

# The challenges of imaging with low-field and low-cost MRI scanners

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C.J. Gorter  
MRI Center



Leids Universitair  
Medisch Centrum



## Conflict of Interest



NO



YES



# Contents

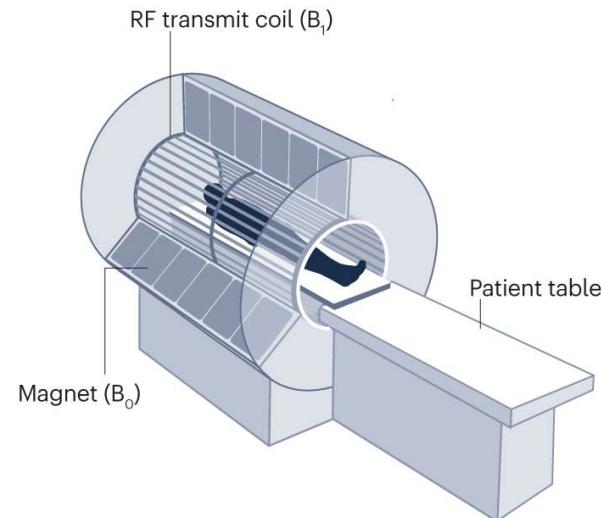
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- What is Low-Field MRI?
- How can we use Low-Field MRI?
- The challenges
- Where are we?
- Conclusion



# MRI scanners

**a Solenoid electromagnet**



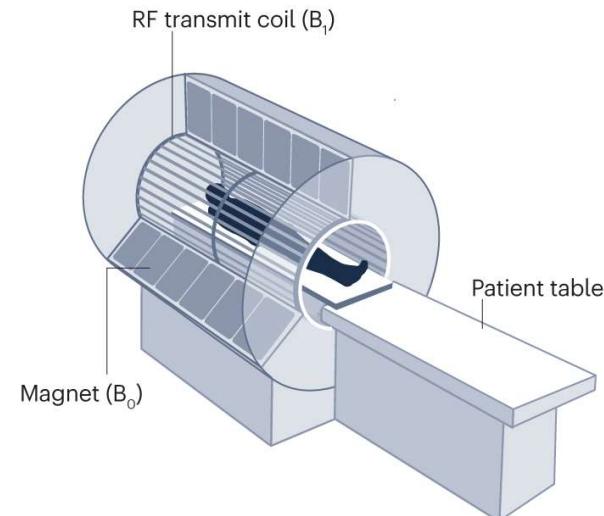
**Magnet cooling:** Typically cryogenic

**Magnet power:** Superconducting  
electromagnet

**Shielding:** RF and magnetic  
shielded room

# Low-cost (<100k €) Low-field (<0.1 T) MRI scanners

**a Solenoid electromagnet**



**Magnet cooling:** Typically cryogenic

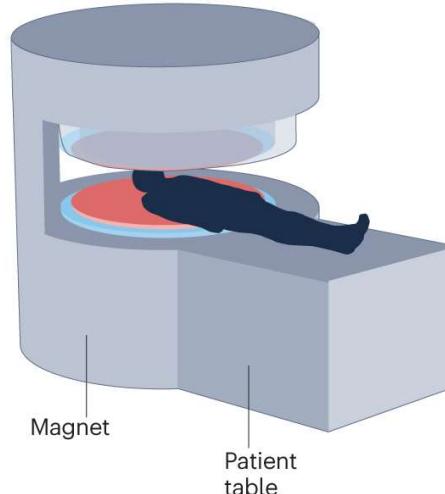
**Magnet power:** Superconducting electromagnet

**Shielding:** RF and magnetic shielded room

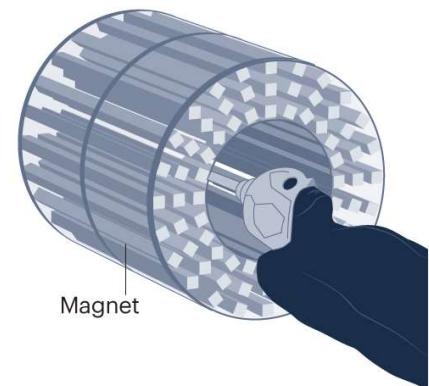
# Low-cost Low-field MRI scanners

Image from Kimberly, W.T., Sorby-Adams, A.J., Webb, A.G. *et al.* Brain imaging with portable low-field MRI.

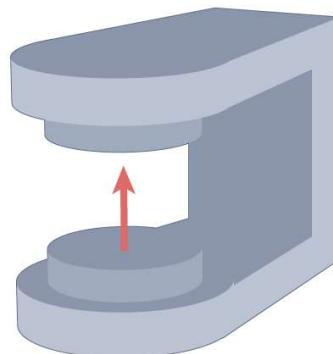
**b Biplanar permanent magnet**



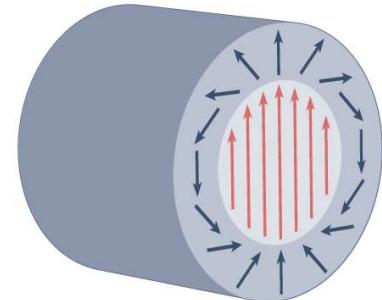
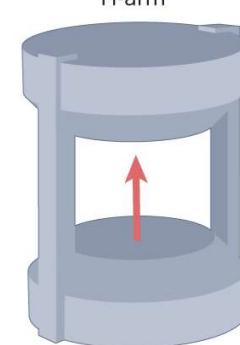
**C Halbach array**



C-arm



H-arm



**Magnet cooling:** No cryogenic requirement

**Magnet power:** None (permanent magnet)

**Shielding:** Typically no magnetic shielding, may or may not have RF shielding

# Low-cost Low field MRI scanners

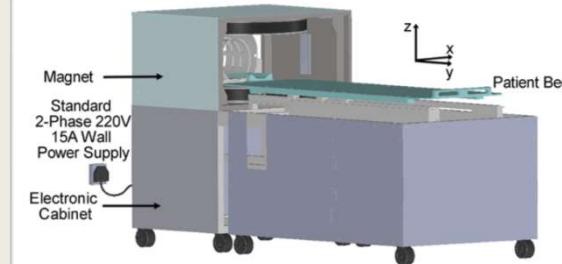


Qiu Y. et al.,  
*MRM*, 2024

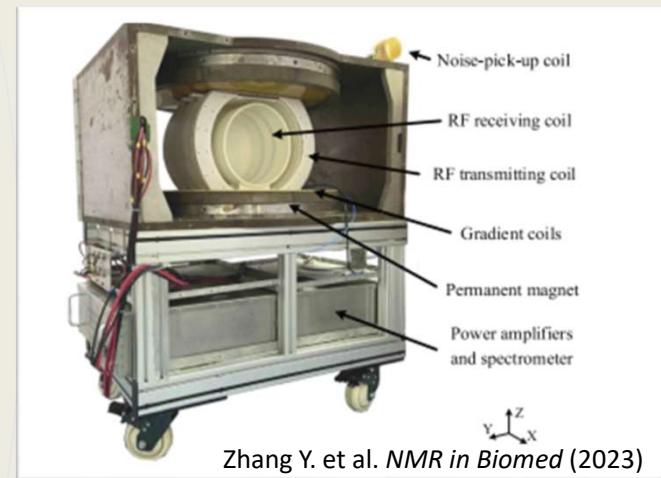
Guallart-Naval T.  
et al. *Sci Rep*  
(2022)



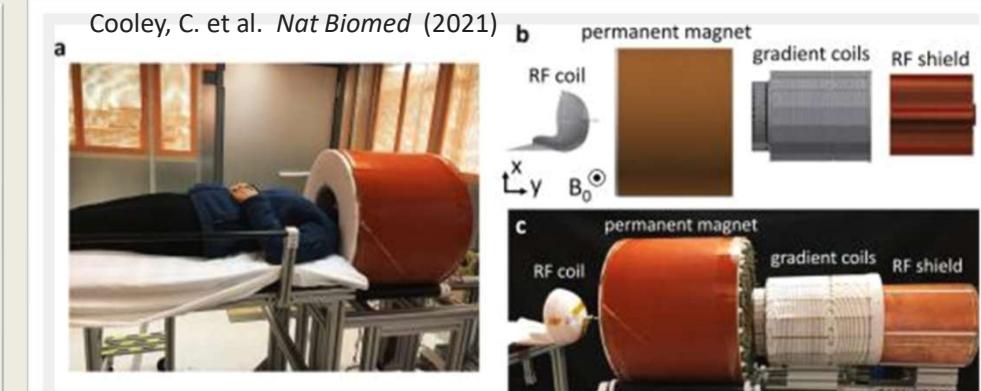
Liu, Y. et al. *Nat Commun* (2021)



Sarracanie, M. et al.  
*Sci. Rep.* (2015)



Zhang Y. et al. *NMR in Biomed* (2023)



# A Low-cost Low field MRI scanner

Single-channel coils



Spectrometer



RF and gradient amplifier



Reconstruction



Separate Tx/Rx

47 mT



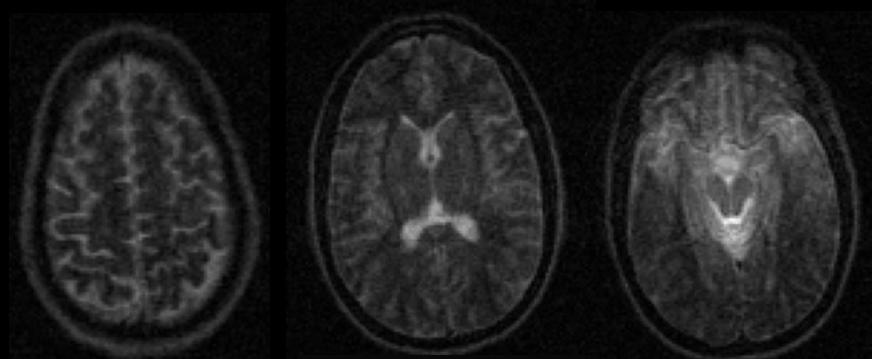
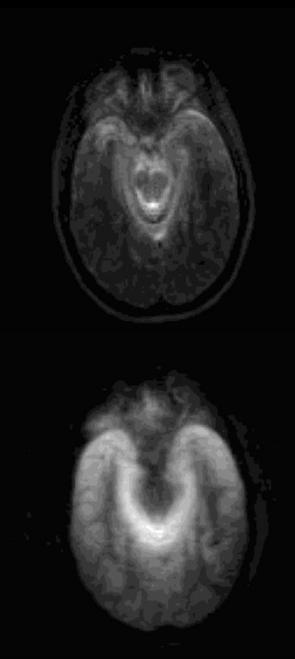
# A Low-cost Low field MRI scanner

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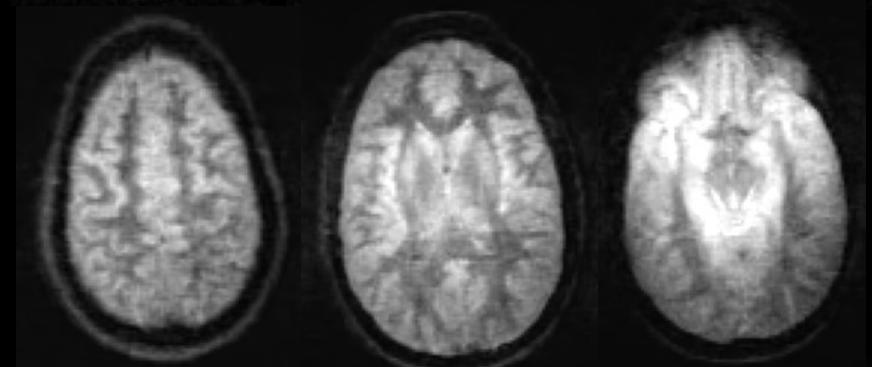
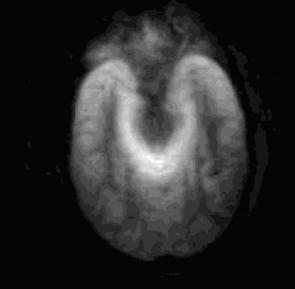


# The successful cases

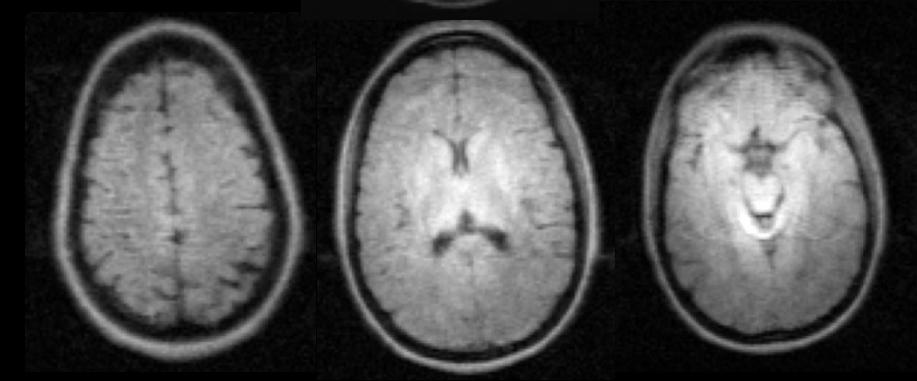
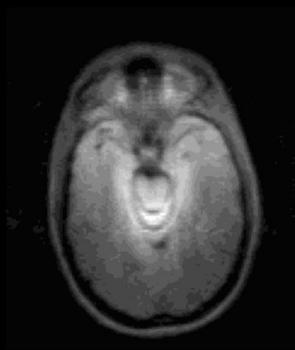
$T_2$ - weighted



Short TI



$T_1$ - weighted

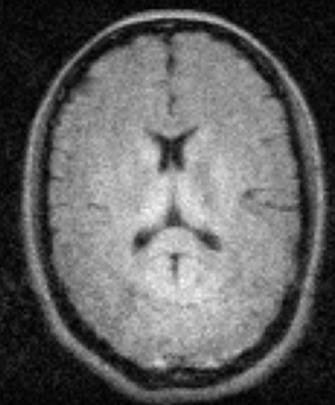


No denoising or filtering applied.

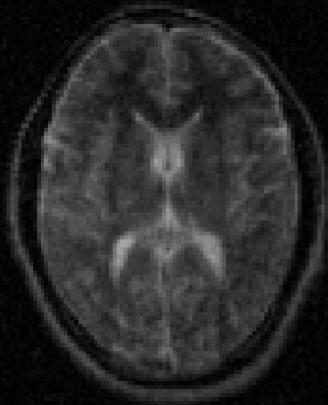
# The successful cases

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T<sub>1</sub>- weighted



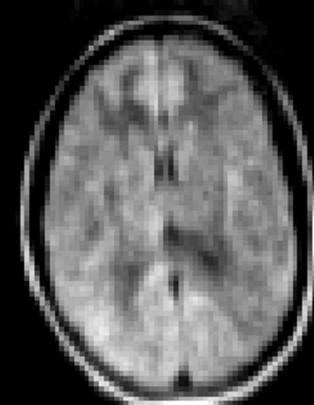
T<sub>2</sub>- weighted



FLAIR



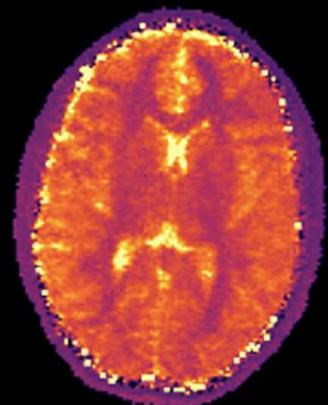
DWI (b=267)



MT

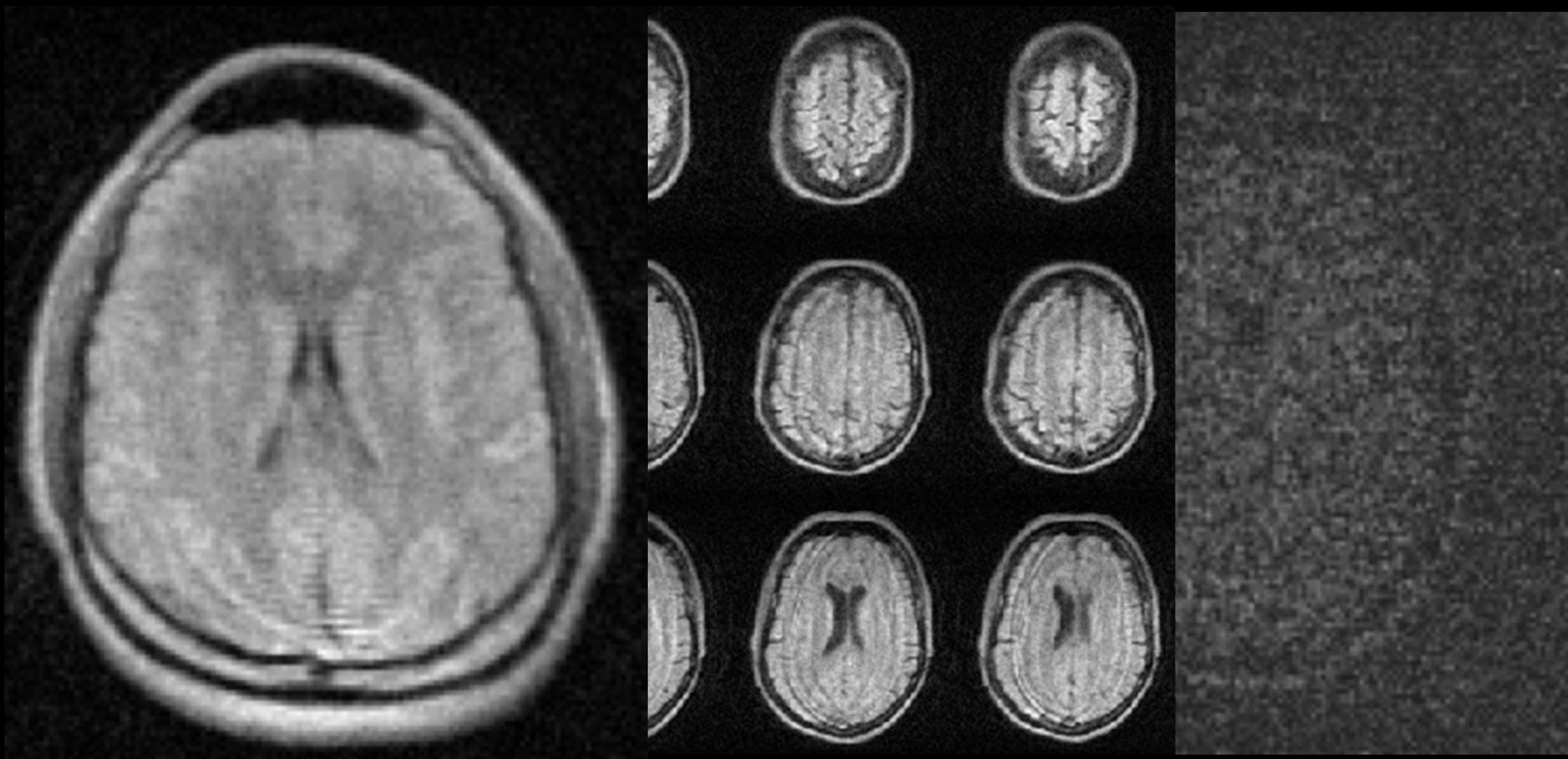


Low-rank rapid T1 mapping



# The less successful cases

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# COST EFFICIENCY

Why  
bother?



# Why bother?

## NHS England patients wait up to two-and-a-half years for an MRI

Exclusive: Figures seen by the Guardian show lengthy wait times for diagnostic tests such as ultrasound and CT scans



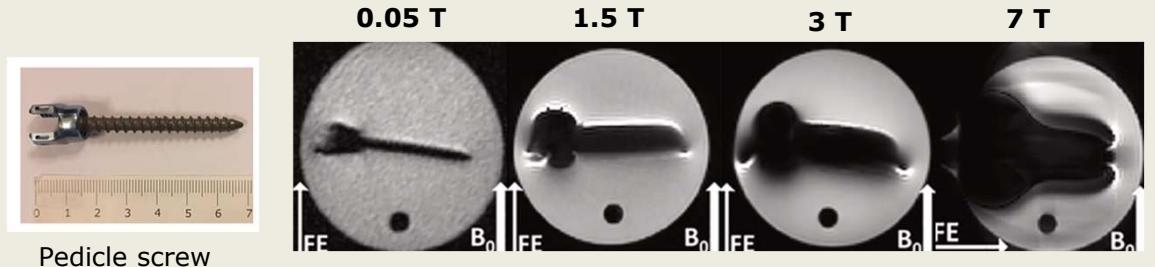
AGGIORNAMENTO 28 NOVEMBRE 2023 9:18

**Una risonanza? Venga nel 2025: così in Campania il diritto alla salute è diventato un lusso**

**Un año y medio en lista de espera por una prótesis de cadera o una resonancia:  
“Esperar a la cita es morirte antes”**

Cientos de miles de hogares españoles esperan por una intervención quirúrgica, una cita con un especialista o una prueba médica: “Me dicen que lamentan las molestias, pero no hay quirófanos”

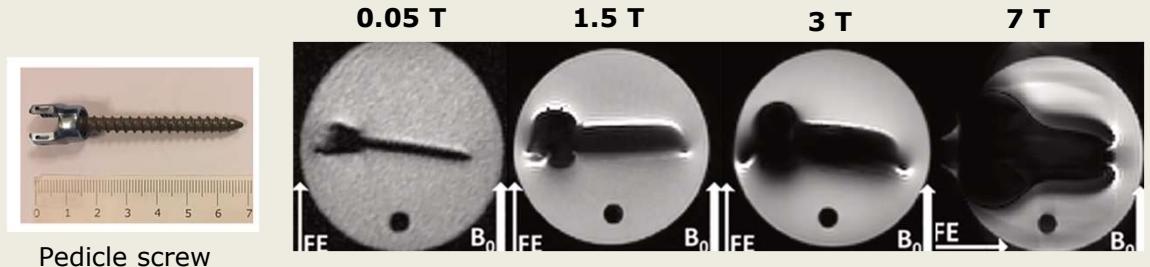
# Why bother?



Adapted from C. Van Speybroeck et al., Phys Med 2021

## 1. Imaging of patients with implants





Adapted from C. Van Speybroeck et al., Phys Med 2021

## 1. Imaging of patients with implants

McLean B. and Thompson D., *Clin Care Res Pract*, 2023

### ICU to MRI scan cycle time for conventional MRI (order to result) Minutes

MRI order to transport initiated	300
Transport initiated to position	because there had previously been no studies validating the predictive value of peri-operative MRI in this group. Additionally, the transport to the MRI scanner and the possible need for sedation are not without significant hazard and require a trained team of
Positioned in MRI to scan complete	providers, including pediatric cardiac anesthesiologists and/or intensivists, to accompany the children to the scanner to maintain their respiratory and hemodynamic stability.
Scan completed to patient in bed	
Patient in bed on unit to result available	30
Total MRI cycle time	500

ICU, intensive care unit; MRI, magnetic resonance imaging.



### During Transport

(i) Poor communication  
between transport team

### Post-Transport

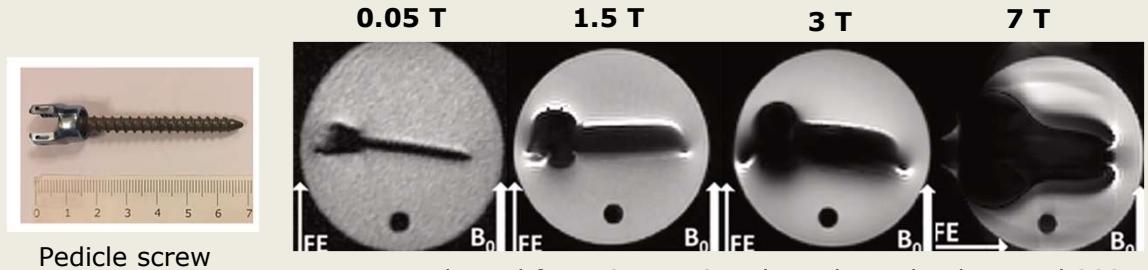
(i) Incomplete transfer to ICU equipment

suite/obstacles  
(v) Transfer to MRI bed for exam

and imaging



# Why bother?

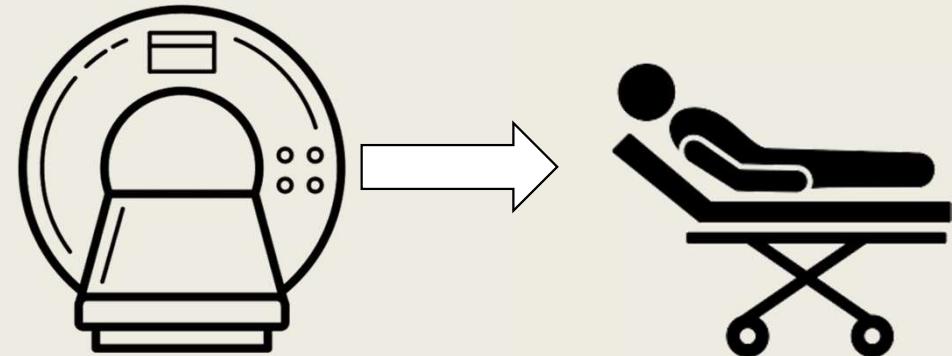


Adapted from C. Van Speybroeck et al., Phys Med 2021

## 1. Imaging of patients with implants

## 2. Less infrastructure

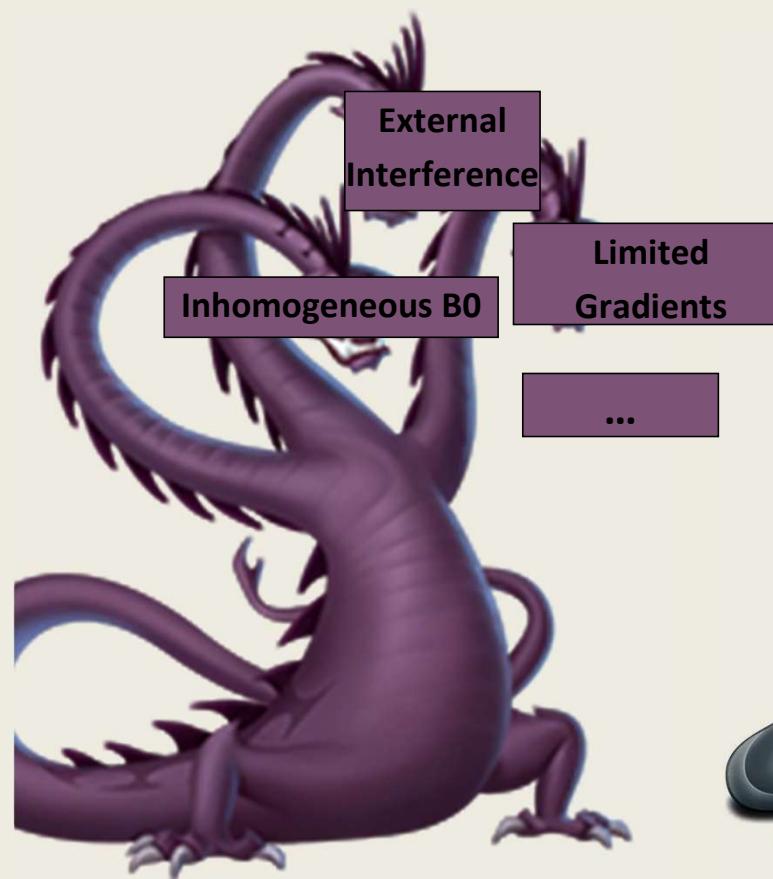
## 3. Point-Of-Care



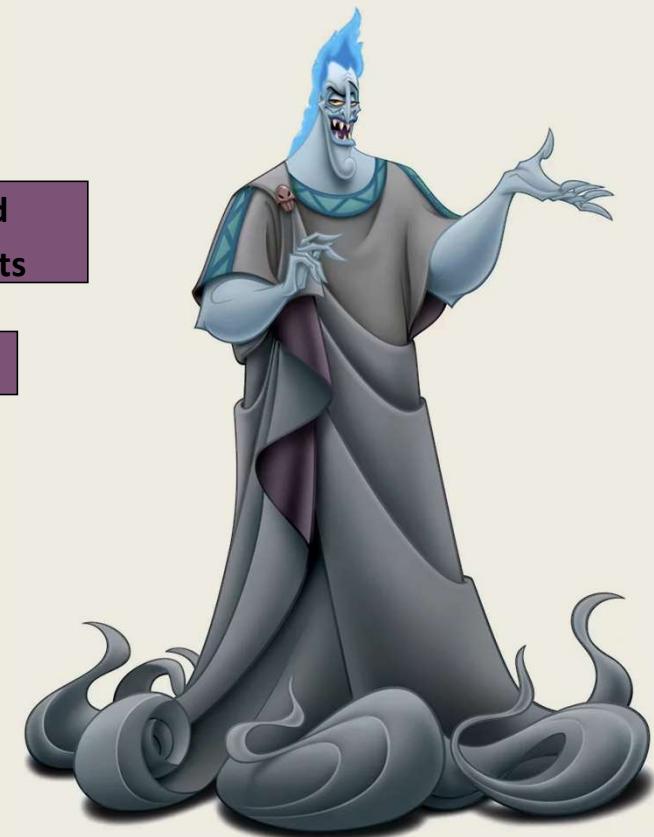
# The challenges



*The "Easy-Fix"*



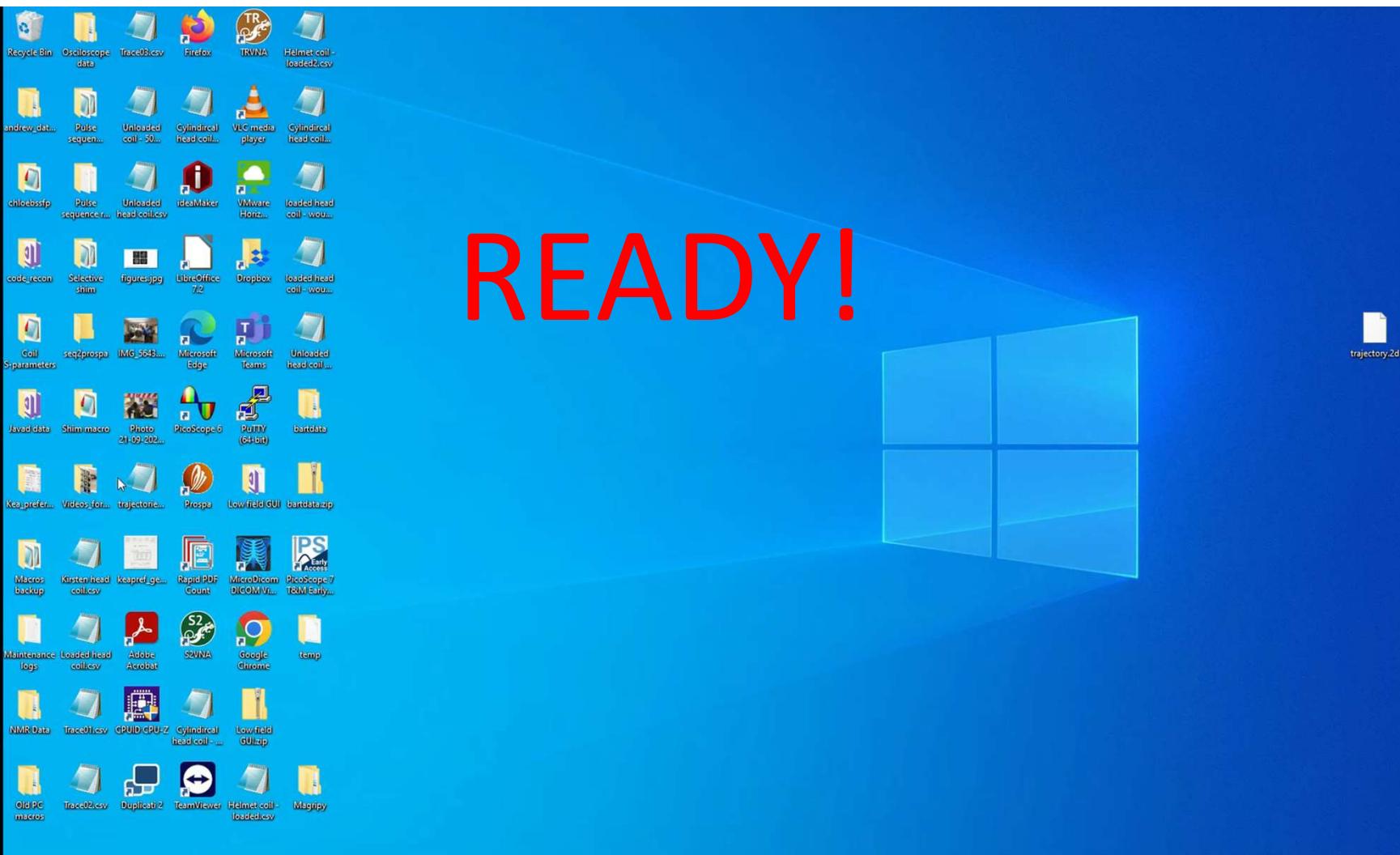
*The Usual Suspects*



*The Titans*



The “Easy-Fix”



**Update the resonance frequency**  
Tuning/matching of the coil

Automated shimming  
Power optimization

Check noise level  
Check position

# The Easy-Fix

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- User-unfriendly
- Coil-related issues



You look awful  
today



# The Easy-Fix

## Coil-related issues



- Dimensions
- Manual Tuning/Matching



From Webb and O'Reilly, *MAGMA*, 2023

An open-source automatic impedance tuning and matching module for low-field systems in clinical settings.

Rubén Bosch<sup>1,2</sup>, José Miguel Algarín<sup>1,2</sup>, Teresa Guallart-Naval<sup>1,2</sup>, Francisco Juan-Lloris<sup>3</sup>, Jesús Conejero<sup>1,2</sup>, and Joseba Alonso<sup>1,2</sup>  
<sup>1</sup>*i3M, CSIC, Valencia, Spain*, <sup>2</sup>*Universitat Politècnica de València, Valencia, Spain*, <sup>3</sup>*Physio MRI SL, Valencia, Spain*





The Usual Suspects

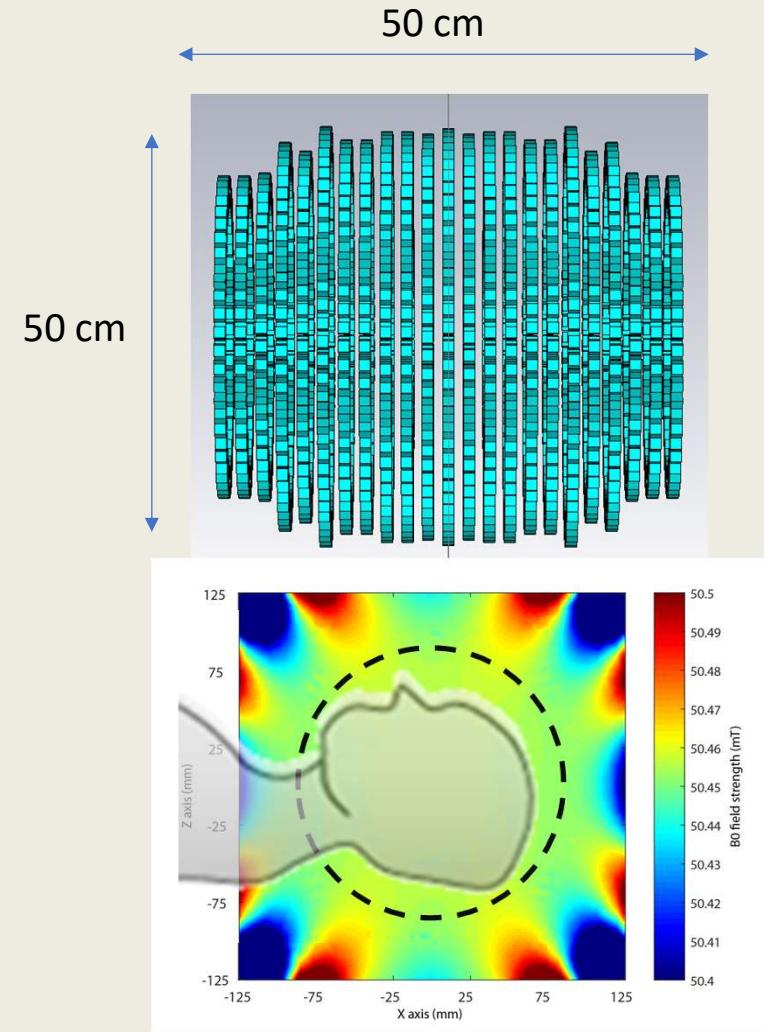
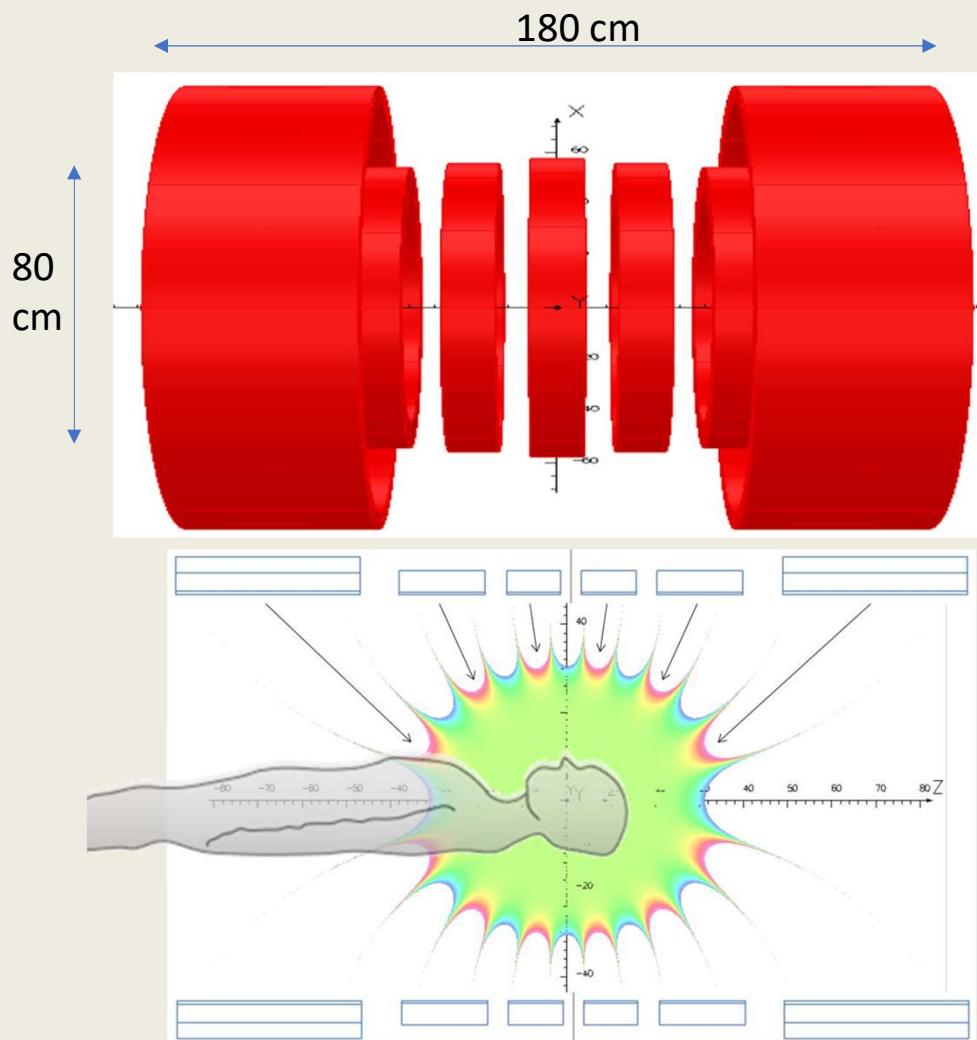
# The Usual Suspects

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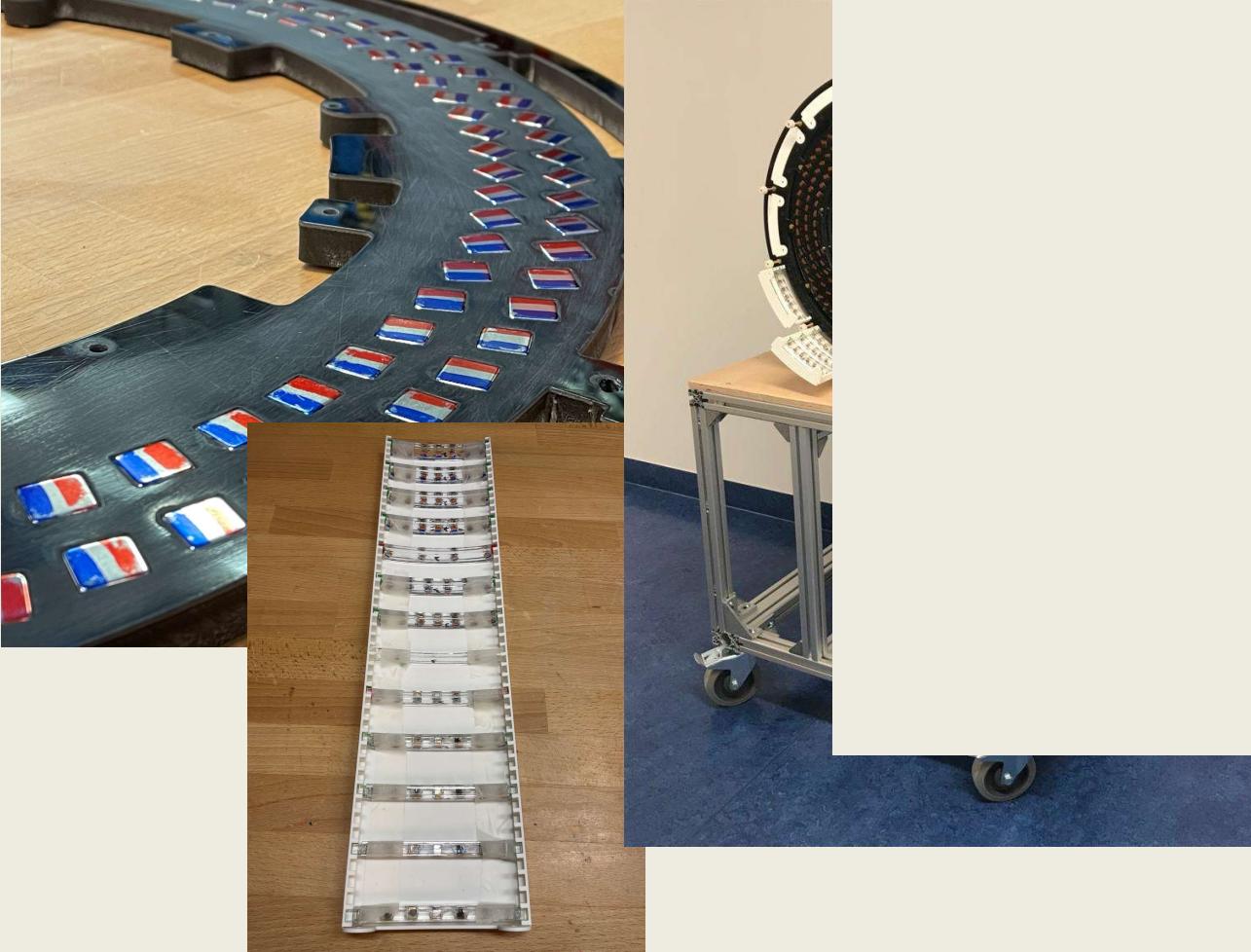
- B0 homogeneity
- Gradient performance
- Lower SNR and similar Relaxation Times: Contrast
- No Faraday Cage
- Decreased parallel imaging performances



# $B_0$ homogeneity



# $B_0$ homogeneity

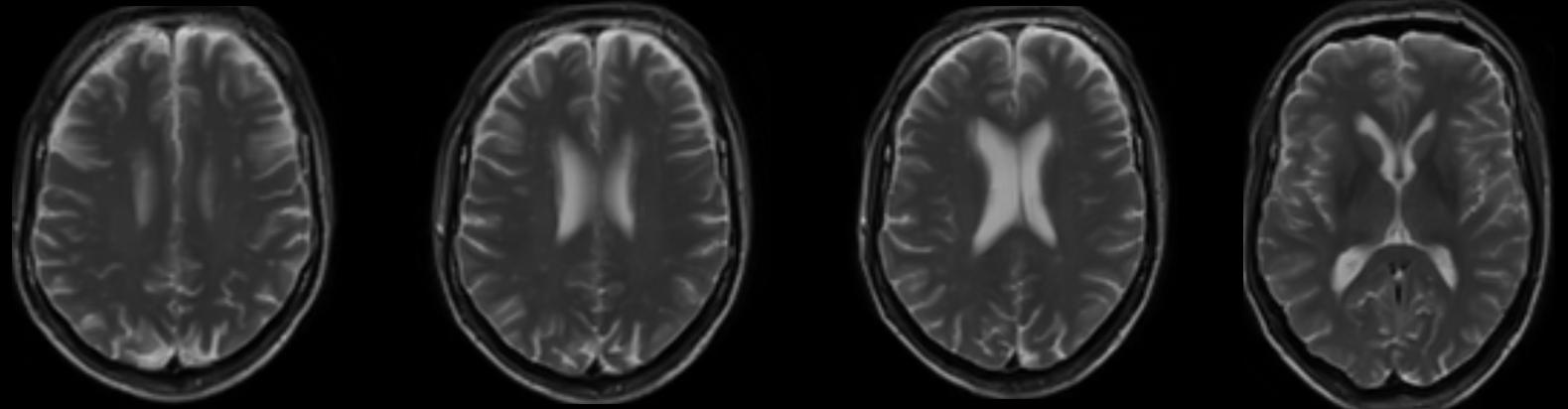


# $B_0$ homogeneity



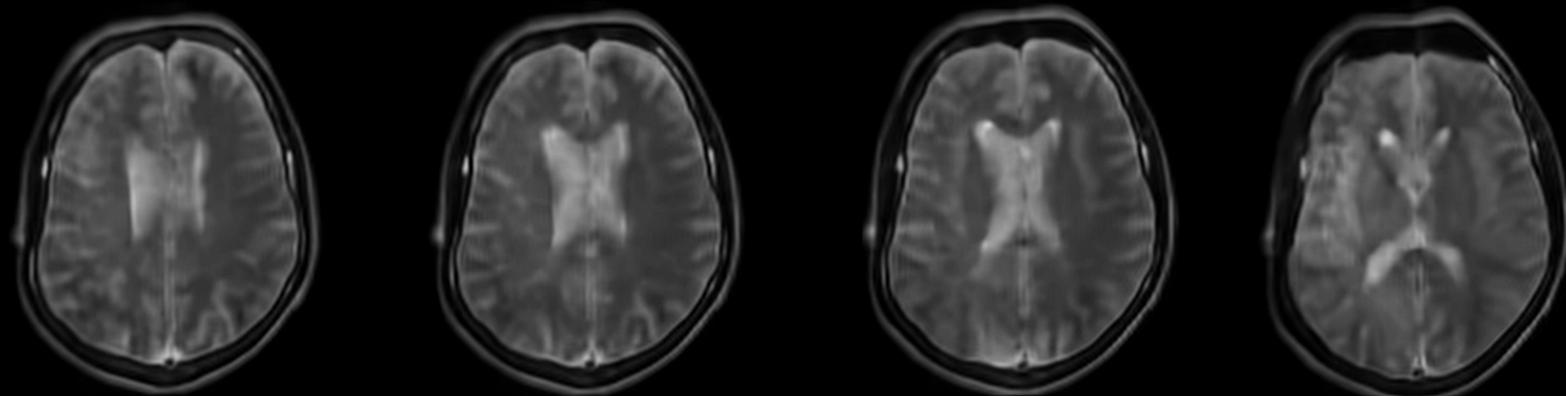
**3 T**

*Scan time:*  $\cong 1.5$  minute  
 $B0: < 1$  ppm



**0.05 T**

*Scan time:*  $\cong 9$  minutes  
 $B0: 100\text{--}1000$  ppm



# SNR... but is that all?



Signal-to-noise

$$\propto B_0^{7/4}$$

3 T → 0.05 T

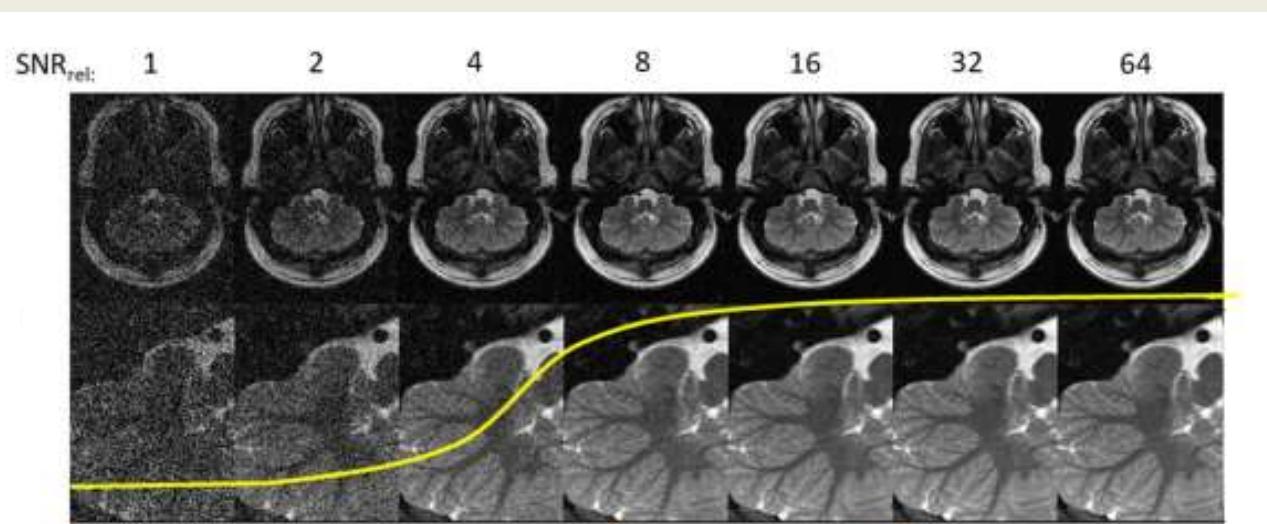
*SNR lower by ~a factor of  
1300*



To acquire the same image, it will take 1700000 longer ...

1min scan at 3T === 3 years at 50mT

# AI or not AI, that is the question...

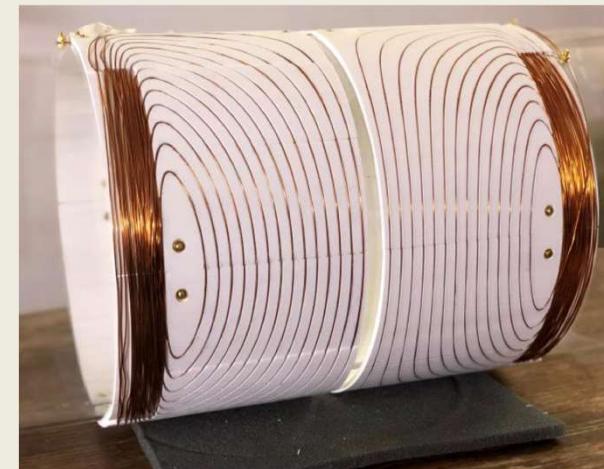
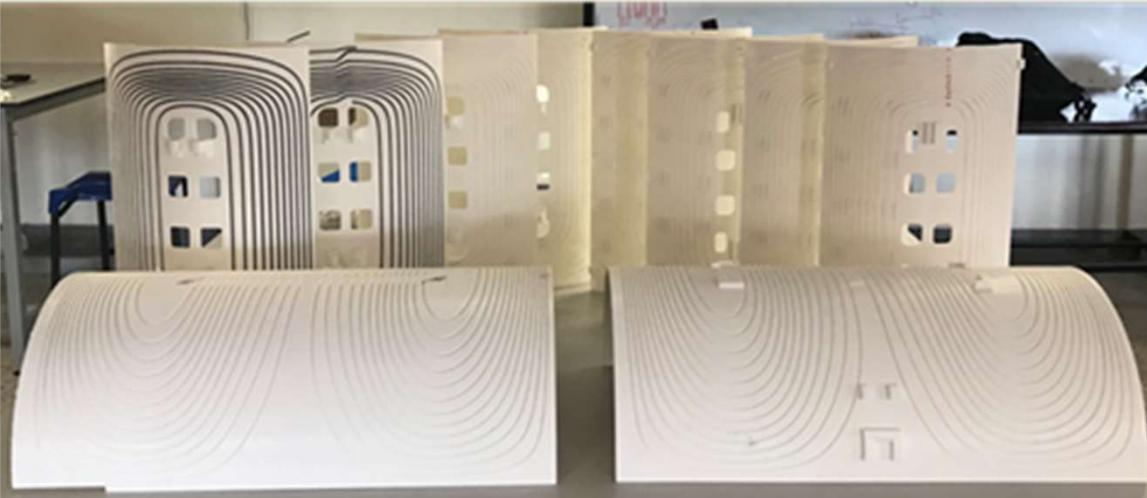


Perceived  
image  
quality

From Hennig J. MAGMA, 2023

With AI image reconstruction, images always look good and it is a much more tricky issue to assess the reliability of diagnosis.

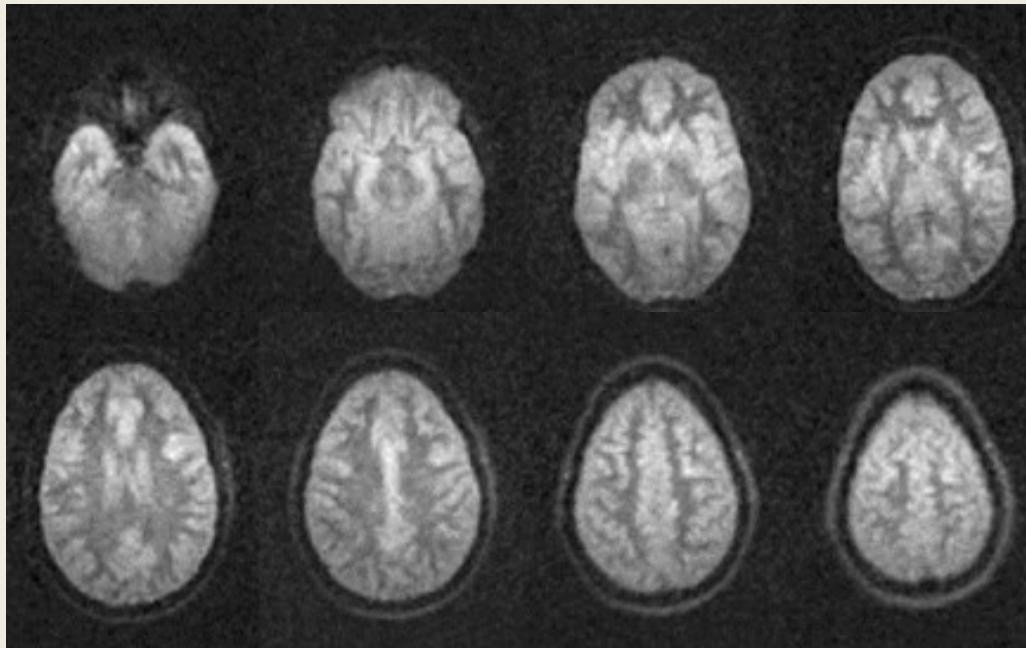
# Gradient performances



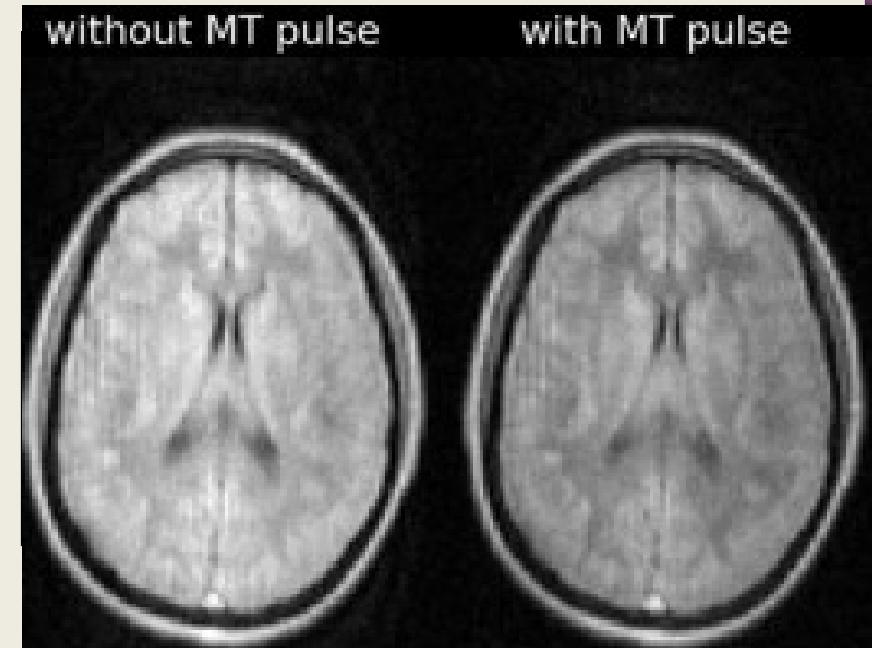
**No cooling ->** lower gradient strength achievable

**Not per se a problem, but longer scan time and limited performance for diffusion**

# Contrast



Short Inversion Recovery T1w scan



Re-think ways to gain contrast  
**Translation of sequences from high to low field doesn't (always) work!**

# Decreased parallel imaging performances



## Noise

$$\sigma^2 \propto 4kT \cdot R_{\text{tot}} \cdot \text{BW}$$

$$R_{\text{tot}} = R_{\text{sample}} + R_{\text{coil}}$$

**Limited benefit of multiple receive arrays,  
often with SNR penalty**

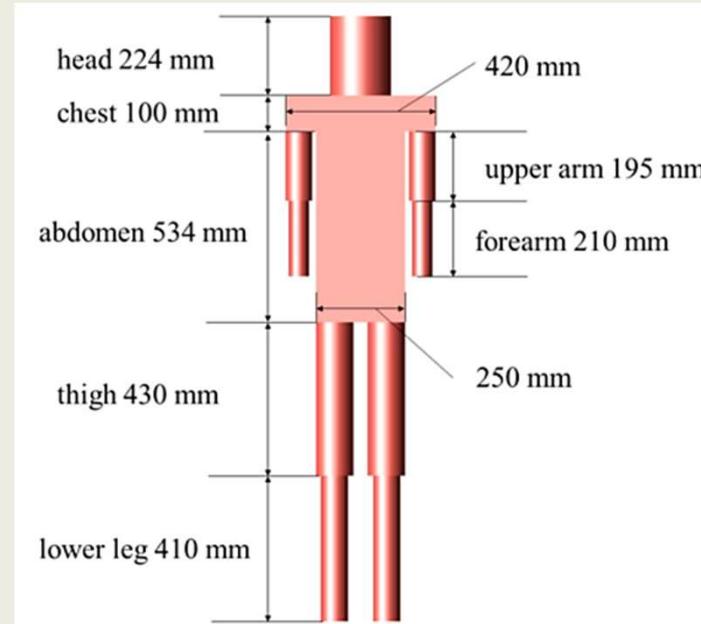
# No Faraday cage



Image everywhere!



Challenging for in-vivo imaging



From Li J. et al., *Sensors*, 2017

Even more challenging for ICU



From Sheth et al., *JAMA Neur*, 2021

# No Faraday cage

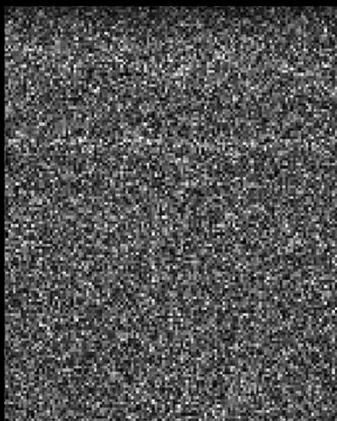
## Subject grounding



For brain imaging



No arc shield  
No Grounding



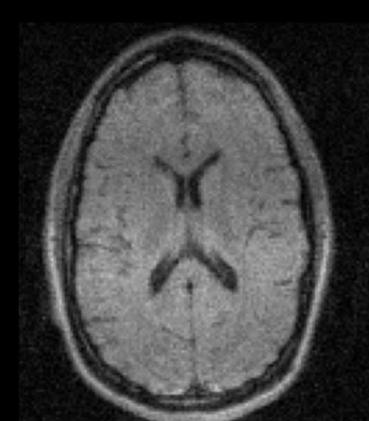
No arc shield  
Grounding



Arc shields  
No Grounding



Arc shields  
Grounding

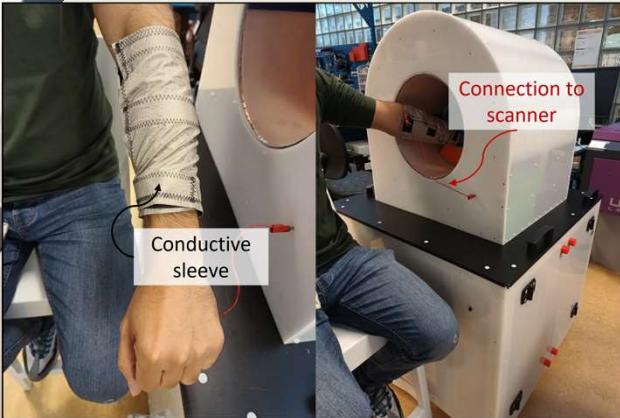


Arc shield + subject grounding (ECG)

# No Faraday cage Subject grounding



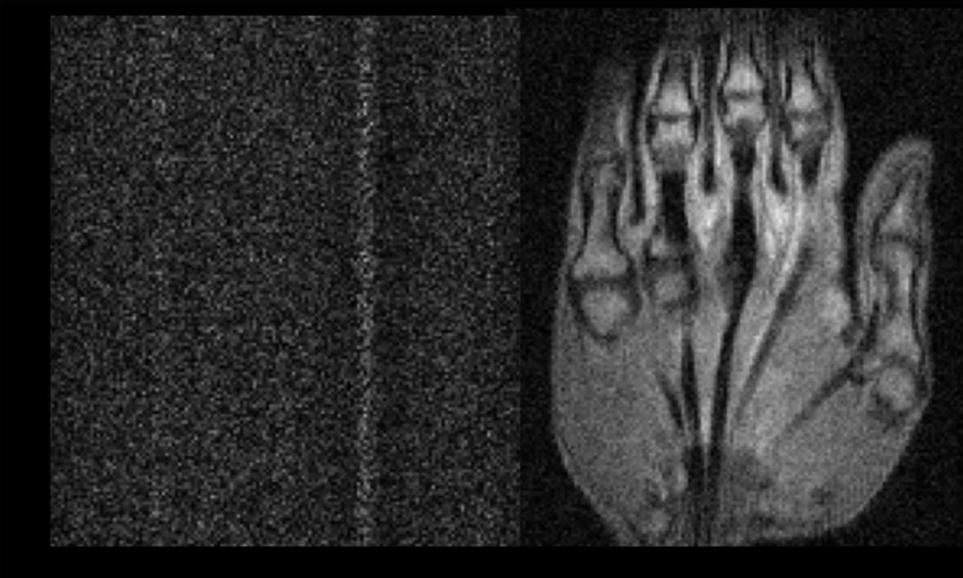
For wrist imaging



**No grounding**  
*No added noise*



**Grounding**  
*No added noise*

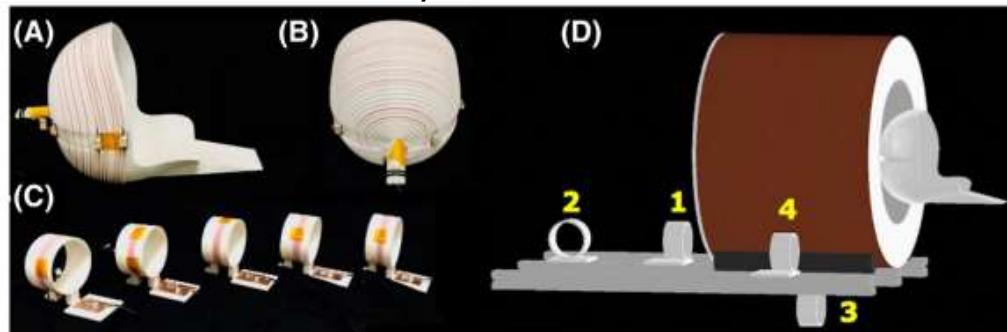


# No Faraday cage

## Other strategies

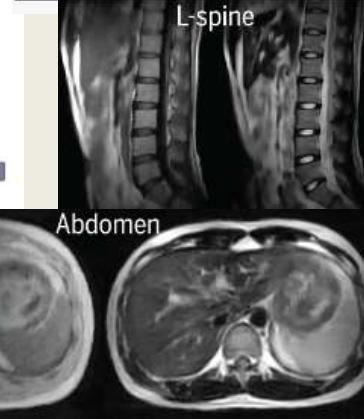
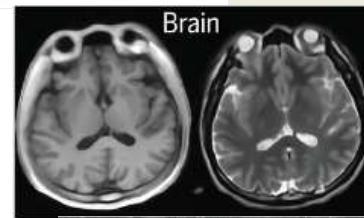
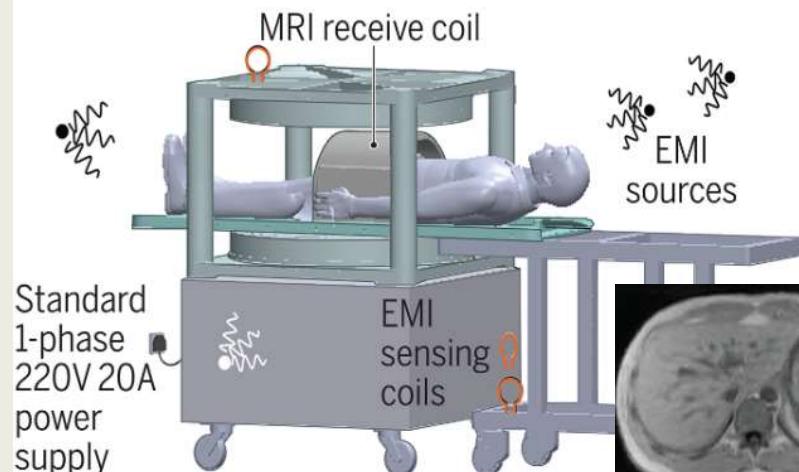


### Use of EMI sensors/coils



Srinivas S.A. al.,  
*MRM*, 2021

**Low-power low-maintenance simplified  
0.05 Tesla MRI scanner**  
(No RF and magnet shielding)



Zhao Y. al.,  
*Science*, 2024

### Use of conductive cloth



Guallart-Naval  
T. et al. *Sci  
Rep* (2022)



O'Reilly et al.  
*MRM* (2021)



The Titans

# The Titans

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- Local regulatory hurdles
- The Titan of traditions



# The Titans

## Local regulatory hurdles



A. Correspondentie

B. Formulieren

C. Protocol

D. Productinformatie

E. Informatie proefpersonen

F. Vragenlijsten e.d.

G. Verzekeringen

H. Cv's

I. Deelnemende centra

J. Financiële vergoedingen

K. Overige documenten

L. Veiligheidsinformatie

M. Voortgang en resultaten

N. Monitoring en audit

O. Privacy, Datamanagement en Statistiek

P. Besluiten

Q. Ondersteunende afdelingen of externe partijen

R. Studie specifieke procedures

A

For a study in healthy adults...

B

D

B. Formulieren		Ja	Nee
B1	ABR-formulier	<input type="checkbox"/>	<input type="checkbox"/>
B2	Eudamed formulier	<input type="checkbox"/>	<input type="checkbox"/>
B3	EudraCT-aanvraagformulier	<input type="checkbox"/>	<input type="checkbox"/>
B4	Gentherapie / GGO-formulier	<input type="checkbox"/>	<input type="checkbox"/>
B5	EudRACT-formulier kennisgeving wijziging	<input type="checkbox"/>	<input type="checkbox"/>
B6	CCMO-formulier melding beëindiging studie	<input type="checkbox"/>	<input type="checkbox"/>
B7	EudRACT formulier einde onderzoek	<input type="checkbox"/>	<input type="checkbox"/>
B8	Bevestiging aanmelding clinical trial register	<input type="checkbox"/>	<input type="checkbox"/>

D. Productinformatie		Ja	Nee	NVT	Dig
D1	Investigator's Brochure (IB)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
D1a	Overzichtlijst SUSAR's	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
D2	Investigational Medicinal Product Dossier (IMPD)  (of Summary of Product Characteristics (SPC))	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
D2	Investigational Medical Device Dossier (IMDD)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
D2	Instruction for use	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
D3	Voorbeeldetiketten	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
D4	Verklaringen en vergunningen (zoals genoemd positief besluit METC)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
D4	Verklaring fabrikant over veiligheid en prestaties medisch hulpmiddel	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
D5	Productgegevens ziekenhuisapotheekers	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
D6	Aanvullende productgegevens	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
D7	Out of specification (OOS) ATMP (advanced therapy medicinal product)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
D8	Drug/device accountability	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

L

M

N

O

P

Q

R

# The Titans

## Local regulatory hurdles



PROBLEM #36  
“WITH GREAT POWER COMES GREAT RESPONSIBILITY”

A cartoon illustration of Spider-Man in his red and blue suit, holding a black microphone. Below him is a yellow rectangular banner with the text "PROBLEM #36" at the top, followed by the quote "WITH GREAT POWER COMES GREAT RESPONSIBILITY".



After the break...

### Medical Device Regulation

Are you also drowning in MDR-paperwork before you can start a study?

With open-source tools, more in-house built devices, comes dealing with IRB committees and learning about MDR, IMDD, etc

Similar to pharma industry for new drugs.

Which lessons can we learn?

- Adaptive clinical trials
- Early engagement with regulatory agencies
- Incorporating patient feedbacks

# The Titan of tradition...



"What can you use it for?"

"It doesn't have the same contrast/resolution of 3T"

"It doesn't have a suitable image quality"

"Some ultrasound probes can do better"

"We are still investigating it"

"And it never will"

"Depends on the application"

"They often rely on the operator's experience, and we cannot use them to image brain"



**Keep the discussion going, at least there is some communication!**



# The Titan of tradition...

... limits how much can be done!



## CONCLUSIONS

The conclusions to be drawn from the above calculations are that:

- (1) Effects associated with the radiofrequency penetration depth suggest that the frequency of operation of the spectrometer with human samples should be less than about 10 MHz.

From Hoult D.I. and Lauterbur P., *JMR*, 1979

Max.  $B_0$  for human scanning:  $\sim 0.25$  T

# So where are we?



We are training  
Some battles we win, some battles we lose.

# Portable medical devices that have changed the world



Stethoscope (1816)



Thermometer (1867)



ECG machine (1903)



Mobile X-Ray car (1911)



Glucose meter (1970)



Portable Defibrillator(1965)



Pulse Oximeter (1980)



Portable Oxygen Concentrator (2000)



Wearable Health Monitor (2010)



Handheld ultrasound (1990)

# MRI panorama

For long time:



1.5T

3T

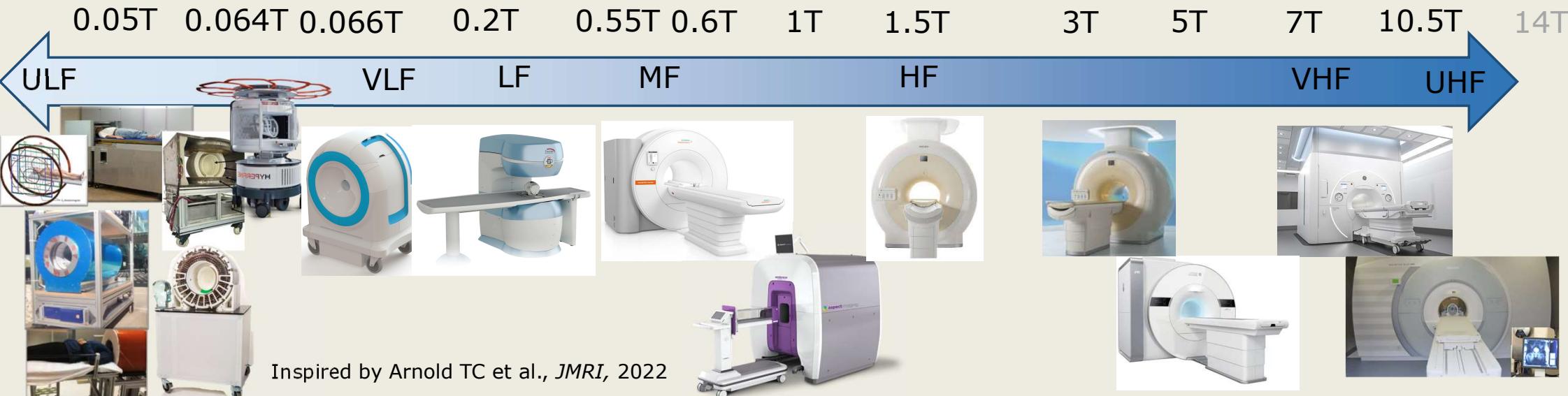
(7T)

LF

UHF

Lately:

Image not to scale



Inspired by Arnold TC et al., *JMRI*, 2022

**Friday October 4**

07:30 – 12:30 • Friday October 4 • Morning Sessions

**FT1: Low-field  
MRI: Emerging  
opportunities**

Focus Topic: MR Beyond  
Trends

08:15 – 09:15

ROOM 6

LECTURE	SPEAKER
The physics of low-field regimes	Luc Darrasse
Adaptable MRI technologies	Mike Ristic
Emerging applications	Mara Cercignani

13:45 – 18:00 • Friday October 4 • Afternoon Sessions

**Sustainable  
Development Goals  
countdown: The role  
of mri in global  
health (CAMERA)**

Working groups

15:30 – 17:00

ROOM 4

**ET2: Hands-on  
primer on full  
acquisition  
simulations**

Educational Tracks 2

15:30 – 17:00

ROOM 4

LECTURE	SPEAKER
Hands-on — Digital Twin of low-field scanner	Moritz Zaib

**ESMRMB 2024  
2-5 OCTOBER  
BARCELONA**  
**40<sup>TH</sup> ANNUAL SCIENTIFIC MEETING**

**ESMRMB**

European Society for Magnetic Resonance in Medicine and Biology

**MR to the limits  
and beyond!**



**Lower purchase price**

Lower Power Consumption

Faster Installation

# Challenging? Yes

But many many many advantages.

Lower Power  
Fewer Safety Concerns

**More accessible in rural and underserved areas.**

Suitable for imaging implants

mobile

**Reduced operational costs**

Less noise and vibration

No Need for Cryogens

Smaller

Point-of-care settings like emergency room

Useful for screening

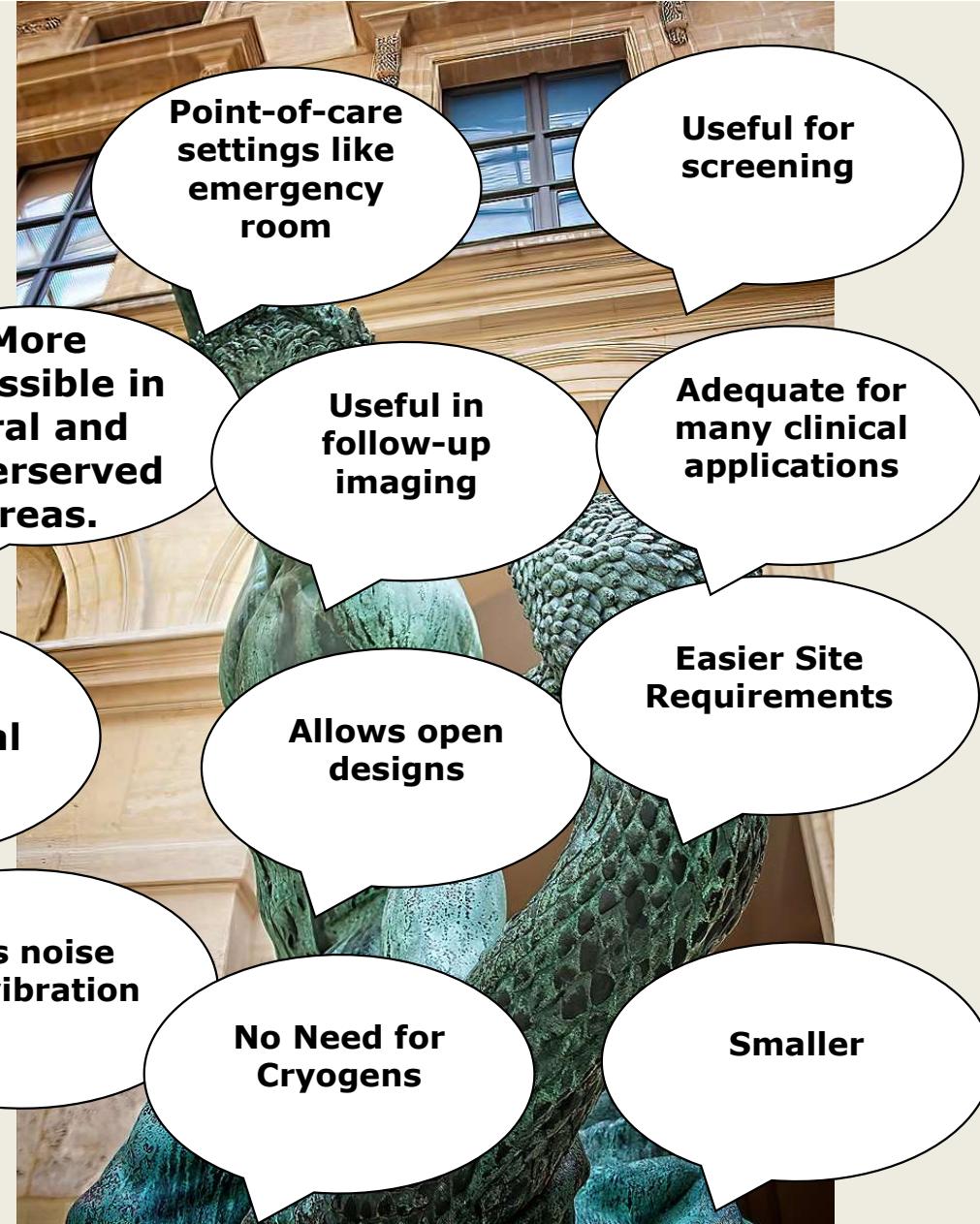
**More accessible in rural and underserved areas.**

Useful in follow-up imaging

Adequate for many clinical applications

Easier Site Requirements

Allows open designs





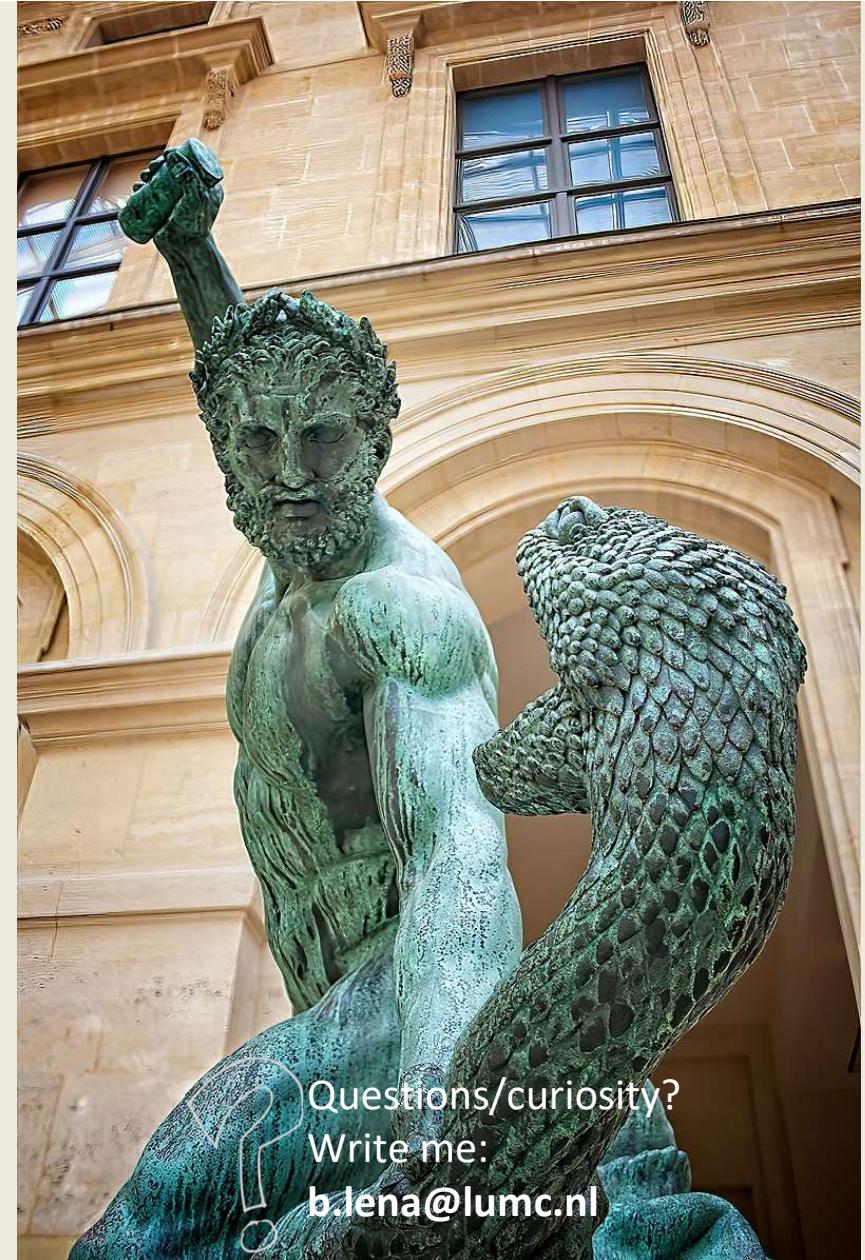
C.J. Gorter  
MRI Center



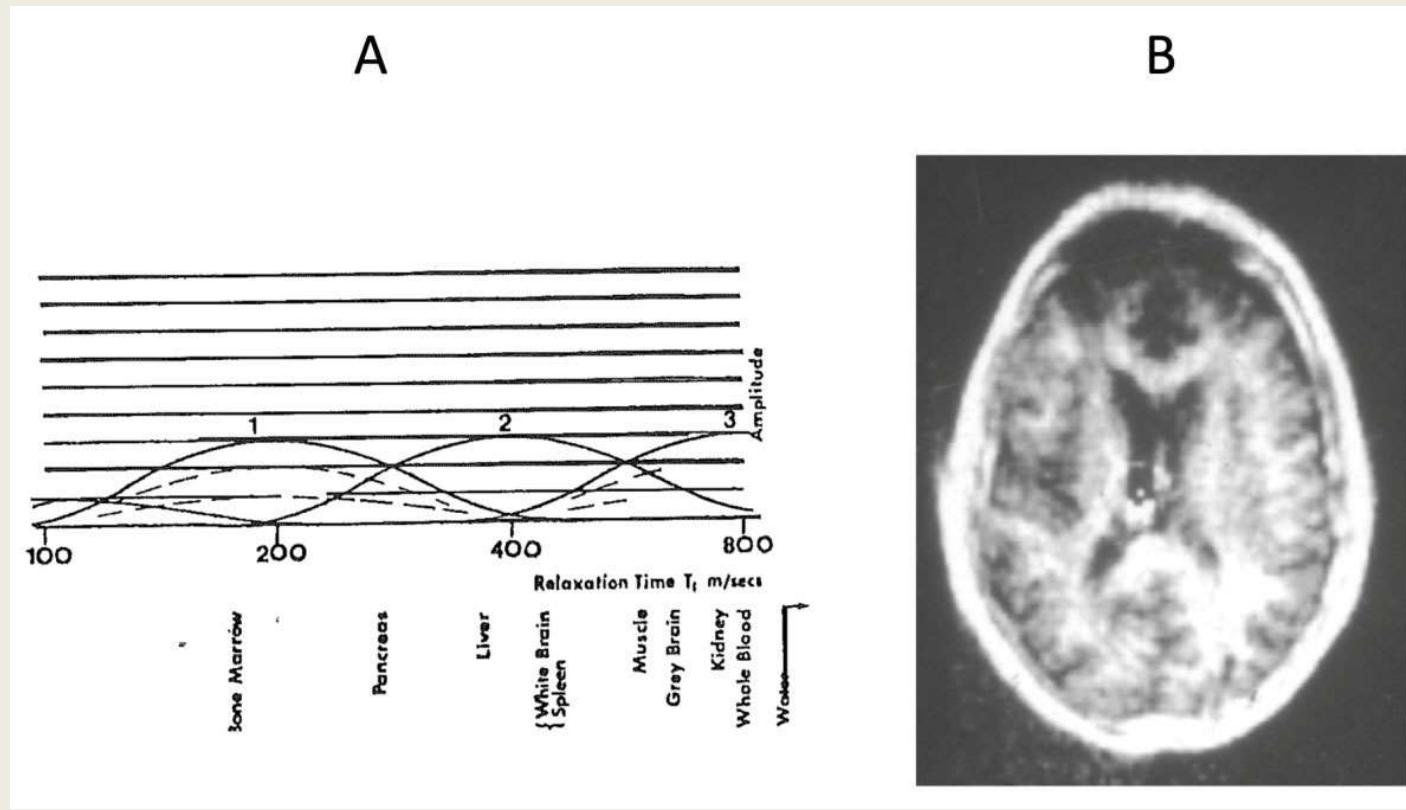
Leids Universitair  
Medisch Centrum

# The challenges of imaging with low-field and low-cost MRI scanners

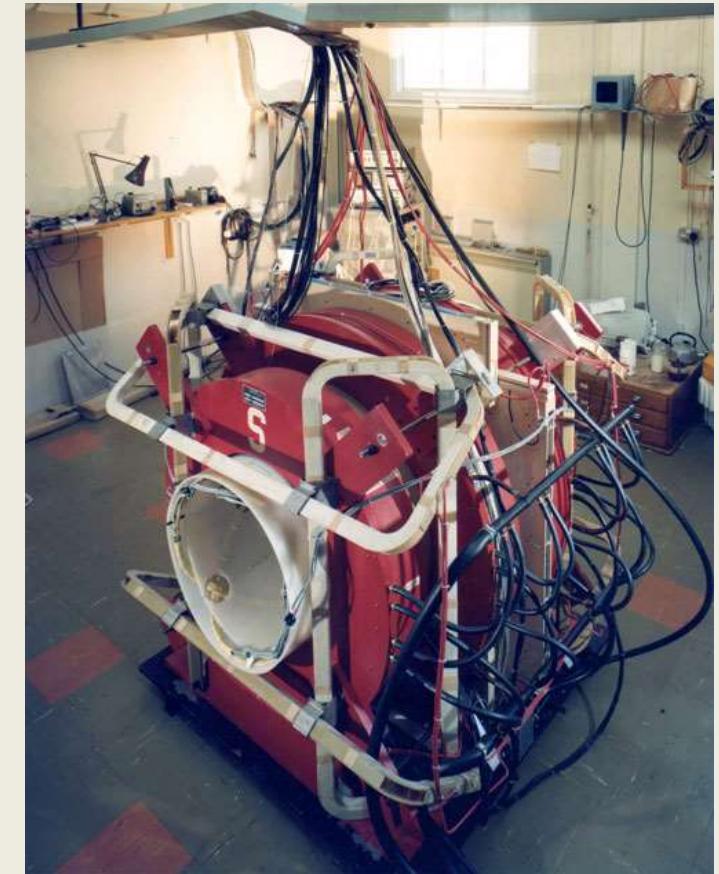
Beatrice Lena



Questions/curiosity?  
Write me:  
[b.lena@lumc.nl](mailto:b.lena@lumc.nl)



Hugh Clow and Ian Young, **the world's first published human MR image of the brain**, November 1978.



0.1T MR scanner