Essential tools for Clinical Cardiovascular MRI

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CHI St. Luke's Health

Outline

Å Cardiovascular Disease and Non-Invasive Imaging

Å Clinical Cardiovascular MRI

ï Cardiac Gating

ï Anatomy

ï Function

ï Flow

ï Perfusion

ï Viability

Å Why CMR?

Å Summary

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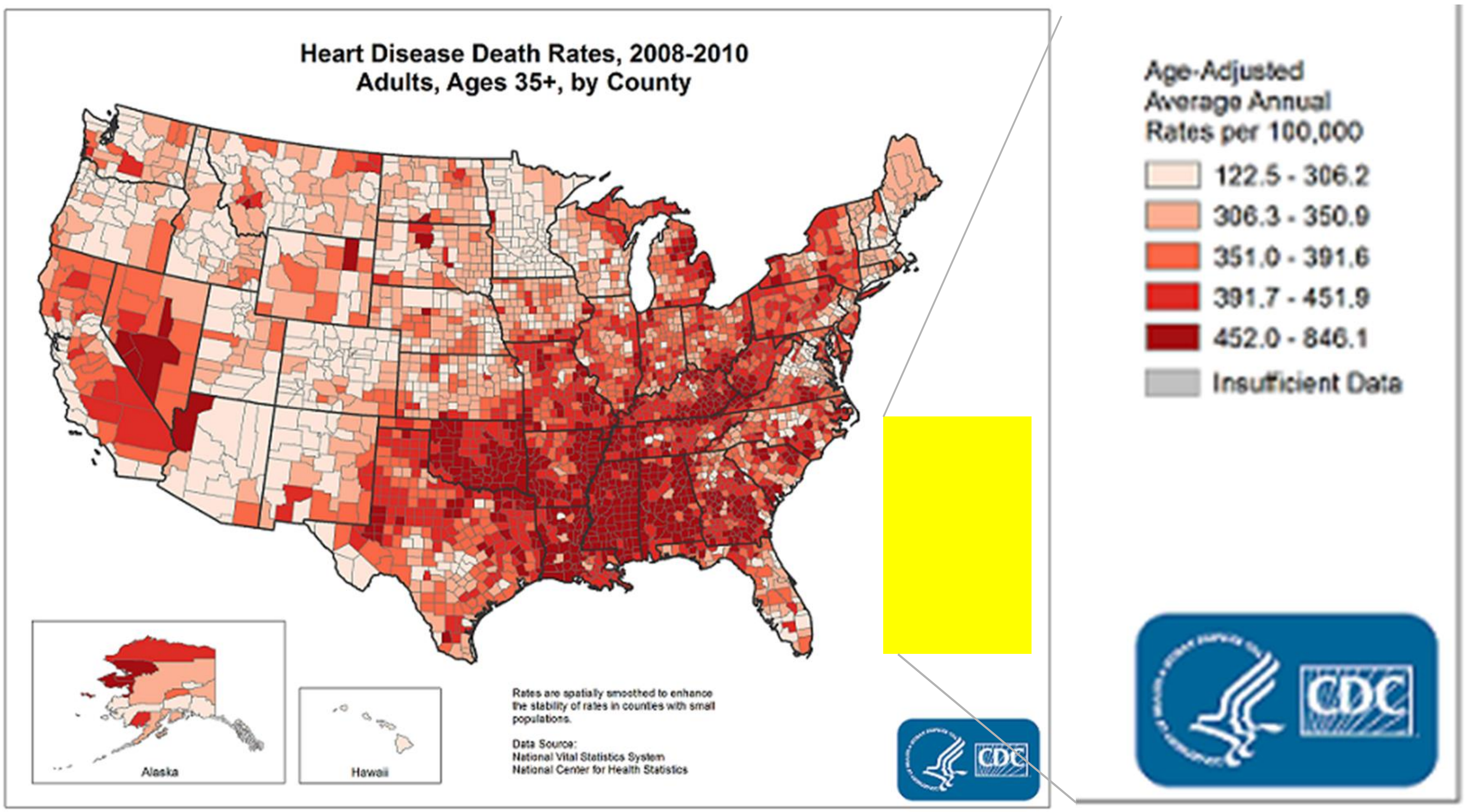
Cost of Heart Disease : Lives



610,000 deaths per year;1 in 4 deaths; ~50% due to CAD ;109 Billion USD

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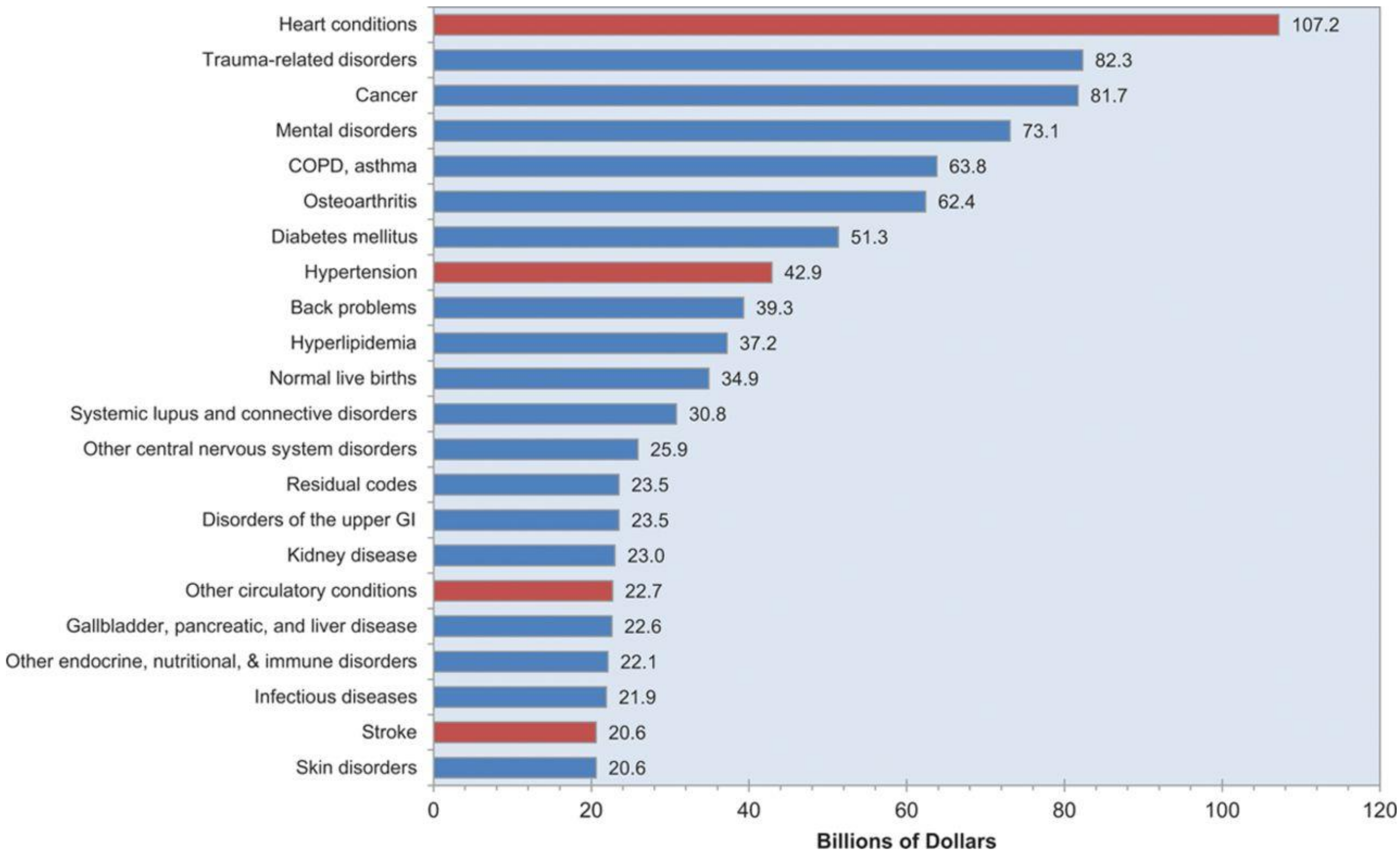
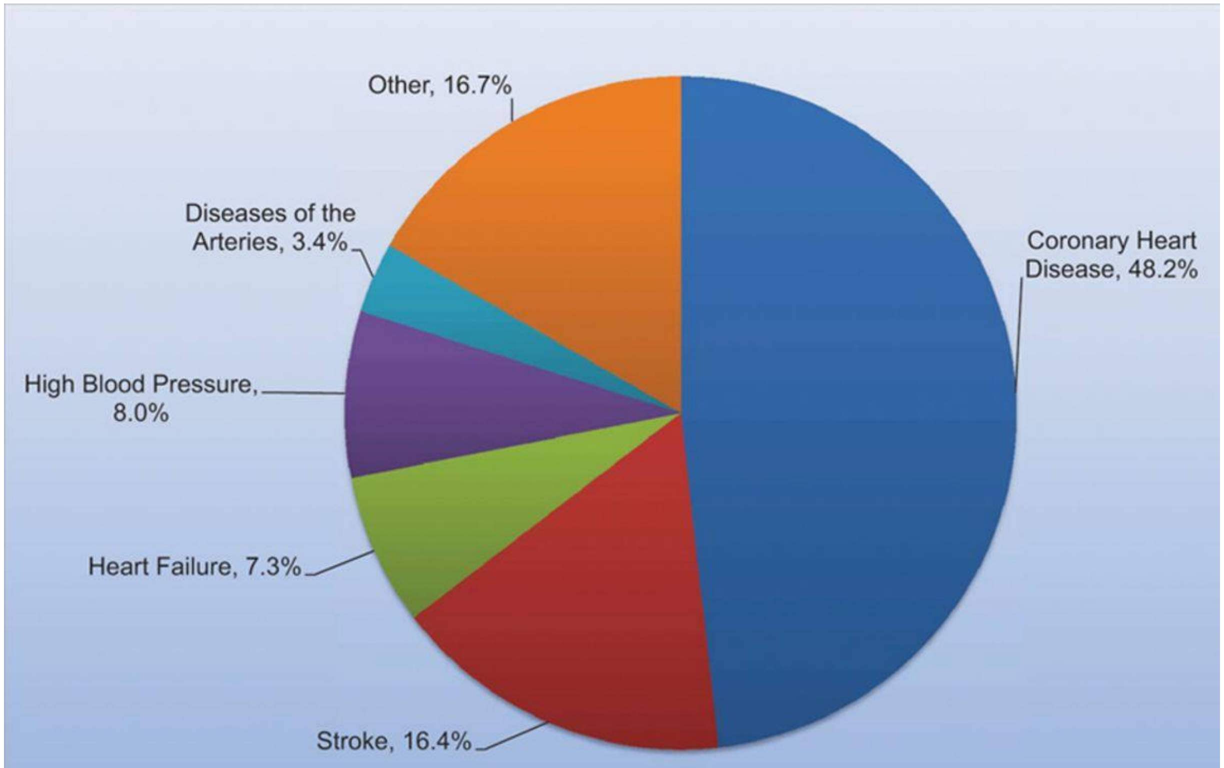
The 22 leading diagnoses for direct health expenditures, United States, 2010 (in billions of dollars).



Alan S. Go et al. Circulation. 2014;129:e28-e292

Percentage breakdown of deaths attributable to cardiovascular disease (United States: 2010).



Alan S. Go et al. Circulation. 2014;129:e28-e292Heart Disease and Stroke Statistics—2014 Update

What we need to see?

- ÅCongenital Anomalies
- ÅCoronaries
- ÅCoronary Blood Flow
  - ÅPerfusion
- ÅMyocardium
  - ÅInfections
  - ÅViability
  - ÅInfiltrative Processes
- ÅCardiac vessels
- ÅValves
- ÅFunctional Information
- Å…

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Cardiac Imaging Modalities: Echo

Echocardiography

Echocardiography

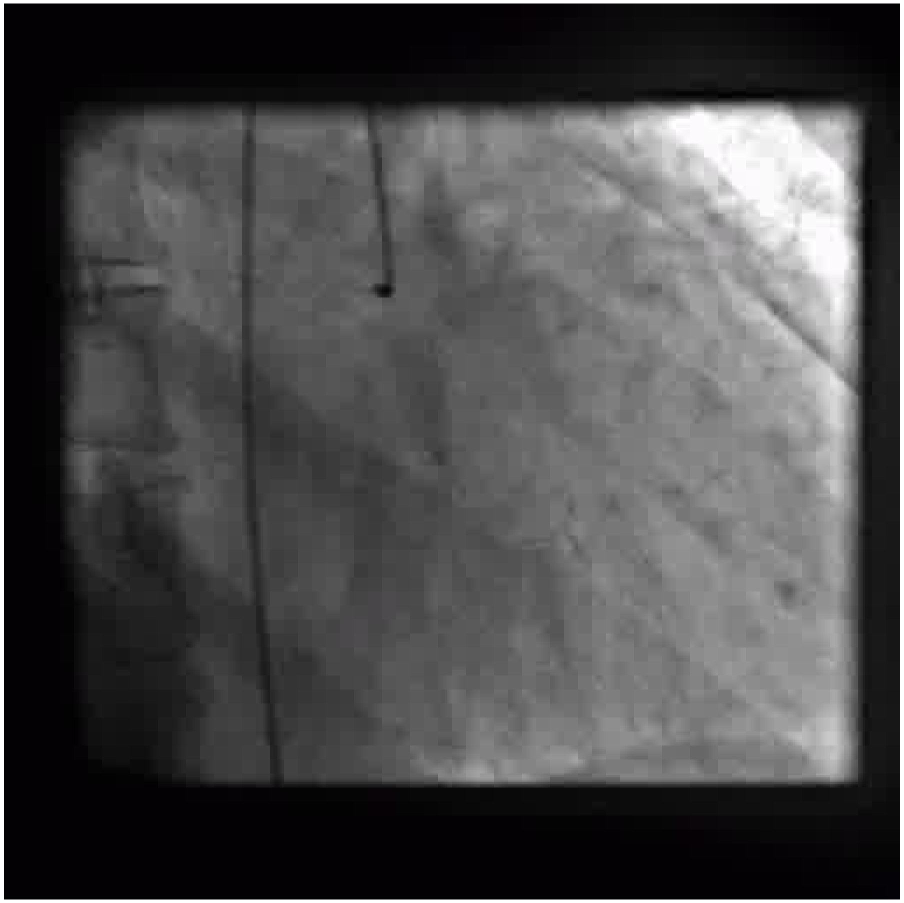
Strengths:

Real-time, Inexpensive
Wall motion
Valvular function
Blood flow velocity

Limitations:

Need for acoustic windows
Limited coverage
Single contrast mechanism

x-ray angiography



X-ray Angiography

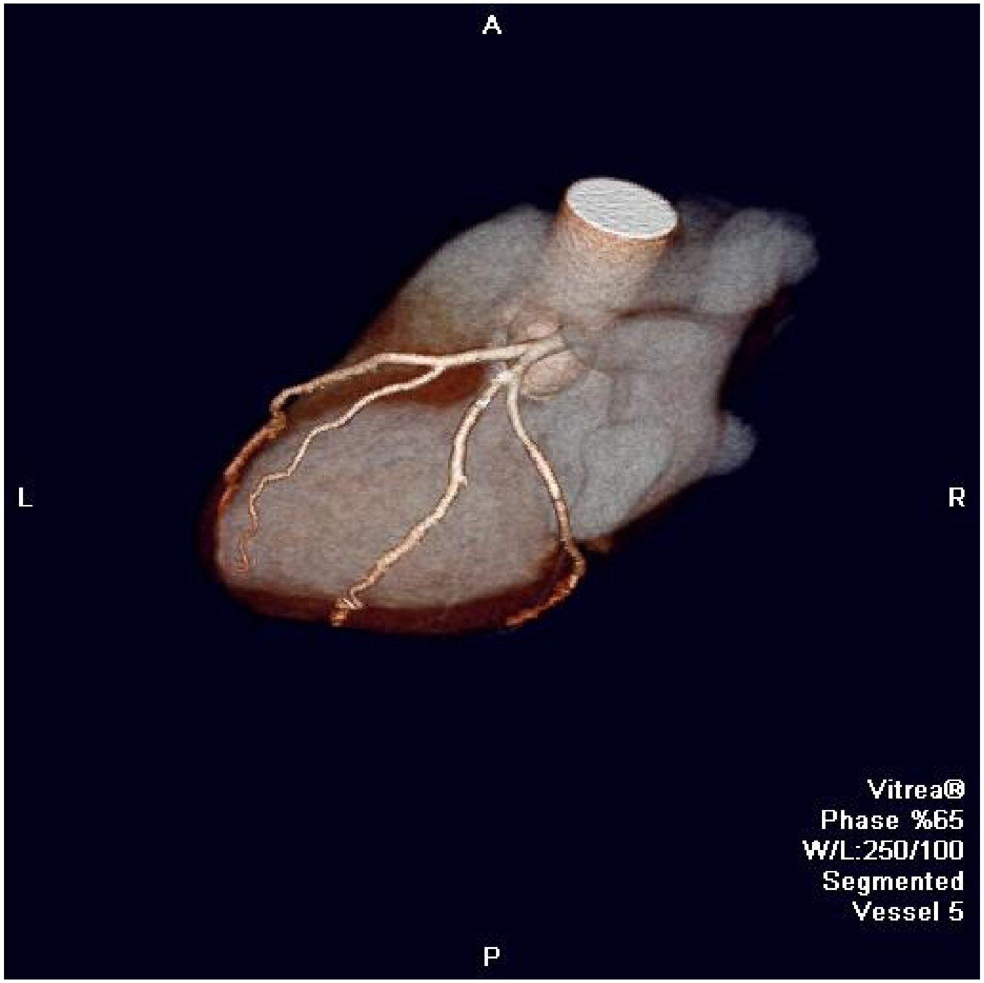
Strengths:

Exquisite spatial resolution
Exquisite contrast resolution
Vascular Morphology
Potential for therapy

Limitations:

Invasive; Non-negligible risk
Lack of tissue structure infor.
Radiation dose
Contrast agent dose

x-ray computed tomography



X-ray CT

Strengths:

High Spatial resolution
Exquisite contrast resolution
Cardiac Anatomy
Calcifications
Surgical Planning
Fast

Limitations:
Cardiac Function
Valve Function
Radiation dose
Contrast agent dose

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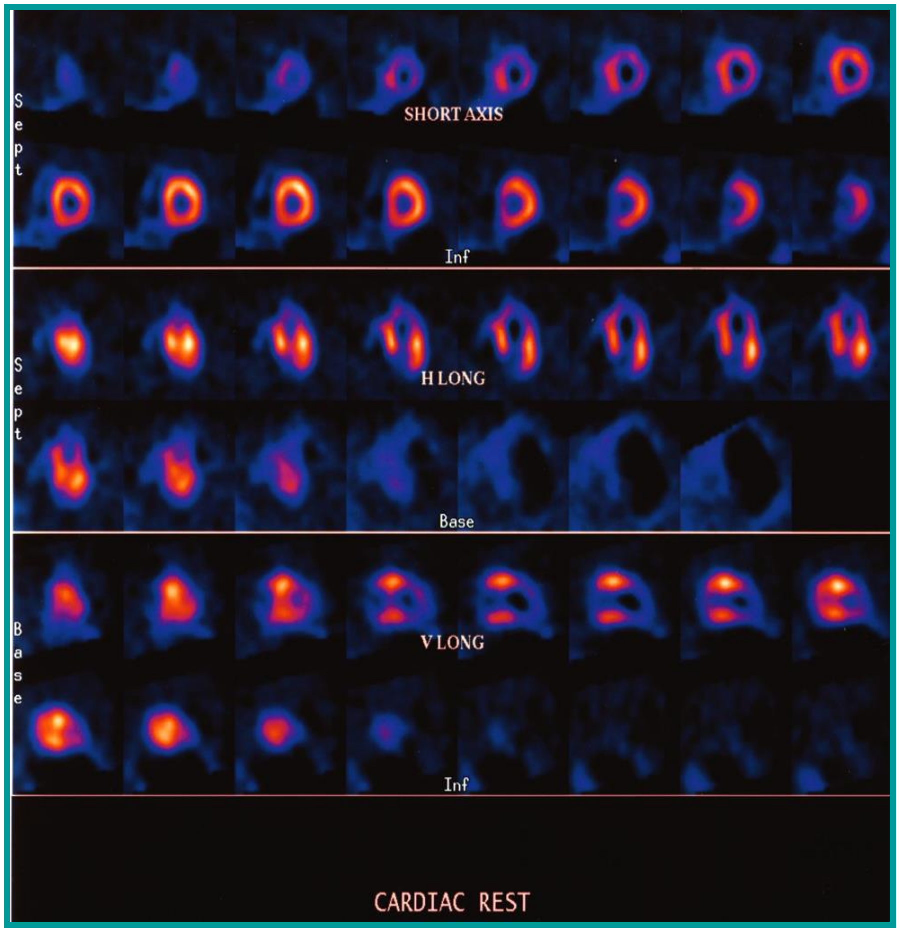
Nuclear Scintigraphy



Nuclear Scintigraphy

Strengths:

Exquisite sensitivity
Functional Imaging method
Perfusion and Viability

Limitations:

Modest Spatial Resolution
Lack of tissue structure infor.
Radiation dose

Cardiac Imaging

Parameter	US	XRA	x-ray CT	NM	MRI
Ventricular Function	☑☑☑	☑	☑	☑	
Valvular Function	☑☑☑	?	?	?	
Tissue Characterization	?	?	☑	?	
Ischemia/Viability	☑	☑☑	?	☑☑☑	
Coronary Arteries	☑	☑☑☑	☑☑	?	
Congenital Anomalies	??	??	☑☑	?	

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Simplified Outline of an MR Experiment

- The patient or the object is placed within a *homogeneous* magnetic field
- A radio-frequency wave is sent in for a short duration
- RF signal from the patient is picked up using a coil
- The received signal is used for forming an image.

- Creates a net magnetization due to the slight excess of protons aligning parallel to B_o.
- Energy Deposition: Creates measurable transverse magnetization
- Energy Emission: Governed by relaxation phenomena
- Reconstruction: The received signal is used for forming an image

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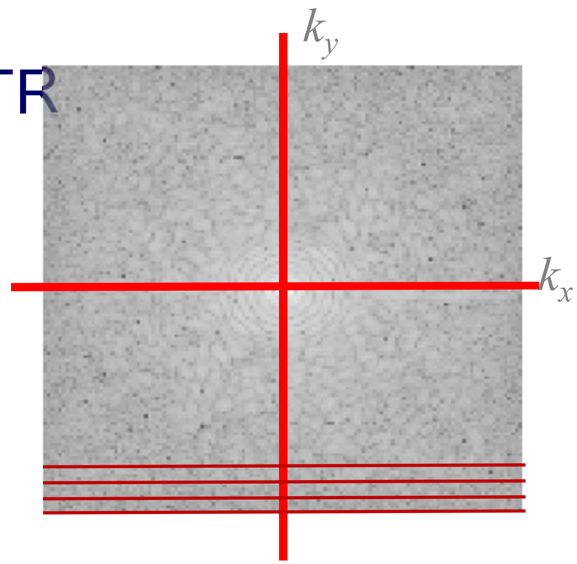
Conventional 2DFT MR imaging

Å Simple 2DFT Imaging:



Time between phase encoding steps : TR

(~ of 100s of ms ; T_1 relaxation time)

Time from excitation to Readout : TE

(~ of 10s of ms ; T_2 relaxation time)

Repeat the experiment over several TR

(Allows for longitudinal relaxation between phase encoding steps)

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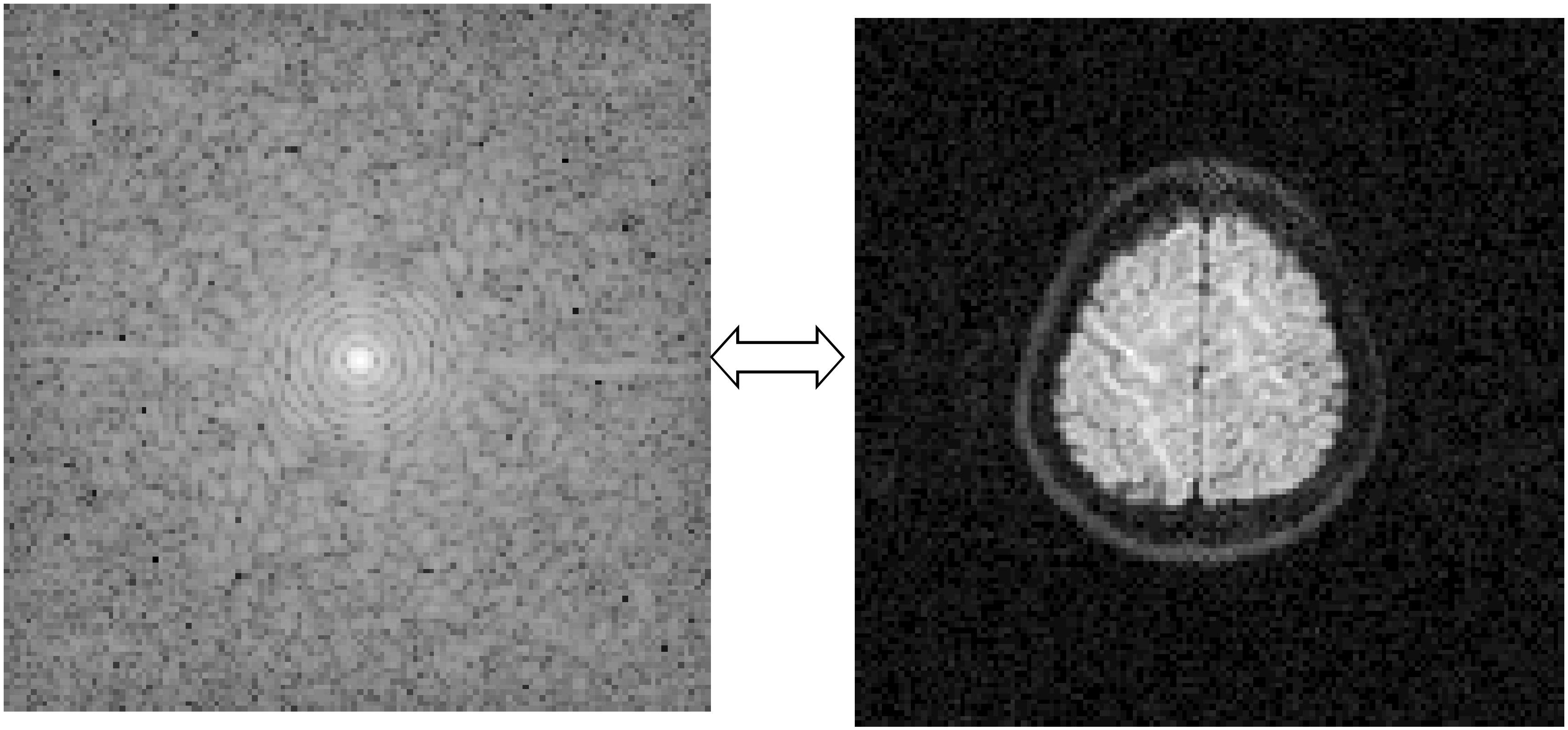
Assumption: Consistency of Data



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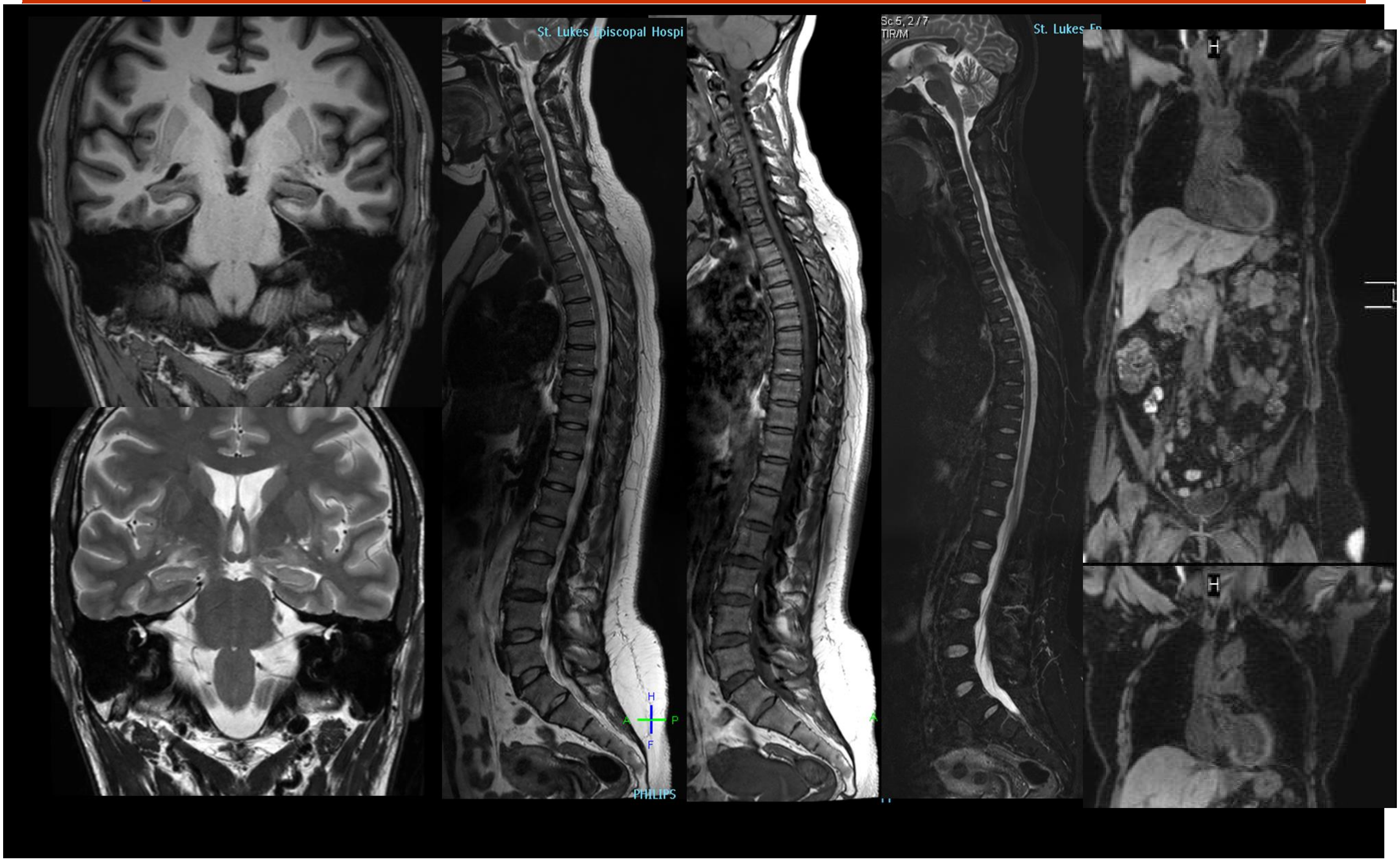
Traditional Radiology Department



1. Cardiac Synchronization

Heart moves substantially with

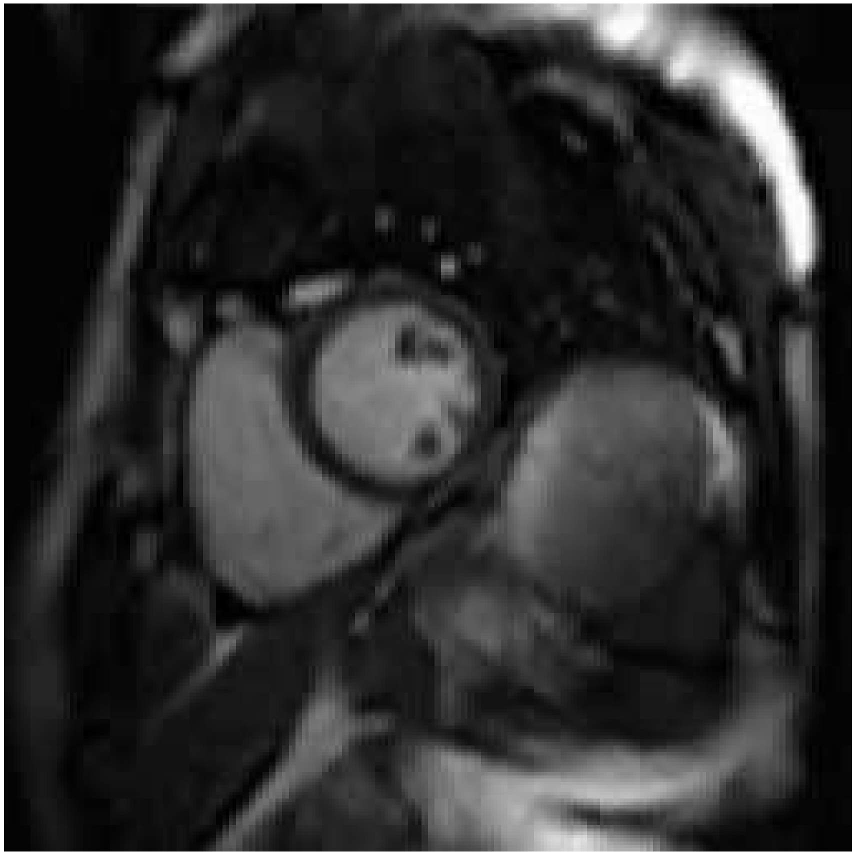
Cardiac Pulsation (~ 1 Hz)

and

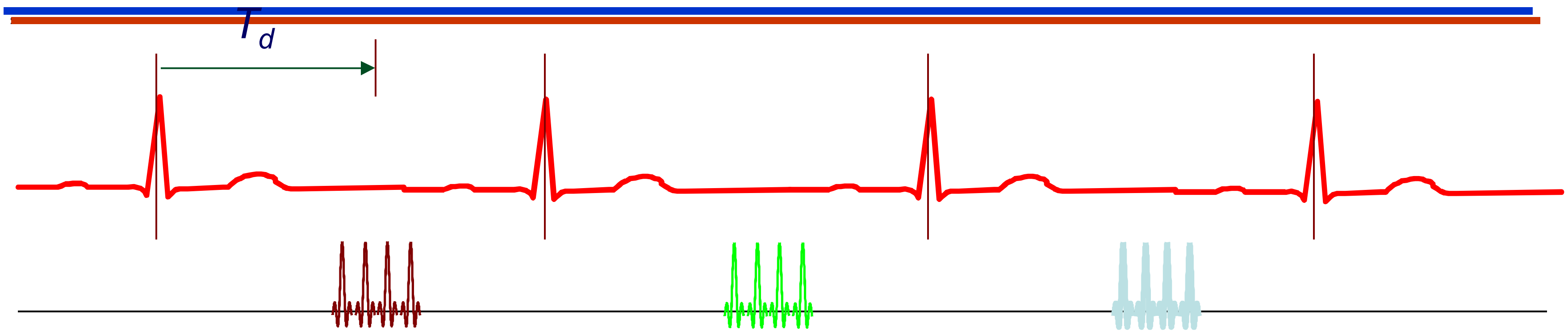
Respiration (0.05 Hz)

T_1 relaxation rates ~ 1 Hz

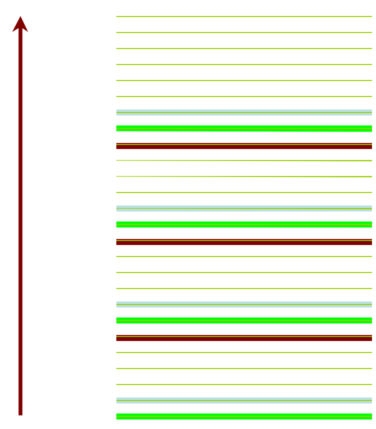
Time scale of MR is on the order of seconds to minutes



Prospectively Triggered CMR Acquisition



shots = Total PE / PE_per_shot



Linear profile order

Good Image Quality
Long Scan time

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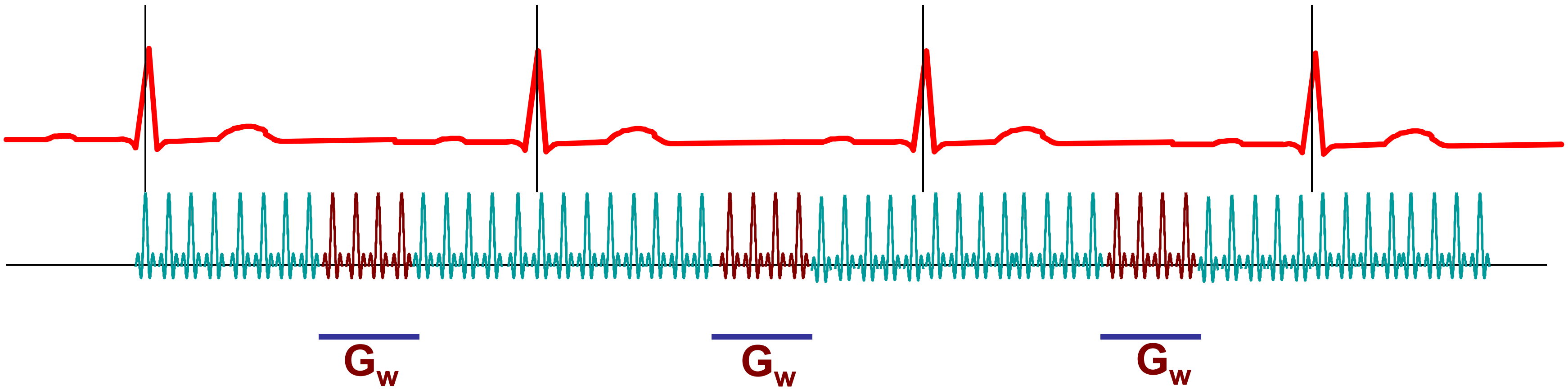
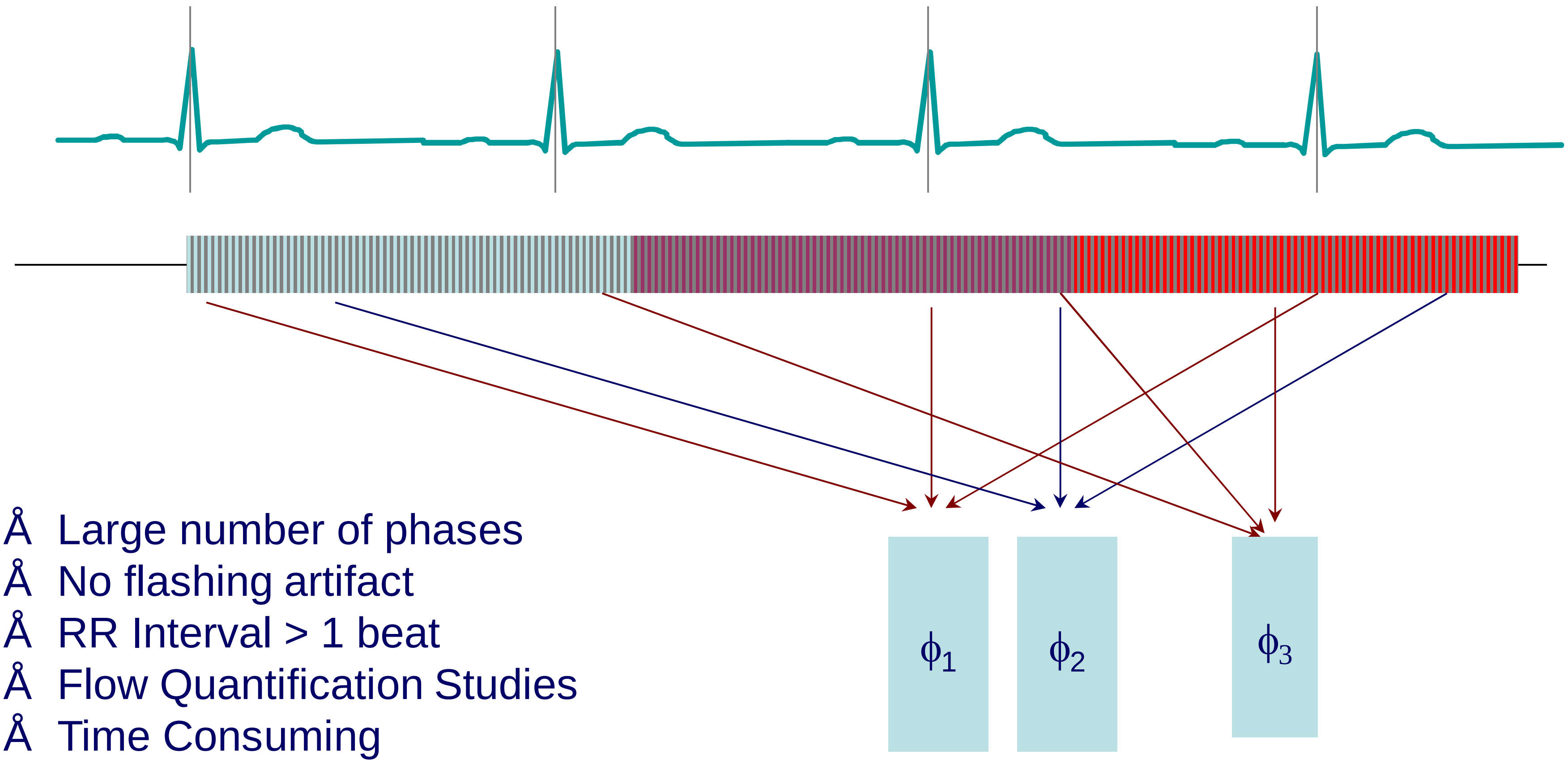
ECG Synchronization: Gating



- Maintains Steady State - Continuous RF excitation
- No flashing artifact
- Single or Multi-phase images
- Low SNR / Time consuming (often used in FQ studies)

Retrospective ECG Gating



- Large number of phases
- No flashing artifact
- RR Interval > 1 beat
- Flow Quantification Studies
- Time Consuming

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(2) Myocardial Morphology: Black Blood Imaging Techniques

Å Blood Appears Black / Dark

Å High Anatomic Detail

Å *Typically* Spin Echo Methods

 ï Spin Echo

 ï Turbo Spin Echo (TSE)

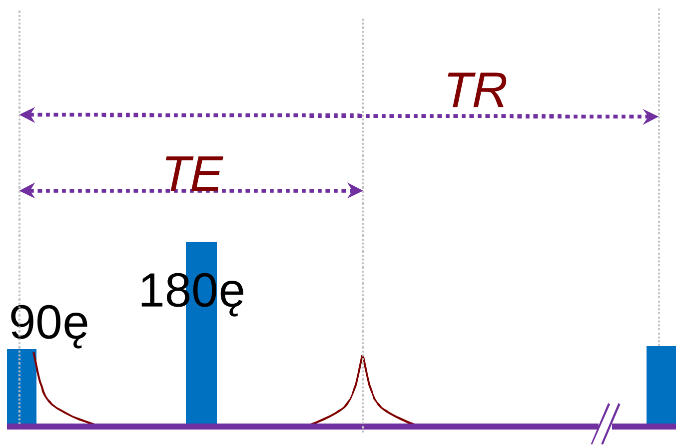
 ï Inversion Recovery TSE

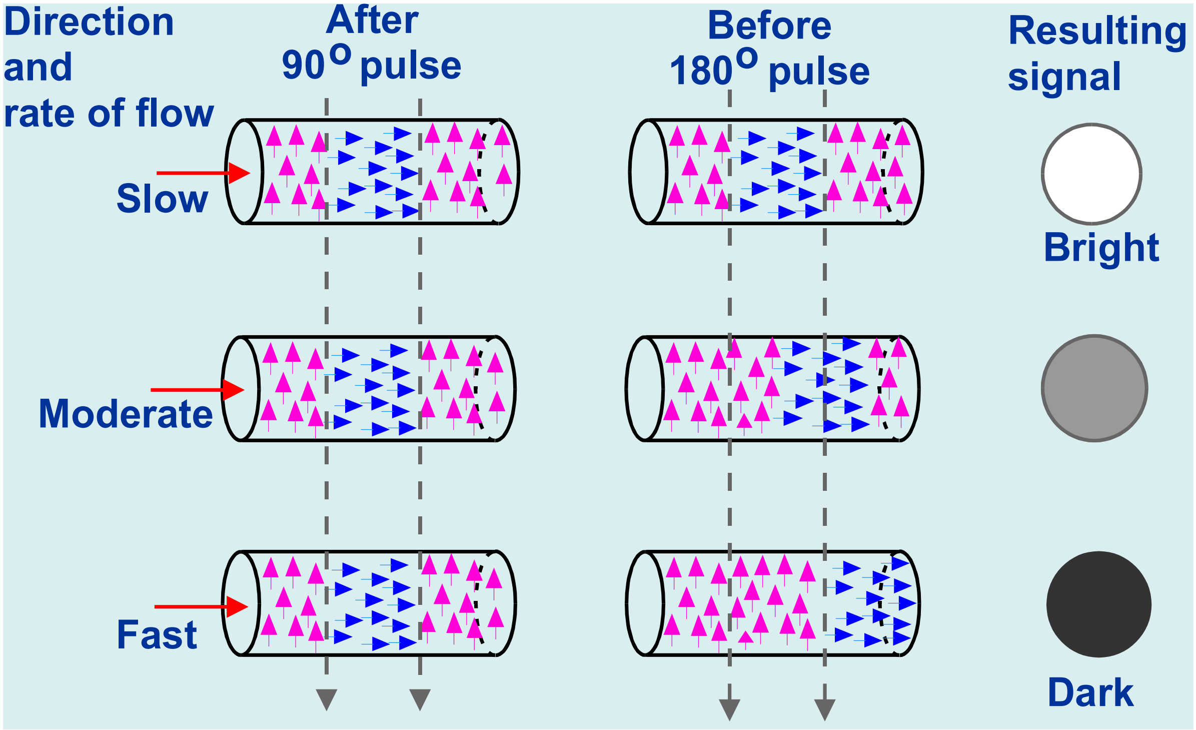
Å Diastolic Images (Diastole)

Å Cardiac Triggered Sequences

Å Rely on blood flow (Outflow)

Simple Spin-Echo and BB contrast





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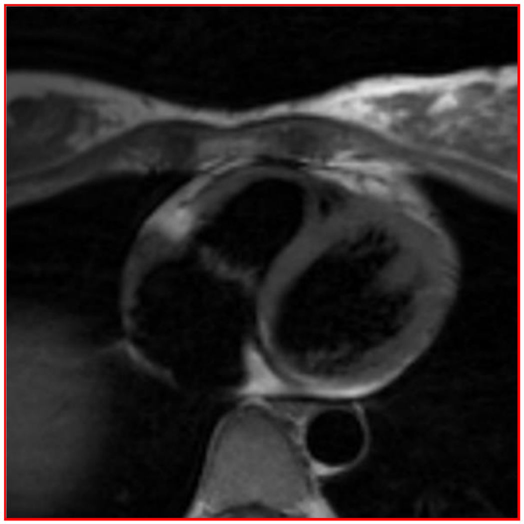
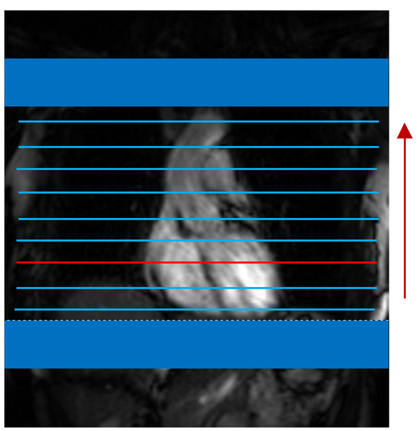
Simple SE Characteristics:



4 NSA
+
REST
+
ASC



ÅCardiac Triggered Scans

ÅFree breathing scans

ÅQuick BB Survey of Anatomy

ÅUse Multiple NSA (with EPI/TSE)

Tips:

ÅUse Systolic Acquisitions (for T_1 wtd scans)

ÅUse Proper Excitation Order (Ascending or Descending)

ÅUse Saturation pulses (to minimize inflow or fat ghosting)

ÅBoth T_1 and T_2 weighting is possible

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Simple SE Limitations

Å Blood Signal Suppression depends on Spin Velocity

  ï Incomplete suppression of slow flow

  ï In-plane flow is problematic

Å Simple SE is time consuming

  ï Faster Acquisition Techniques - TSE, EPI

Å SE-EPI sequence

  ï Can introduce artifacts

Å Alternative: T_1 based suppression (akin to STIR)

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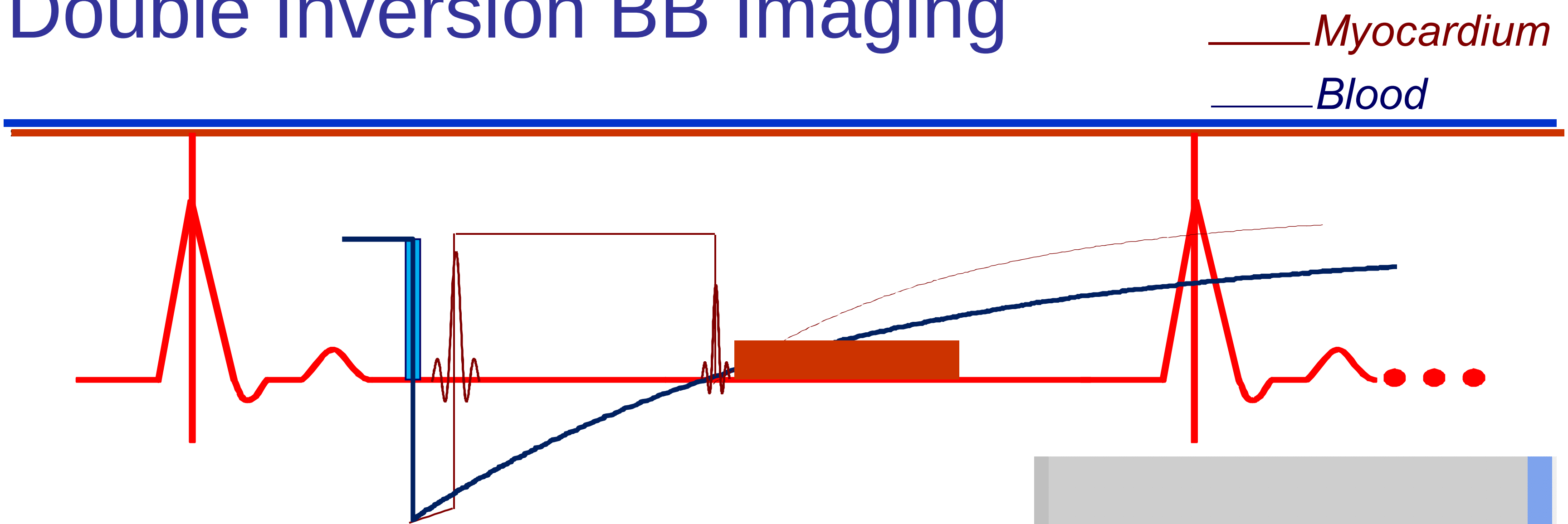
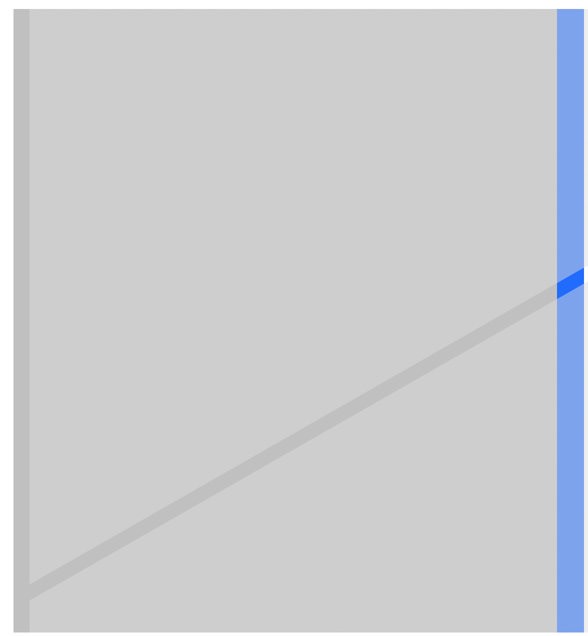
Double Inversion BB Imaging



- The first non-selective inversion inverts everything

- The second selective inversion pulse re-inverts the signal within slice



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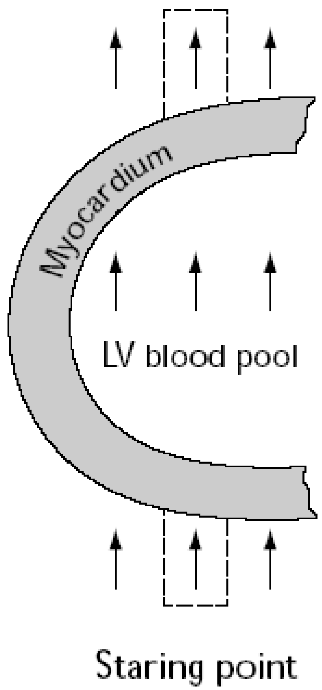
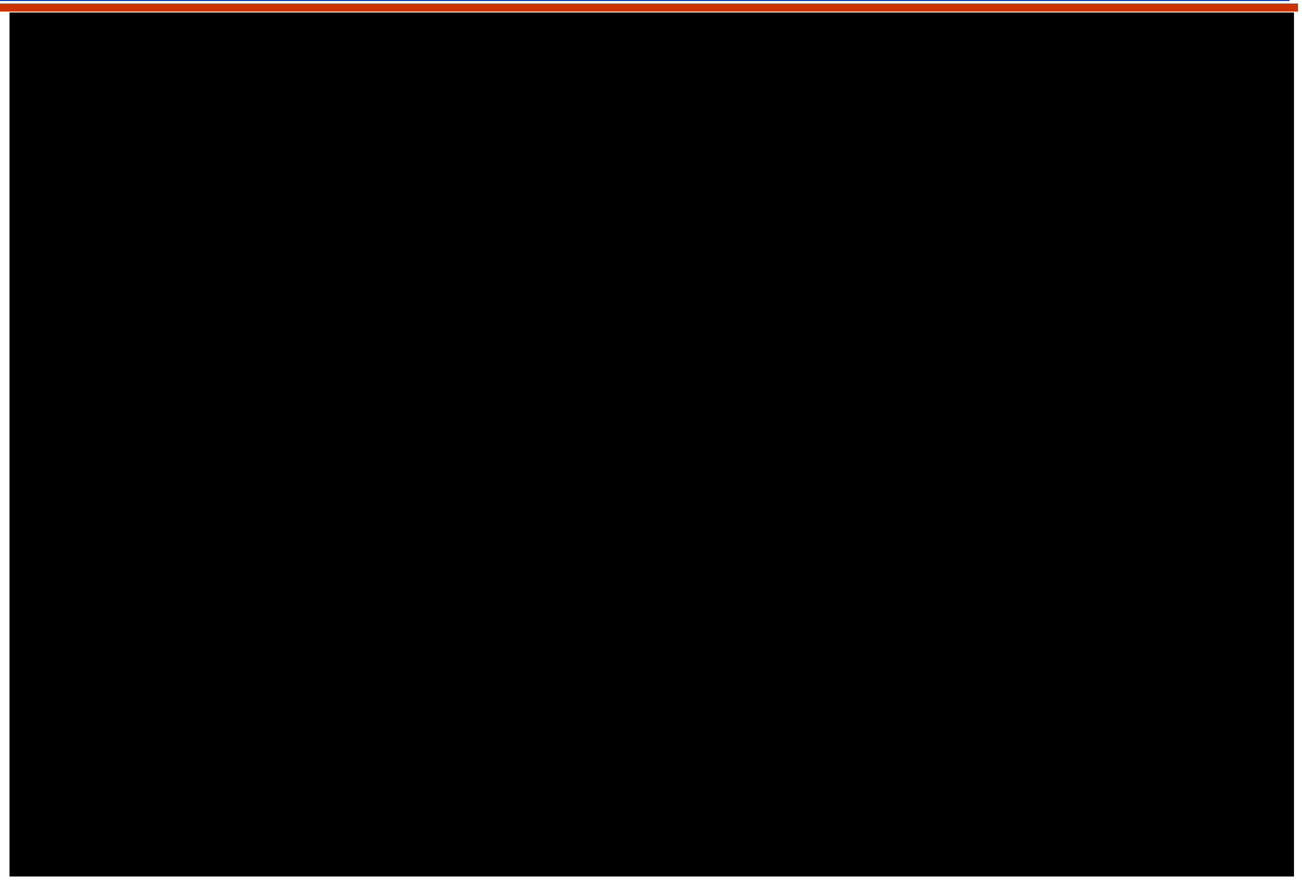
BB Pre-pulse ï A recap





Double Inversion BB : Summary

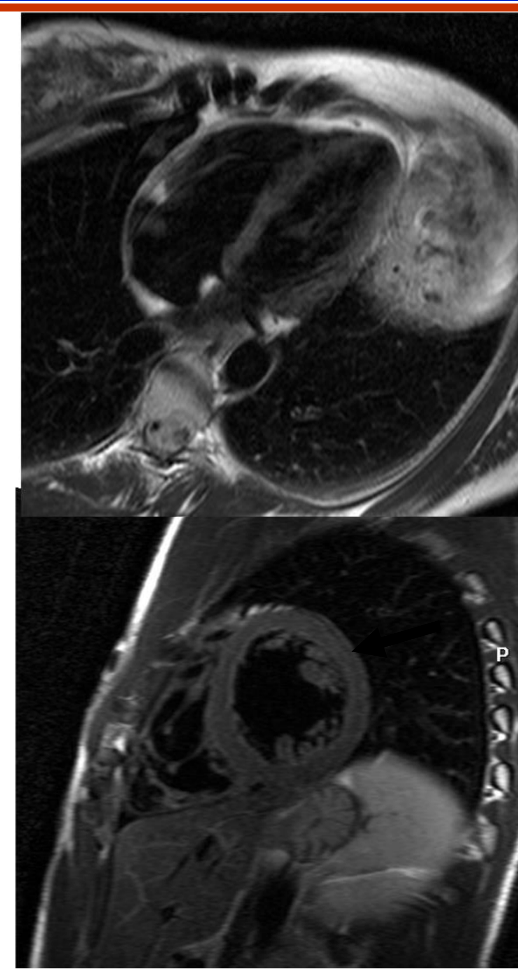
Å Null the blood based on its T_1 (like conventional IR)

Å Retain the full signal for the stationary tissue

Å Minimized the dependency on flow dynamics

Å T_1 and T_2 weighting is possible (1 or 2 heart beats)

Å Blood Signal within slice still gives signal out of plane



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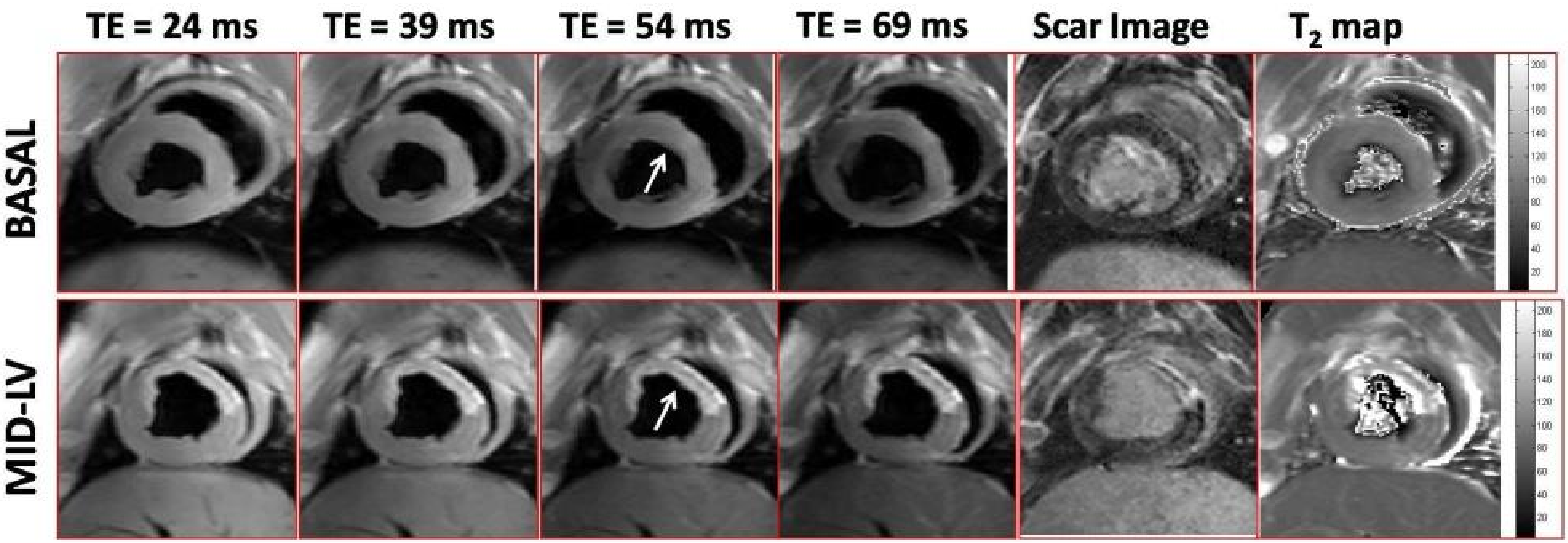
Edema ñWeightedò Imaging Vs T_2 mapping in AMI



Acute Myocardial Infarction Model
Evaluation of stem cell therapy

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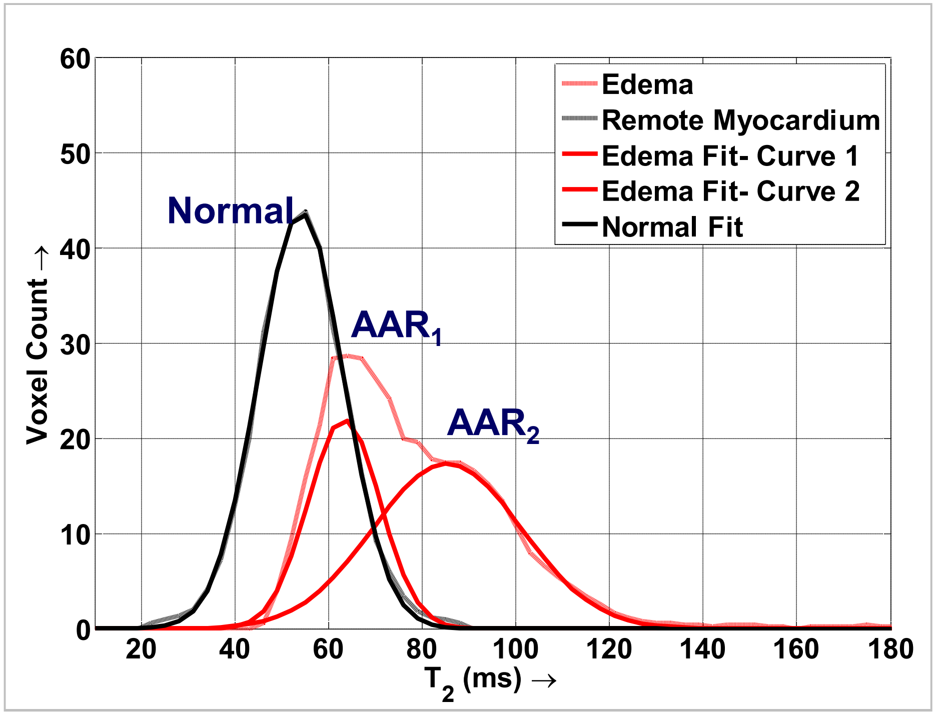
Quantitative Imaging: T_2 Analysis

Å The histogram of T_2 has:

ï A well defined normal myocardium with a Gaussian distribution with a mean of 51 ± 4.8 ms at all cut offs, and at all TE

ï The AAR had a broad range of T_2 values, with a well defined T_2 peak at a T_2 of 57.3 ± 6.7 ms , and another broad peak located at 83.5 ± 9 ms



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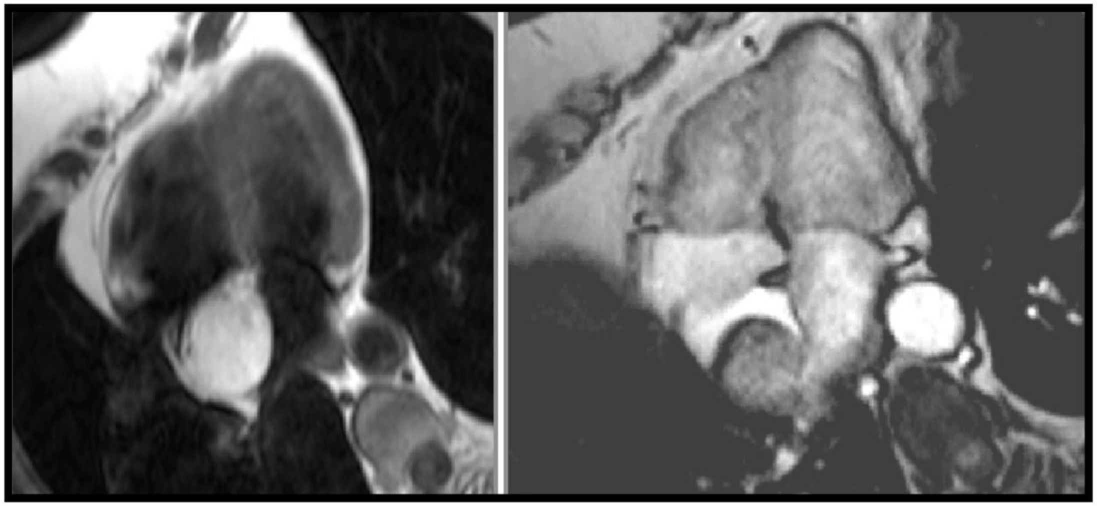
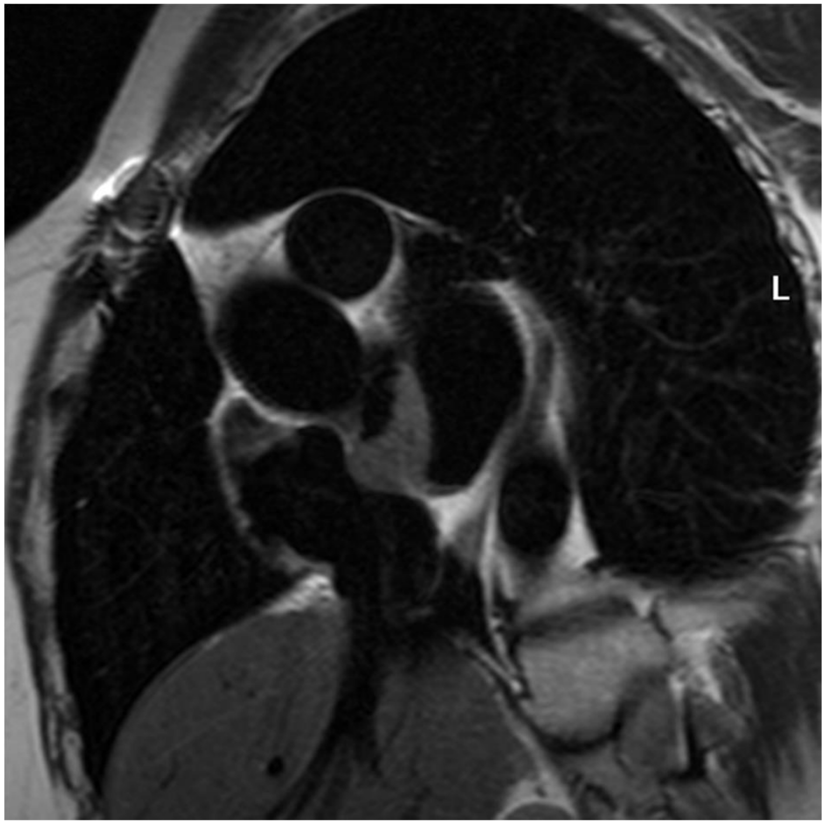
Cardiac Mass - Tissue Characterization:

Lipomatous Hypertrophy of the Interatrial Septum/Right Atrium



Fat Suppression - Triple IR



Double IR

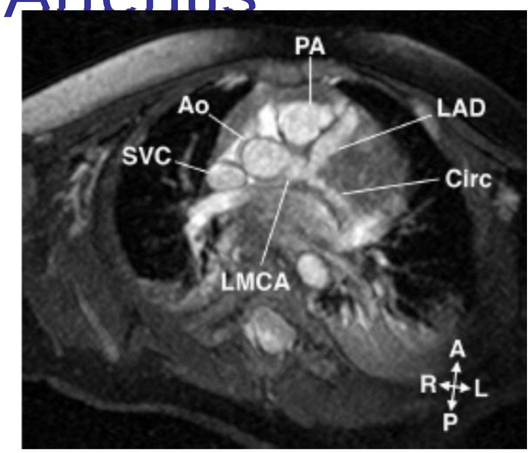
Triple IR

BB Imaging and Tissue Characterization: Inflammation

Å Dual IR Prep + STIR

Å Inflammation Imaging

  ï Vasculitis ï Takayasuôs Arteritis



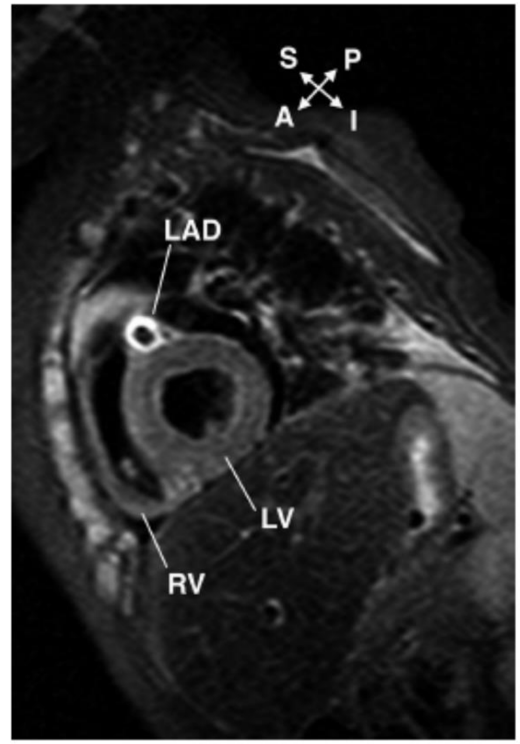


Figure 2. Fat-suppressed double inversion recovery short-tau inversion recovery (STIR)-turbo spin echo image (or triple IR). Note high signal intensity in cross section of left anterior descending coronary artery (LAD). LV indicates left ventricle; RV, right ventricle; S, superior; I, inferior; P, posterior; and A, anterior. Time to echo was 80 ms; time to repeat was 1500 ms.

Detection of Active Coronary Arterial Vasculitis Using Magnetic Resonance Imaging in Kawasaki Disease

Colin J. McMahon, MB, MRCPI; Jason T. Su, DO; Michael D. Taylor, MD, PhD; Rajesh Krishnamurthy, MD; Raja Muthupillai, PhD; John P. Kovalchin, MD; Taylor Chung, MD; G. Wesley Vick III, MD, PhD

Circulation 2005

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CMR Morphologic Assessment

Å Size/Shape of heart and vessels

Å Freely angulated field of view; Large field of view

Å Soft tissue contrast:

- ï Tumor Characterization
- ï Inflammation, Edema
- ï Quantitative imaging

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Gradient Echo Basics

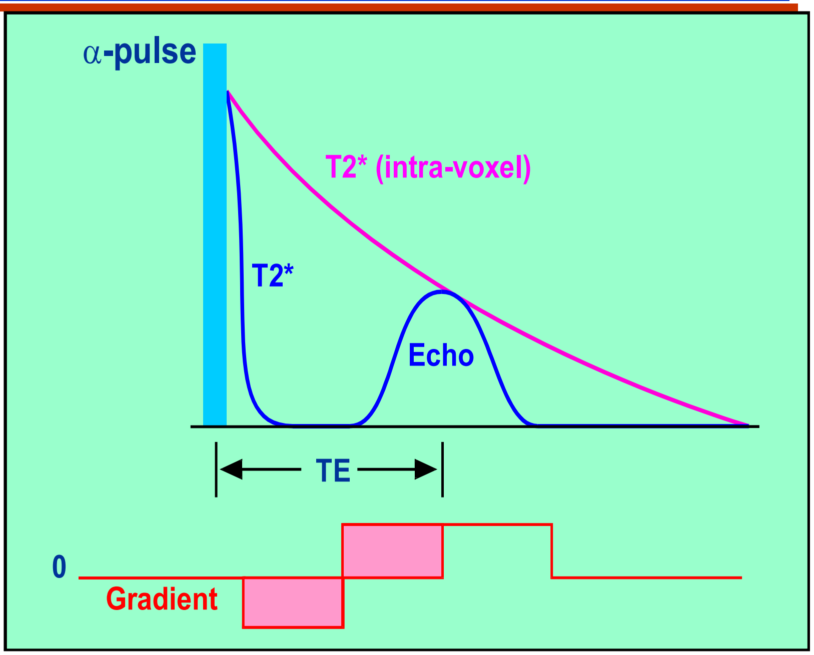
Å After one RF pulse, FID

Å After two or more RF pulses, we get an FID + Spin Echo

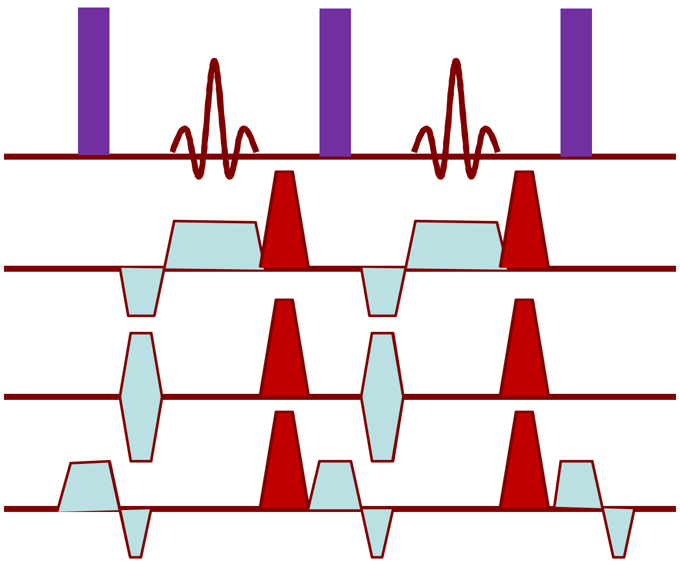
Å When the transverse magnetization is spoiled or destroyed, we get T_1-FFE or spoiled gradient echo

Å When it is preserved carefully we get TrueFISP, or bFFE.

Å The preservation is done by carefully balancing the gradient areas along all axis to be zero for each TR

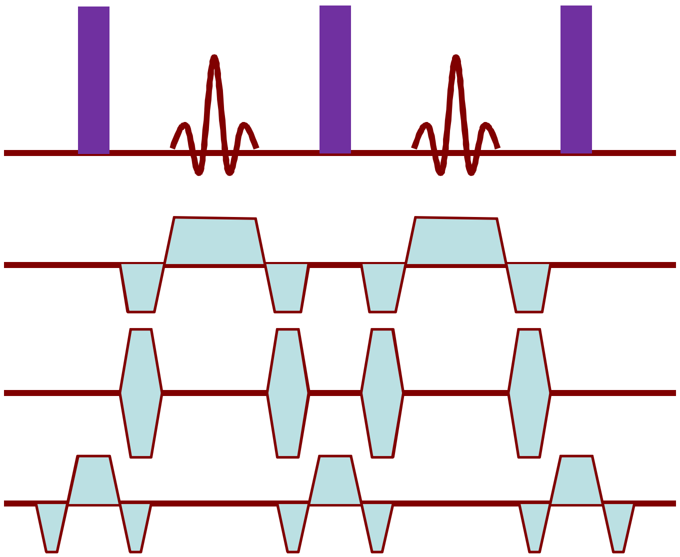


Steady State Free Precession Vs T_1-FFE



T_1-FFE

Transverse magnetization spoiled after each RF pulse.
They do not contribute any signal in subsequent excitations



b-FFE

Transverse magnetiztion coherence is carefully preserved after each RF pulse - by unwinding the phase encoding gradient, balancing the read and slice-select gradients, and with short TR

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Bright Blood Imaging - Function

TFE

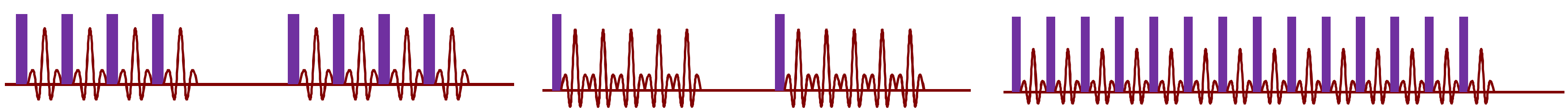
FLASH, SPGR
Short TE/Short TR
Routine Evaluation

FFE-EPI

Modest TE
High Temporal Res

SSFP

bFFE/TrueFISP/FIESTA
High Blood/Tissue Contrast
High Temporal Resolution
Flow “Independent”



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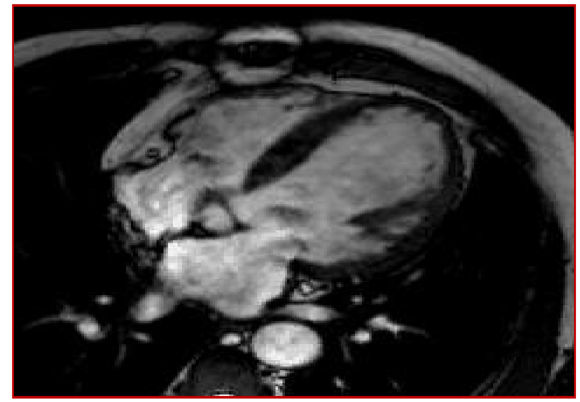
Myocardial Function: Bright Blood Imaging



T_1-TFE:

1. Flashing (HR)
2. Robust
3. Suitable for 3.0 T
4. Inflow-dependent

T_1-wtd EPI:

1. Flow Sensitive (Long TE)
2. Valvular Assessment
3. High Frame Rate
4. Prone to EPI Artifacts

SSFP:

1. High Bld/Myo contrast (T_2/T_1 ratio difference)
2. Sequence of choice
3. Flow ñInsensitveò
4. Challenging for 3.0T

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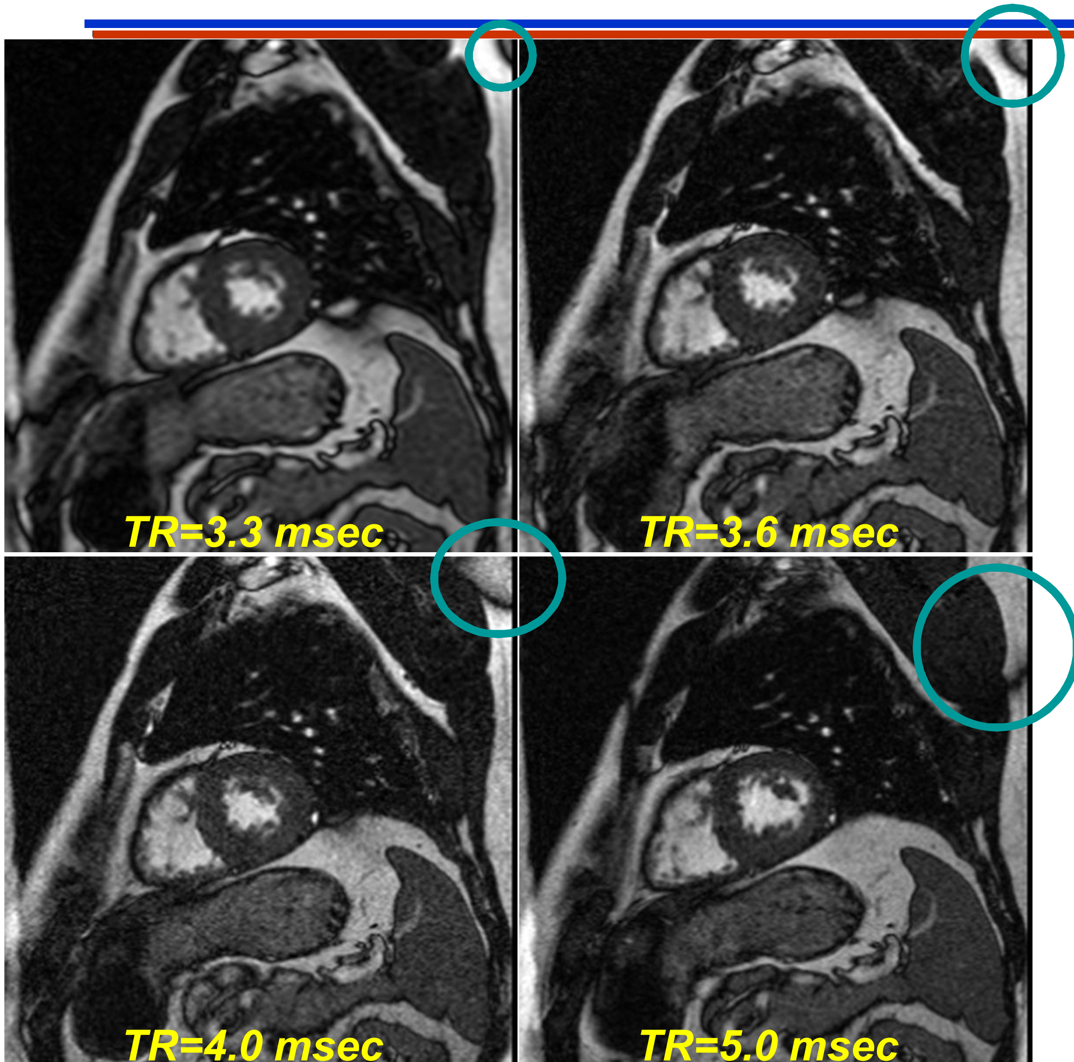
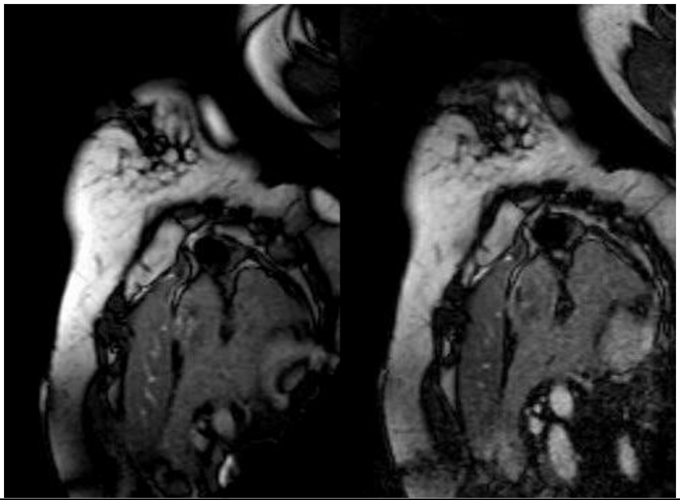
SSFP ï Field Homogeneity Requirements



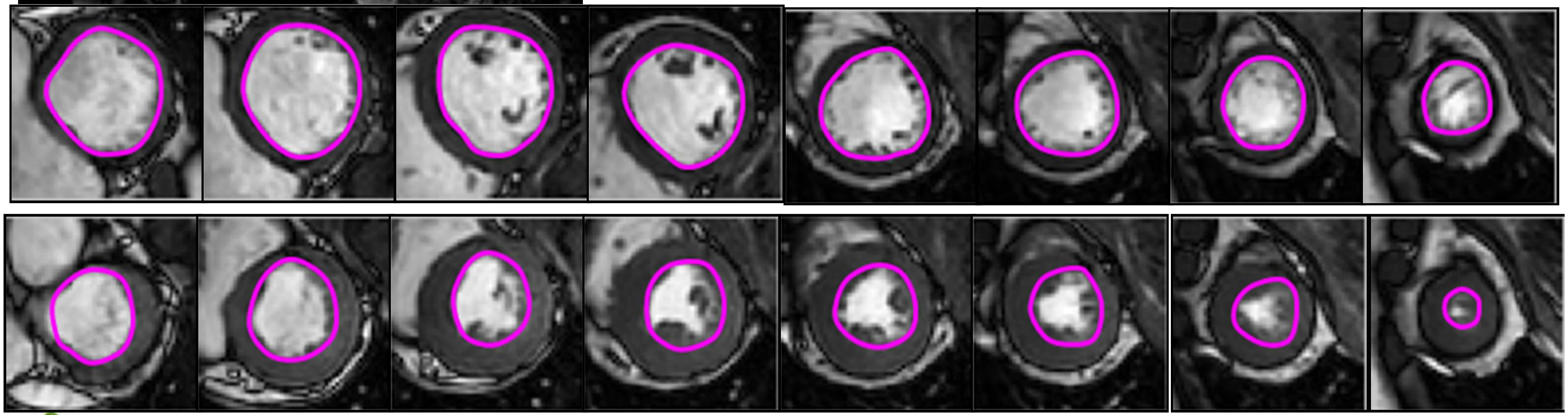
Å SNR independent of TR
Å Shortest possible TR
Å Requires high field homogeneity
Å Autoshim /Use shim volumes if necessary!
Å Typical TR <= 4 msec

LV function Evaluation



End Diastolic Volume (EDV)
End Systolic Volume (ESV)
Stroke Volume (SV)
Ejection Fraction (EF (%))
Cardiac Mass

Regional Wall motion information

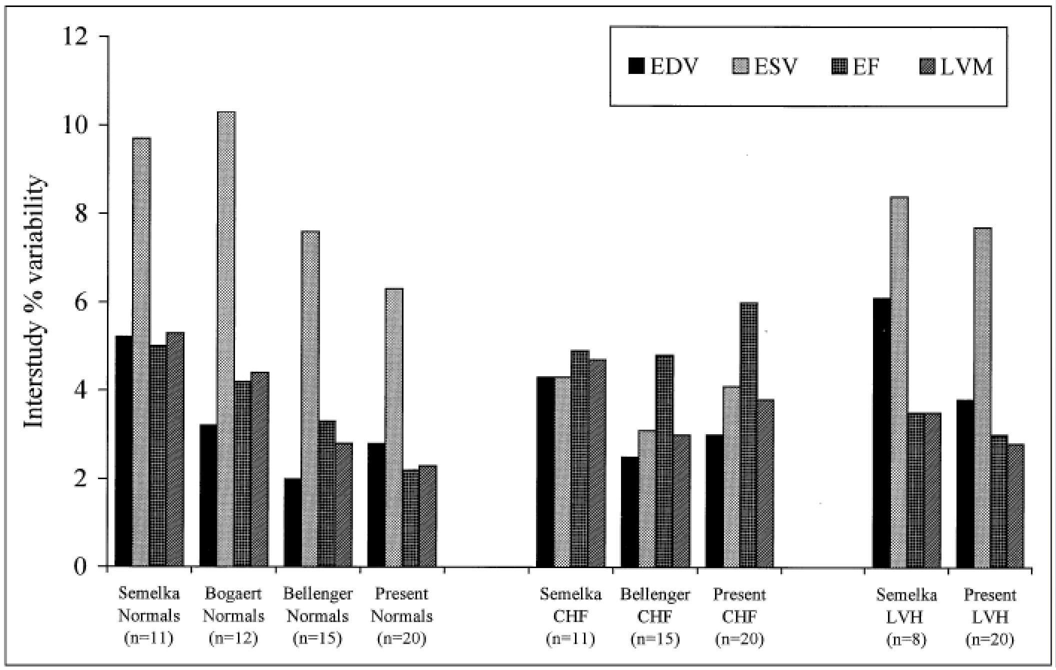


Why is this important?

Å CMR is highly reproducible;

Å Devoid of geometric assumptions

Å *Both* RV and LV volumes



To detect	*n* req. for Echo	*n* req. for MR
10 ml change in EDV	66	13
10 ml change in ESV	82	12
10 gm change in LV mass	194	20
3% change in EF	73	7

Comparison of Interstudy Reproducibility of Cardiovascular Magnetic Resonance With Two-Dimensional Echocardiography in Normal Subjects and in Patients With Heart Failure or Left Ventricular Hypertrophy

Frank Grothues, MD, Gillian C. Smith, BSc, James C.C. Moon, MB BCh, Nicholas G. Bellenger, MD, Peter Collins, MD, Helmut U. Klein, MD, and Dudley J. Pennell, MD

In **heart failure** patients; power = 0.9
$p < 0.05$

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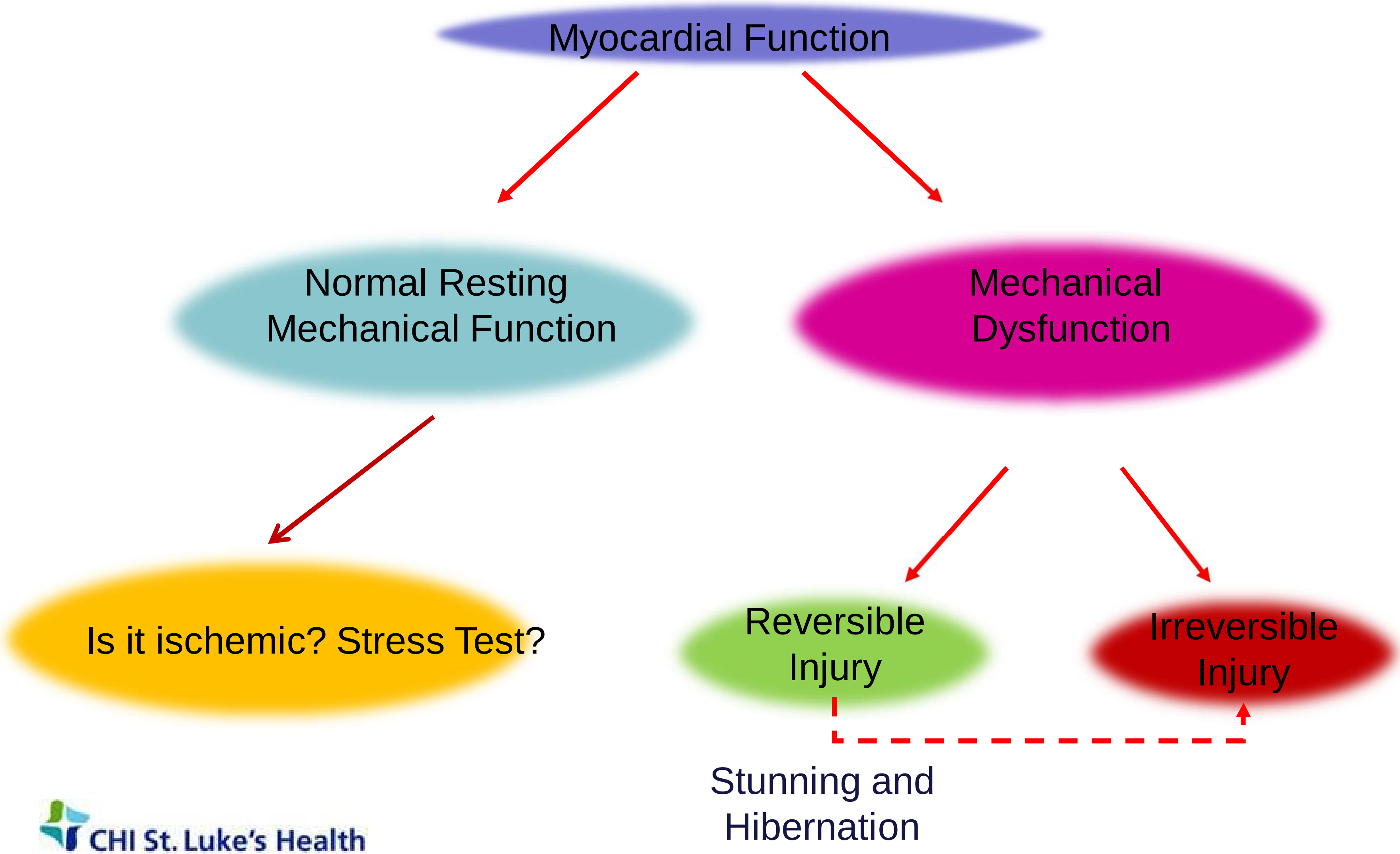
Myocardial Ischemia ï Overview



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Some Definitions

Ischemia: Impaired blood supply; inducible defect with stress

Stunning: Transient Mechanical Dysfunction due to acute ischemic insult

Hibernation: Adaptation to chronic ischemia via down-regulation.

Cell death: Loss of cell membrane integrity ï irreversible injury either via apoptosis or necrosis.

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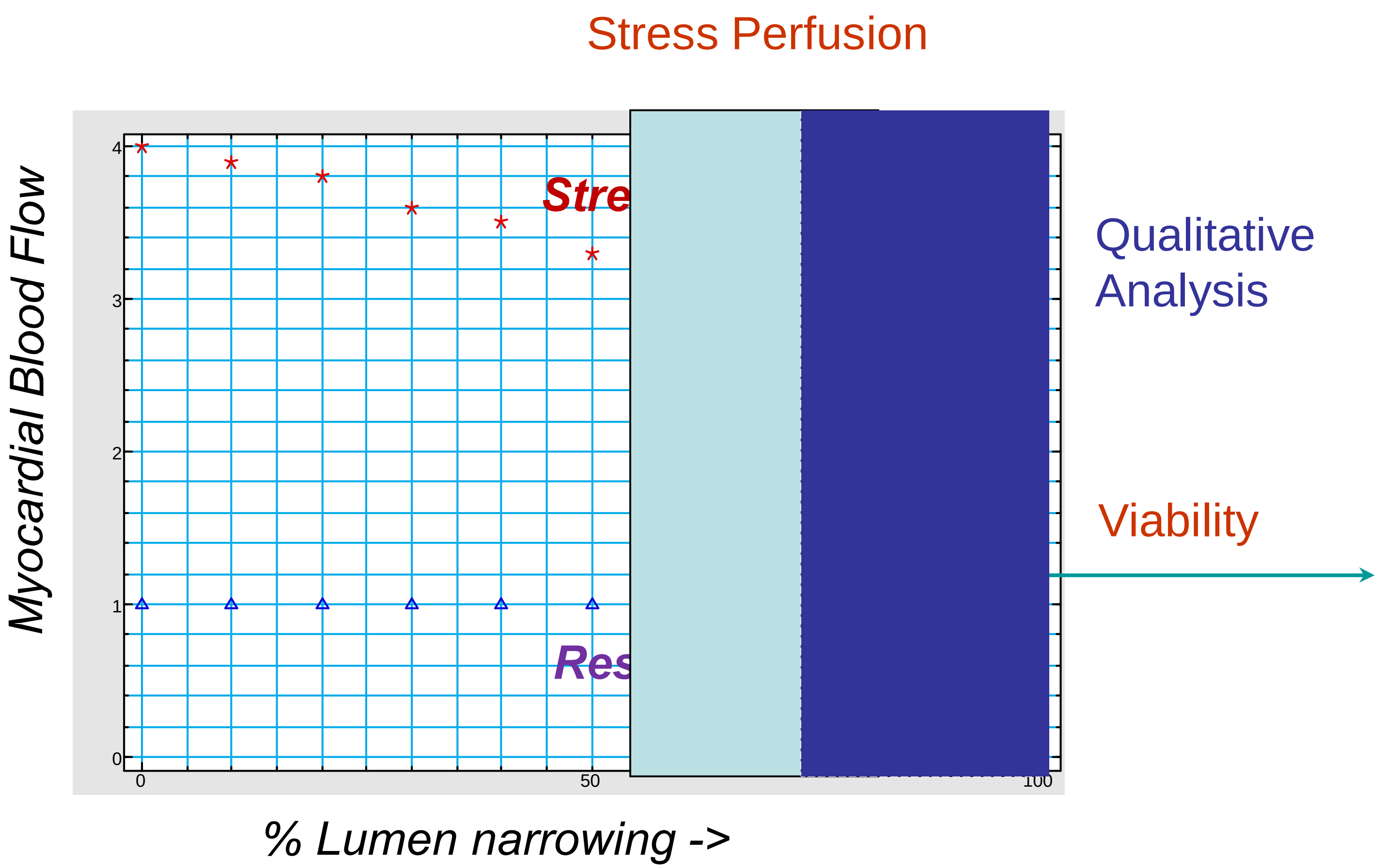
Myocardial Blood Flow Reserve



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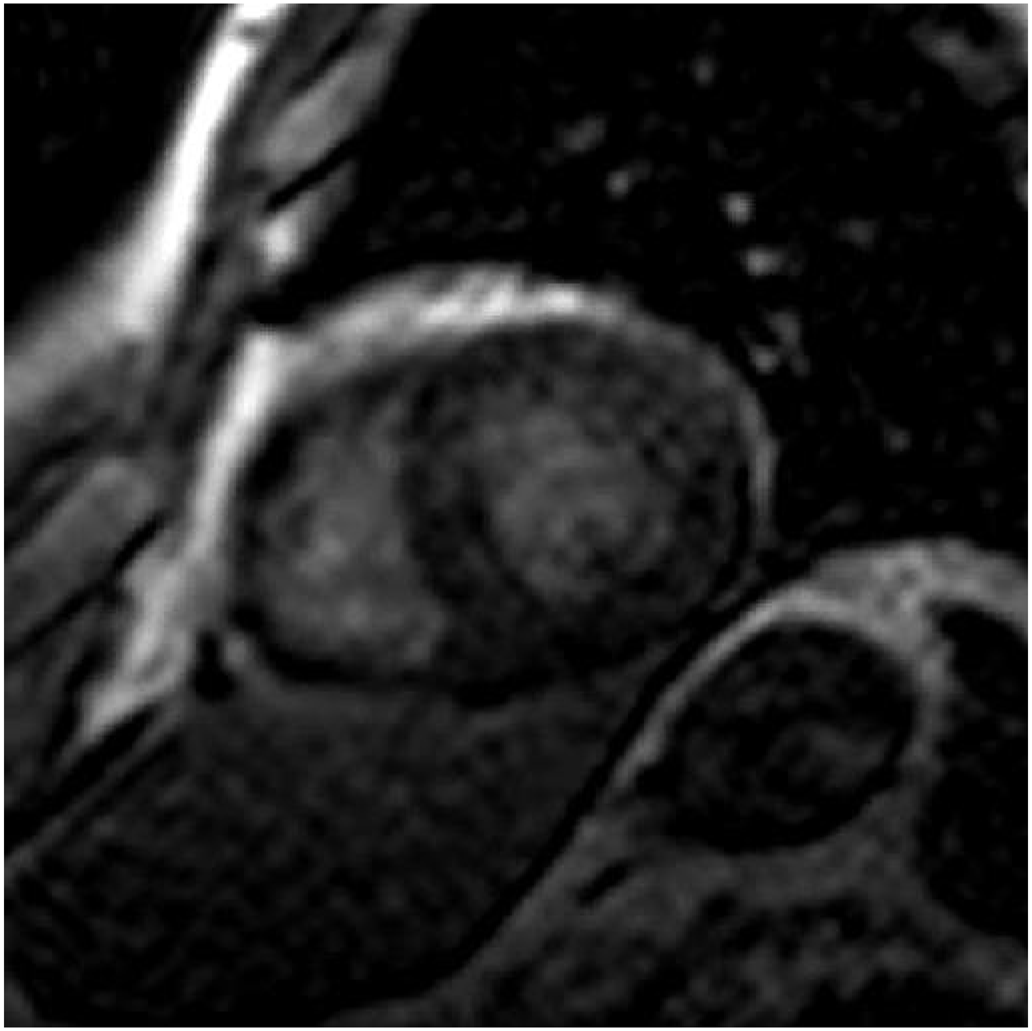
MR Perfusion Measurement

Å Changes in T_1 caused by Gd-DTPA during first pass indicate microvascular flow.

Å At low concentrations, T_1 changes are linearly related to concentration of Gd-DTPA.

Å The SI in a T_1 weighted sequence can therefore be linked to the concentration of Gd-DTPA.



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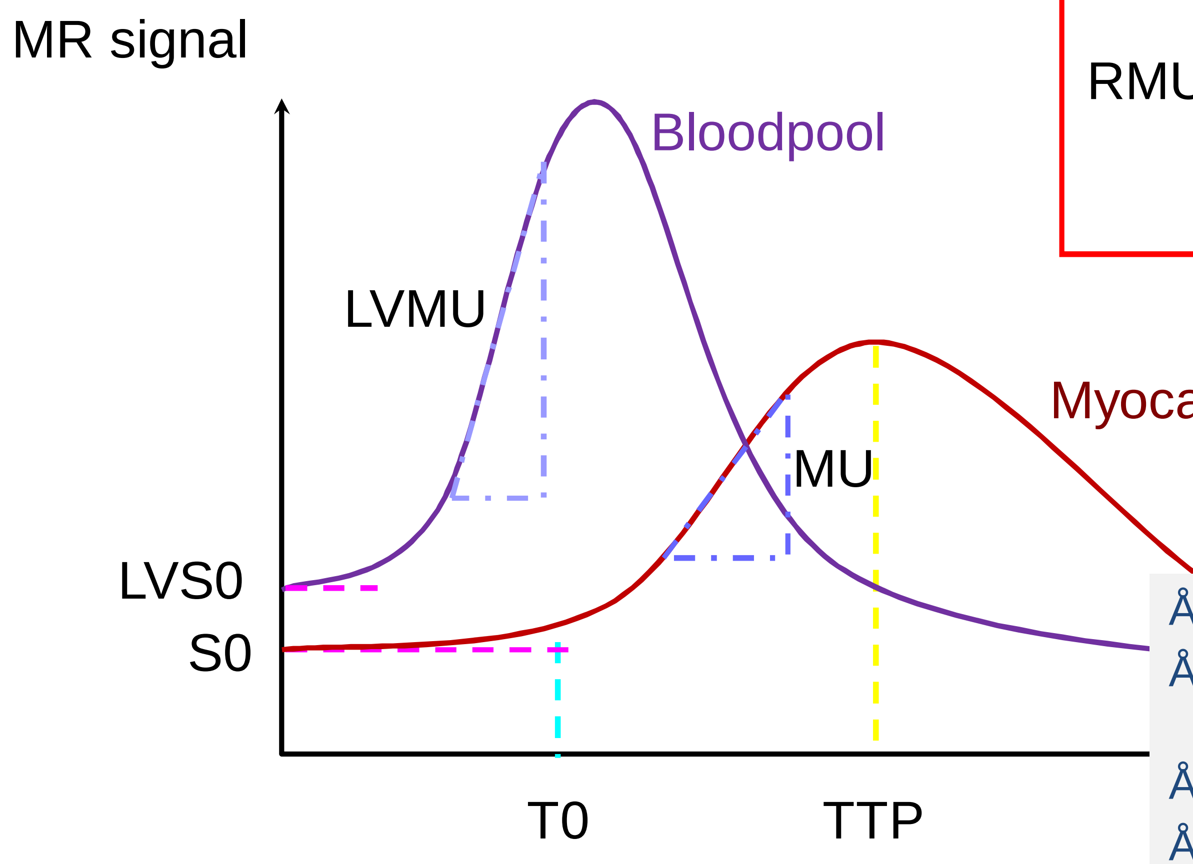
Perfusion Analysis :

$$RMU = \frac{\frac{MU}{S0}}{\frac{LVMU}{LVS0}} \times 100\%$$



Å Mean upslope

Å Relative mean upslope

Å Time to arrival

Å Time to peak

Å Peak enhancement

Å Relative peak enhancement

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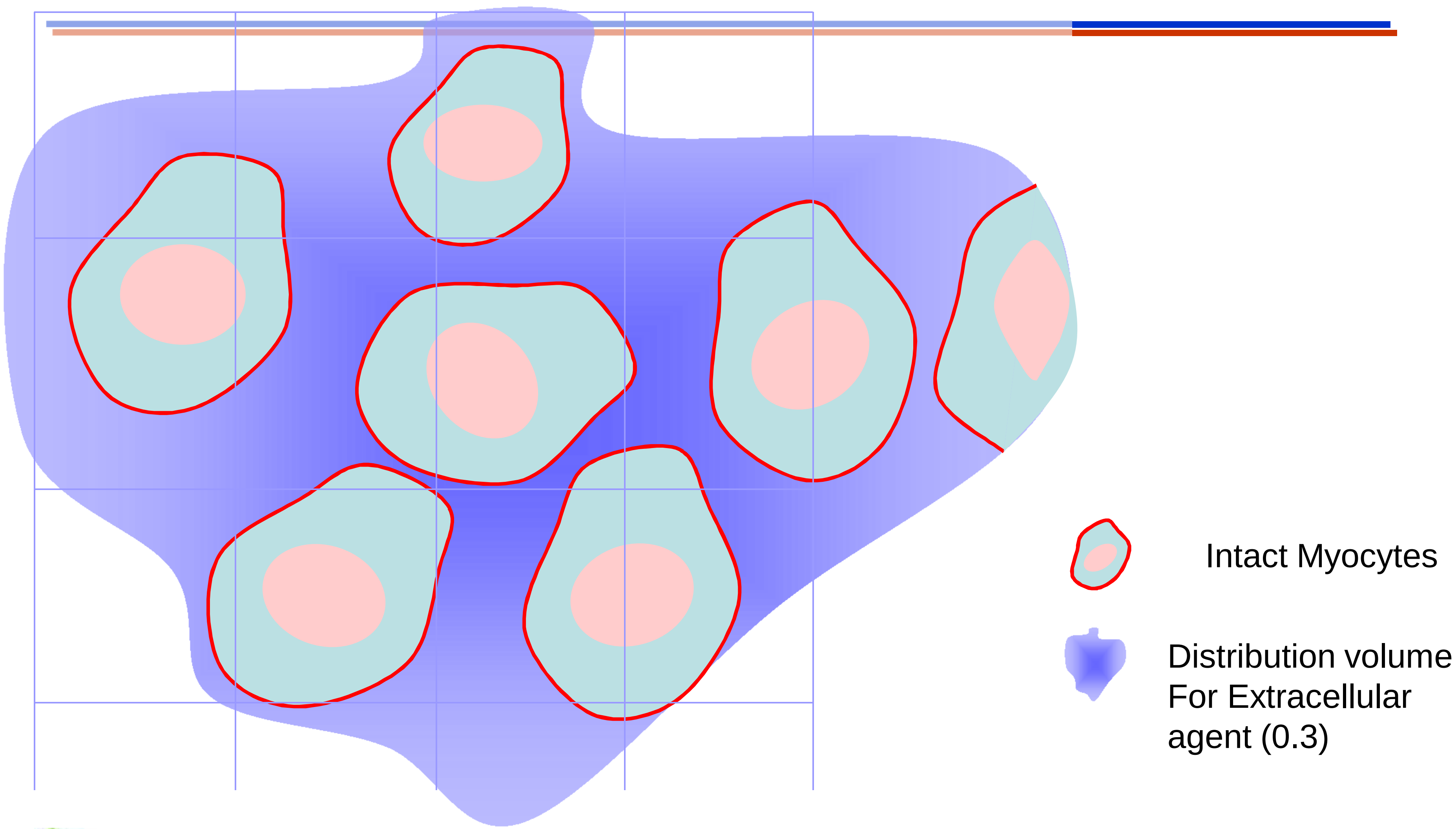
Myocellular matrix: Before Injury



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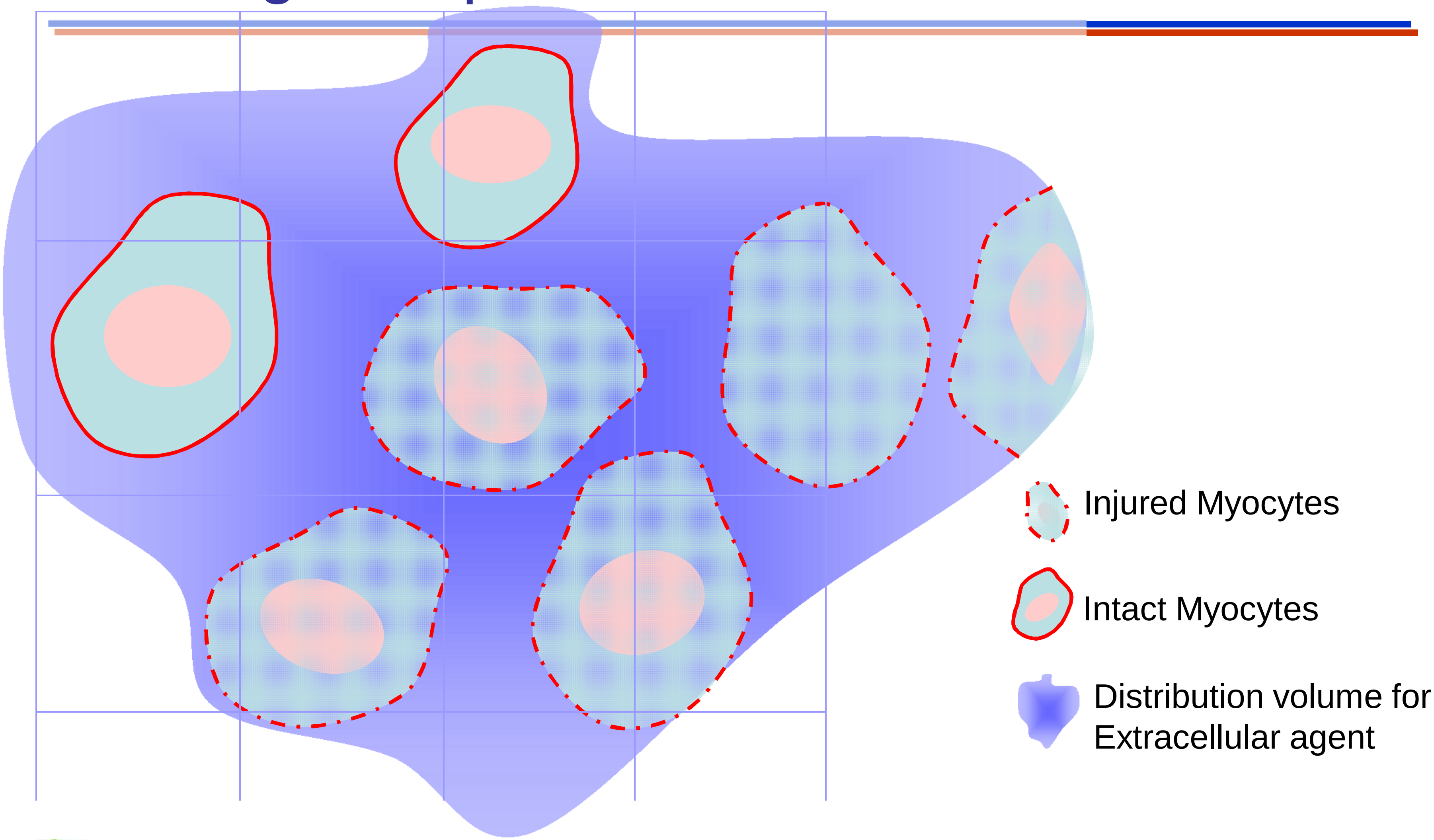
Irreversible Injury : Distribution volume (V_d) for Gd goes up



Myocellular Injury and V_d

Å Loss of cell membrane integrity

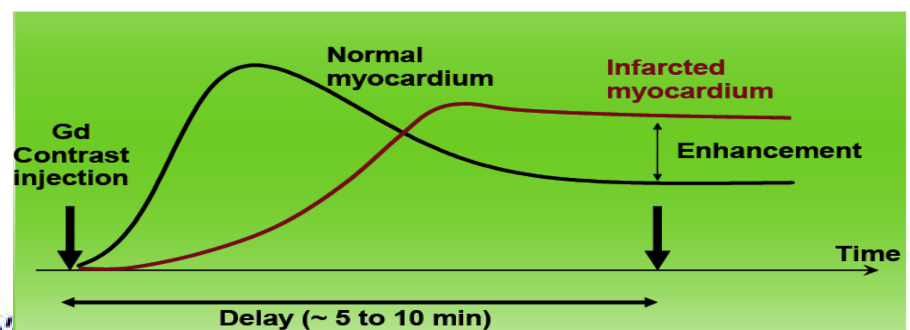
  ï Increased Distribution volume for Gadolinium

Å Chronic Case

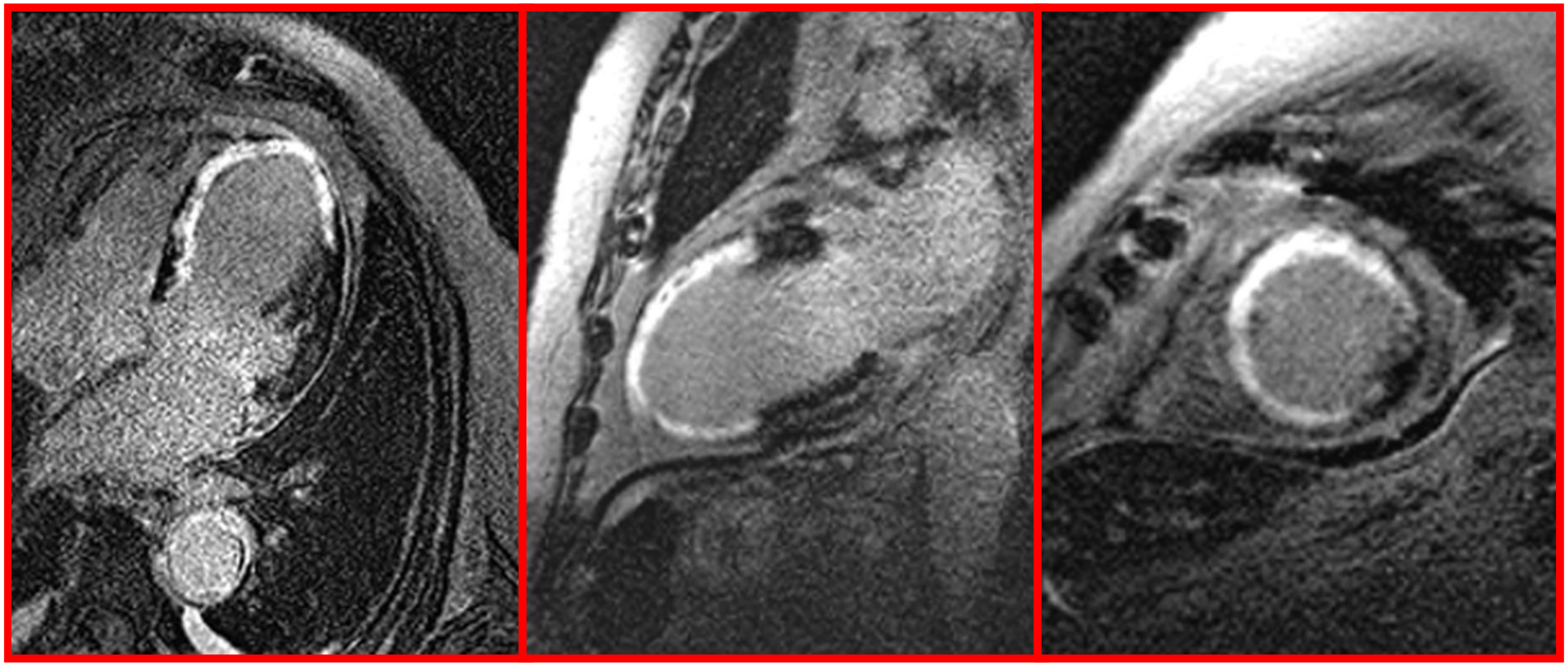
  ï Increased deposition of fibrous tissue ï Collagen matrix

  ï Increased distribution volume for an extracellular contrast medium

Å **Differential Accumulation of Extravascular agent**



Delayed-Enhancement MRI



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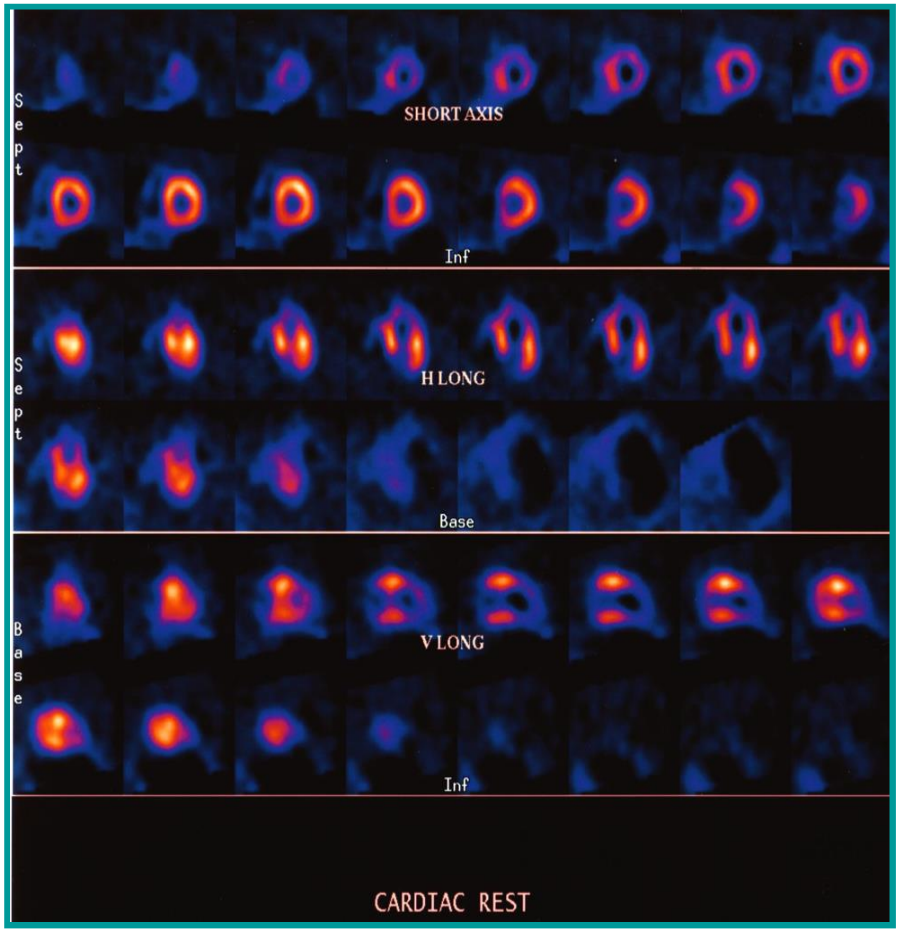
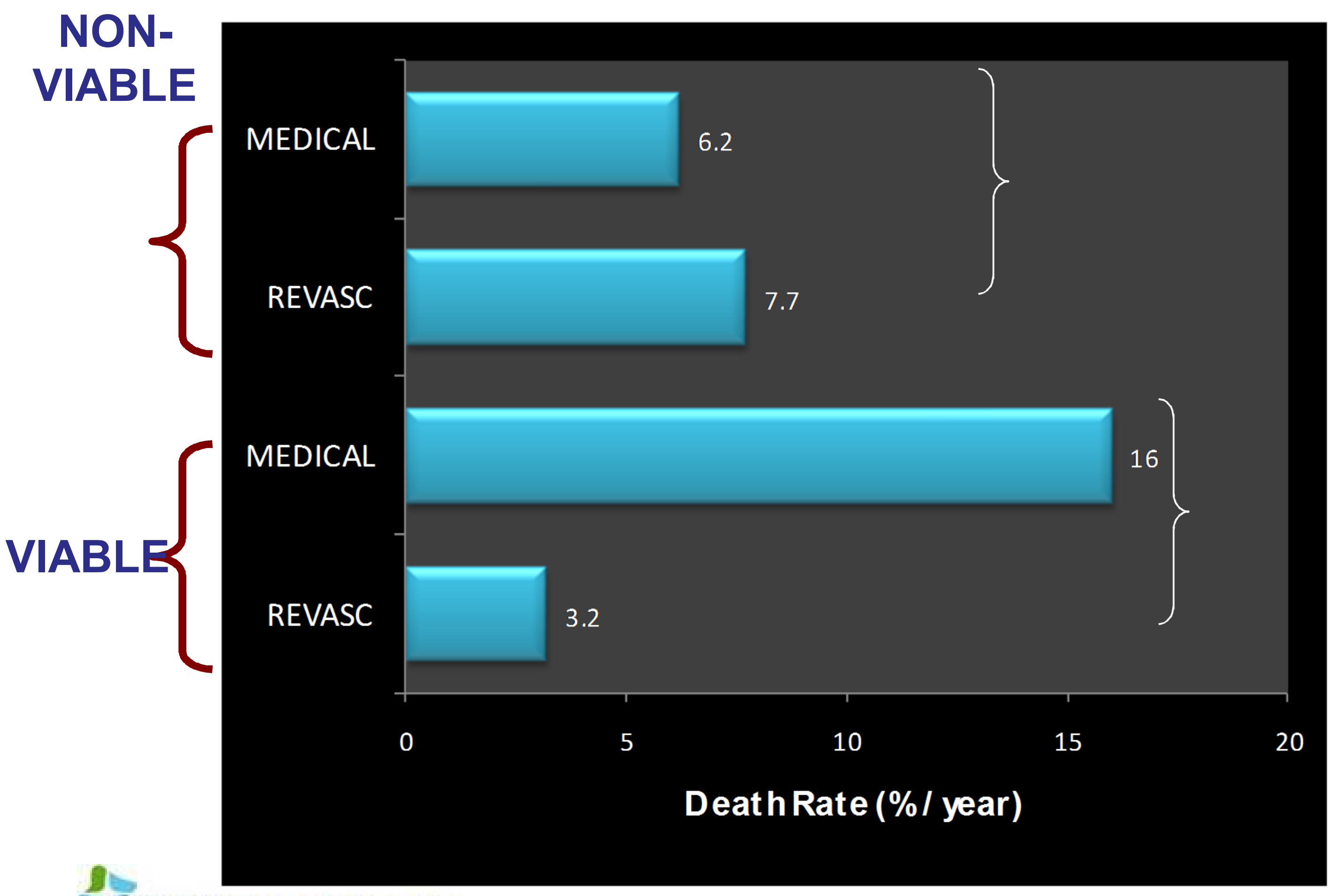
Myocardial Viability MRI



- High Contrast Resolution
- Transmurality of Infarction
- Well validated
- Clinically Simple to Use

Why assess myocardial viability?

Death Rates in Patients +/- Revascularisation



P = 0.23
(Δ 23%)

P < 0.0001
(Δ 80%)

Meta-analysis > 3000 pts

PET, Tl SPECT, ECHO

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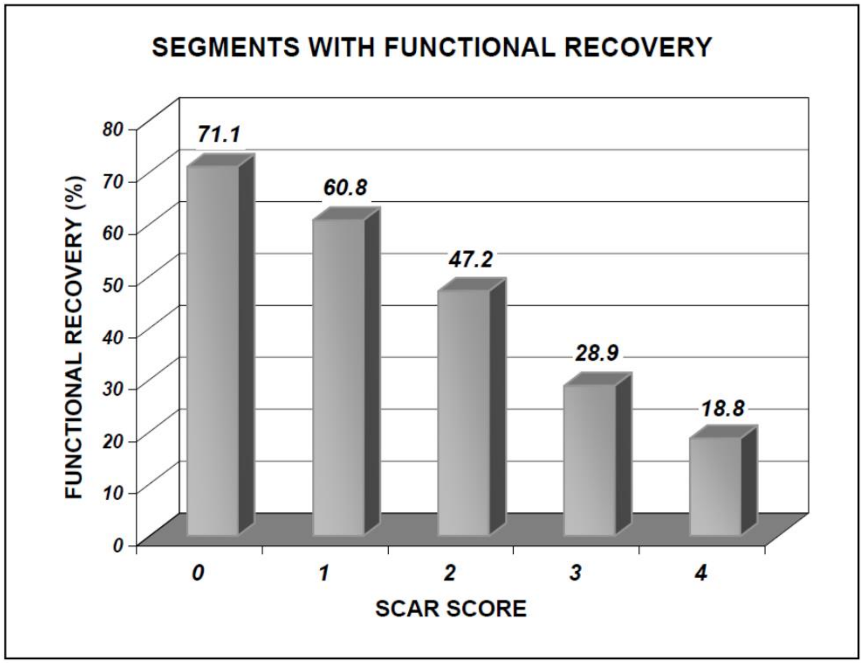
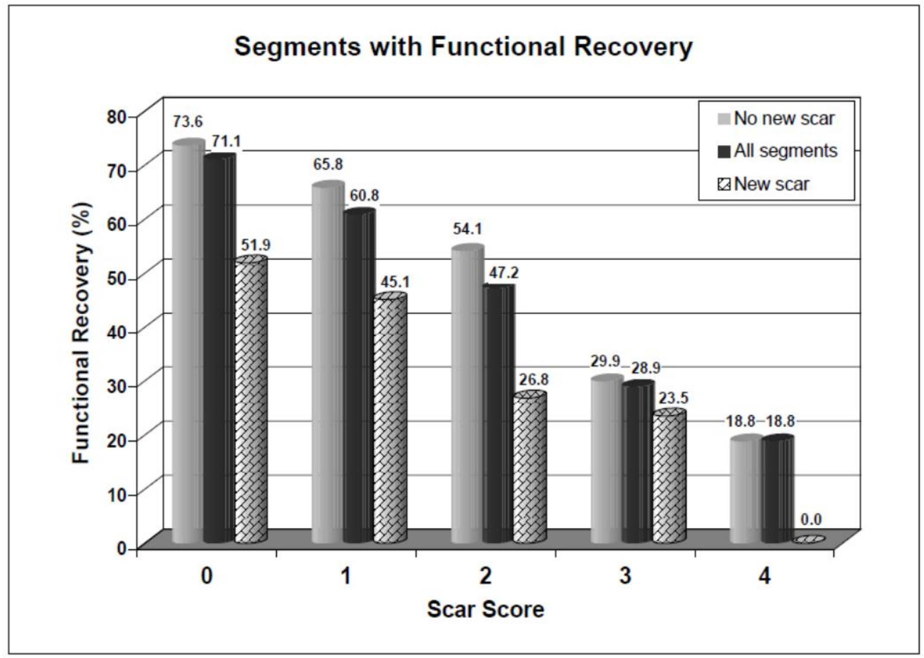
KC Allman at al. JACC 2002;39:1151-1158.

Courtesy: Dr. Cheong, MD, BSLMC

SLEH MV Trial : Segmental Wall Motion





Accepted for publication, JACC 2013

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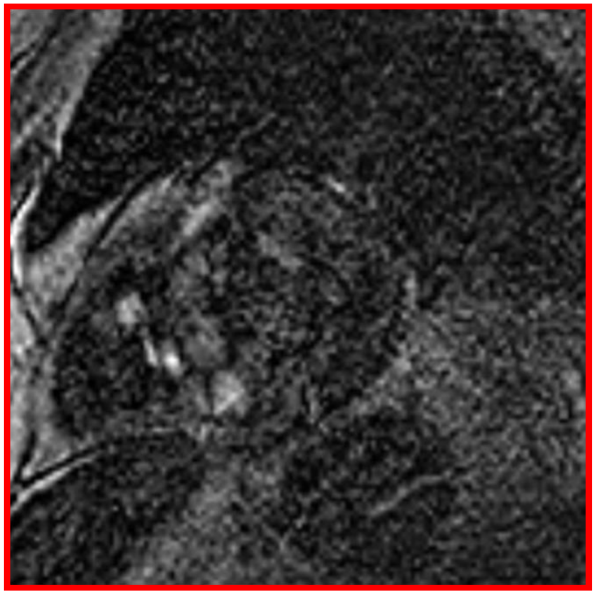
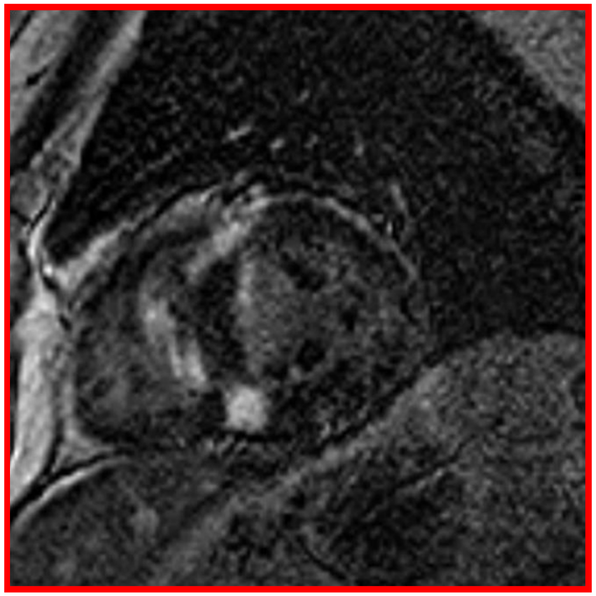
Texas Heart® Institute at St. Luke's Episcopal Hospital

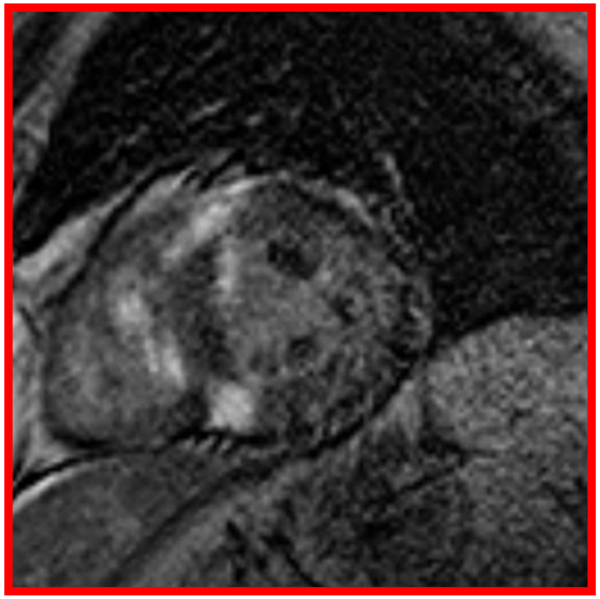
Non-Ischemic CM



TI: 200



TI: 250



TI: 300

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CMR and Viability

Å Simple technique to use

  ï IV line and MR contrast

Å High contrast resolution

Å Transmurality of Infarction

  ï Guides clinical decision making

Å Ischemic Cardiomyopathy

  ï Acute and Chronic MI

Å Non-ischemic cardiomyopathy

  ï Comprehensive Evaluation (T_2, T_1, $T_{1\rho}$ etc.)

Outline

- Cardiovascular Disease and Non-Invasive Imaging
- Clinical Cardiovascular MRI
  - Cardiac Gating
  - Anatomy / Tissue Characterization
  - Function
  - Flow
  - Perfusion
  - Viability
- Why CMR?
- Summary

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Cardiac Imaging

Parameter	US	XRA	x-ray CT	NM	MRI
LV Function	☑☑☑	☑	☑	☑	☑☑☑
Valvular Function	☑☑☑	?	?	?	☑☑
Tissue Characterization	?	?	☑	?	☑☑☑
Ischemia/Viability	☑	☑☑	?	☑☑☑	☑☑ ☑☑☑
Coronary Arteries	☑	☑☑☑	☑☑	?	☑
Congenital Anomalies	??	??	☑☑	?	☑☑

CMR : Clinical Outcomes

Å Multitude of soft-tissue contrast manipulations:

  ï Tissue characterization; Tumors; Structure; Freely Angulated FOV

Å Ventricular Function: Global and Regional

  ï Devoid of geometrical assumptions; Accurate/Precise; Both RV and LV

Å Flow : Evaluation of Valvular Function

  ï Assessment of regurgitation and stenosis

Å Perfusion

  ï Non-invasive assessment of ischemia; Quantitation; No-radiation

Å Myocardial Viability

  ï High contrast resolution; Non-transmural infarction; Patient mgt.

CMR: Impediments

Å Cumbersome technology; Time consuming

Å Not suitable for claustrophobic patients

Å Not suitable (at the moment) for patients with pacemakers

Å Requires Expertise : Technologist / Clinician / Physics

Å Radiology / Cardiology Practice Cultures

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Thank you!

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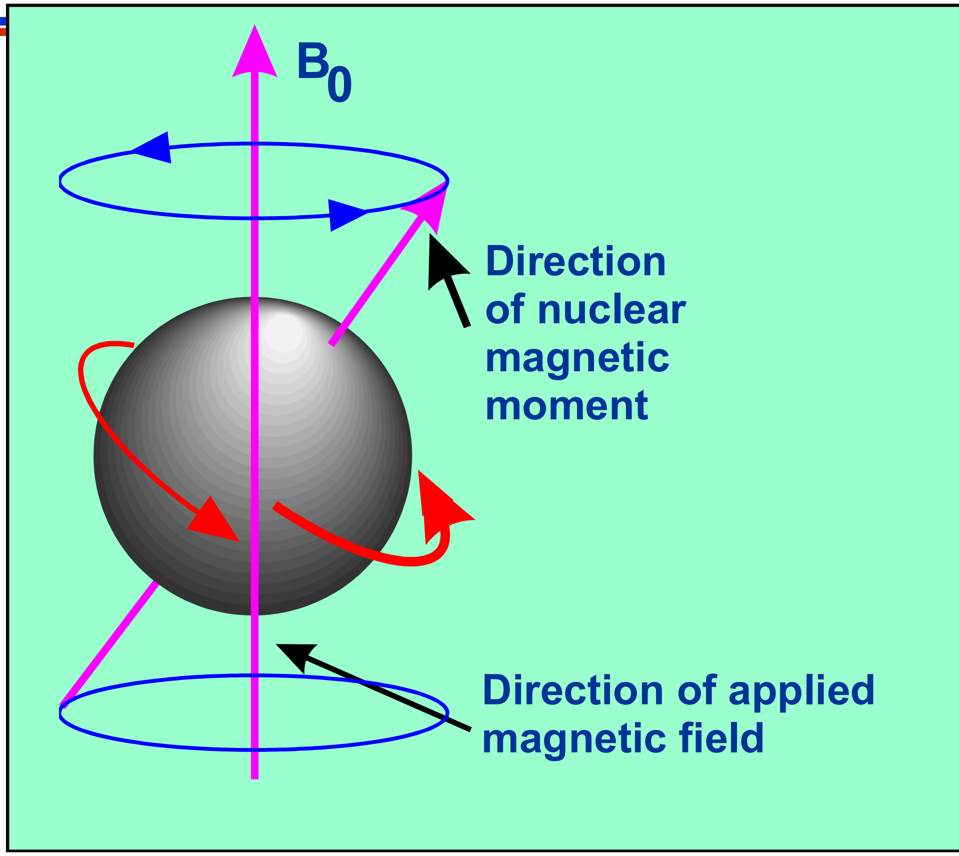
Phase contrast MRA: Principles



$$\omega \; \alpha \; B_o$$

Precessional Frequency is proportional to field gradient.

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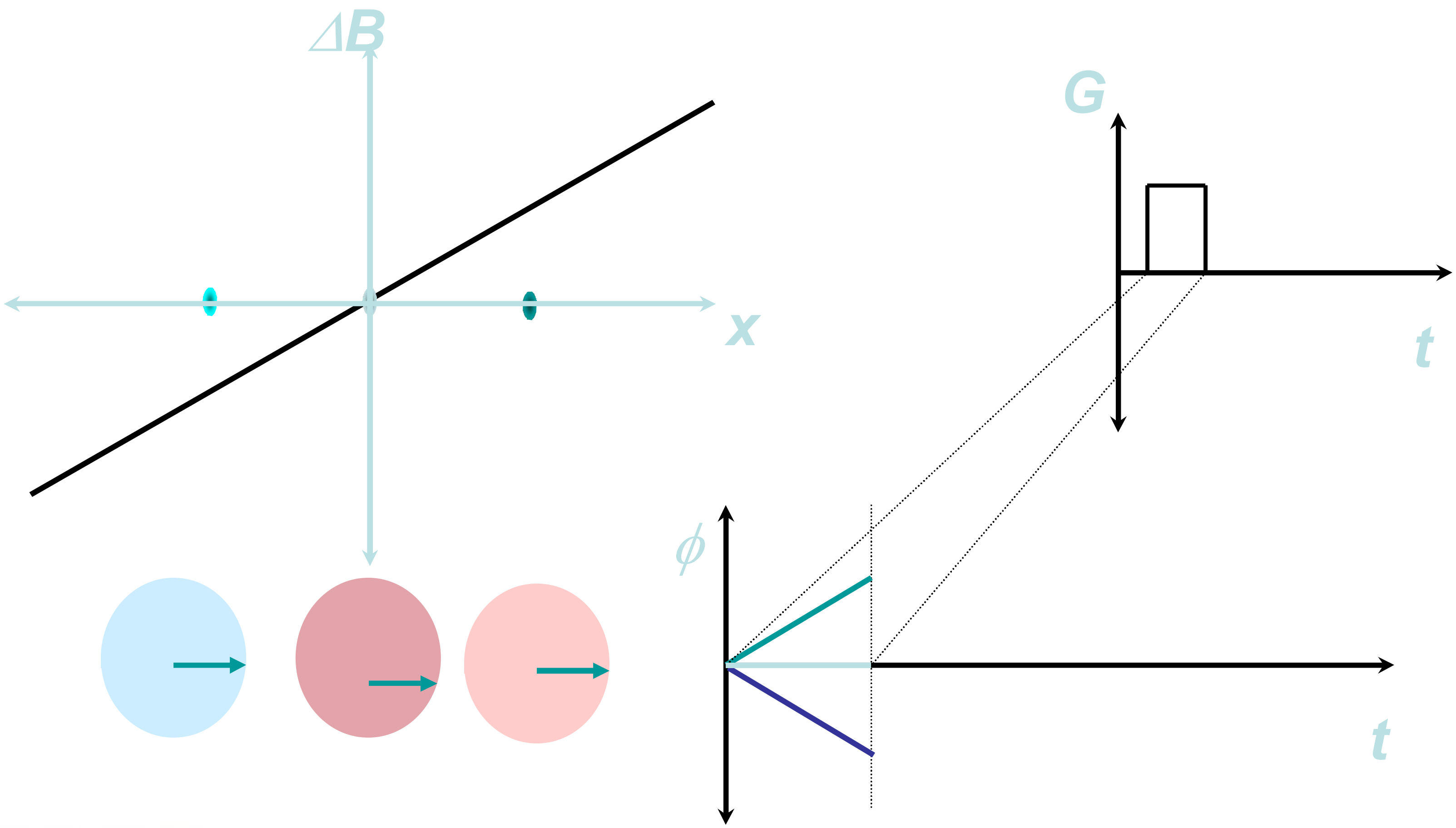
Phase Velocity Mapping: Principle - I

Å Static Spins and magnetic field gradients



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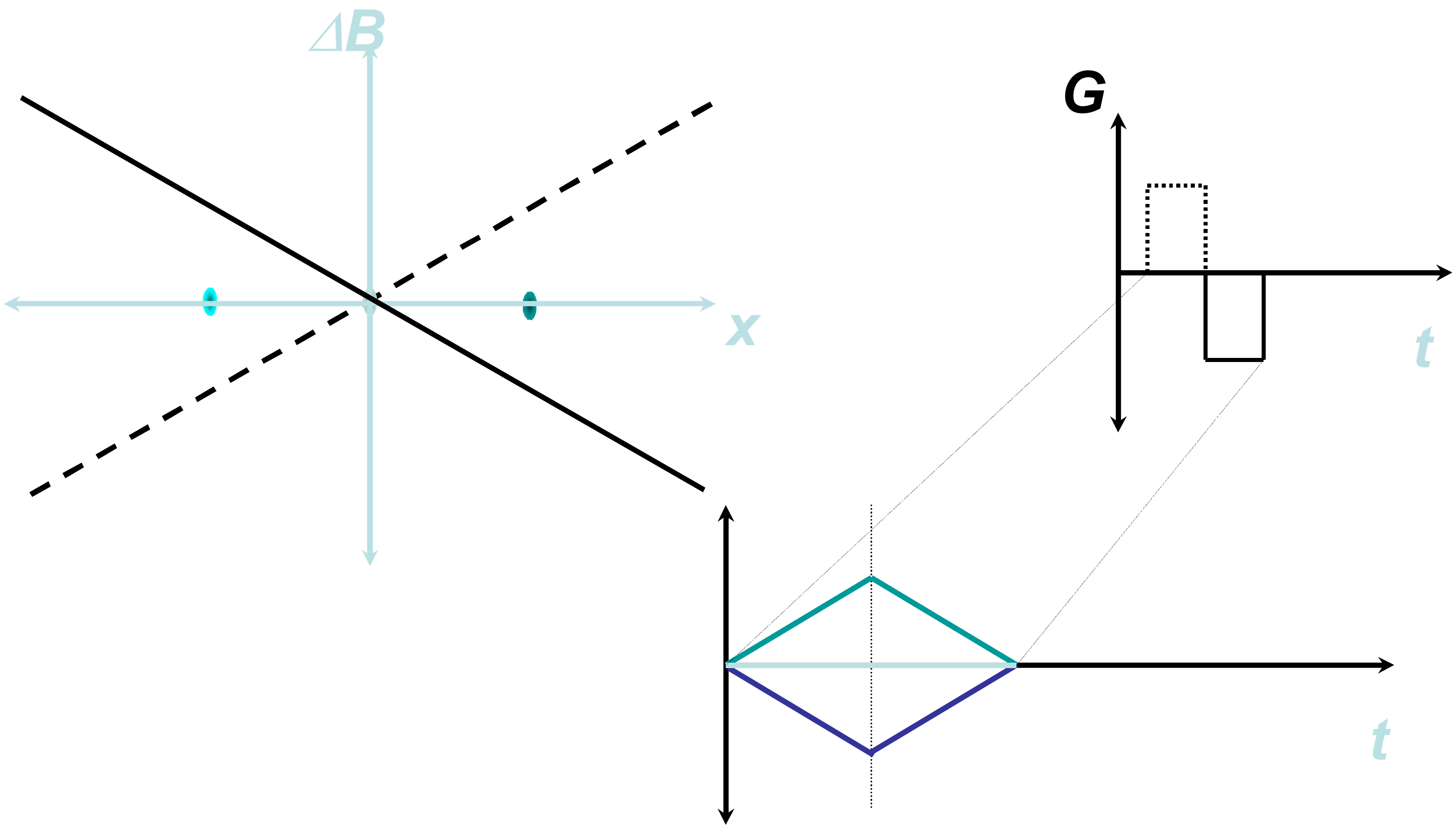
Phase Velocity Mapping: Principle - 2

Å Static Spins and magnetic field gradients



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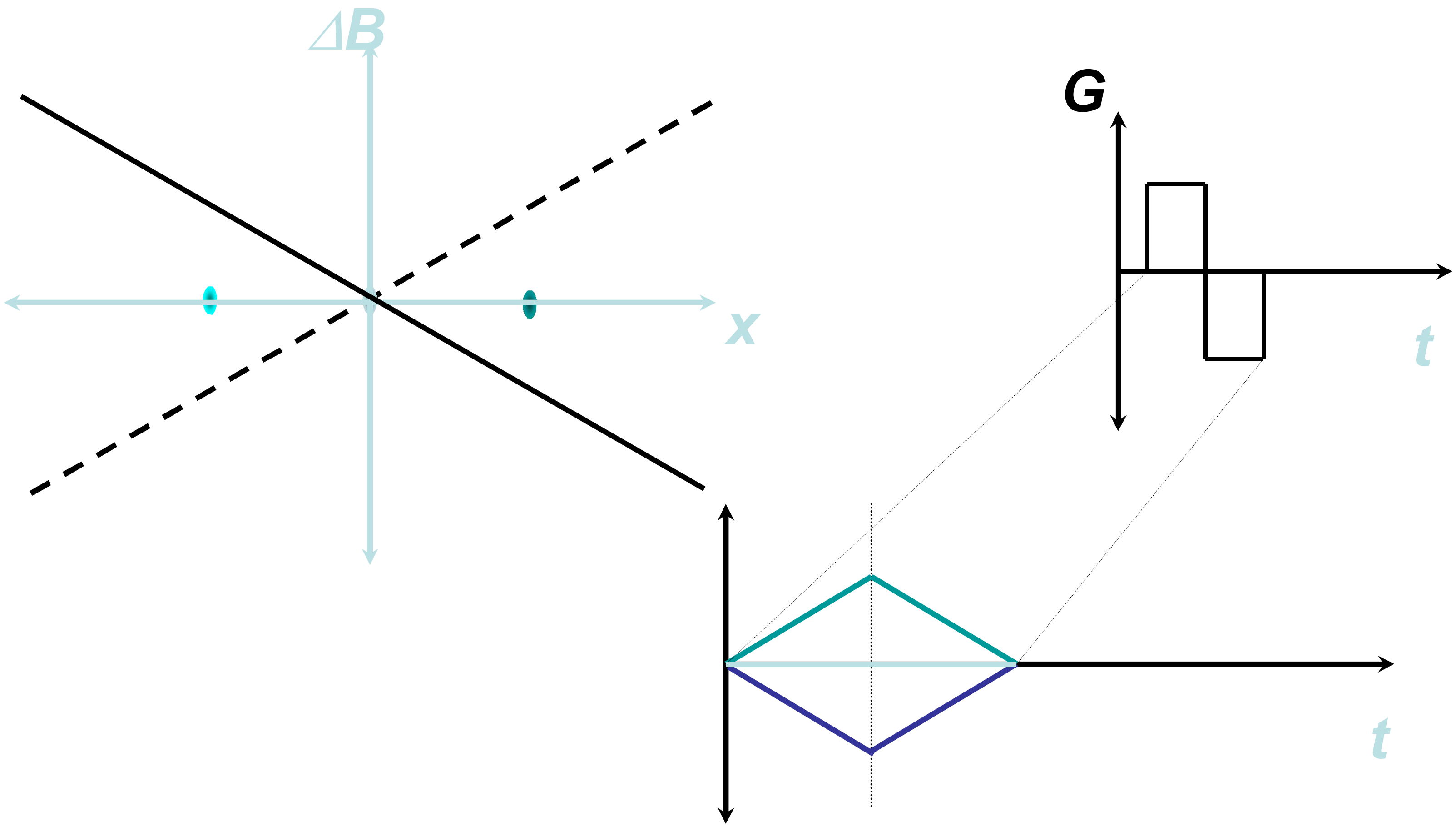
Phase Velocity Mapping: Principle - 2



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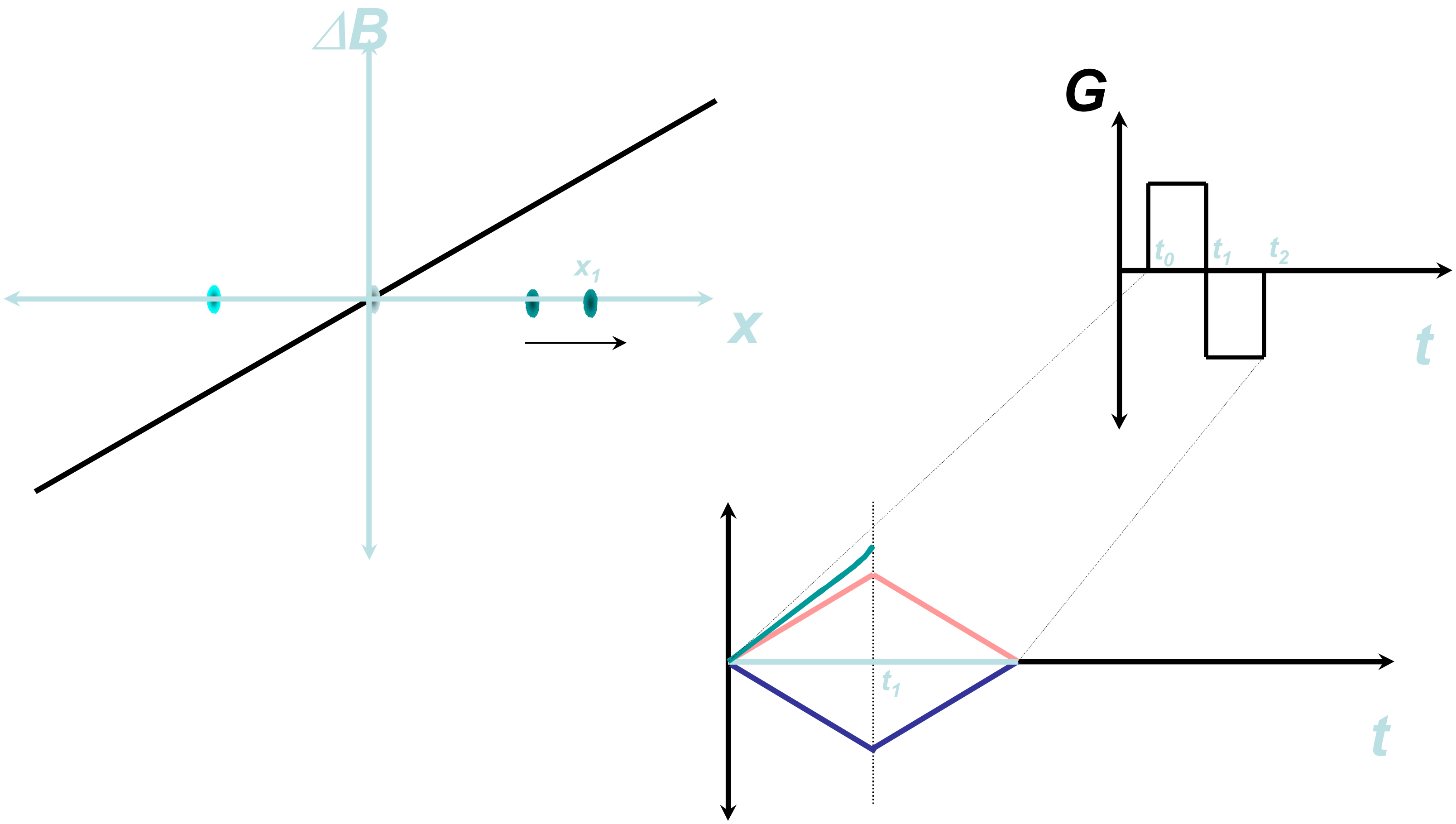
Static spins do not accrue phase in the presence of bipolar gradients (or any other gradient with a zero net area)!

Phase Velocity Mapping: Principle - 3



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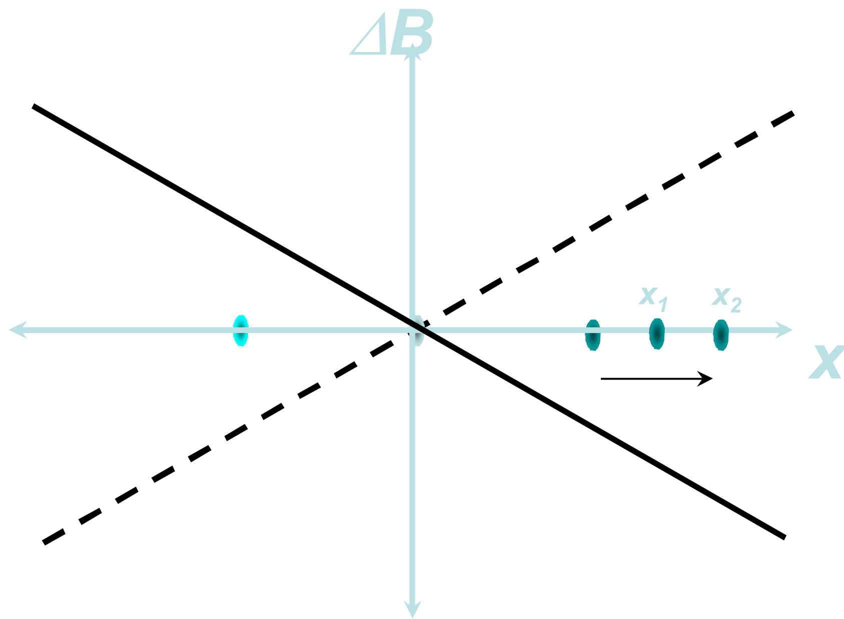
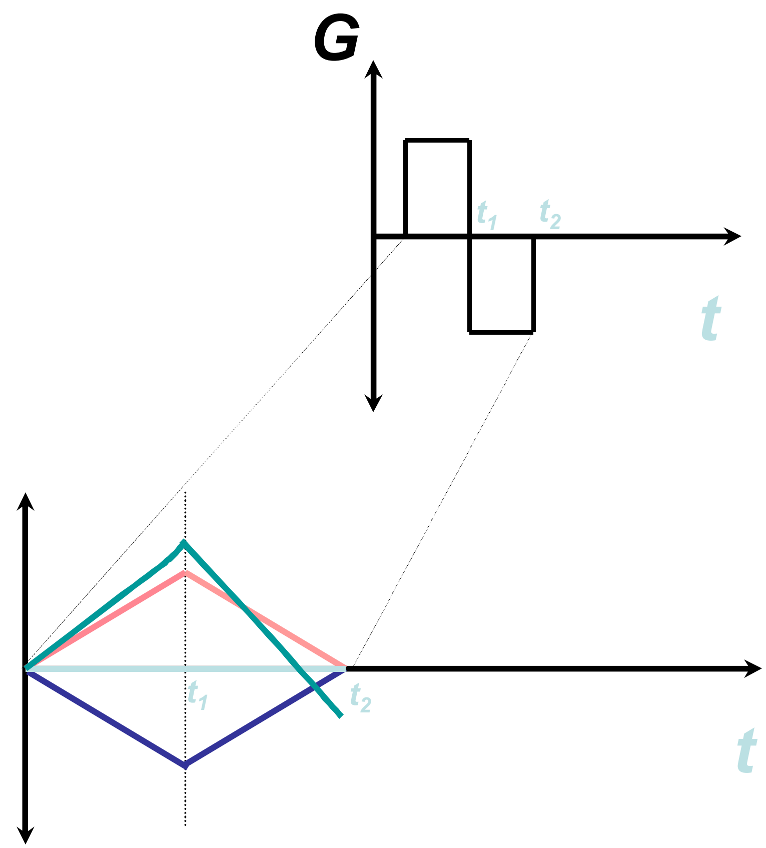
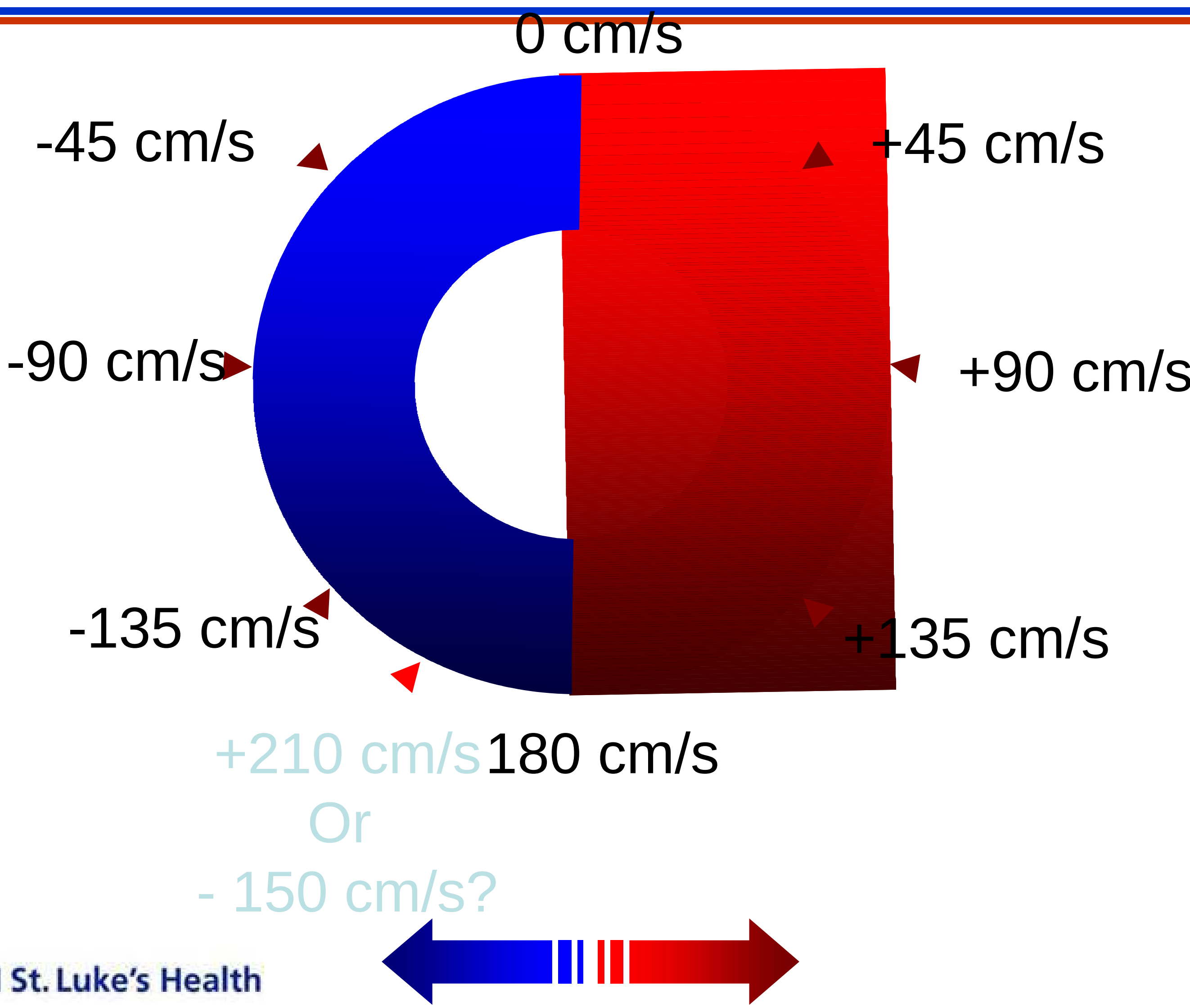
Phase Velocity Mapping: Principle - 3





Spins moving in the direction of a bi-polar gradient do accumulate a net phase shift.

Concept of Velocity Aliasing



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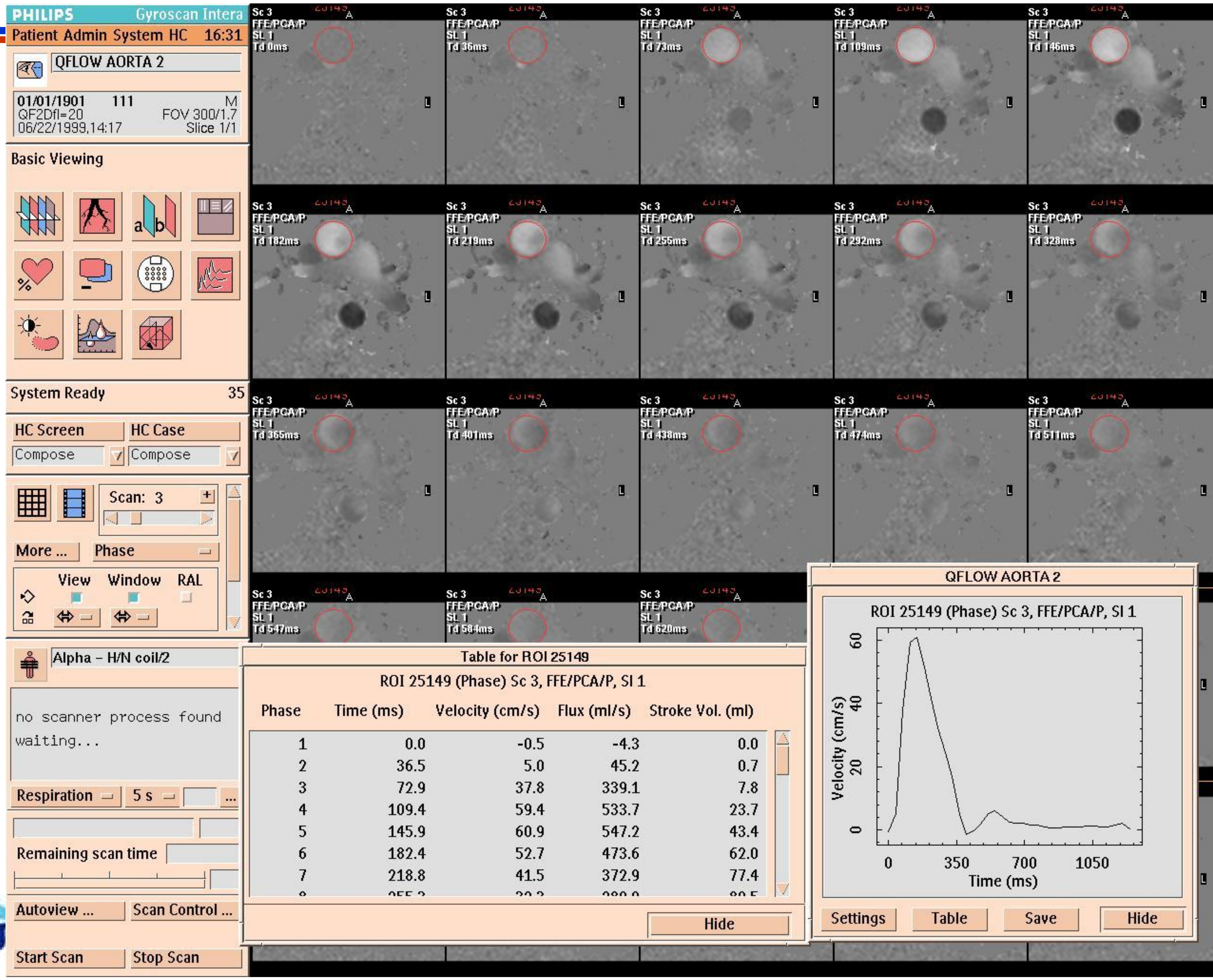
Phase Contrast MRA
Qflow analysis on console



Phase Contrast : Key Points

- Å Amplitude of Velocity (Speed) → MR Angiography, Peak Velocity, Pressure gradient
- Å Direction of Velocity (Vector) → Regurgitation, Flow shunts, etc.
- Å Strength of Velocity Encoding : (V_{enc}) → Aliasing, Visualization of arteries/veins
- Å Shape of flow wave form → Wall-shear stress; Systemic Physiology

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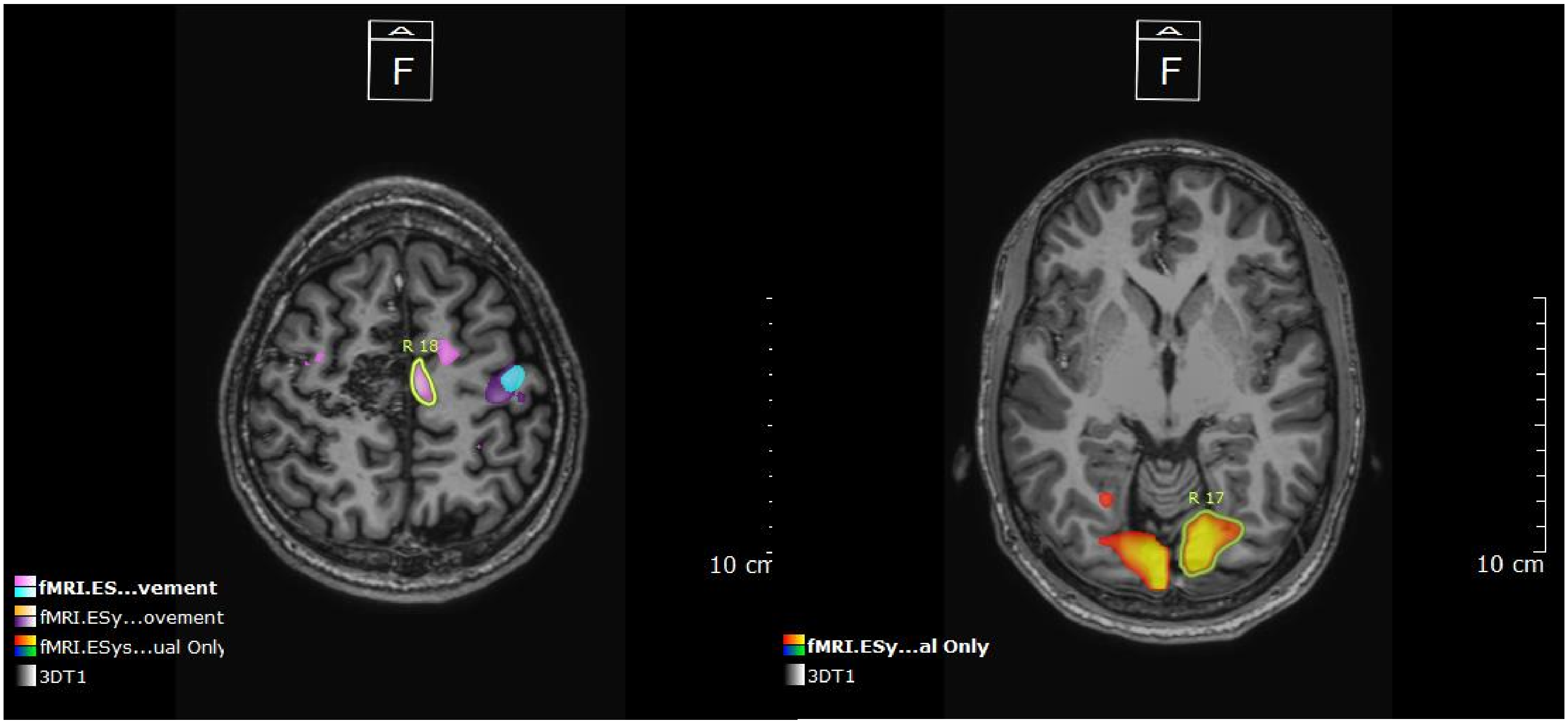
Functional MRI for pre-surgical planning



Foot Movement

Visual System

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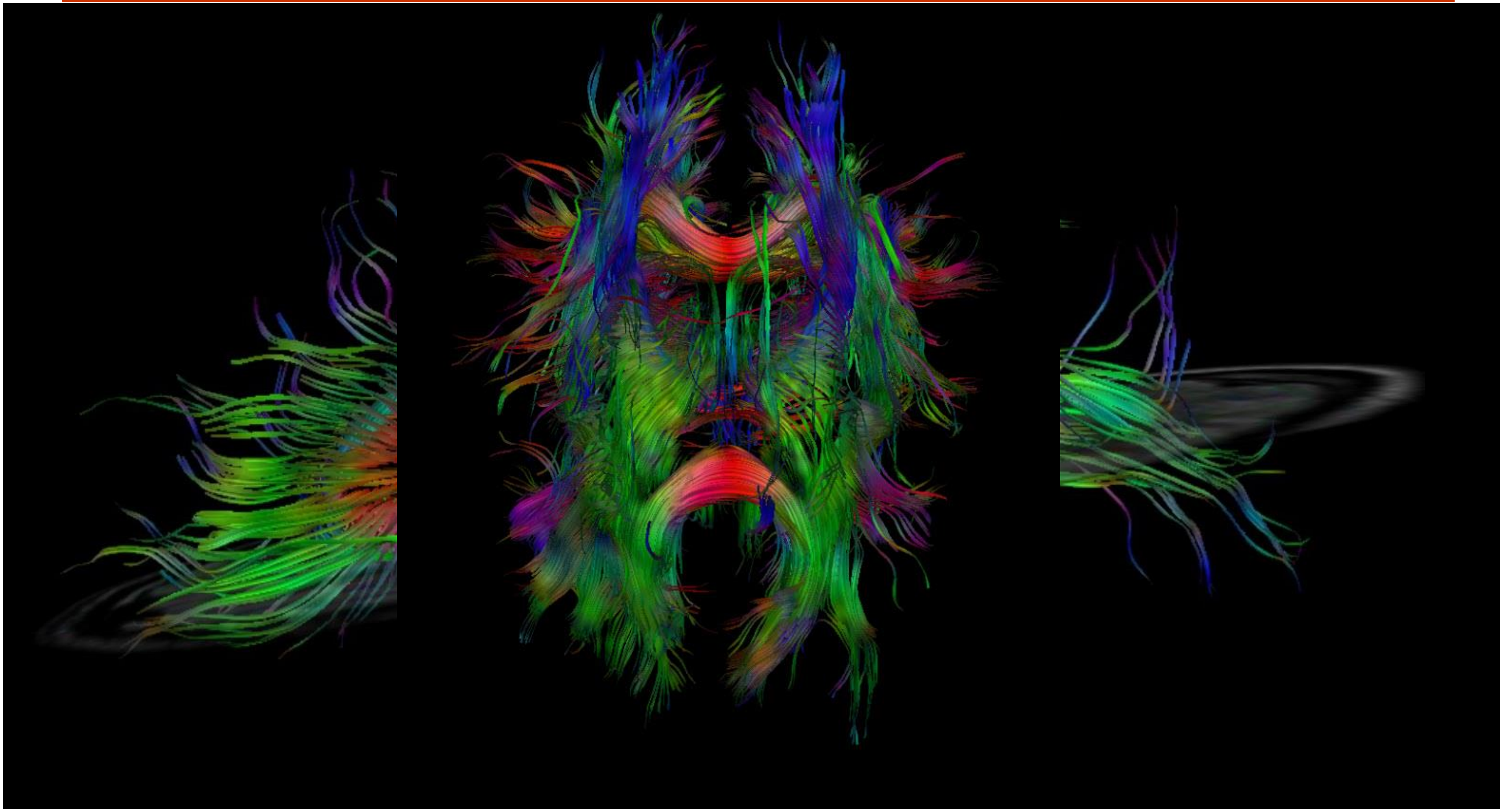
Diffusion Tensor Imaging



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Thank you!

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