MRI for the Non-Expert

Diffusion MRI

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Outlook

Introduction
Principles of diffusion MRI
Data acquisition
Data analysis
Unresolved issues

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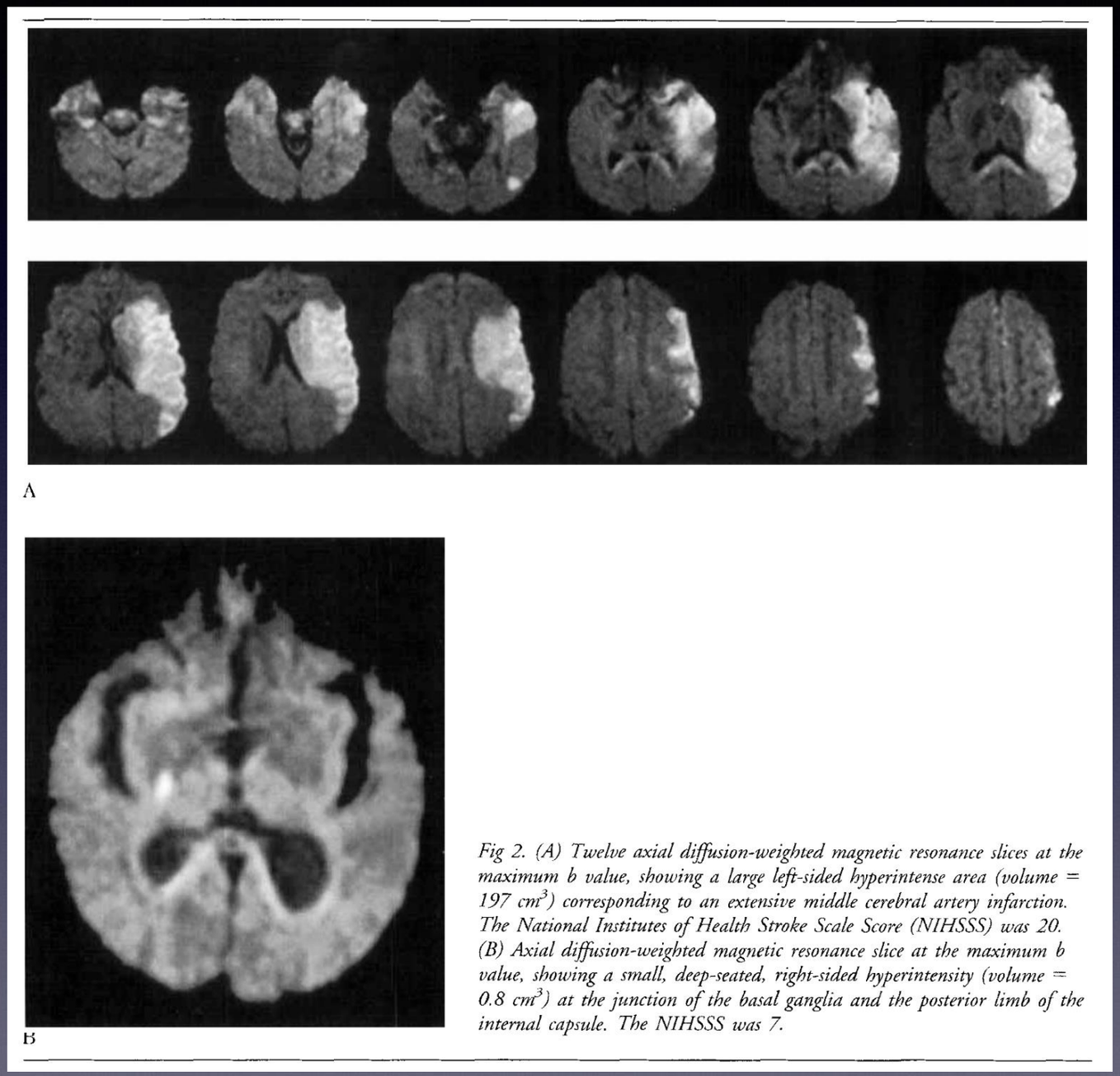
DWI earliest marker of stroke



A

B

Fig 2. (A) Twelve axial diffusion-weighted magnetic resonance slices at the maximum b value, showing a large left-sided hyperintense area (volume = 197 cm^3) corresponding to an extensive middle cerebral artery infarction. The National Institutes of Health Stroke Scale Score (NIHSSS) was 20. (B) Axial diffusion-weighted magnetic resonance slice at the maximum b value, showing a small, deep-seated, right-sided hyperintensity (volume = 0.8 cm^3) at the junction of the basal ganglia and the posterior limb of the internal capsule. The NIHSSS was 7.

Lovblad Ann Neurol 1997 Aug;42(2):164-70.

Prostate cancer

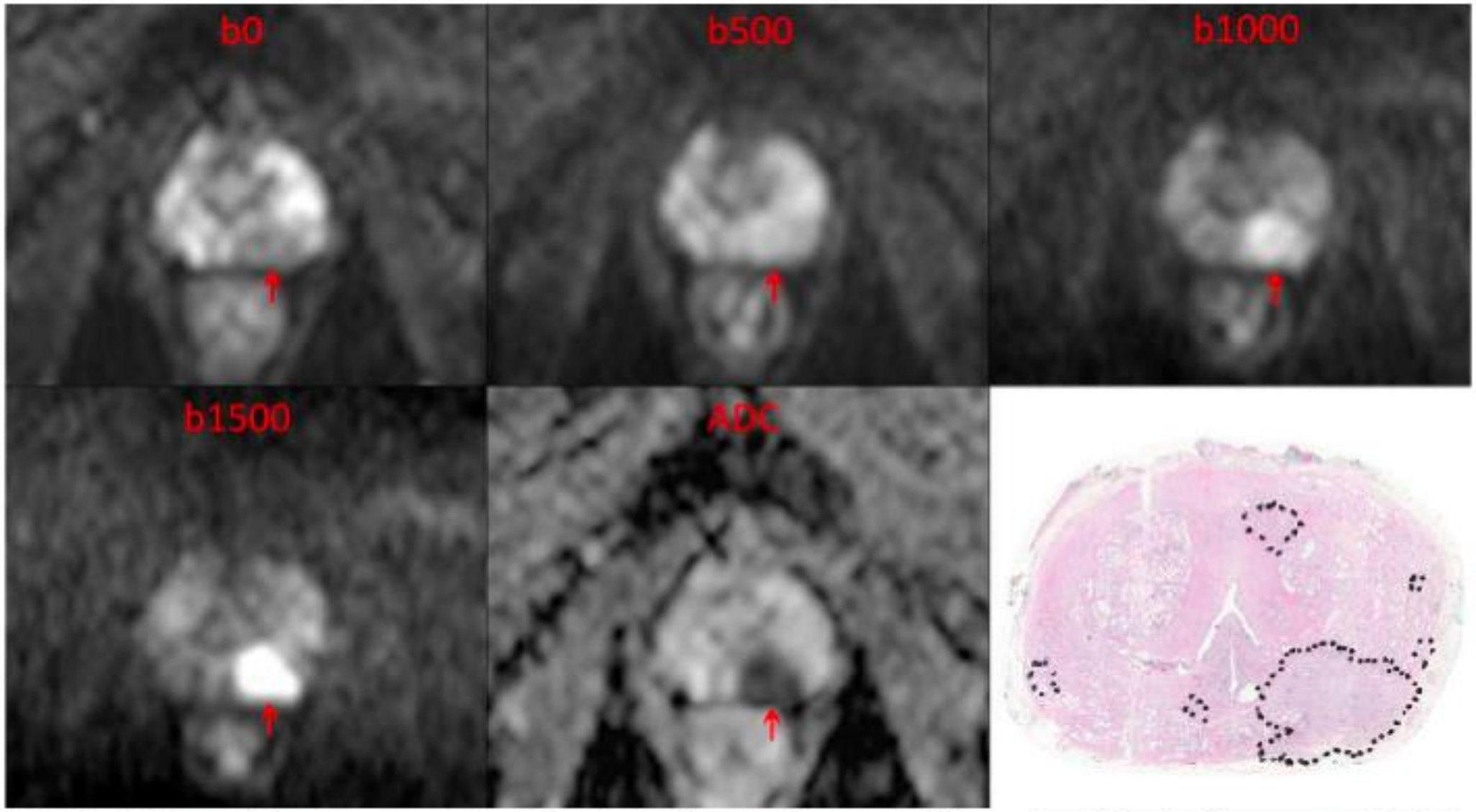


FIGURE 1: A 67-year-old patient, serum PSA 17.8 ng/mL. A low ADC lesion is visible at the mid-level of the prostate. The lesion presents a progressive signal increase on the b-value images starting from low intensity at b0, when compared with the prostatic parenchyma. The low ADC combined with a "flashing" high signal intensity on the b1500 image is typical for a cancerous lesion (arrow). Combining of the ADC map with the b-value images allows for a better accuracy in cancer detection.

de Perrot et al. JMRI 2016

Prostate cancer

PI-RADS Assessment

Peripheral Zone (PZ)

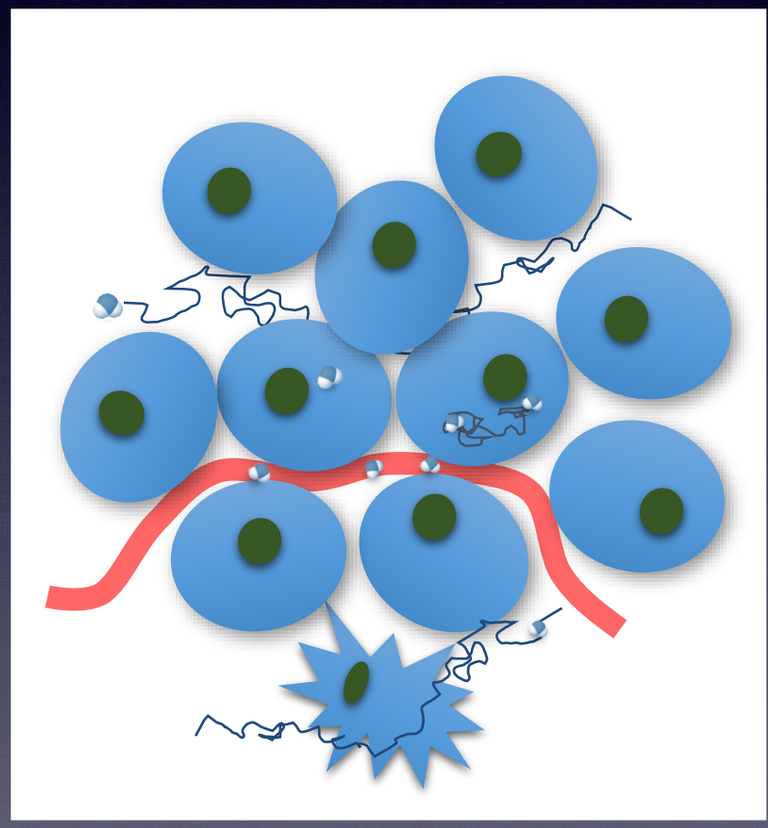
DWI	T2W	DCE	PI-RADS
1	Any*	Any	1
2	Any	Any	2
3	Any	–	3
		+	4
4	Any	Any	4
5	Any	Any	5

* "Any" indicates 1-5

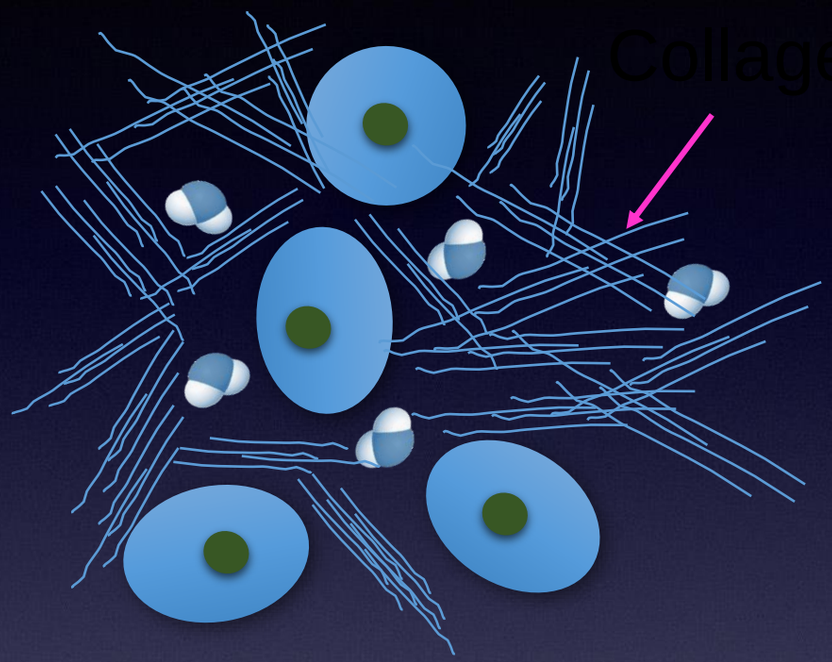
American College of Radiology® 2019 PI-RADSv2.1

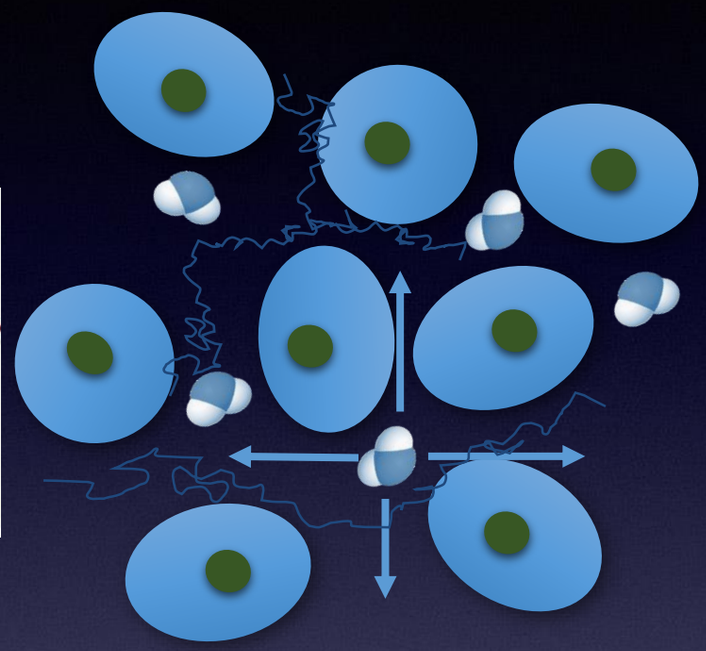
What is measured in diffusion MRI (DWI)?

- Displacement of water molecules:
  - Typical range 1–17 µm (extracellular)
  - Brownian motion, microcirculation….
  - Probe of the interstitial space



Reduced diffusion in renal fibrosis



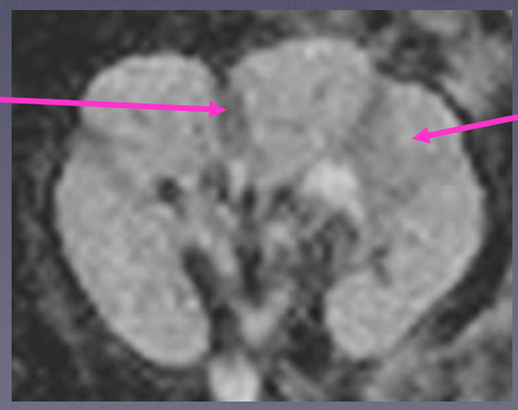


High-grade fibrosis 80%

Normal Absence of fibrosis

ADC

$1300\times10^{-6}mm^2/s$



$2000\times10^{-6}mm^2/s$

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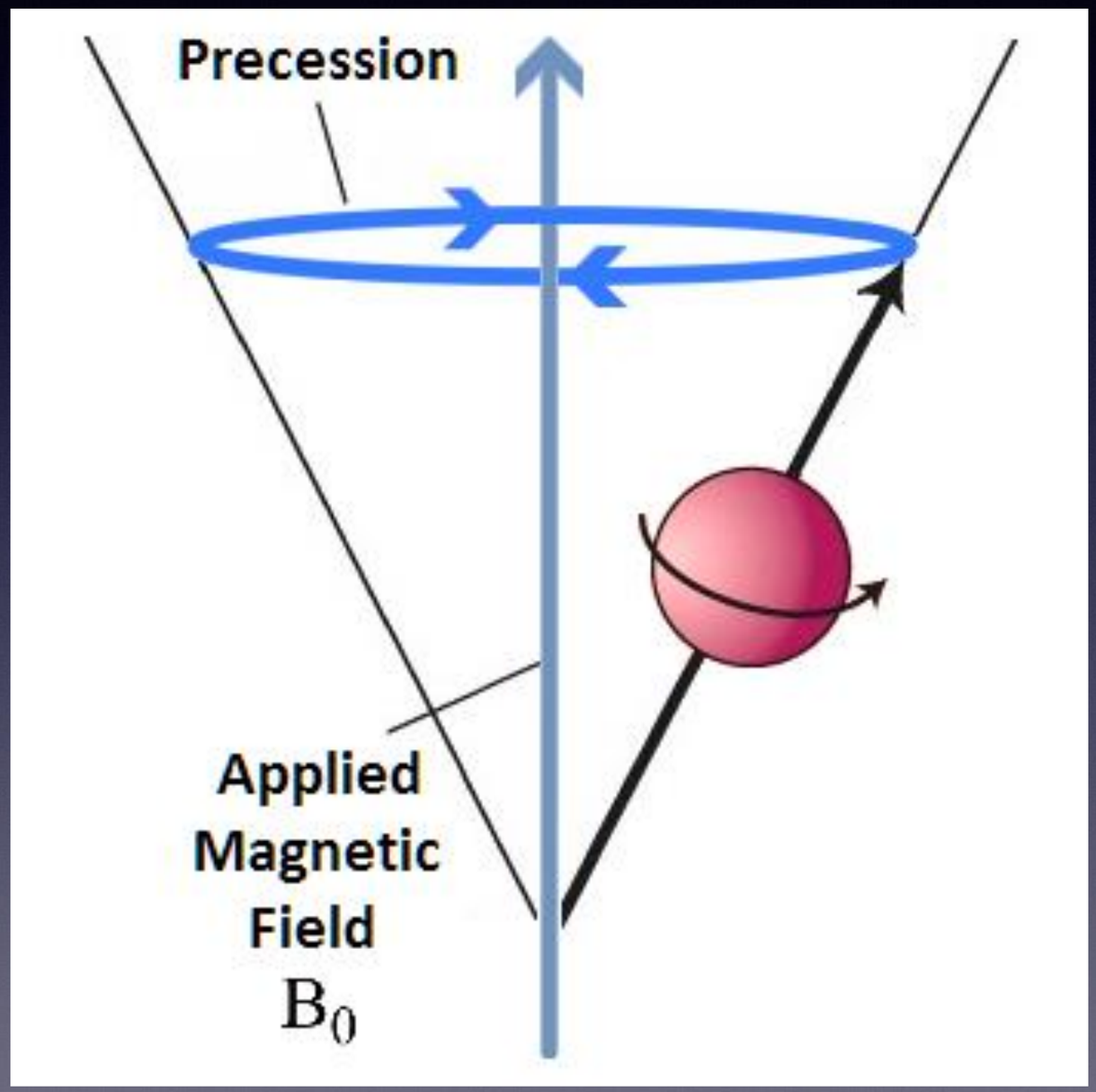
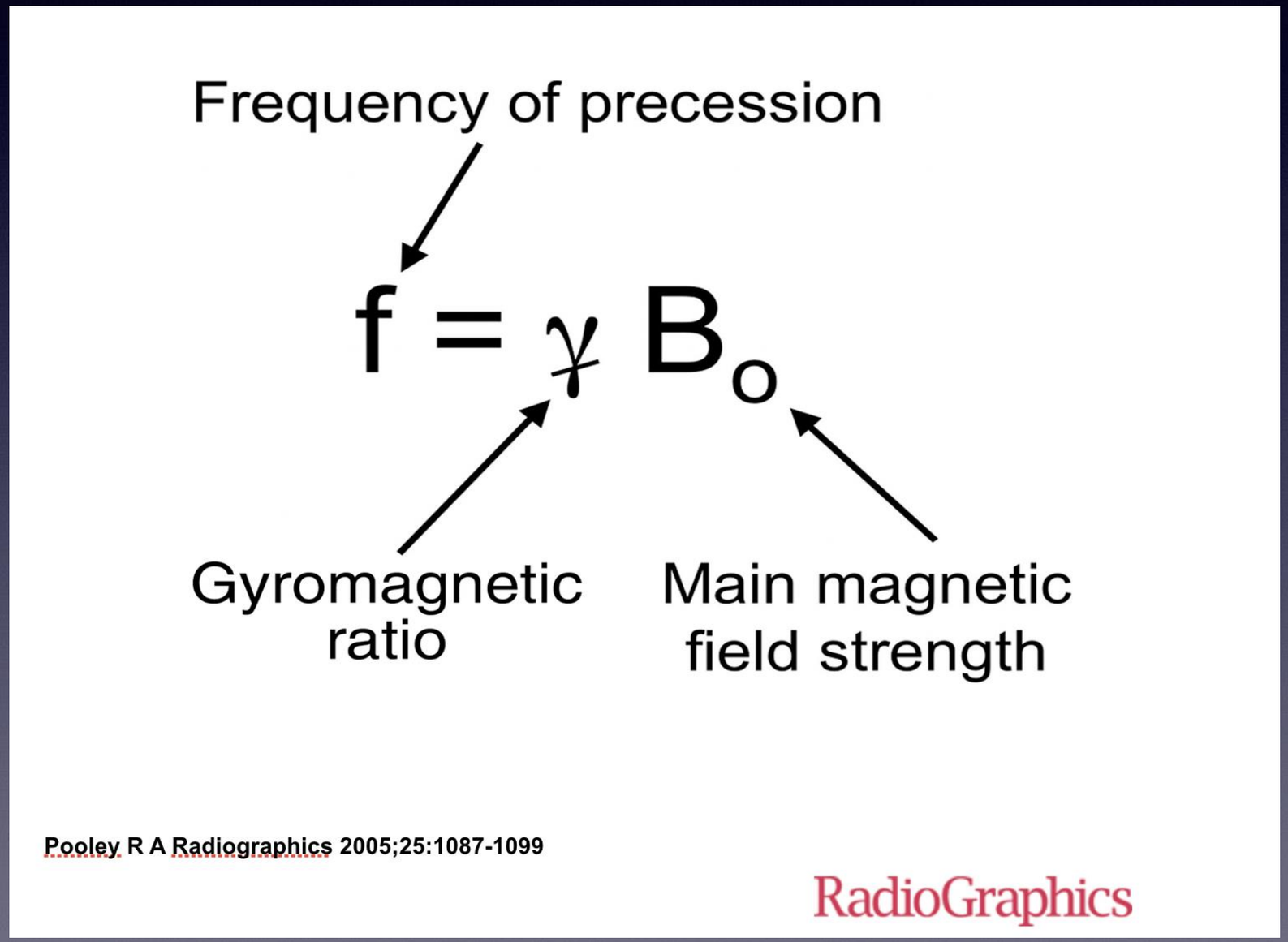
Spin motion in a magnetic field



https://my-ms.org/mri_physics.html

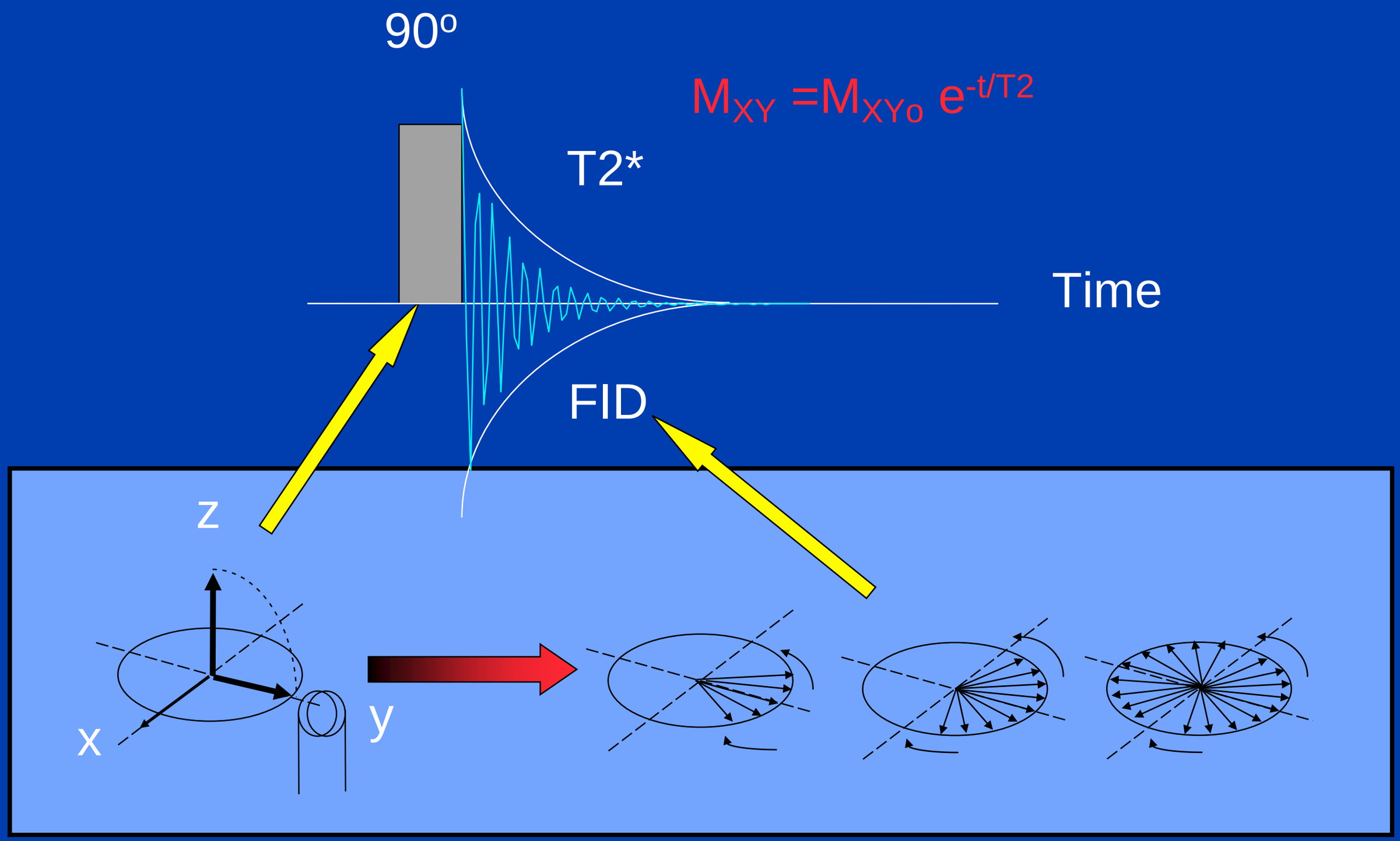
Larmor frequency



Pooley R A Radiographics 2005;25:1087-1099

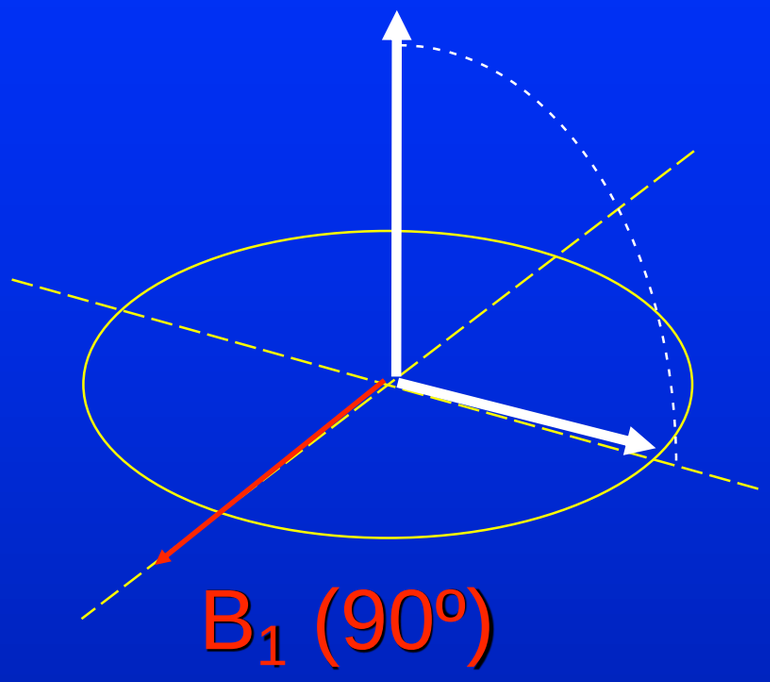
RadioGraphics

T2 relaxation

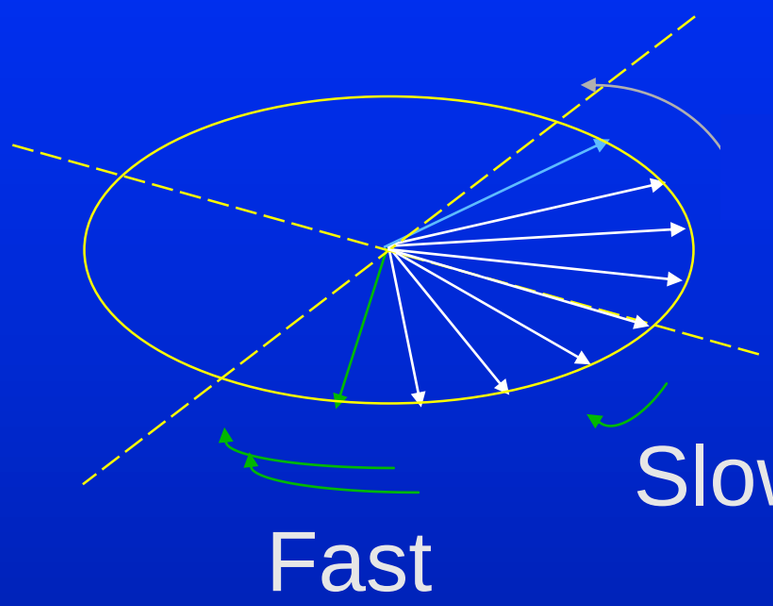


Gradient echo

No Bo inhomogeneity compensation



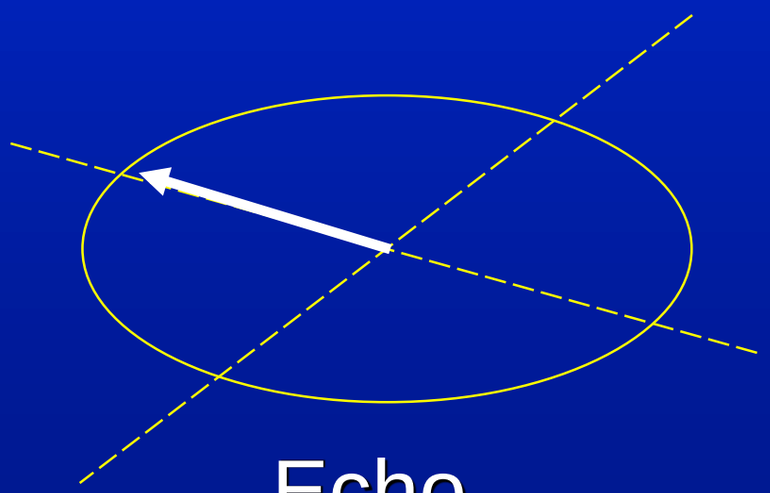
B_1 (90º)



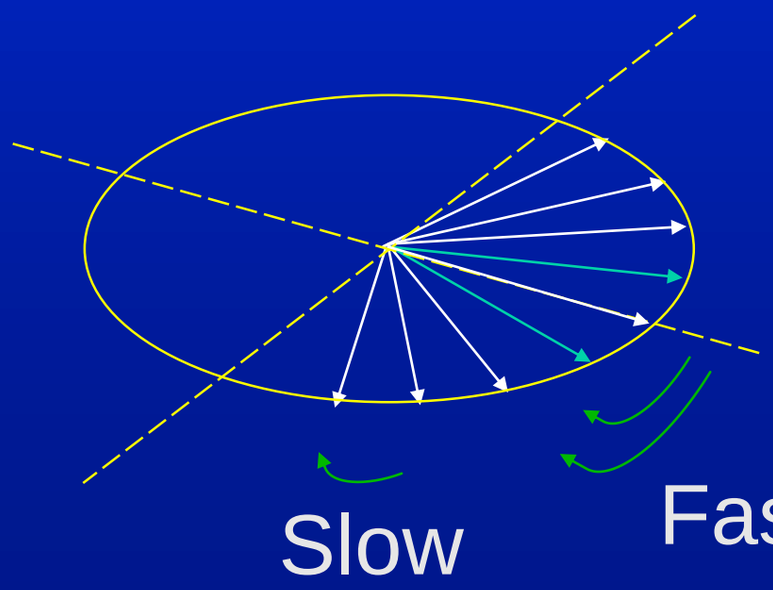
Fast

Slow

Bo Gradient



Echo

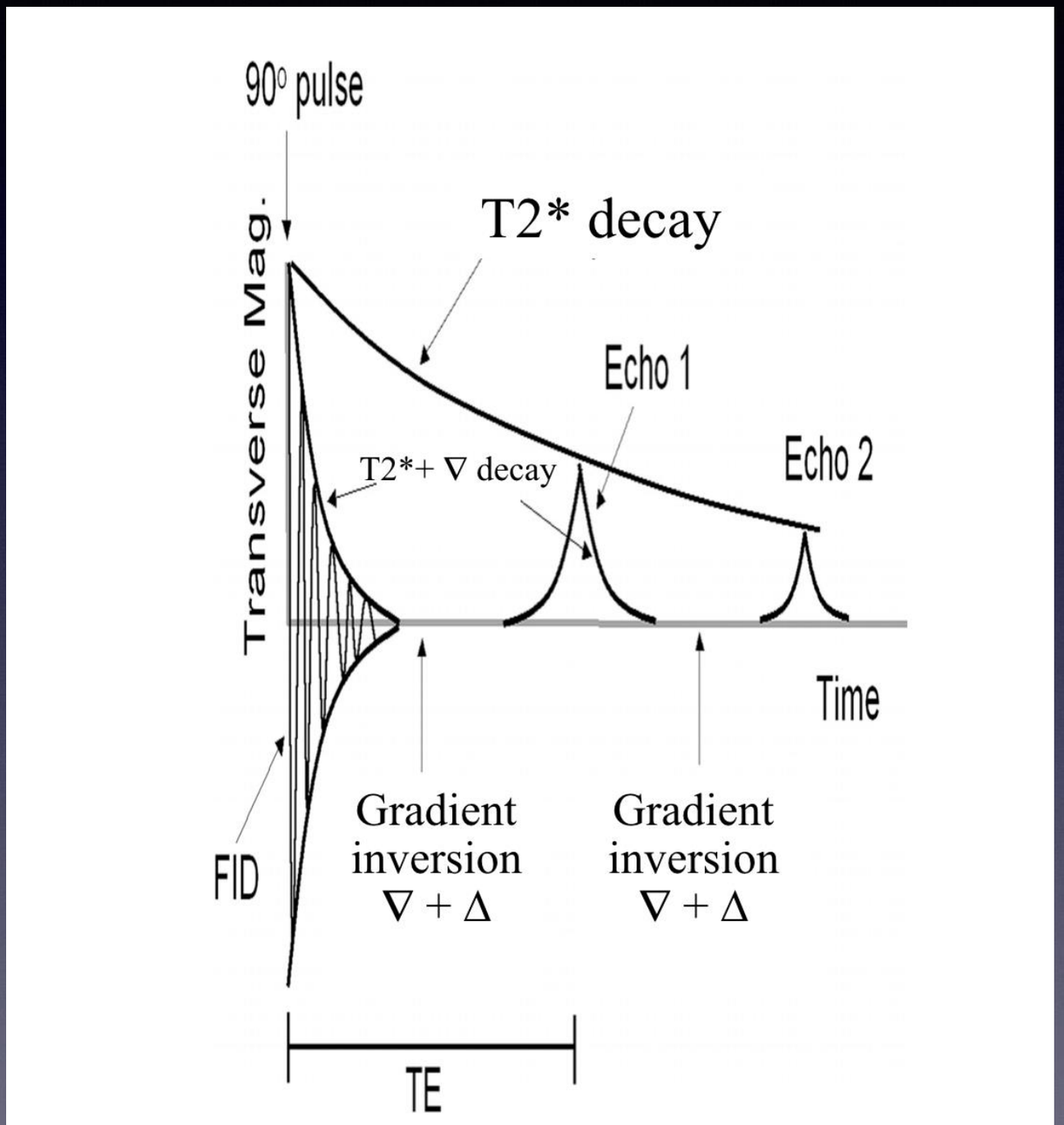


Slow

Fast

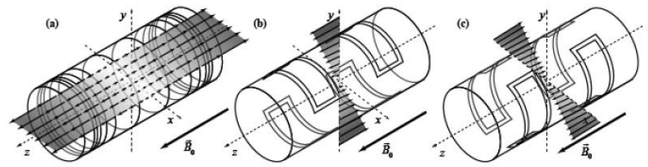
Bo Gradient inversion

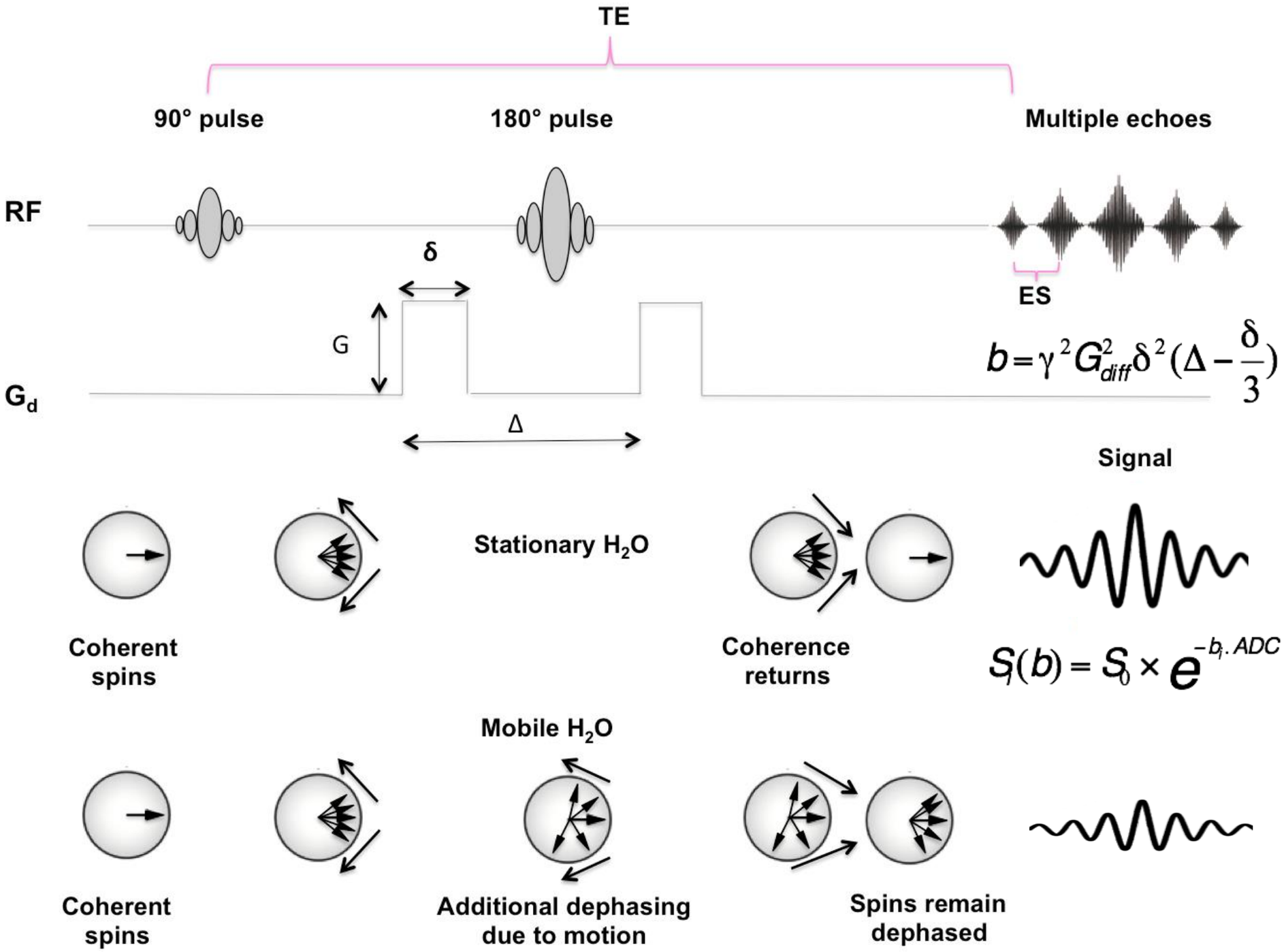
Echoes formation



Modified from Pooley R A Radiographics 2005;25:1087-1099

How to image diffusion?





Courtesy of I.Friedli

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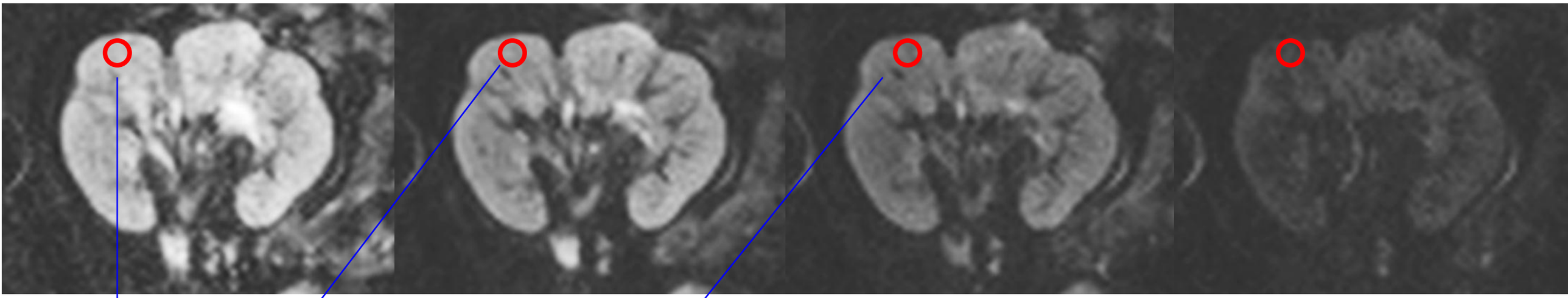
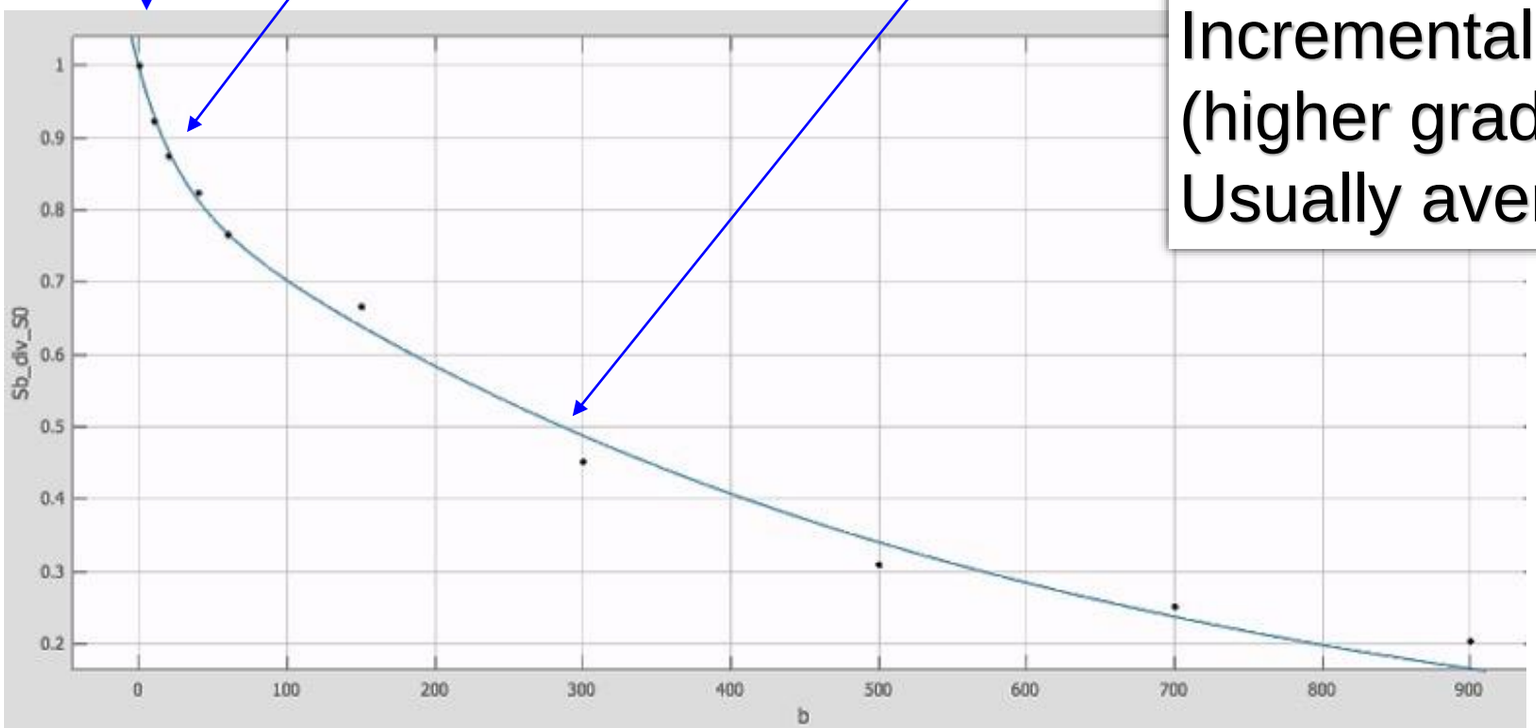
Unresolved issues

DWI acquisition

b0 b20 b300 b700 s/mm²





Multiple acquisitions
Incremental magnetic gradients
(higher gradient = smaller motion probe)
Usually average of 3 spatial directions

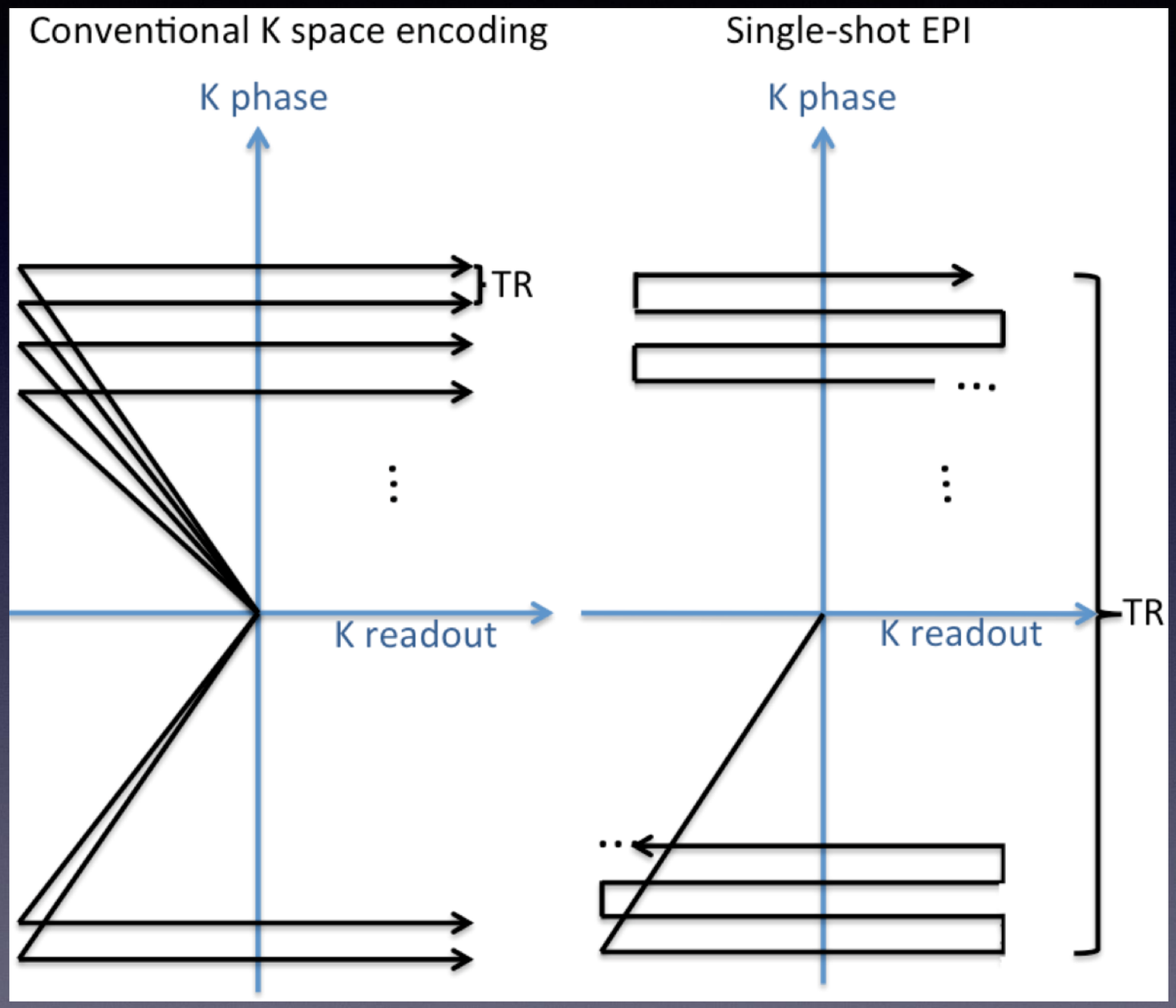
DWI acquisition

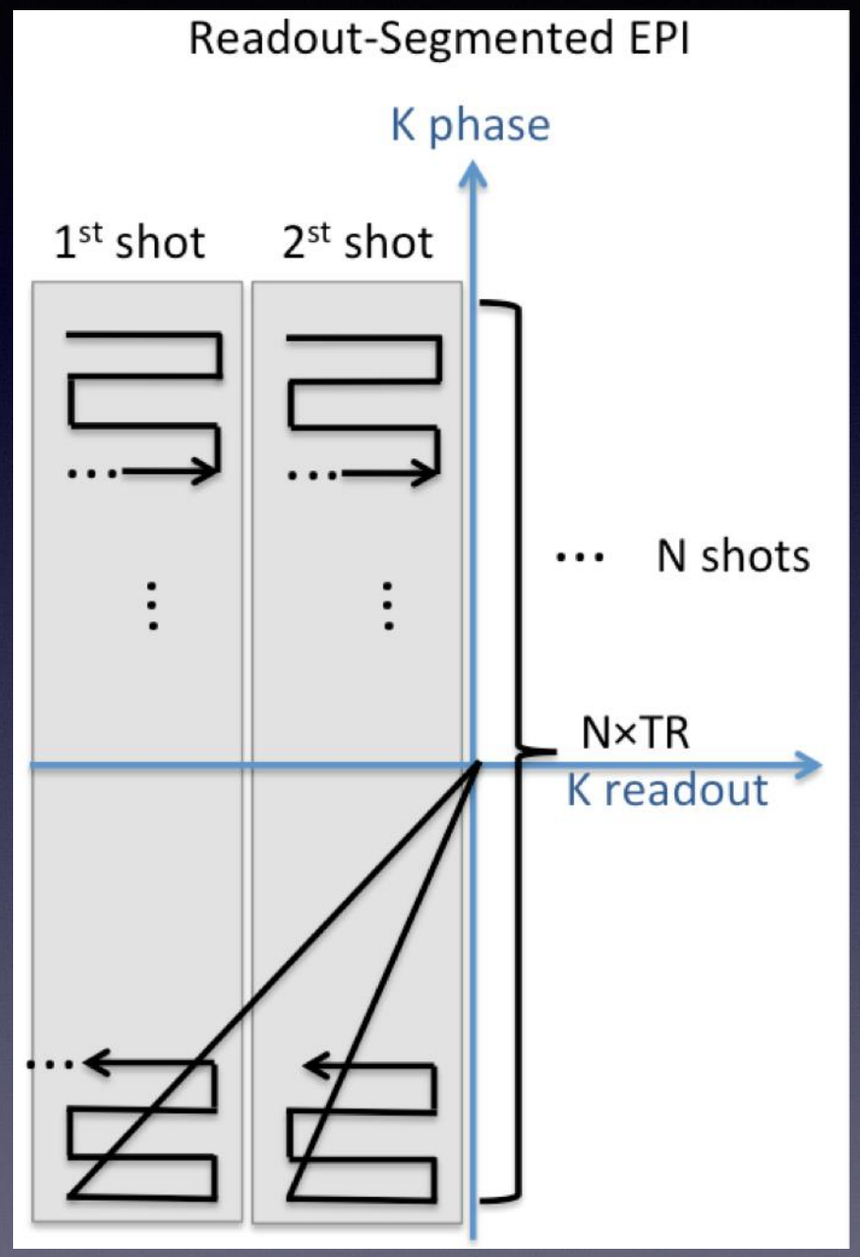
Table 1. DWI in the kidney: key aspects

Patient preparation	
Hydration	Potential confounder Control by hydrating the patient whenever possible
Data acquisition	
Echo time	Minimize to optimize SNR Minimum limited by maximum *b*-value
Repetition time	Long enough to allow for T1 relaxation (>1500 ms) Minimum limited by number of image slices
Image orientation	Axial: less motion in image plane Coronal: easier full kidney coverage
Field of view	Usually covers the entire abdomen (320–400 mm) *Z*-dimension dependent on image orientation
Resolution	Increase: sharpness$_{\uparrow}$ partial volume effects$_{\downarrow}$ Decrease: ETL$_{\downarrow}$ kidney coverage$_{\uparrow}$ SNR$_{\uparrow}$
ETL	Shorten to lessen susceptibility artefacts Measures: parallel imaging, multi-shot EPI, partial Fourier
Motion compensation	Physiological triggering using external devices Intrinsic triggering using MRI signal (navigator)
b-values	Tailor to respective DWI biomarker Increase number to improve parameter estimates
Image post-processing	
Image quality control	Discard problematic image(s) to ensure imaging parameter value reliability
Motion correction	To account for motion artefacts and eddy current-induced deformations
ROI definition (kidney/medulla/cortex)	From more than one section to have representative average values; no vessels, artefacts, lesions
Model fitting	To compute DWI biomarkers by fitting appropriate signal attenuation models

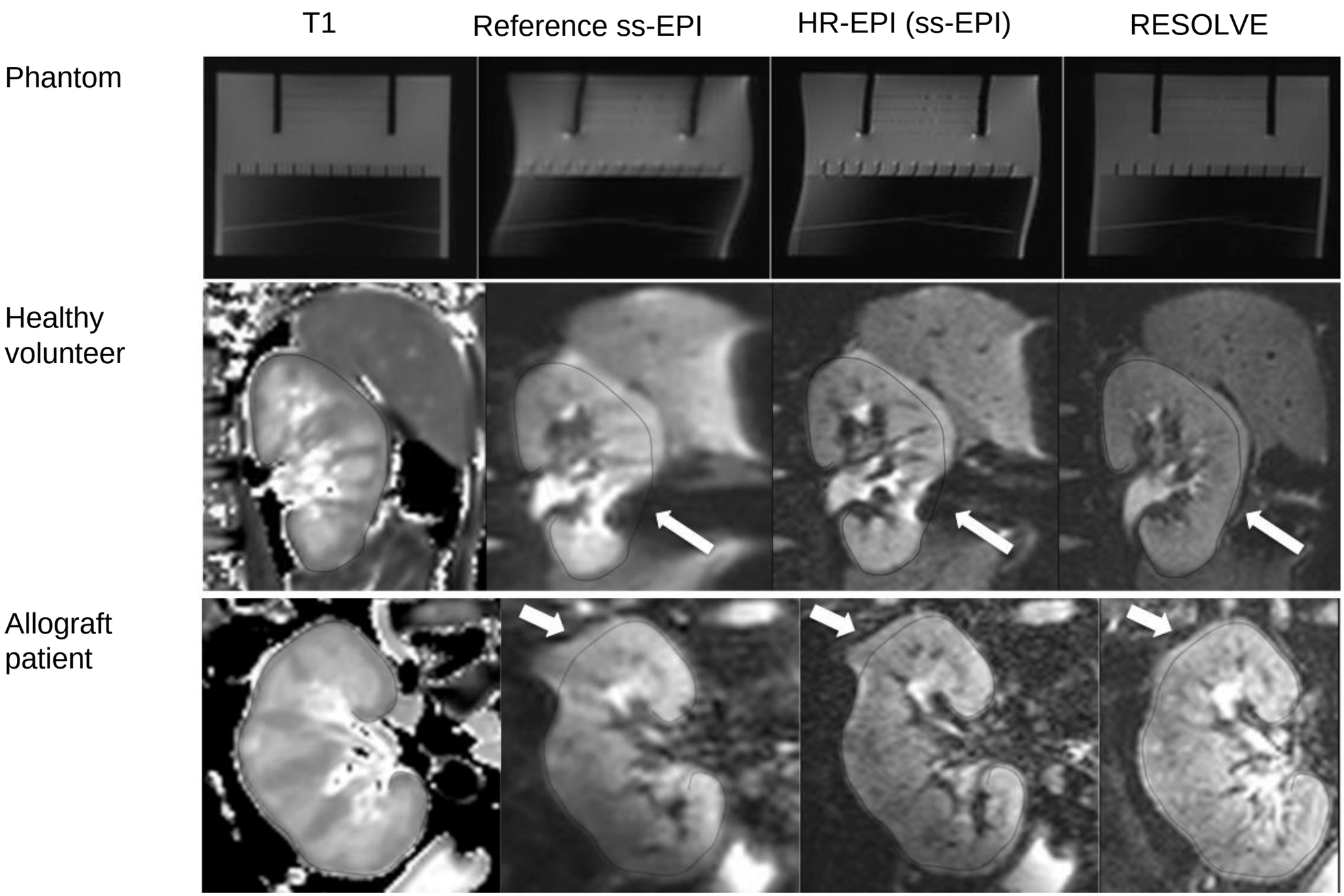
EPI, echo-planar imaging; ETL, echo train length; MRI, magnetic resonance imaging; SNR, signal to noise ratio

K-space sampling strategy



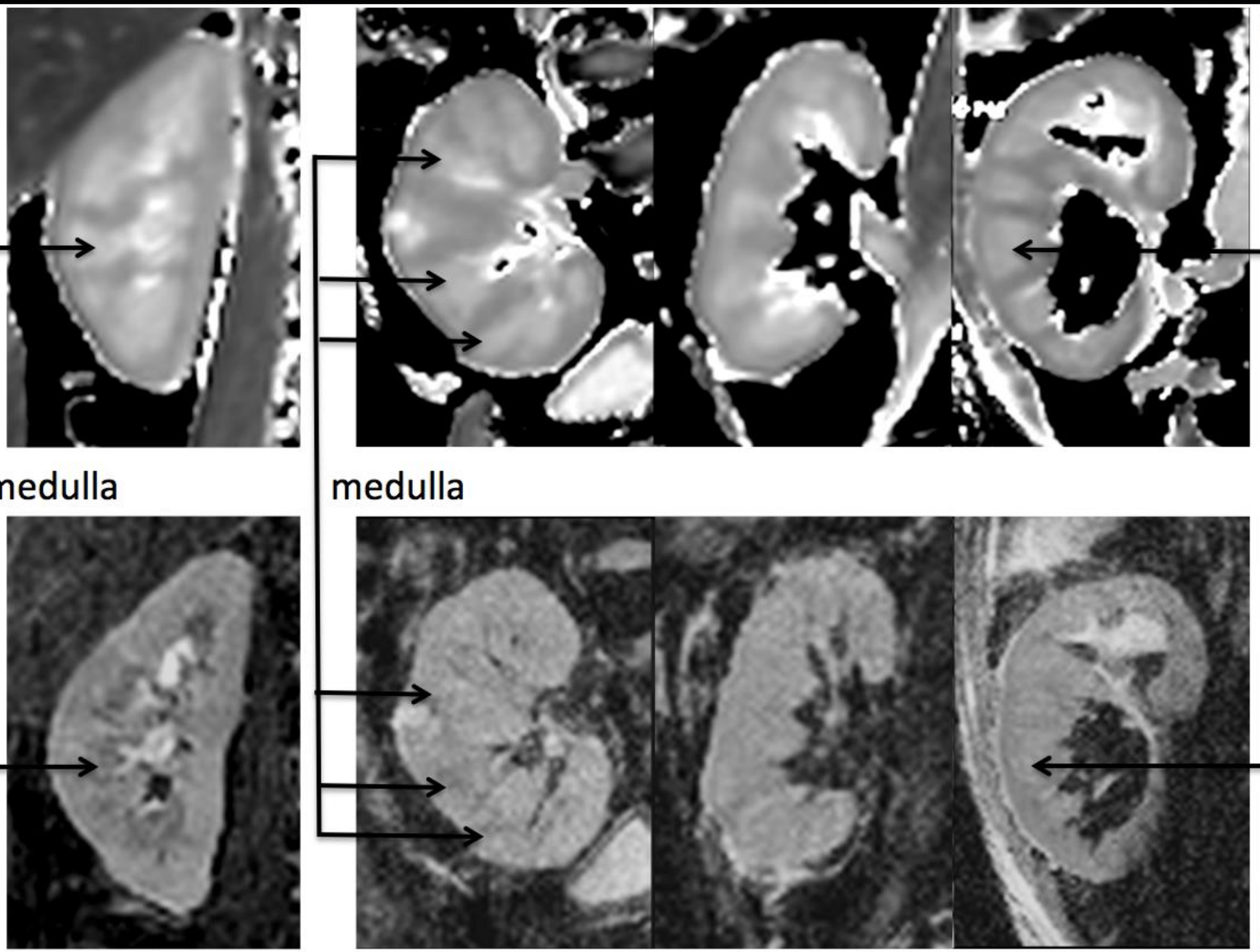


(1) Optimization of the acquisition strategy with RESOLVE as a new renal DWI



Friedli I et al MRI 2015

RESOLVE enhanced significantly the quality of renal DWI by reducing susceptibility effects and increasing sharpness.



ΔADC positive	ΔADC positive	ΔADC ‘0’	ΔADC negative
347×10^{-6} mm²/s	196×10^{-6} mm²/s	5×10^{-6} mm²/s	-91×10^{-6} mm²/s
0% fibrosis -healthy	**20% fibrosis**	**30% fibrosis**	**80% fibrosis**

Friedli I et al Scientific Reports 2016

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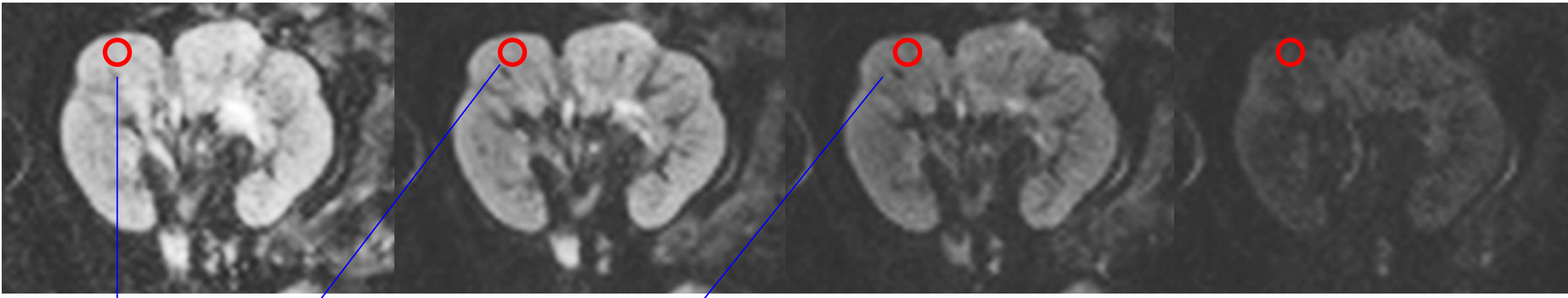
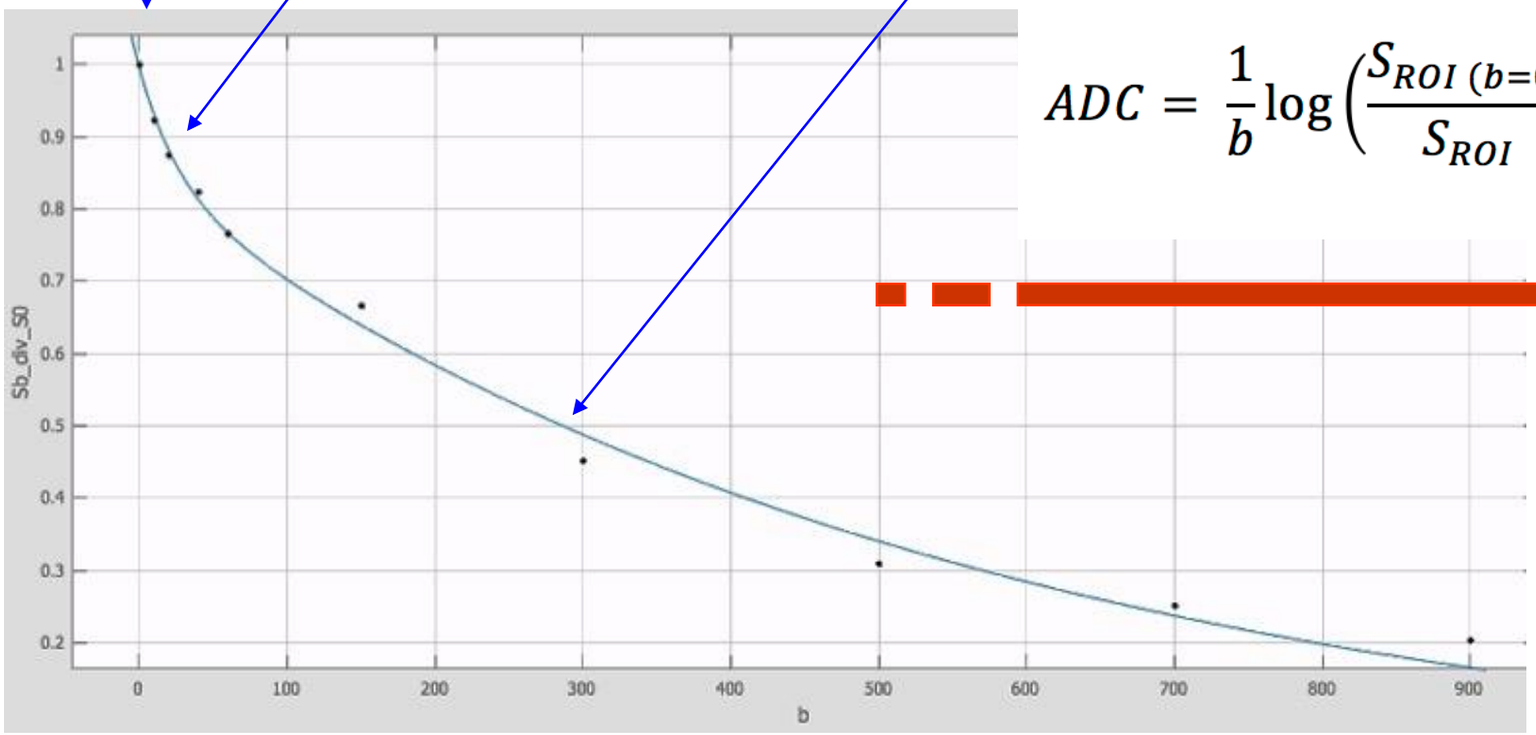
ADC (monoexponential fit)

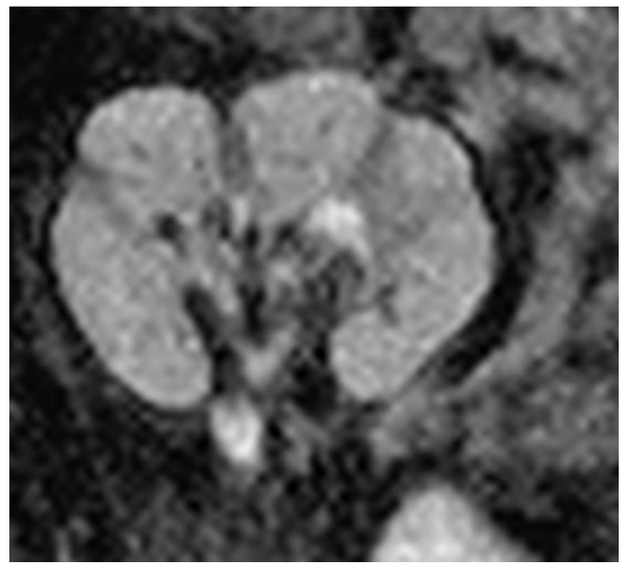
b0 b20 b300 b700 s/mm²



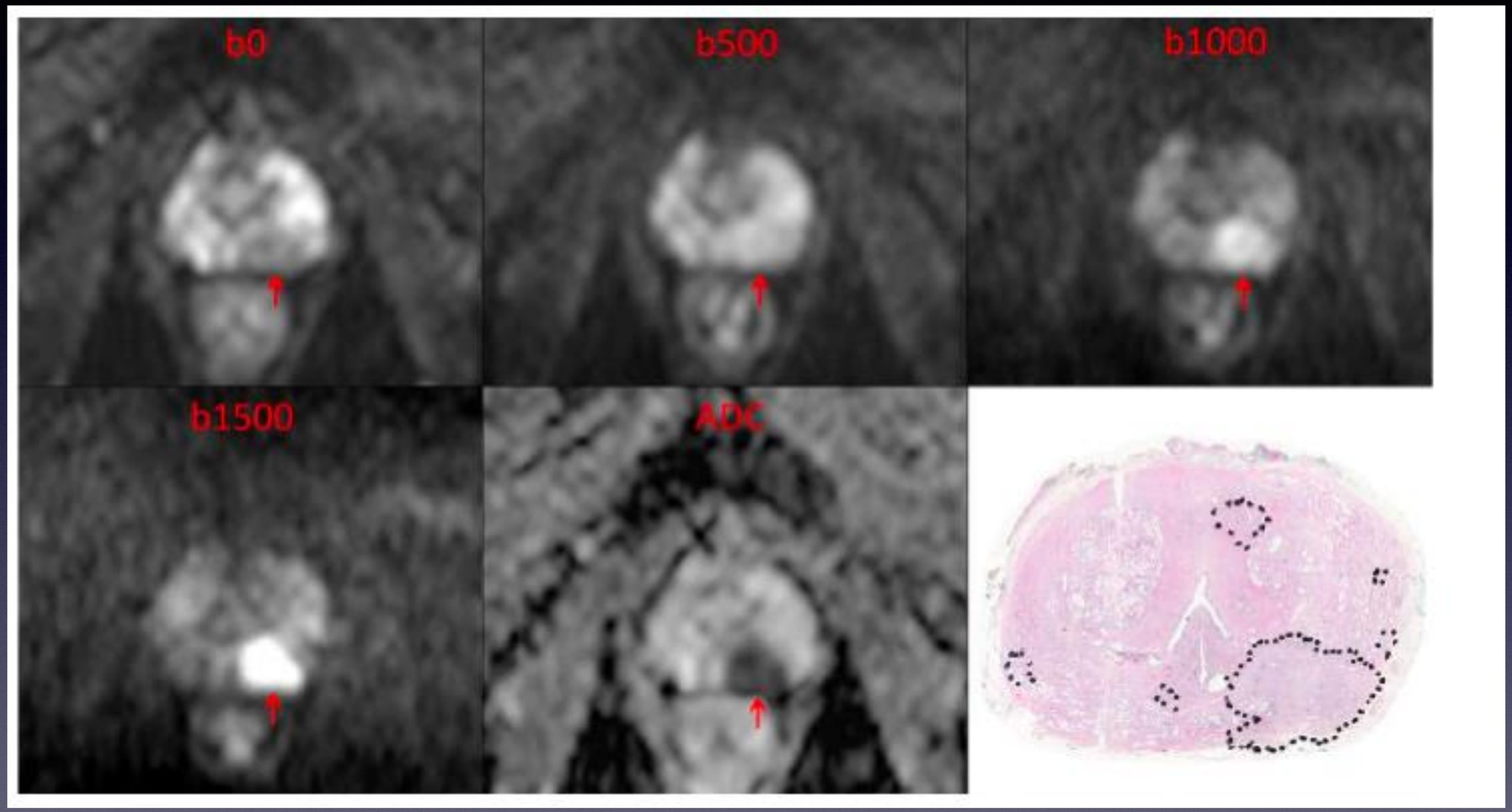
ADC (Coefficient Apparent de Diffusion) [mm²/s]



$$ADC = \frac{1}{b}\log\left(\frac{S_{ROI\ (b=0)}}{S_{ROI}}\right)$$



How to read the images?



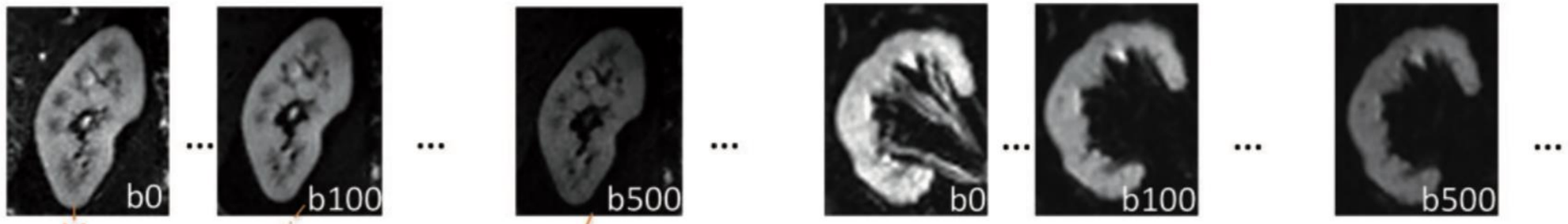
Water restriction = DWI ⇧ (high b) = ADC ⇩

de Perrot et al. JMRI 2016

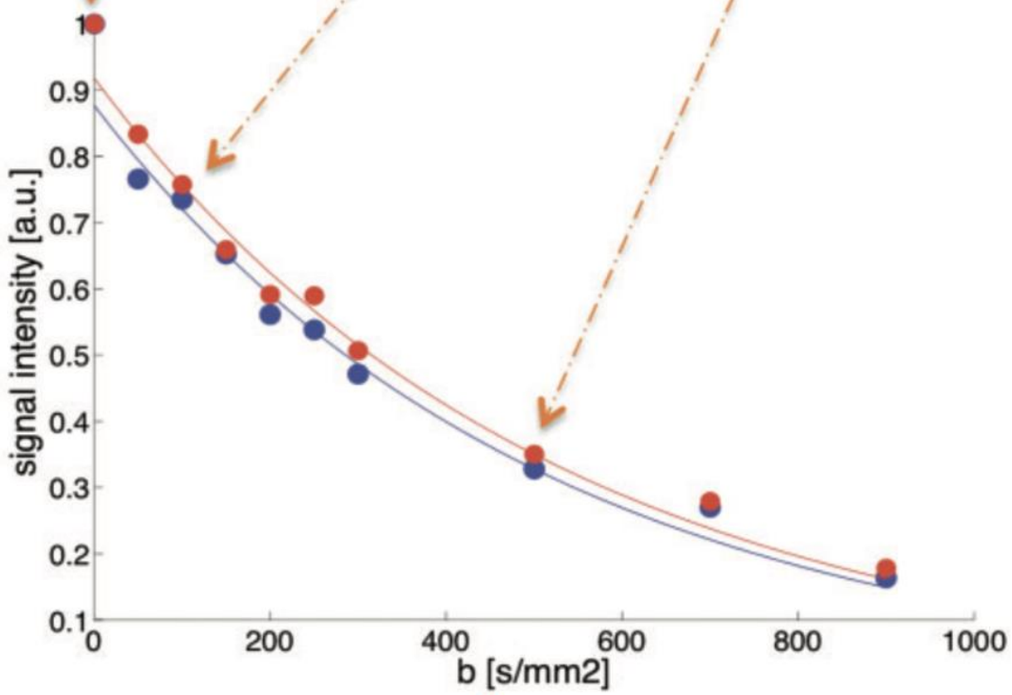
Normal kidney

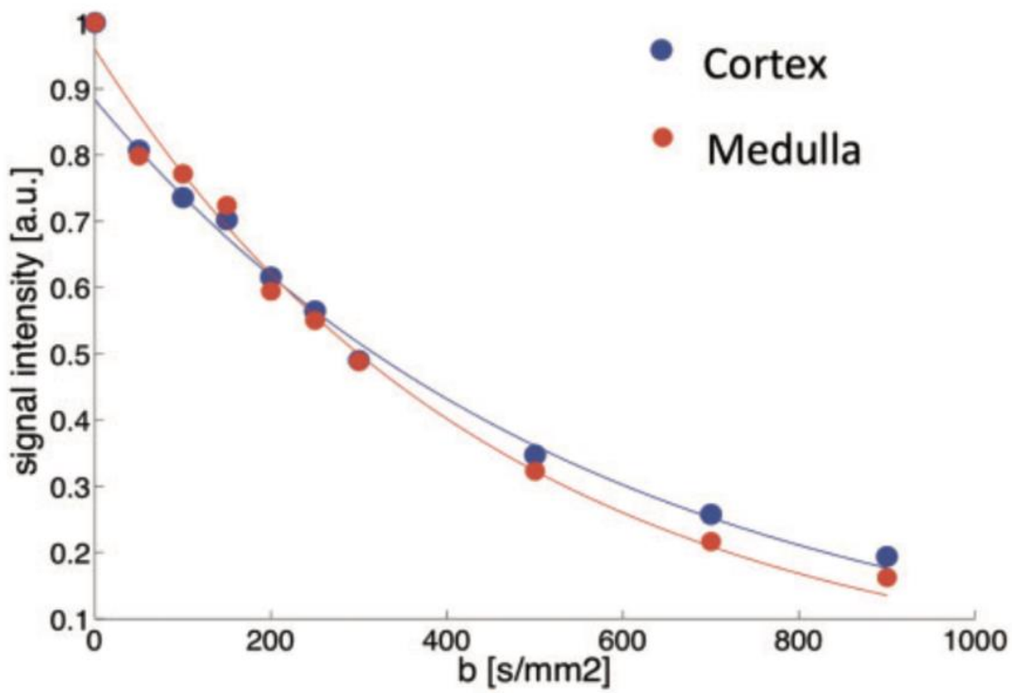
CKD patient with 60% fibrosis

Acquisition

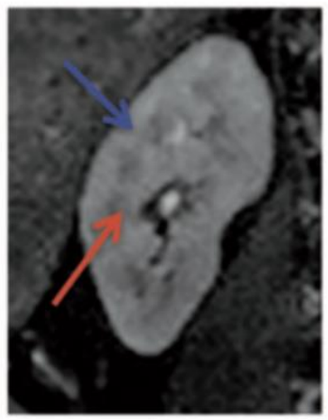


Curve fitting

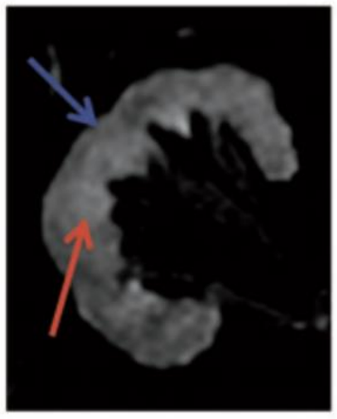




ADC map



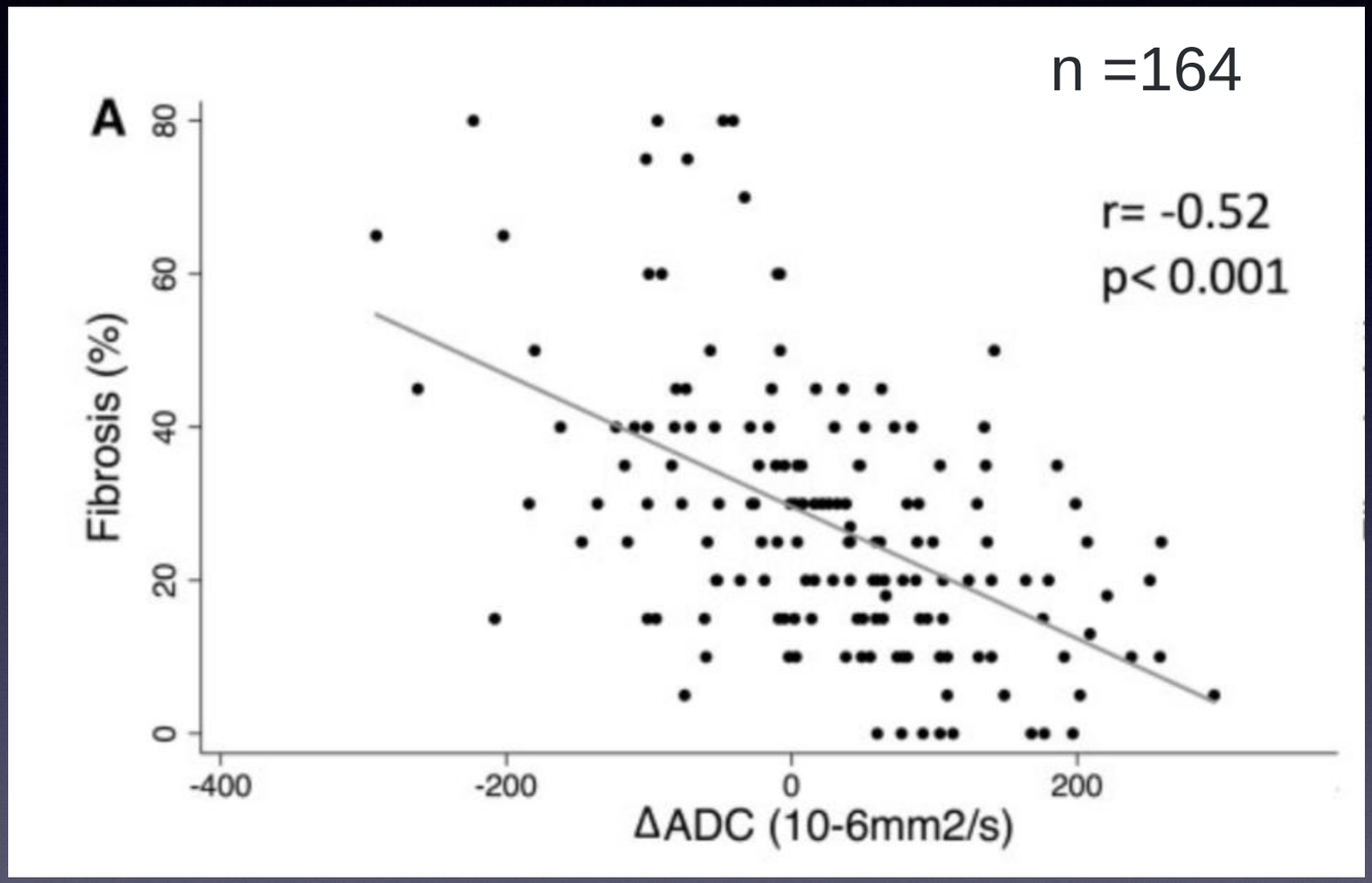
ADC cortex > ADC medulla



ADC cortex < ADC medulla

Caroli et al, NDT, 2018

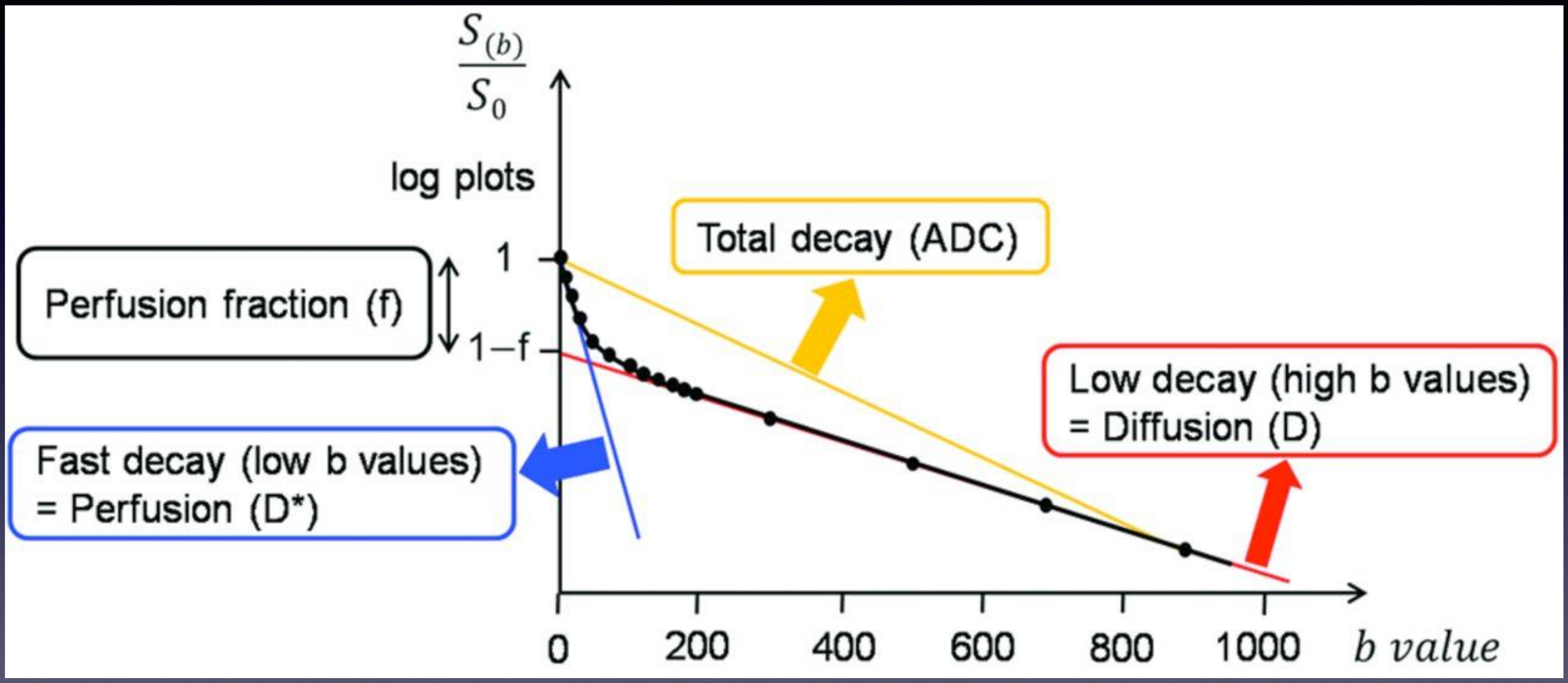
ADC & renal Bx



Berchtold, et al, NDT, 2019

Negative correlation of ADC with interstial fibrosis in CKD well validated

IVIM fitting



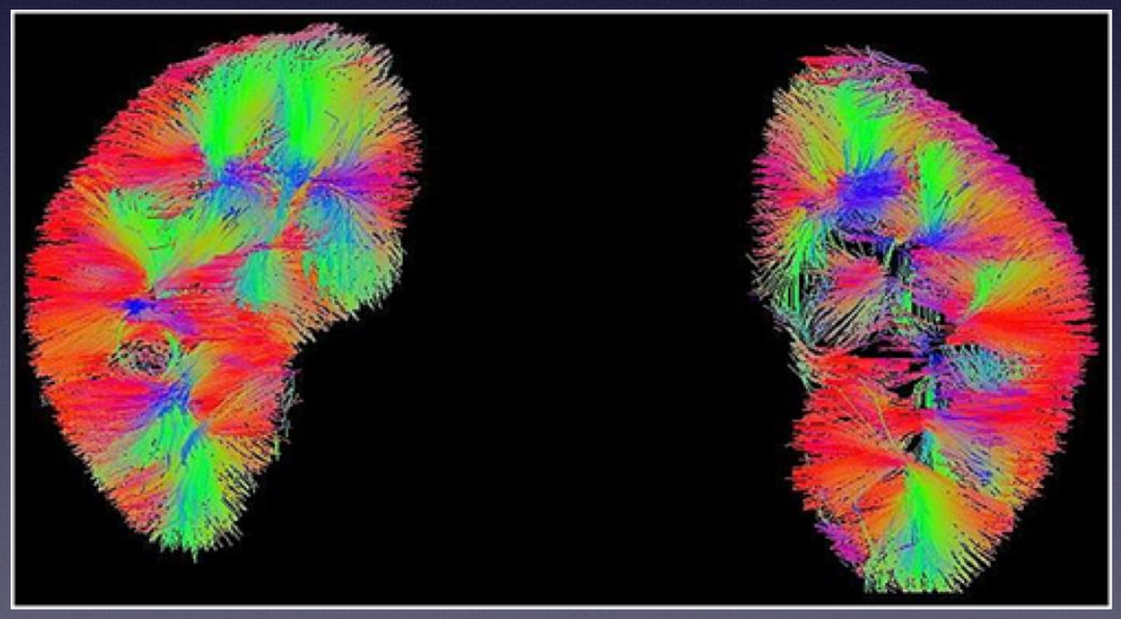
$$S(b) = S_0 e^{(-b \times ADC)} \rightarrow S(b) = S_b((1-f)e^{(-D \times b)} + fe^{(-(D^* + D) \times b)})$$

Kim, American Journal of Neuroradiology 2014, 35 (3) 490

Diffusion tensor imagine (DTI)

Require multiple directions acquisitions (6 - 12)

Parameters:
Fractionnal anisotropy (FA)
Mean diffusivity (MD)
Tractography



NMR in Biomedicine, Volume: 30, Issue: 3, First published: 11 November 2015, DOI: (10.1002/nbm.3434)

Table 2. DWI biomarker estimation models to investigate renal tissue microstructure

Model	Biomarker(s)	Pros (+) and cons (−)
Monoexponential	ADC: apparent diffusion in the tissue	+ Most robust against noise + Wide availability and ease of use of biomarker estimation tools − Provides limited information (apparent diffusion only) − Fits DWI data the least
IVIM	D: water diffusion in the tissue D*: pseudodiffusion F: flowing fraction	+ Describes DWI signal attenuation at best provided sufficient signal-to-noise + Can separate diffusion from pseudodiffusion − No standardized algorithm to compute IVIM parameters
DTI	FA: fractional anisotropy diffusion anisotropy imposed by the tissue microstructure MD: anisotropy-independent mean diffusivity	+ Provides information on tissue anisotropy − Requires a dedicated acquisition sequence (DTI) with multiple directions
Extended IVIM	D: water diffusion in the tissue D*: pseudodiffusion F: flowing fraction Additional model-specific biomarkers	+ Potentially advances the characterization of the renal microstructure and microcirculation − Requires complex biomarker estimation − Need further investigation, especially in pathological kidneys
Non-Gaussian	ADC: apparent diffusion in the tissue K/σ/δ: measure of the degree of deviation of diffusion from a Gaussian law	+ Accounts for the complexity of diffusion in the renal tissue − Requires complex biomarker estimation − Fits DWI data better than monoexponential but worse than IVIM model

Caroli et al, NDT, 2018

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Unresolved issues

- Best MR sequence / protocol to use (SS-EPI, Resolve, DTI)
- Best analysis to use (ADC, IVIM, DTI)

=> no gold standard

=> Standardisation versus technical evolution!

Unresolved issues

- Origin of the diffusion signal decrease in CKD (water motion restriction, reduced GFR, reduced perfusion or tubular exchanges…)

=> specificity of DWI ??

but strong validation
(negative correlation of ADC with interstial fibrosis in CKD)

Unresolved issues

- Validation ++ but qualification is missing
  - Bx replacement in selected CKD
  - New therapy monitoring
  - Selection of Bx patients in acute graft dysfunction (*Steiger, Eur Rx 2017*)

=> multiparametric & multicentric effort

Acknowledgments

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