

# Low Mid-field Cardiac MRI

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# Les motivations pour l'imagerie cardiaque à champs moyen

- L'accès
  - Dans les pays en développement
  - Et ici...



IRM cardiaque à Orsay : réservez en ligne

Cardiologue

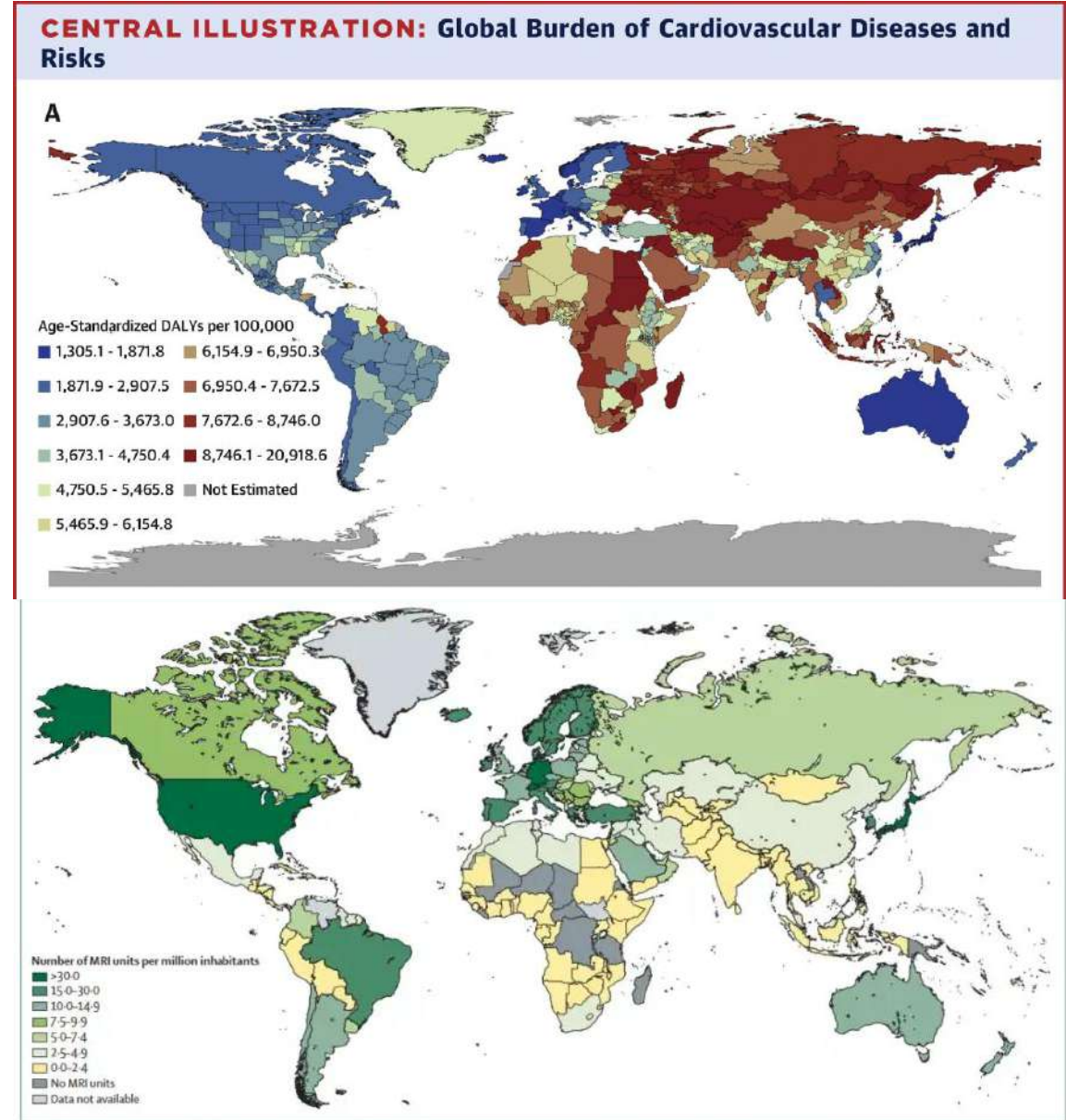
8,4 km

📍 2Ter Avenue de France 91290 Massy

€ Conventionné secteur 2 avec OPTAM

Prochaine disponibilité

mercredi 4 novembre

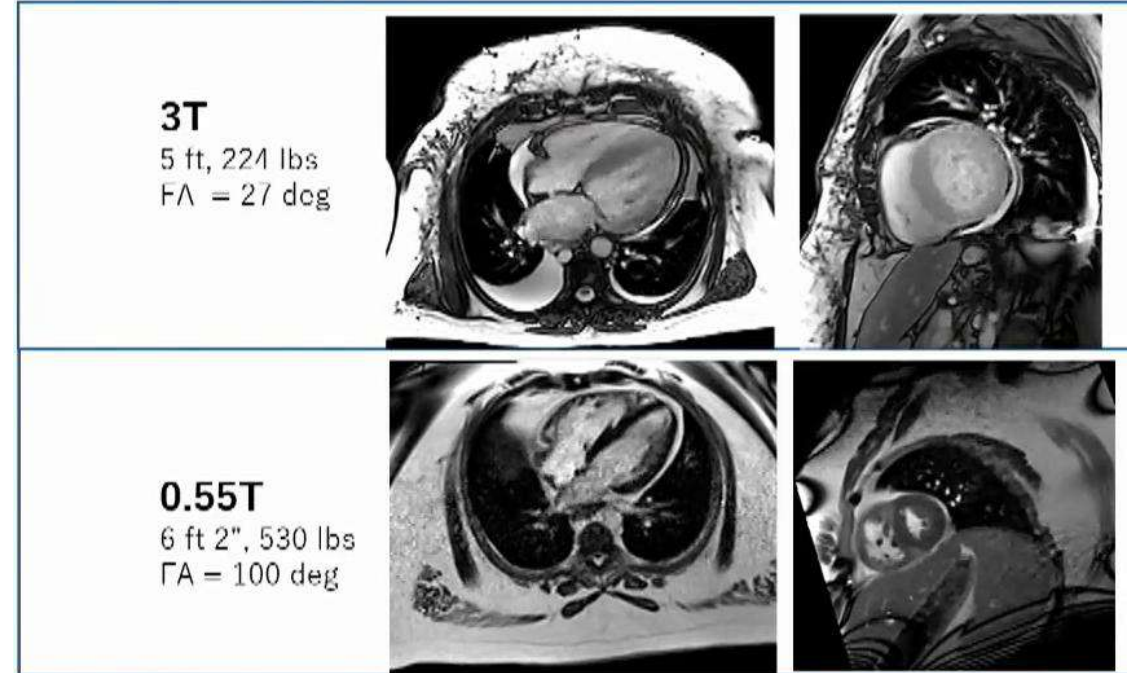
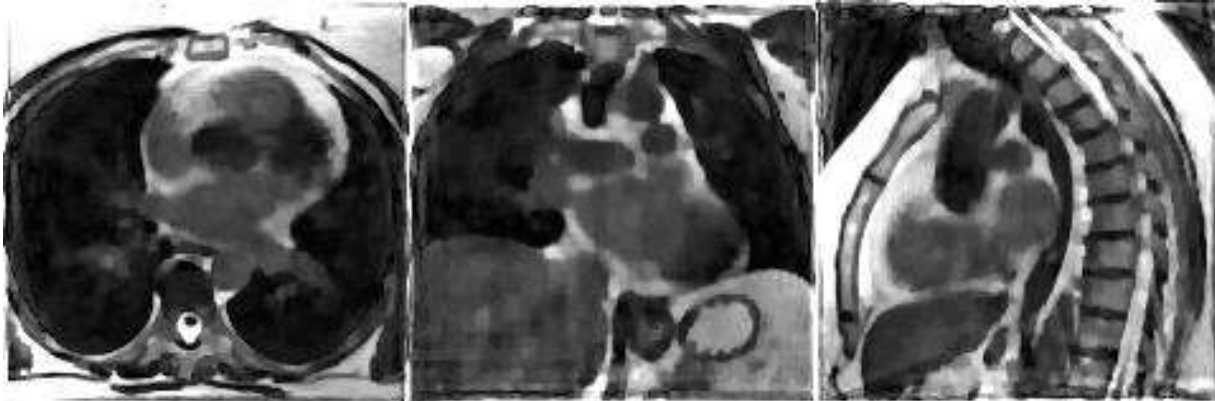


Vaduganathan, Mensah, et al. 2022. <https://doi.org/10.1016/j.jacc.2022.11.005>. International Atomic Energy Agency

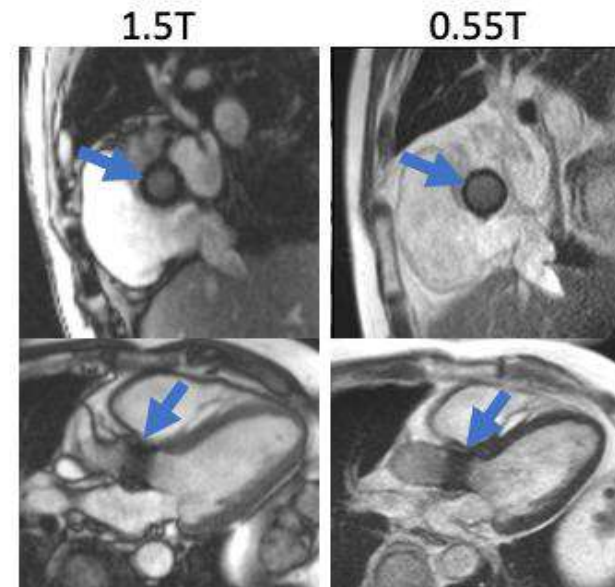
Figure 5: Estimates of the number of MRI units per million inhabitants. Data are from the International Atomic Energy Agency medical imaging and nuclear medicine global resources database (IMAGINE). The map was produced by the International Atomic Energy Agency (Vienna, Austria) and is included here with permission.

# Les motivations pour l'imagerie cardiaque

- Les patients:
  - Obèses

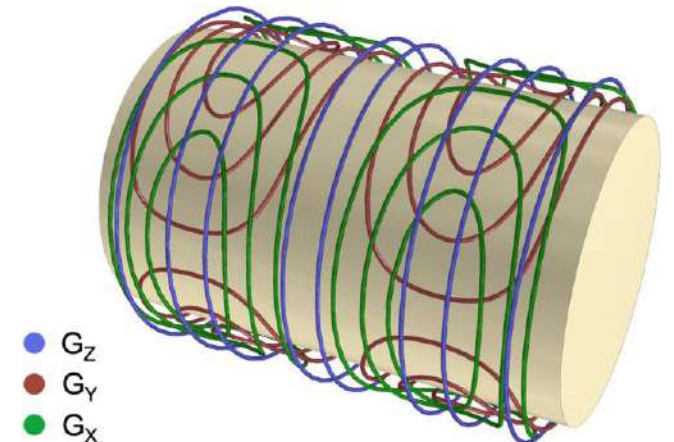


- Avec implants métalliques



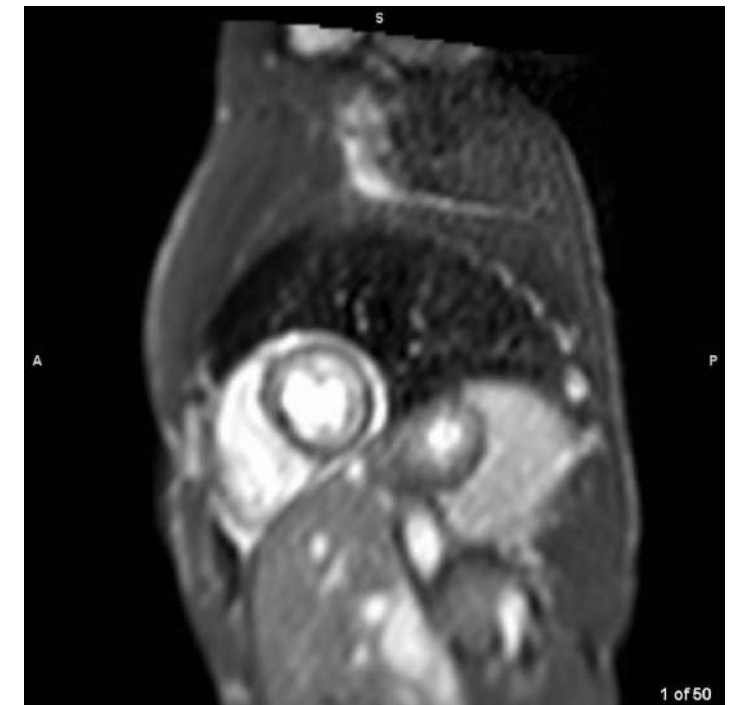
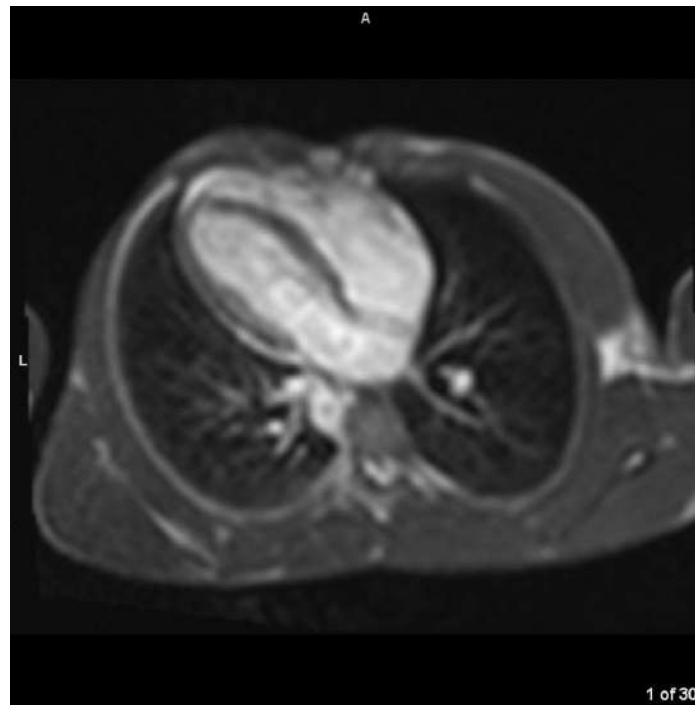
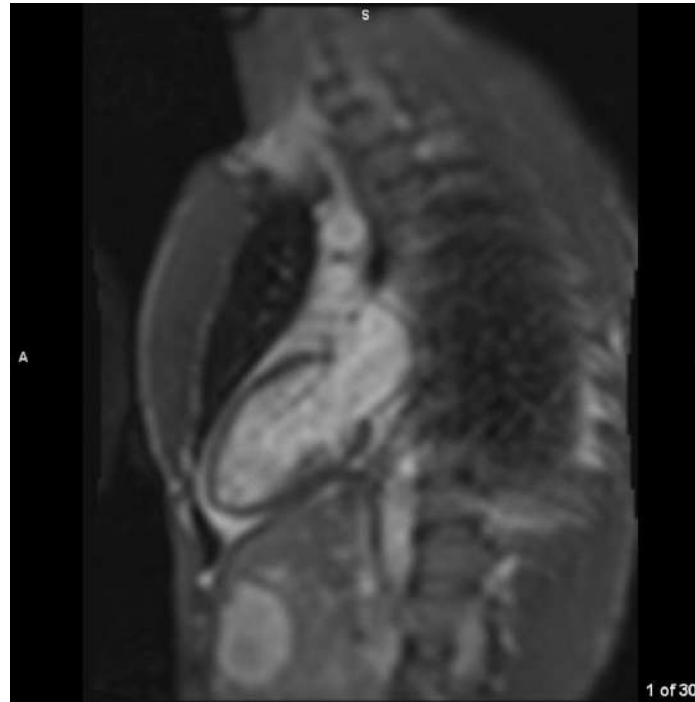
# La réalité...

- Le matériel
  - 80 cm  $\varnothing$  intérieur
  - Pas d'ECG
  - Gradients très limités (1/4 de la normale)
  - Antenne postérieure sous la table
  - Shim au 1<sup>er</sup> ordre
  - GPU & RAM limités
- Le logiciel
  - Pas de séquence cardiaque (fonction/flux)
  - CBM: charge balance model



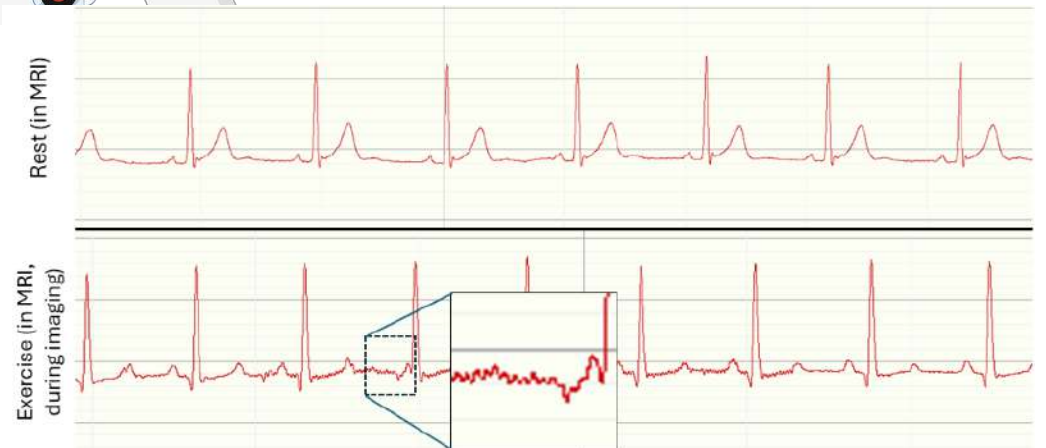
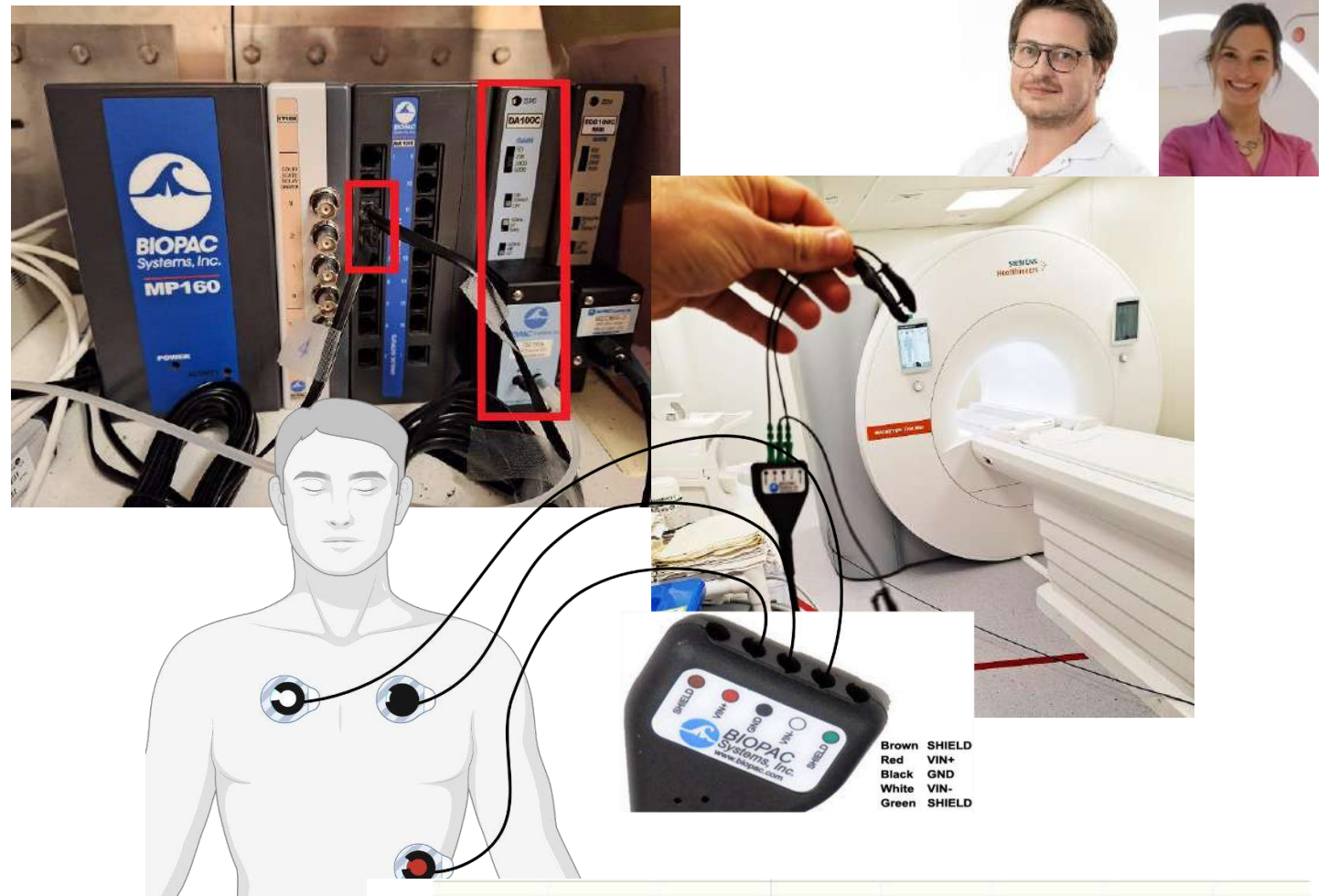
# Prise en main

- Real-time cine
  - 180 ms / frame
  - 1.9 x 1.9 x 10 mm<sup>3</sup> (interp. x2)
  - MOCO (recalage d'images)

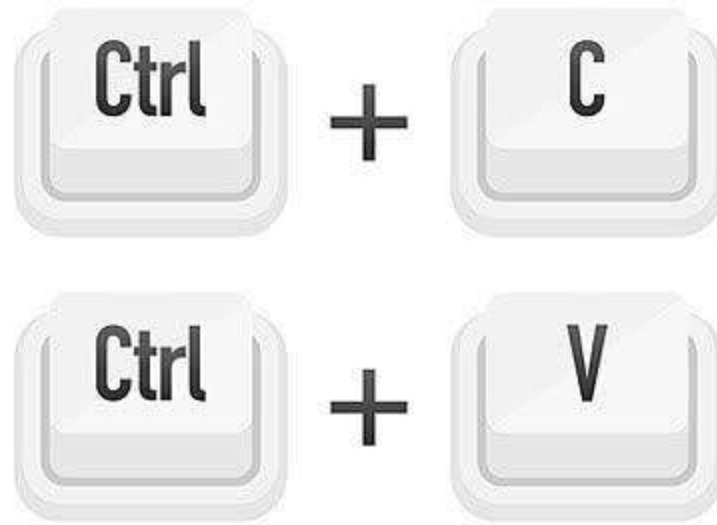


# Prise en main

- Ajout d'un ECG externe
  - Biopac (système préclinique)
- Trigger interne pour sortie TTL
- Connecté en TTL sur l'IRM
- Bruit électronique dans les 20MHz?
- Câbles = antennes



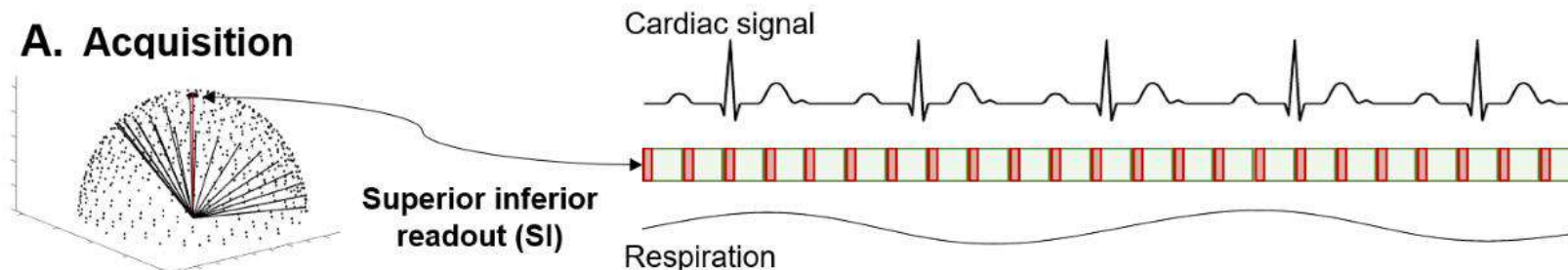
# La translation



# La translation: 5D free-running

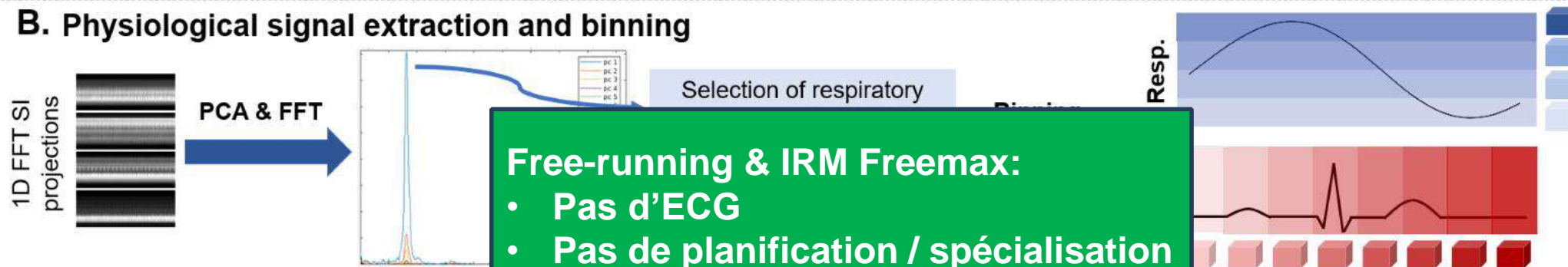


## A. Acquisition



- 3D free-running bSSFP
- 3D golden angle phyllotaxis trajectory
- No ECG, free-breathing
- 10 healthy volunteers

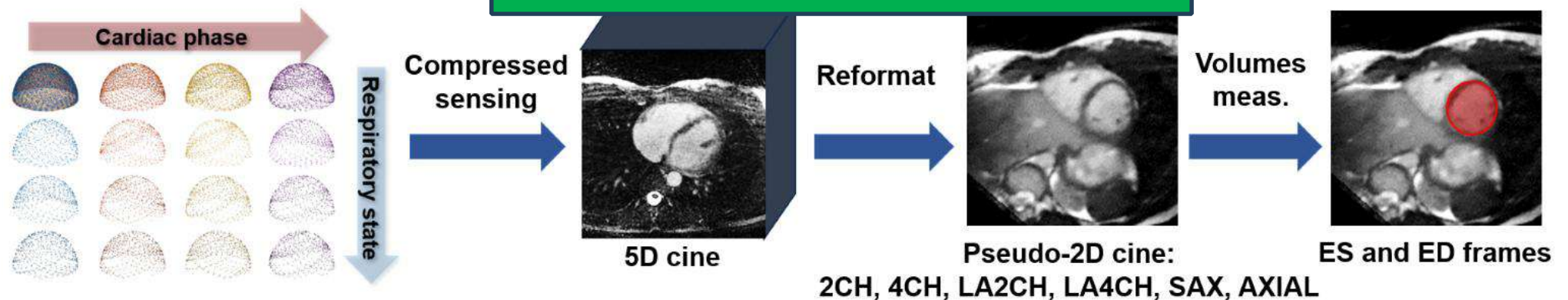
## B. Physiological signal extraction and binning



**Free-running & IRM Freemax:**

- Pas d'ECG
- Pas de planification / spécialisation
- Pas d'apnée

## C. Compressed sensing reconstruction



# La translation: 5D free-running

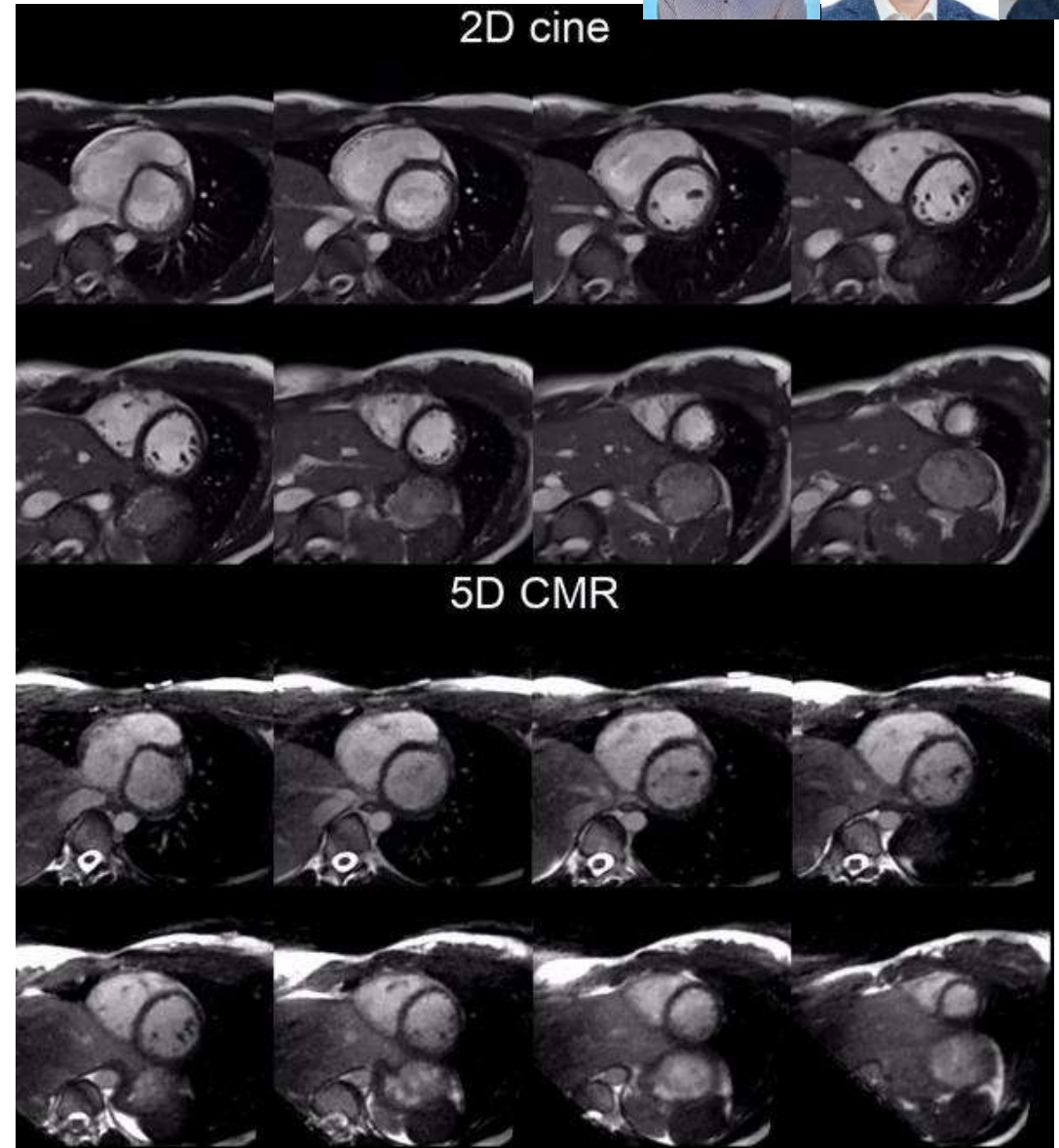


5D free-running vs 2D cine (10 vol.):

- Lower sharpness
- Lower blood-myocardium contrast
- Similar ventricle areas in peak systole and end diastole
- Similar structural details
- The RV, LV and LA volumes could be segmented in all volunteers.

	2D cine	5D CMR
TE/TR (ms)	1.95/4.2	1.97/4.93
FOV (mm)	288×360	220×220×220
Spatial resolution (mm)	1x1x8	1.4x1.4x1.4
RF excitation angle (°)	100	110
ECG gating	Prospective	None
Number of breath-holds	25-35	0
Acquisition time (min:sec)	35-45 min	7:20 min

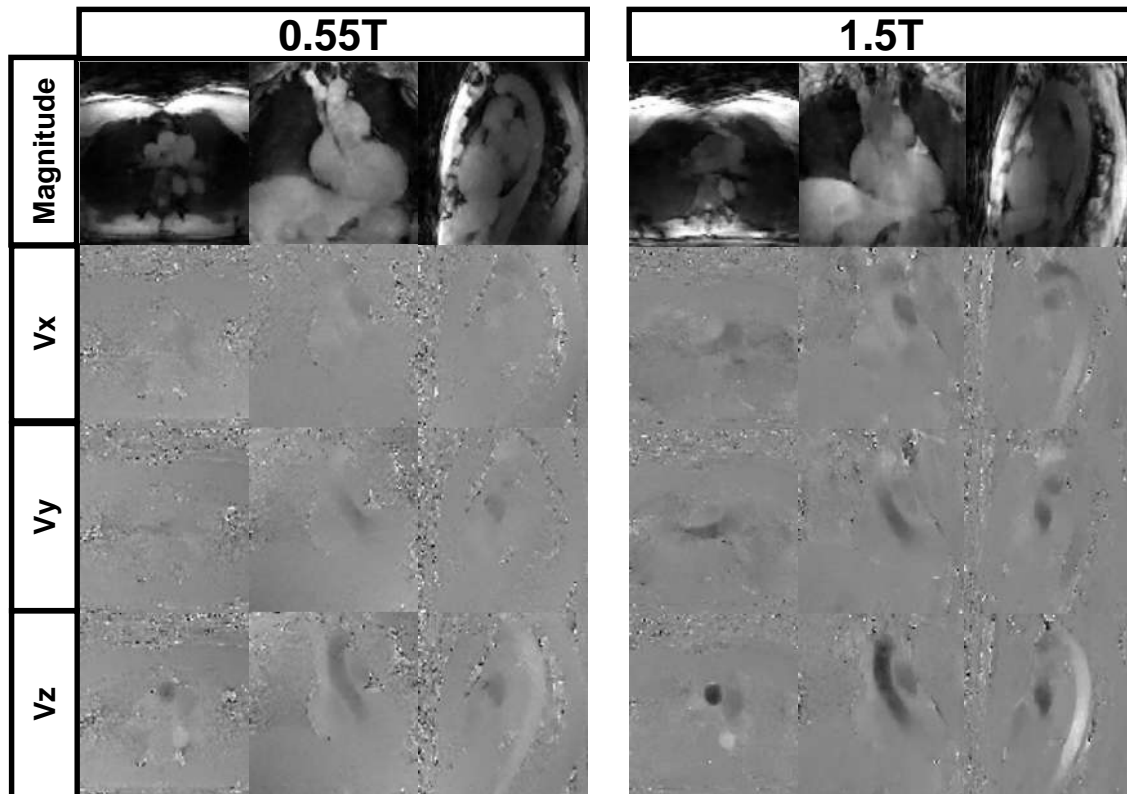
SAX Cardiac motion



# La translation: 5D flow

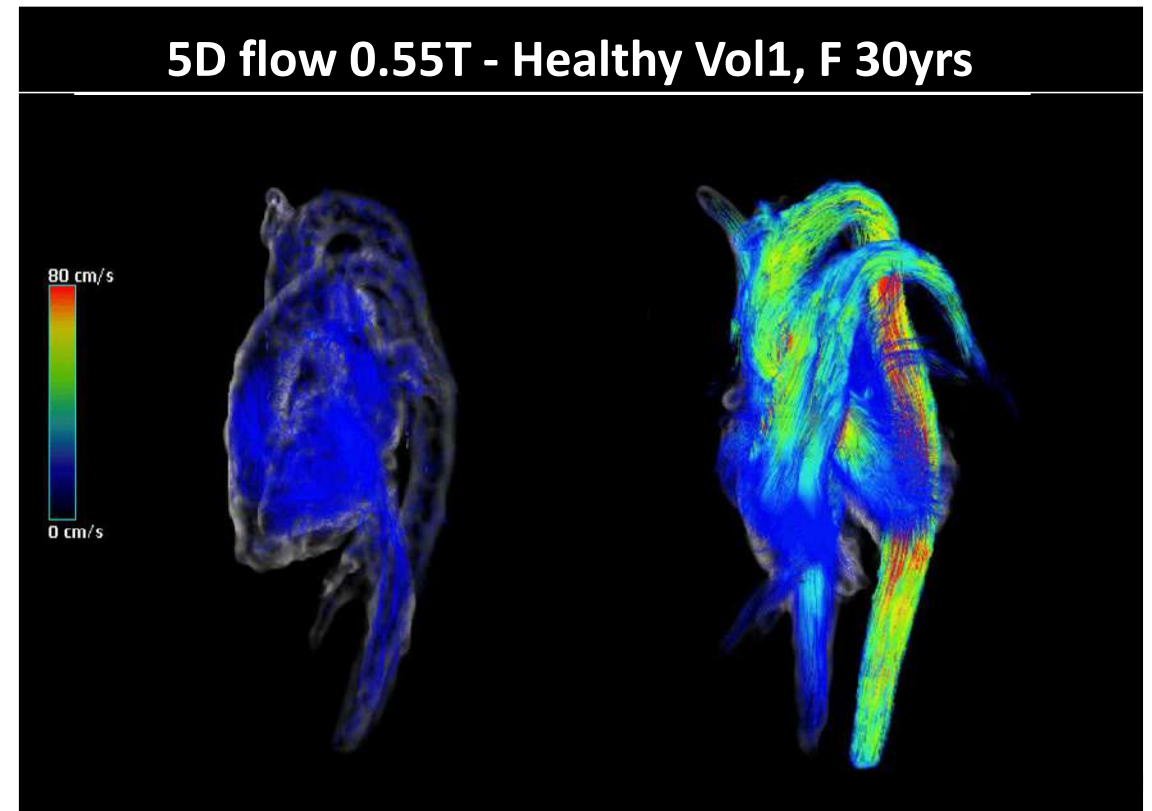


- Comparing phase-contrast free-running at 0.55 and 1.5 T:

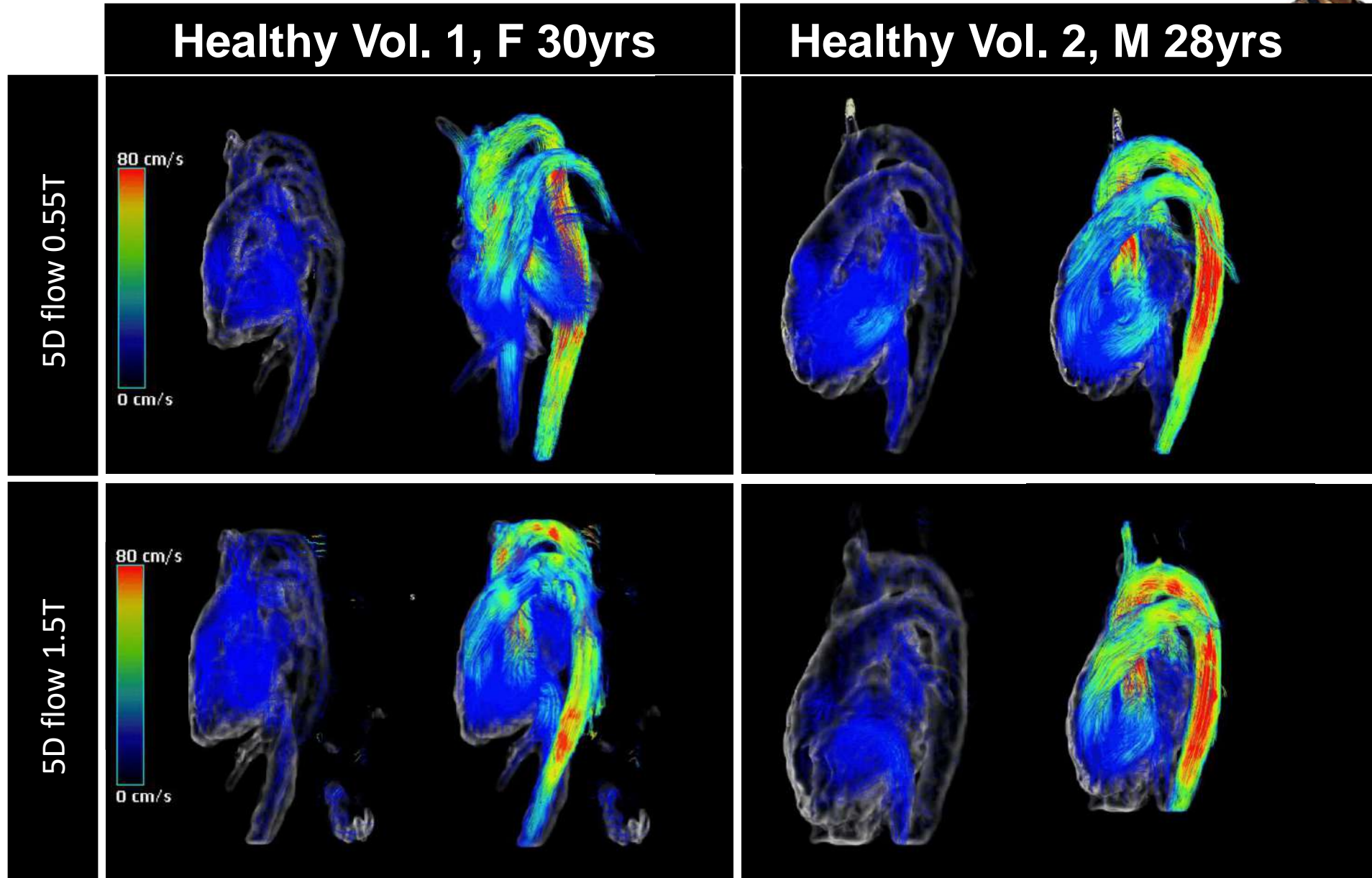


**Table 1:** Sequence parameters for the acquisition at 0.55T and 1.5T.

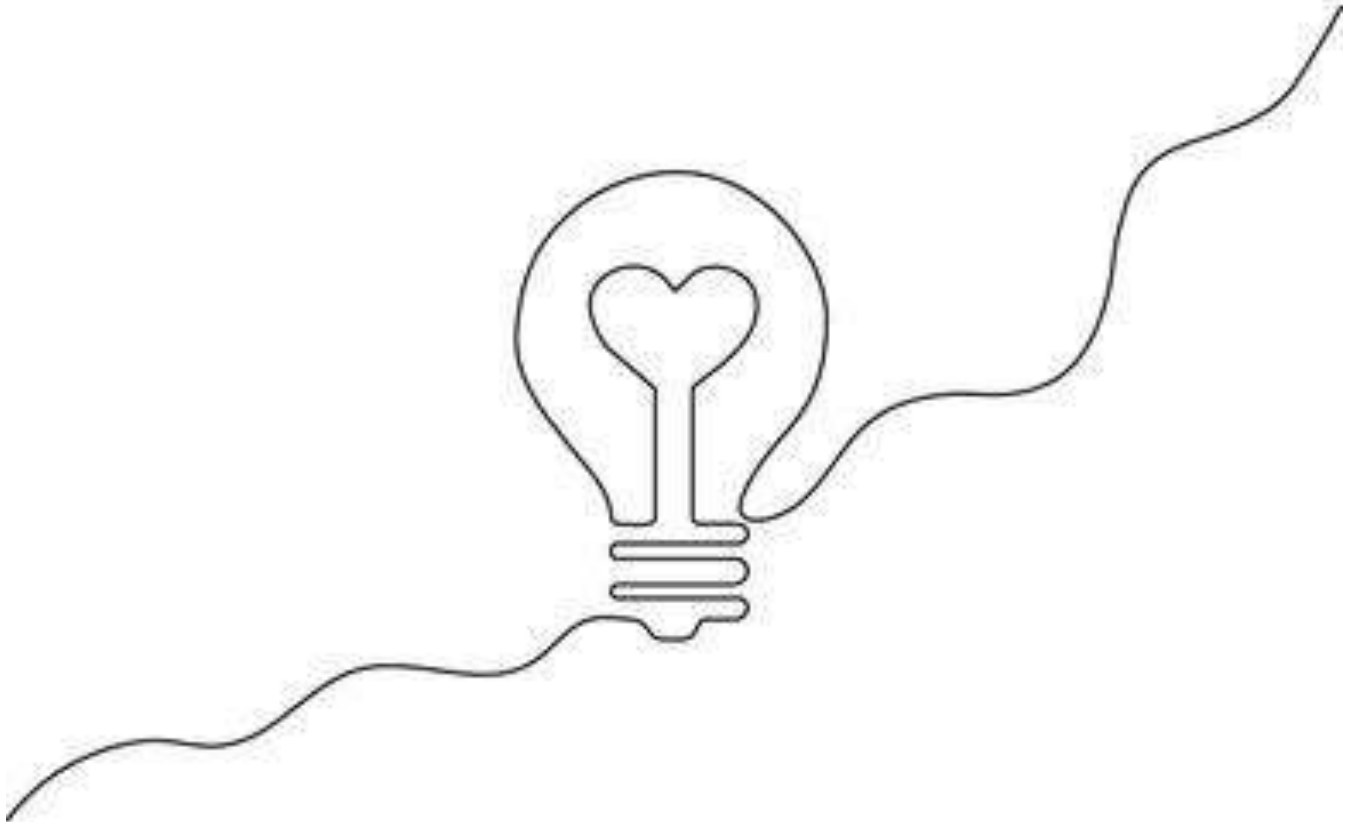
Parameters	0.55T	1.5T
TE/TR [ms]	5.81/9.25	2.99/4.80
Scan time [min:sec]	17:50	9:15
Spatial resolution [mm <sup>3</sup> ]	2.5x2.5x2.5	2.5x2.5x2.5
VENC [cm/s]	150	150
Gradient amplitude/slew rate	26mT/m, 45mT/m/ms	45mT/m, 200mT/m/ms



# La translation: 5D flow



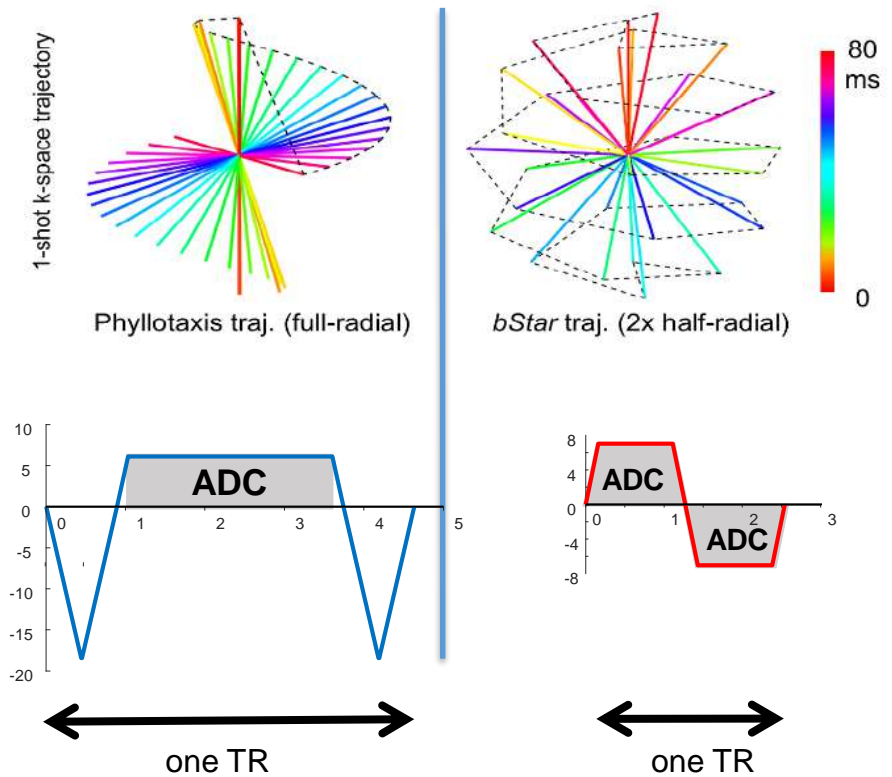
# L'innovation



# L'innovation: cardiac bStar free-running

- bStar (1) :
  - « **duty-cycle** » multiplié par deux
  - **deux échos** dont un temps d'écho ultra-court (UTE)
  - **TR court** (moins d'artefacts de bande bSSFP)
- Inconvénients :
  - faible densité des **hautes fréquences** de l'espace-k
  - sensibilité élevée aux **imperfections des gradients**

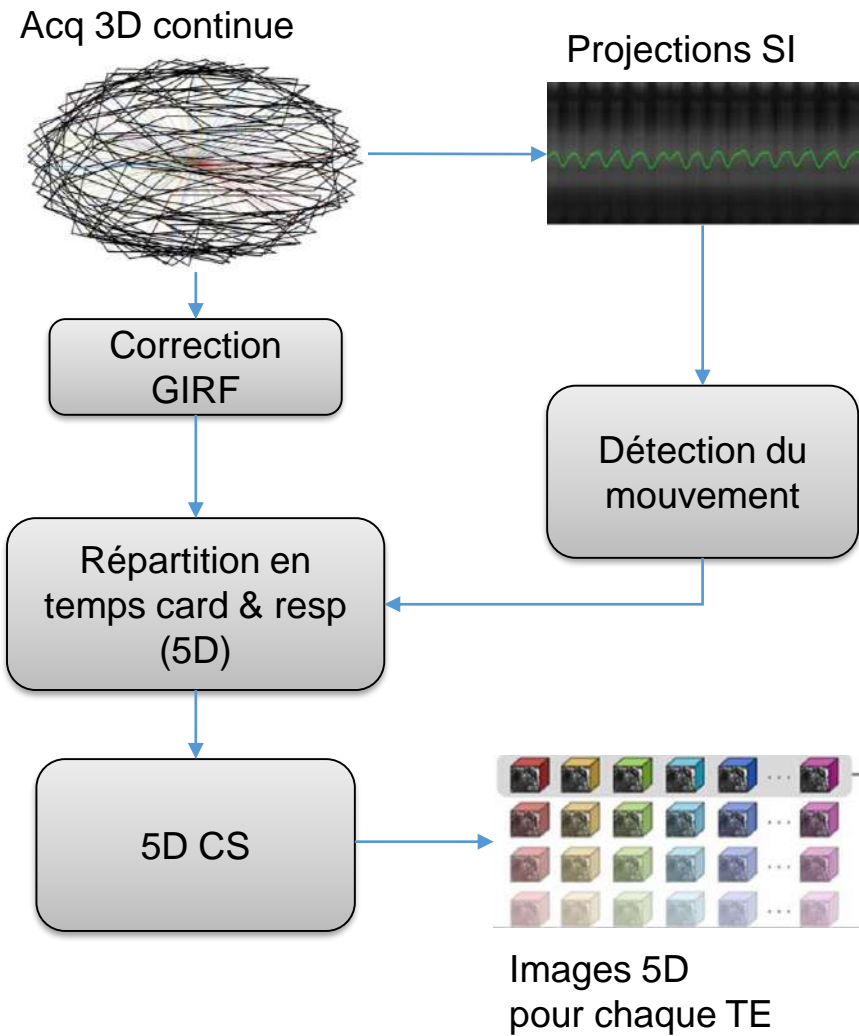
Séquence bSSFP	Cartésien	Radial (phyllotaxis)	bStar (400Hz/px)
eff. tmps( $\delta$ )	0.40	0.40	0.75
eff. Kspace ( $\eta$ )	1	0.75	0.30
Eff. Tot. ( $\delta * \eta$ )	0.4	0.3	0.26



$$\delta = \frac{\tau_{ADC}}{TR}$$

$$\eta = \frac{V}{\sqrt{\int^V D \int^V 1/D}}$$

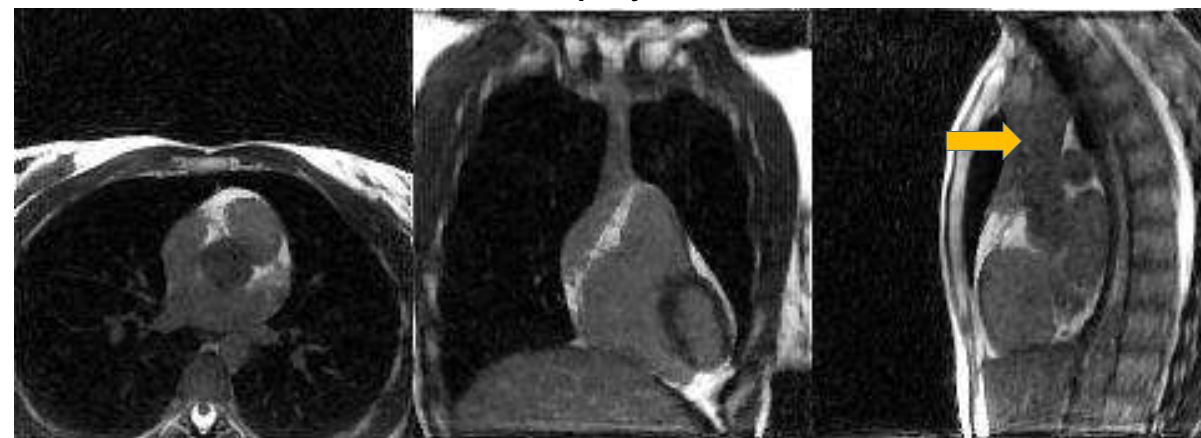
# L'innovation: cardiac bStar



- **bStar réduit les artefacts de bande & inhomogénéité B0**
- **Des artefacts de flux avec bStar**



Radial phyllotaxis



bStar

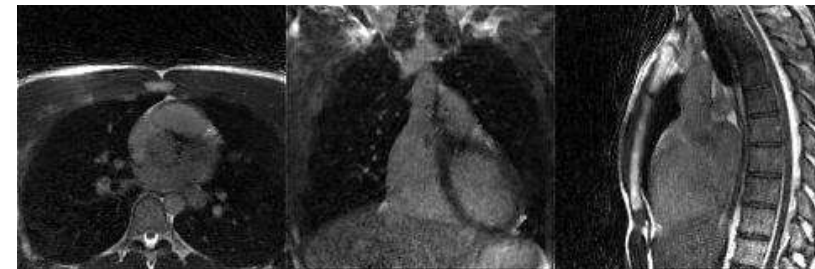
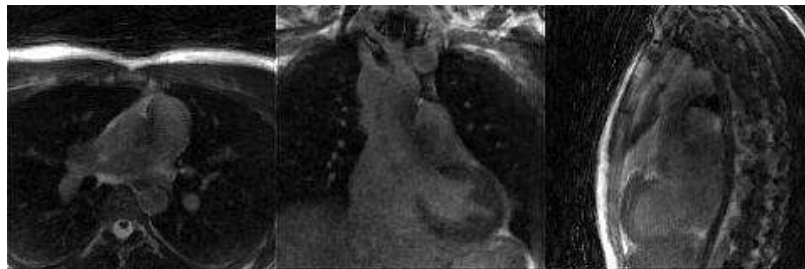
# bStar & phyllotaxis free-running: Résultats in vivo

Volontaire 01

Vol 02

Vol 03

Phyllo



bStar



Vol 04

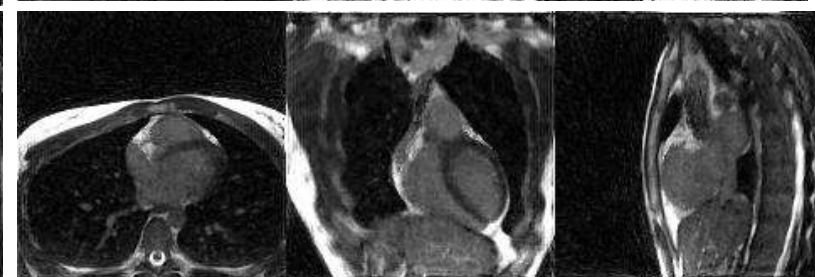
Vol 05

Vol 06

Phyllo



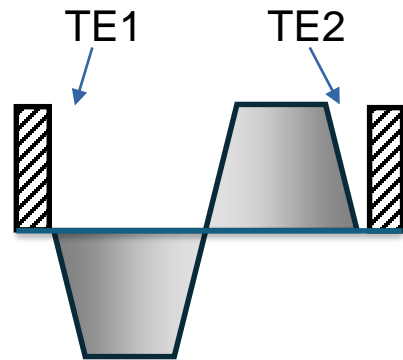
bStar



# L'innovation: cardiac bStar

bStar possède 2 temps d'échos:

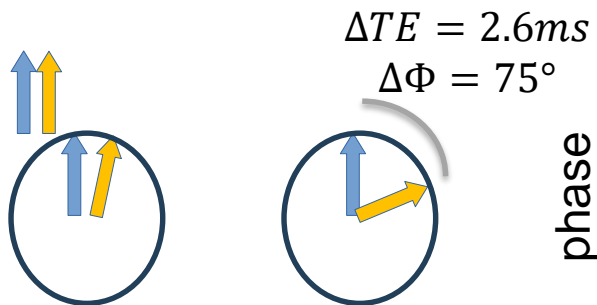
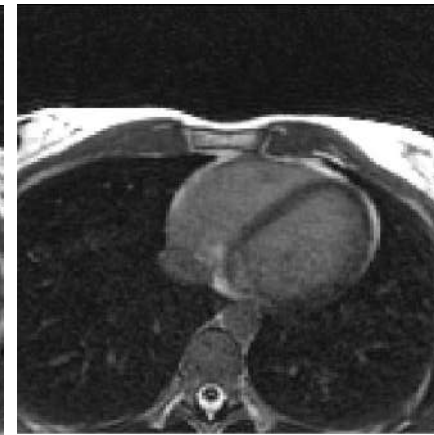
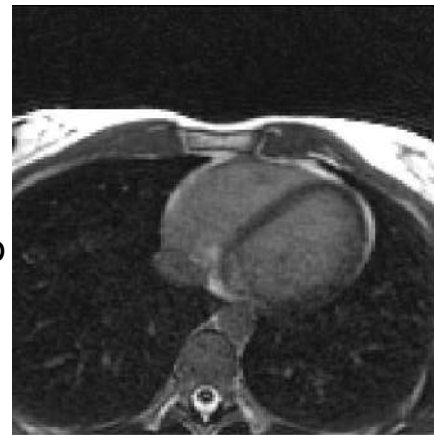
>> peut-on séparer l'eau et la graisse??



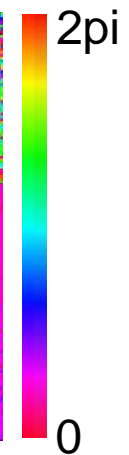
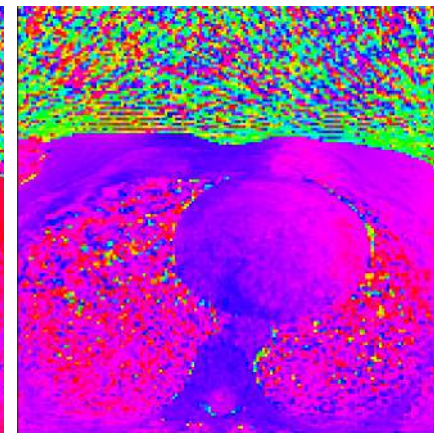
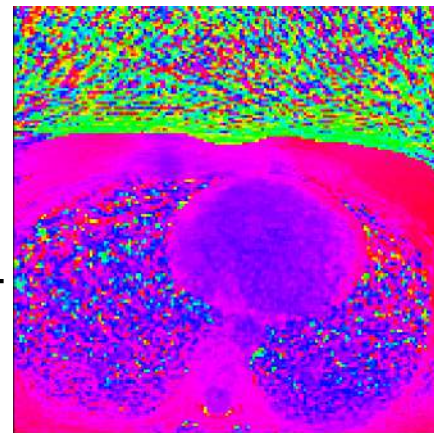
TE1 – 0.2ms

TE2 – 2.8ms

magnitude



phase



0

2pi

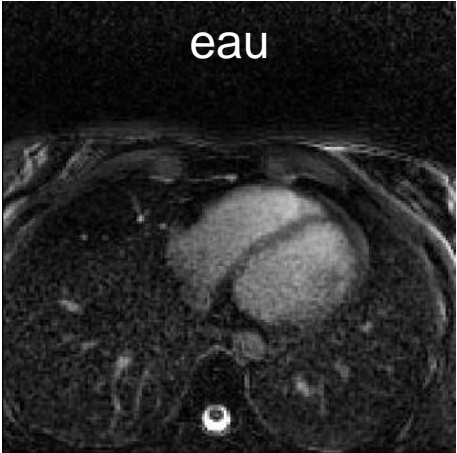
# bStar : adapter la separation eau-graisse à bas champ!

A bas-champ, nous pouvons faire quelques **hypothèses** :

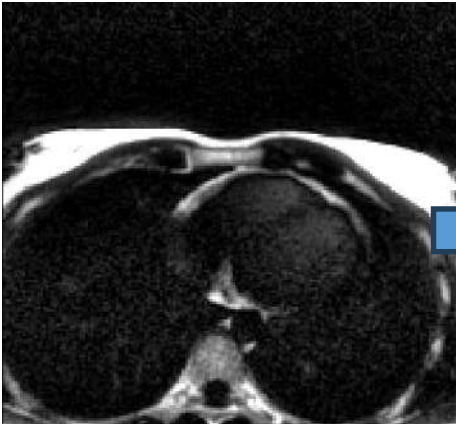
- L'horizon fréquentiel bStar est plus grand que toute hors-résonance:  $(\Delta f_0 + CS) < 1/\Delta TE$
- Intensité de la graisse > intensité de l'eau
- Les voxels de graisse ont une phase qui ne dépend QUE du décalage chimique et B0
- Il y a assez de tissu adipeux dans le champ de vue thoracique

$$I_{fat} = I_{TE1} - I_{TE2} * \exp(-i\Delta f_0 \Delta TE)$$

$$I_{water} = I_{TE1} + I_{TE2} * \exp(-i(\Delta f_0 + CS)\Delta TE)$$



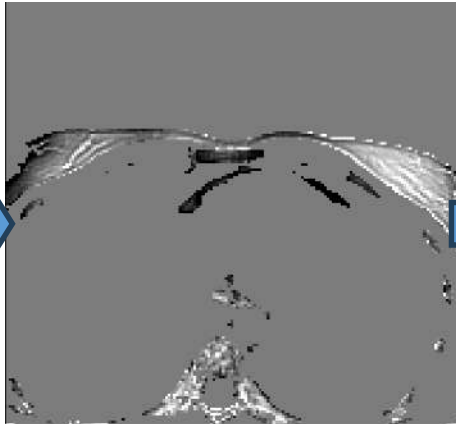
eau



1<sup>ère</sup> estimation graisse



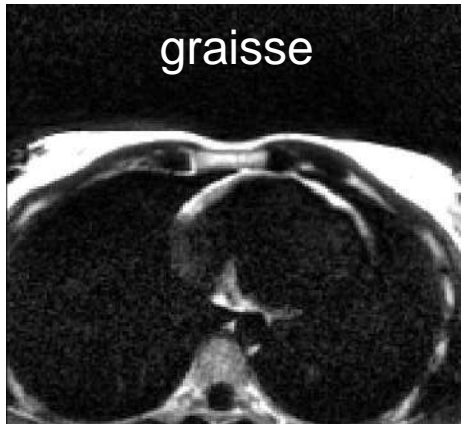
Masque de la graisse



B0 dans la graisse



B0 interpolé et lissé



graisse

Séparation eau-graisse avec B0

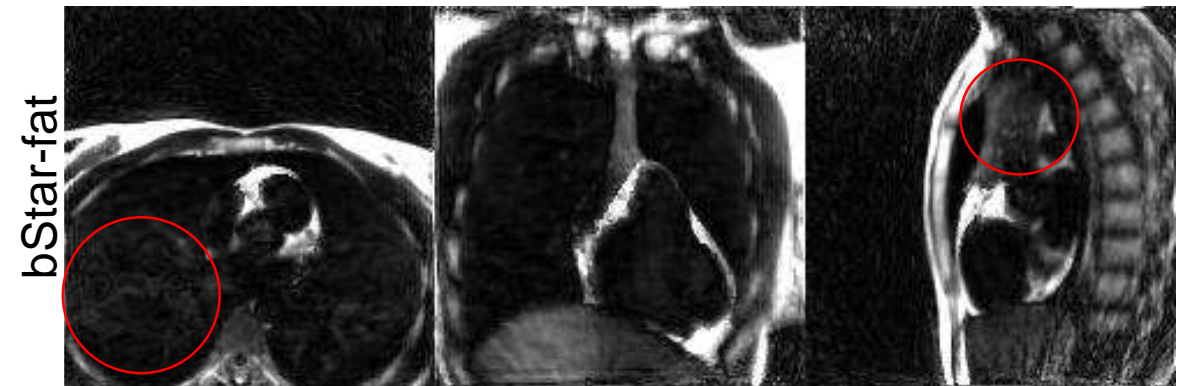
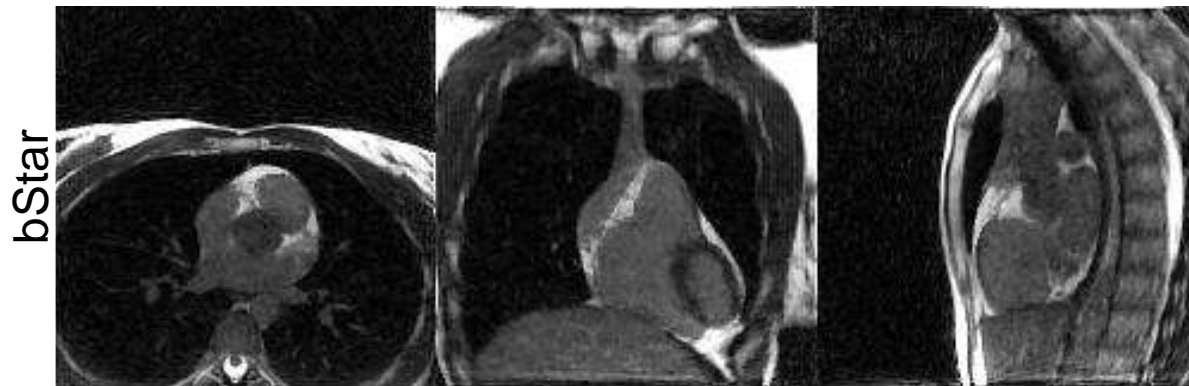
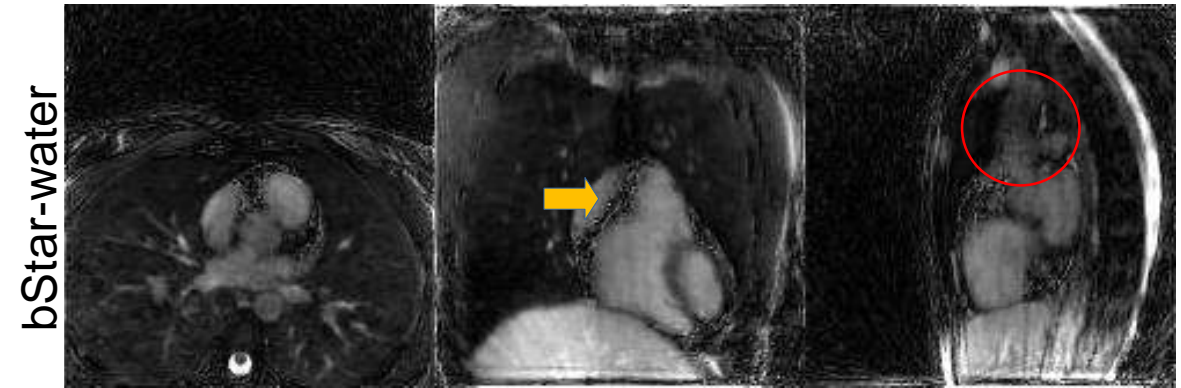
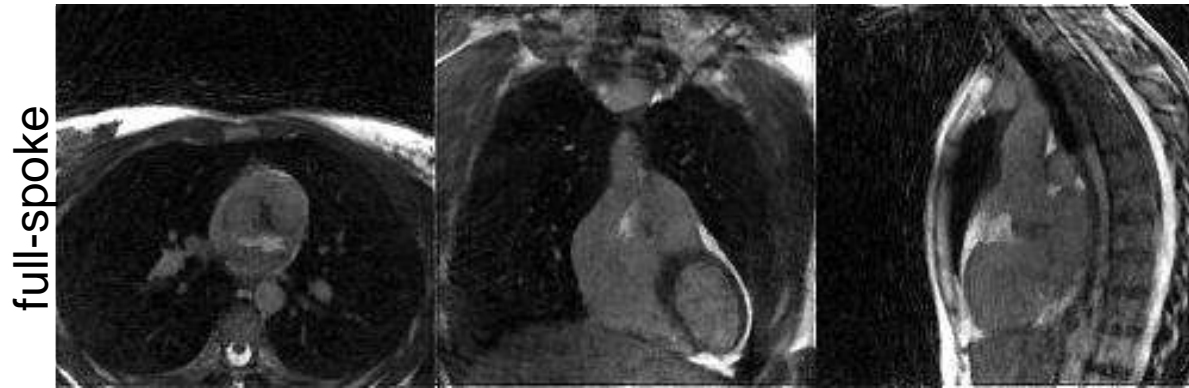


17  $I_{fat} = I_{TE1} - I_{TE2}$

$\Delta\phi = (\Delta f_0 + CS) * \Delta TE$

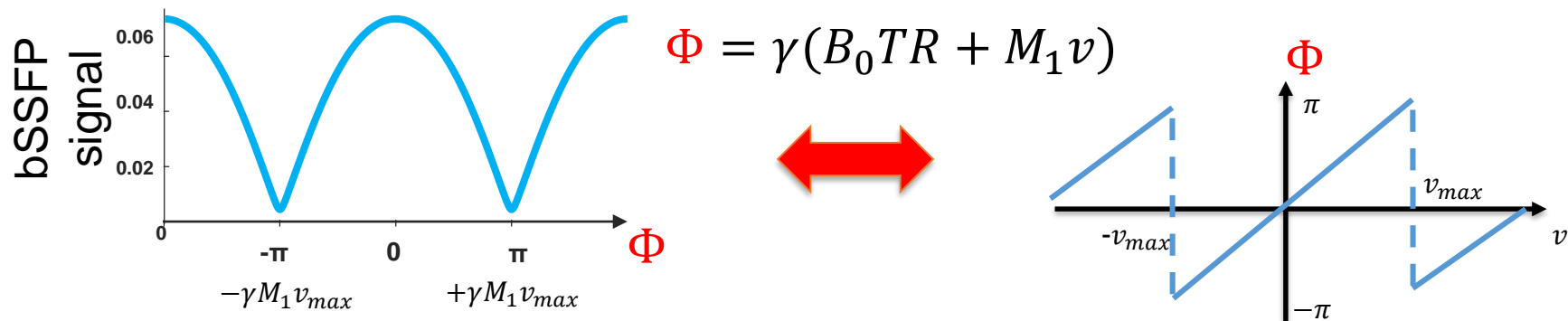
## bStar free-running: 3D + temps c&r + eau-graisse en 6min à 0.55T!

- Loin d'être parfait, la technique semble prometteuse:
  - Les images d'eau restent bruitées / artefactées par du **streaking**
  - Des **artefacts de flux** causent une perte de signal et une inversion eau-graisse (aorte, poumons)

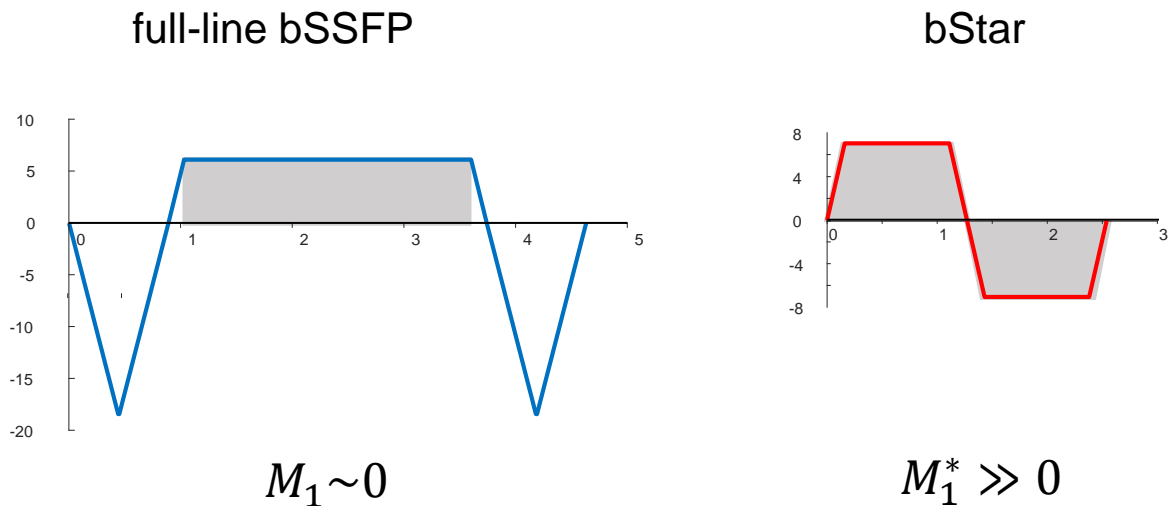


# L'innovation: cardiac bStar v2

- Le signal bSSFP dépend de la phase accumulée à chaque TR:

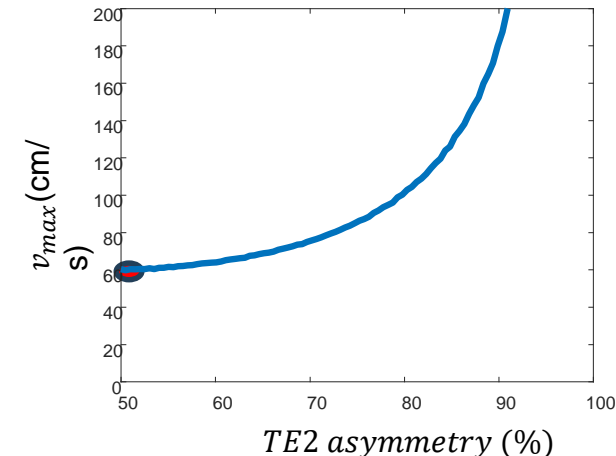
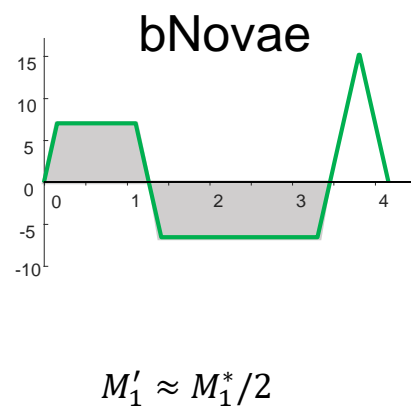
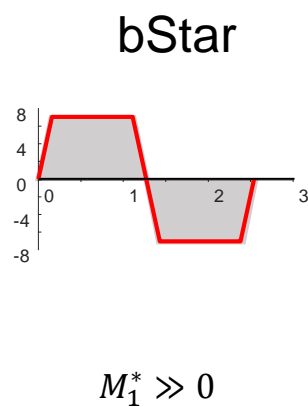
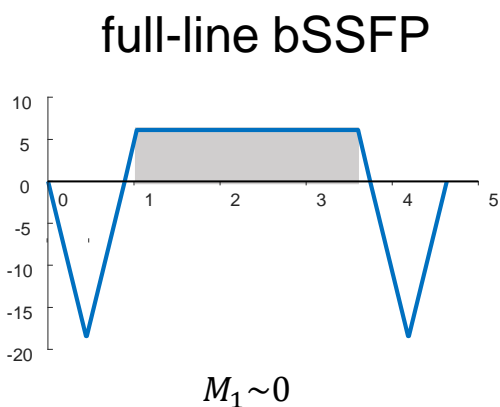


- A l'inverse du bSSFP standard, bStar est très sensible au flux!!



# L'innovation: cardiac bNovae

- bStar 2<sup>nd</sup> echo was extended to achieve velocity banding > 200 cm/s
- The 3 FRF flavors were implemented in Pulseseq[2] on a commercial low-field MRI (26mT/m, 45T/m/s), with self-nav Compressed Sensing reconstruction[1]



Resolution=(1.5 mm)<sup>3</sup>      BW = 390 Hz/px  
 FOV=(240 mm)<sup>3</sup>      FreeMax gradients

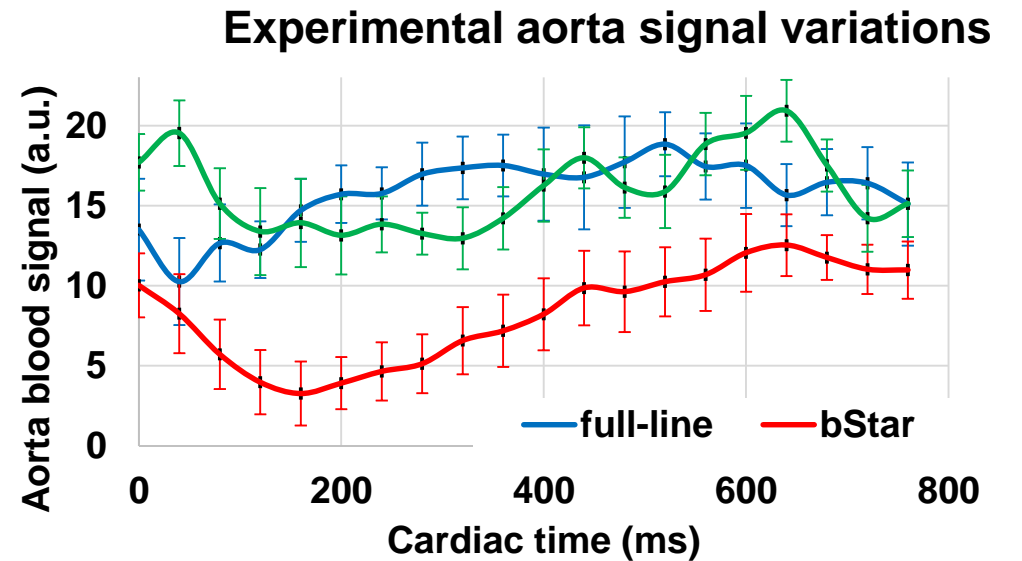
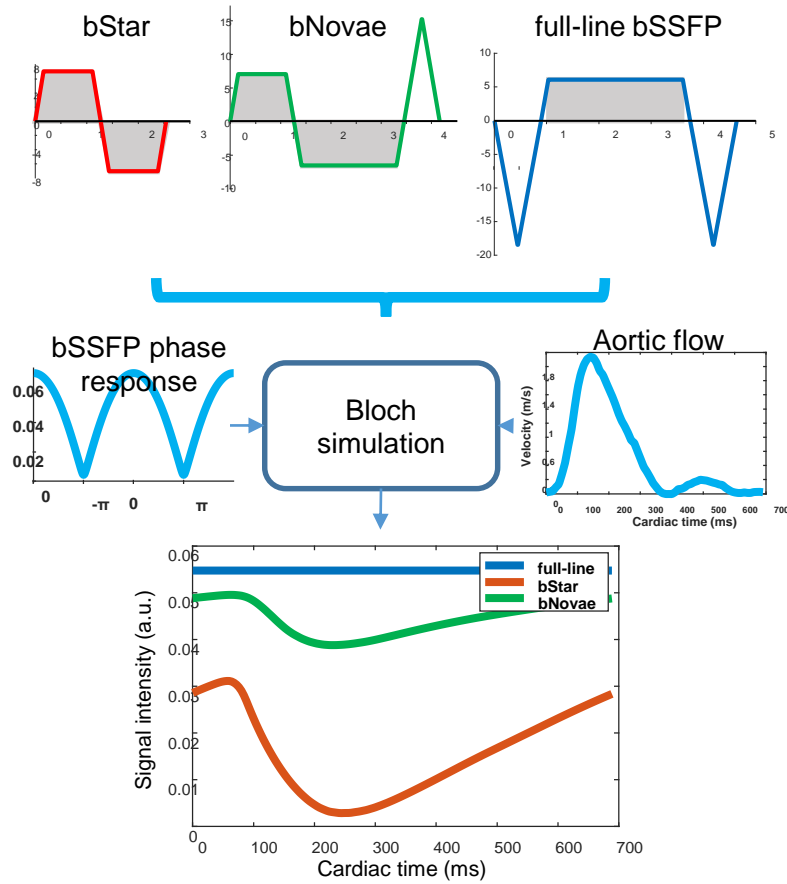
	full-line FRF	bStar FRF	bNovae FRF
TE/TR (ms)	2.7 / 5.4	0.4, 2.8 / 3.3	0.4, 3.7 / 5.1
FOV (mm <sup>3</sup> )	250 x 250 x 250		
Spatial res. (mm <sup>3</sup> )	1.5 x 1.5 x 1.5		
Total duration (min)	6:00		
Resp. x cardiac phases	4 x 20		
Duty cycle (=ADC/TR, %)	44	73	64

[1] Di Sopra, Piccini, et al. 2019. MRM

[2] Layton et al. 2017. MRM

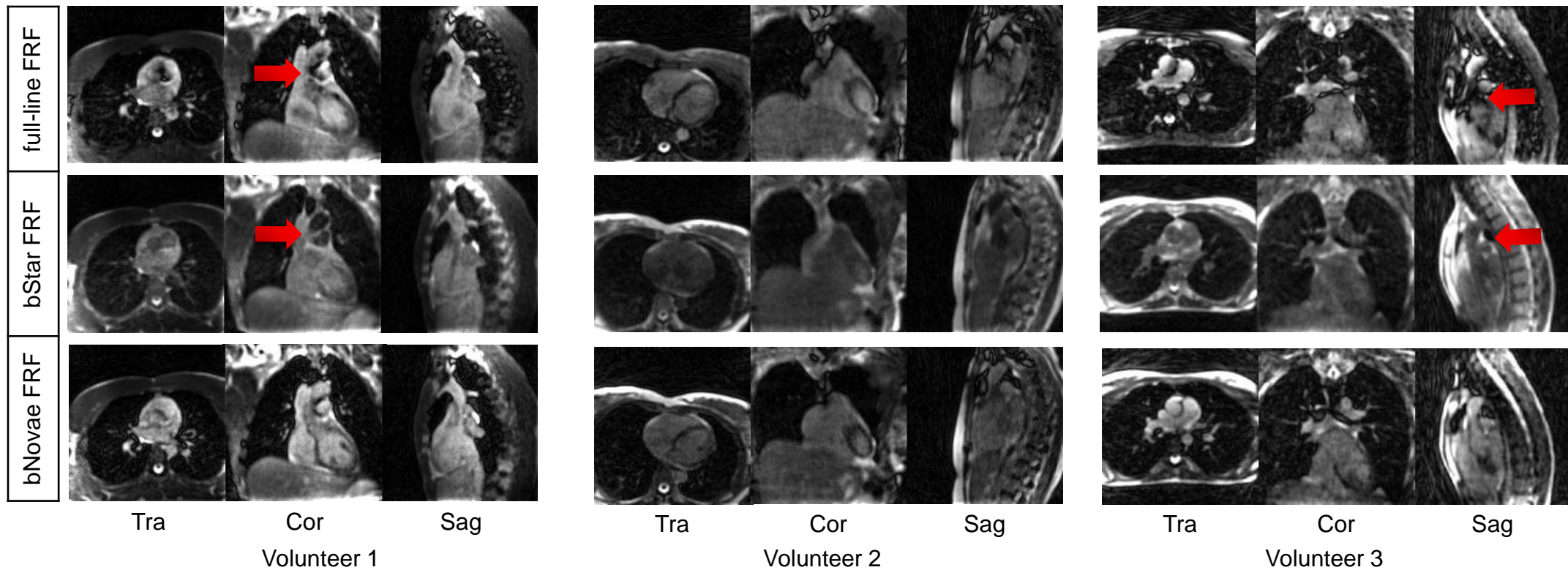
# L'innovation: cardiac bStar

- In the aorta, the average intensity loss improved from 51% (47% in simulation) for bStar to 7% (3% simu) for bNovae compared to full-line.



# L'innovation: cardiac bStar

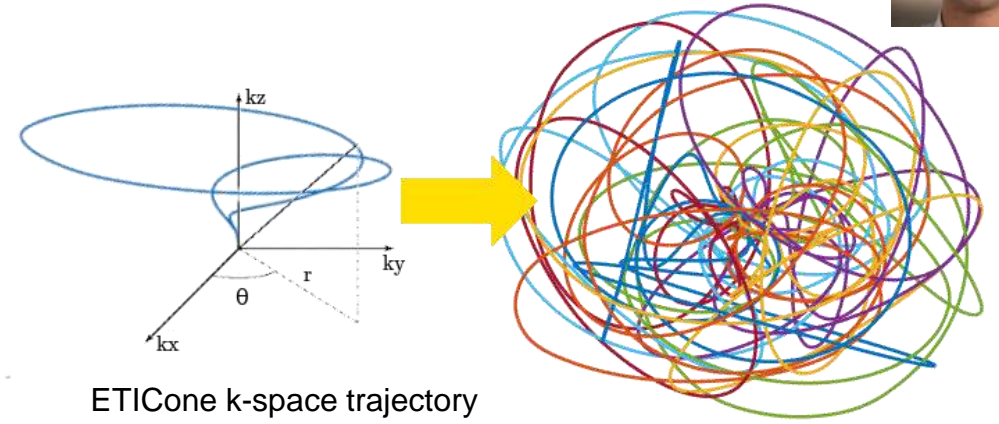
- Minimum blood-myocardium contrast was 51%, -33% and 46% for full-line, bStar and bNovae resp.
- Future extensions to free-running dual-echo bSSFP :
  - fat-water imaging - cardiopulmonary MRI



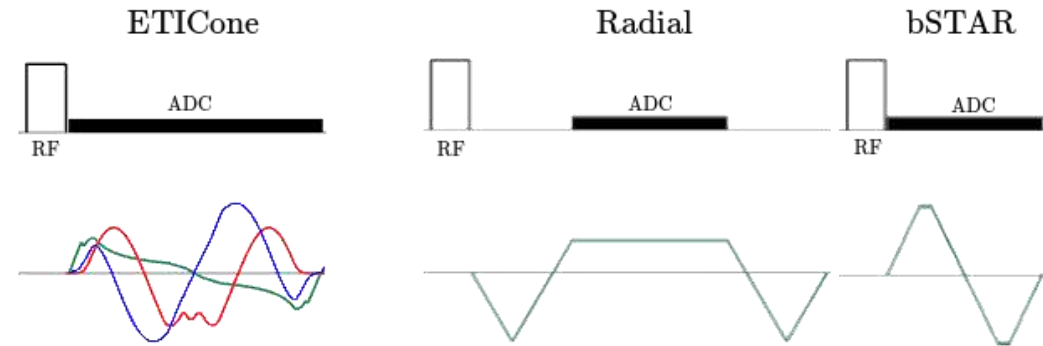
# L'innovation: cones 3D



- Like spirals outperform 2D radial...
- **ETICone : Dual-Echo Time Cone trajectory**
  - Center-out / center-in cone readout
  - Trajectory optimized by minimizing **PSF peak-to-sidelobe ratio (PSR)**
  - Additional gradients for M1 compensation
- **Implementation**
  - ETICone, radial and bSTAR implemented in **Pulseseq<sup>4</sup>**
- **Free-running reconstruction**
  - 6 min acquisition
  - 20 cardiac x 4 respiratory bins
  - GIRF correction
  - Self-gating signal from k-space center
  - 5D Compressed-sensing



ETICone k-space trajectory



	ETICone	Radial	bSTAR
TR (ms)	4.90	5.25	2.64
TE1/TE2 (ms)	0.29/3.75	2.63	0.28/2.28
res (mm)		1.5	
TA (min)		6:00	

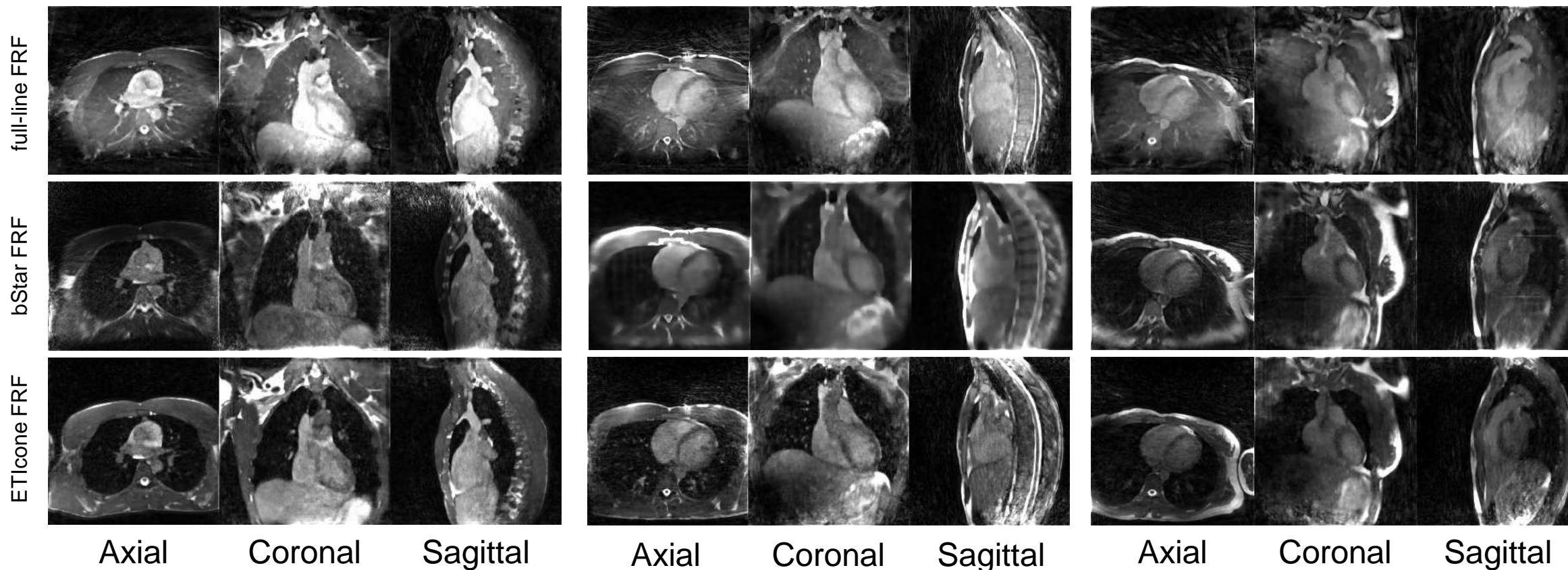
<sup>4</sup>Layton, MRM, 2017  
Nicoletti et al. SCMR 2026

# L'innovation: cones 3D



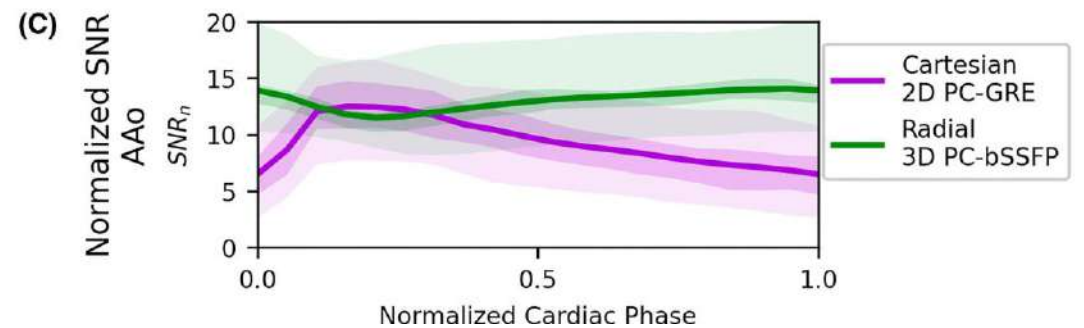
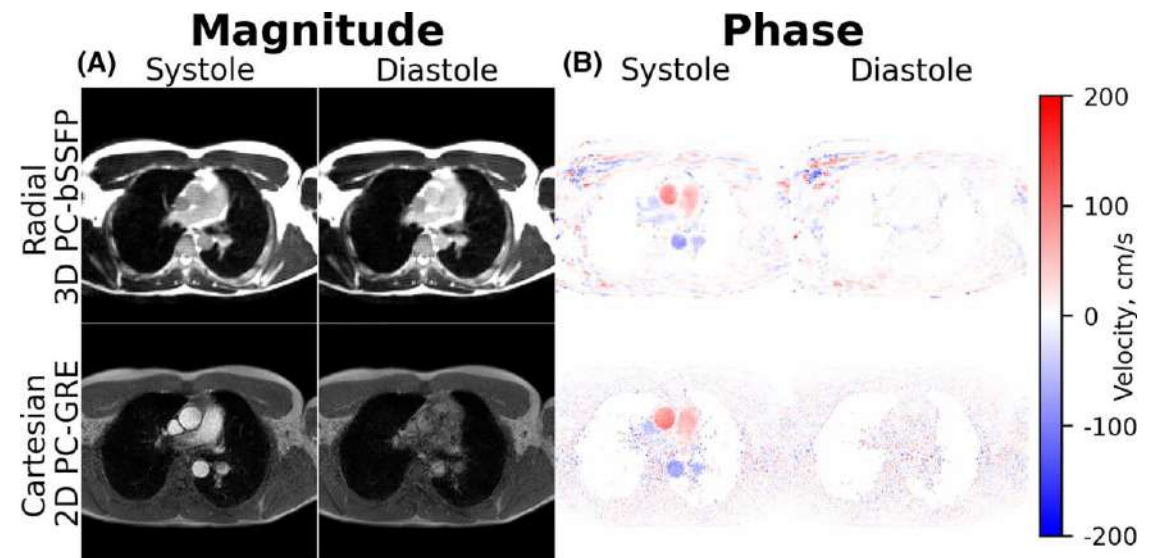
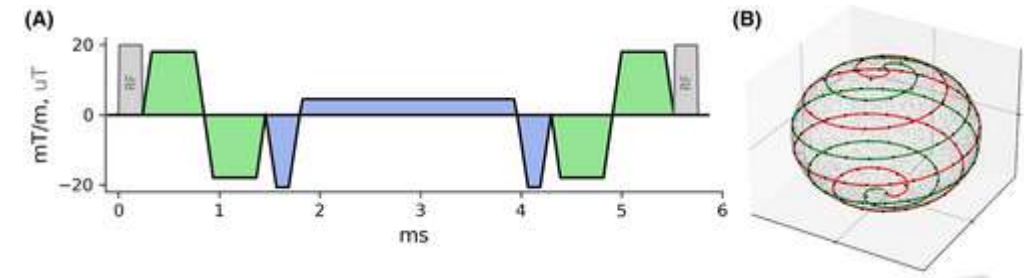
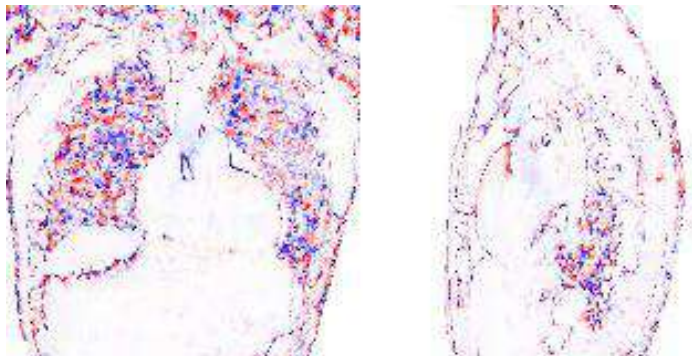
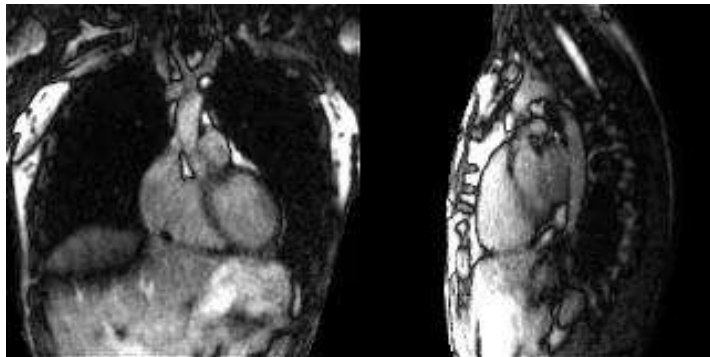
Proposed Free-Running ETICone:

- **Reduced coherent aliasing**
- Enhanced **image quality** (+10% sharpness over radial, +15% over bStar)



# L'innovation: Phase-contrast bSSFP

- Phase-Contrast bSSFP:
  - TR étendu sans (trop d') artefacts de bande
  - SNR ++
  - « 2 en 1 »: flux et anatomie



# Les perspectives



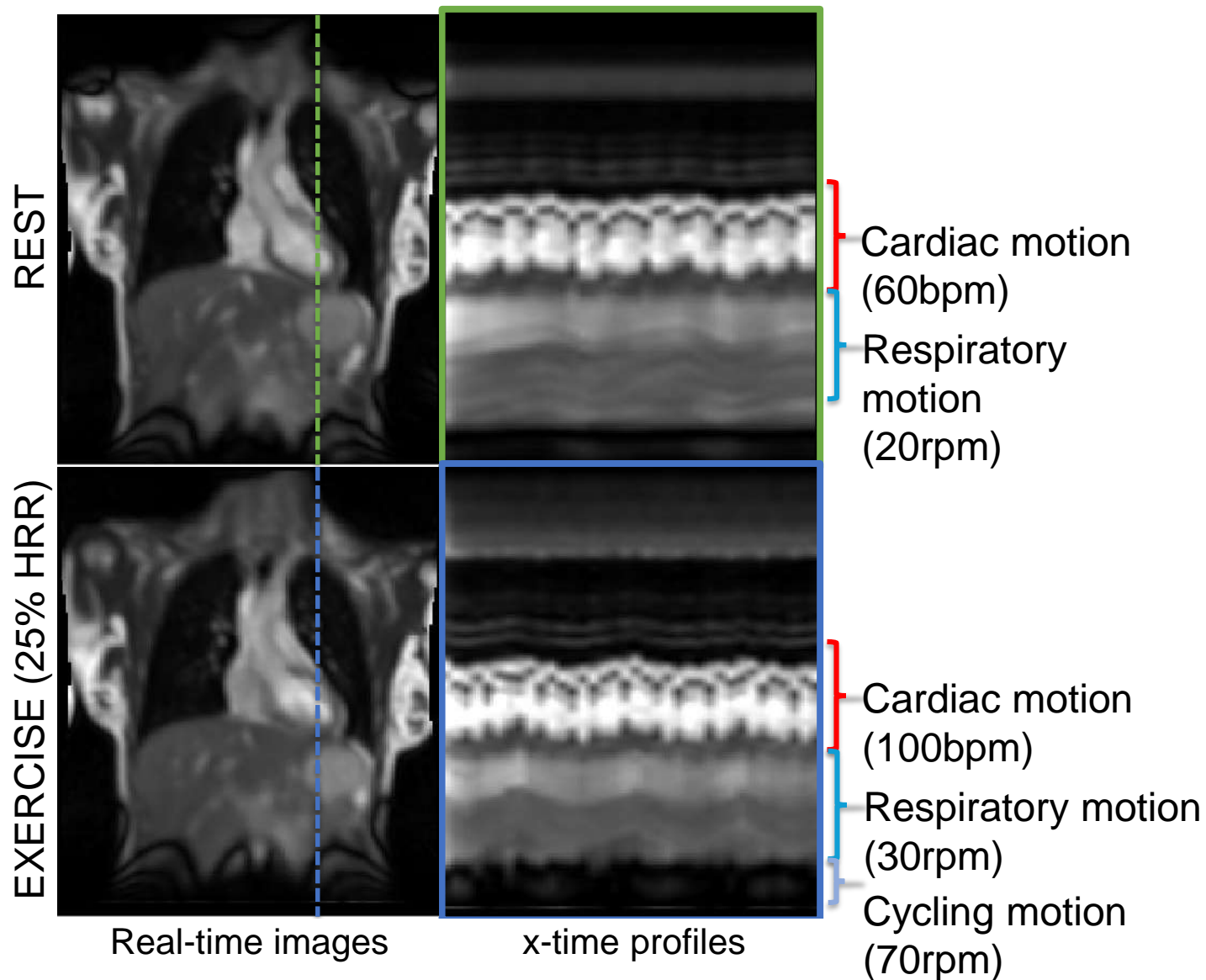
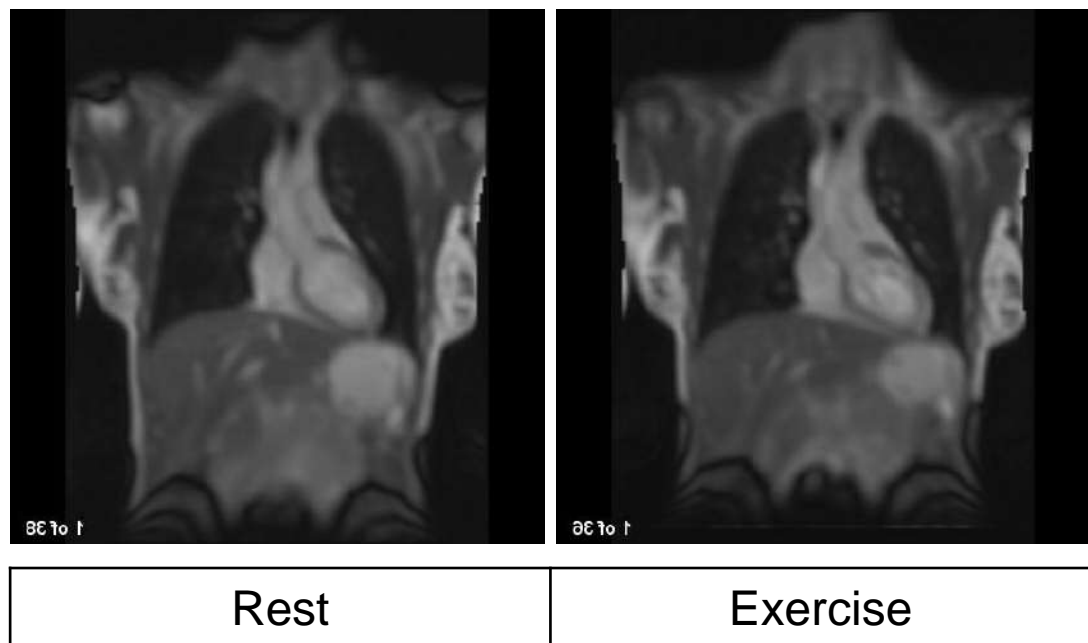
# Une perspective: IRM cardiaque de l'exercice

- Freemax & Cycling ergometer: the perfect fit!



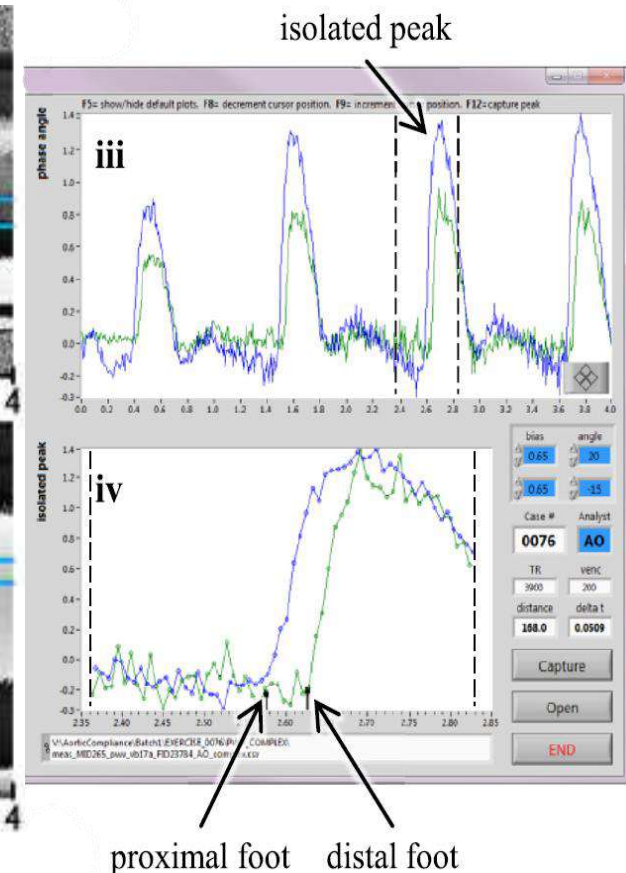
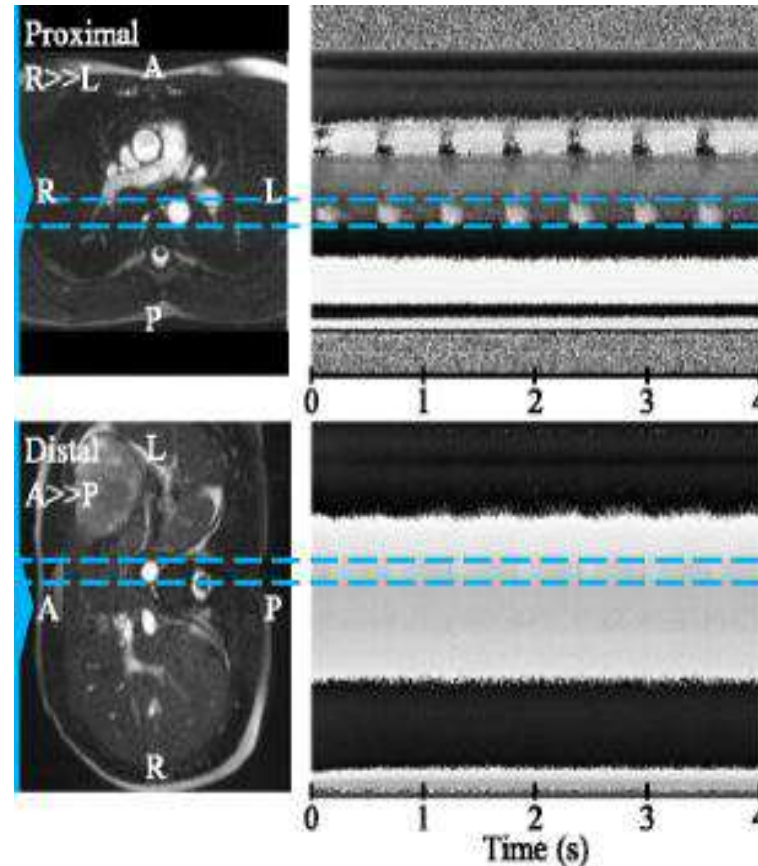
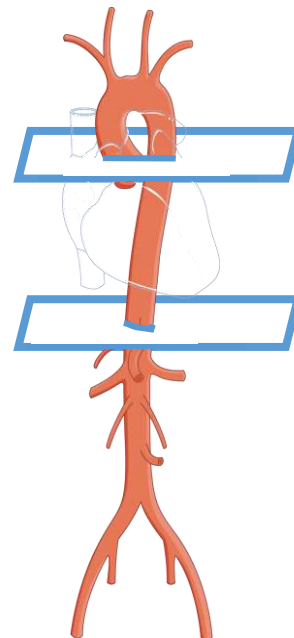
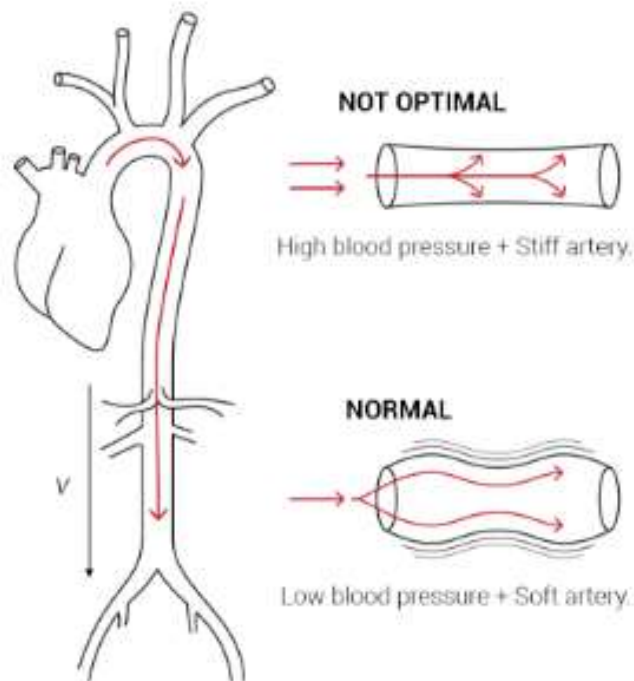
# Les perspectives: IRM cardiaque *pendant* l'exercice

- Real-time imaging is readily available at the scanner



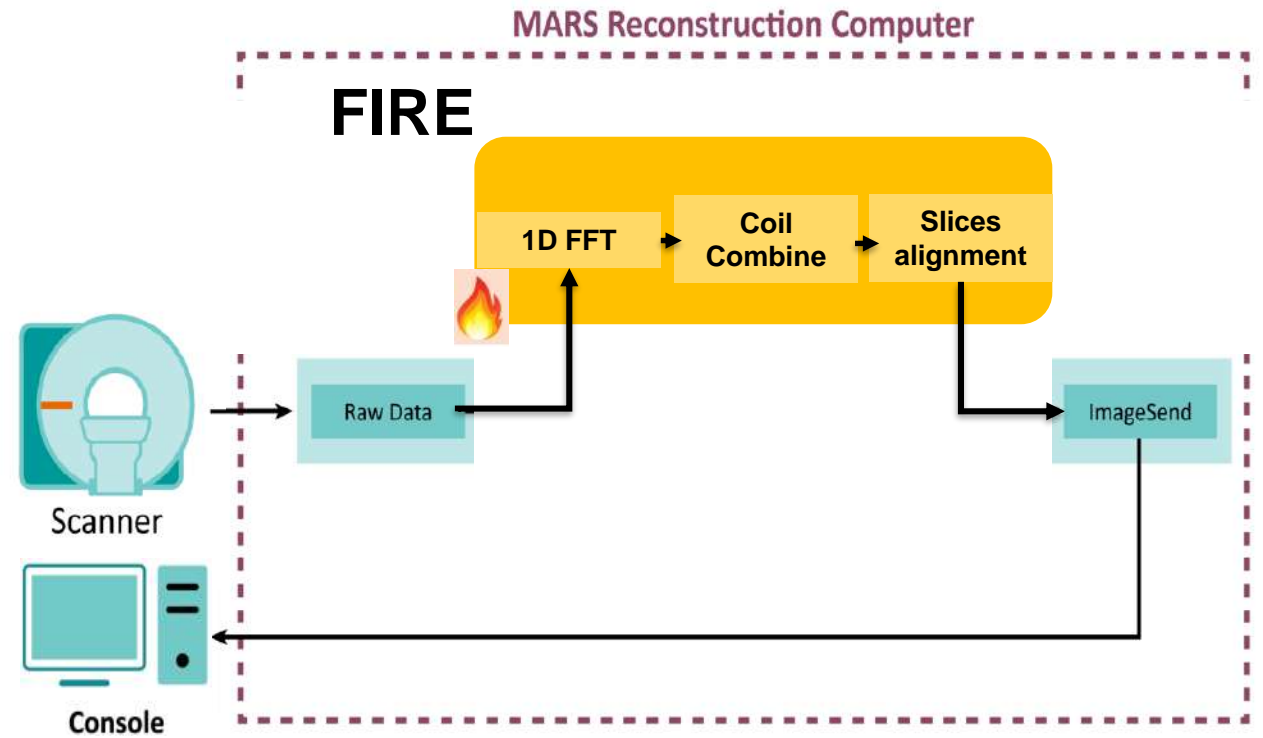
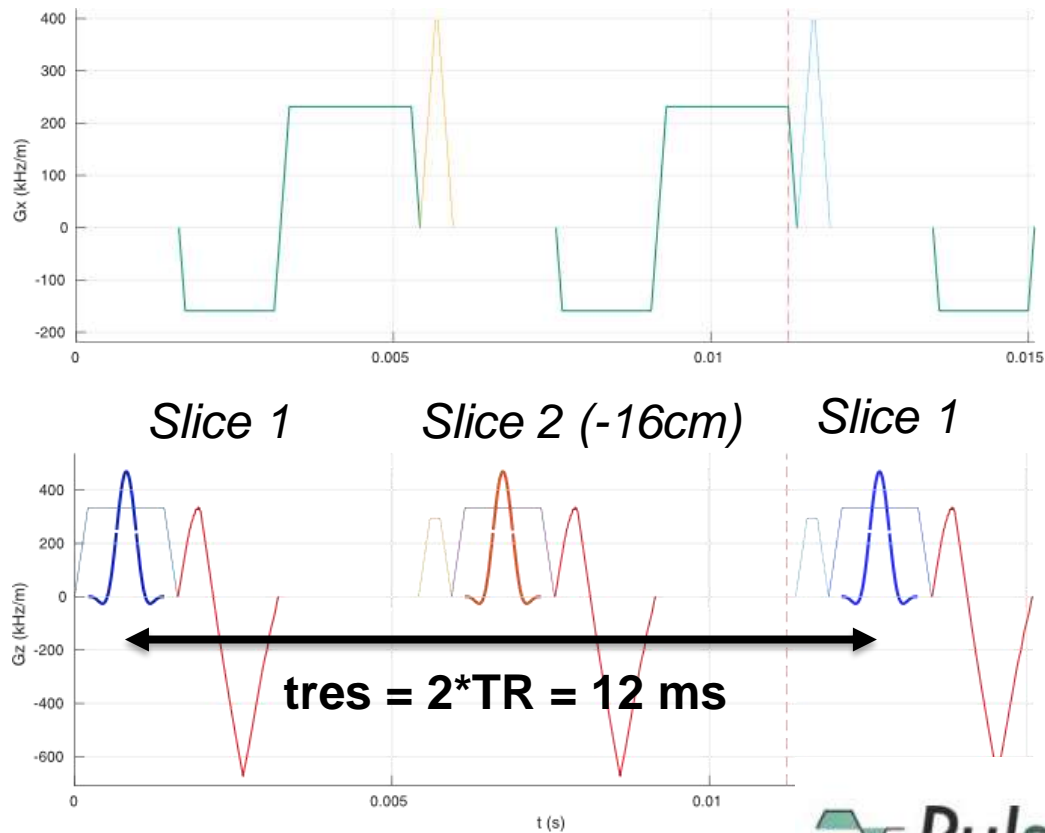
# Les perspectives: mesure de la vitesse de l'onde de pouls (PWV)

- Mesure de la vitesse de l'onde de pouls (pulse wave velocity: PWV)
  - 2 points de mesure distants sur l'arbre vasculaire
  - $PWV = Dz / Dt$  ( ~300-800 cm/s!! )



# Exercise MRI: implementing PWV M-mode

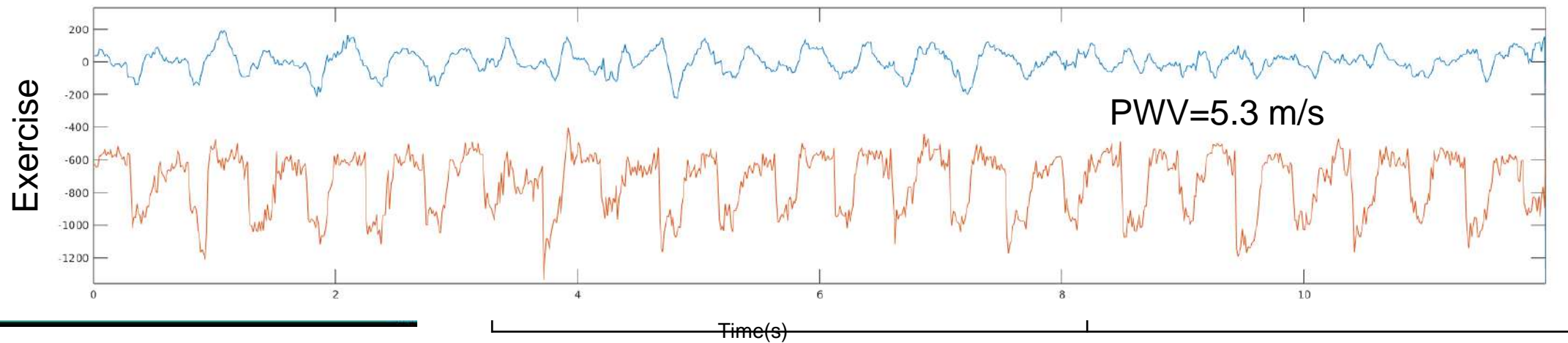
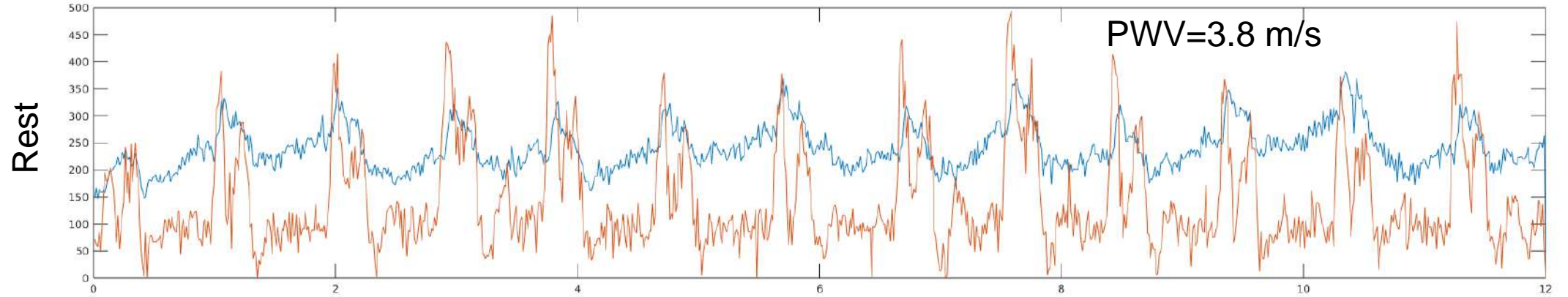
- Roadblocks to build PWV: a sequence (Pulseq) + a reconstruction (FIRE)



# Exercise MRI: PWV

- Resultats

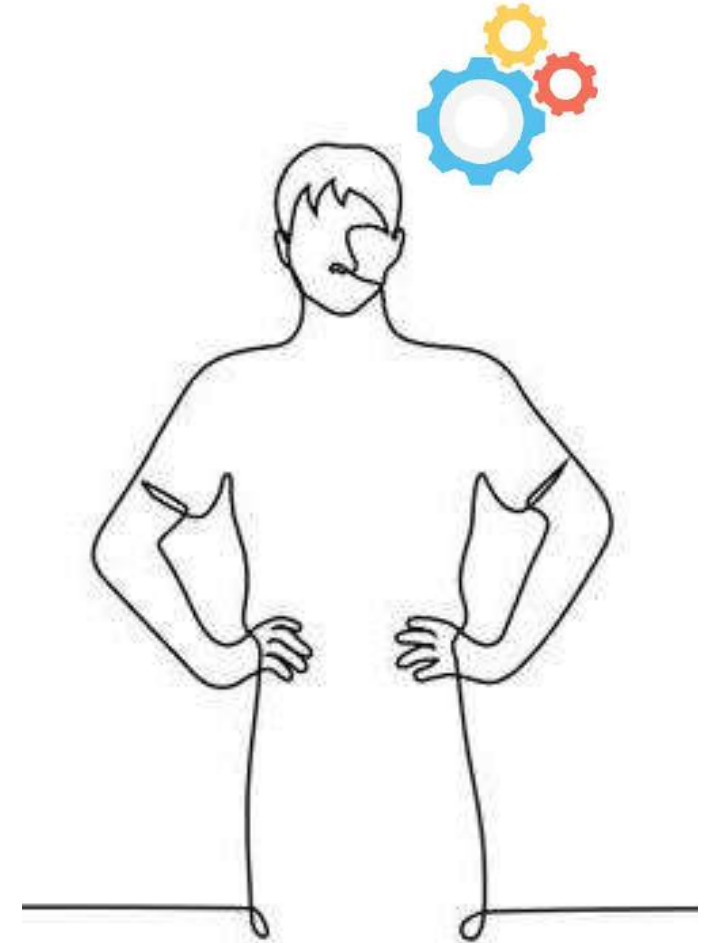
— Thoracique  
— Abdominal



Time(s)

# Est-ce que le Freemax est une IRM cardiaque??

- Non
- Mais:
  - Possible, motivé pour les patients obèses ou ayant des implants, pour un accès facilité
- Contraint par les gradients principalement
  - ECG et SNR dans une moindre mesure
- Des opportunités sont à construire:
  - 4D/5D free-runningS / Flow bSSFP
  - IRM de l'exercice
  - Interventionnel ??



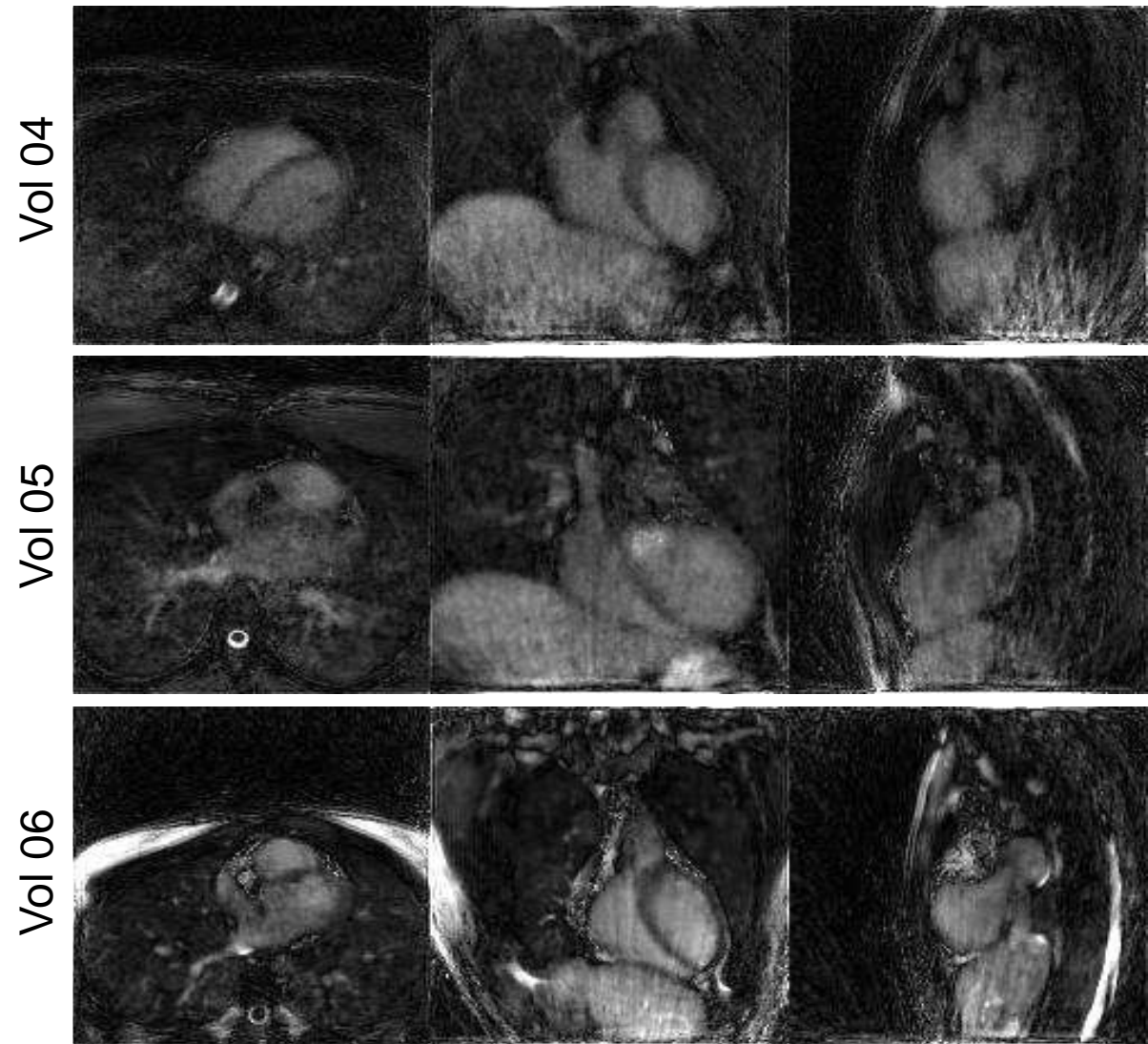
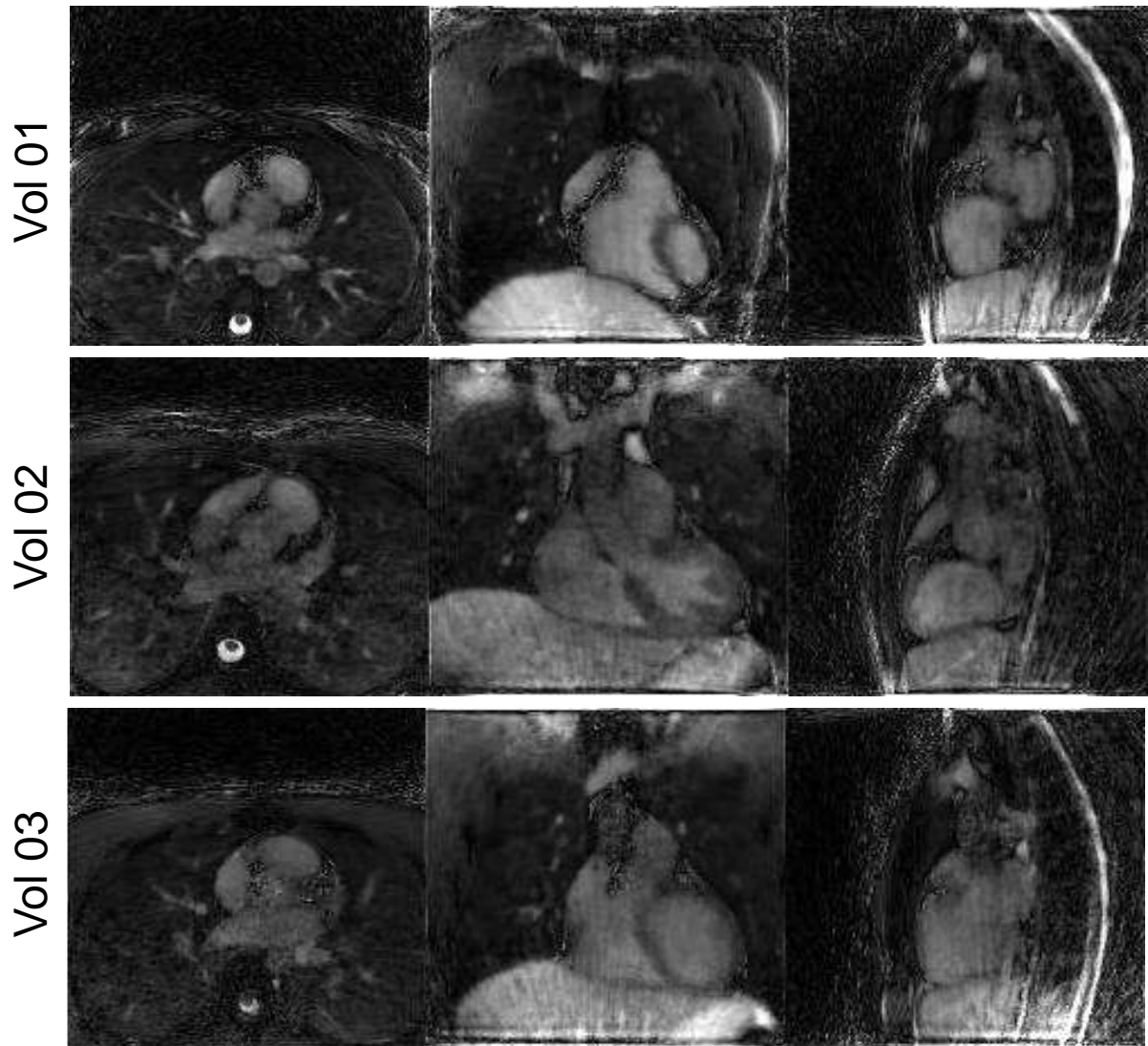
# Challenge me! Questions??



# Extra slides

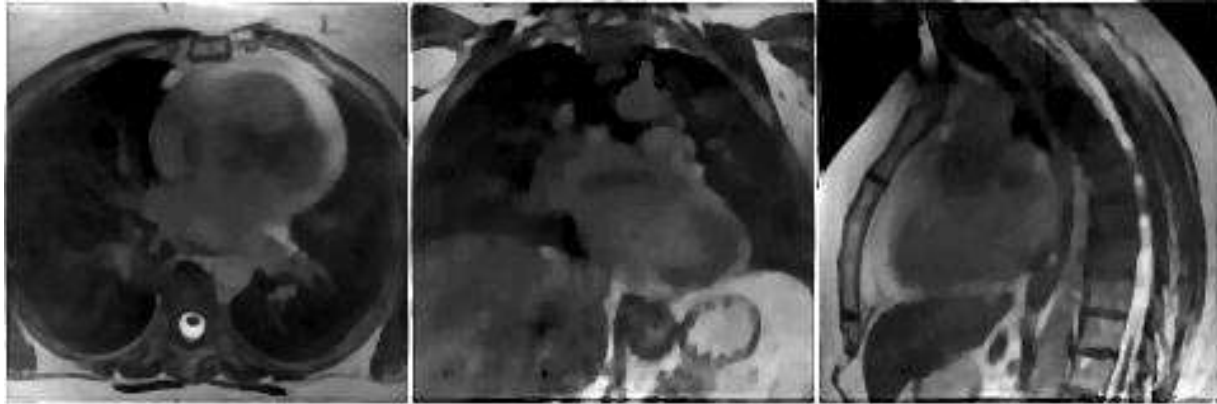
# bStar: fat-water free-running in 6min at 0.55T!

- With some limitations : streaking, flow, swaps artifacts

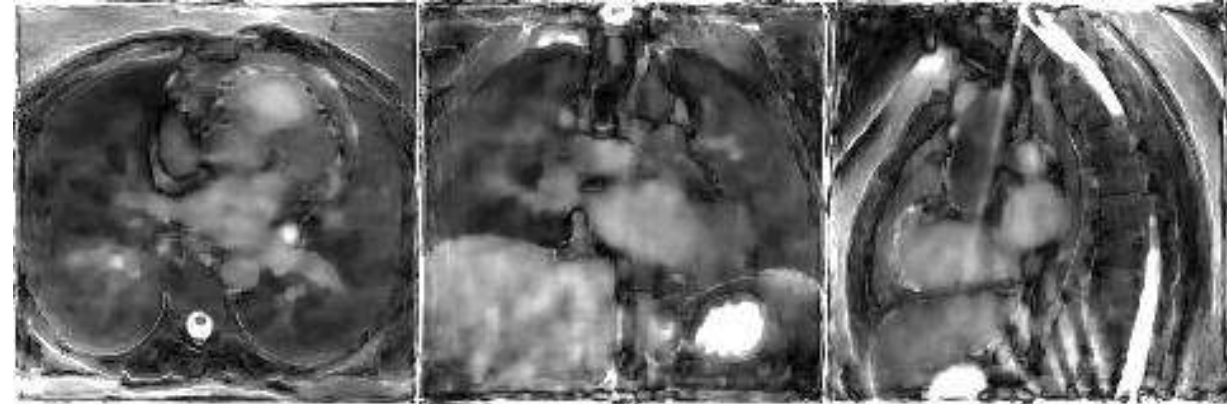


# bStar: fat-water free-running in 6min at 0.55T!

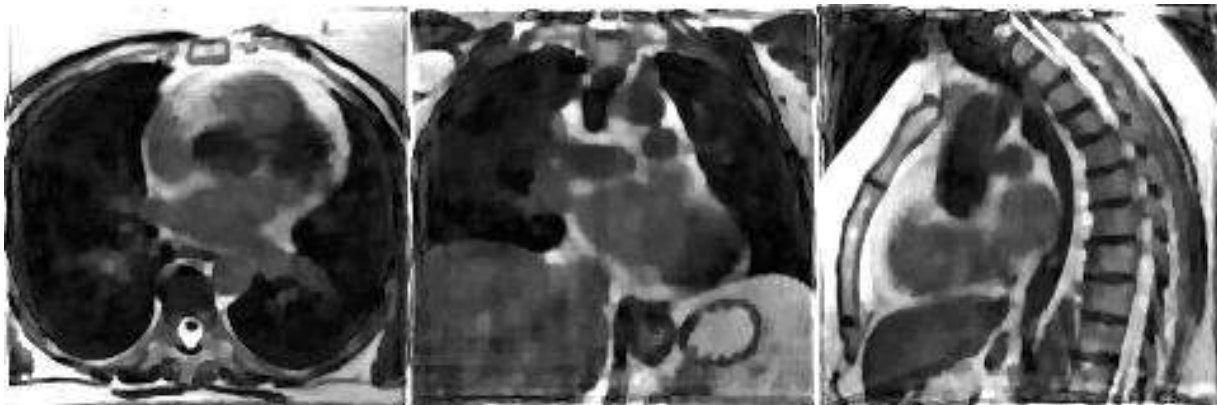
- Volontaire obèse (femme, 97kg, 158cm)



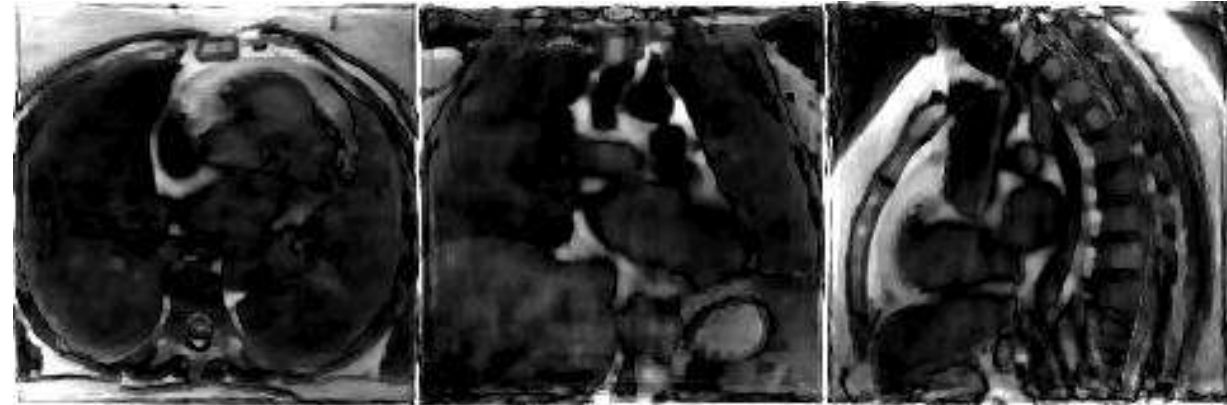
Phyllotaxis



eau



bStar



graisse