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Monitoring hemodynamic parameters in heart failure patients with wearable RF sensing

Cornelis van den Berg + (Bart Steensma)
Prof. Computational Imaging for MRI diagnostic and therapy
University Medical Center Utrecht

c.a.t.vandenberg@umcutrecht.nl

University Medical Center Utrecht

Declaration of conflict of interest related to the topic

Minority share holder of PrecorDx b.v.

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Stuck at home during Covid-19

Bart Steensma

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MRI : RF coil/antennas are motion sensors

- Reflection & scattering of RF fields is modulated by the motion of tissue structures
- This can be measured either actively by monitoring antenna impedance over time or passively by thermal noise modulations.

Buikman D, Helzel T, Roschmann P. The RF coil as a sensitive motion detector for magnetic resonance imaging. Magn Reson Imaging 1988;6:281–289.

IMAGING METHODOLOGY - Notes

Magnetic Resonance in Medicine 80:633–640 (2018)

Cardiac Gating Using Scattering of an 8-Channel Parallel Transmit Coil at 7T

Sven H.F. Jaeschke, Matthew D. Robson, and Aaron T. Hess*

Purpose: To establish a cardiac signal from scattering matrix or scattering coefficient measurements made on a 7T 8-channel parallel transmit (pTx) system, and to evaluate its use for cardiac gating.
Methods: Measurements of the scattering matrix and scattering coefficients were acquired using a monitoring pulse sequence and

Key words: parallel transmit; cardiac gating; motion sensor; cardiac MRI; reflected power; RF scattering

COMPUTER PROCESSING AND MODELING - Notes

Magnetic Resonance in Medicine 79:1730–1735 (2018)

Respiratory Motion Model Based on the Noise Covariance Matrix of a Receive Array

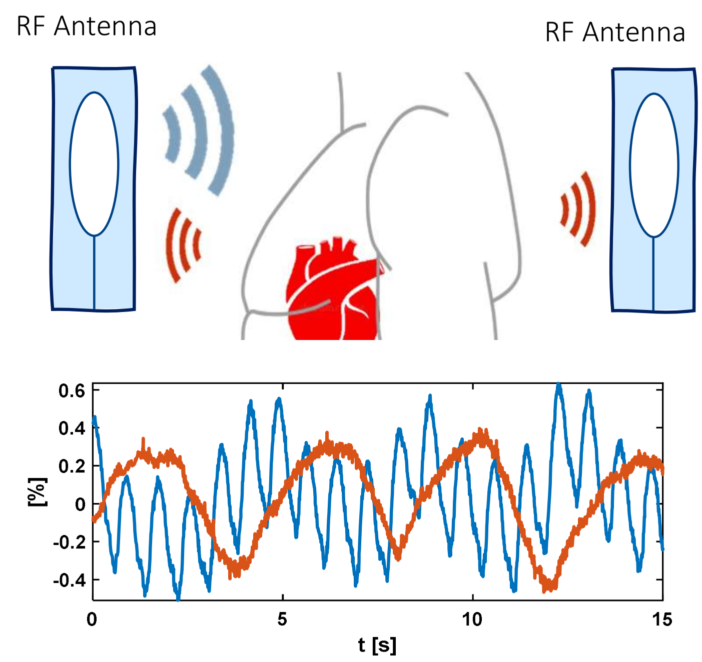
A. Andreychenko,[1]* B. Denis de Senneville,[1,2] R.J.M. Navest,[1] R.H.N. Tijssen,[1] J.J.W. Lagendijk,[1] and C.A.T. van den Berg[1]

Purpose: Tracking of the internal anatomy by means of a motion model that uses the MR-derived motion fields and noise covariance matrix (NCM) dynamic as a surrogate signal.

be directly quantified. However, the motion information obtained from such systems is strongly limited by the update time and latency constraints imposed by the MR-

Radiofrequency Sensing of heart

- Actively monitoring impedance of RF antennas placed on body with a nano-VNA
- $Z_{11}(t)$ or $Z_{12}(t)$
- We could easily observe both imprint of respiration an cardiac induced motion
- These are caused by mechanical motion
- Can we use RF antennas to monitor pumping function of the heart in a non-invasive manner?



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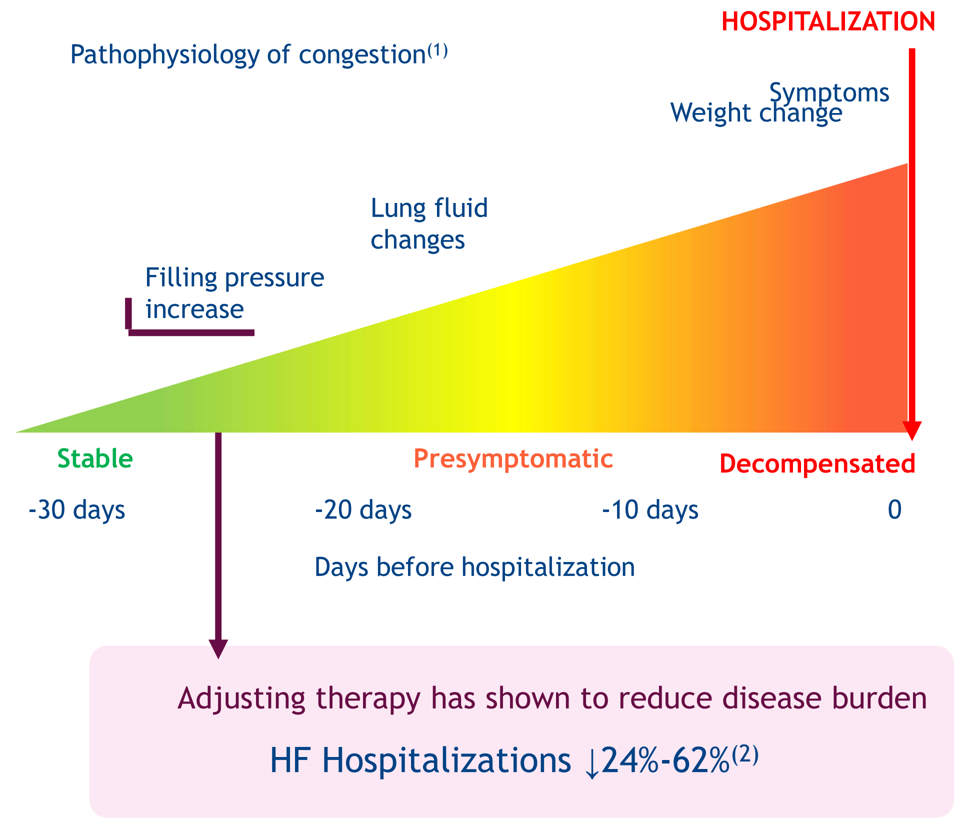
Chronic heart failure is a severe and growing healthcare problem

- 64M patients worldwide
- HF deteriorates from chronic to acute unnoticedly
- Home monitoring of heart function -> medication optimization -> prevents hospitalization



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(1) Adapted from (2) 33-48% CHAMPION trial (Lancet 2016, JACC 2016), 57% PAS study (CIRC 2020), 62% MEMS-HF (), GUIDE-HF was not significant but showed significant 24% reduction pre-COVID (Lancet 2021); Several trials ongoing (GUIDE-HF observational, COAST, MONITOR-HF)

Invasive sensors to monitor heart function for heart failure

- Most common methods such as ECG, or weight monitoring lack sensitivity to mechanical pumping function.

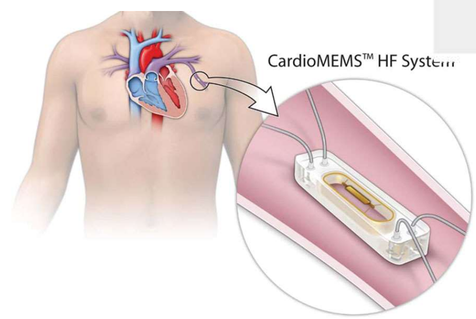
HeartLogic
CRT device based algorithmic HF monitoring

Boston Scientific
Advancing science for life™

CardioMEMS
Invasive PA monitoring

Abbott

NATIONAL MEDICARE RATE
$29,460



Invasive procedure required -> costs + potential complications

Can this be done in non-invasive manner by RF sensing?

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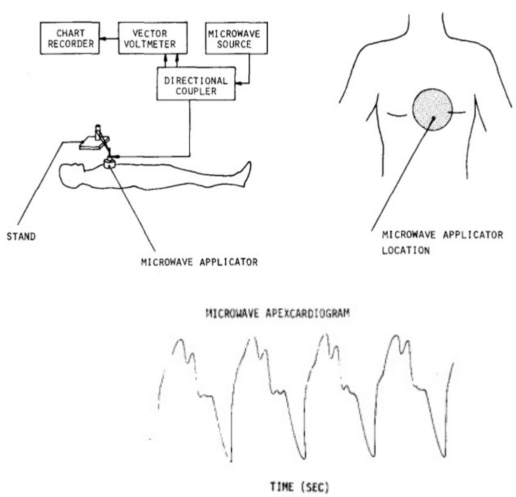
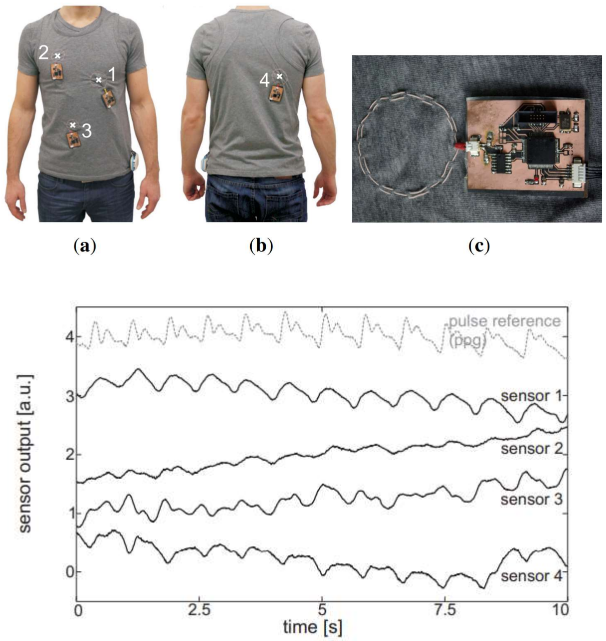
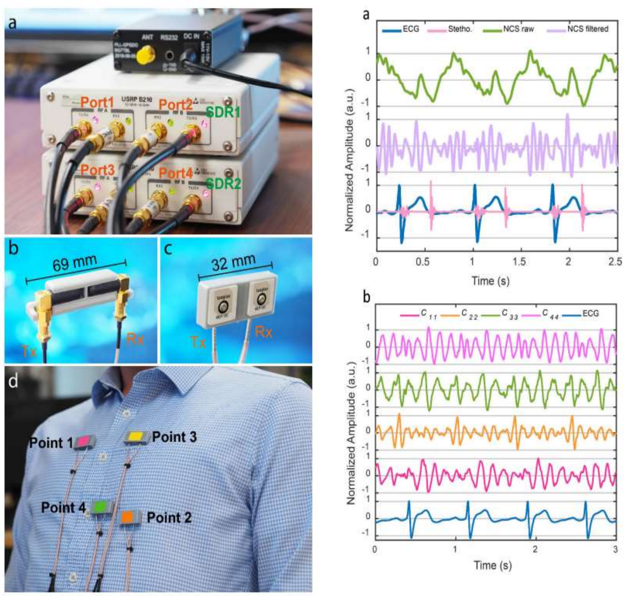
Large variety of RF sensing for cardiac motion exists outside MRI field



1. Microwave Apexcardiography
Frequency range: 2100 – 2500 MHz
Lin et al, 1979, IEEE TMTT, 27:6



2. The MAIN Shirt: A Textile-Integrated Induction Sensor Array
Frequency range: 17-20 MHz
Teichmann et al, Sensors 2014, 14, 1039-1056



3. Near field coherent sensing
Frequency range: 900-950 MHz
Hui et al, Nature Electronics 2018, 1, 74-78

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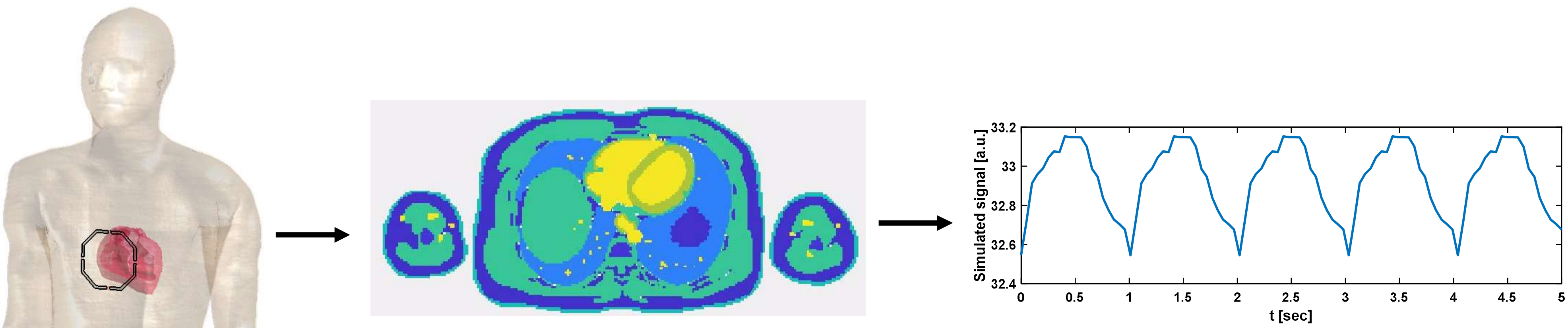
EM simulations provide a better understanding of RF sensing signal

- Sim4Life (Zurich Medtech, Zurich, Switzerland)
- 4D XCAT model with beating heart (Segars et al, Phys Med Biol 2010)
- Predict interaction RF coil with body



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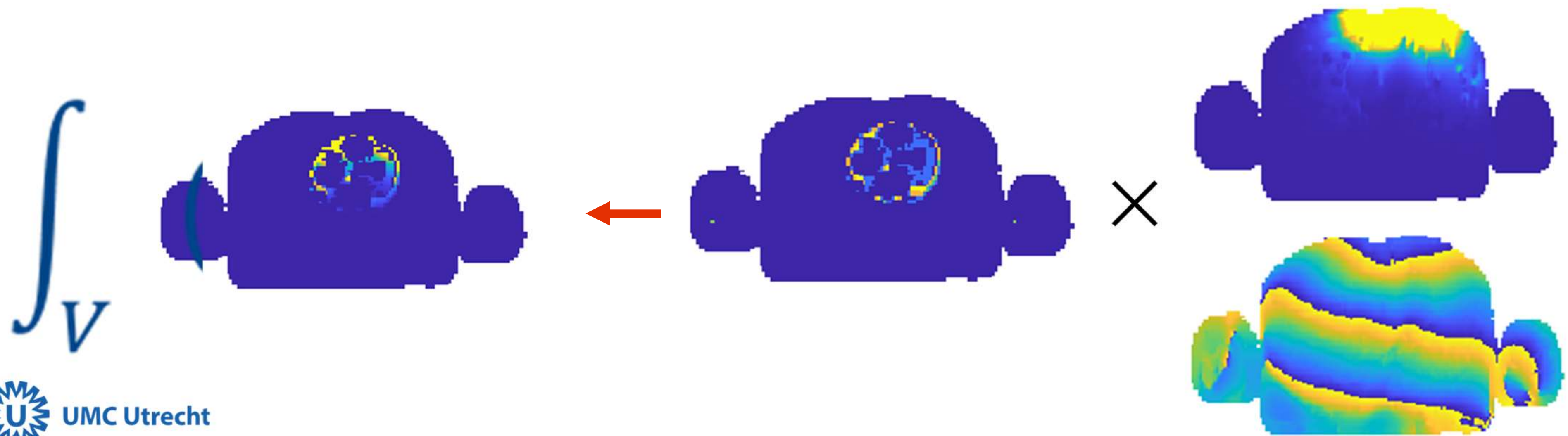
Spatial sensitivity of RFS to cardiac motion is described by Reaction theorem[1]

$$\overbrace{Z_t - Z_0}^{\text{Signal}} = -\frac{\overbrace{j\omega}^{\text{freq}}}{I^2} \int_V \underbrace{\overbrace{(\epsilon_{r,t} - \epsilon_{r,0})}^{\text{Tissue params}} \overbrace{E_{r,t} \cdot E_{r,0}}^{\text{EM field}}}\, dV$$



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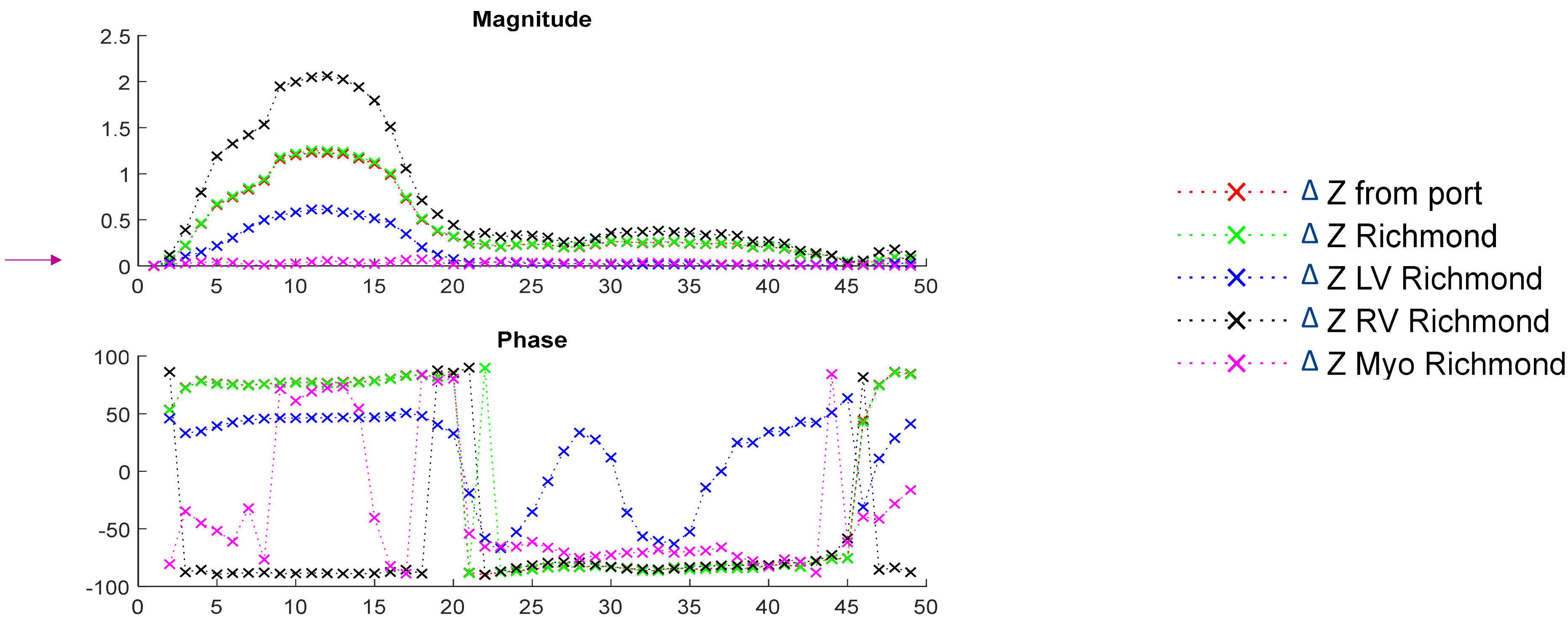
1: Richmond, IEEE Transactions on Antennas and Propagation 1961 9:6, 515-520

Verifying port's and field's perspectives on Z modulation



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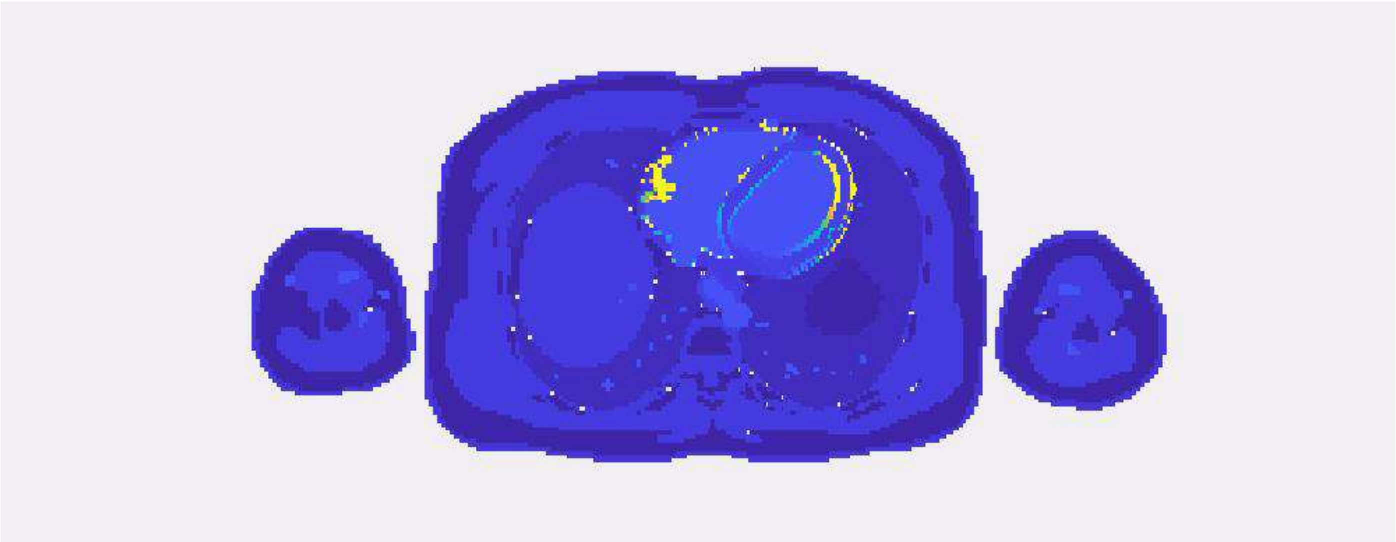
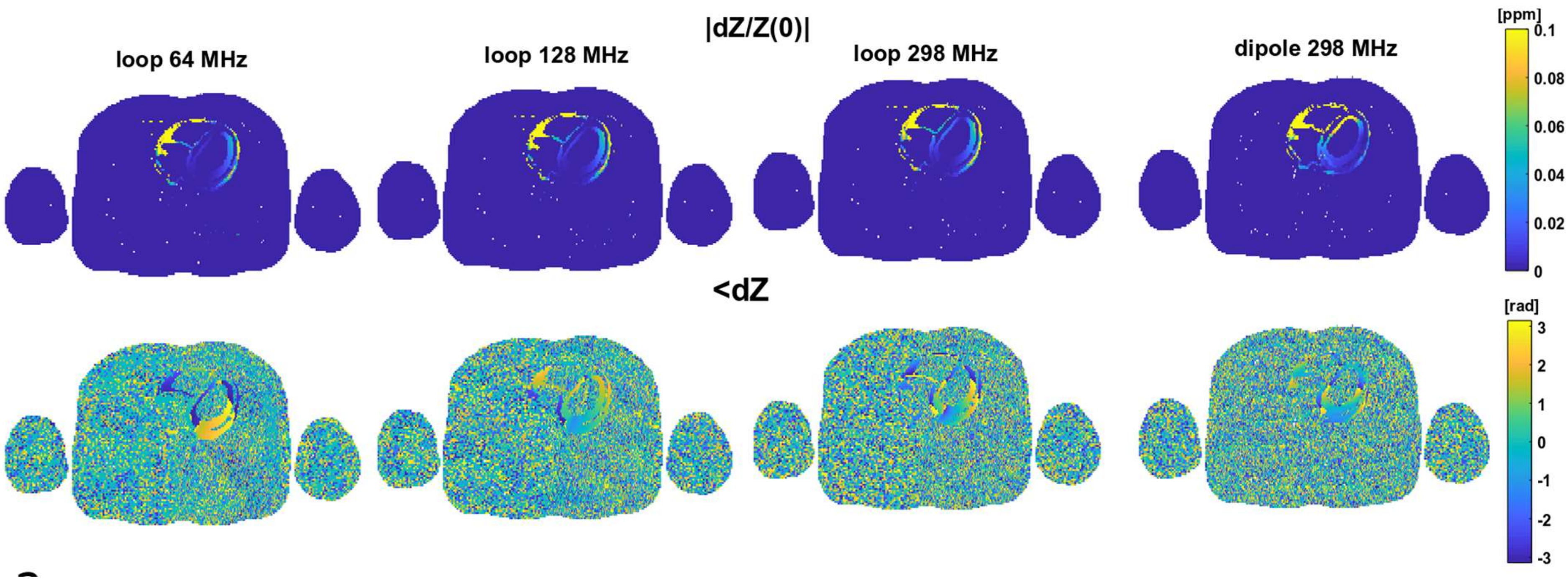
$$Z(t) - Z(0) = -\frac{i\omega}{I^2}\int_V \left[\left(\epsilon(r,t) - \epsilon(r,0)\right)\ E(r,t)\cdot E(r,0)\right]dV = \int_V\ dZdV$$

Richmond. IRE transactions on antennas and propagation. 1961

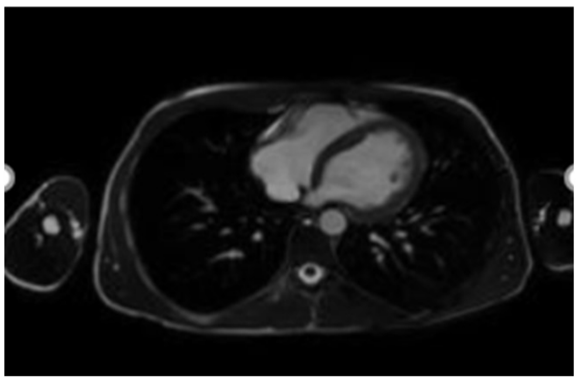
Loop antenna is sensitive to edges of heart moving through EM field

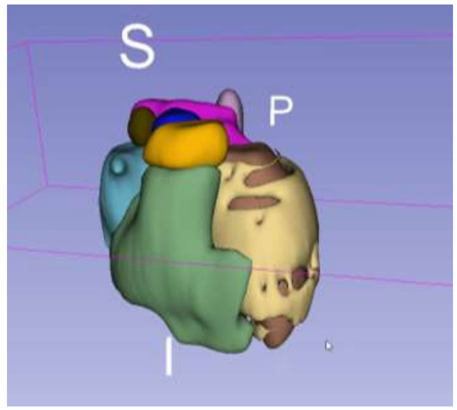


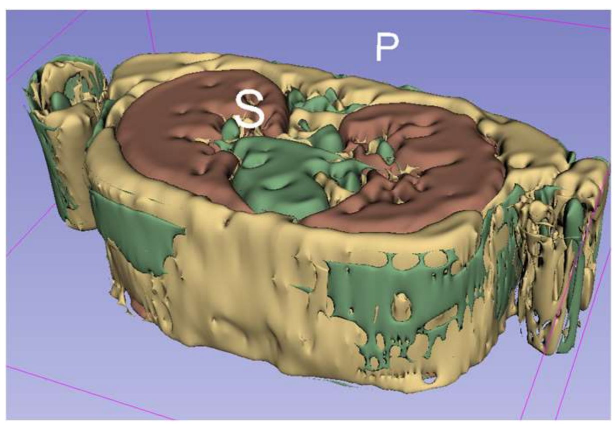

|dZ/Z(0)|
loop 64 MHz
loop 128 MHz
loop 298 MHz
dipole 298 MHz
[ppm]
0.1
0.08
0.06
0.04
0.02
0
<dZ
[rad]
3
2
1
0
-1
-2
-3

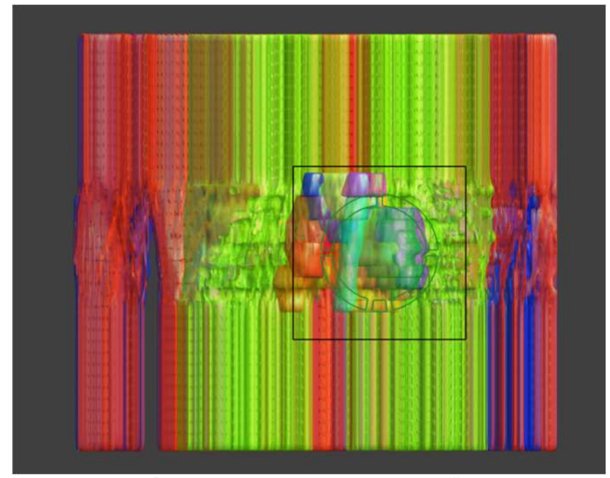
Validation with a subject specific model based on MRI

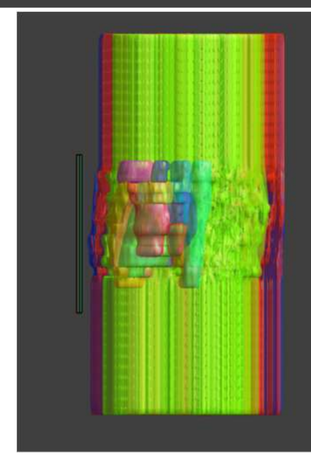
2d Transverse CINE
FOV 400*250*100 mm^3
Res 1.8*1.8*10 mm^3











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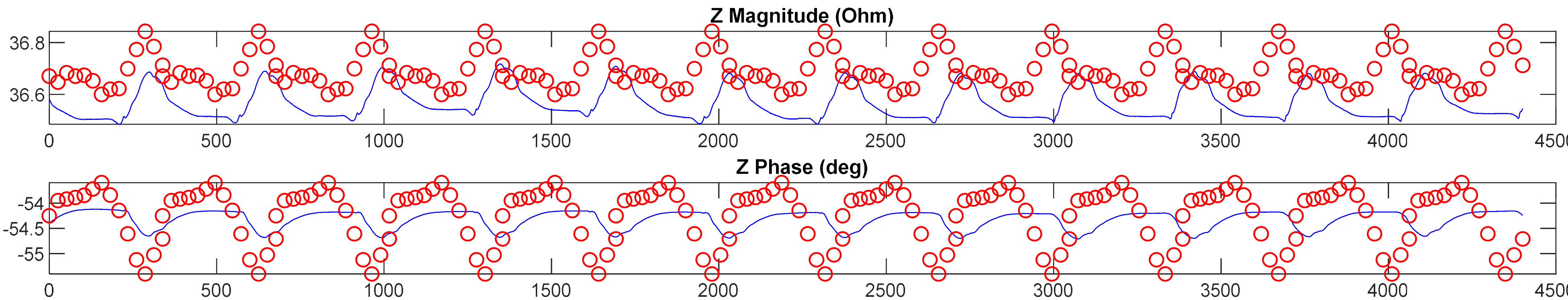
Matching between simulation and measurement



Time →

Christina Louka

Flavio Meliado

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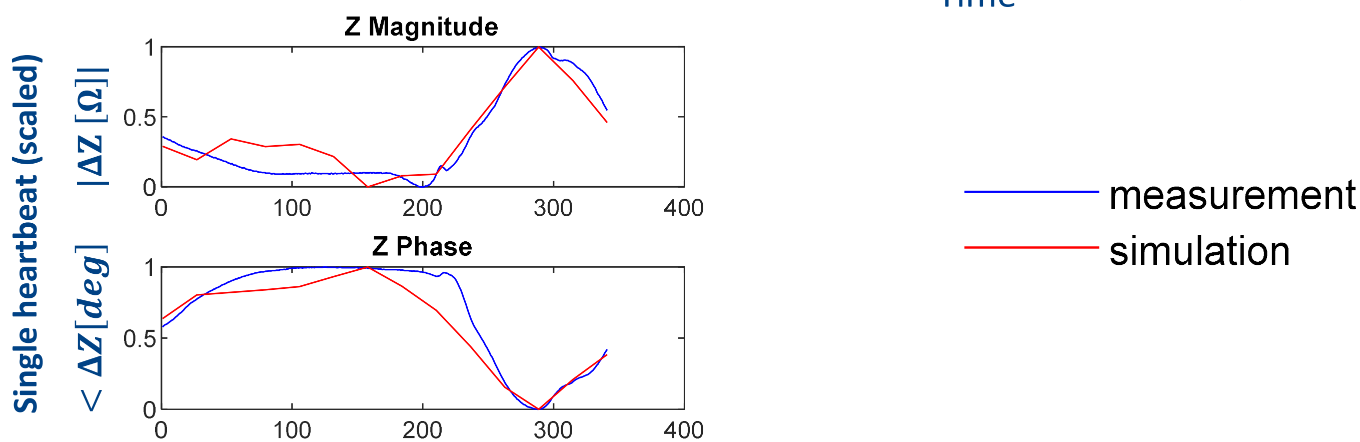
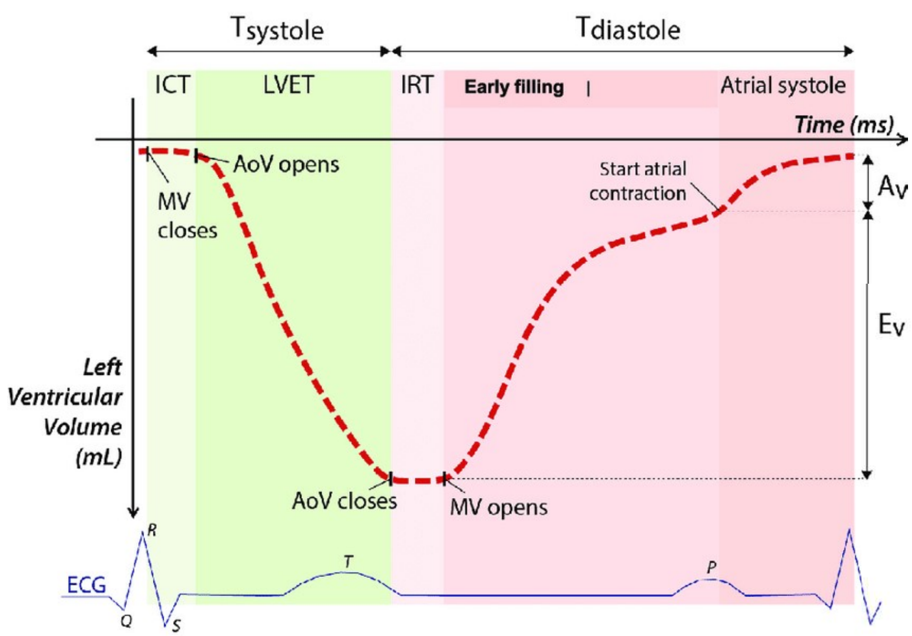
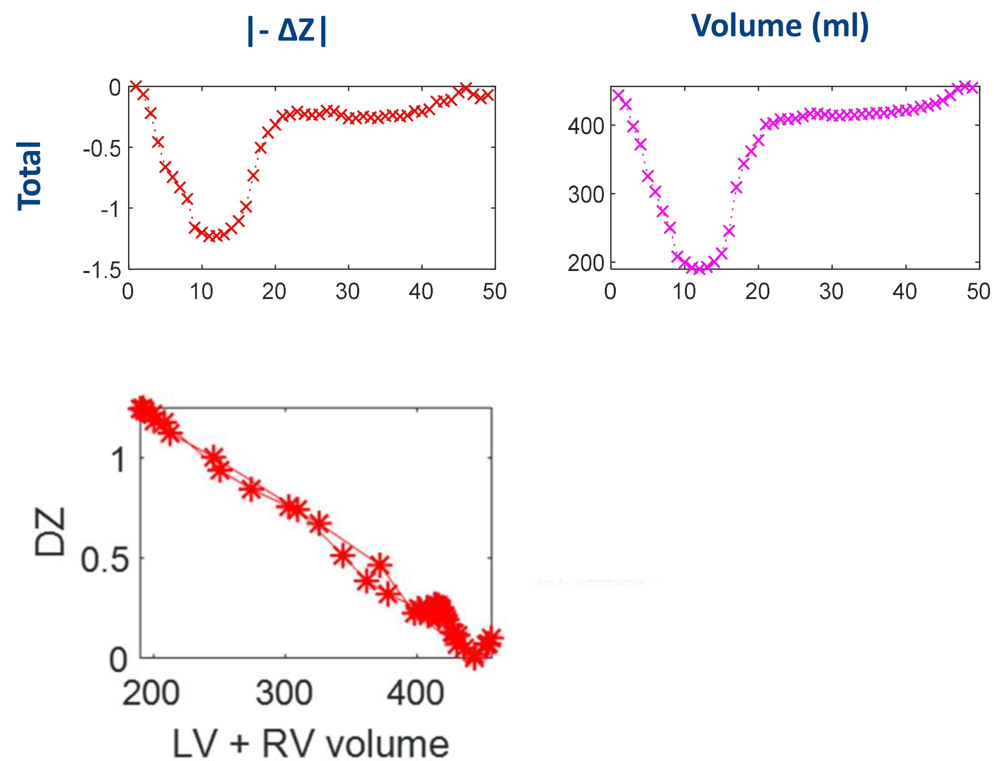


Near-linear relation between RFS signal and ventricular volumes





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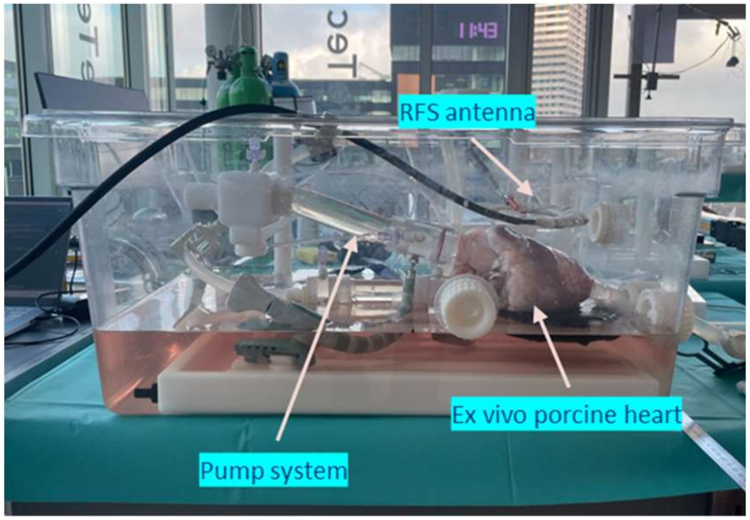
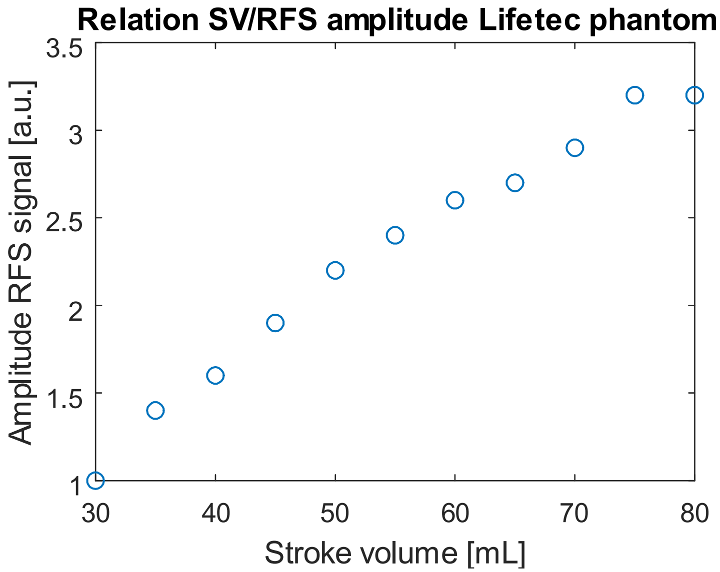
Ex vivo experiments in controlled environment confirm sensitivity to stroke volume

- The Lifetec Group, Eindhoven, The Netherlands
- Stroke volume gradually increased over time





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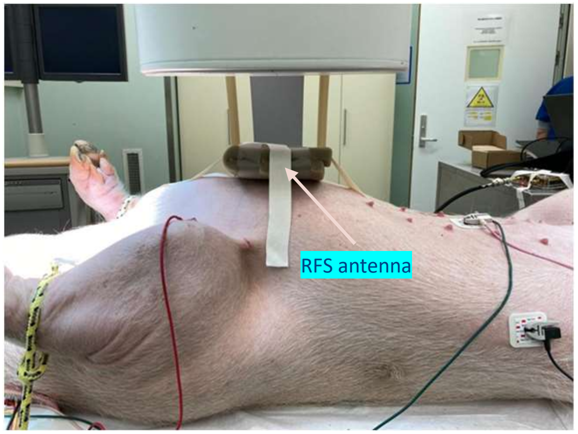
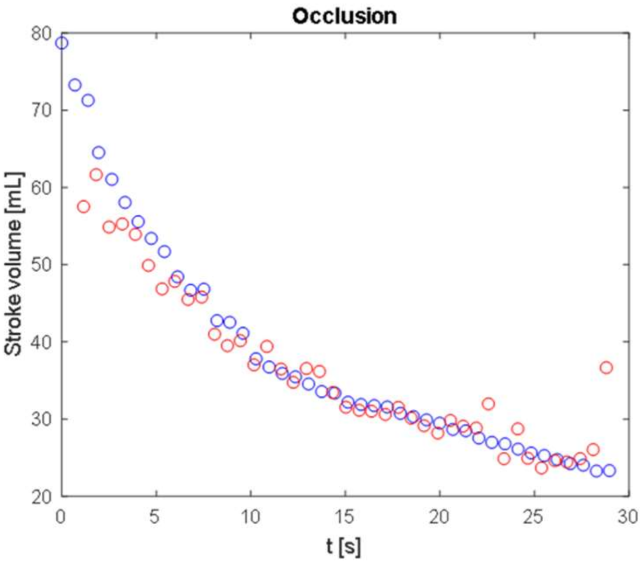
In vivo porcine stroke volume correlates to amplitude RFS

- Existing experiments were occlusion balloon is tested (cardiothoracic surgery)
- Stroke volume and pressure are measured with admittance catheter (van Hout et al, Physiol Rep 2014)





○ Admittance cathether (ground truth)

○ RF Sensing

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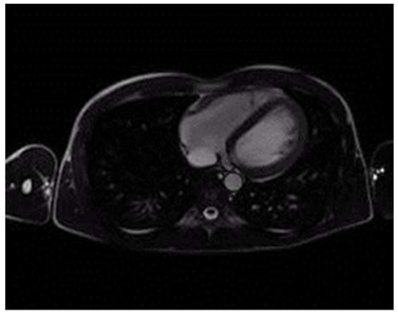
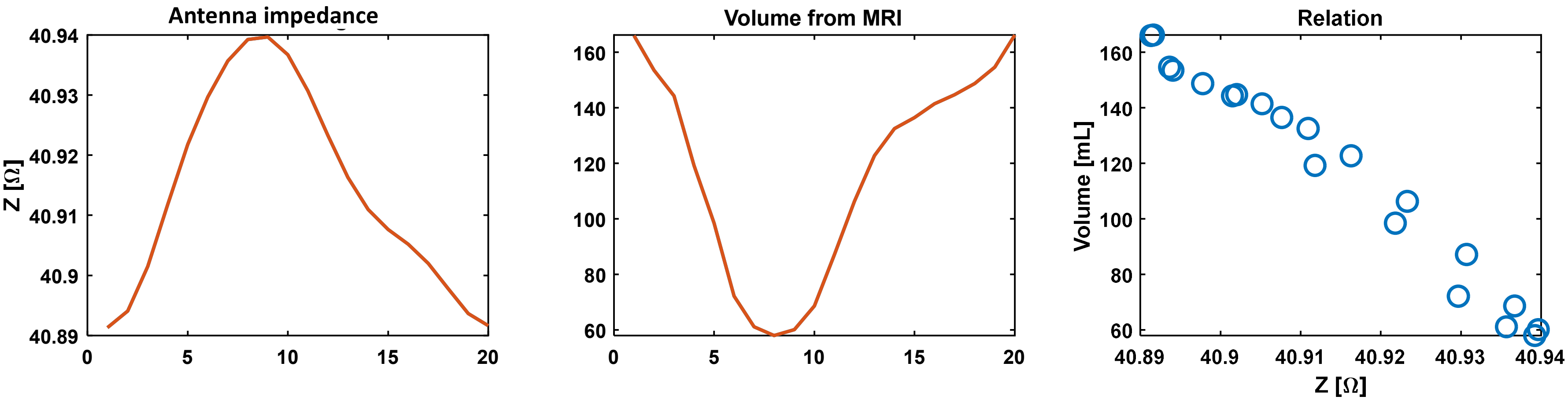
Experimental comparison to MRI shows linear relationship between RF signal and LV volume





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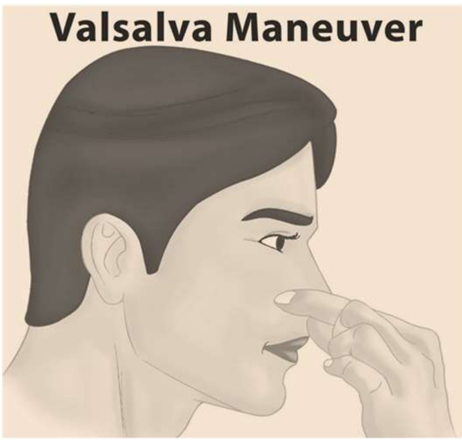
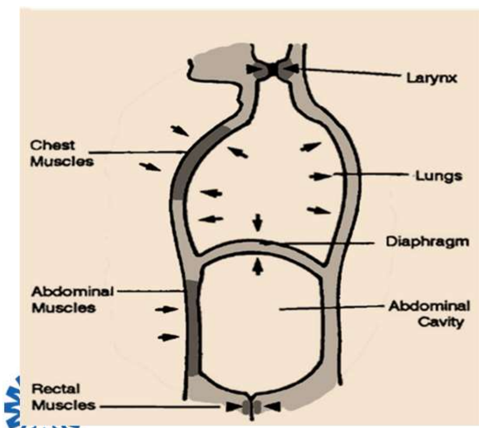
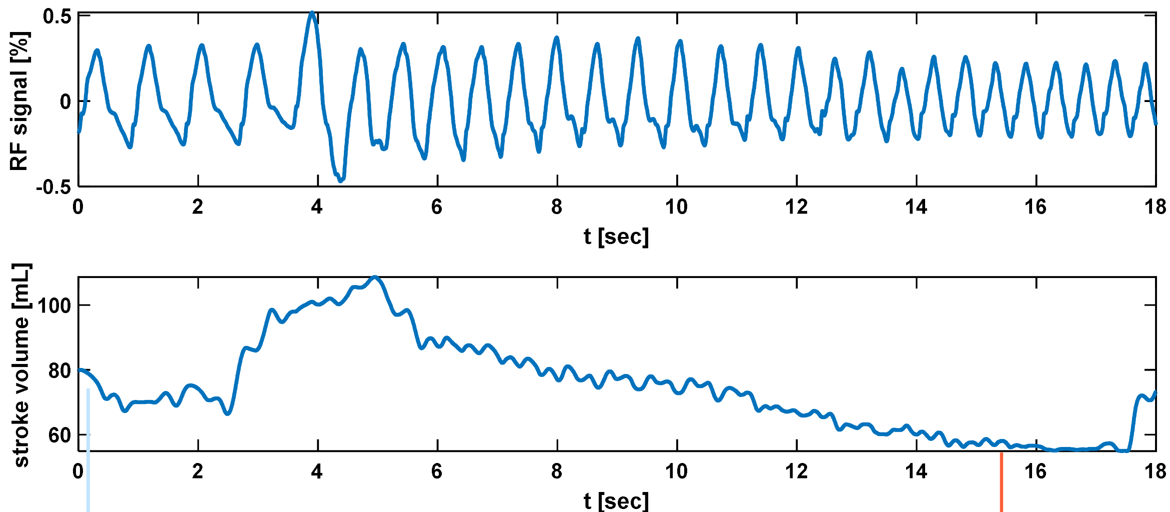
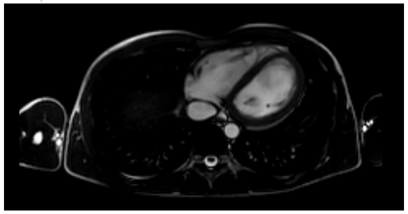
Valsalva manoeuver changes the stroke volume

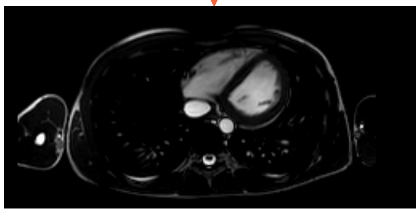






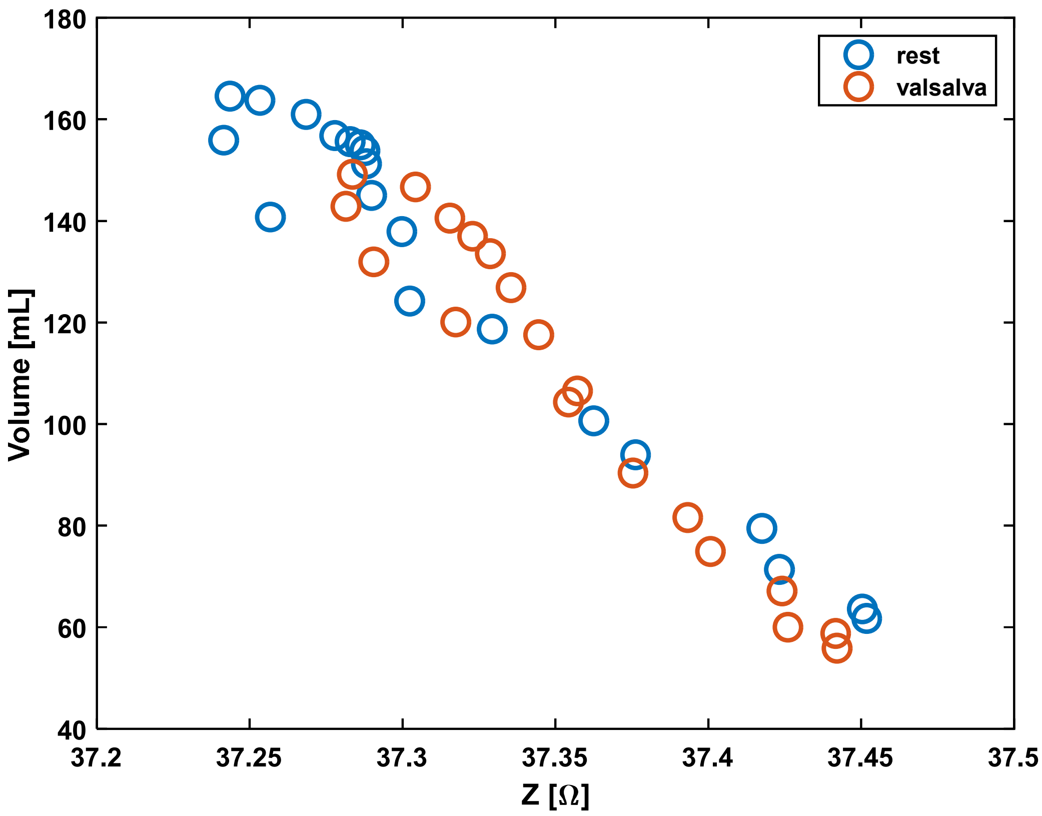


84 mL



63 mL

Valsalva manoeuver decreases left ventricular volume



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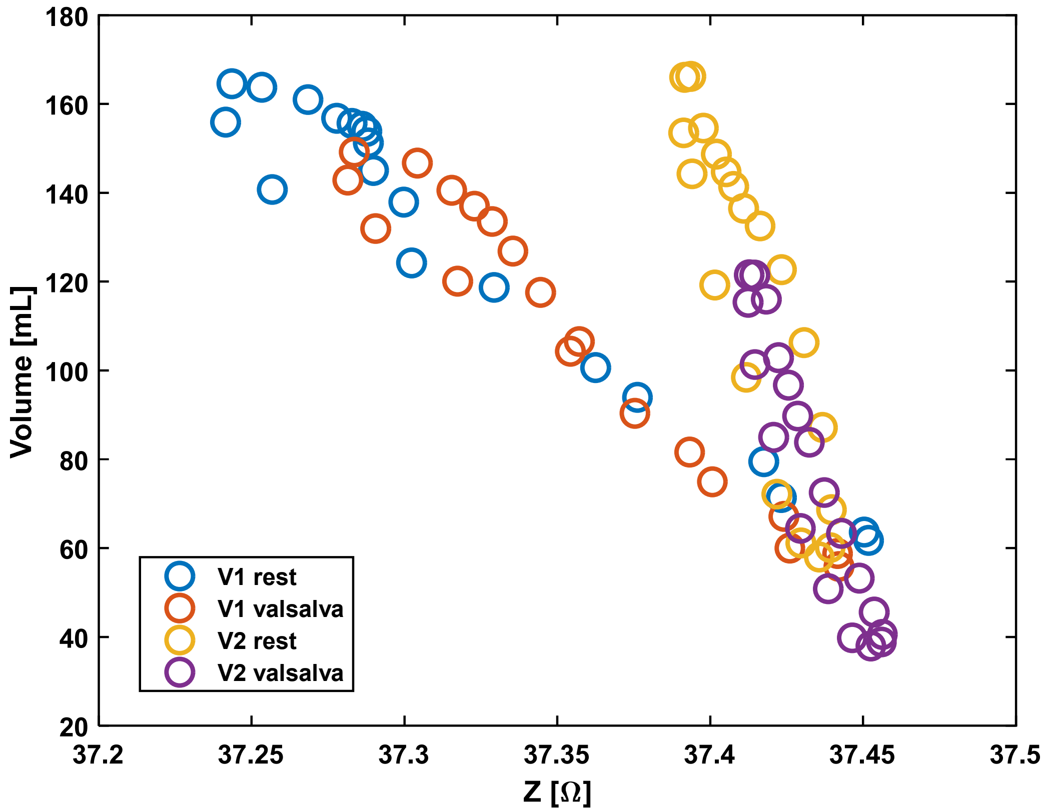
Individual calibration for LV volume is required



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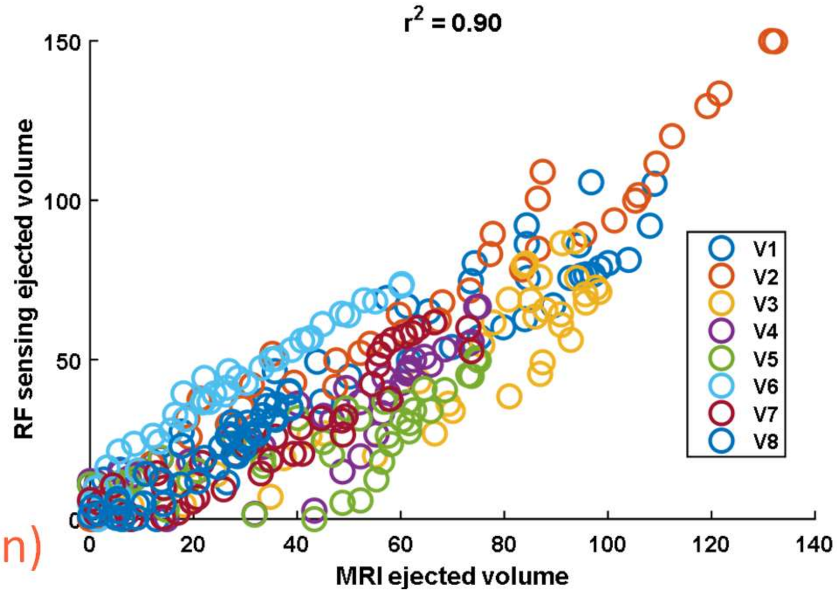
Strong correlation observed between RF sensing and MRI measurements

- **Minimize confounding factors**
- E.g. placement

- **However, calibration could be required**
- Subject specific (modelling)
- Population based (modelling +data-driven regression)



- **Medical imaging, AI and EM simulations important building blocks**

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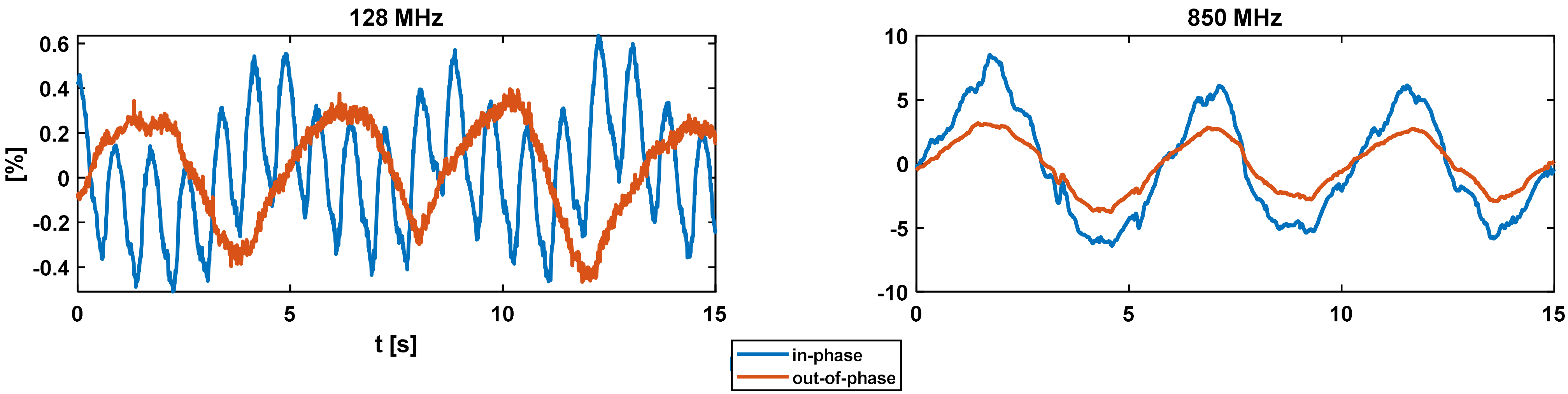
Measurement frequency strongly affects sensitivity to cardiorespiratory motion

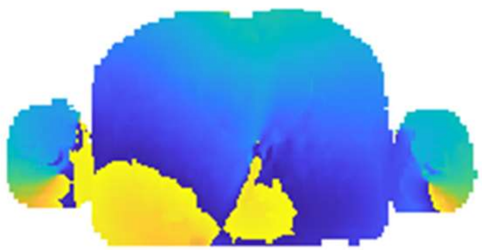
Data acquired on the same subject, in free breathing



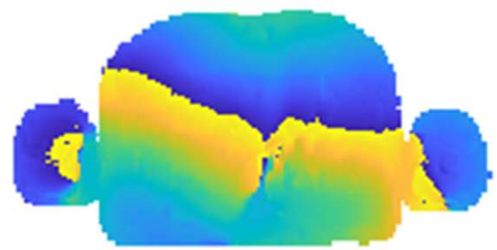
Increasing RF frequency leads to more complex spatial weighing

$$Z_{\mathrm{t}} - Z_0 = -\frac{j\omega}{I^2}\int_V \left(\epsilon_{r,t} - \epsilon_{r,0}\right)\overbrace{E_{r,t} \cdot E_{r,0}}^{\text{EM field}}\, dV$$

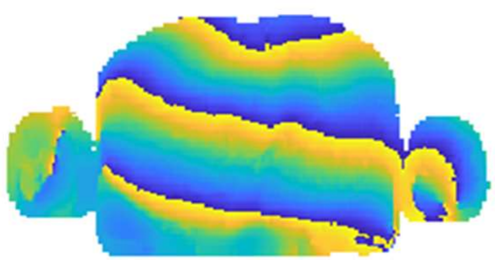
64 MHz



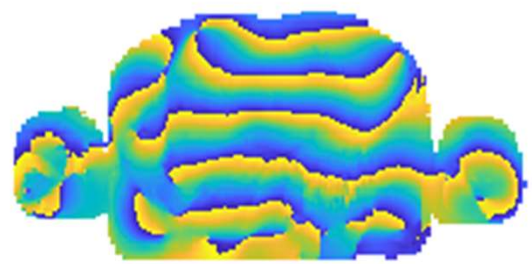
128 MHz



300 MHz



600 MHz



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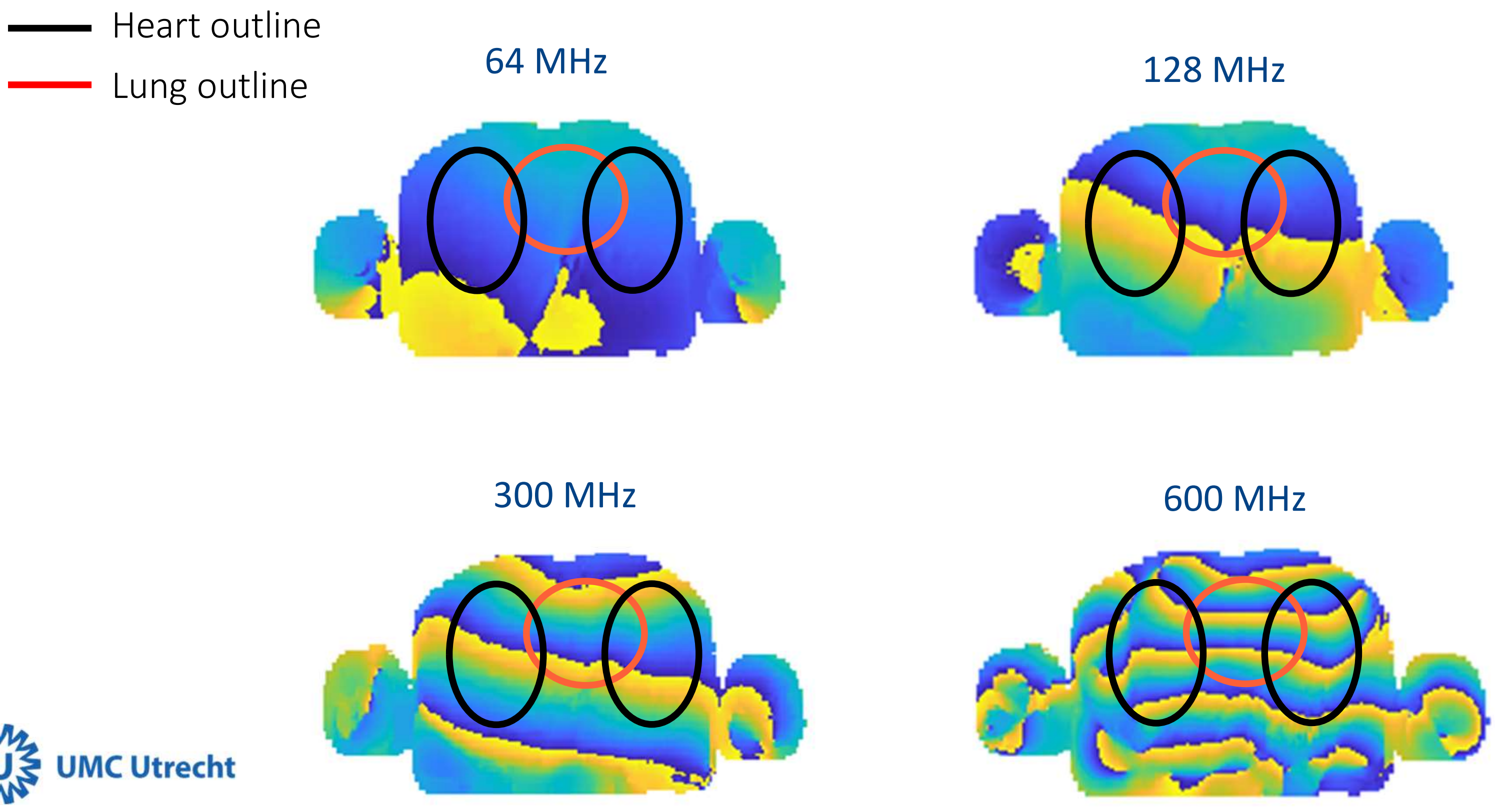
Increasing RF frequency leads to more complex spatial weighing

$$Z_{\mathrm{t}} - Z_0 = -\frac{j\omega}{I^2}\int_V \left(\epsilon_{r,t} - \epsilon_{r,0}\right) E_{r,t} \cdot E_{r,0}\, dV$$



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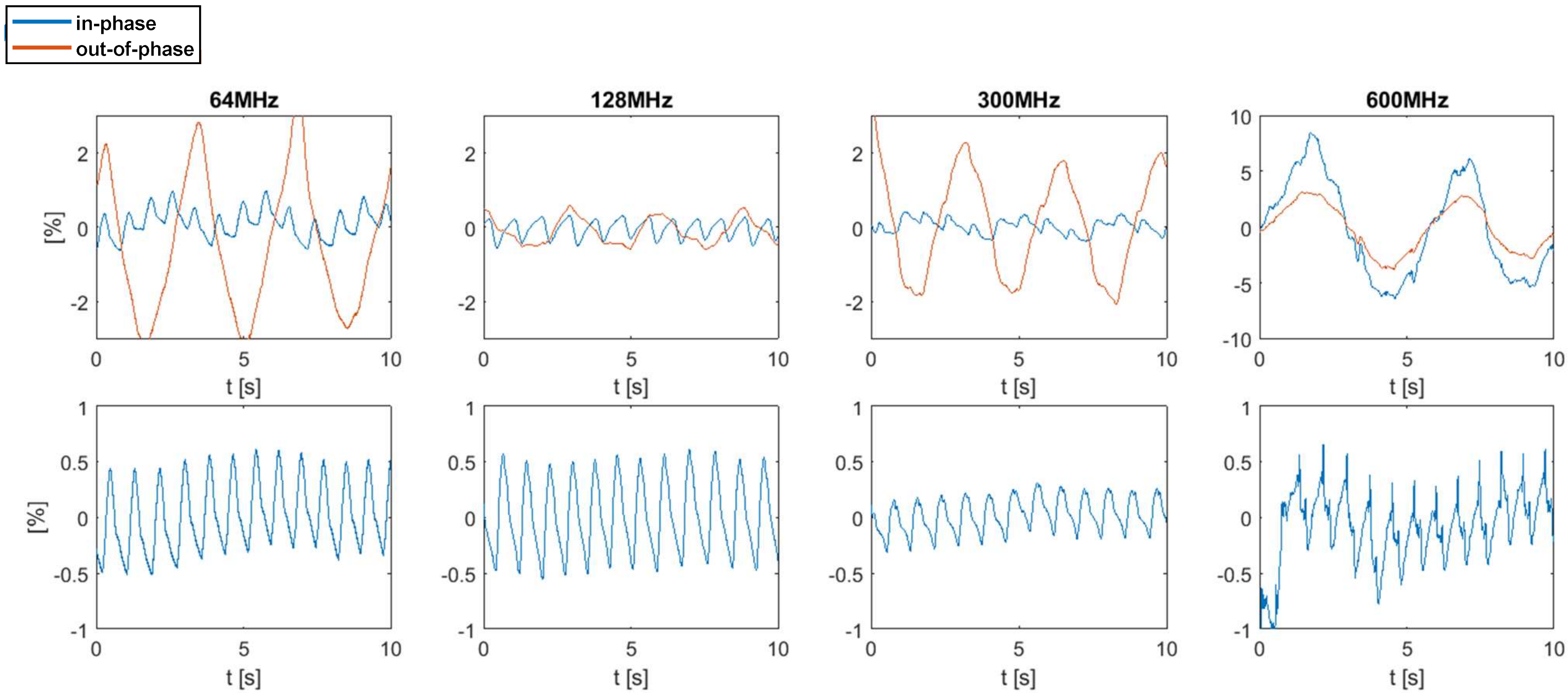
Experimental frequency comparison



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Preliminary conclusions on frequency optimization

- At lower frequencies (< ~300 MHz), better sensitivity to ventricular volume
- Likely sensitive to surface motion or motion of substructures at higher frequencies
- higher frequencies -> more spatial encoding capability
- Experimental results best with 128 MHz, best separation between respiratory and cardiac motion

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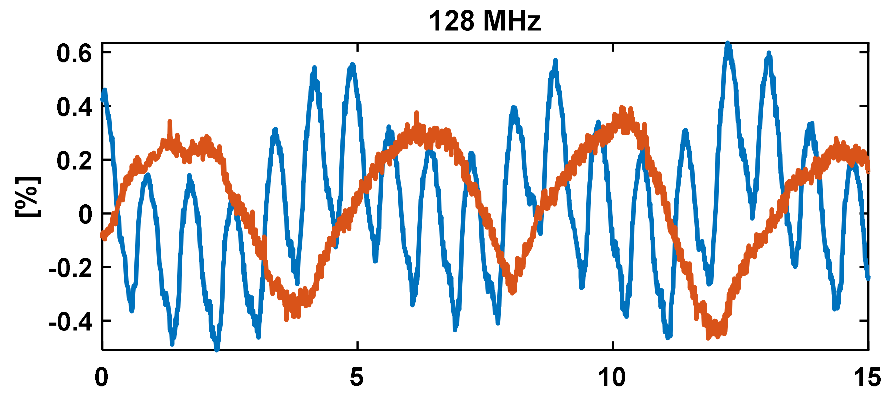

Conclusions and discussion

- Simulation platform enables in-depth study into physical principles and feasibility of RF sensing of stroke volume

- RFS sensing provides none-invasive mechnical information about cardiac function.

- Preliminary validation studies indicate feasibility of measuring stroke volume -> heart failure monitoring

- RF sensing combined with ingredients like MRI, AI and physical modelling will provide new ways of measuring cardio-vascular function outside a hospital setting.

Thank you all

Computational Imaging Group
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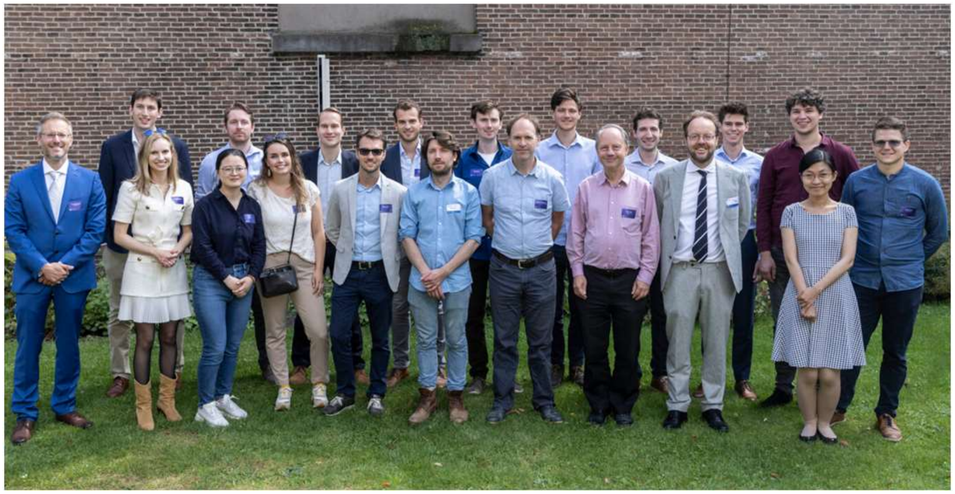
Mats Vervoorn

Technology Transfer Office
Frederieke Smeitink
Holger Veenhuis

PrecorDx
Jaap de Bruin



Circulatory Health UMC Utrecht

NWO

Hartstichting

Dutch CardioVascular Alliance

UTRECHT HOLDINGS

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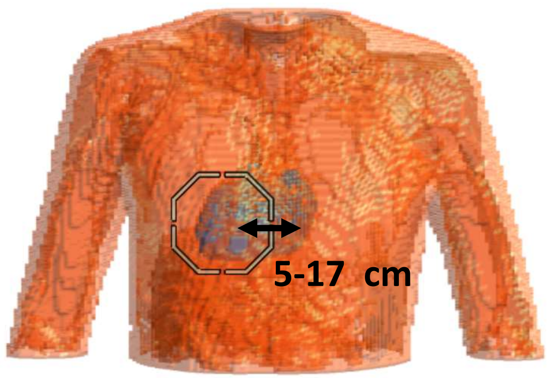
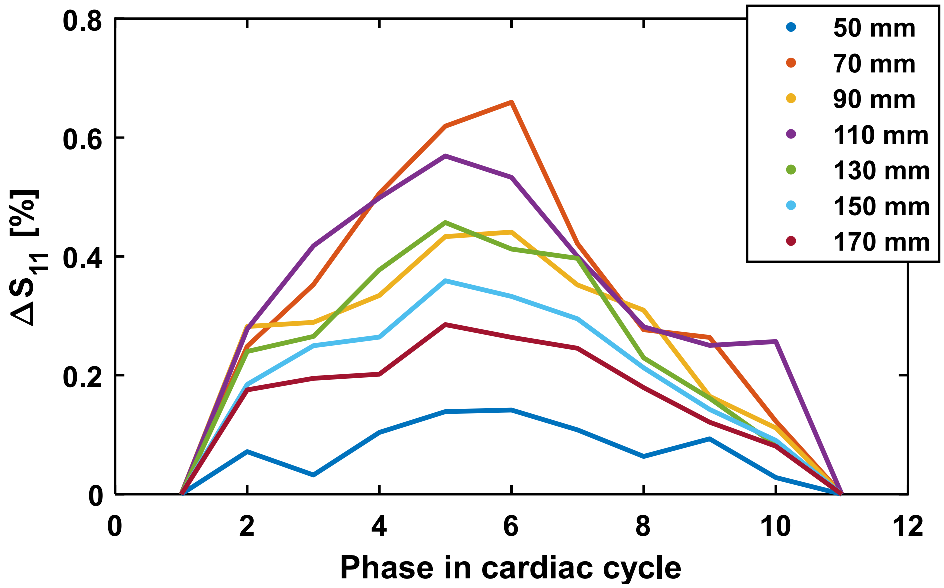
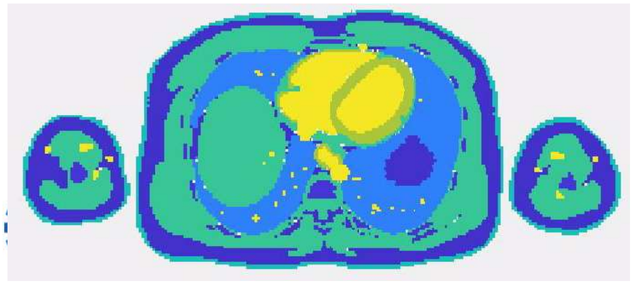
In silico optimization of loop antenna diameter

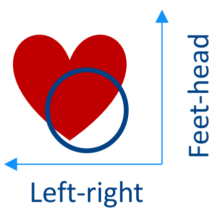


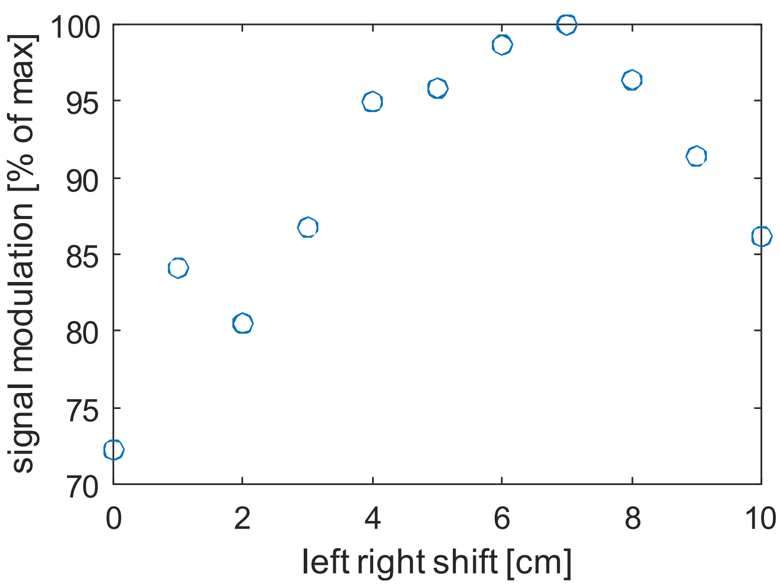


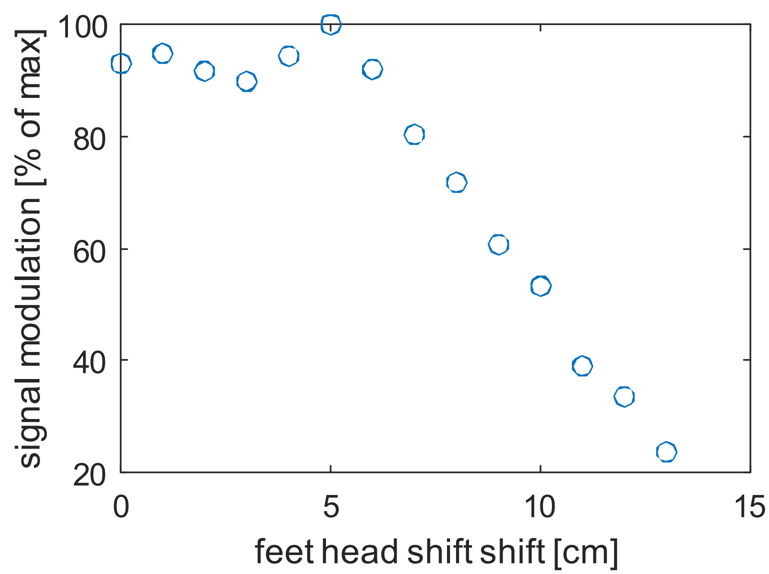


11 simulations to simulate full cardiac cycle,
11*7 for all different loop sizes

Antenna positioning needs to be precise within ~1 cm







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Optimal loop size and position differs per subject

Results from Romy O’Connor