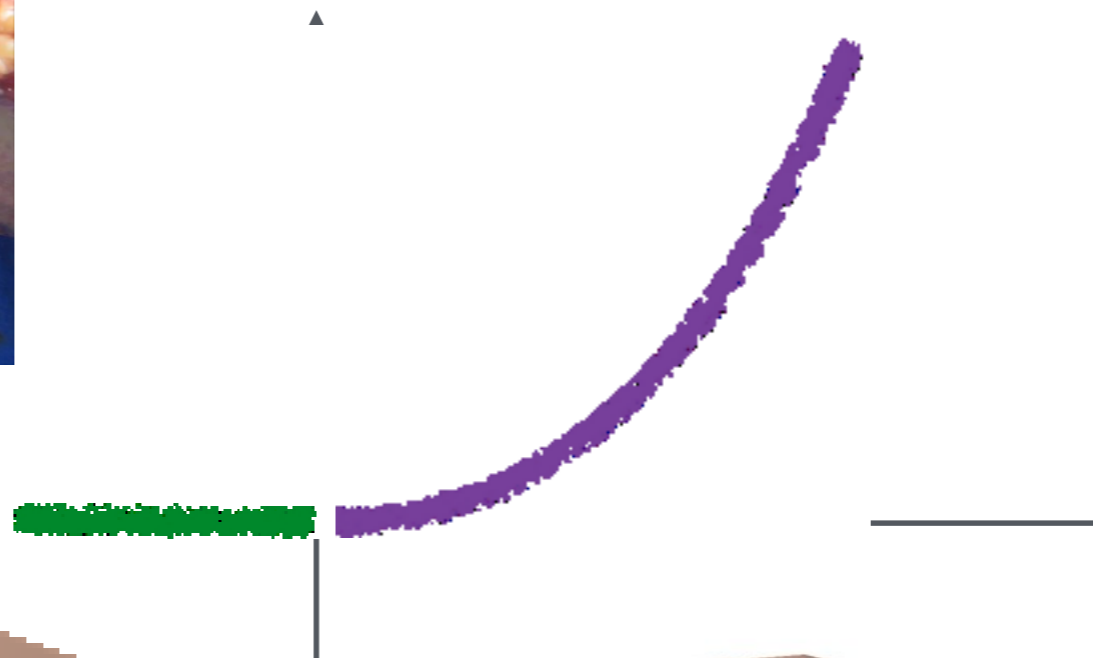
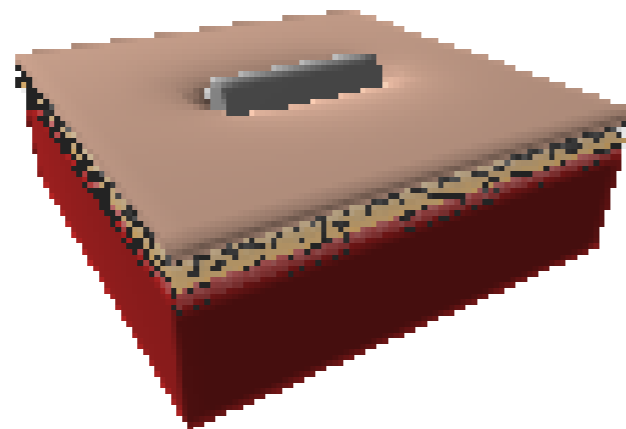
Tepole et al. 2012





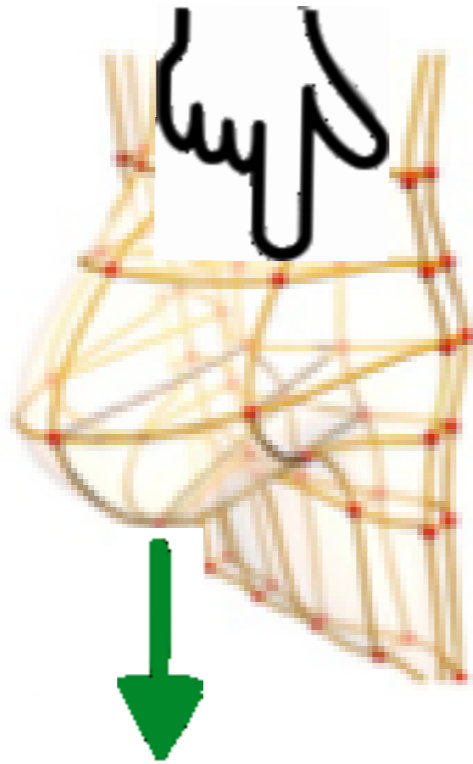
# Amélioration mécaniques

## Raideur Biphaseique du TCSC



# Améliorations mécaniques

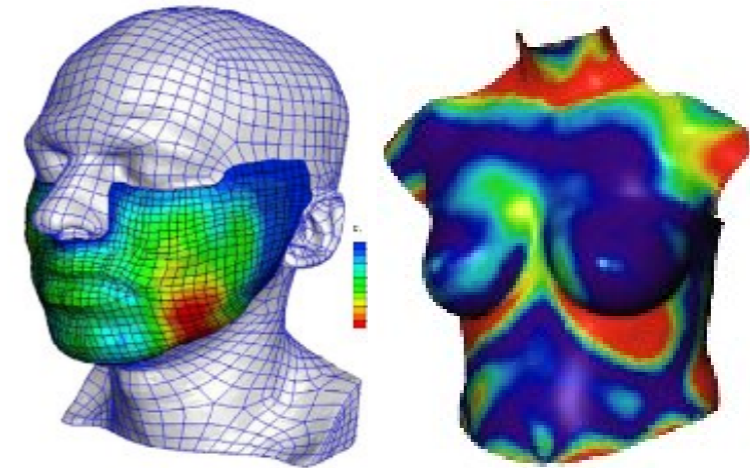
## Prise en compte de la pesanteur



Rajagopalet al.. 2007

### Validation

*acquisitions 3D surfaciques DD/DV/Ortho*



# Amélioration des simulations



Implants

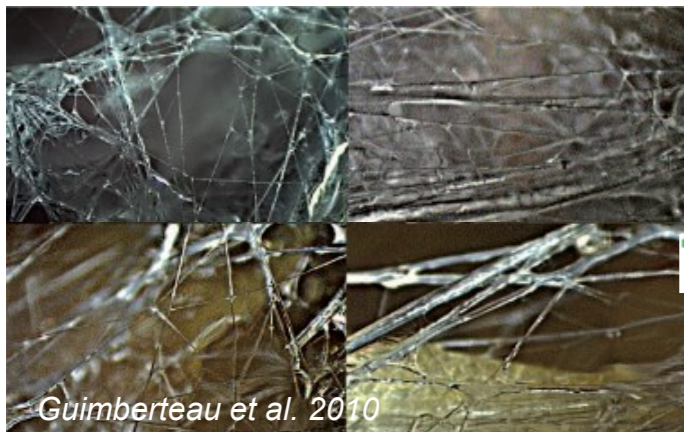
## Bibliothèque prothèses



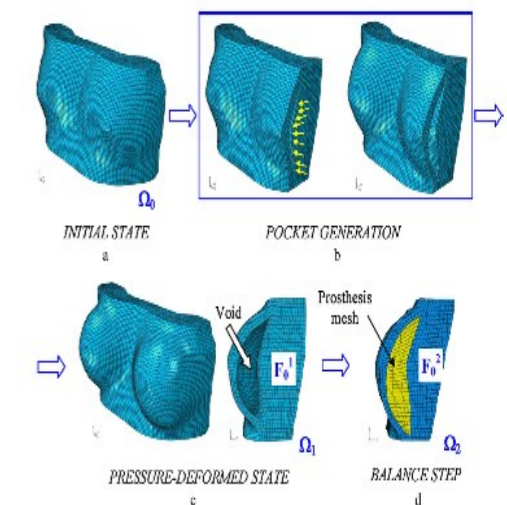
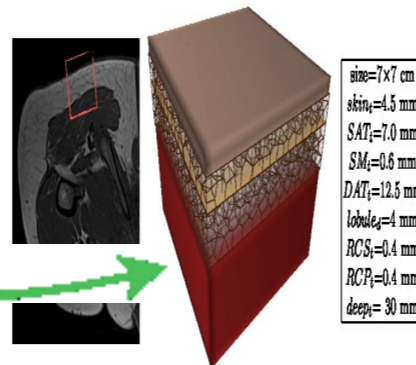
Gladilin et al.. 2011

## Gestion des Glissements & Insertion

*système fibrillaire et micro-vacuolaire*



Guimberteau et al. 2010



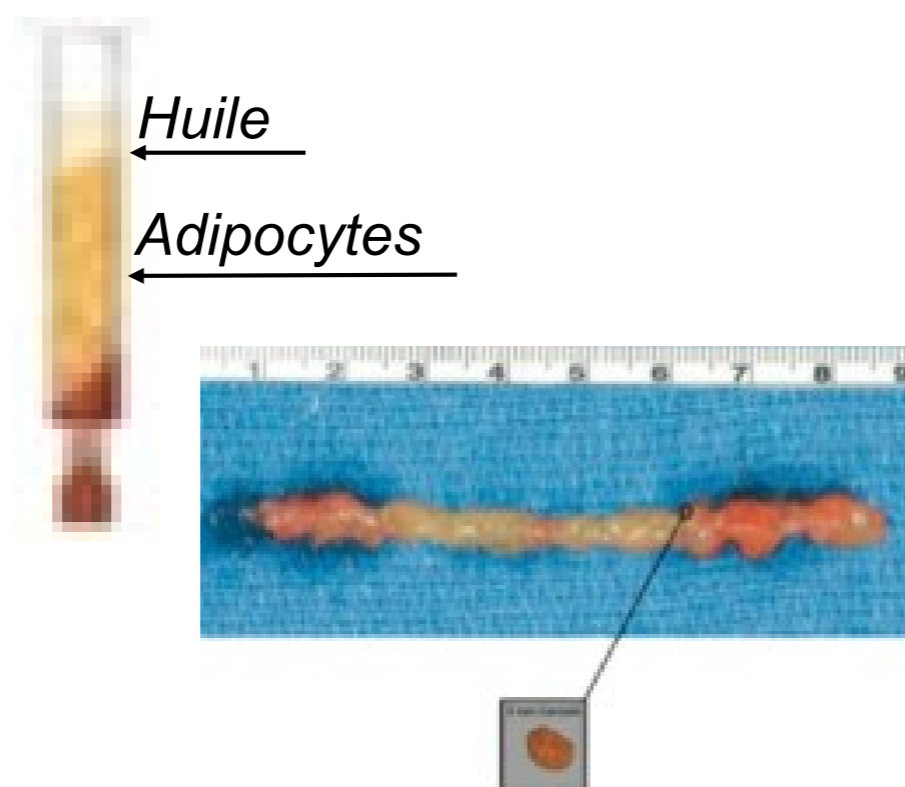
*Insertion d'un modèle compressé d'implant*

# Amélioration des simulations



## Modélisation des greffons adipocytaires

AGA



Thomsen 2012

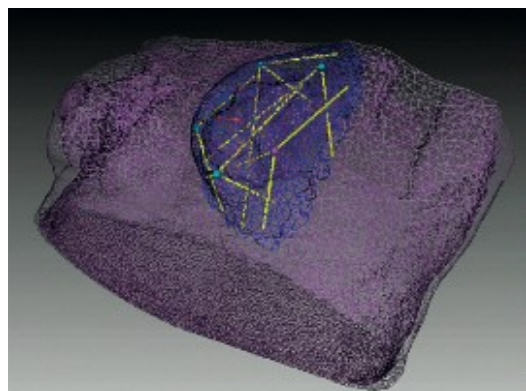
*Acquisition en nano CT d'une AGA marquée  
avant et après injection*

# Amélioration des simulations

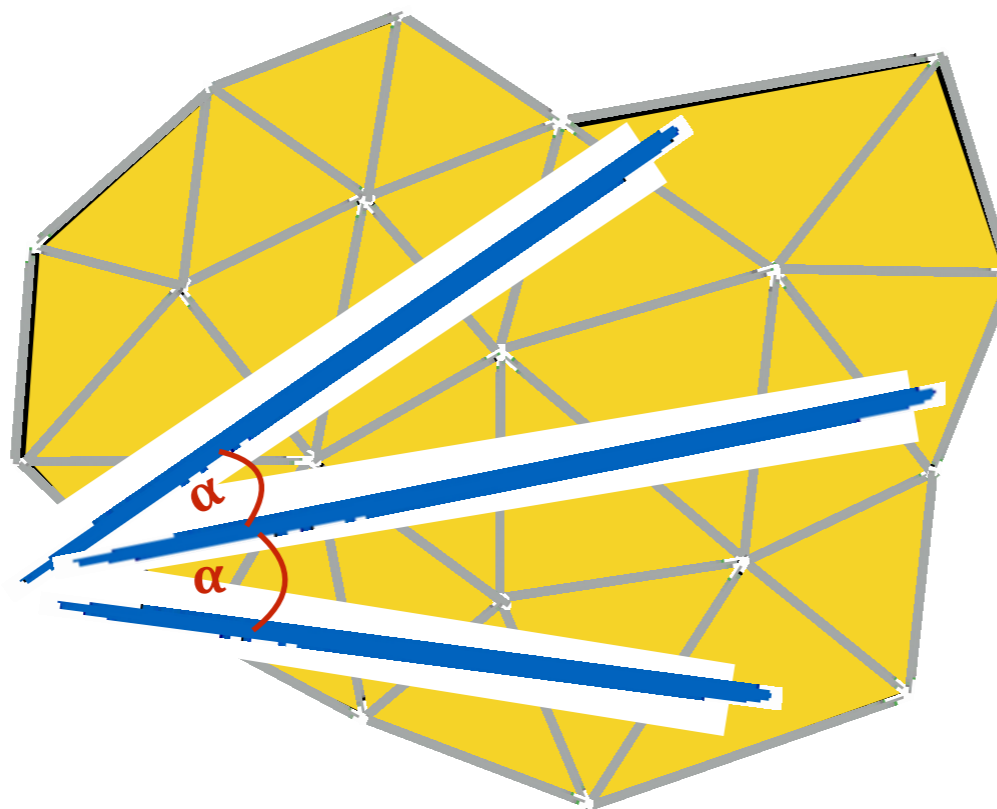


## Dégradation et porosité des septas

AGA



Papete et al. 2012



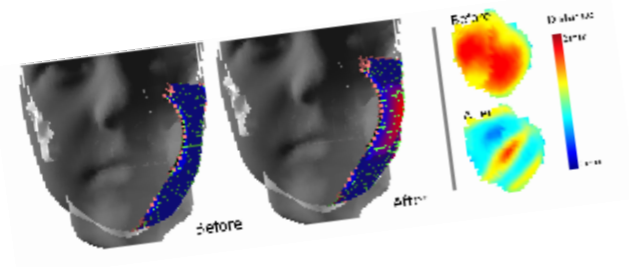
→ *Création d'une dégradation automatique des septas par des **trajets provenant de quelques points d'entrées***

# Amélioration des simulations



## Prise en charge de la partie fluide de la graisse

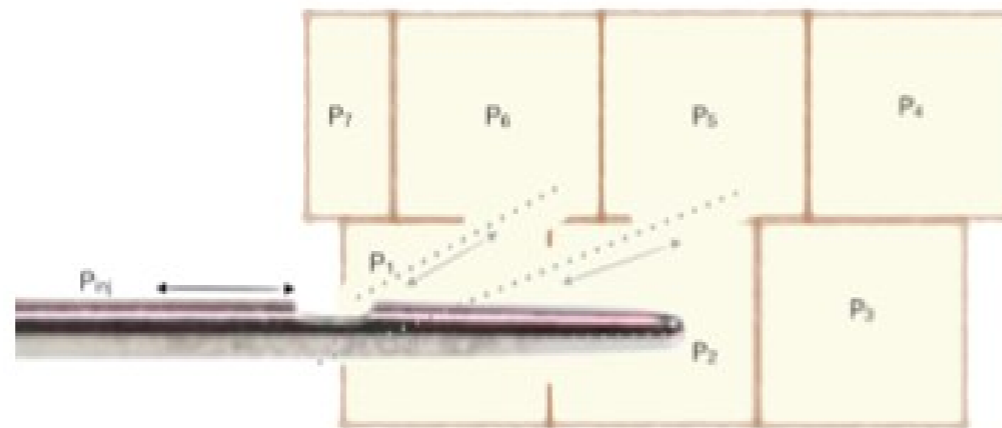
AGA



Majorczyk et al. 2013



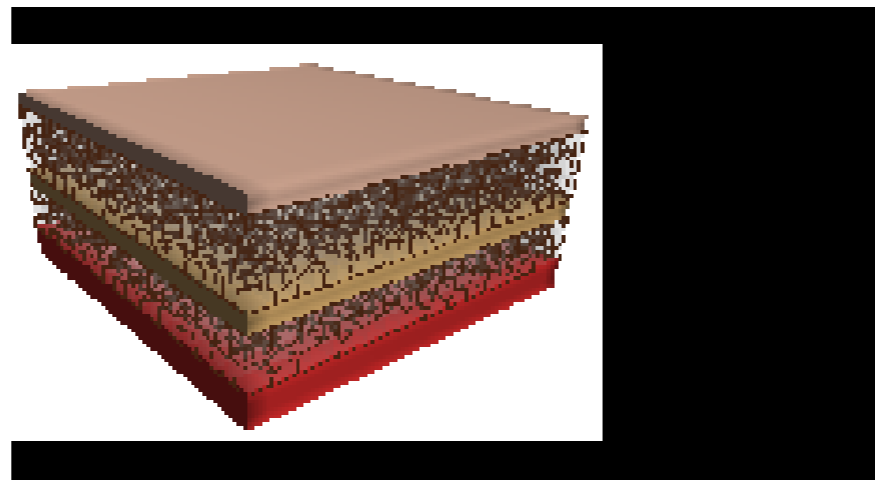
Cas Pr .Sinna



→ Gestion des **flux**: rendre les **septas poreux**

# Validation & utilisation clinique

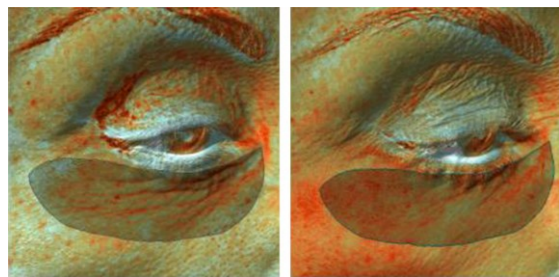
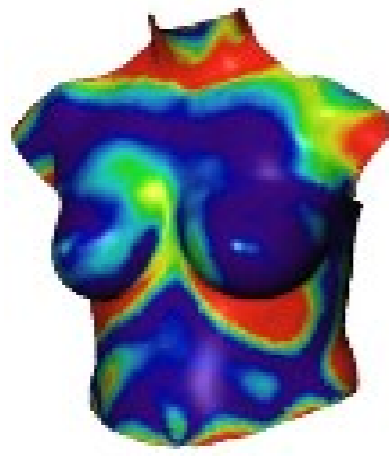
## Paramétrage géométrique & mécanique du modèle commun



# Validation & utilisation clinique

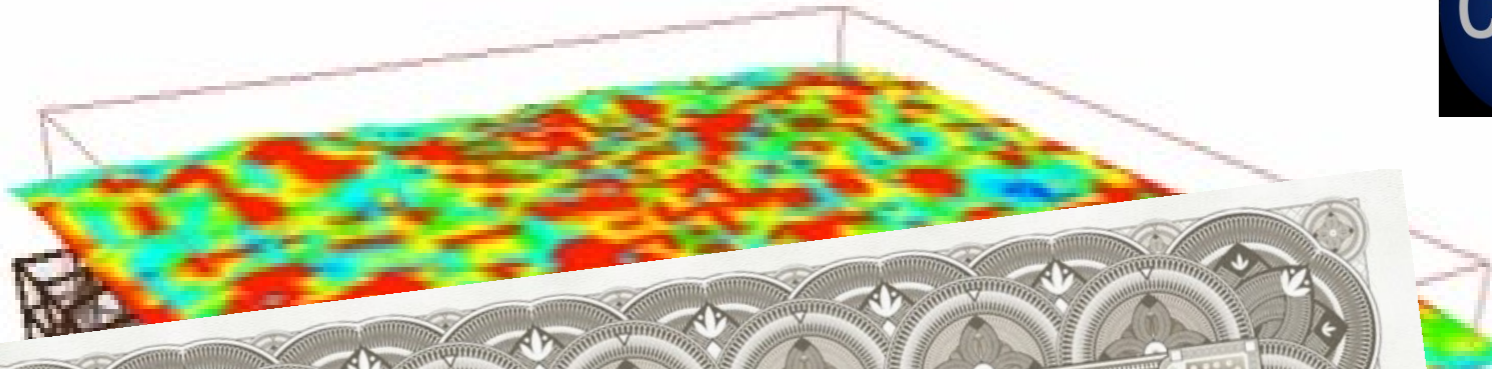
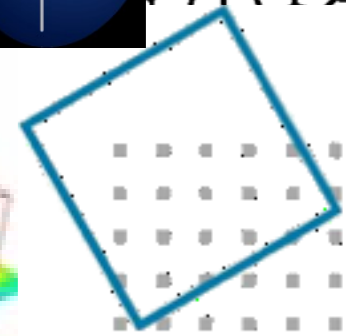
des modèles

et des conditio



Herlin et al. 2011





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