

Perfusion MRI Toolbox

Kathleen M. Schmainda, PhD

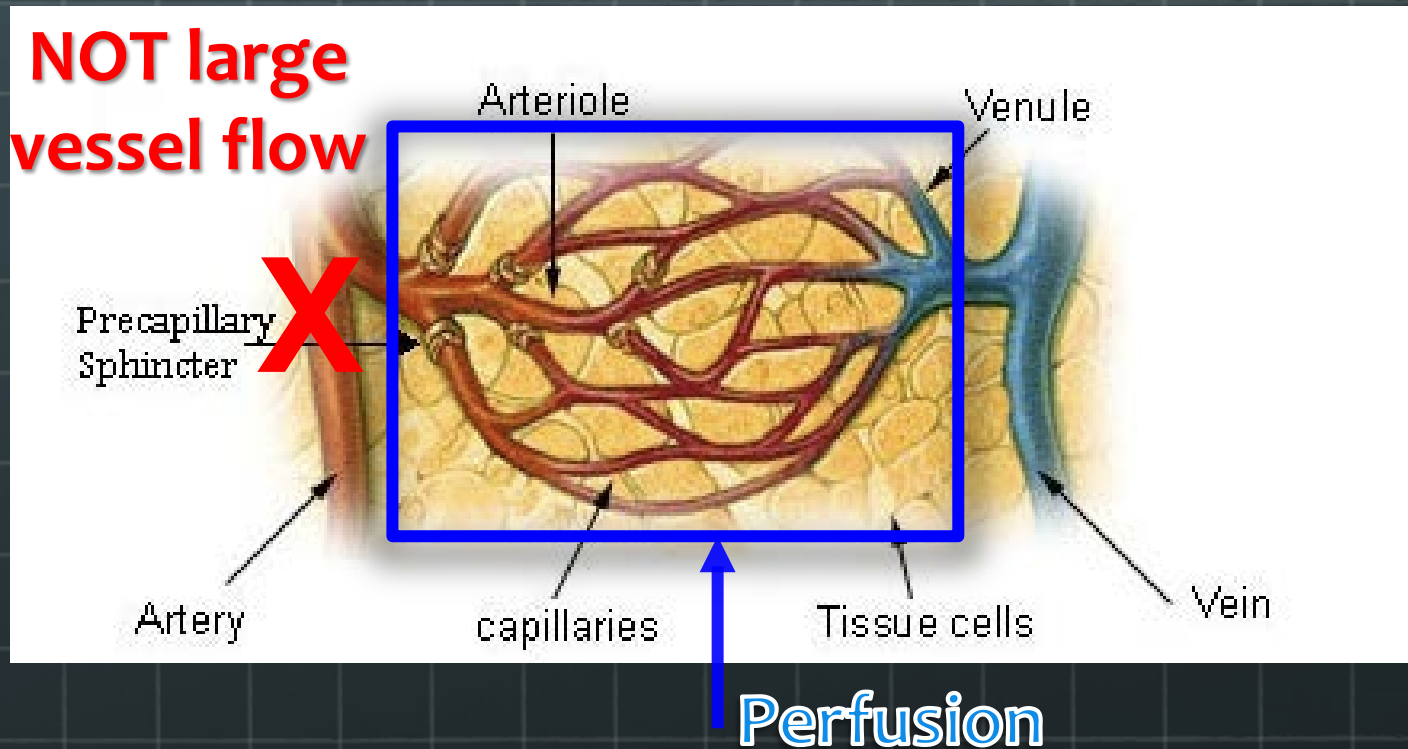
Professor, Radiology & Biophysics

Vice-Chair, Radiology Research

Medical College of Wisconsin

Perfusion-MRI Definition

- 🌐 Delivery of Blood Flow to tissue



Perfusion-MRI **Methods**

- Dynamic Contrast Enhanced (DCE-MRI)
- Dynamic Susceptibility Contrast (DSC-MRI)

**Exogenous
Contrast**

- ASL: Arterial Spin Labeling
- BOLD: Blood Oxygenation Level
- IVIM: Intravoxel Incoherent Motion

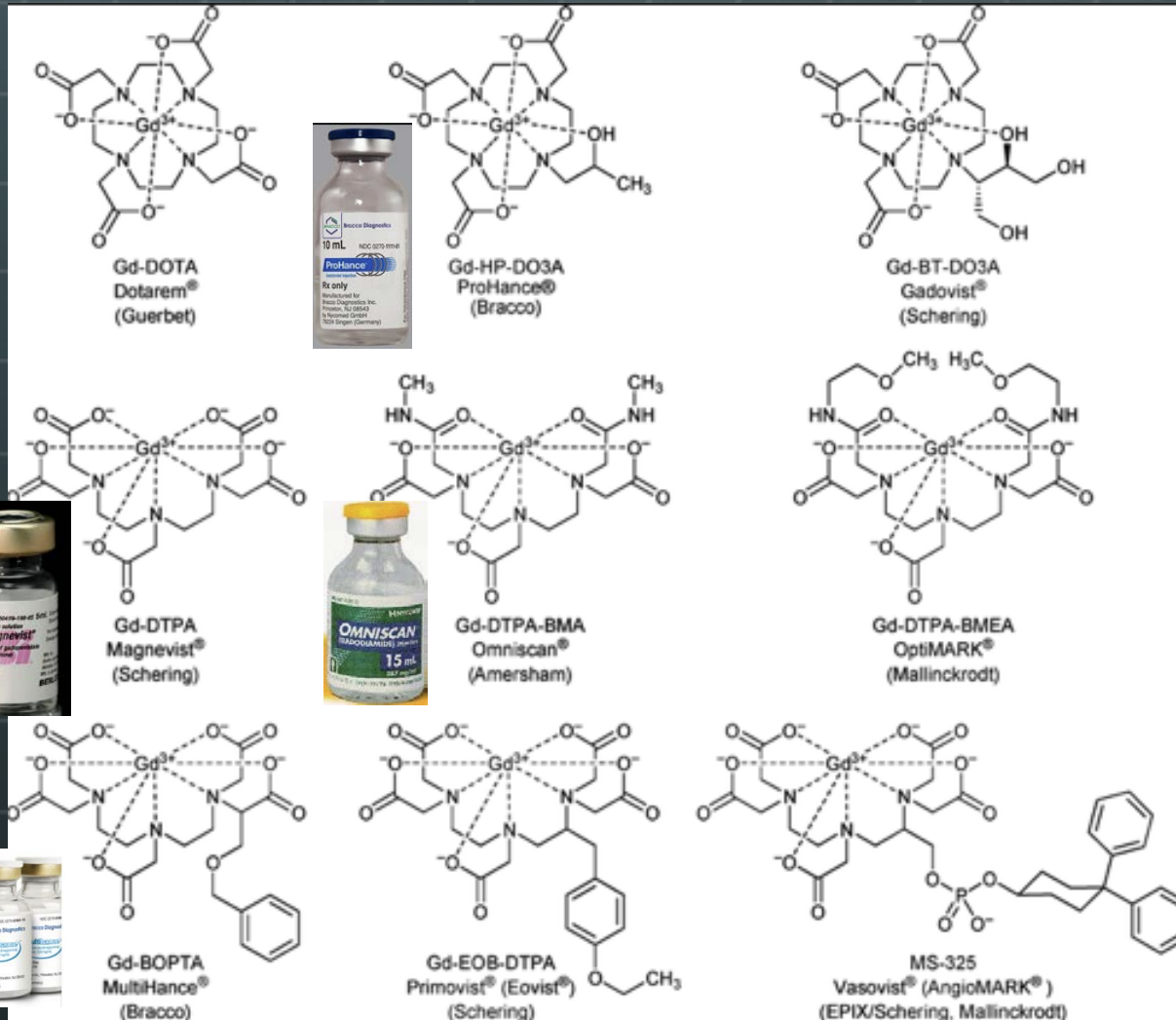
**Endogenous
Contrast**

Introduction: Gadolinium

Periodic Table of the Elements

1 1IA 1A	2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.00794	2 He Helium 4.002602											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.00644	8 O Oxygen 15.999	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
3 Li Lithium 6.941	4 Be Beryllium 9.01224	3 III 3B	4 IV 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 9	10 VIII 10	11 IB 11	12 IIB 12	13 Al Aluminum 26.9815385	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.06	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938	26 Fe Iron 55.847	27 Co Cobalt 58.9332	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.9216	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90584	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium 98.9062	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.9055	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.757	52 Te Tellurium 127.6	53 I Iodine 126.90549	54 Xe Xenon 131.29
55 Cs Cesium 132.90545196	56 Ba Barium 137.327	57-71 Lanthanide Series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.222	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.59	81 Tl Thallium 204.3871	82 Pb Lead 207.2	83 Bi Bismuth 208.9804	84 Po Polonium 209	85 At Astatine 208.9804	86 Rn Radon 222.01758
87 Fr Francium 223	88 Ra Radium 226.0254	89-103 Actinide Series	104 Rf Rutherfordium 261	105 Db Dubnium 262	106 Sg Seaborgium 263	107 Bh Bohrium 264	108 Hs Hassium 265	109 Mt Meitnerium 266	110 Ds Darmstadtium 267	111 Rg Roentgenium 268	112 Cn Copernicium 269	113 Uut Ununtrium 270	114 Uuq Ununquadium 271	115 Uup Ununpentium 272	116 Uuh Ununhexium 273	117 Uus Ununseptium 274	118 Uuo Ununoctium 276
57 La Lanthanum 138.90547	58 Ce Cerium 140.12	59 Pr Praseodymium 140.90766	60 Nd Neodymium 144.242	61 Pm Promethium 144.9127	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.9304	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.967			
88 Ac Actinium 227.0278	90 Th Thorium 232.0377	91 Pa Protactinium 231.036888	92 U Uranium 238.02891	93 Np Neptunium 237.048173	94 Pu Plutonium 244.06422	95 Am Americium 243.06136	96 Cm Curium 247.07537	97 Bk Berkelium 247.0703	98 Cf Californium 251.0832	99 Es Einsteinium 252.0832	100 Fm Fermium 257.1035	101 Md Mendelevium 258.1035	102 No Nobelium 259.1035	103 Lr Lawrencium 260.1035			
Alkali Metal	Alkaline Earth	Transition Metal	Rare Metal	Semimetals	Nonmetals	Halogens	Noble Gas	Lanthanides	Actinides								

Introduction: Gadolinium



Gd-enhanced MRI

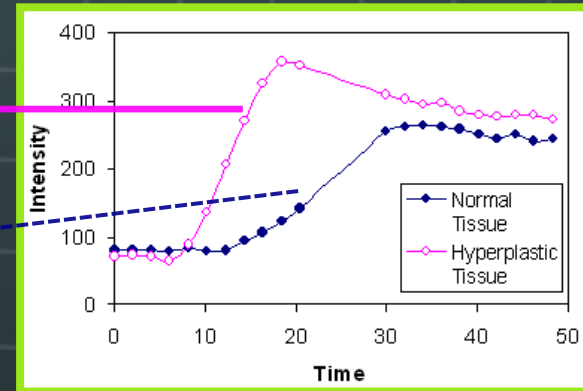
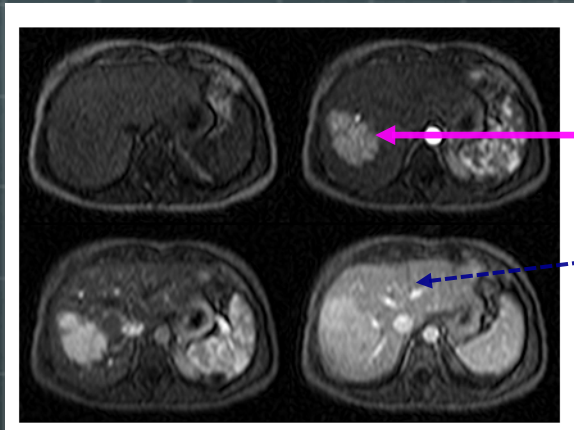


T1-weighted MRI

T1-weighted MRI with contrast agent

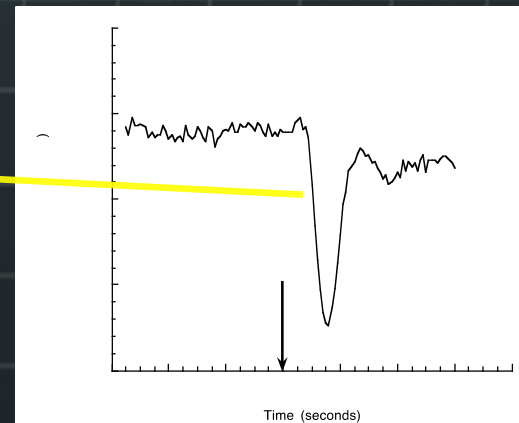
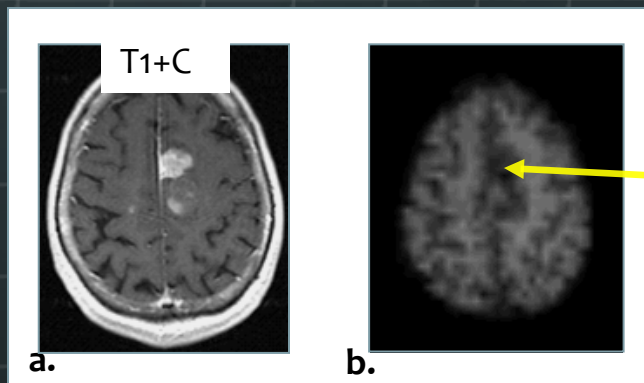
Dynamic Approaches

Dynamic Contrast Enhanced (DCE-MRI)



“T₁”
Brighter

Dynamic Susceptibility Contrast (DSC-MRI)



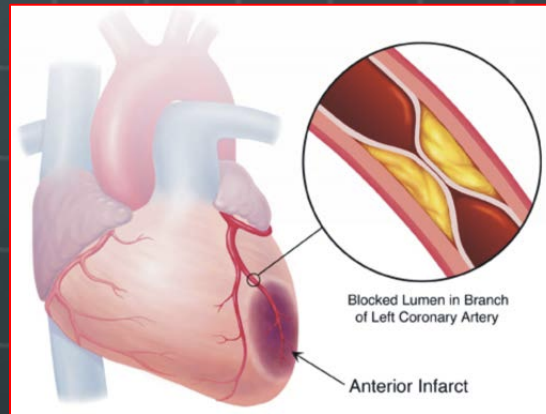
“T₂”
Darker

Two Primary Applications

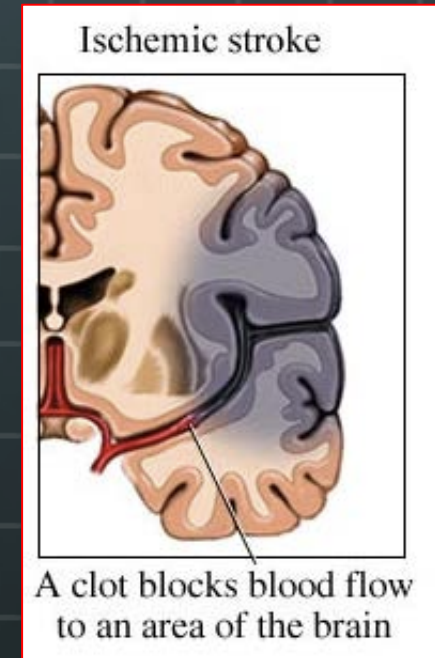


Ischemia:

Cardiac Ischemia

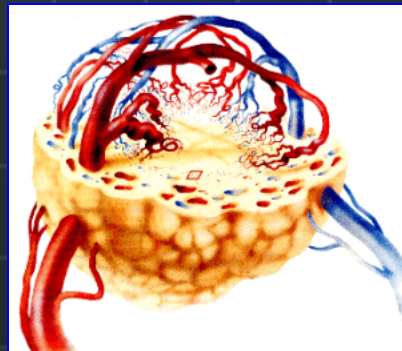


Cerebral Ischemia



Cancer:

Tumor Angiogenesis



Perfusion-MRI **Methods**

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**Exogenous
Contrast**

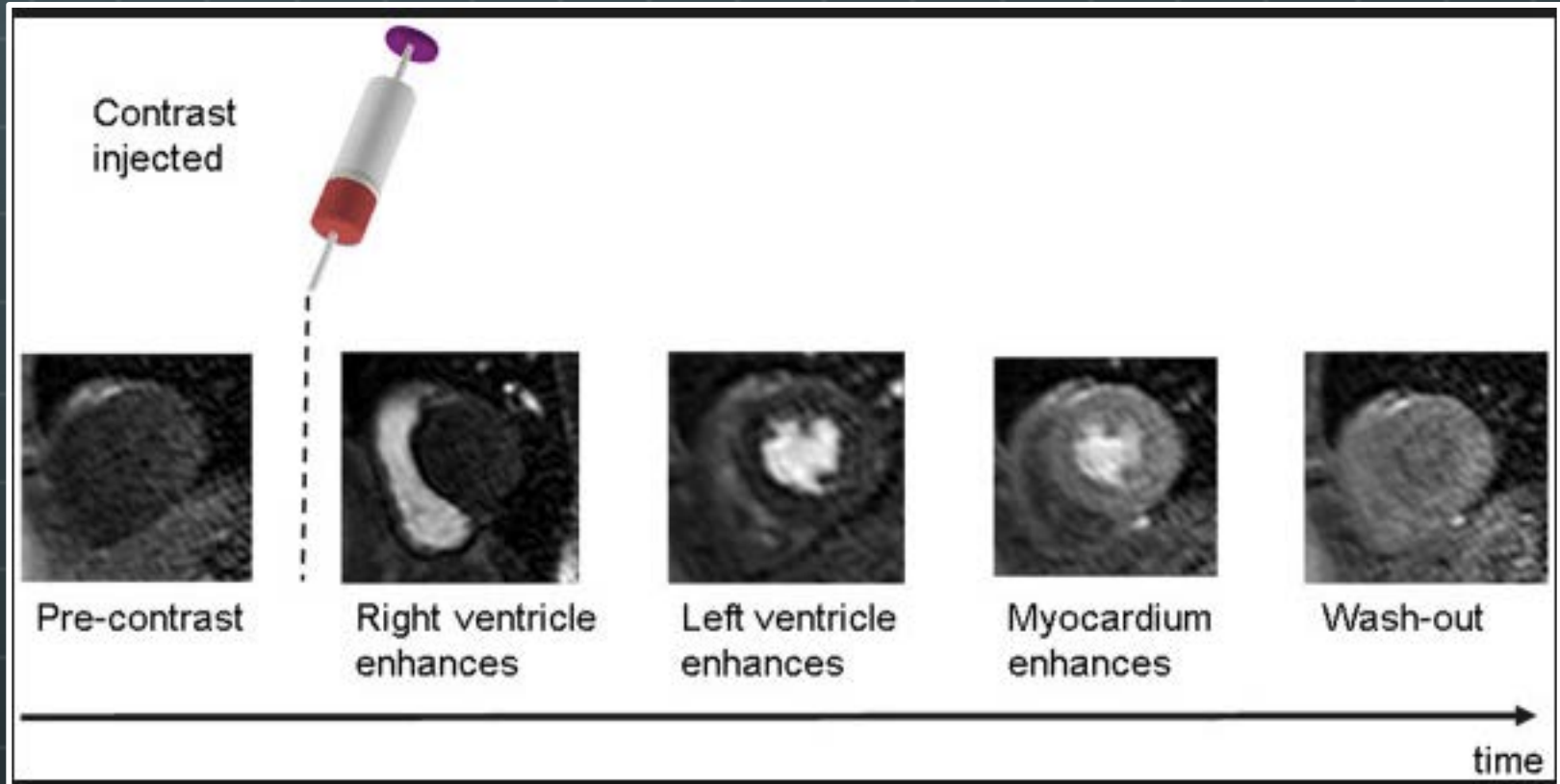
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**Endogenous
Contrast**

Perfusion-MRI Methods

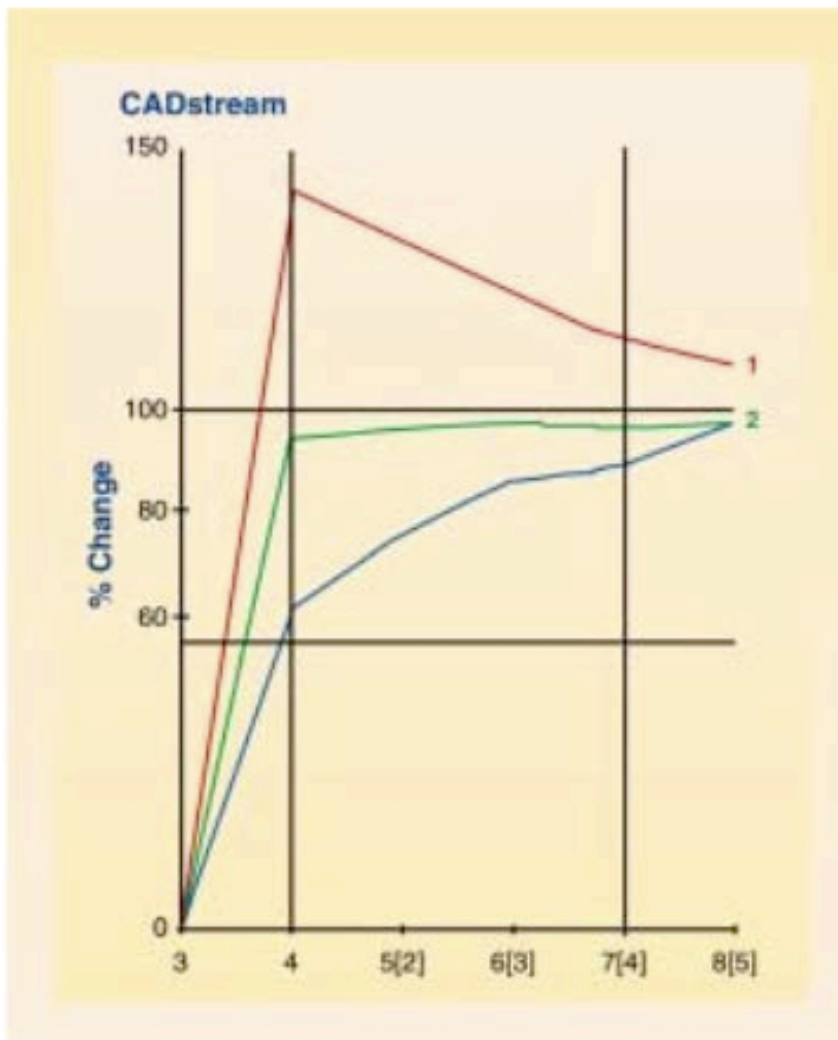
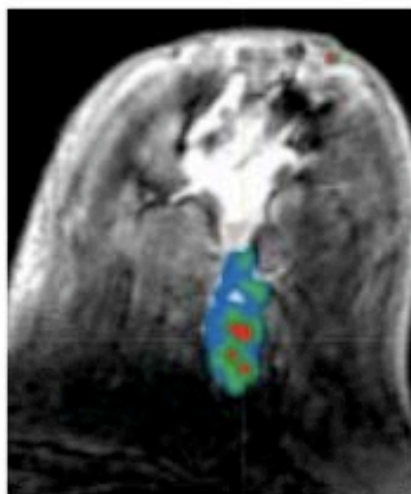
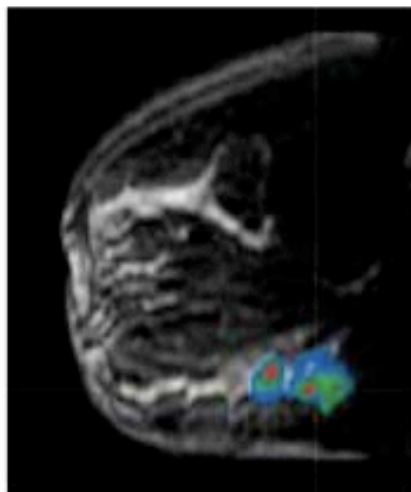
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Cardiac DCE-MRI



Breast DCE-MRI

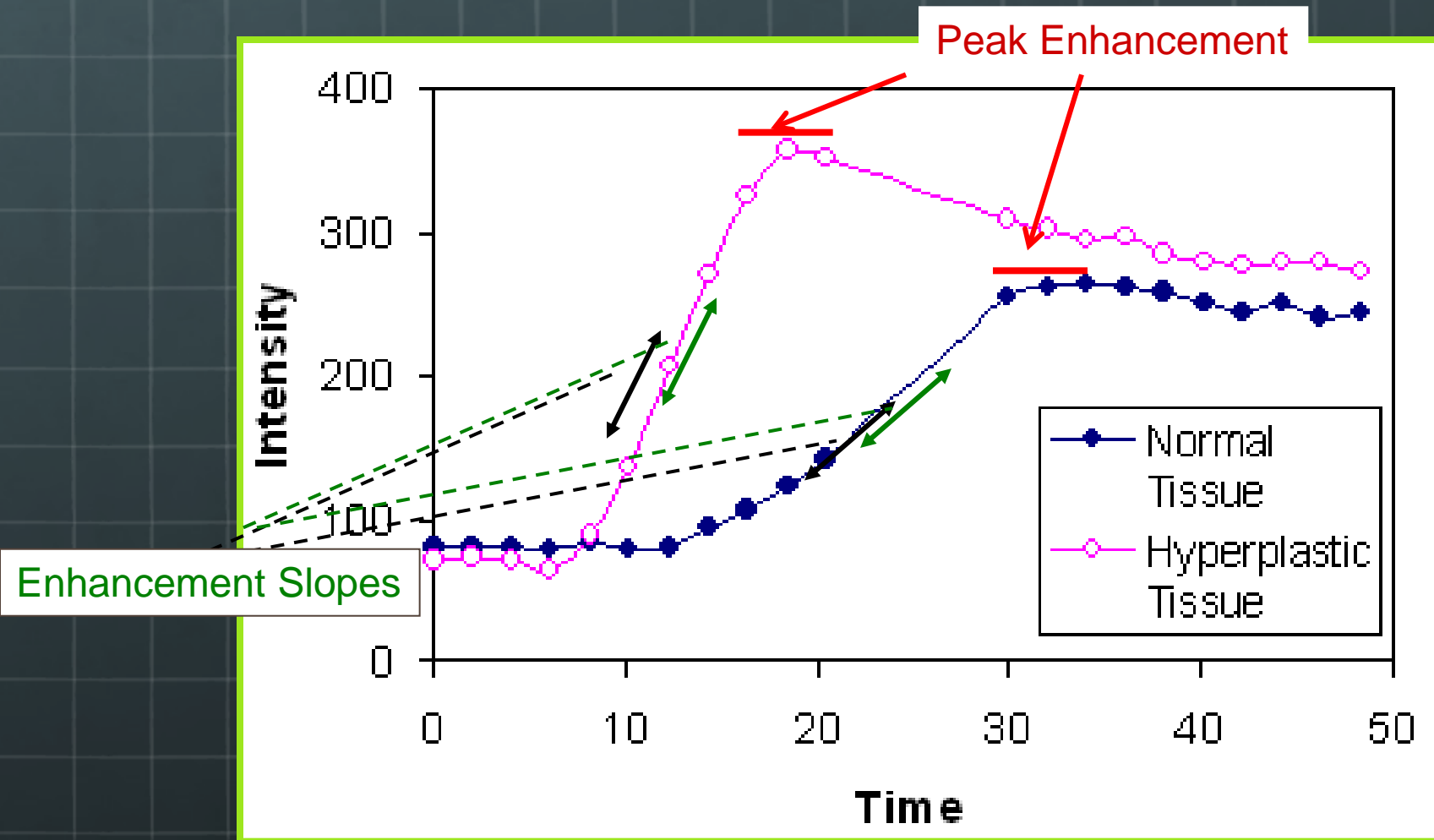




◀ Figure 2. These CADstream real-time dynamic contrast curves of MRIs from the same patient as in Figure 1, interactively demonstrate contrast uptake and washout levels representative of the tissue demonstrating angiogenesis. Based on the work of Christiania K. Kuhl, MD, red washout type curves are more commonly seen with invasive neoplasms than are green curves, and green curves are more commonly associated with invasive neoplasms than are blue curves. Image courtesy of Fir Hill Diagnostic Imaging, Seattle, Washington.

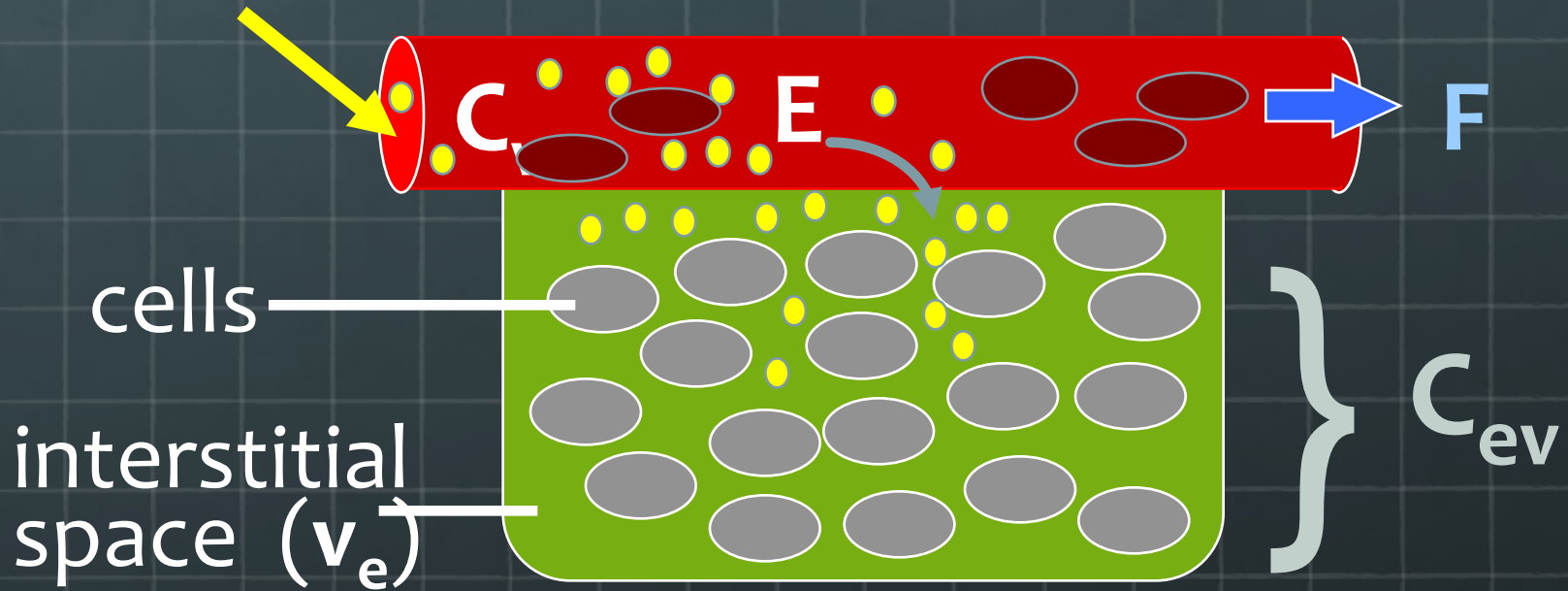
▼ Figure 3. CADstream maximum intensity projection (MIP) image. This feature allows radiologists to view enhancing lesions in three dimensions. Clinical image courtesy of First Hill Diagnostic Imaging, Seattle, Washington.

Liver DCE-MRI



Contributions to Intensity Changes:

Gd-DTPA



Consensus *Tofts* Model:

JOURNAL OF MAGNETIC RESONANCE IMAGING 10:223-232 (1999)

Review

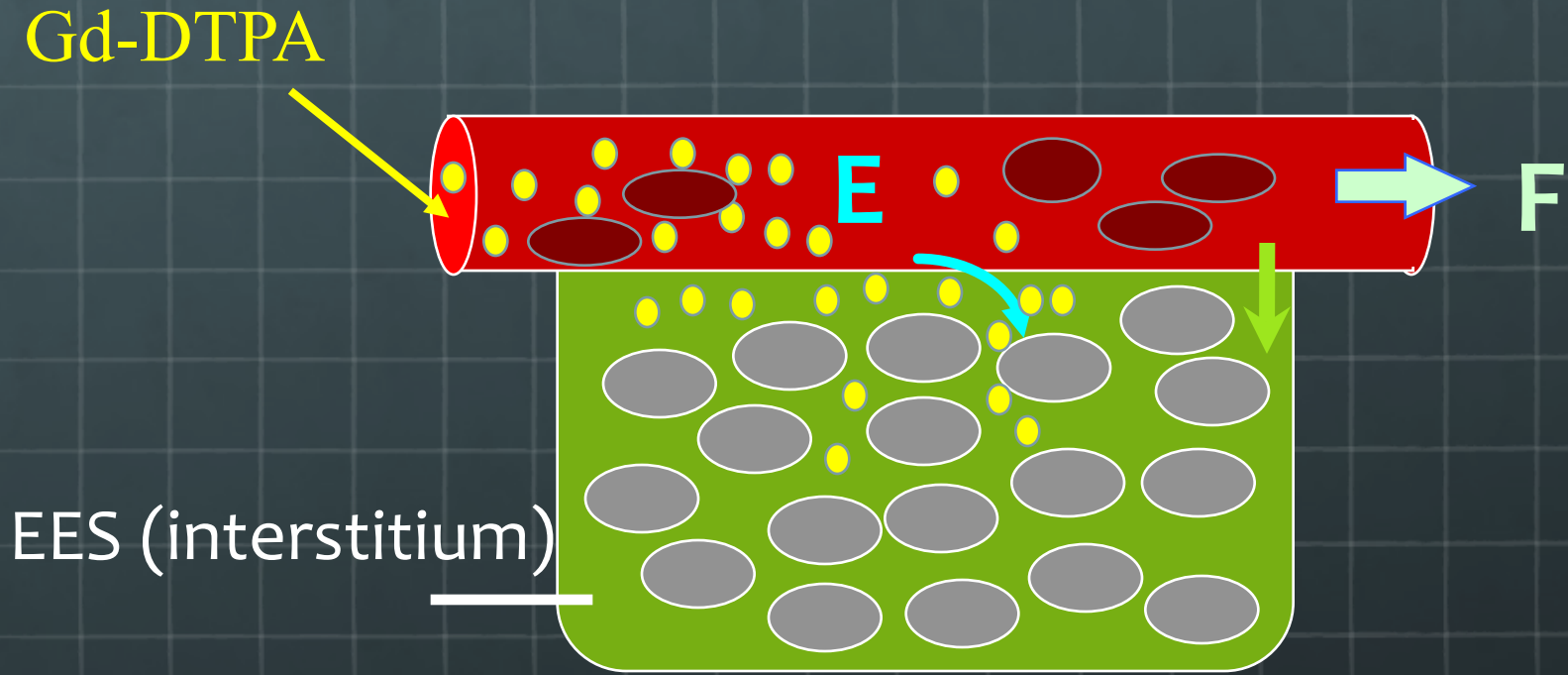
Estimating Kinetic Parameters From Dynamic Contrast-Enhanced T₁-Weighted MRI of a Diffusible Tracer: Standardized Quantities and Symbols

Paul S. Tofts, DPhil,^{1*} Gunnar Brix, PhD,² David L. Buckley, PhD,³ Jeffrey L. Duerksen, PhD,⁴ Elizabeth Henderson,⁵ Michael V. Knopp, MD,⁶ Henrik B.W. Larsson, MD,⁷ Ting-Yim Lee, PhD,⁵ Nina A. Mayr, MD,⁸ Geoffrey J.M. Parker, PhD,¹ Ruediger E. Port, MD,⁶ June Taylor, PhD,⁹ and Robert M. Weisskoff, PhD¹⁰

$$C_t(t) = K^{trans} \int C_p(\tau) e^{\left(-K^{trans} / v_e\right)(t-\tau)} d\tau$$



Delivery of Gd-based contrast agent to tissue:

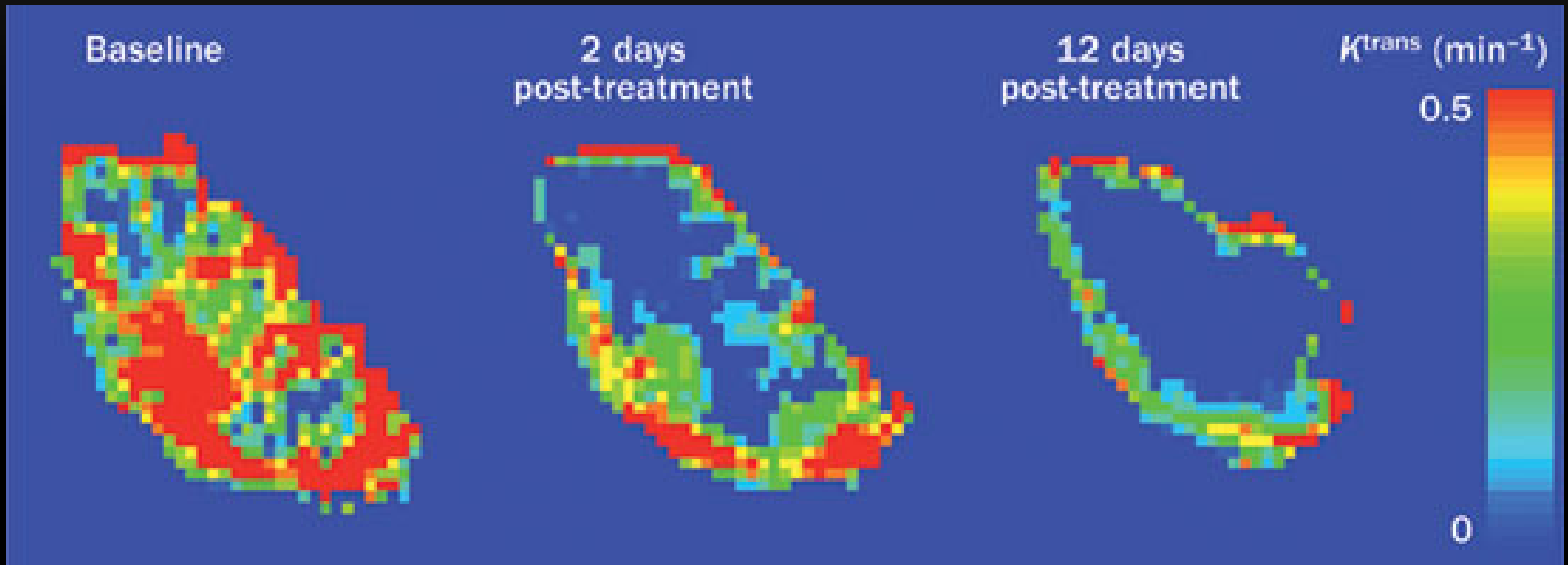


K^{trans} (min^{-1}): volume transfer constant = EF

EES : the volume of extravascular extracellular space per unit volume of tissue (v_e ; $0 < v_e < 1$).

k_{sp} (min^{-1}): the flux rate constant between EES and plasma

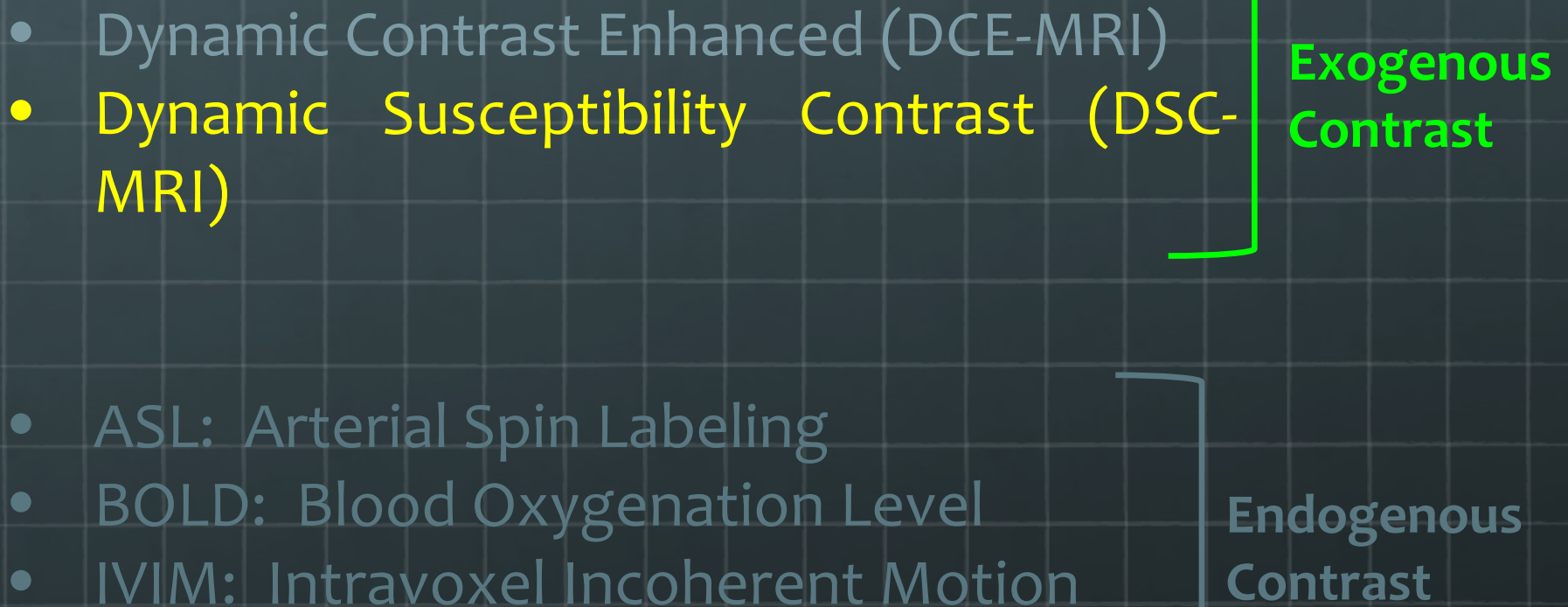
Figure 2 Example of three K^{trans} parameter maps



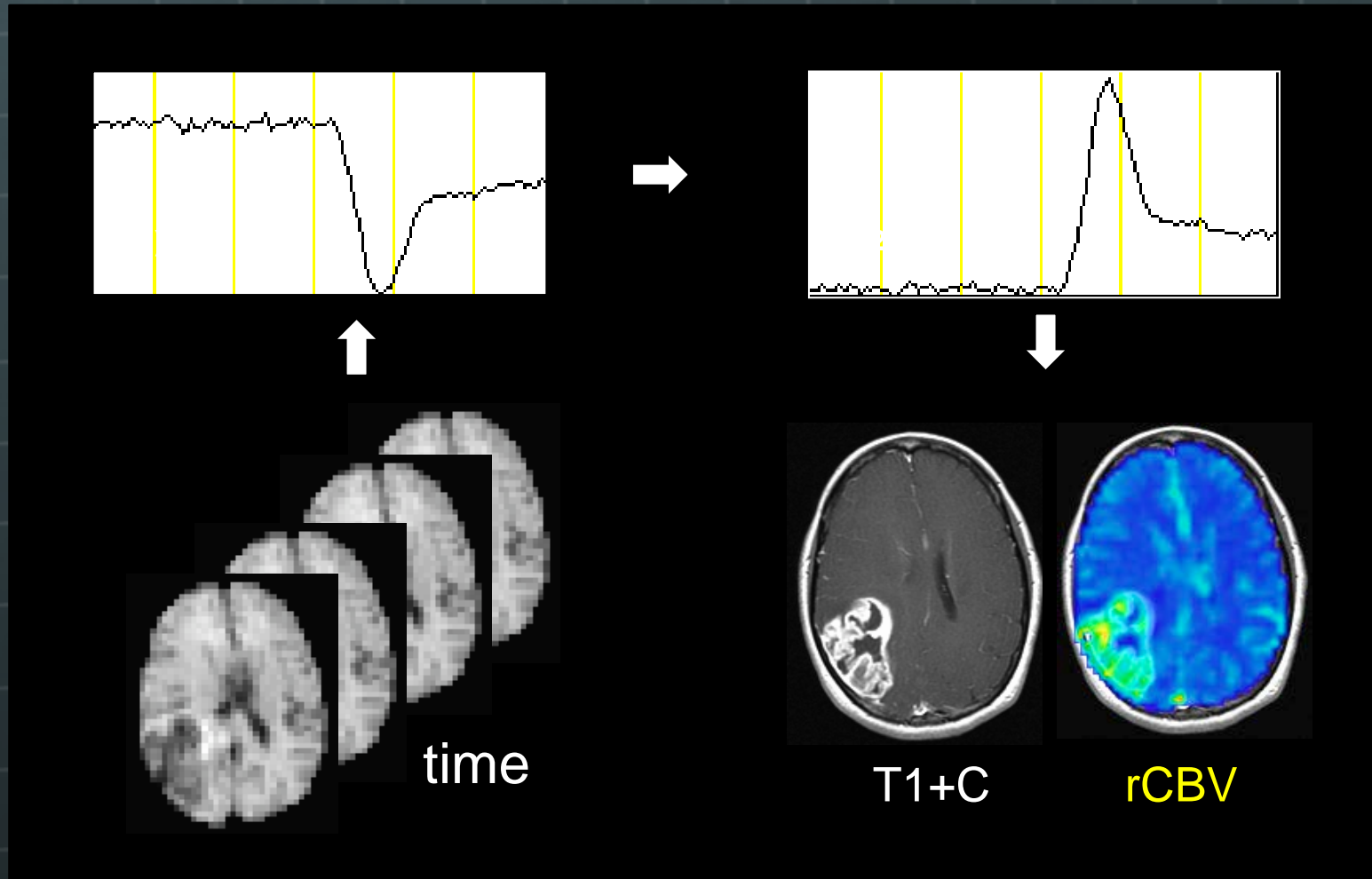
O' Connor, J. P. B. *et al.* (2012) Dynamic contrast-enhanced MRI in clinical trials of antivasular therapies

Nat. Rev. Clin. Oncol. doi:10.1038/nrclinonc.2012.2

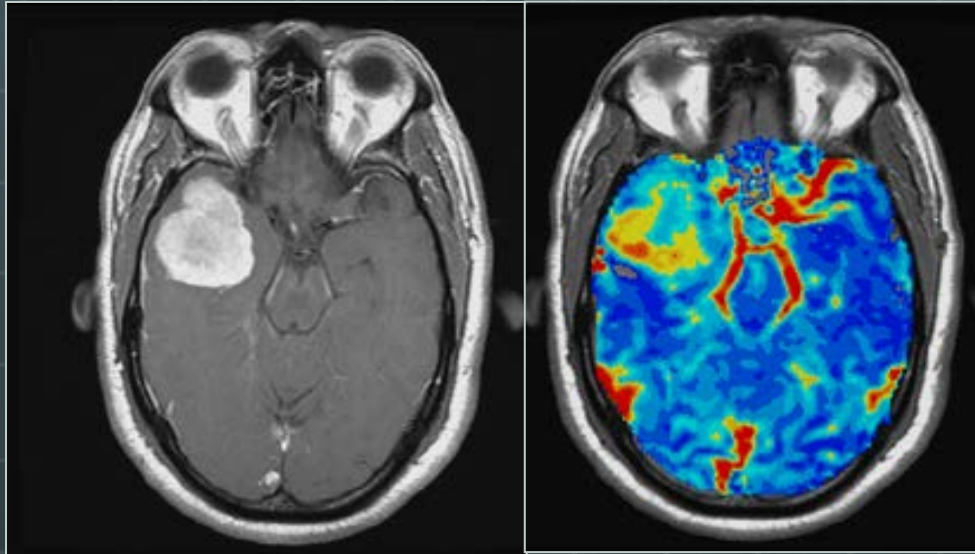
Perfusion-MRI Methods

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- 

DSC-MRI in *Brain Tumor*



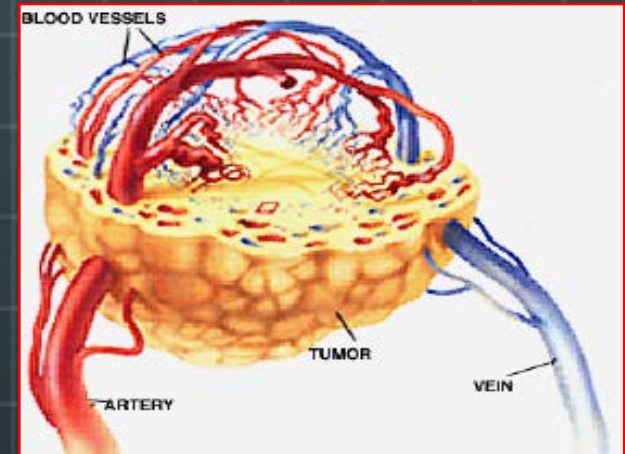
DSC-MRI in *Brain Tumor*



Standard MRI

Perfusion MRI
“rCBV”

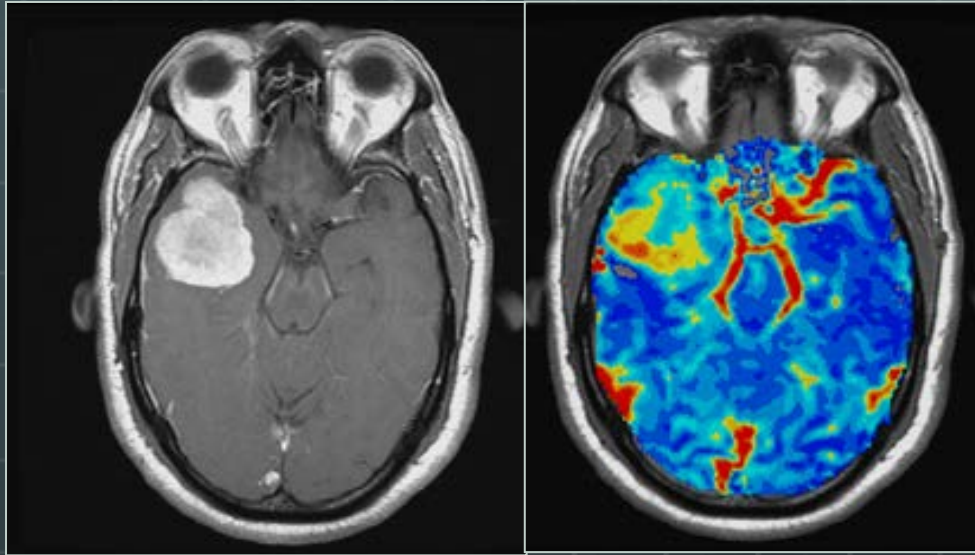
Angiogenesis



From: RK Jain, Sci. Am. 271(1):58 (1994)

...provides information on
tumor angiogenesis (new
vessel growth)

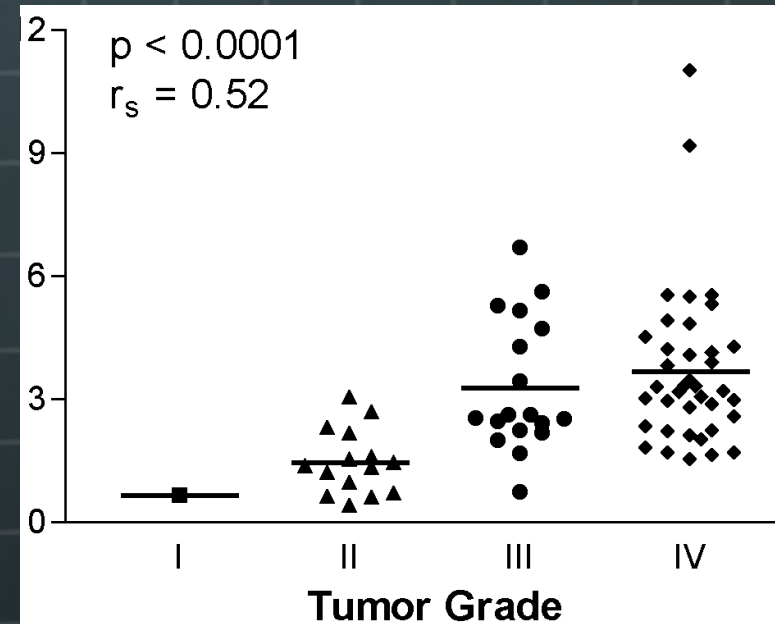
DSC-MRI in *Brain Tumor*



Standard MRI

Perfusion MRI
"rCBV"

➤ rCBV Predicts Tumor Grade



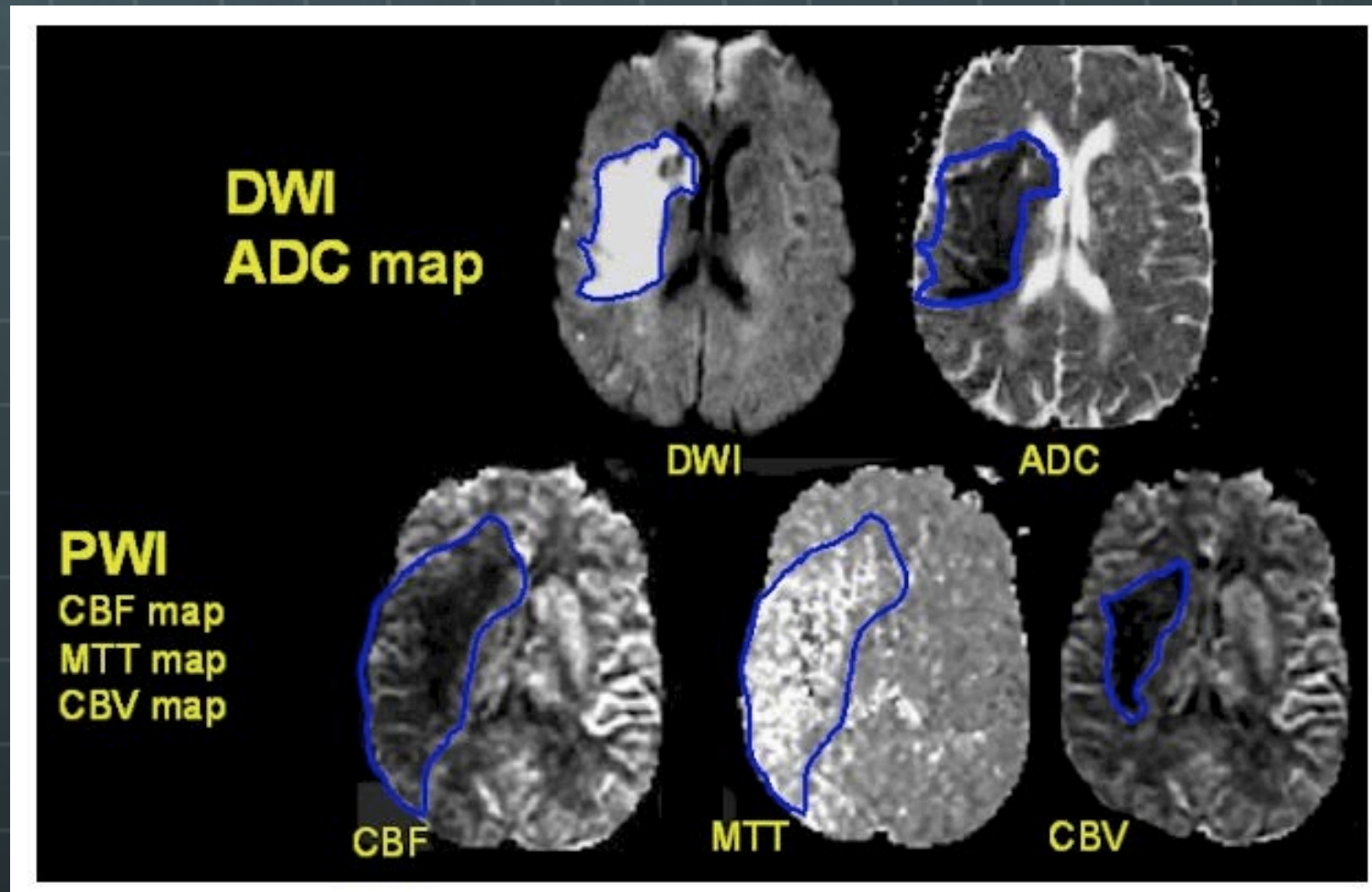
DSC-MRI in *Stroke*

$$C_{VOI}(t) = CBF \int_0^t C_a(t-\tau) R(t-\tau) d\tau$$

CBF:

- requires measurement of arterial input function (AIF)
- deconvolve tissue function with arterial input function to get a residue function
- peak of residue function = **CBF**
- **CBV** = integration of $c(t)$
- **MTT** = “CBV / CBF”; integration of residue function

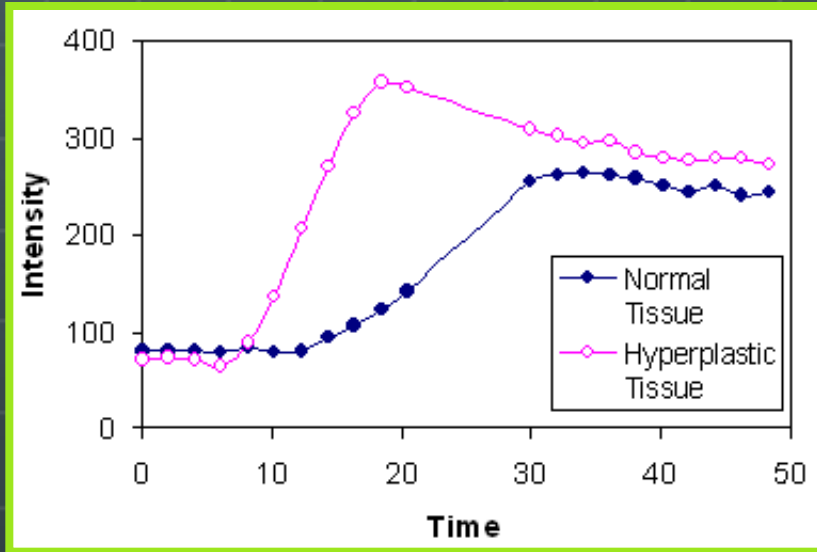
DSC-MRI in *Stroke*



<http://www.asnr.org/neurographics/2/2/1/11.shtml>

Summary

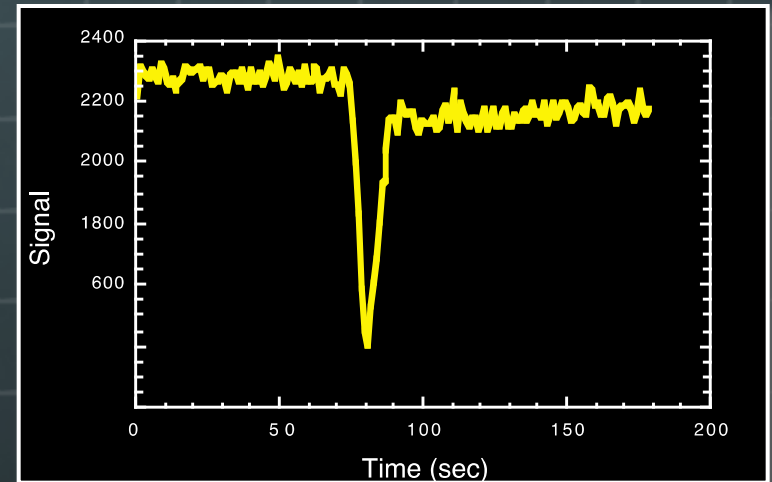
DCE:



- **Temporal Resolution:** many seconds; better image quality
- **T1-weighted** sequence (min TE)

Body

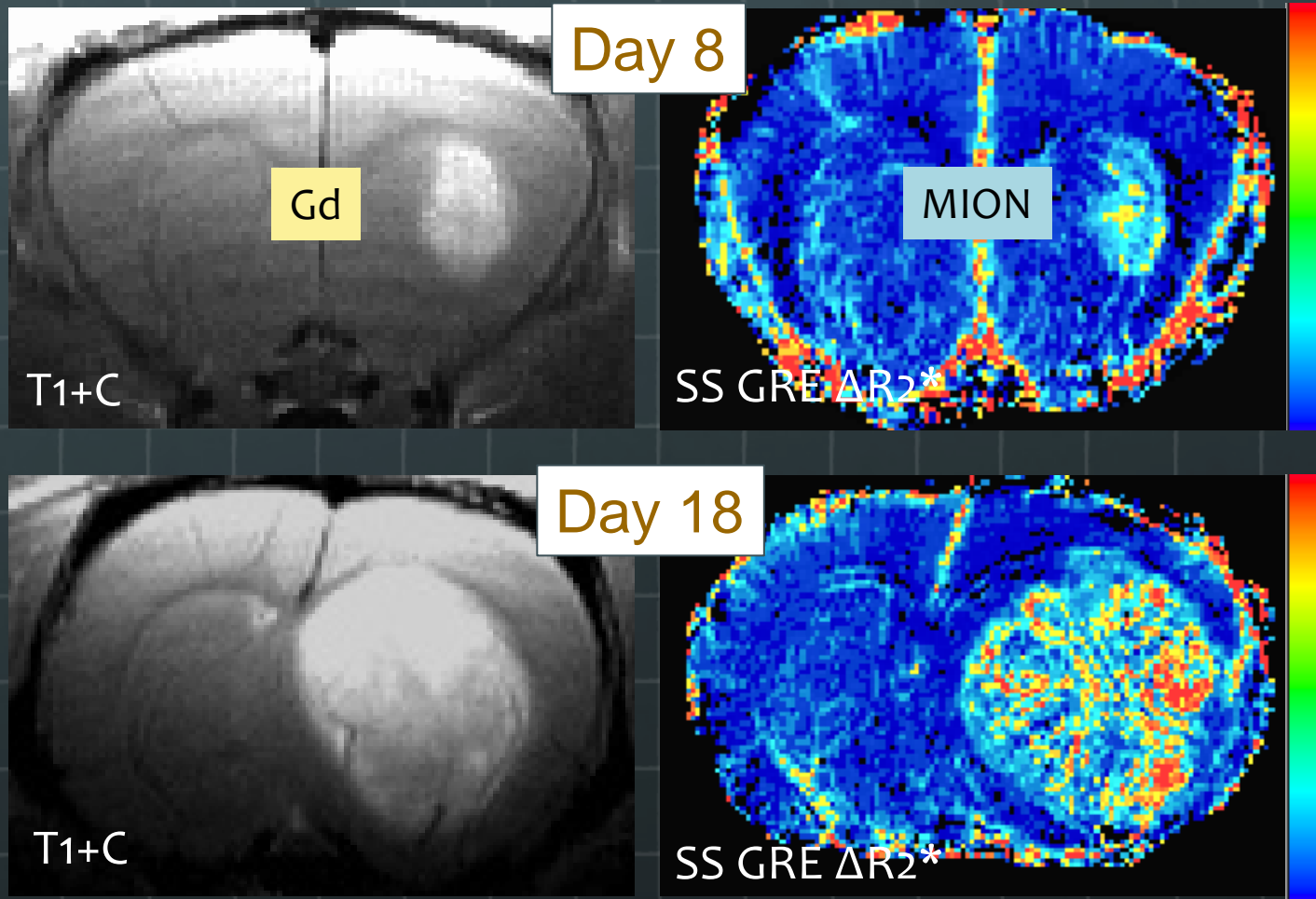
DSC:



- **Temporal Resolution:** ≈ 1 sec; spatial/temporal trade-off
- **T2/T2*-weighted** sequence (longer TE)


Brain


Use Intravascular (Iron) Agent



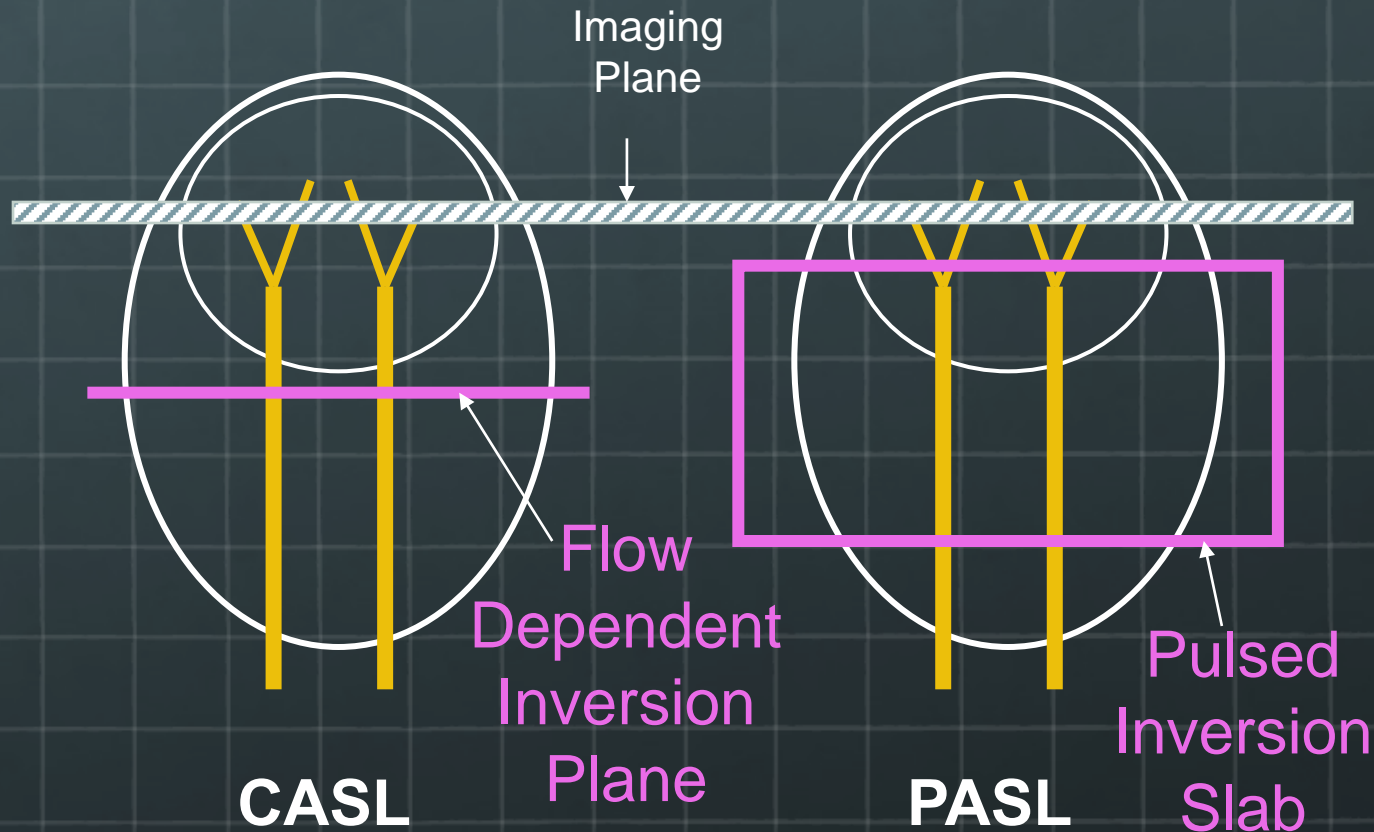
From: Pechman et al., Poster #430

Perfusion-MRI Methods

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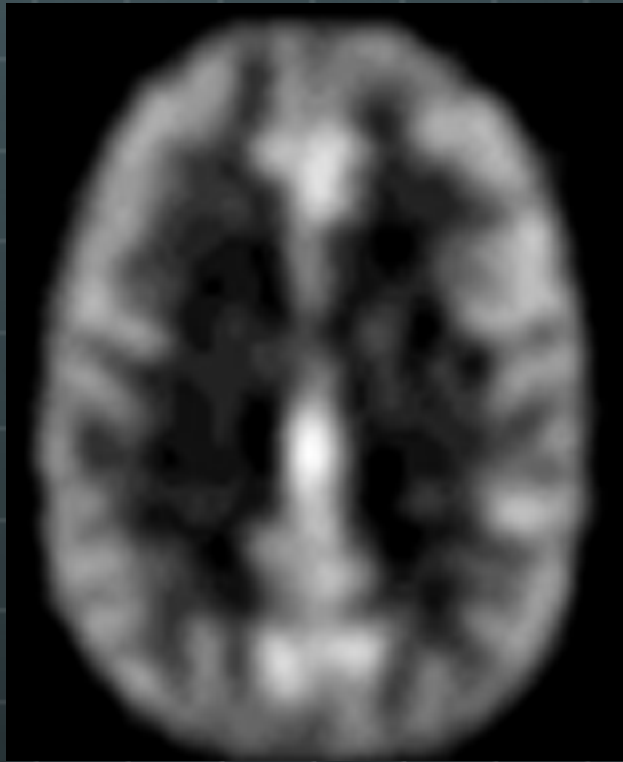
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Arterial Spin Labeling

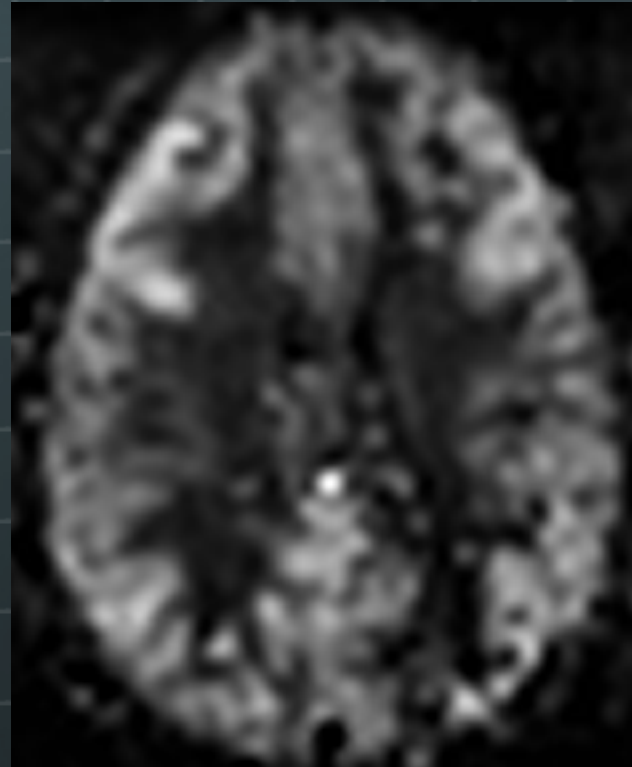


..... "Label" Arterial Blood Water with RF Pulses

Arterial Spin Labeling (ASL)





PET: $H_2^{15}O$



MRI: ASL

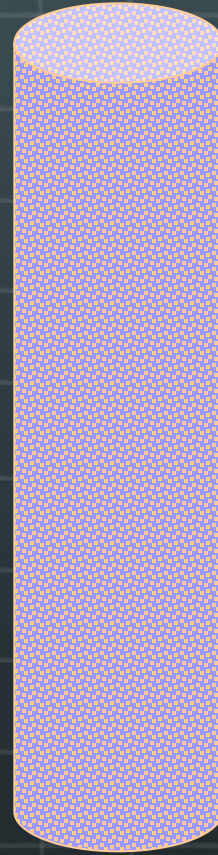
Perfusion-MRI Methods

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BOLD: Blood Oxygenation Level Dependent

blood
vessel

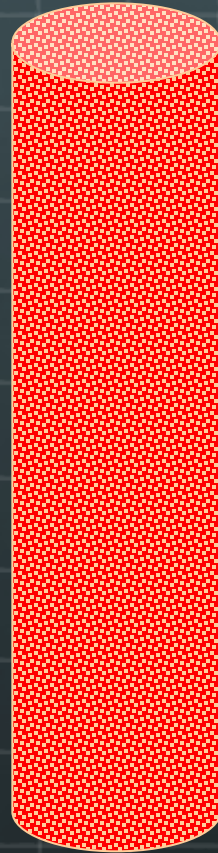
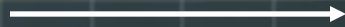


MRI
SIGNAL

deoxygenated blood

BOLD: Blood Oxygenation Level Dependent

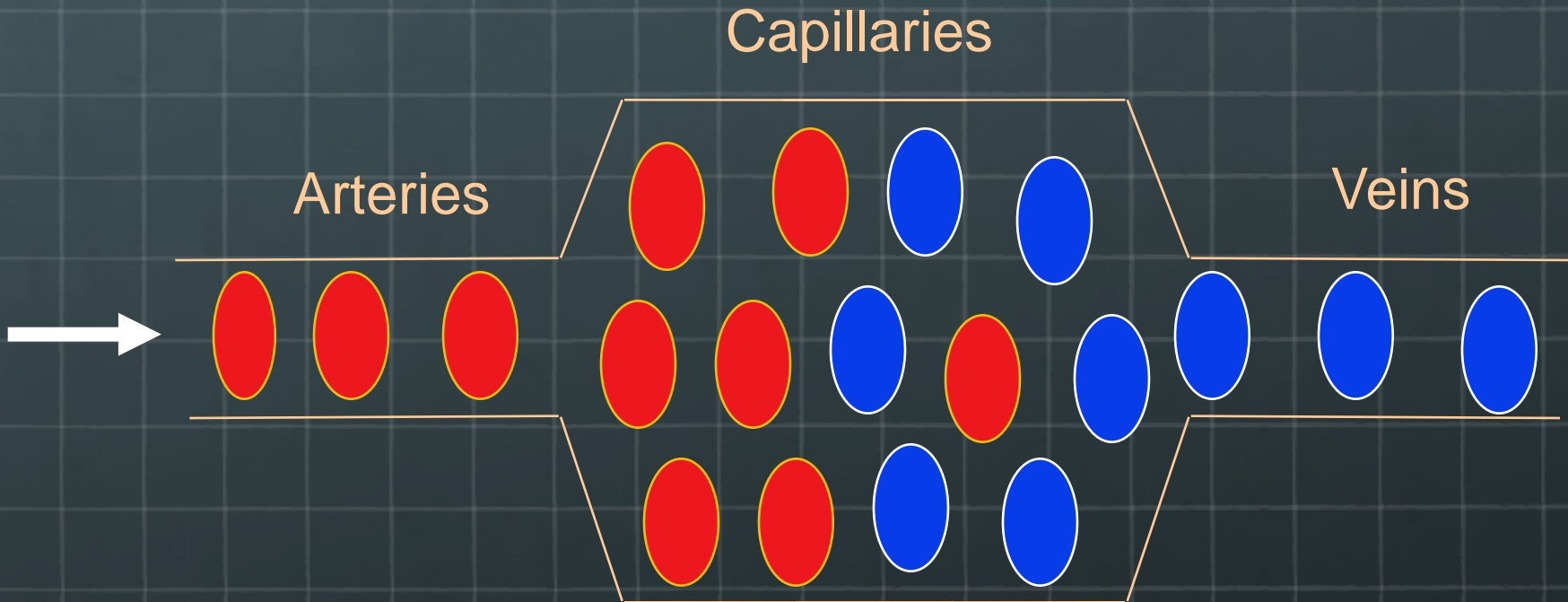
blood
vessel



**MRI
SIGNAL**

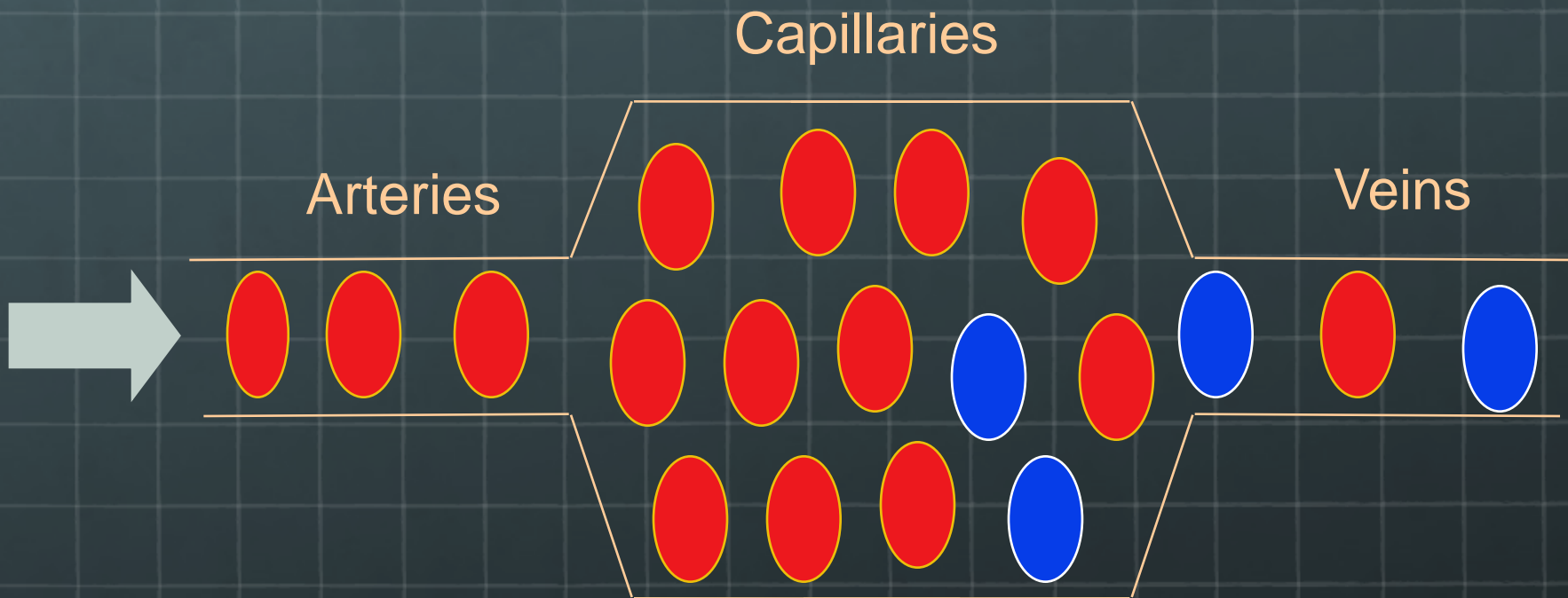
oxygenated blood

BOLD: Resting



SIGNAL

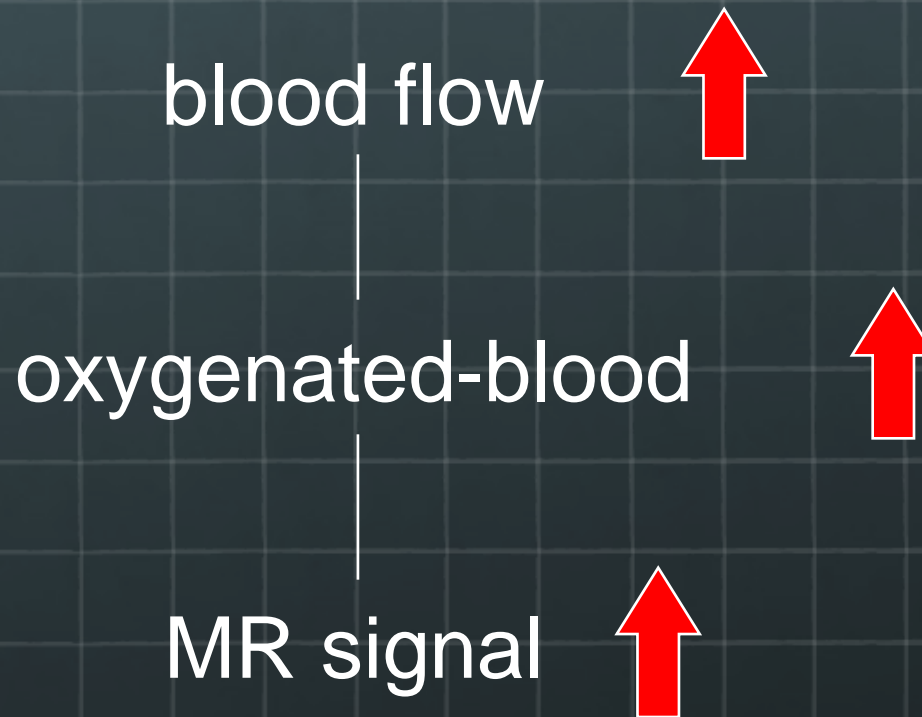
BOLD: ACTIVATION



SIGNAL

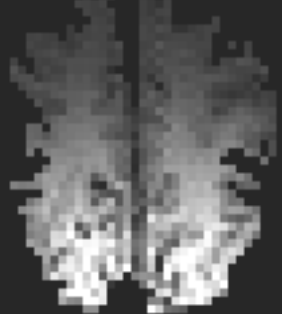
BOLD

(blood oxygenation level dependence)



BOLD: *Visual Activation*

Baseline



(Kwong et al, May 1991)

Gradient Echo
TE=40 TR=3000
Thickness = 10

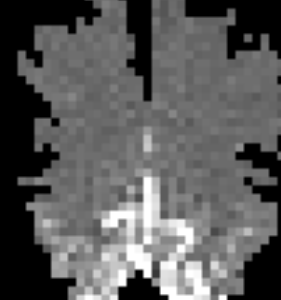
OFF 15 s



OFF 45 s



ON 75 s



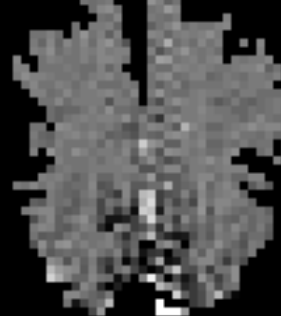
ON 105 s



OFF 135 s



OFF 165 s



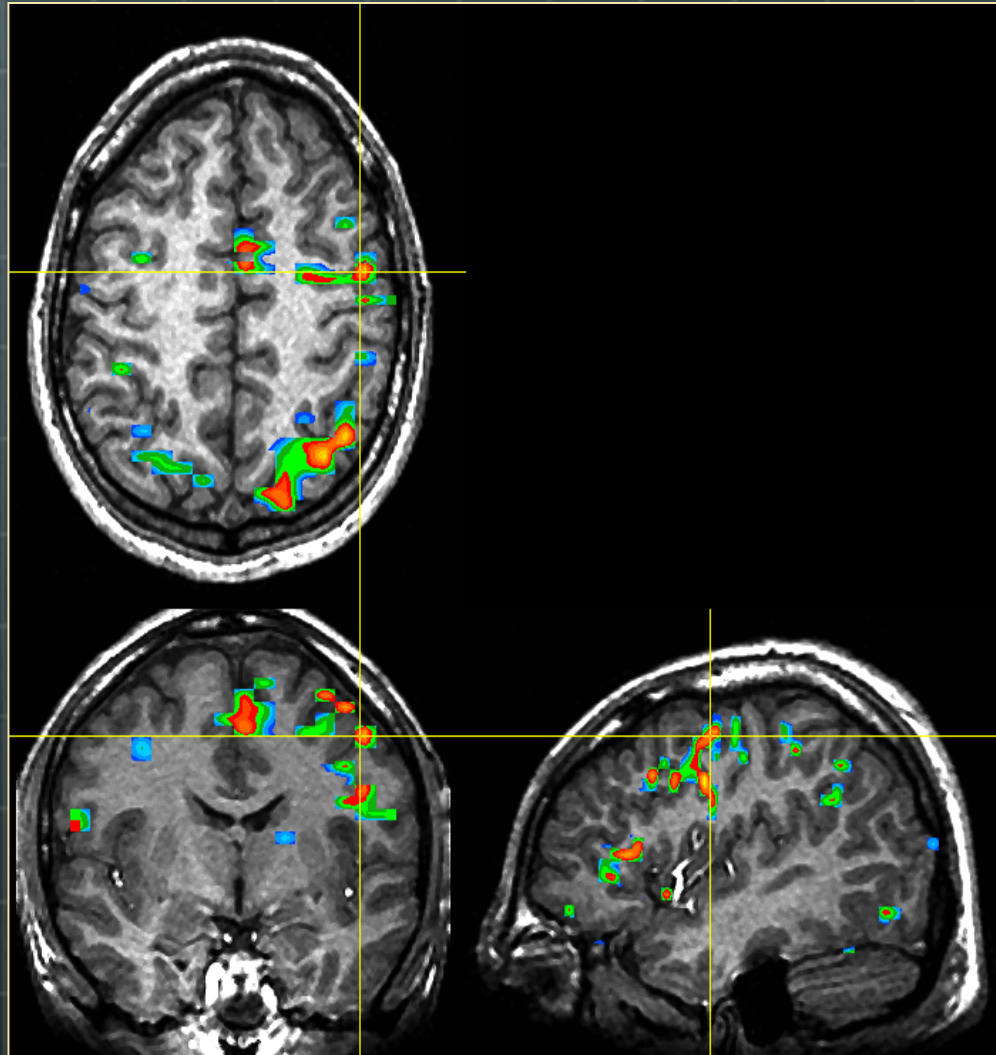
ON 195 s



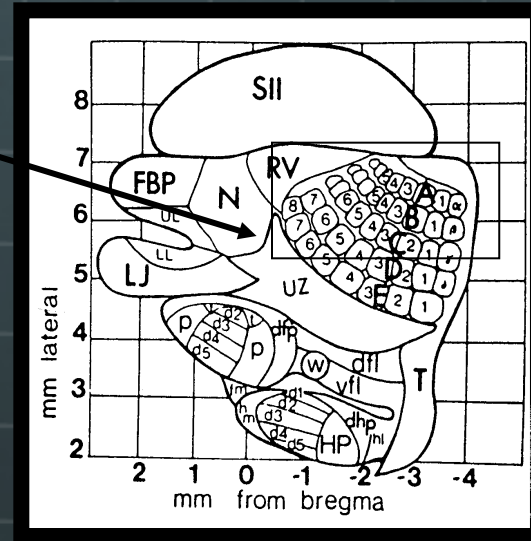
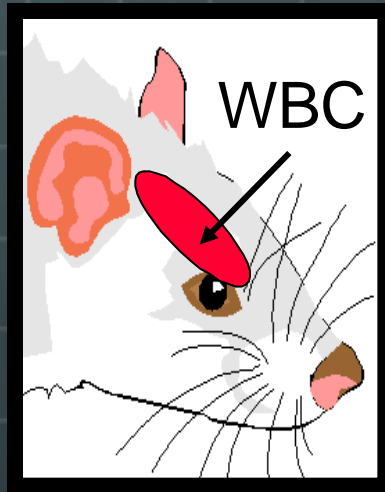
ON 225 s



BOLD: *Results Presentation*

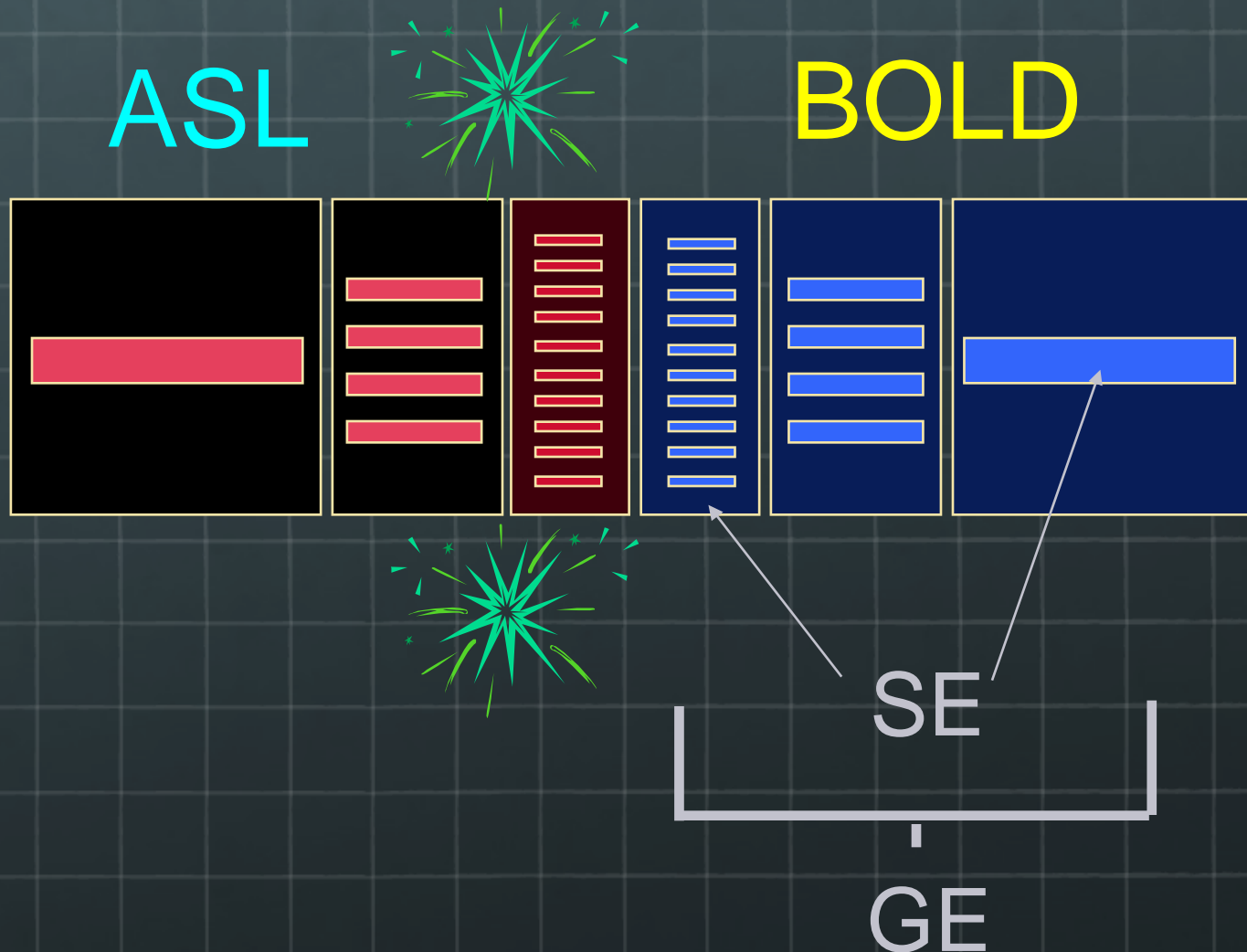


BOLD: *Rat Whisker Barrel*





- The large whiskers of the rat correspond in a one to one fashion with groups of cell bodies (barrels) in cortical layer IV of contralateral somatosensory cortex.
- Whiskers are cut to 3cm, and fitted through a comb and connected to a piezoelectric-driven actuator arm, which is run with a reproducible “on/off” cycle

ASL vs BOLD: *Vascular Specificity*



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Diffusion-Weighted Imaging

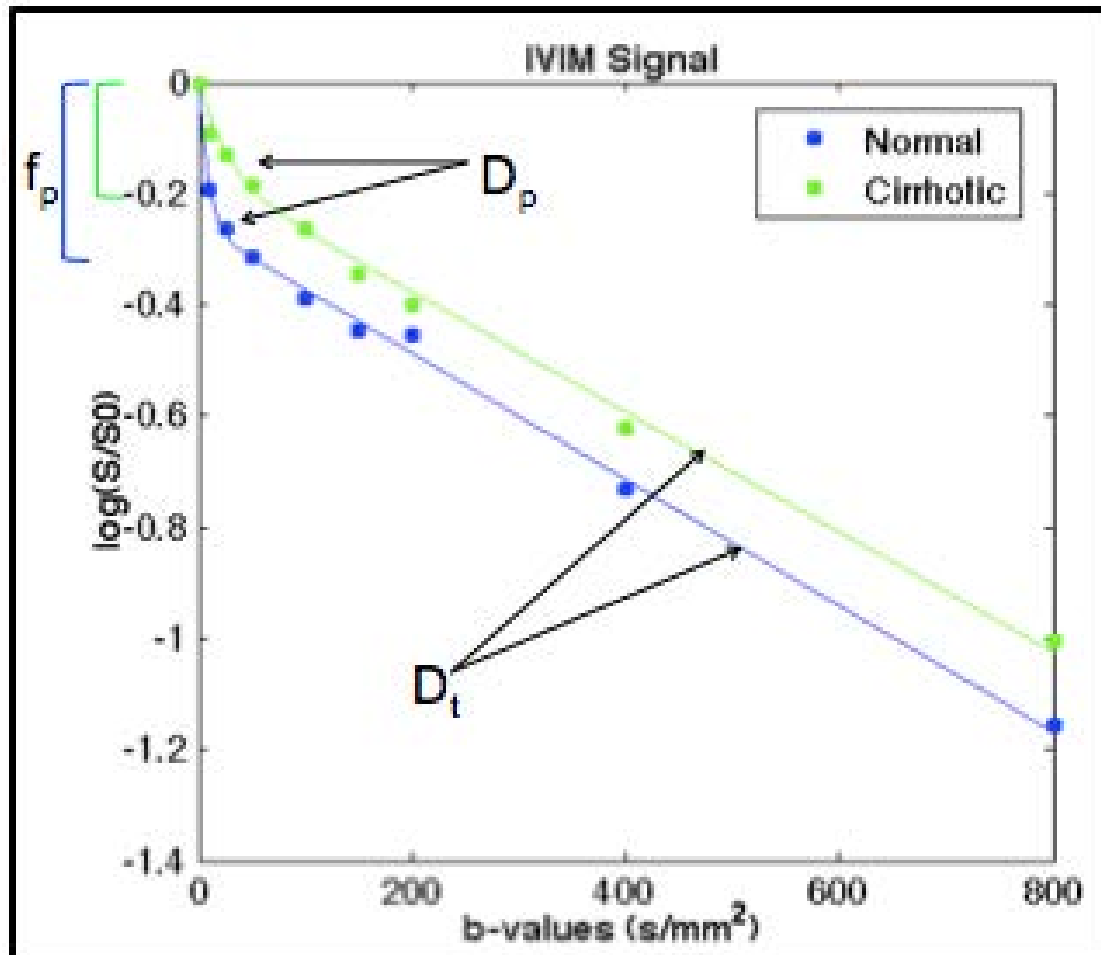


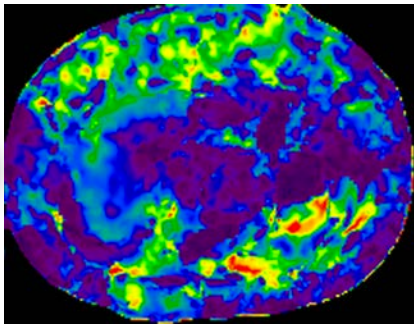
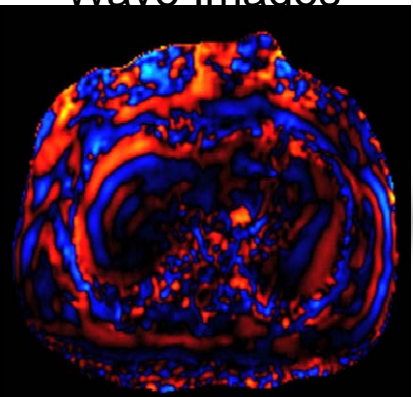
Figure 1. Example IVIM signal curves for a control (blue) and cirrhotic (green) patient.

Magnetic Resonance Elastography

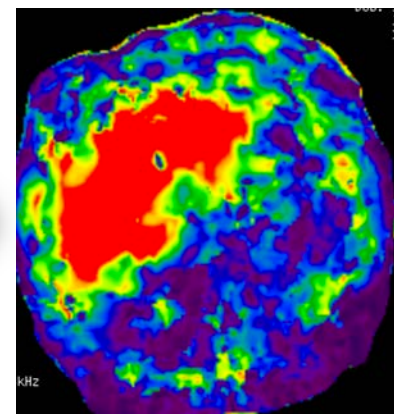
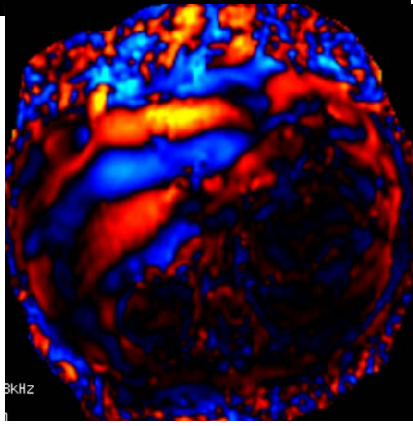
Wave Images

Stiffness Images

Control Subject



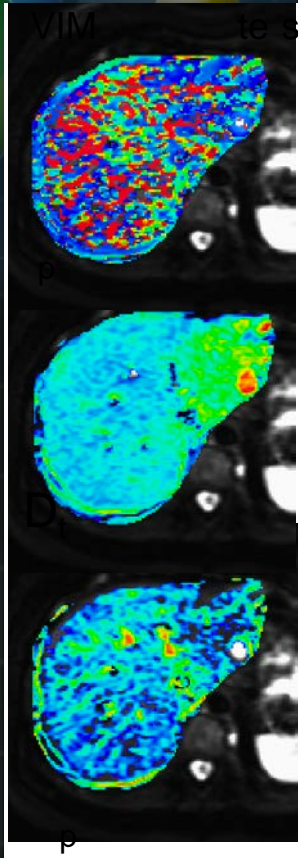
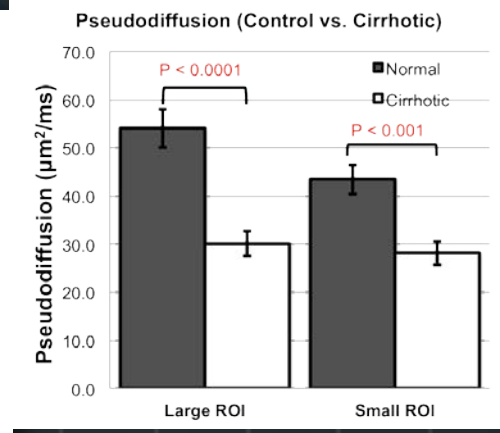
Cirrhotic Patient



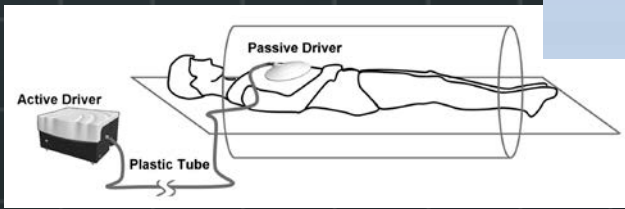
Liver Imaging

Diffusion Weighted Imaging

IVIM: The collection of multiple diffusion weightings (b-values) allows for the extraction of perfusion information from the diffusion signal



MRE allows for the extraction of tissue stiffness through the use of a vibrating driver



These parameters are different in cirrhotic patients vs. normal control subjects

SUMMARY

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- Dynamic Susceptibility Contrast (DSC-MRI)

Exogenous
Contrast

- ASL: Arterial Spin Labeling
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Endogenous
Contrast

Acknowledgements

1. Funding

- NIH/NCI RO1 CA082500
- NIH/NCI R43 CA134031, R44 CA134031
- AHW - Translational Brain Tumor Research Program

2. Lab Members / Collaborators

- Mona Al-Gizawy
- Devyani Bedekar
- Alex Cohen
- Pete LaViolette
- Eric Paulson
- Kim Pechman
- Melissa Prah
- Jennifer Connelly
- Elizabeth Cochran
- Mark Malkin
- Wade Mueller
- Scott Rand