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Instituts
thématiques  **Inserm**
Institut national
de la santé et de la recherche médicale



LBI
Laboratoire des
Biomarqueurs en
Imagerie

Caractérisation tissulaire par élastographie en IRM

09-12-2015

CERF - module technologies avancées

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Centre de Recherche sur l'Inflammation, INSERM U1149 - UP7

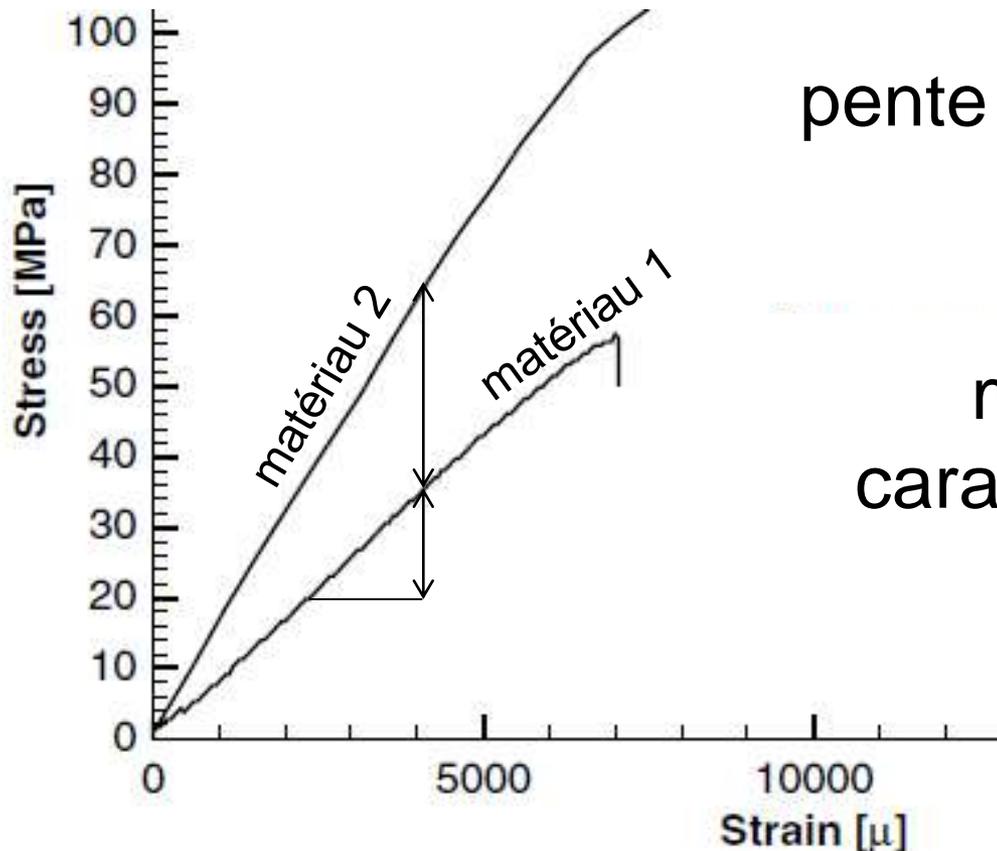
- Pathologie: affecte la structure des tissus
 - échelle moléculaire
 - échelle cellulaire
 - échelle systémique
- Structure: dicte les propriétés mécaniques des tissus
- ERM: mesure des propriétés mécaniques par IRM
- ERM comme outil radiologique de caractérisation pathologique

Propriétés mécaniques des solides

Propriétés mécaniques

qu'est-ce que c'est ?

- Propriétés mécaniques: quantifier la relation entre
 - force appliquée à un matériau
 - déformation qui en résulte



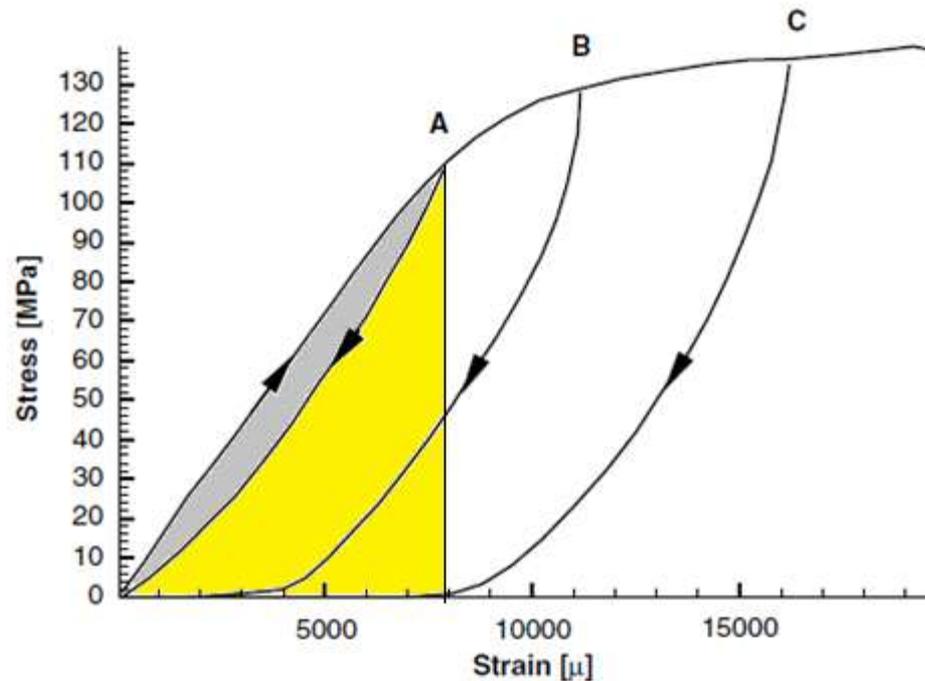
pente = tension / déformation

mesure de la pente =
caractérisation d'un matériau

Propriétés mécaniques

en réalité: effet du temps !

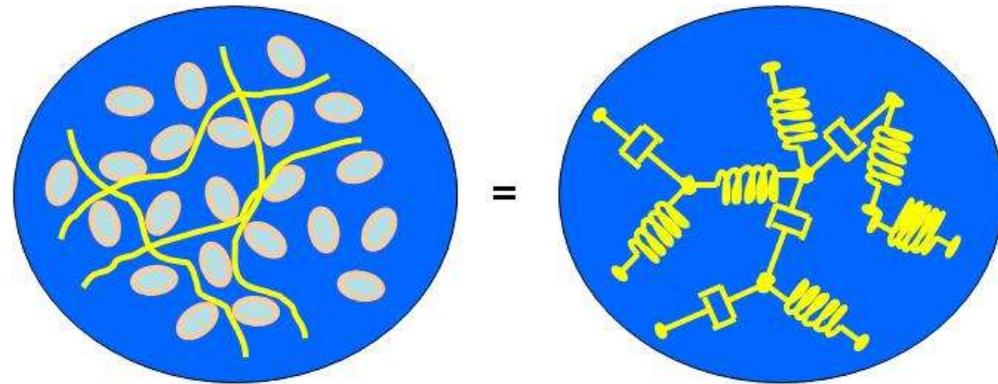
- Moins d'énergie restituée que d'énergie dépensée:
"perte"



modèles

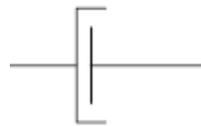
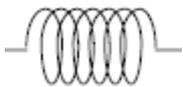
- Propriétés mécaniques:

- module de stockage
- module de perte

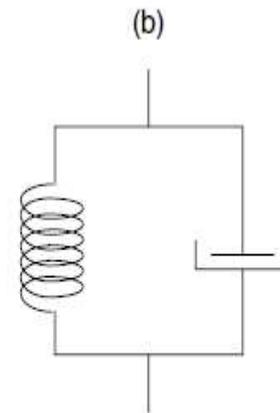


- Pourquoi ?

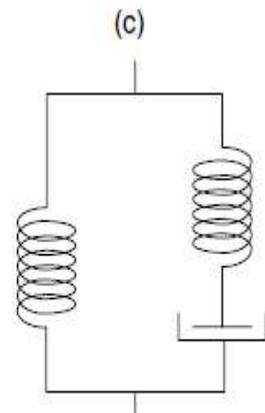
- Modèles des matériaux: ressorts et amortisseurs



Maxwell

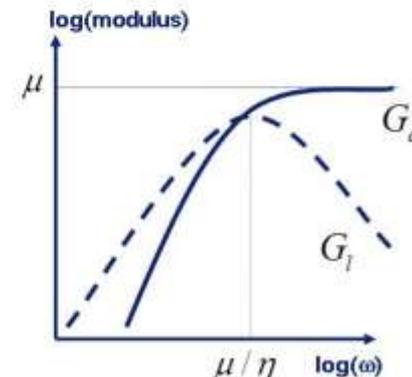
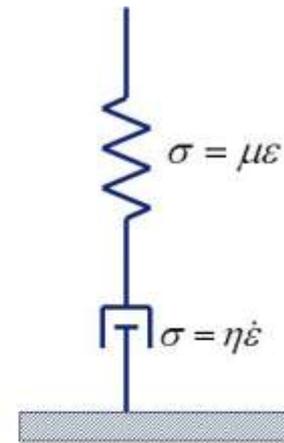
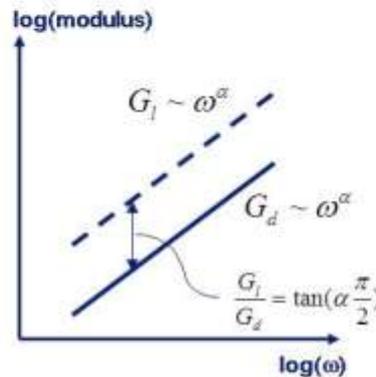
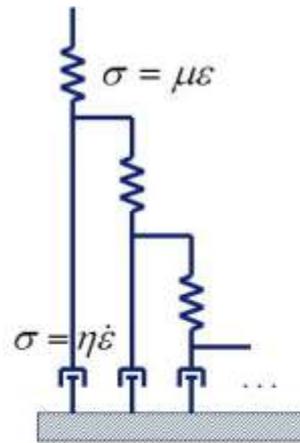
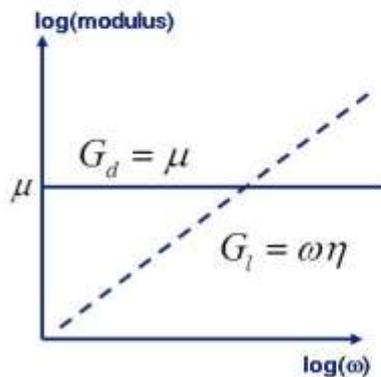
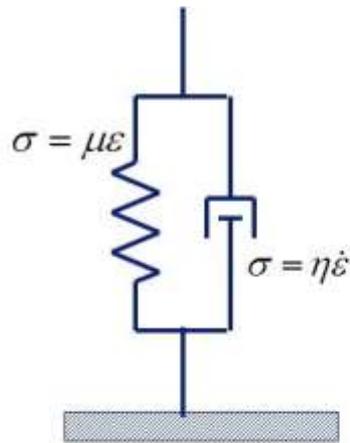


Voigt



Kelvin

- Modèles: doivent expliquer les données expérimentales !



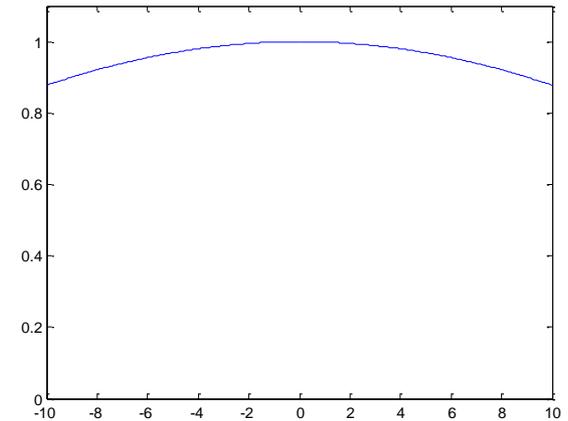
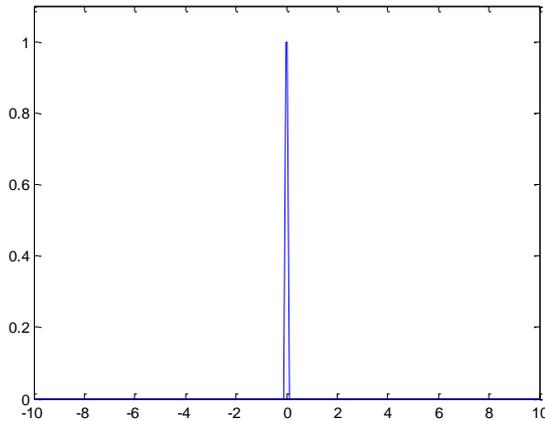
Propriétés mécaniques

Modes d'acquisitions en élastographie

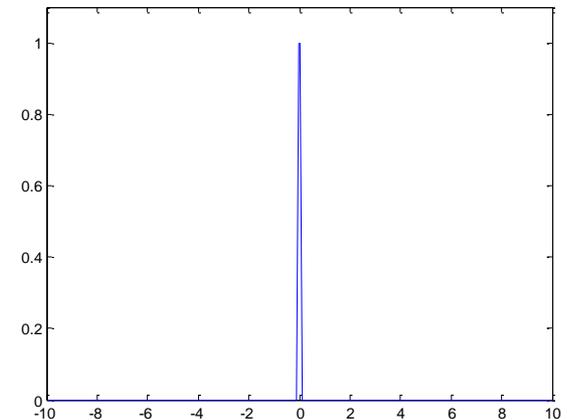
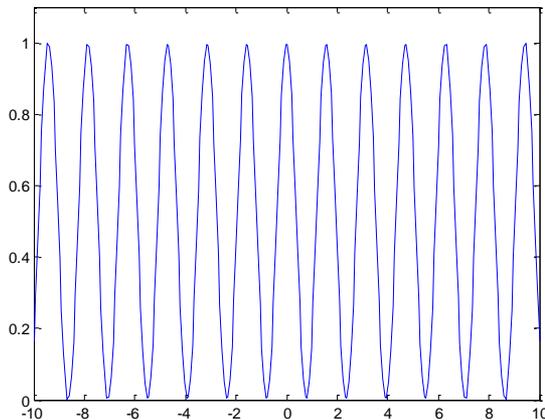
temps

fréquence

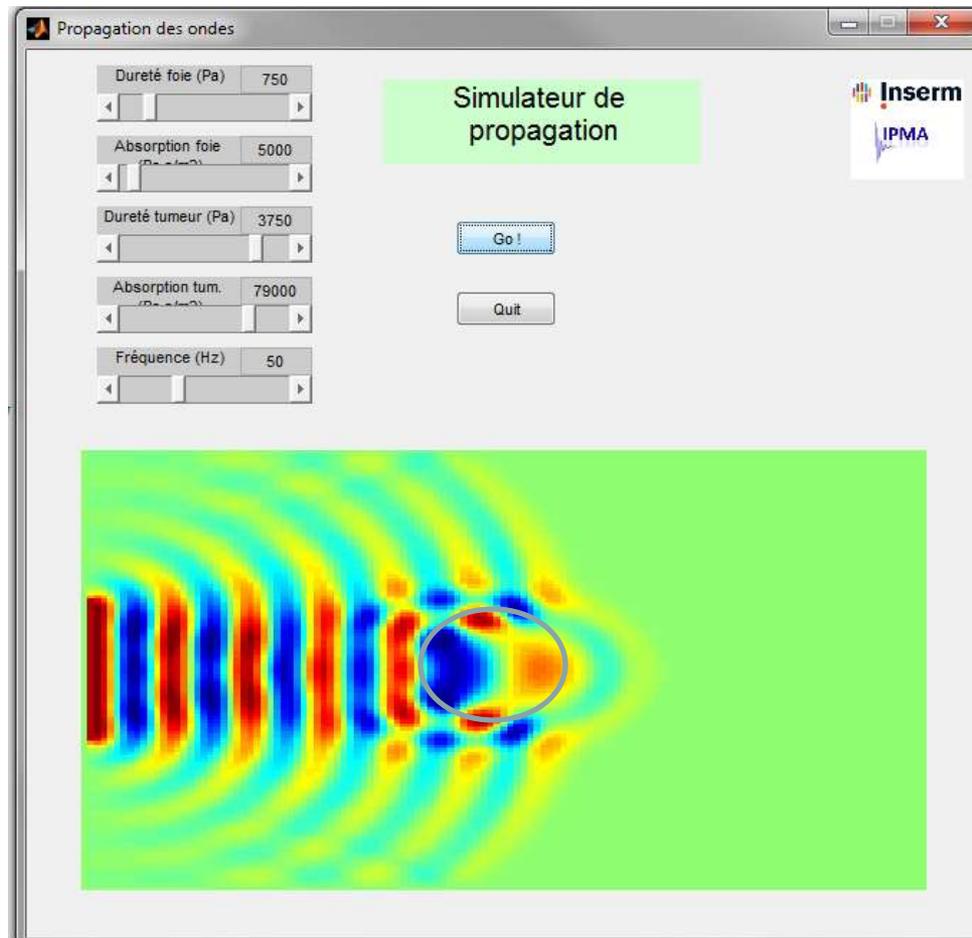
Méthodes
impulsionnelles
(FS, SSI, ...)



Méthodes à
l'équilibre
(ERM)



- Exemple: simulateur 1d



Vitesse, élasticité

$$G = \rho \cdot \left(\frac{\omega}{k}\right)^2$$

Module de cisaillement

Hz==s⁻¹

m⁻¹

m·s⁻¹: c'est une vitesse

$$G = \rho \cdot v^2$$

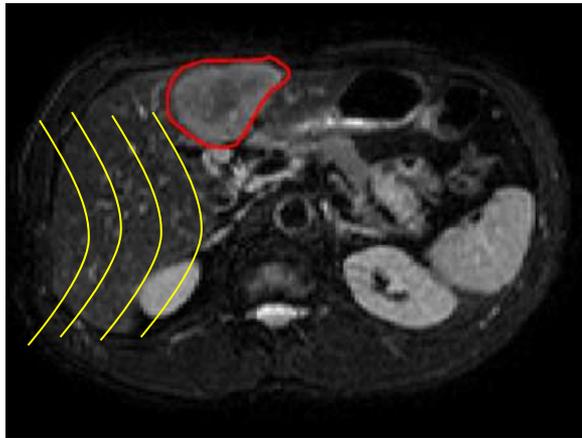
Propriétés mécaniques

équivalence propagation - propriétés mécaniques

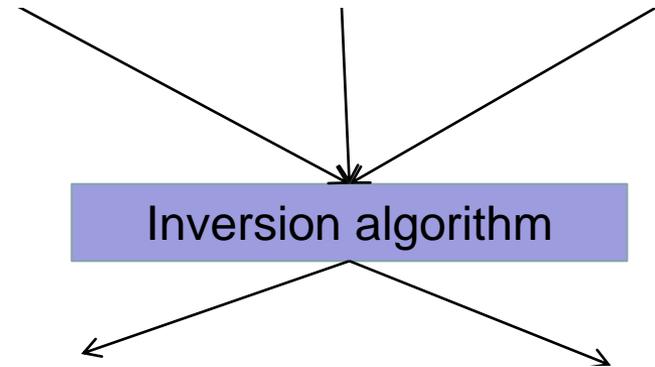
Propriétés de l'onde	Propriété du tissu
Propagation	Elasticité
Atténuation	Viscosité
Vitesse ou longueur	Dureté
Fréquence	Fréquence

- Exploiter la sensibilité au mouvement de l'IRM
- Onde acoustique: déplacements microscopiques au sein des tissus
- Encodage de ce déplacement dans la phase IRM

ERM: méthodes d'acquisition



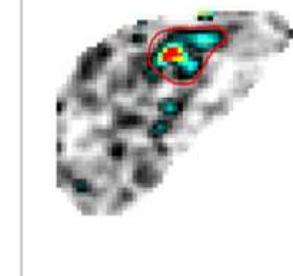
- Mechanical wave (transducer)
- Acquisition of phase images with MRI
- Resolution: $4 \times 4 \times 4 \text{ mm}^3$, motion encoded
- Encoding of 1 or more orthogonal direction
- Sampling of several points per vibratic period
- Wave equation for viscoelastic materials
- *Exclusion in case amplitudes $< 7.5 \mu\text{m}$*



Storage modulus, kPa



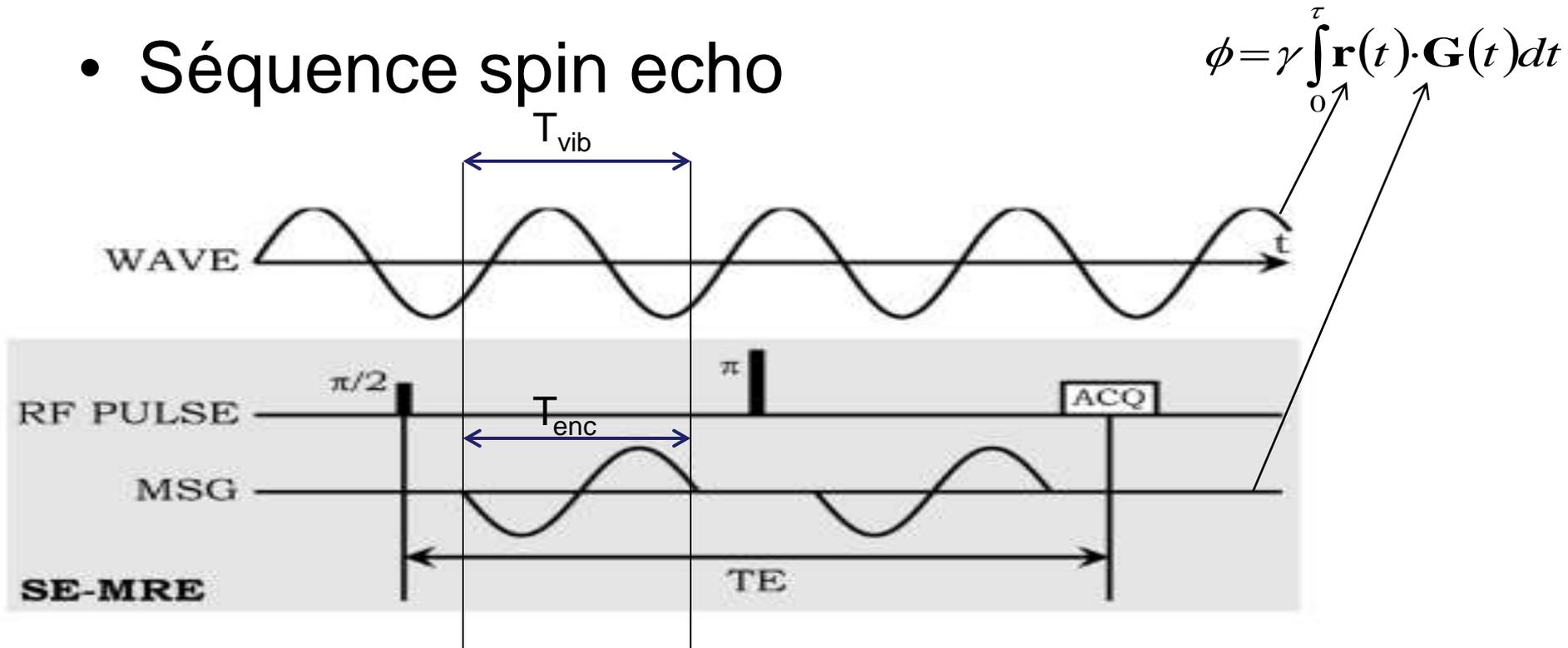
Loss modulus, kPa



ERM hépatique

séquences d'acquisition

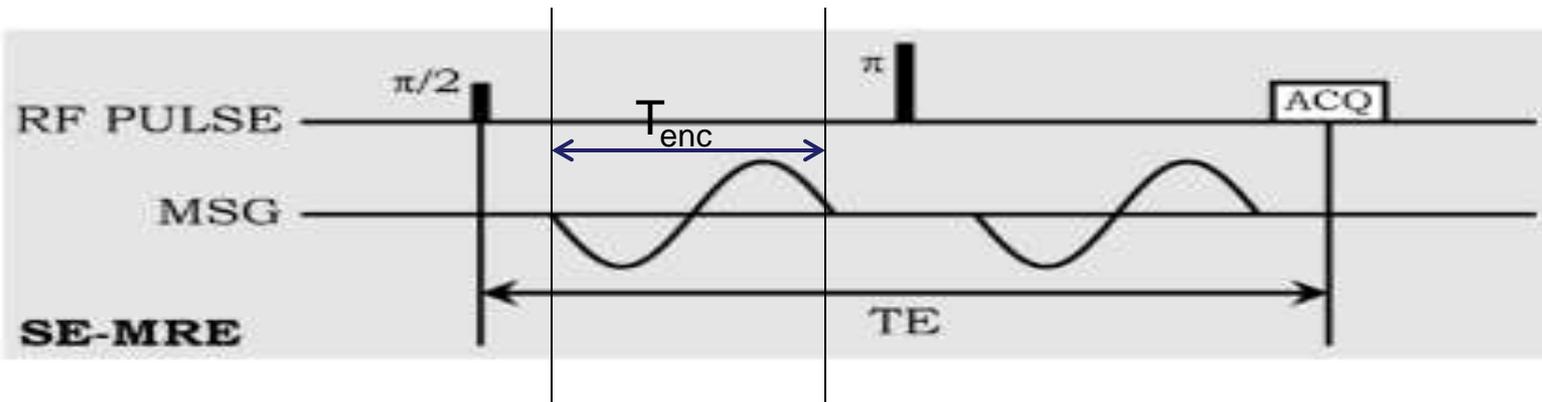
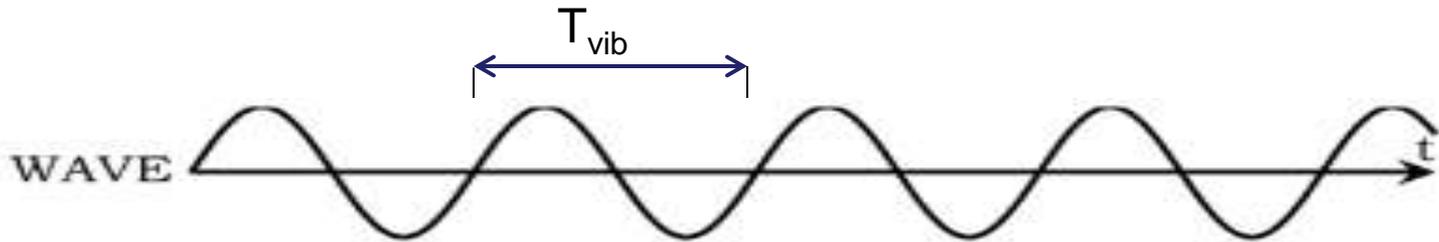
- Séquence spin echo



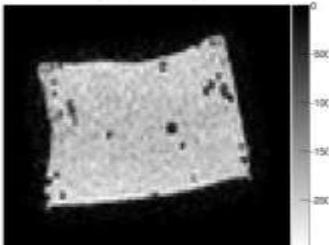

 on encode la *position à un instant t* dans la phase de l'image

ERM hépatique

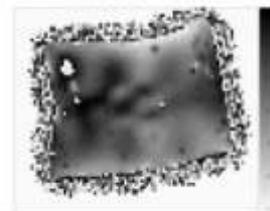
séquences d'acquisition



x-magn @ time step 0



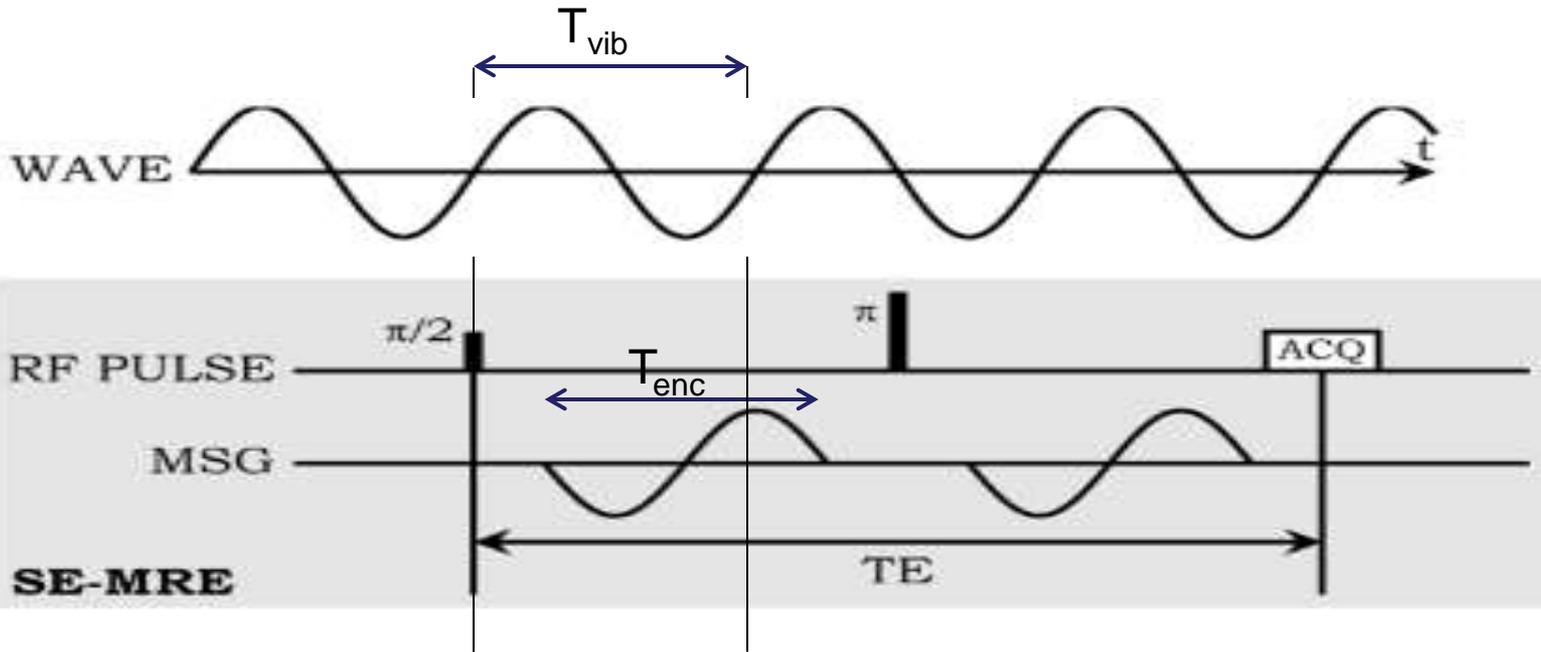
x-wave [ac] @ time step 0



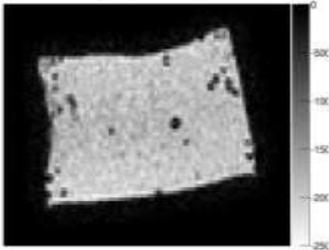
on encode la position à un instant t dans la phase de l'image

ERM hépatique

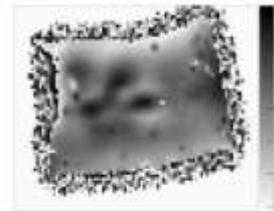
séquences d'acquisition



x-magn @ time step 2



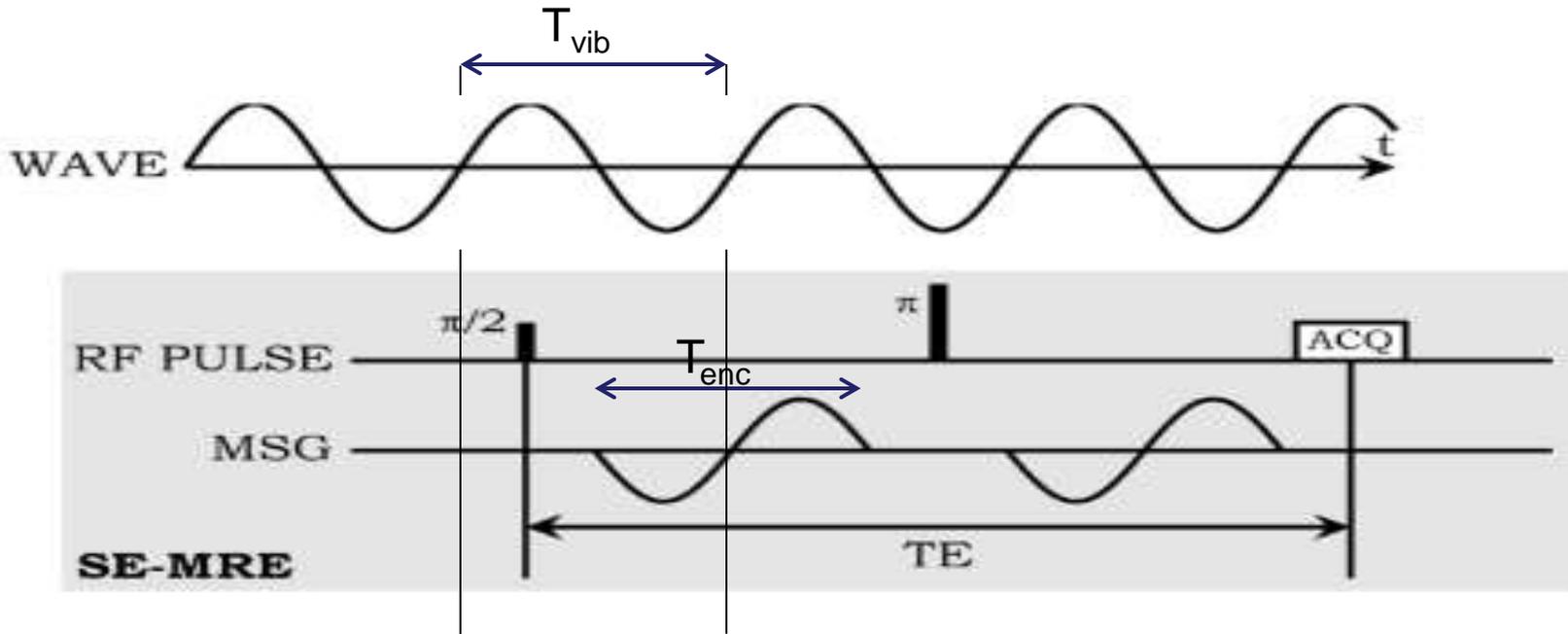
x-wave [rad] @ time step 2



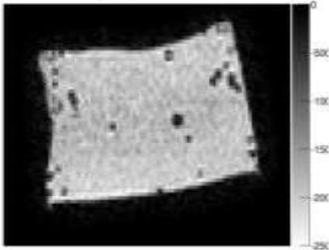
on encode la position à un instant t dans la phase de l'image

ERM hépatique

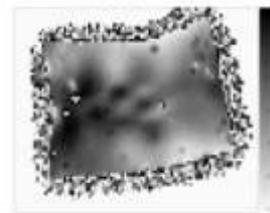
séquences d'acquisition



x-magn @ time step 4



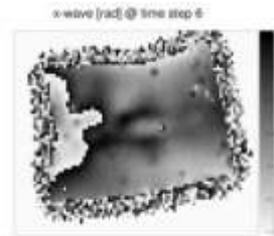
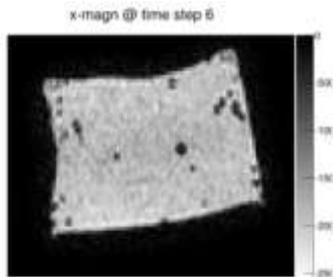
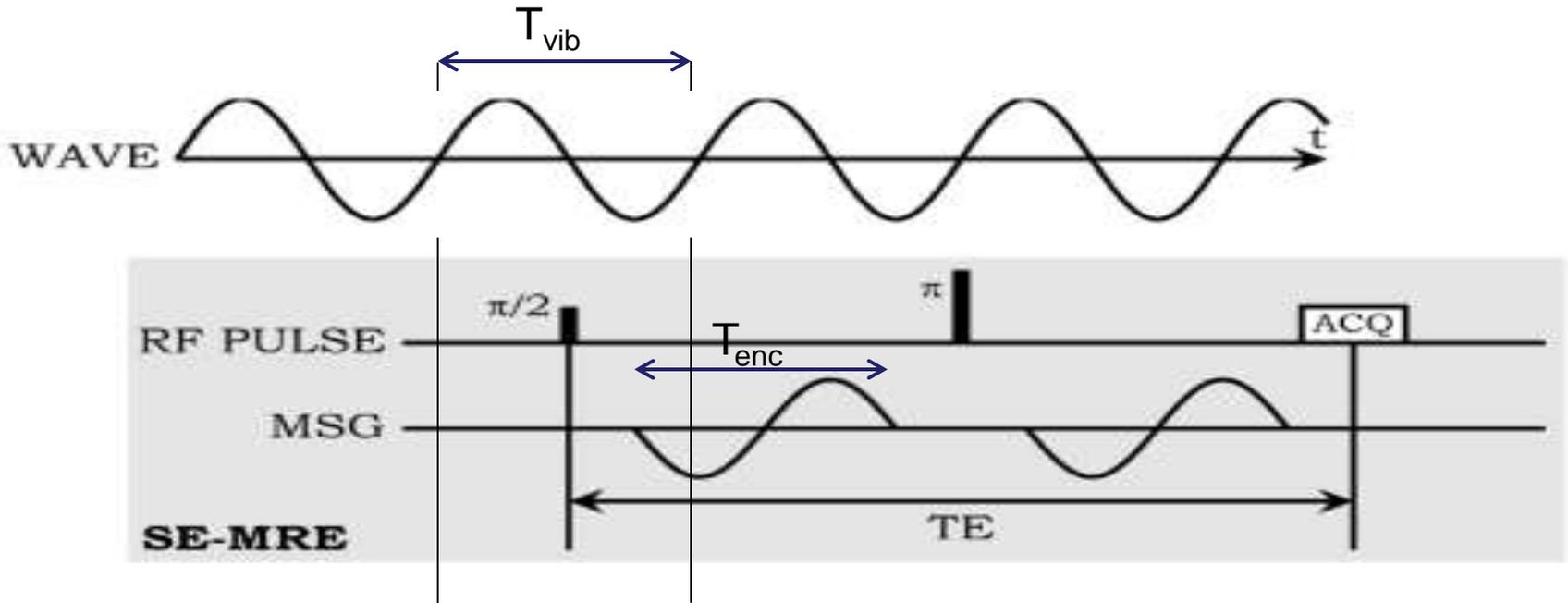
x-wave [rad] @ time step 4



on encode la position à un instant t dans la phase de l'image

ERM hépatique

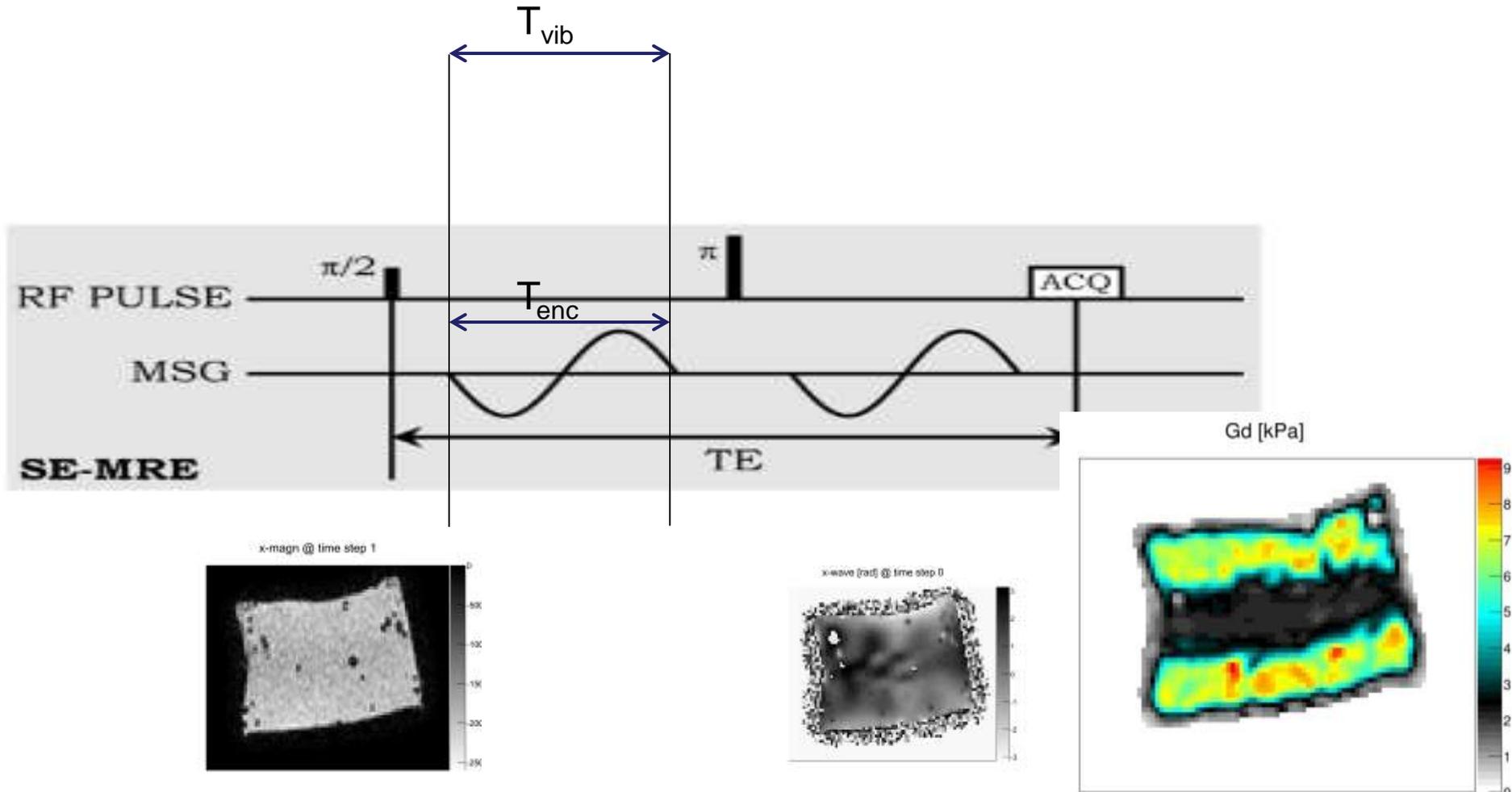
séquences d'acquisition



on encode la position à un instant t dans la phase de l'image

ERM hépatique

séquences d'acquisition

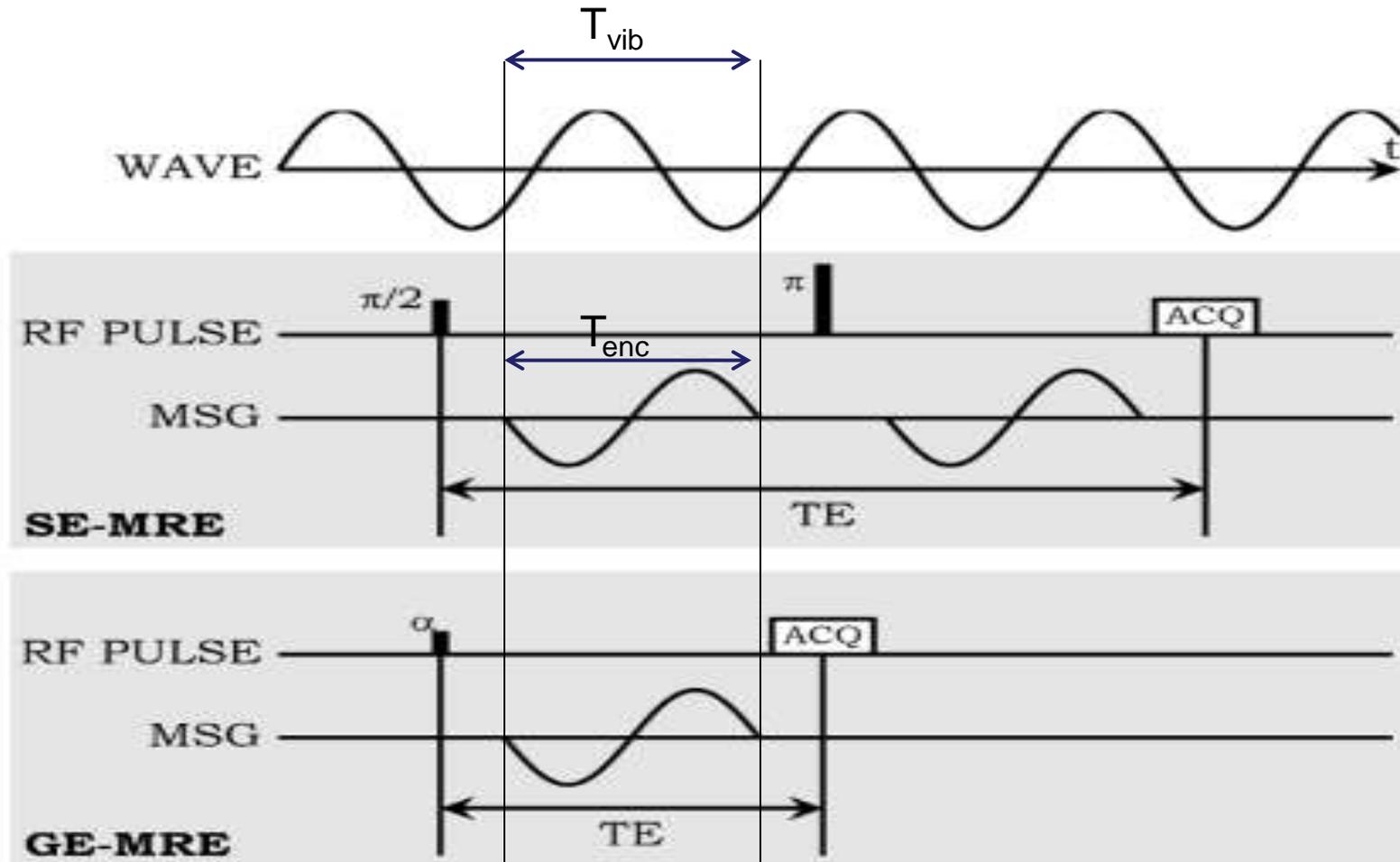


on encode la position à un instant t dans la phase de l'image

ERM hépatique

encodage fractionnel

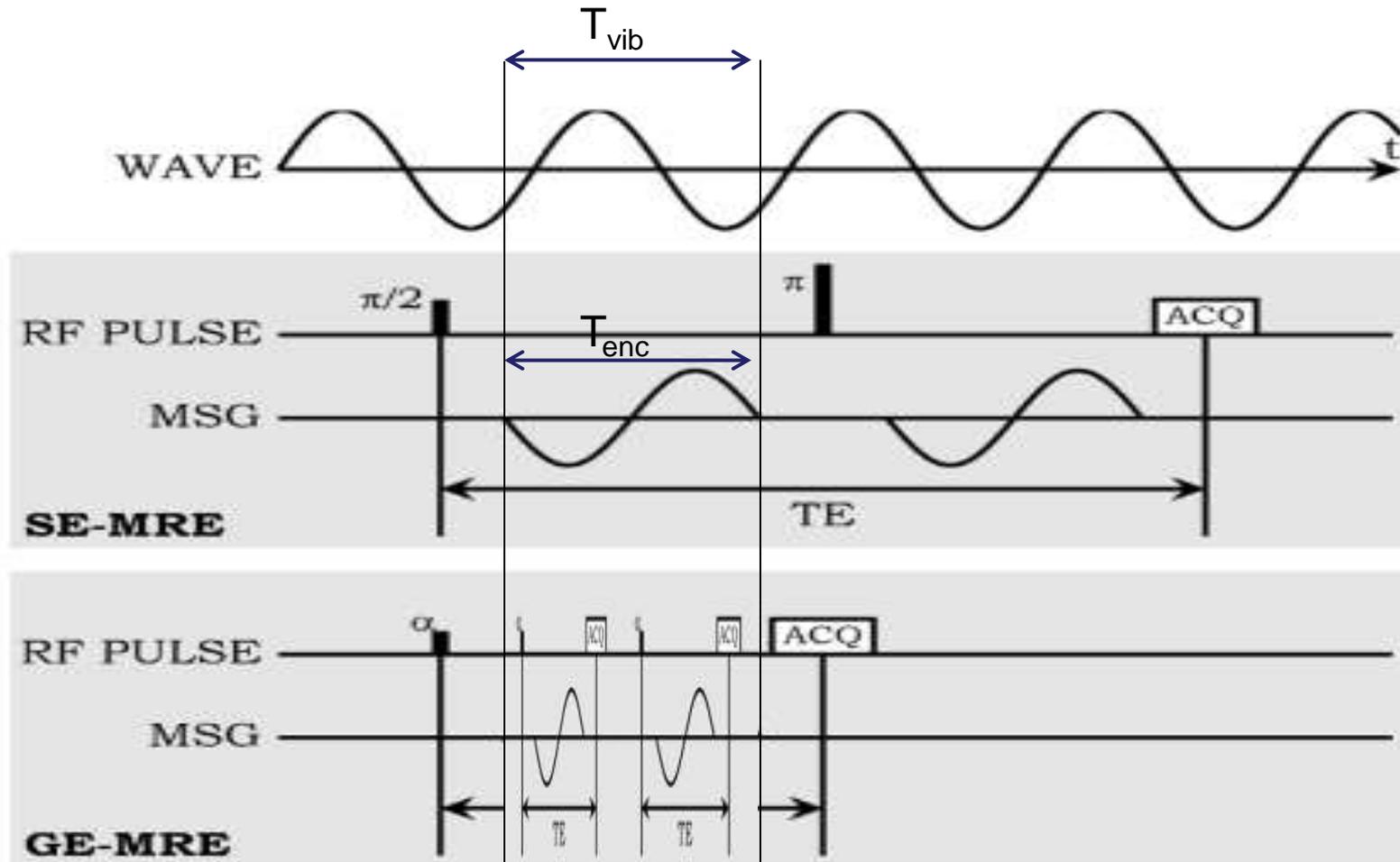
- Autres types de séquences



ERM hépatique

encodage fractionnel

- $F_{\text{enc}} > F_{\text{vib}}$: *encodage fractionnel*

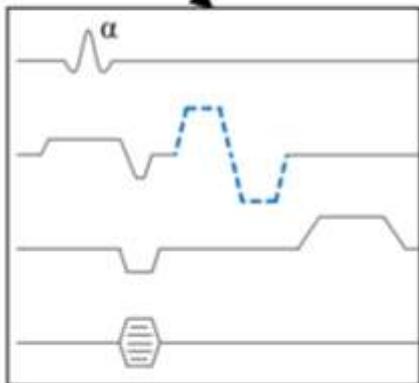
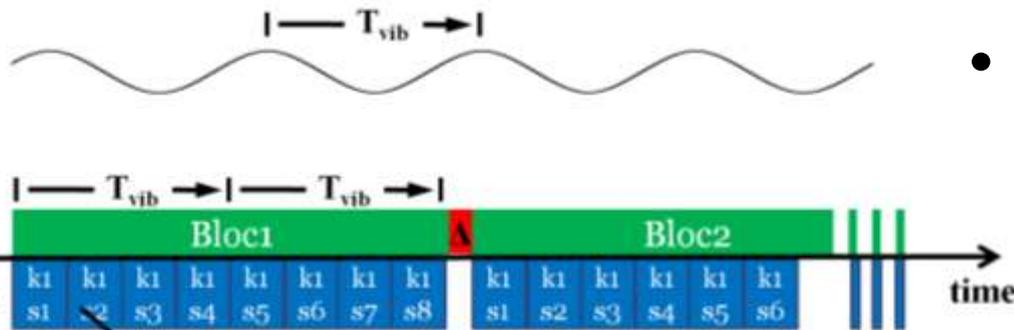


ERM hépatique

encodage fractionnel

- Echos de gradients
- Encodage fractionnel

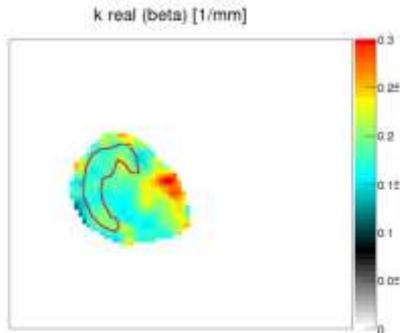
- *encodage 3-directionnel*
- *8 échantillons de temps*
 - *matrice 80x80x9*
- *résolution jusqu'à 2mm isotropique*
- *4 apnées*



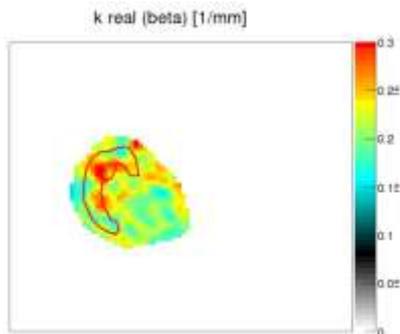
ERM hépatique

multifréquence

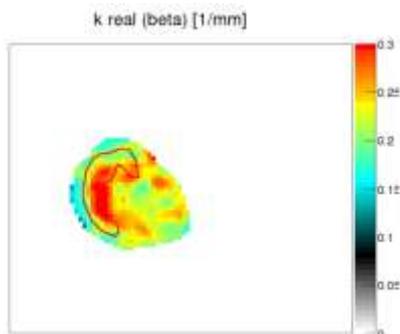
- Hypothèse: viscosité et distribution de la taille des objets change le comportement en fréquence des paramètres viscoélastiques
- Comportement attendu: $G = A \times \omega^Y$
- On examine la "pente"; γ



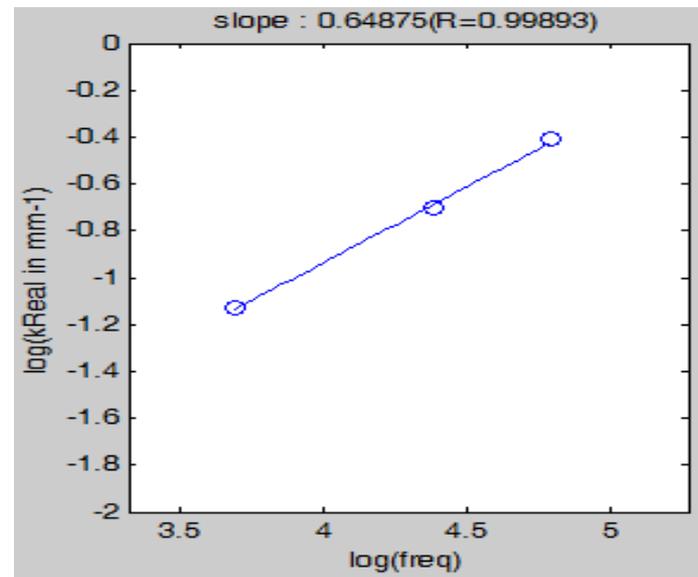
28Hz



56Hz



84Hz

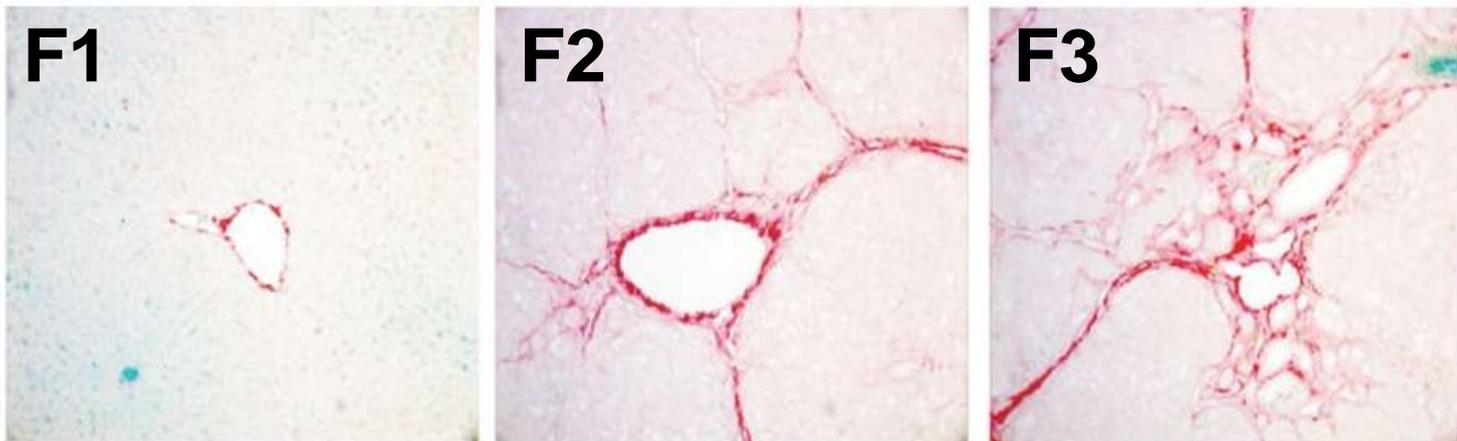


ERM: applications -fibrose hépatique

ERM hépatique

applications: fibrose

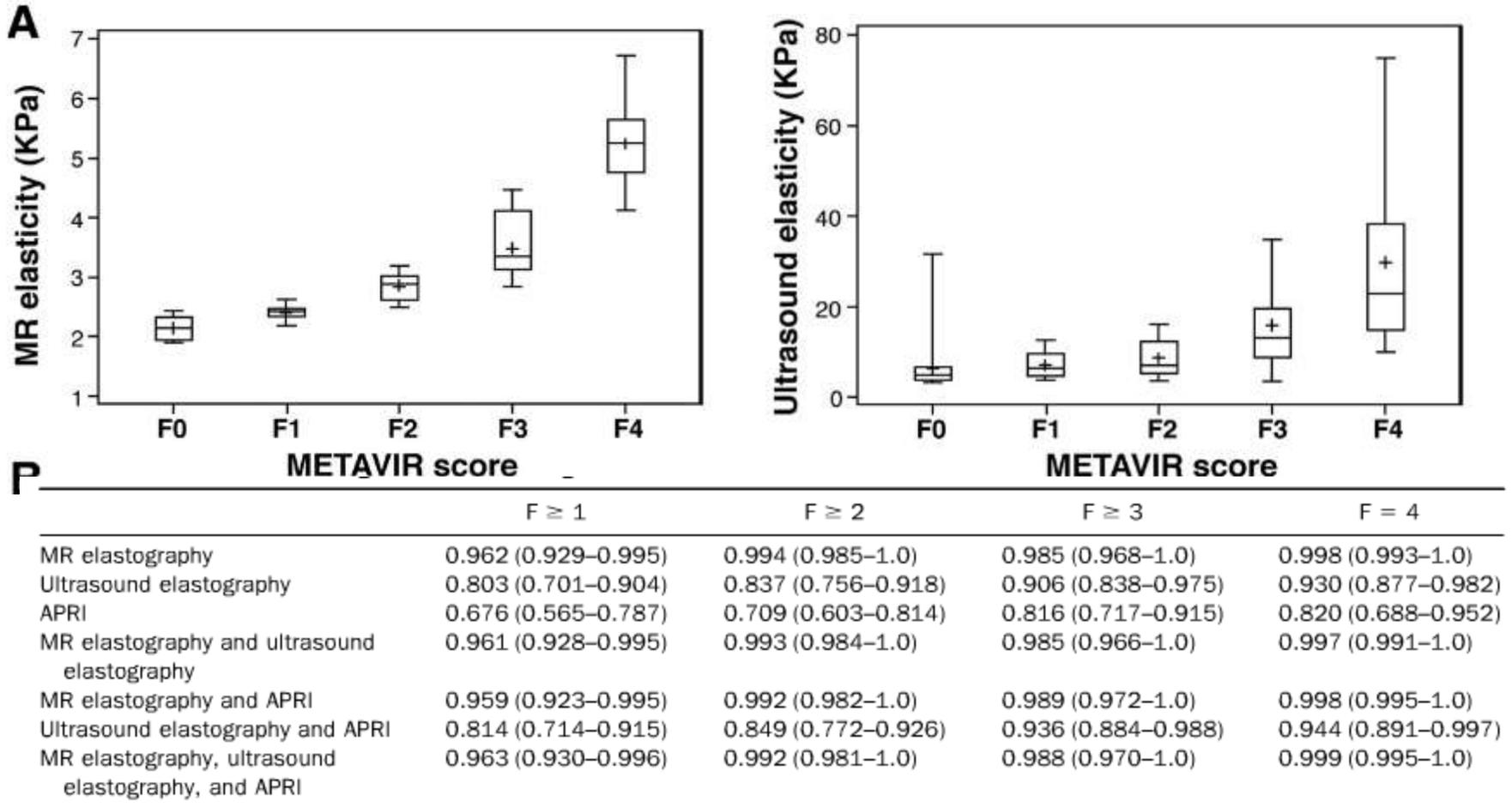
- Fibrose: dépôts de collagène extracellulaire



- Collagène: dureté >>> dureté du parenchyme sain

ERM hépatique

applications: fibrose (virale / alcool)

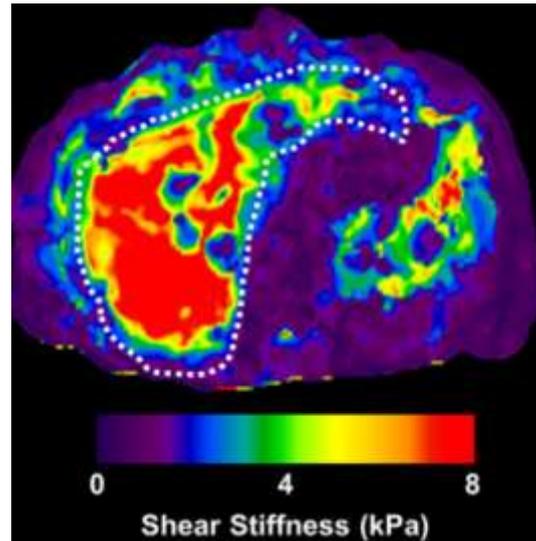
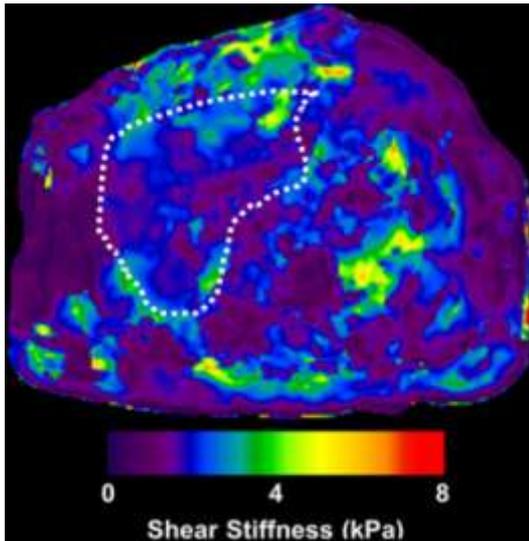


NOTE. Values are expressed as area under the ROC curve (95% CI).

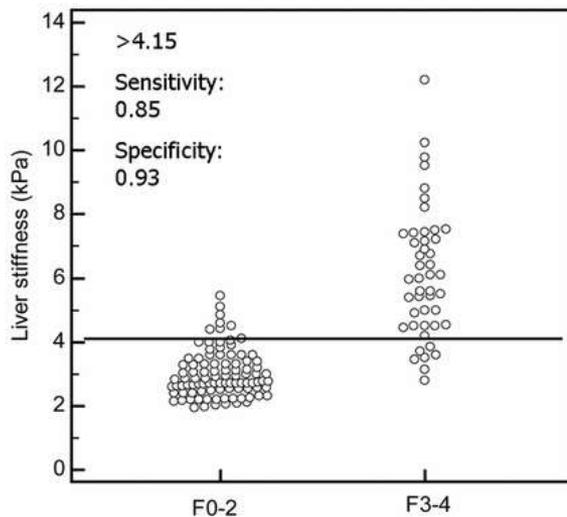
Huwart, L. *et al.* Magnetic resonance elastography for the noninvasive staging of liver fibrosis. *Gastroenterology* **135**, 32–40 (2008).

ERM hépatique

applications: fibrose (NAFLD)



Kim, D. *et al.* Advanced fibrosis in nonalcoholic fatty liver disease: noninvasive assessment with MR elastography. *Radiology*, in press (2013).

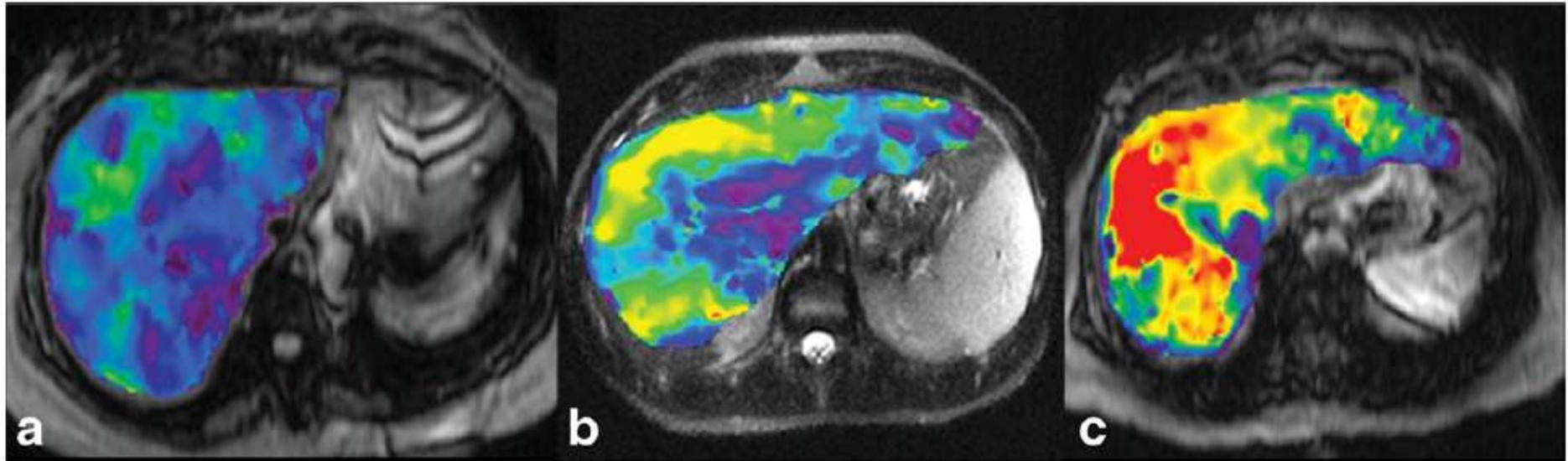


Test	Standard AUROC*	P Value
MR elastography ($n = 142$)	0.954 (0.905, 0.982)	Reference
FIB-4 score ($n = 141$)	0.829 (0.757, 0.887)	.003
NAFLD fibrosis score ($n = 132$)	0.799 (0.720, 0.864)	<.001
AST/ALT ratio ($n = 142$)	0.706 (0.624, 0.780)	<.001
APRI ($n = 141$)	0.741 (0.661, 0.811)	<.001
BARD score ($n = 142$)	0.715 (0.633, 0.788)	<.001
Simple panel ($n = 132$)	0.754 (0.671, 0.825)	<.001

ERM hépatique

applications: fibrose

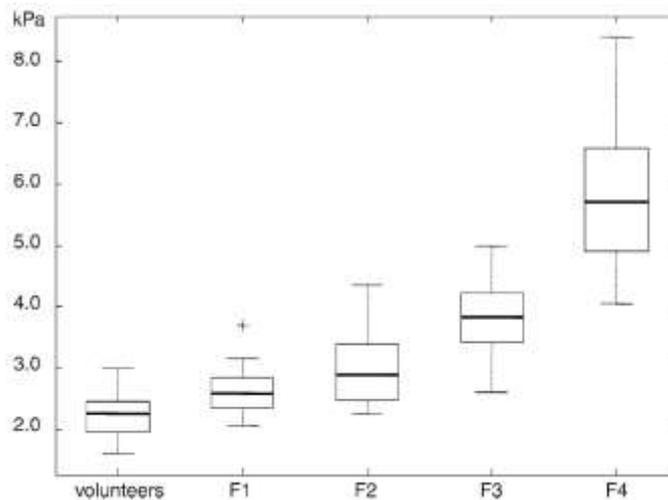
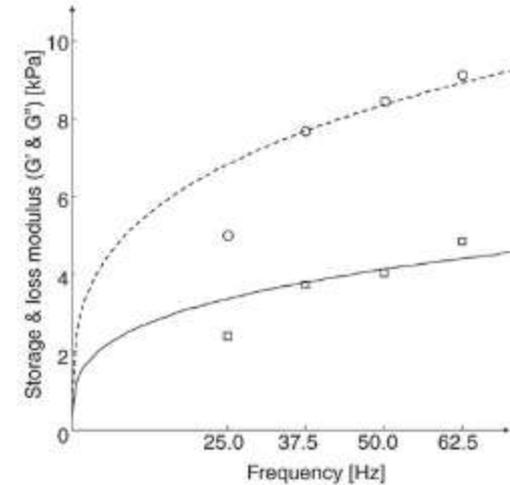
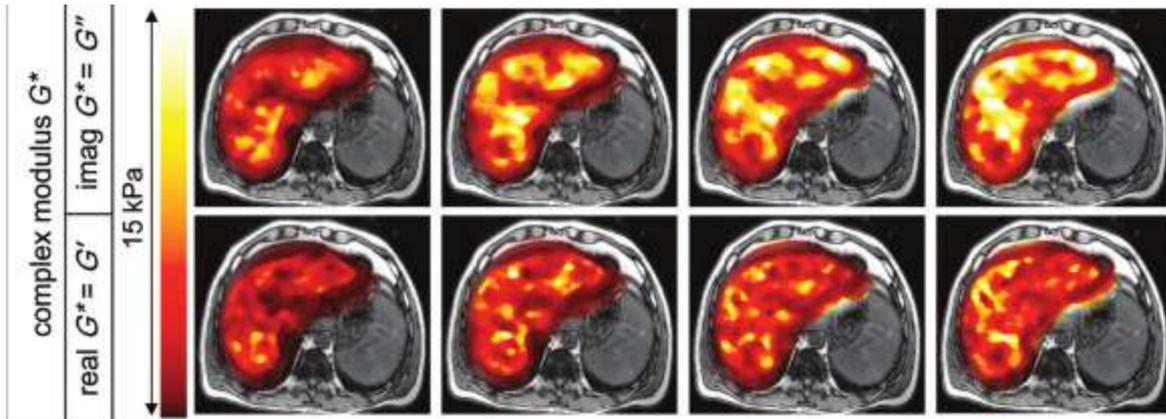
- ERM: technique d'*imagerie*; on a accès à l'hétérogénéité des tissus



Venkatesh, S., Yin, M. & Ehman, R. Magnetic resonance elastography of liver: Technique, analysis, and clinical applications. *Journal of magnetic resonance imaging: JMRI* **37**, 544–55 (2013).

ERM hépatique

applications: fibrose



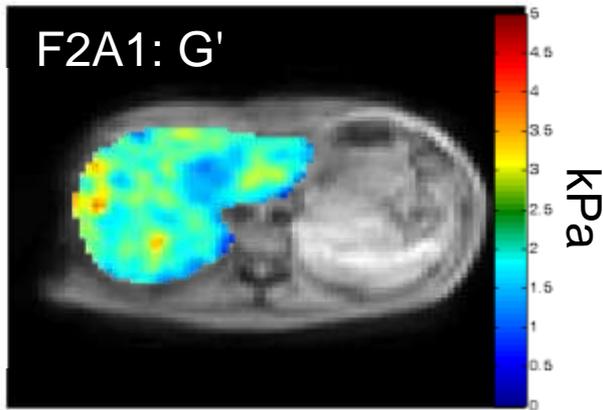
Asbach, Klatt et al. Viscoelasticity-based staging of hepatic fibrosis with multifrequency MR elastography radiology **257**, 80–86 (2010).

ERM: applications -inflammation hépatique

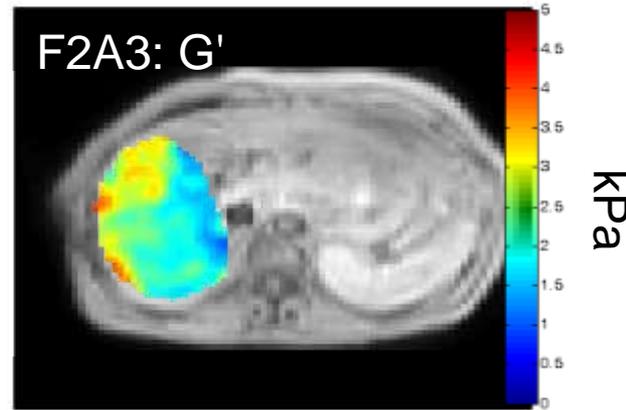
ERM hépatique

applications: inflammation

patient A



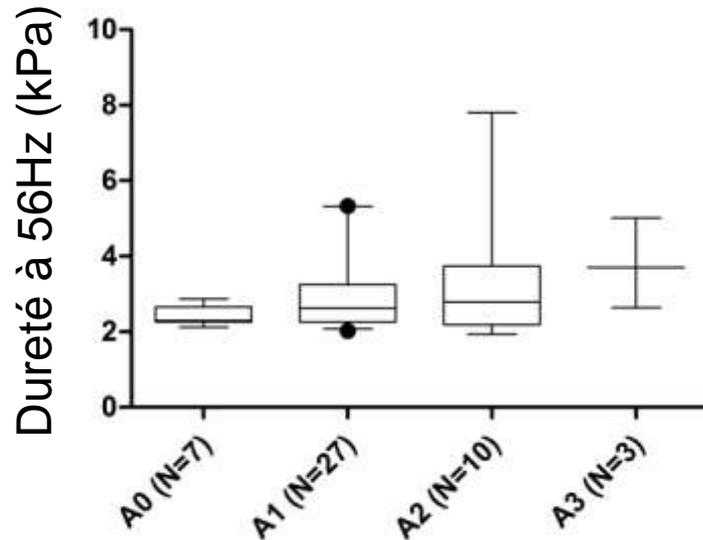
patient B



ERM hépatique

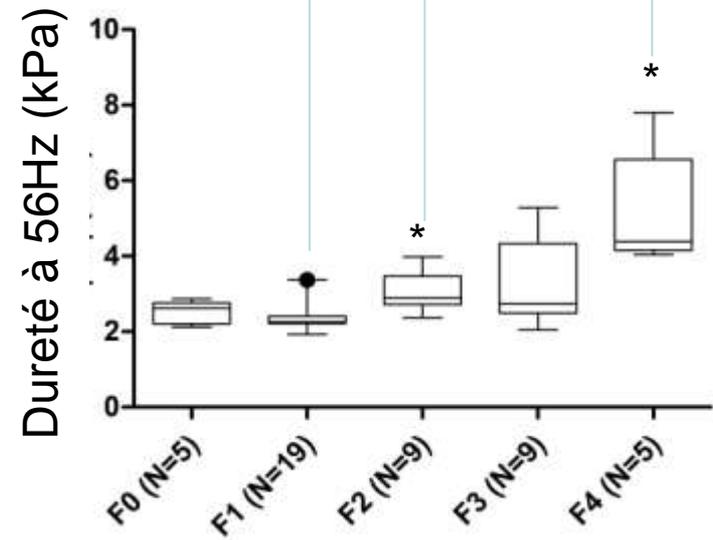
applications: inflammation

inflammation



ANOVA: ns

fibrose



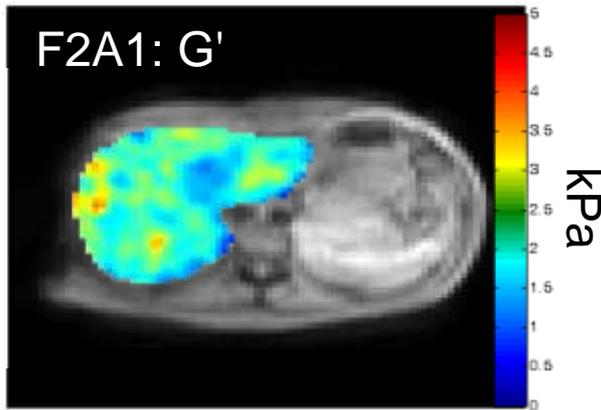
ANOVA: ***

Des variations sont visibles, mais le paramètre ERM monofréquence ne semble pas être affecté par l'inflammation

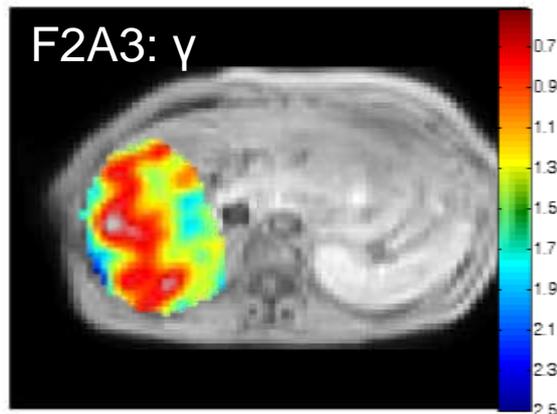
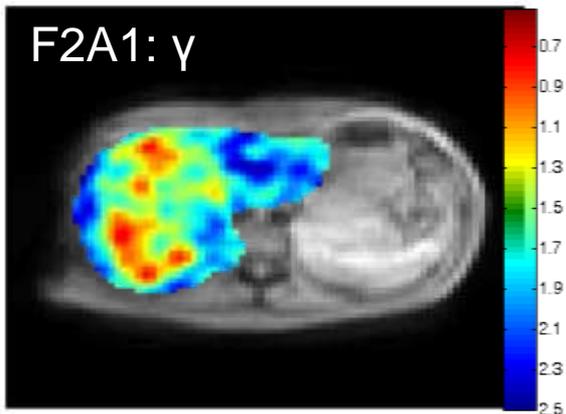
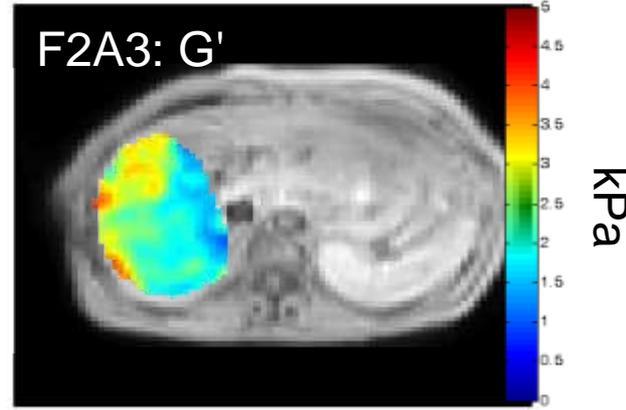
ERM hépatique

application: inflammation

patient A

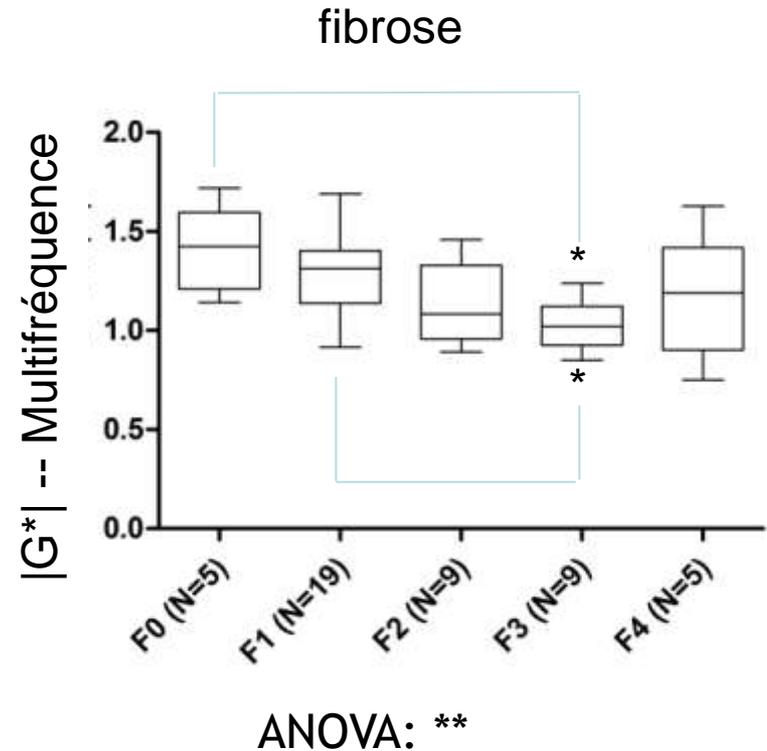
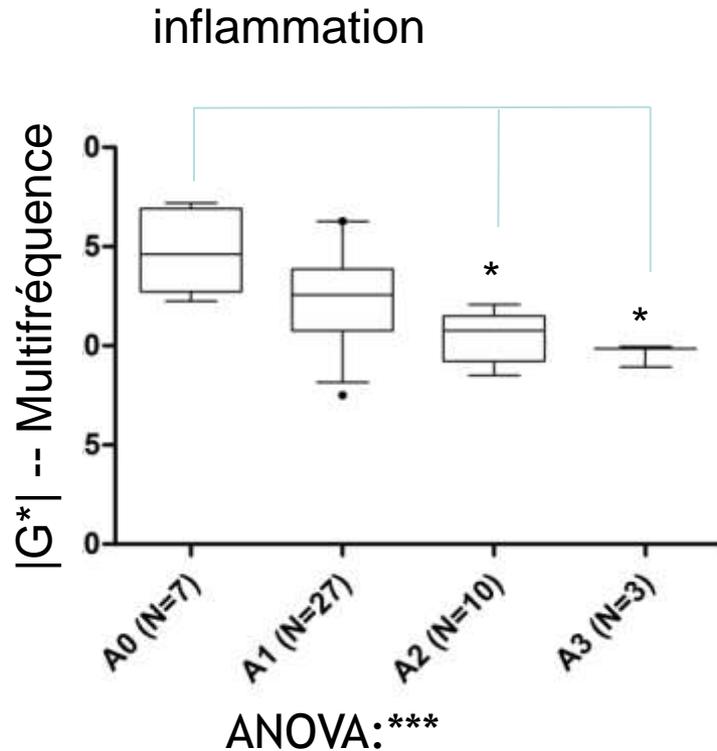


patient B



ERM hépatique

application: inflammation



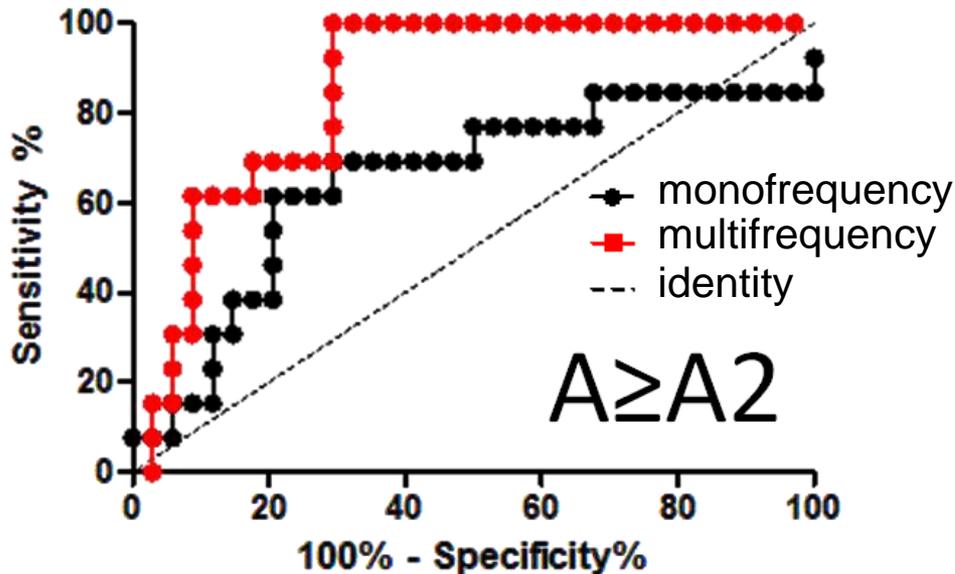
Le paramètre multifréquence de la dureté est modifié significativement par la fibrose et l'inflammation

ERM hépatique

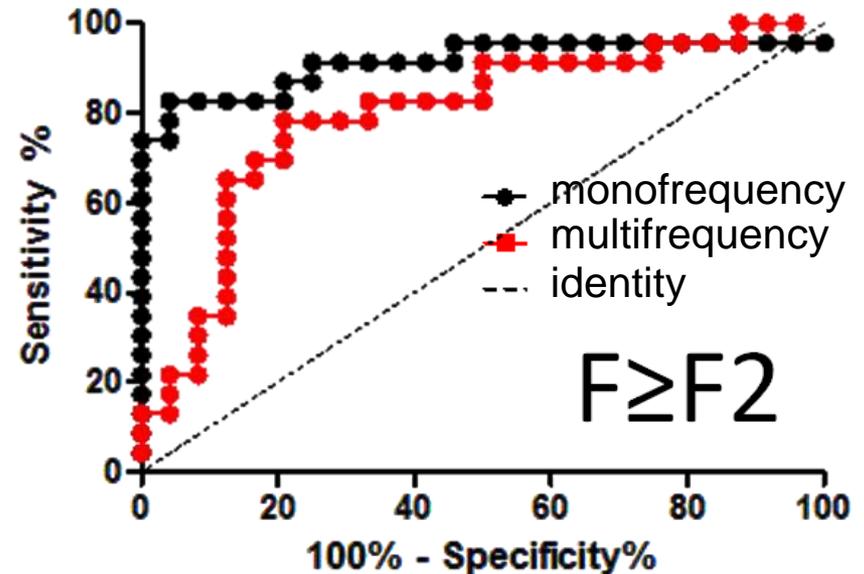
applications: inflammation

- Courbes ROC

inflammation



fibrose



multifrequence < 1.22 == inflammation significative
 dureté > 2.62kPa == fibrose / cirrhose

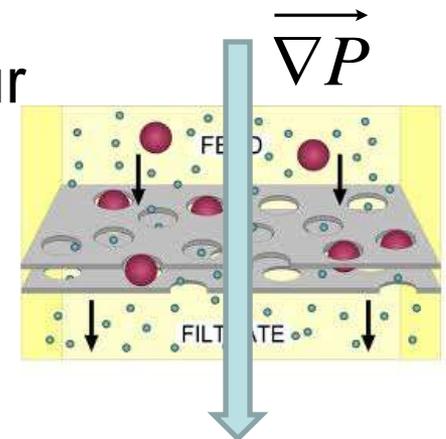
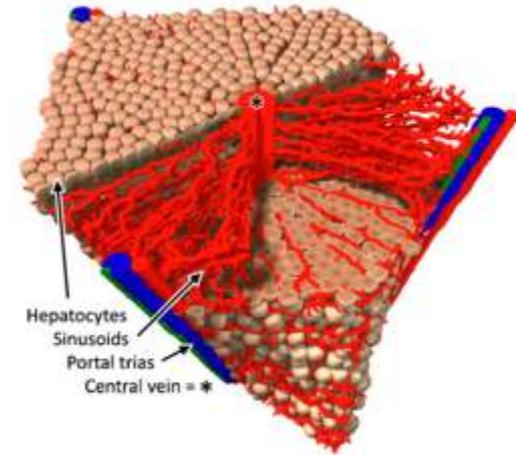
ERM: applications -hypertension portale

applications: hypertension portale

- Patients avec cirrhose: exposés à l'hypertension portale
- Peut résulter en varices oesophagiennes
- Risque de rupture, une des principales causes de mortalité dans la cirrhose
- Méthodes de diagnostic actuelles: très invasives
 - Endoscopie pour évaluation du risque de rupture
 - Gradient hépatique pour hypertension portale

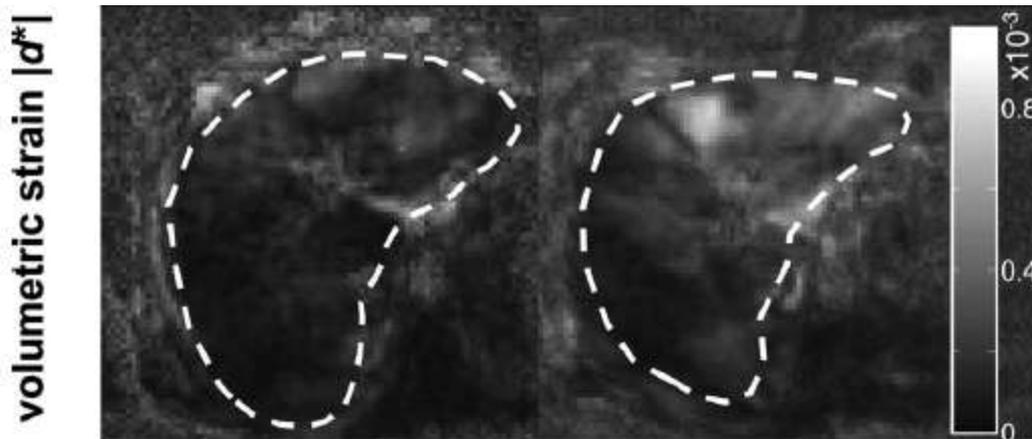
applications: hypertension portale

- Foie: 25-33% vasculaire. Parcours également de canaux biliaires et vaisseaux lymphatiques
- Poroélasticité: introduction d'un compartiment fluide dans le modèle - "*pores*"
 - densité du fluide; ρ_f
 - fraction volumique; ϕ
 - conductivité hydraulique; κ
- Actuellement: mesures de pression (tenseur des variations volumétriques)



applications: hypertension portale

- Mesure de la compressibilité avant / après TIPSS:

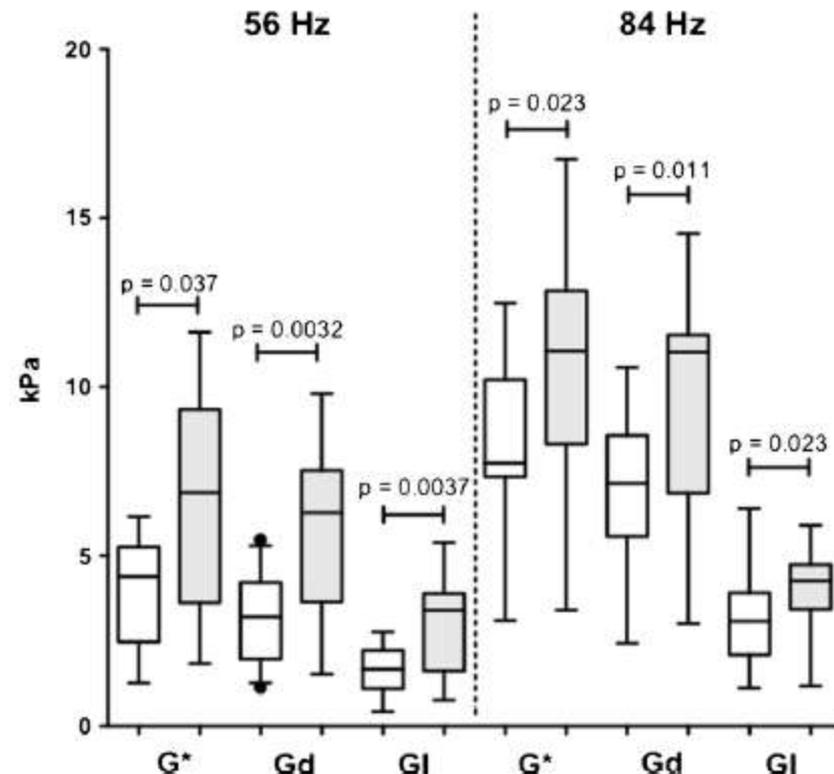
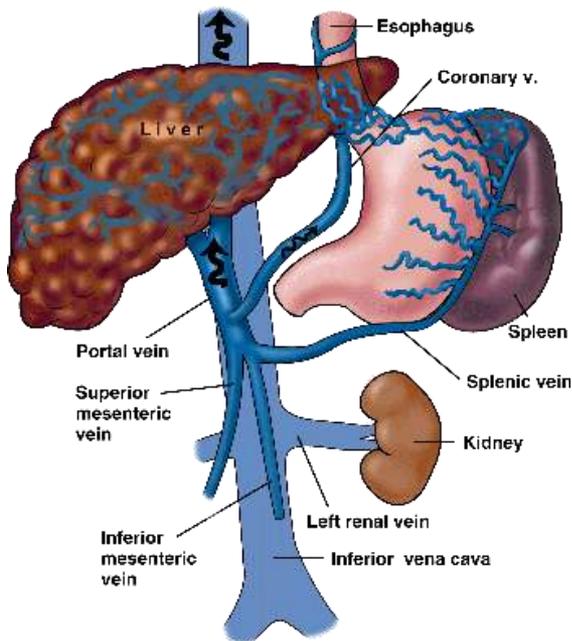


- Pose du TIPSS: regain de compressibilité lié au soulagement de la pression intrahépatique

ERM hépatique

applications: hypertension portale

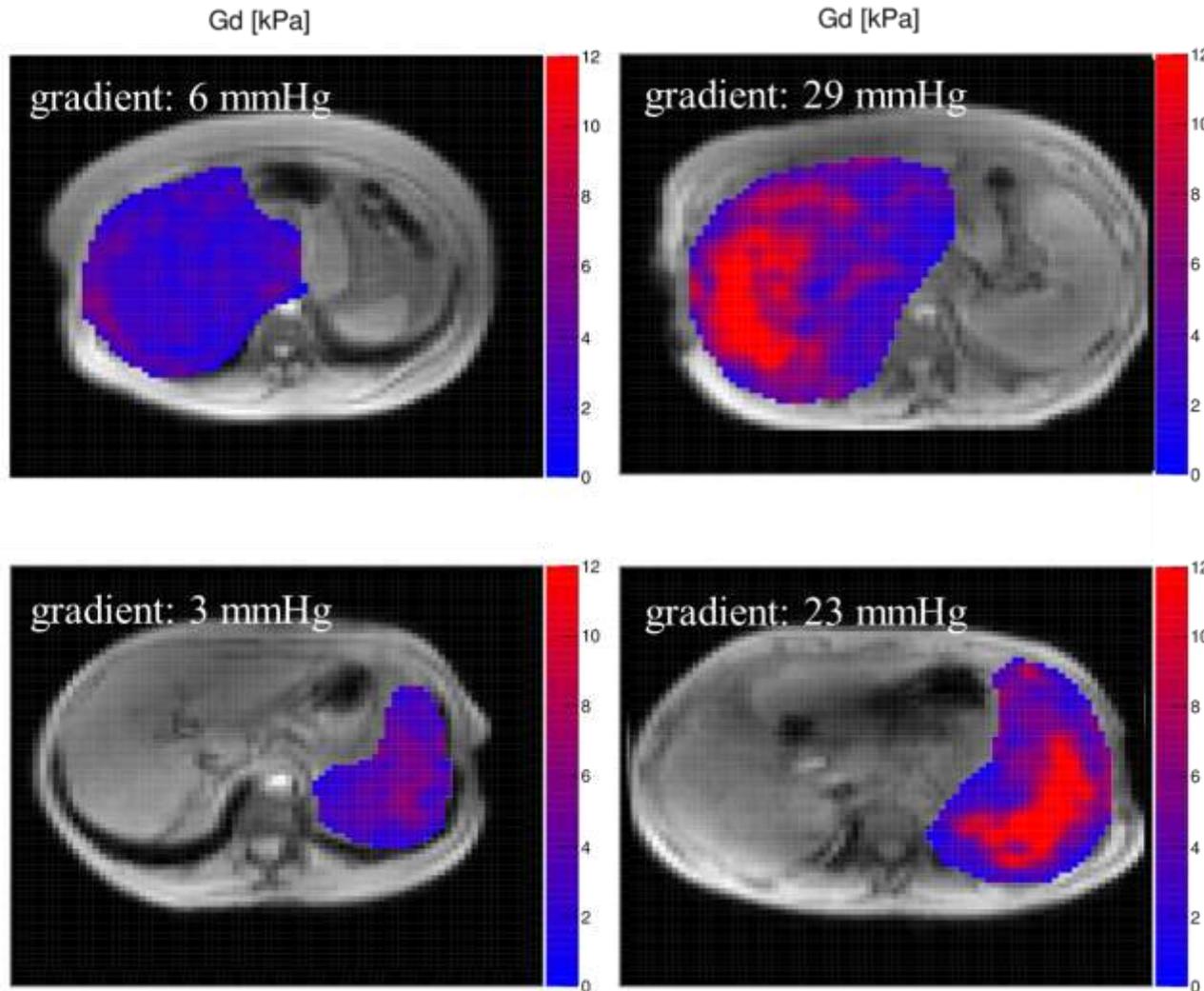
- hypertension portale: augmentation des propriétés mécaniques apparentes dans la rate



applications: hypertension portale

- Séquence "eXpresso" en monofréquence
- 4.6ms TE
- 74Hz, 12 points par cycle mécanique
- Acquisitions sur foie et rate au cours du même examen

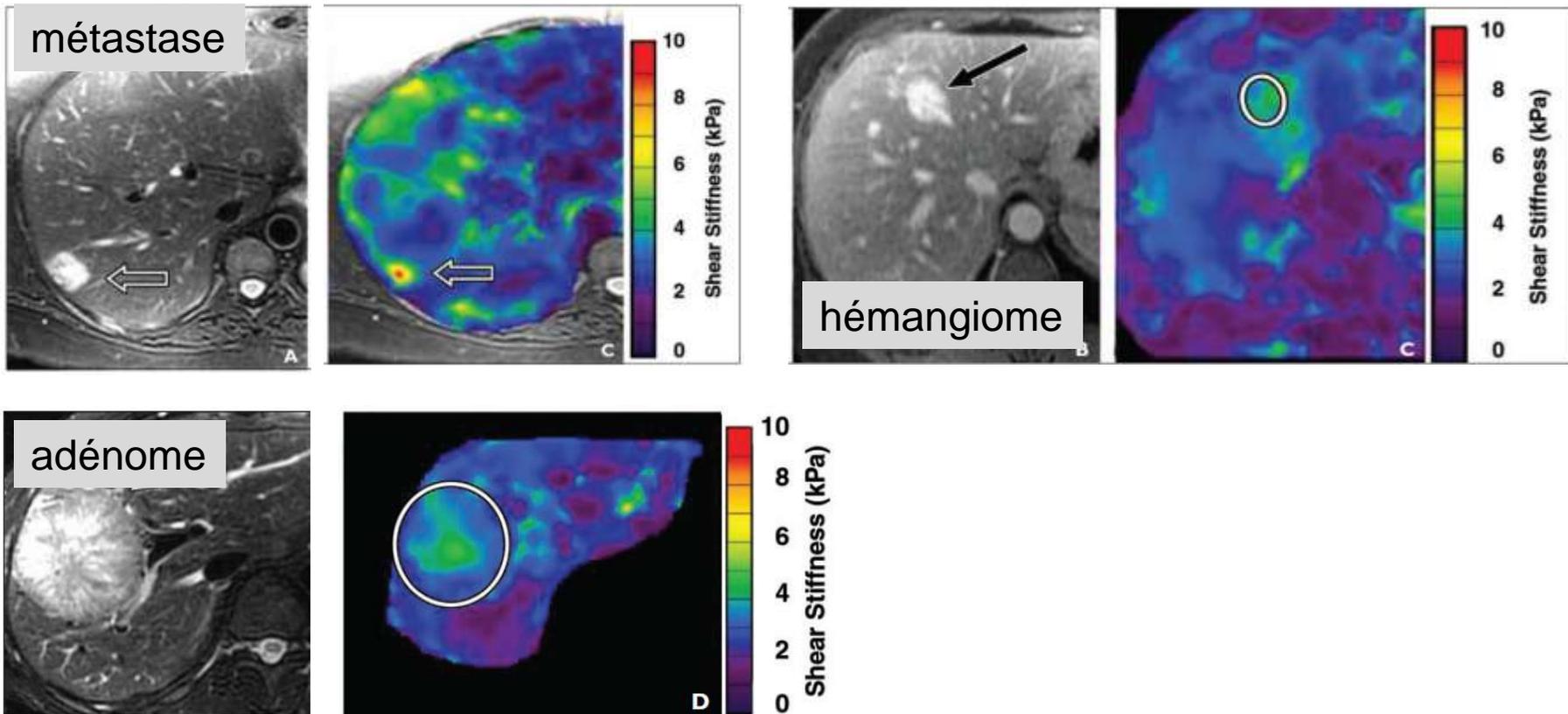
Applications: hypertension portale



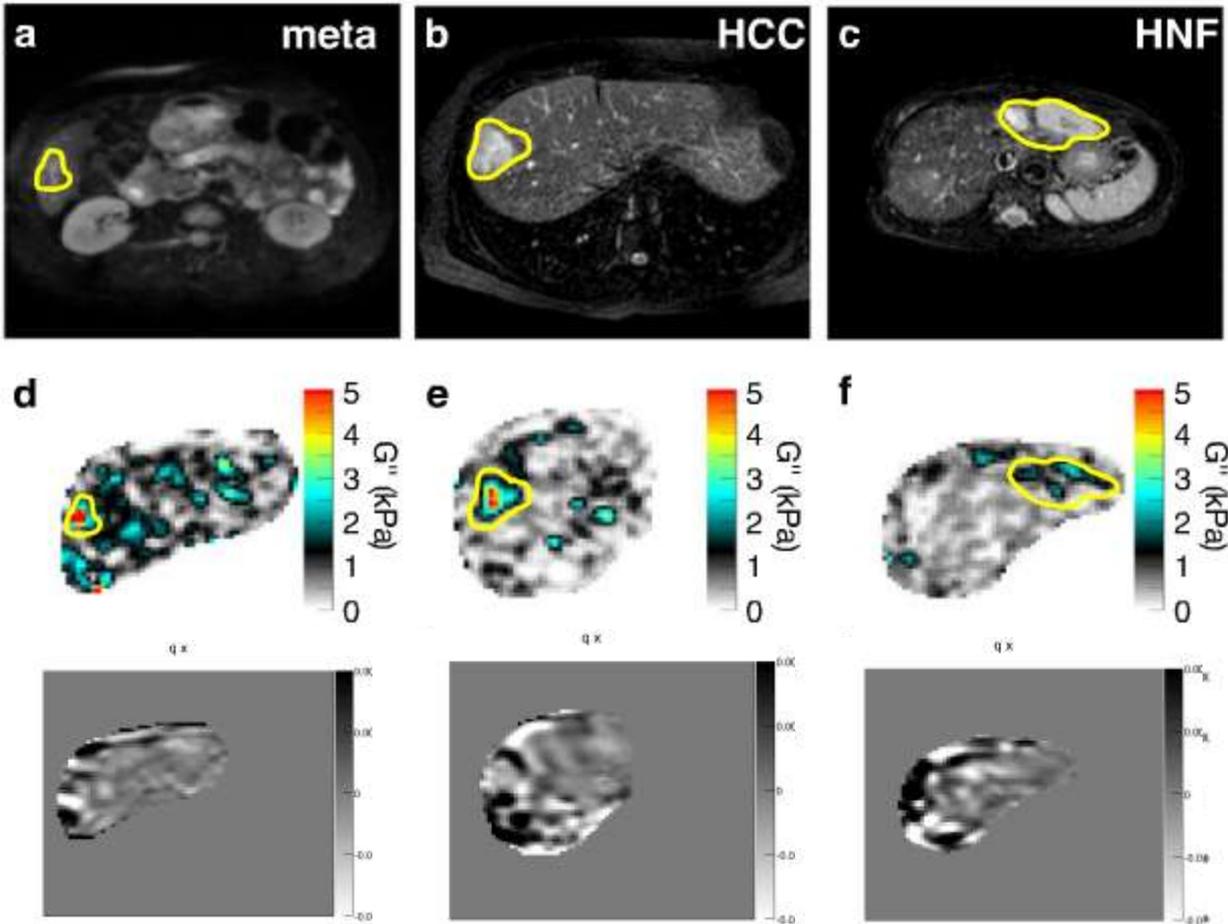
ERM: applications -lésions focales

applications: tumeurs hépatiques

- ERM: imagerie des lésions focales

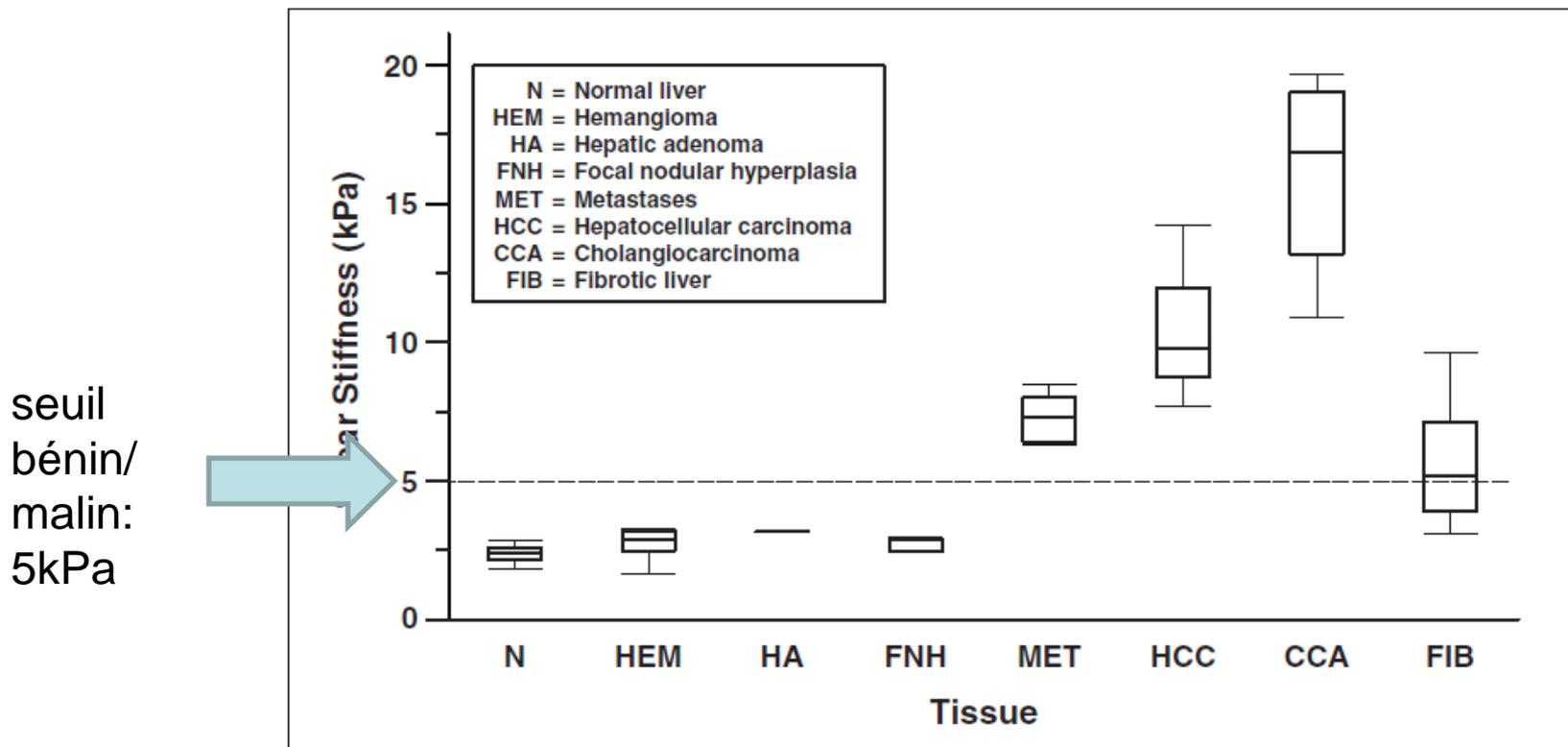


applications: tumeurs hépatiques



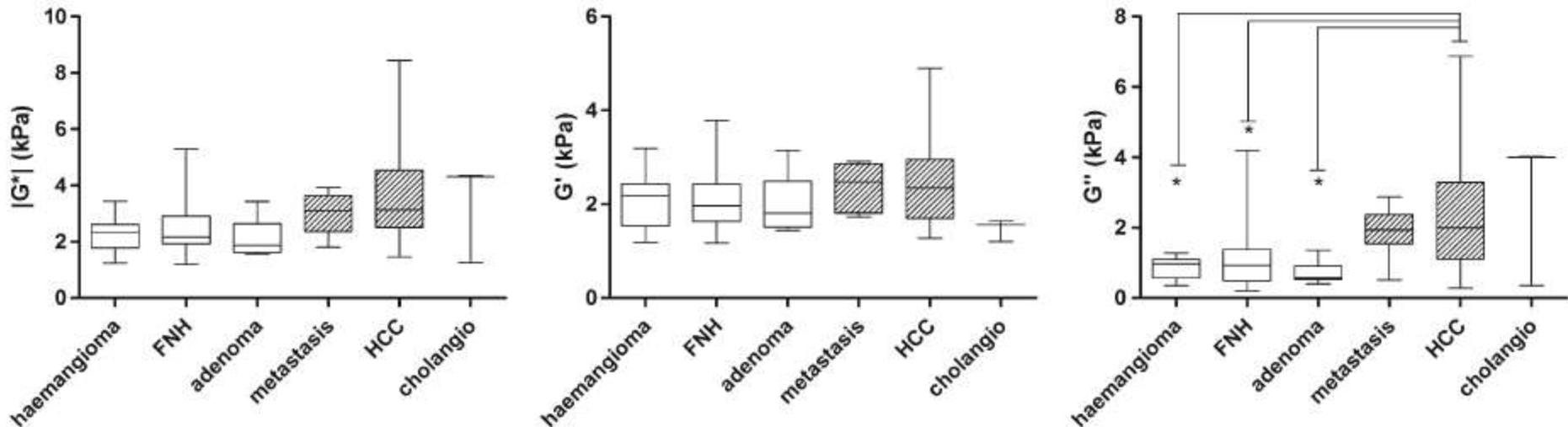
applications: tumeurs hépatiques

- ERM: imagerie des lésions focales
- classification des tumeurs selon leur dureté



applications: tumeurs hépatiques

- Imagerie visco-élastique des tumeurs



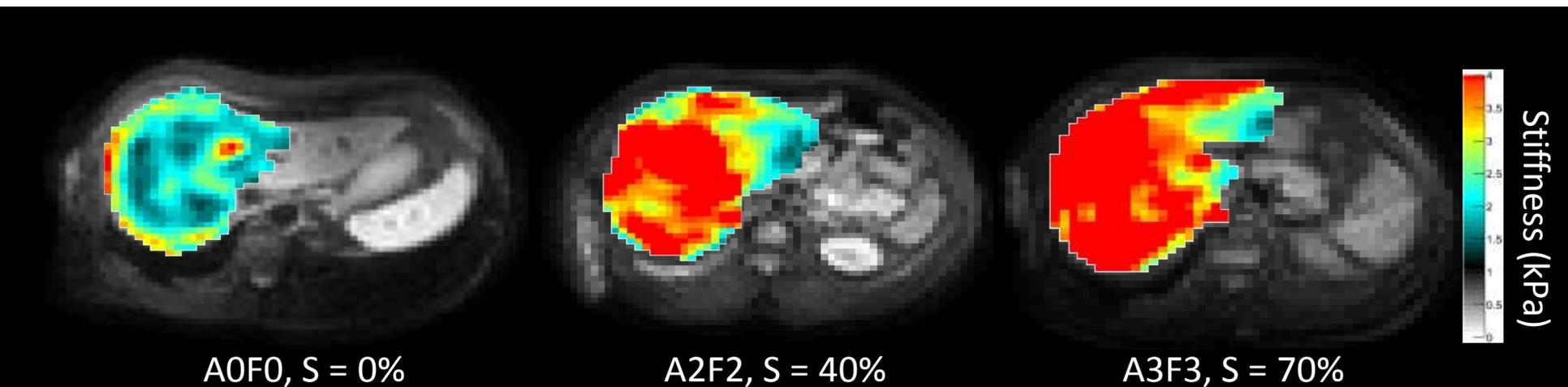
Garteiser, P. *et al.* MR elastography of liver tumours: value of viscoelastic properties for tumour characterisation. *European radiology* **22**, 2169–77 (2012).

- C'est le module de perte ("viscosité") des tumeurs qui explique ce comportement
- Viscosité seuil bénin/malin: 1,4 kPa

ERM: applications -imagerie multiparamétrique

applications: imagerie multiparamétrique

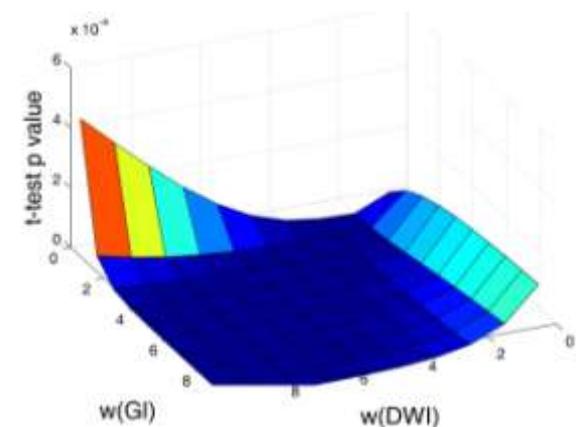
- ERM: nécessite un examen IRM
- = disponibilité immédiate d'informations parfaitement coregistrées
- ==> En complément pour approches multiparamétriques
- Combinaison d'informations complémentaires
- Caractérisation tissulaire plus complète



applications: imagerie multiparamétrique

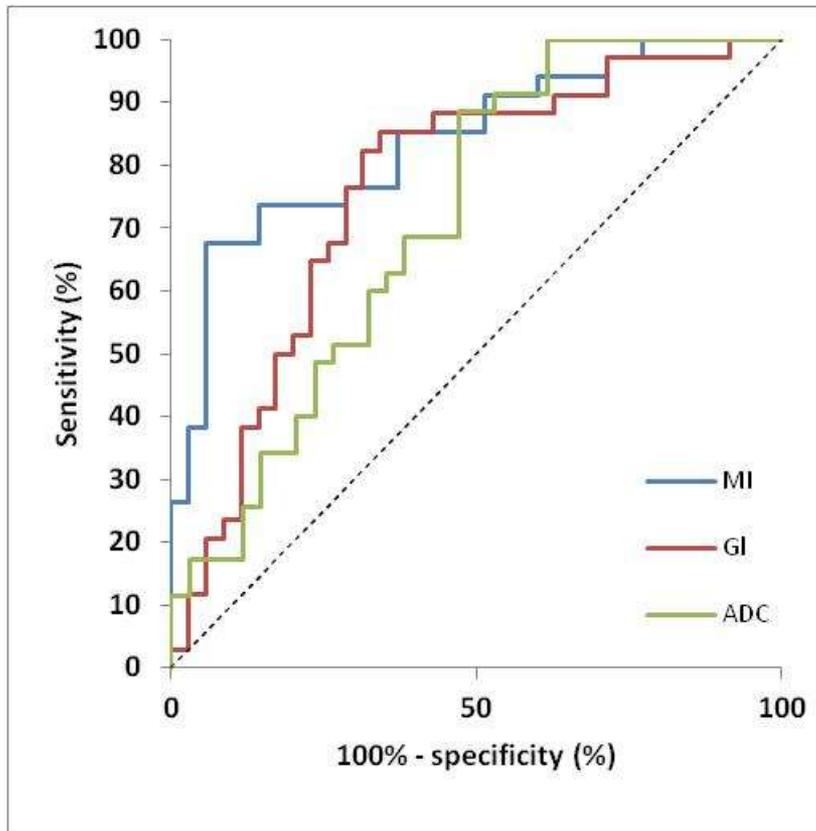
- Exemple: combinaison ERM + ADC
- Caractérisation tissulaire des tumeurs hépatiques
- Hypothèse: dans les tumeurs malignes
 - Module de perte G_I : ↗
 - ADC ($1/ADC$) : ↘ (↗)

→
$$MI = w_{G_I} \cdot \frac{G_I}{G_I^{ref}} + w_{ADC} \cdot \frac{1/ADC}{1/ADC^{ref}}$$



applications: imagerie multiparamétrique

- Exemple: combinaison ERM + ADC: "MI"
- Caractérisation de tumeurs hépatiques



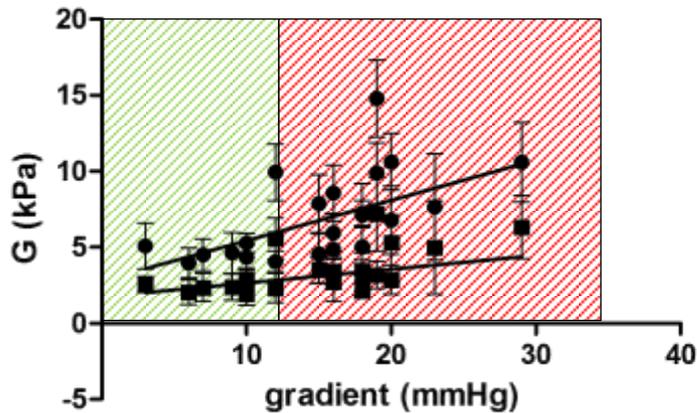
	Area under the ROC curve	T-test <i>p</i> value
G''	0.76, $p < 0.001$	$p < 0.005$
ADC	0.71, $p < 0.01$	$p < 0.005$
MI	0.84, $p < 0.0001$	$p < 0.0001$

application: imagerie multiparamétrique

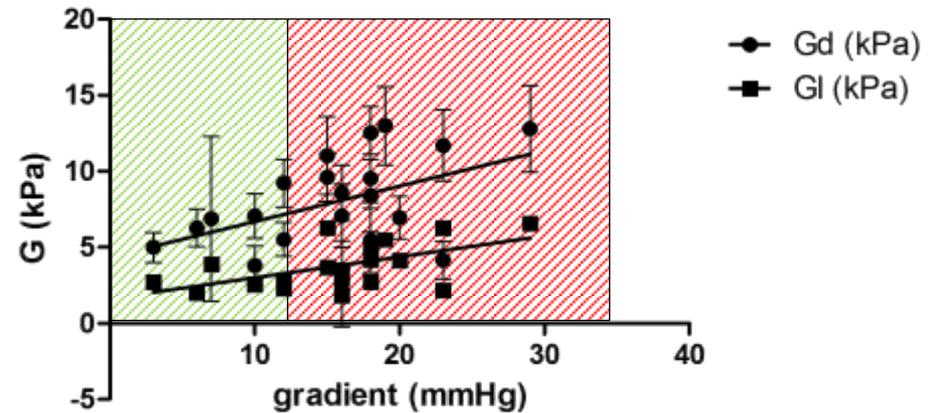
Parameter	Gd (kPa)	GI (kPa)
Number of XY Pairs	23	23
Spearman r	0,6041	0,6111
95% confidence interval	0.2433 to 0.8181	0.2536 to 0.8217
P value (two-tailed)	0,0023	0,0020
P value summary	**	**

Parameter	Gd (kPa)	GI (kPa)
Number of XY Pairs	21	21
Spearman r	0,4206	0,5010
95% confidence interval	-0.02726 to 0.7279	0.07474 to 0.7724
P value (two-tailed)	0,0576	0,0207
P value summary	ns	*

foie

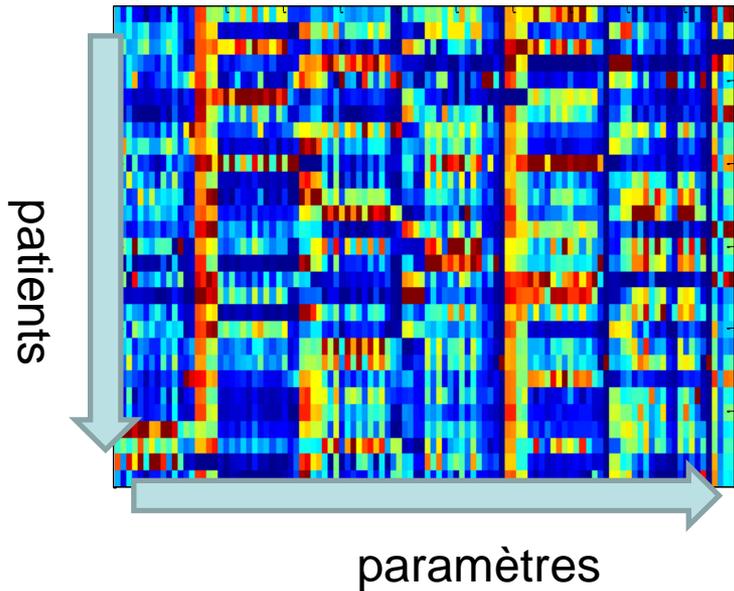


rate

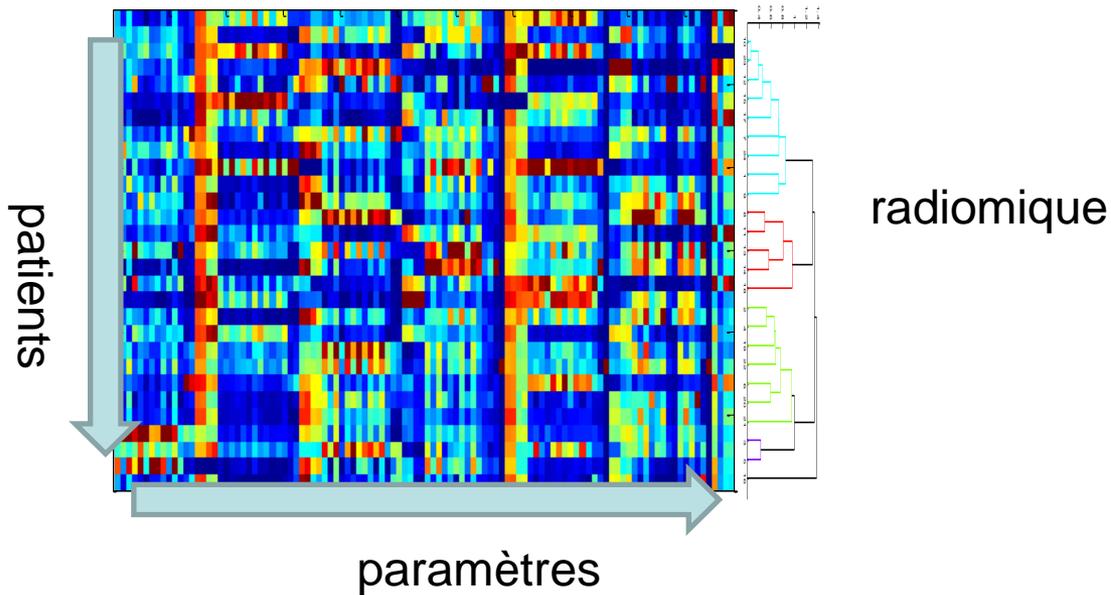


93% PPV pour le gradient avec G'' du foie

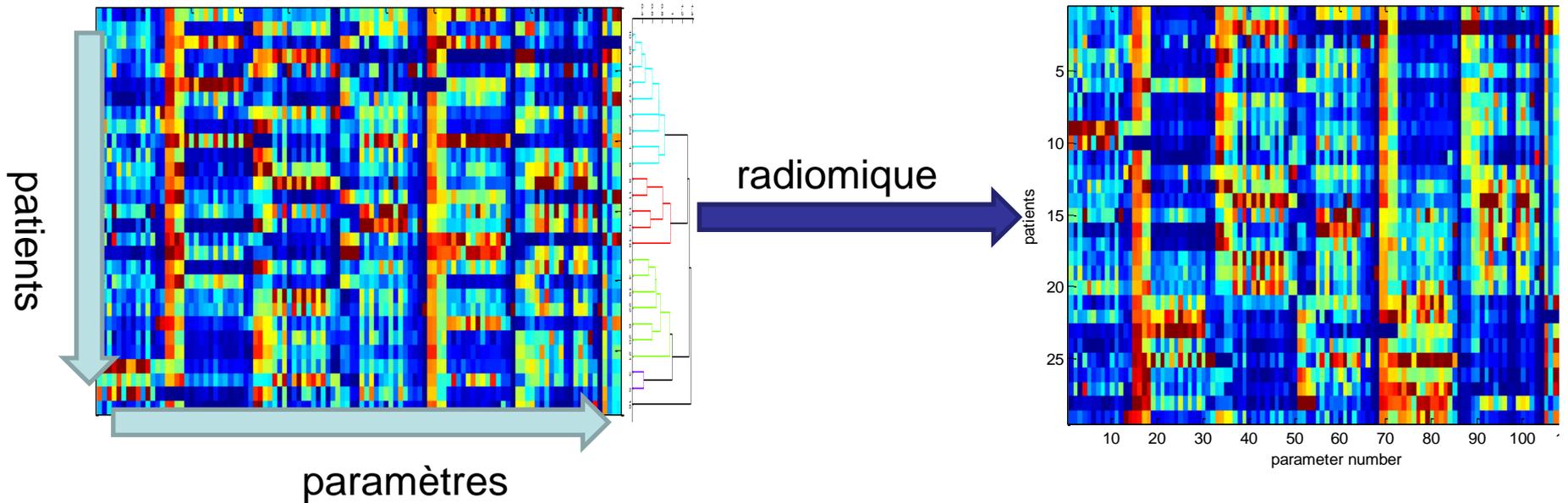
application: imagerie multiparamétrique



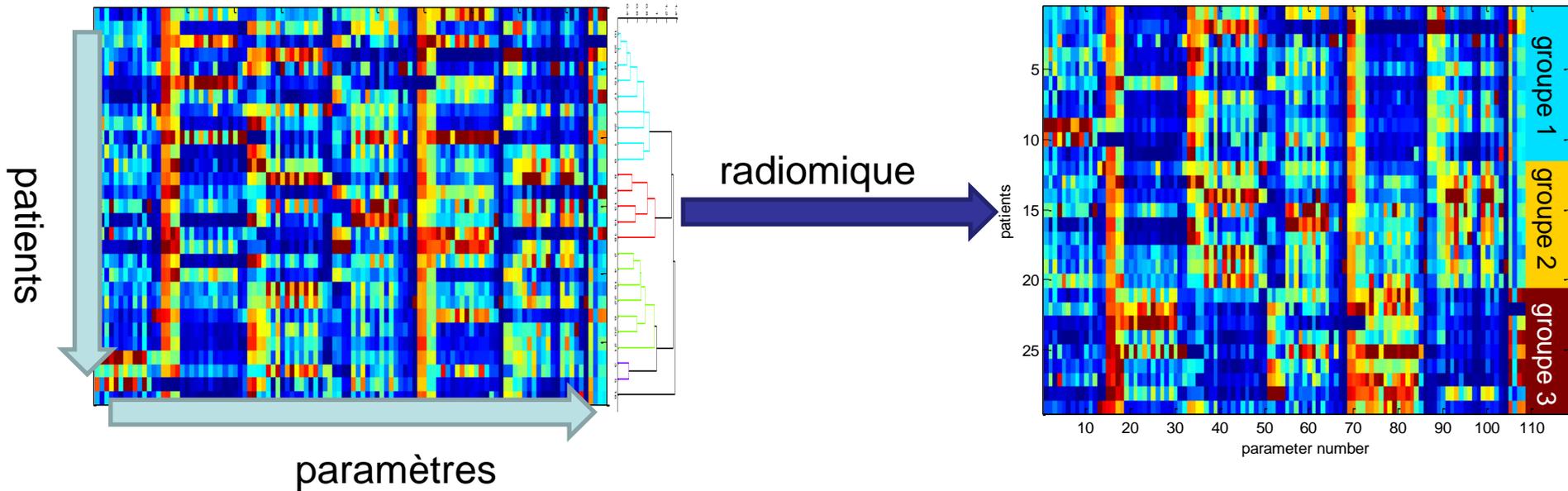
application: imagerie multiparamétrique



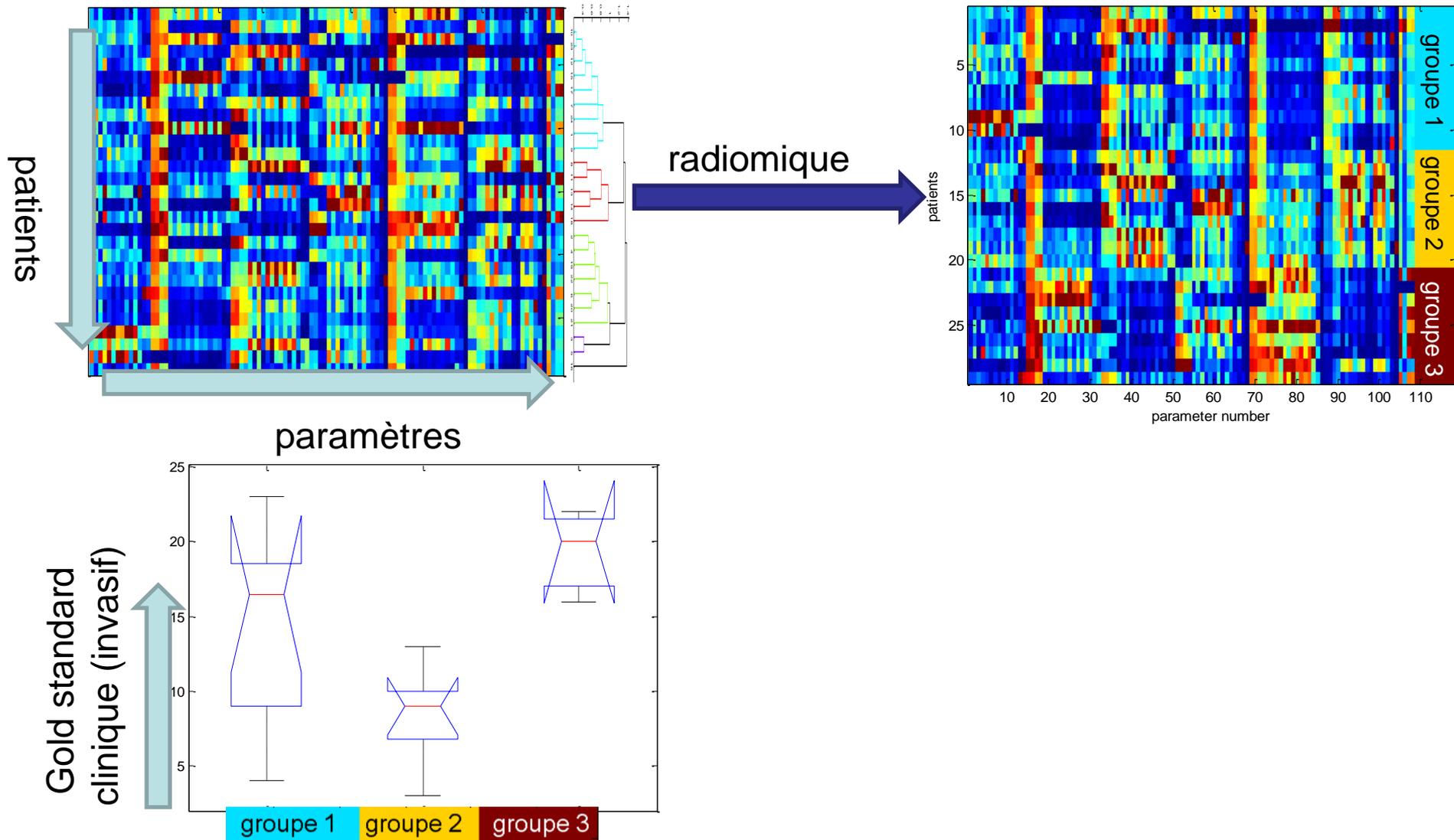
application: imagerie multiparamétrique



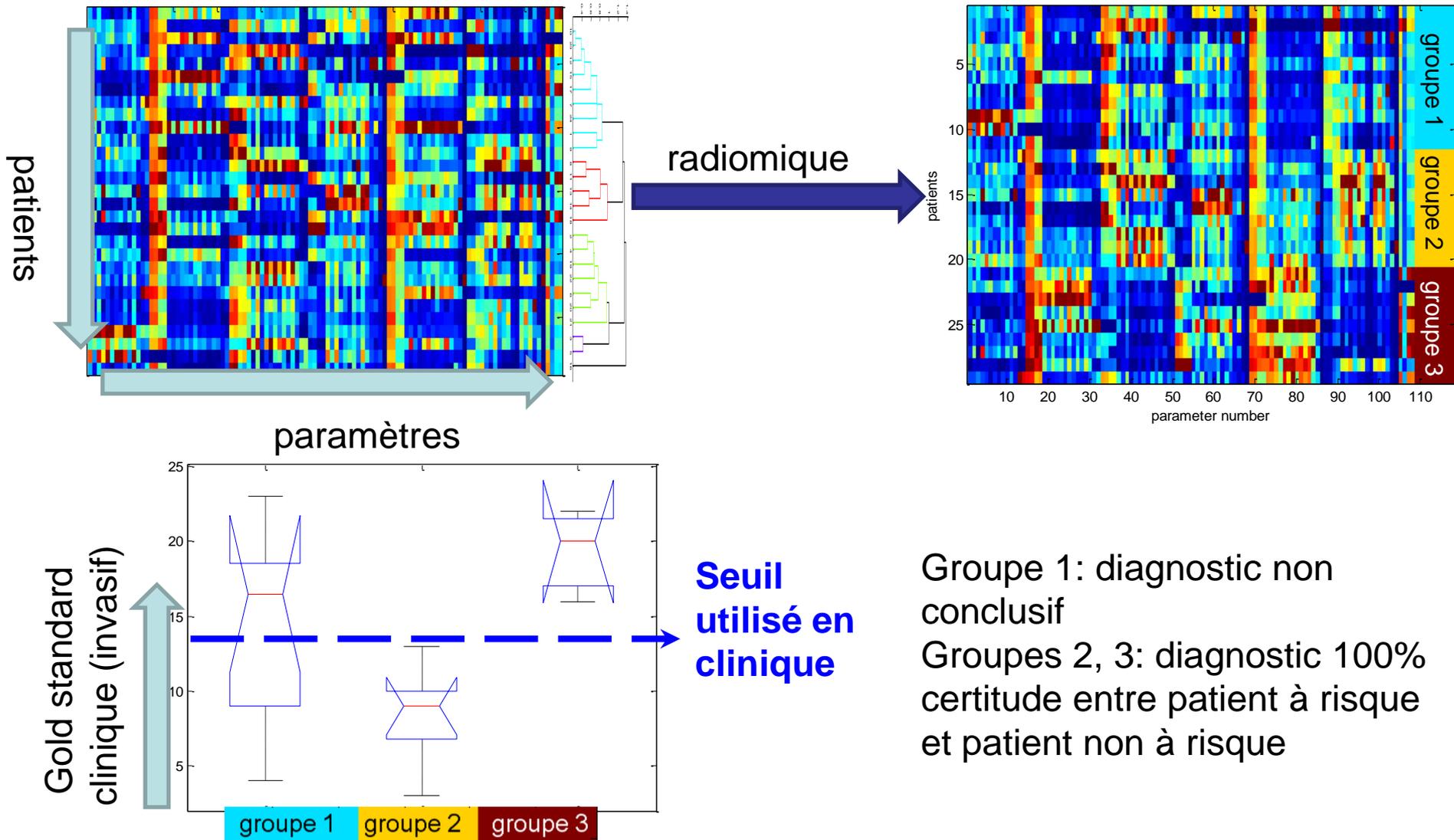
application: imagerie multiparamétrique



application: imagerie multiparamétrique

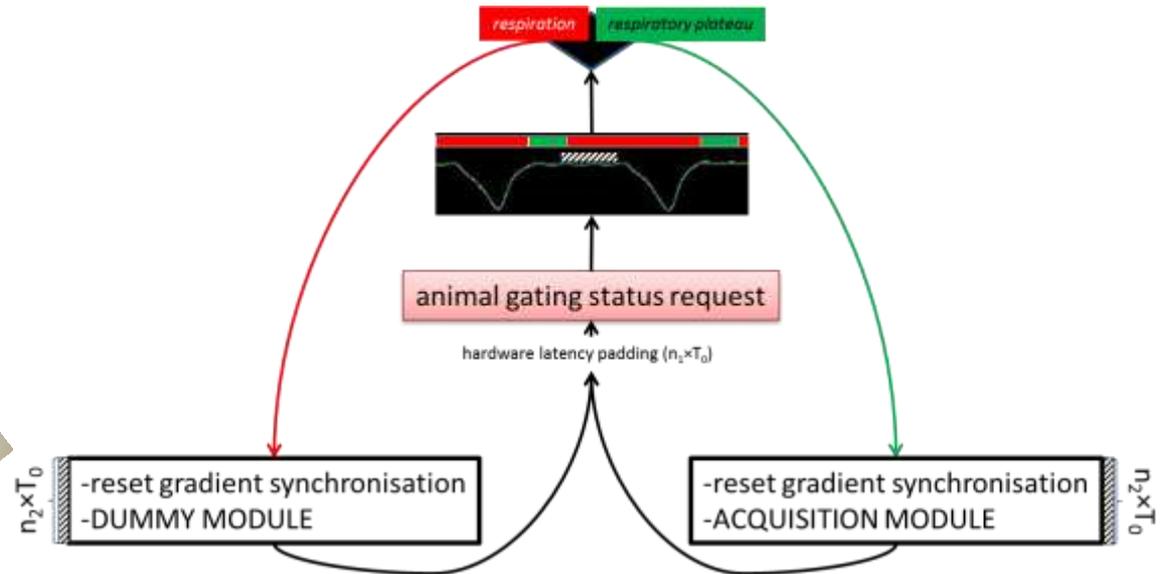


application: imagerie multiparamétrique



Chez le petit animal

Développements: ERM petit animal



Applications:

- ERM hépatique
- ERM de la graisse

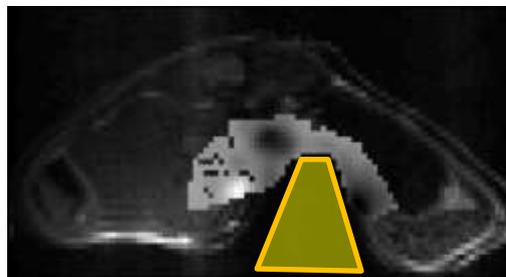
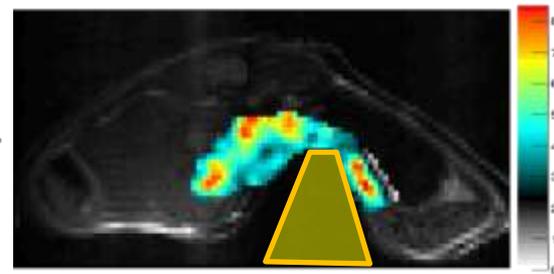
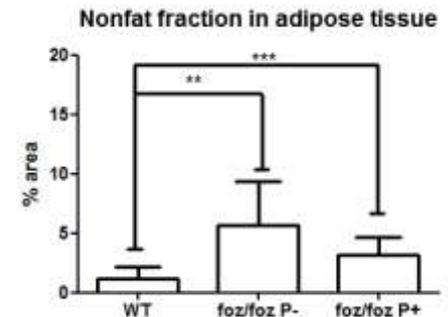
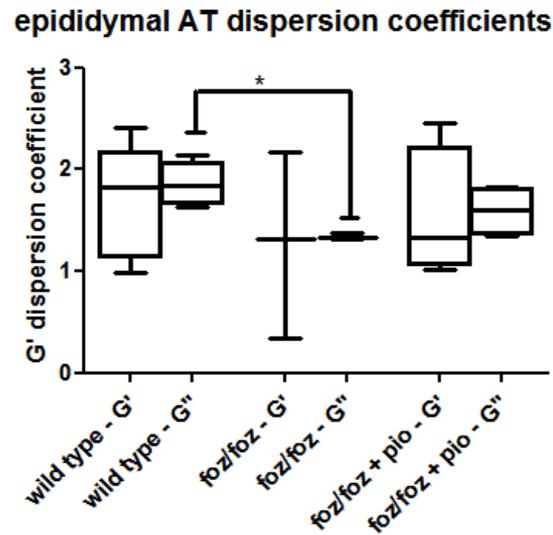
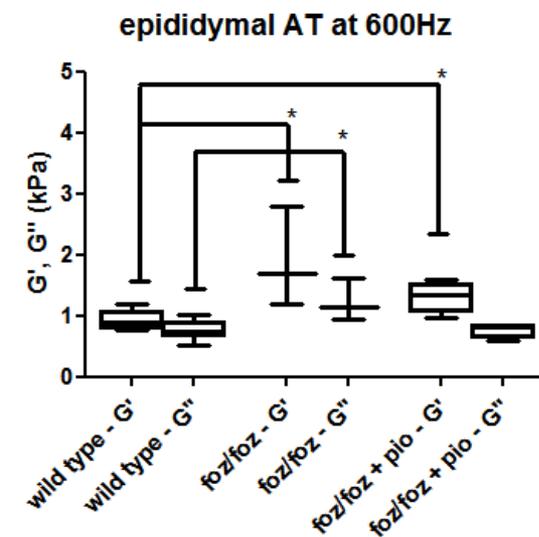
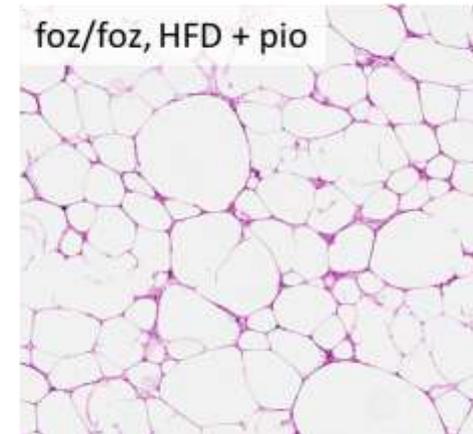
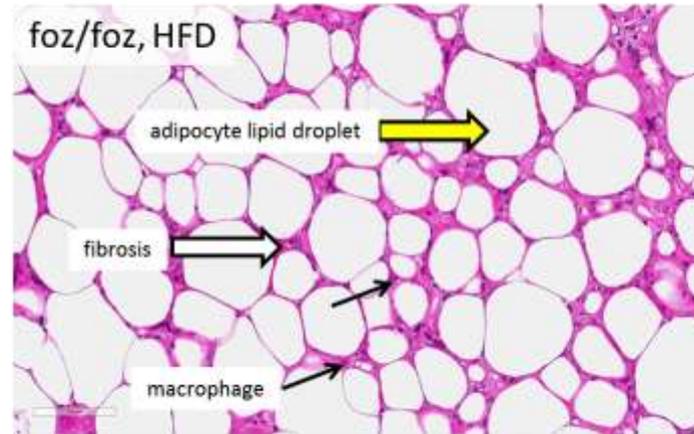
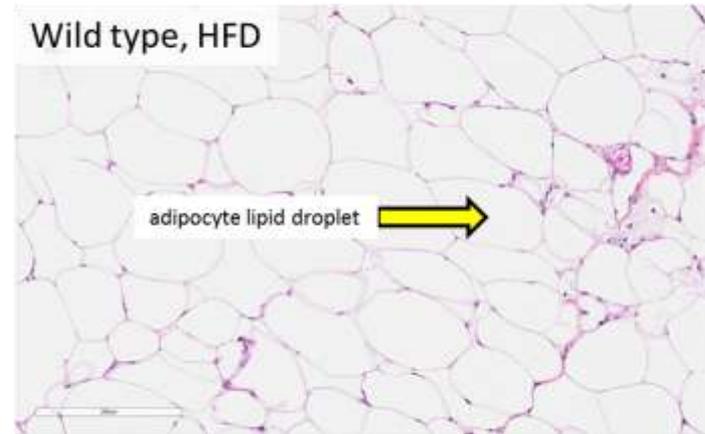


Image d'onde

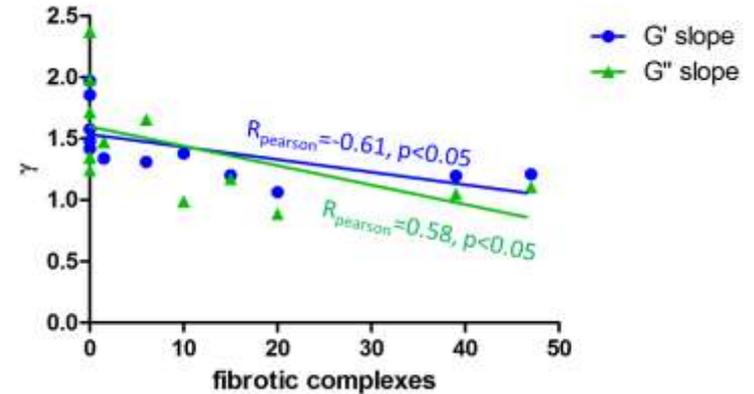
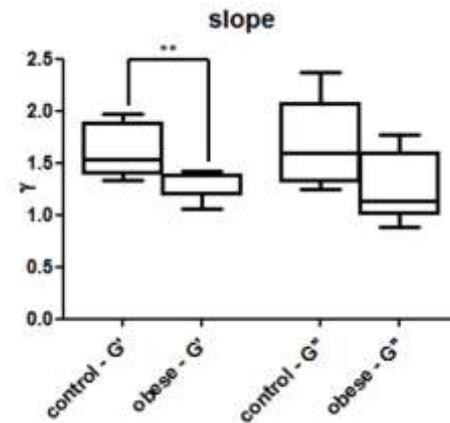
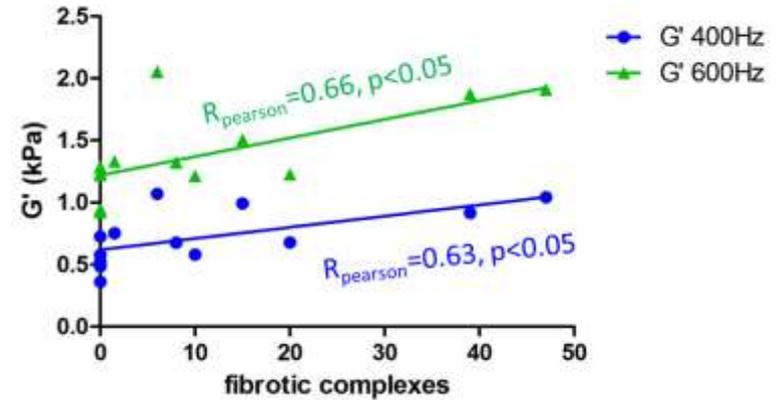
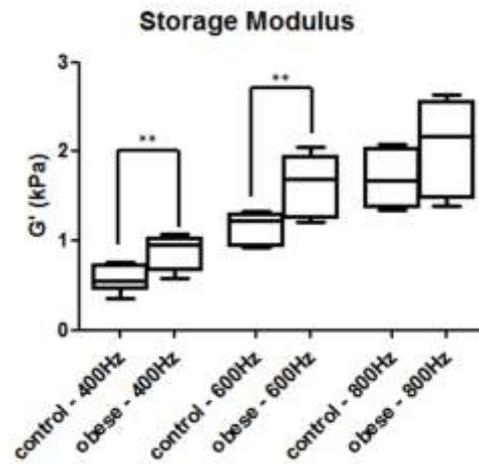
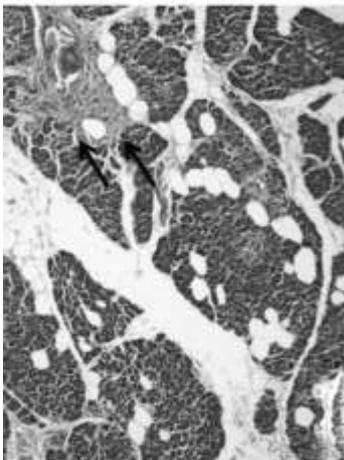
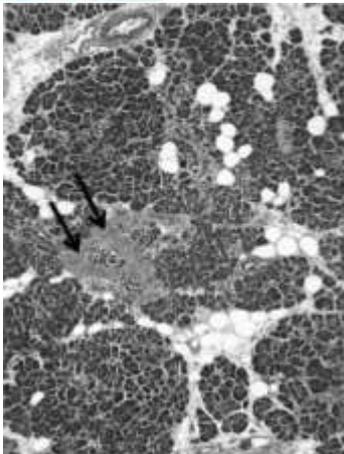
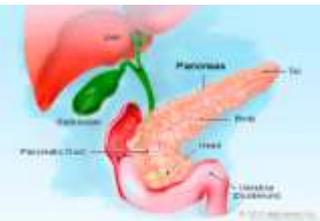


G'

ERM petit animal - obésité (graisse)



ERM petit animal - obésité (pancréas)





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de la santé et de la recherche médicale



LBI
Laboratoire des
Biomarqueurs en
Imagerie

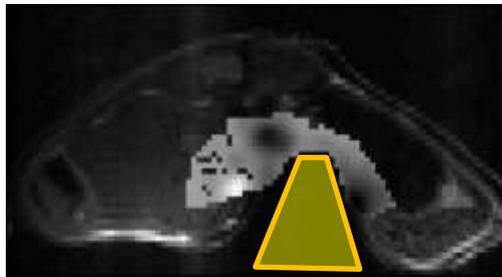
09-12-2015

CERF - module technologies avancées

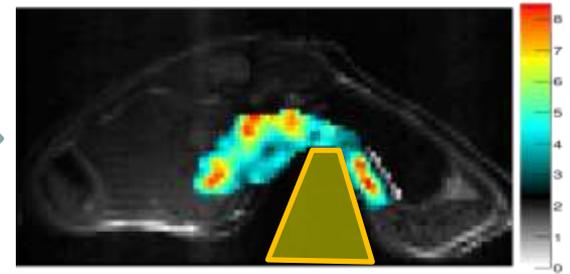
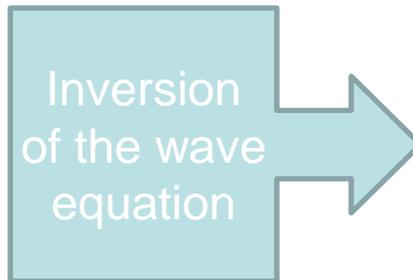
Philippe Garteiser, PhD

Centre de Recherche sur l'Inflammation, INSERM U1149 - UP7

Développements: ERM petit animal



Shear wave (from phase image)



Storage modulus