# High Spectral and Spatial Resolution MR Imaging for Radiation Therapy

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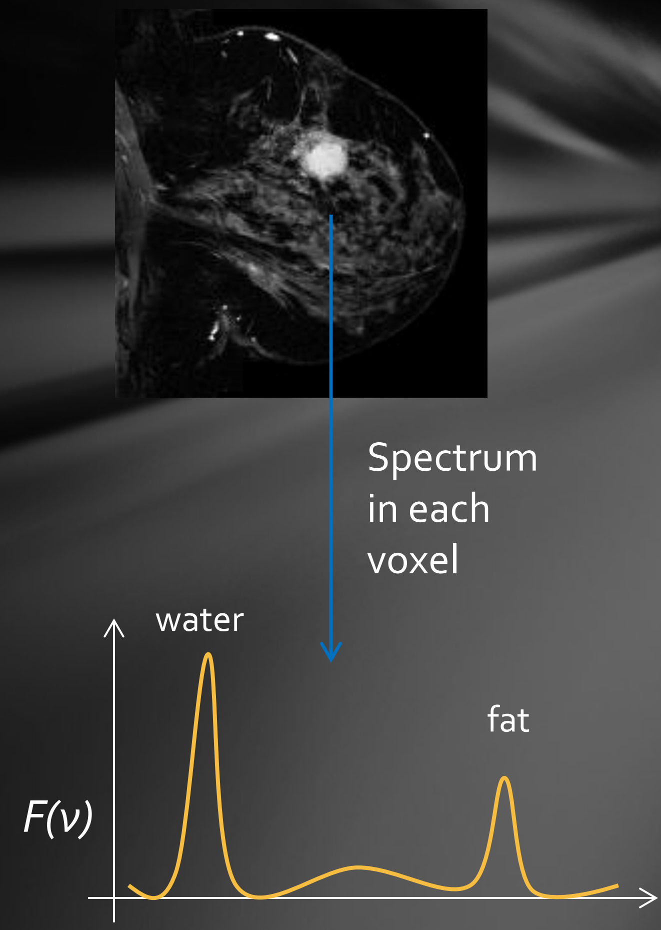
# Outline

- High Spectral and Spatial Resolution MR Imaging (HiSS)
  - What it is
  - How to do it
  - Ways to use it
- HiSS for Radiation Therapy
  - Potential role in RT

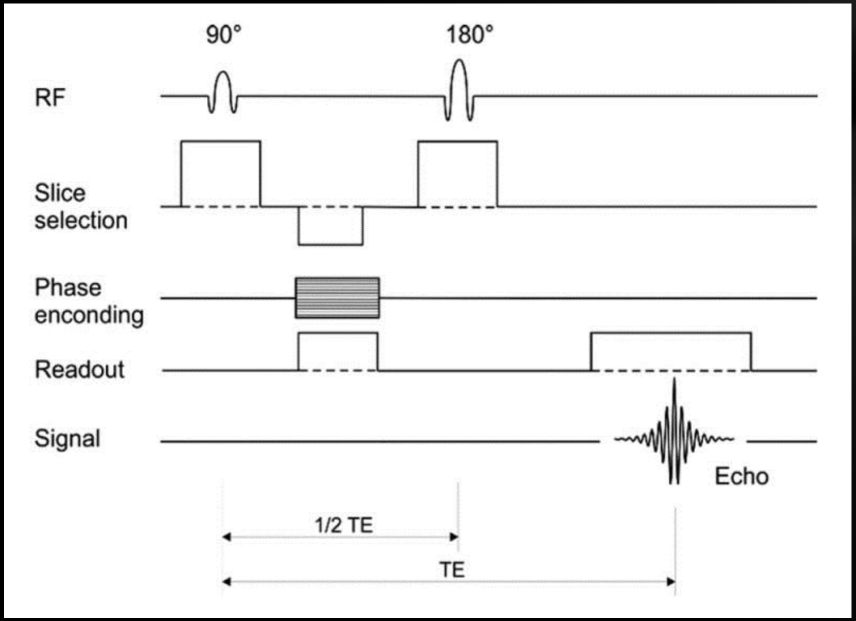
# High Spectral and Spatial Resolution MR Imaging

- Spectroscopic imaging (SI) technique
  - High spatial resolution ≈ $mm^3$
  - 1 spectrum in each voxel
    - Water and fat peaks
- Advantages:
  - Near-complete fat suppression[1,2]
  - High quality images[2,3]
  - Investigate sources of broadening of the water resonance[4,5,6]
- Disadvantages:
  - Long imaging time
  - Computationally demanding processing

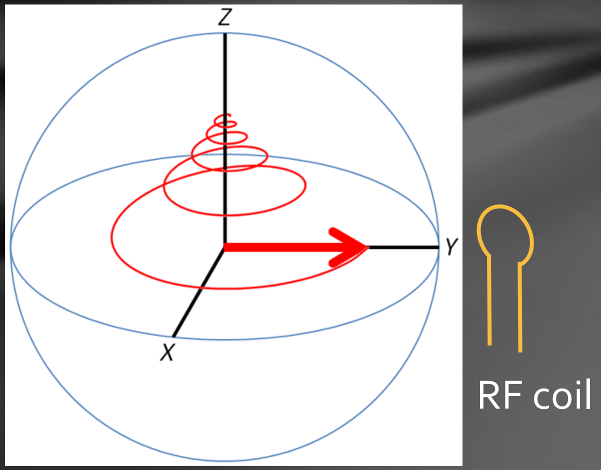


# MR Data Acquisition

- RF excitation produces free induction decay (FID)
- k-space data acquired at "Echo time" or TE
- Wait for signal to decay then repeat
  - "Repetition time" or TR

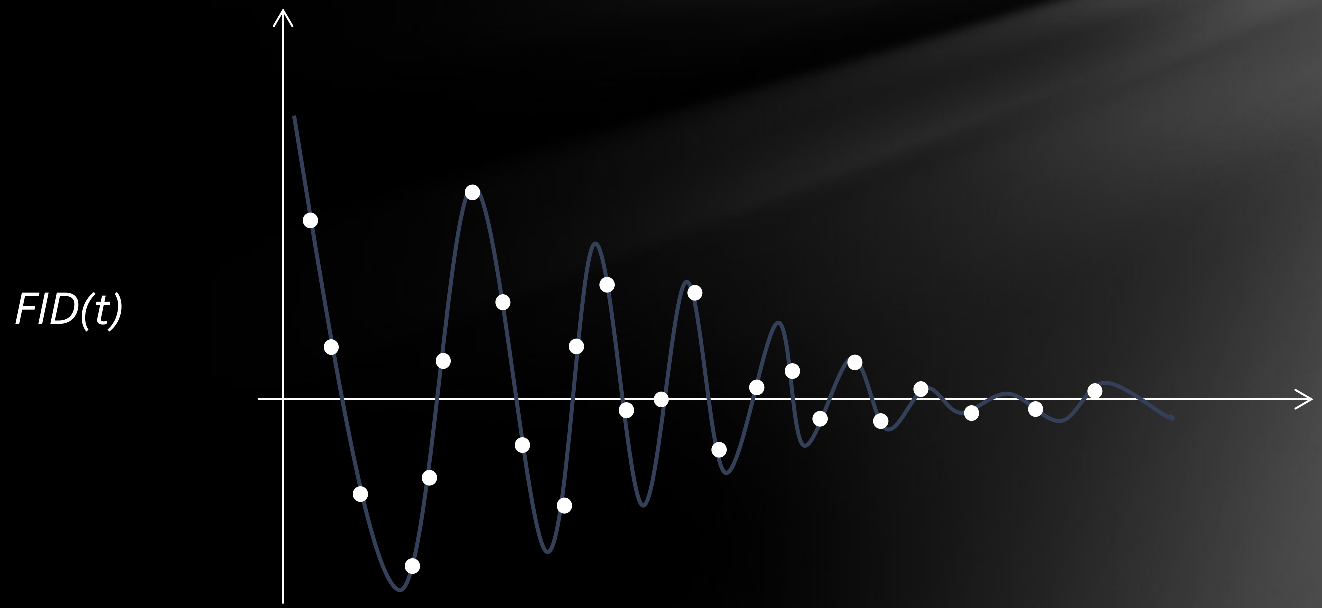



Free induction decay

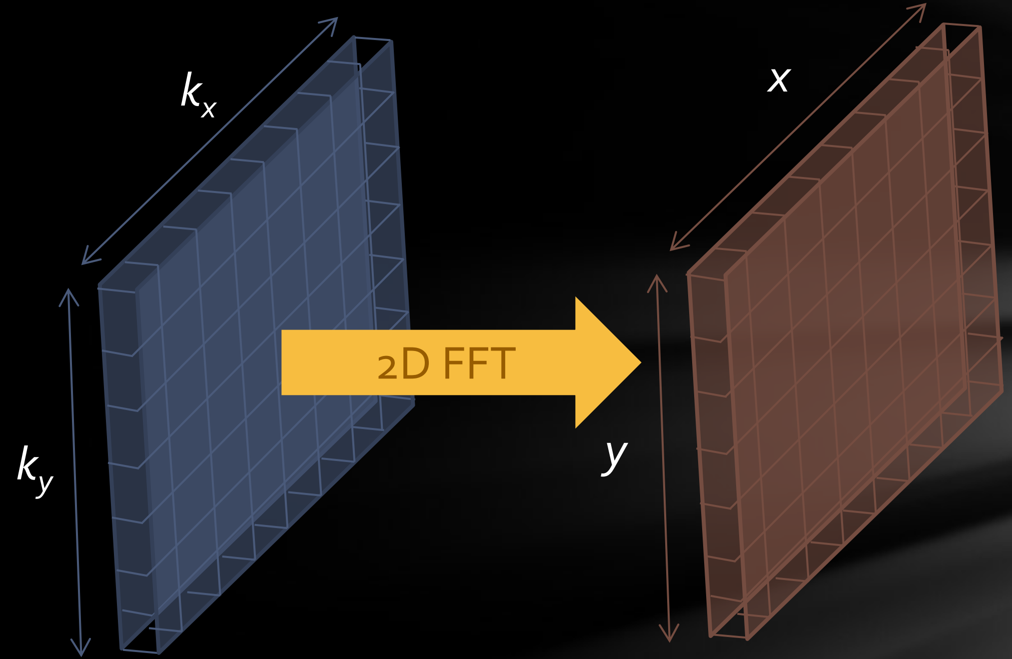


# HiSS - Sampling the Free Induction Decay

- Waiting for signal to decay, why not sample it?
- Acquire several "echoes"
  - Turn readout gradient on
- Drastically improves SNR
  - Computationally costly to process
  - Offload and process on external workstation



# MR Data Reconstruction



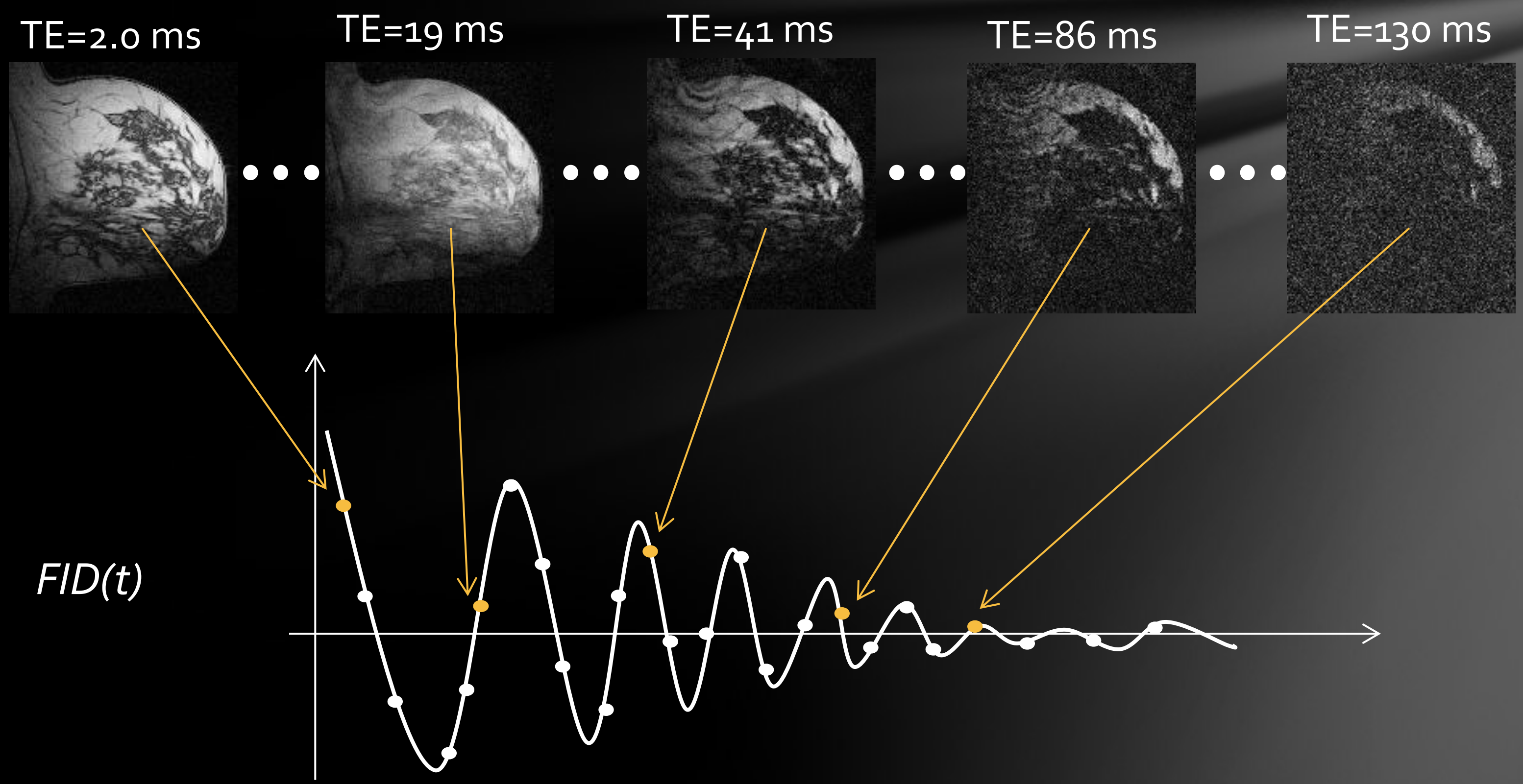

*"k-space"* *"x-space"*


$$F(x) = \sum_{n=0}^{N-1} f(n) e^{-j2\pi(x\frac{n}{N})}$$

$$f(n) = \frac{1}{N} \sum_{n=0}^{N-1} F(x) e^{j2\pi(x\frac{n}{N})}$$

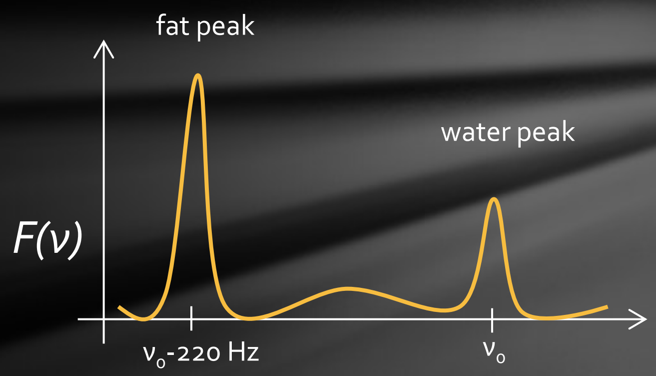
# HiSS Data Reconstruction

- Start with 2D FFT of k-space planes
  - 2D image for each echo time
  - FID per voxel



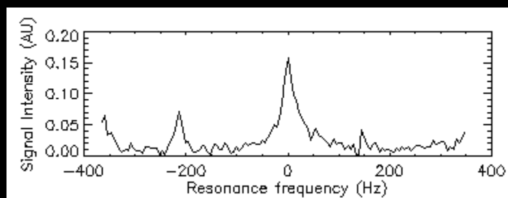
# HiSS Data Reconstruction

- FID per voxel
- FFT (FID) = NMR spectrum
  - → A spectrum in each voxel
- Some voxels have both fat and water
- Can create
  - Water peak height image
  - Fat peak height image
  - Use known separation of fat and water
    - ≈220 Hz at 1.5T

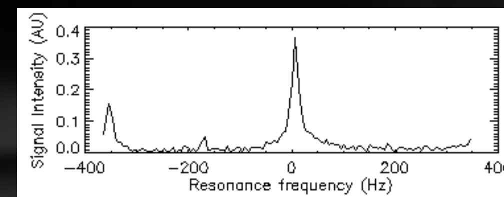


# HiSS Data Processing

- Problem: Peaks are not in the same spectral bin for all pixels

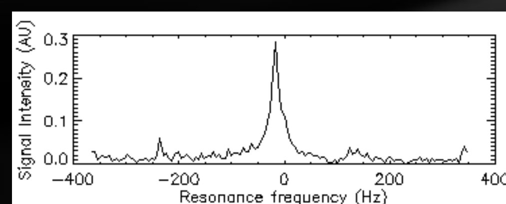



0 Hz

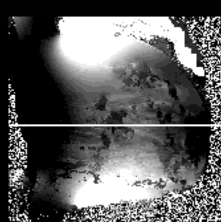


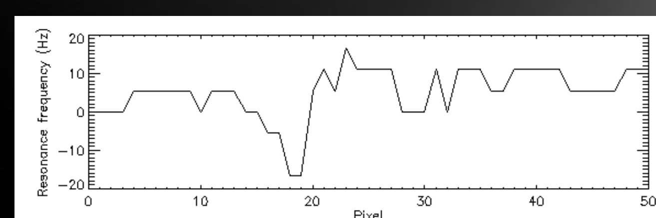

5 Hz

-10 Hz



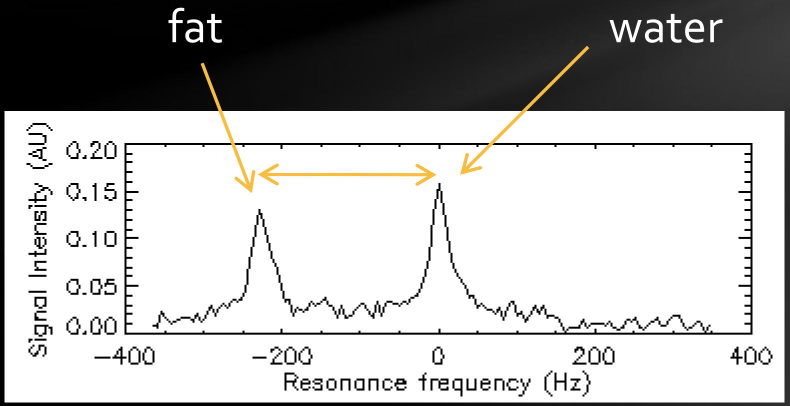

Map of water peak resonance frequency





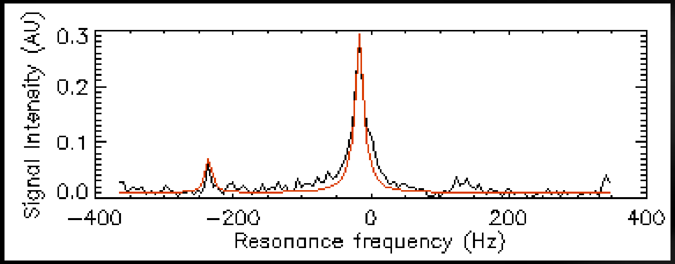
# HiSS Data Processing

- Start with a seed pixel of known tissue type
  - Automatically determined or manually input (forced)
  - Check & label neighboring pixels
- If water, is there a fat peak too?
  - Check based on fat-water separation of 220 Hz

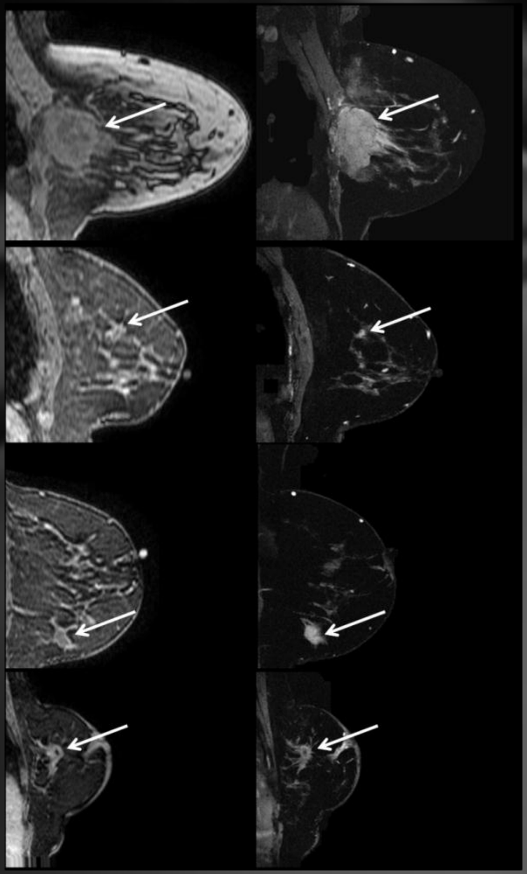


# HiSS Data Processing

- 'Label' as fat or water
  - Fit with Lorentzian lineshapes




- Near-complete fat suppression by subtracting fitted fat peak

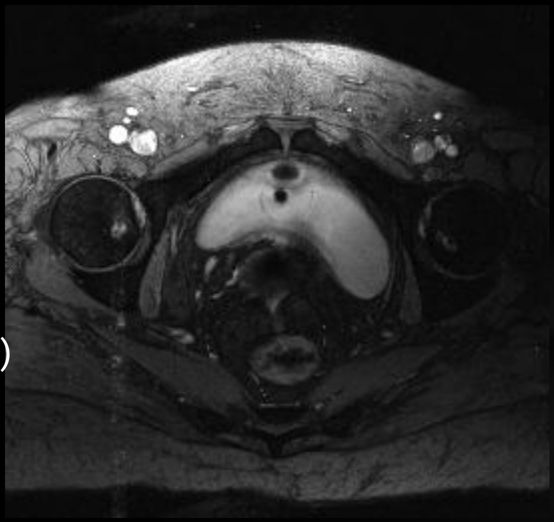


T1W fatsat

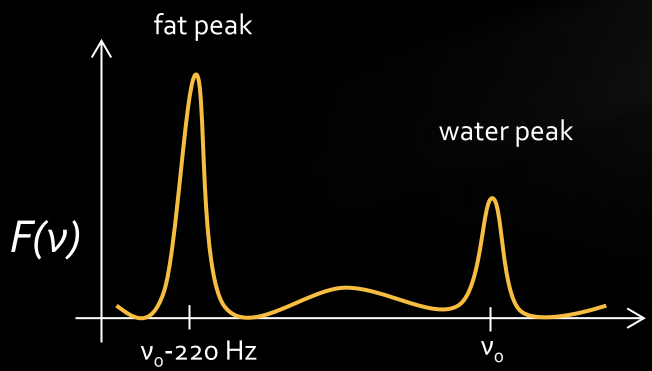
HiSS water peak height image

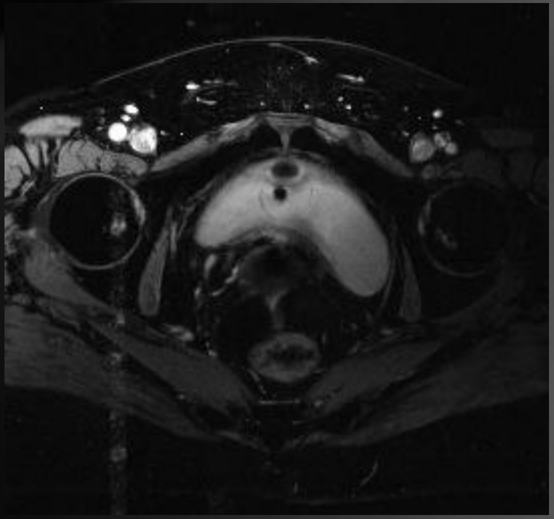
# HiSS Peak Height Images

Maximum peak (water OR fat)



**Fat** peak height image



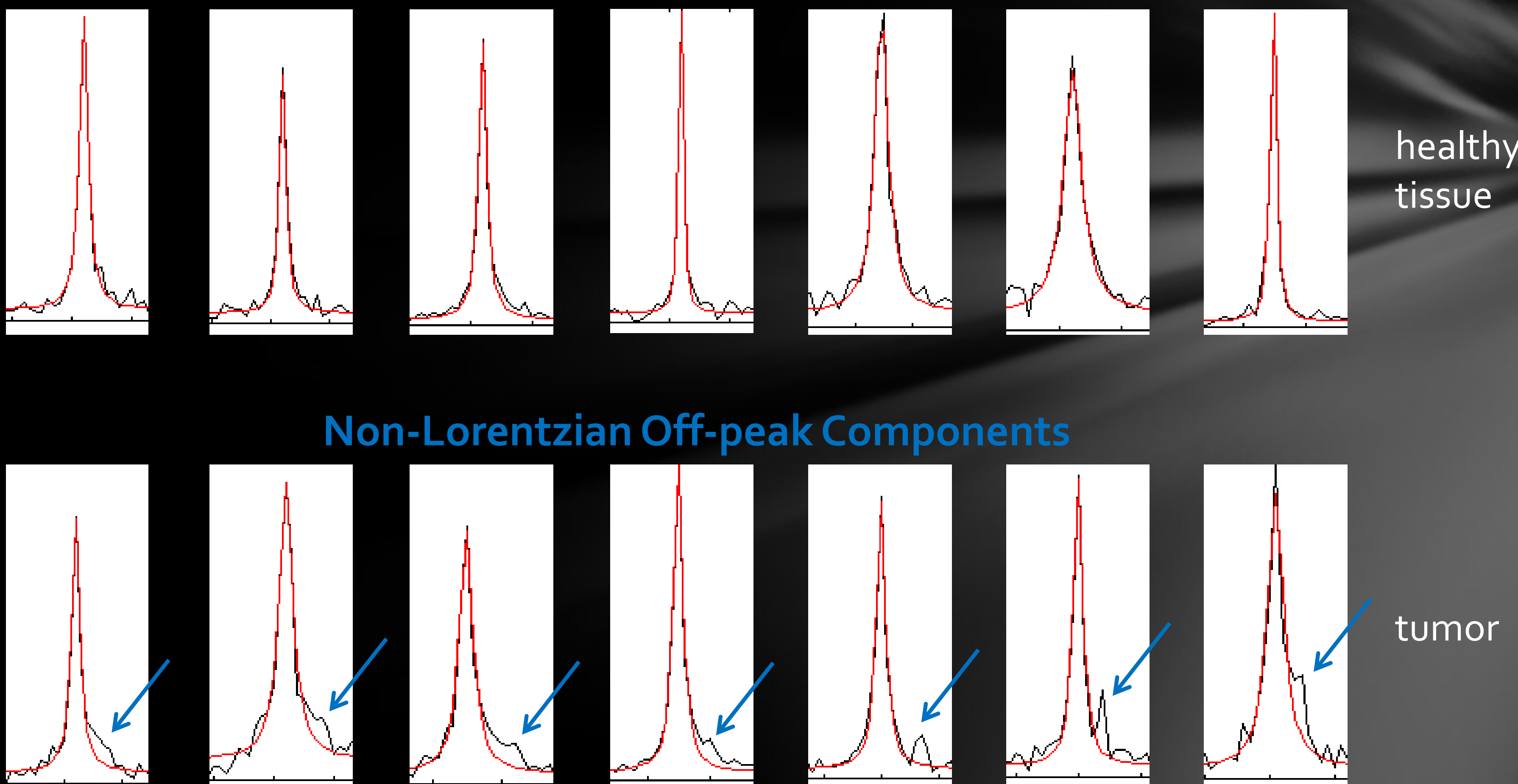



**Water** peak height image

# HiSS Imaging Overview: Conclusions

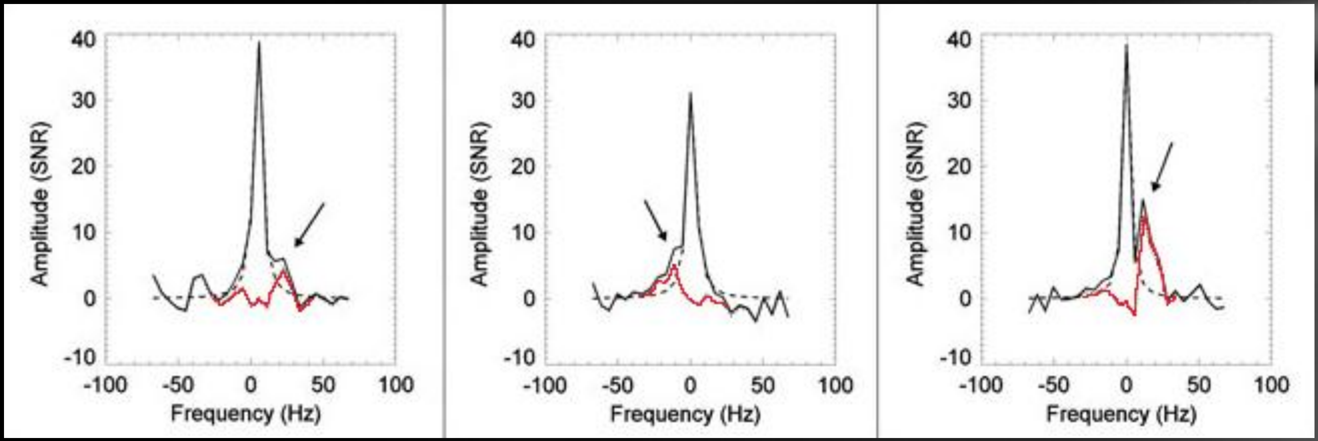
- Proton spectra in small voxels
- Generate high quality images based on fat-water separation
  - Water peak height
  - Fat peak height
- Relatively easy to acquire
- Data exported for offline processing
  - Time consuming
- What else can we gather from HiSS data?

# HiSS Spectra: Untapped Source of Contrast



# Quantifying Off-peak Components

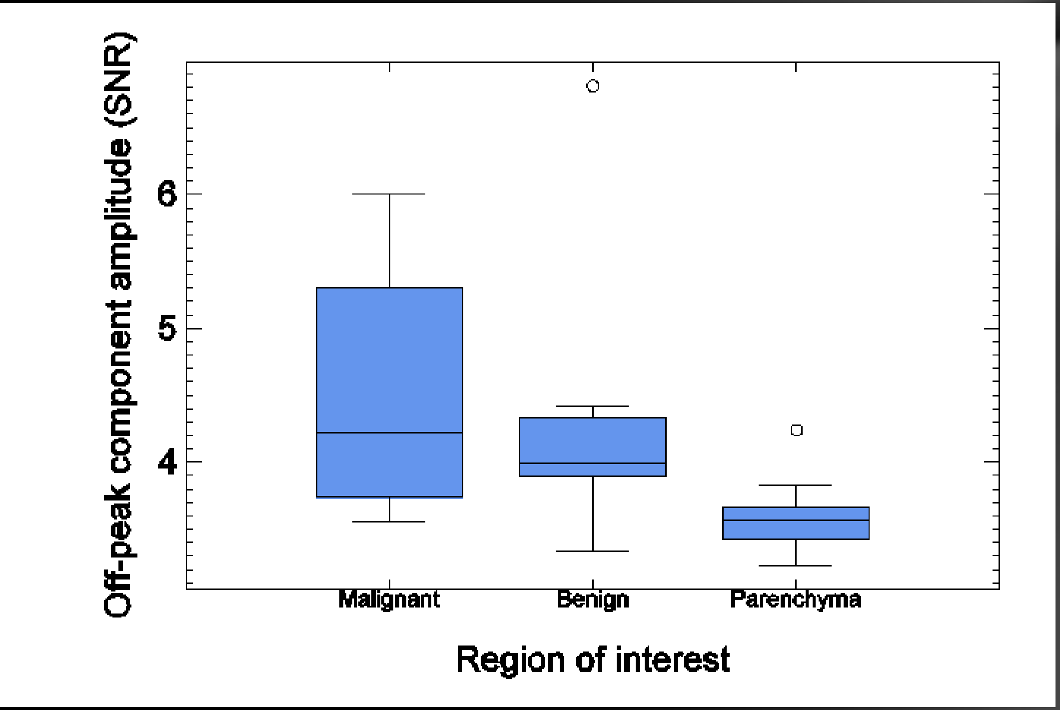
- Non-Lorentzian components
- Look at residual spectra after subtracting Lorentzian fit



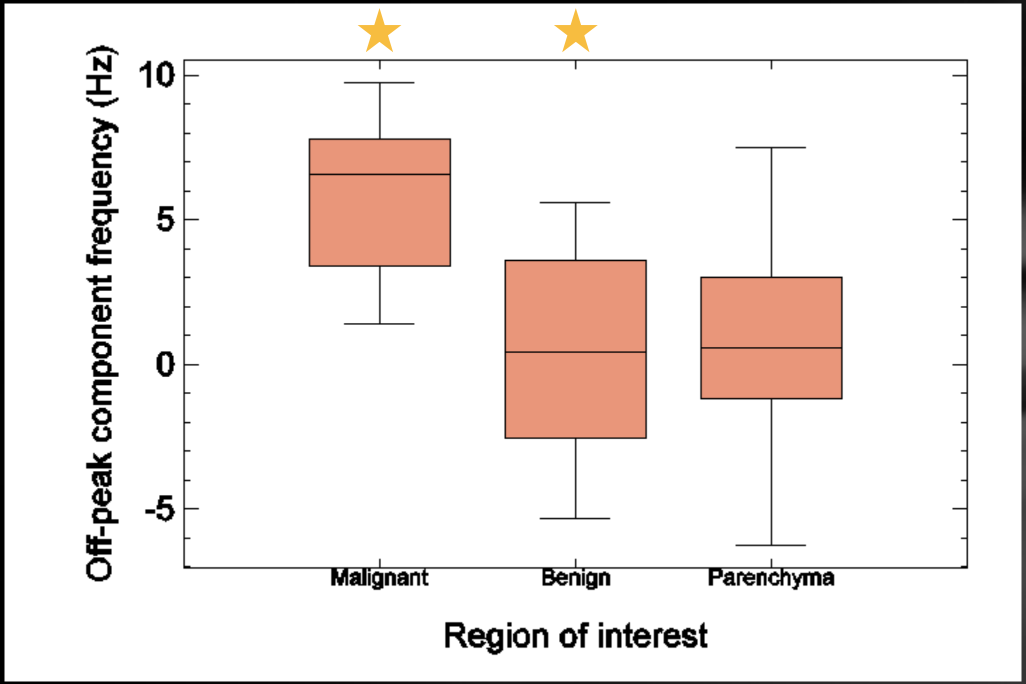

- Looked at amplitude and frequency offset of off-peak components (OPCs)

# Off-peak components - breast

- 27 patients[6]
  - 18 malignant lesions
  - 9 benign lesions
  - Parenchymal ROIs when available
- No significant differences in OPC amplitude



# Off-peak components - breast

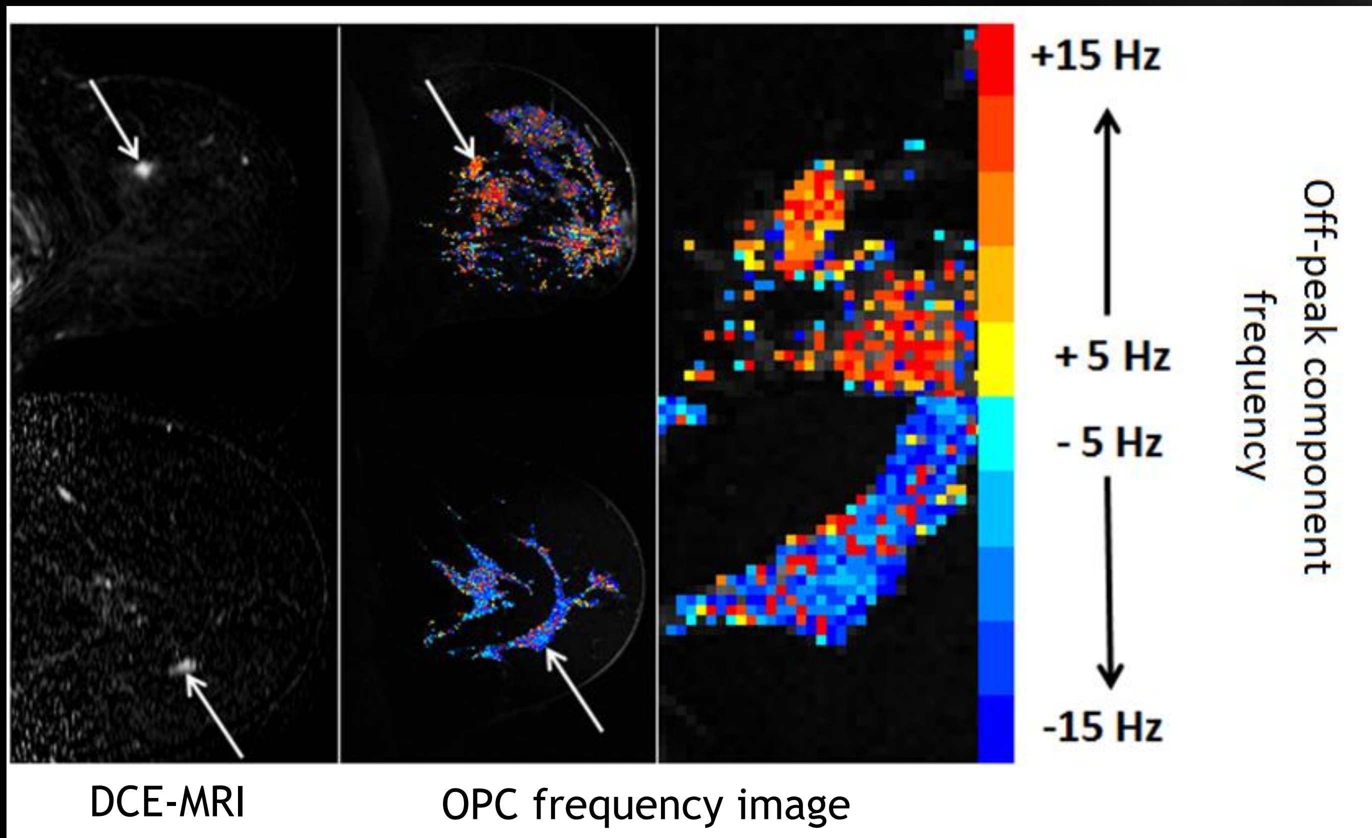



- OPC frequency significantly different between malignant and benign lesions
  - *11.3 Hz vs. 1.3 Hz*
- OPC frequency similar in benign lesions and parenchyma

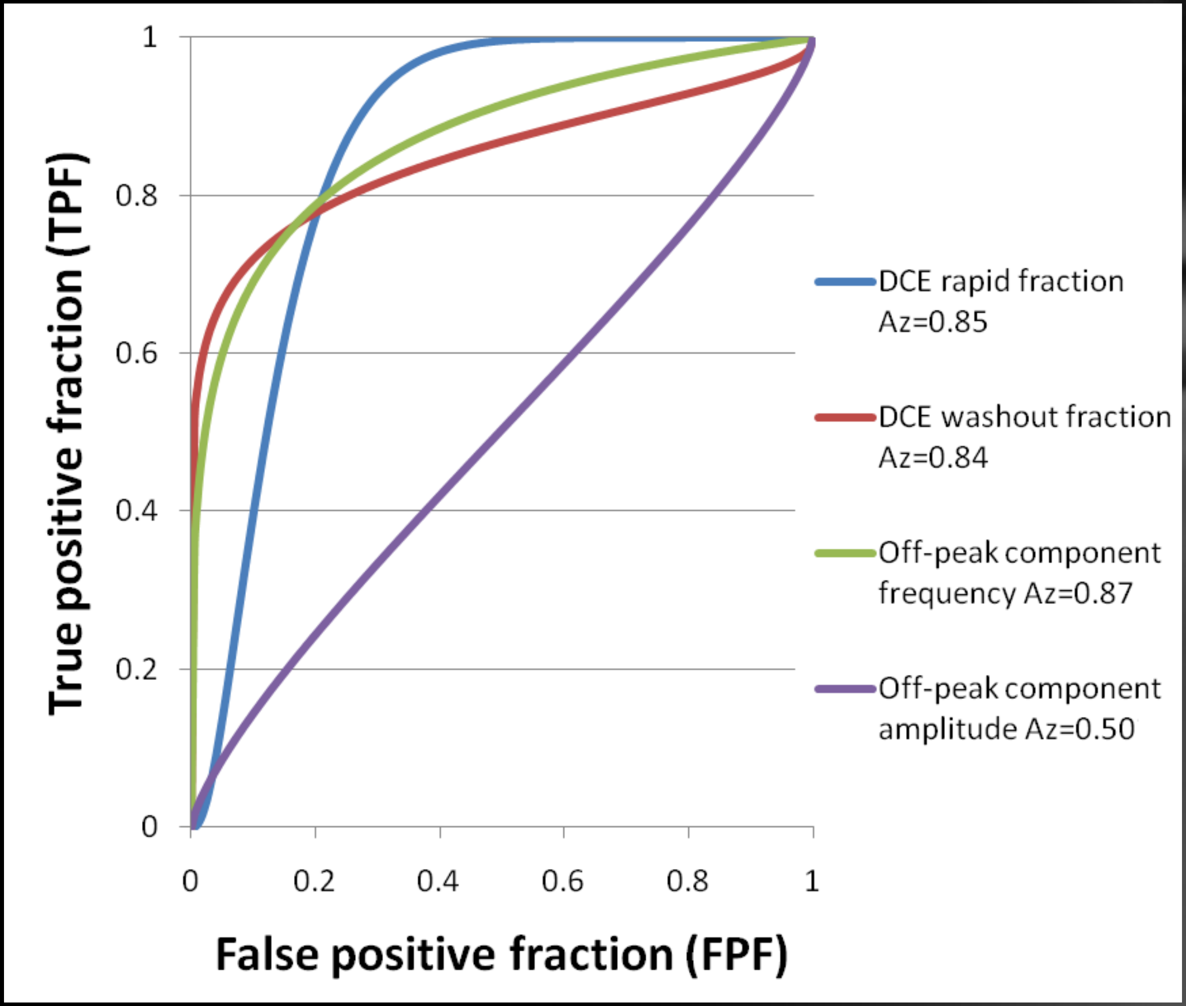
# Off-peak component images

Malignant IDC

Benign FA

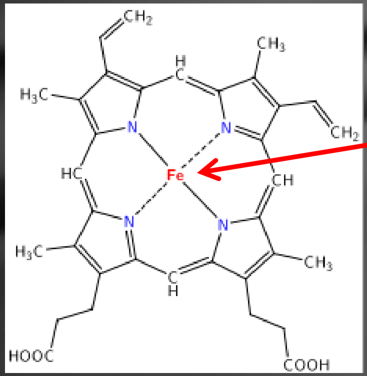


# ROC Analysis



# What Causes Off-peak Components?

- Frequency offset of OPCs larger in malignant lesions
  - What is causing this effect?
- Something is altering local magnetic field/susceptibility
  - Paramagnetic effect
  - Calcifications?
  - Hemosiderin?
  - Deoxyhemoglobin?
    - Iron atom in heme is unshielded when no $O_2$ is bound




heme group

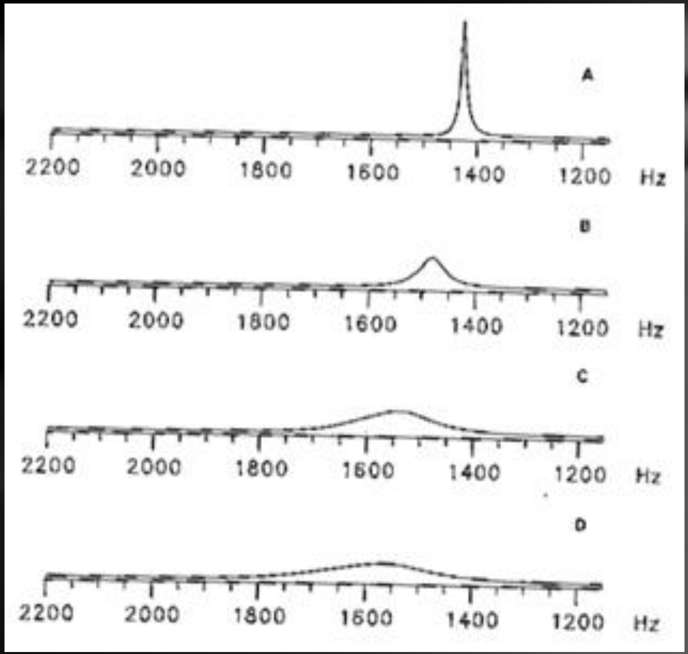
# Peak Shifting and Broadening in Deoxygenated Blood

Effect of oxygenation on proton NMR lineshape of RBC suspensions at high field[7]

- Peak broadens and *v* shifts
- Direction of shift (+/-) is orientation-dependent

At 1.5T *in vitro* studies show 0.27ppm between fully oxygenated and deoxygenated blood[8]

- Translates to 17.3Hz at 1.5T
- Supports our results of OPCs at ≈11 Hz
  - Don't expect **fully** deoxygenated blood *in vivo*




$pO_2$ > 400 mmHg

$pO_2$ = 43 mmHg

$pO_2$ = 17 mmHg

$pO_2$ = 0 mmHg

# HiSS Off-peak Components: Conclusions

- Malignant breast lesions showed more non-Lorentzian lineshapes than healthy tissue
- Frequency of OPC was significantly different
- ROC analysis demonstrated its usefulness in diagnostic setting
- Evidence of role of deoxyhemoglobin in inhomogeneous broadening

- In radiotherapy, deoxygenated (hypoxic) tissue is important
  - Radioresistance
  - Potential to use information from HiSS in context of radiotherapy

# Role of HiSS in Radiotherapy

- Water peak height images – higher quality images compared to conventional MR
  - Image texture, edge delineation, lesion conspicuity, internal definition[1,2,3]
  - Potential to help decrease margins/escalate dose
    - Higher confidence in drawing volumes

- HiSS off-peak components
  - Predict response to treatment
    - Hypoxic regions → off-peak components → poor response
  - Use to design adaptive treatment plans
    - Boost hypoxic regions

# HiSS for Decreasing Margins/Target Definition

How to make it work…

- MR simulator
- OR cooperation with Radiology and Radiation Oncology

Requires:

- Volume coverage
  - Feasible if using parallel imaging (multi-coil)
- Minimize processing time
  - On-line processing?
- Fusion software

# HiSS Off-peak Components: Biological Adaptation?

- Adapting treatment plans to target hypoxic regions
- Many unanswered questions:
  - How often to scan?
    - Daily (i.e. View-Ray)
    - Weekly
    - Bi-weekly
  - What to do with information?
    - How much extra dose to give to hypoxic regions?

# HiSS MRI in Radiotherapy

Advantages

- Imaging in different planes
- Adding other sequences for multiparametric imaging
  - DCE-MRI
  - DWI
- Monitor response to treatment over the course of RT

Disadvantages

- Still need CT for dose calculation
- Geometric distortion near $B_0$ field edges
- Some sites not applicable
  - Lung, H&N

# Future Work

- Design a phantom
  - Establish direct correlation between blood oxygenation and OPC frequency
- Using HiSS to predict response to treatment
- Correlate HiSS off-peak components with biopsy data in other sites
- Imaging with HiSS under hyperoxic conditions to determine tissue response
- Investigate role in adaptive radiotherapy

# Acknowledgements

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Milica Medved, PhD[3]

[1]Loyola University Medical Center, Dept. of Radiation Oncology

[2]Loyola University Medical Center, Dept. of Radiology

[3]University of Chicago, Dept. of Radiology

# References


[1]Radiology 224(2):577

[2]JMRI 24(6) 1311

[3]AJR 186(1):30

[4]MRM 61(2):291

[5]PMB 53(17):4509

[6]NMR Biomed 26:569

[7]MRM 26(2): 274

[8]MRM 45:533

# Image Sources

http://chem.ch.huji.ac.il/nmr/techniques/1d/pulseq_files/fid.gif

https://www.soils.org/images/publications/vzj/9/2/373fig1.jpeg