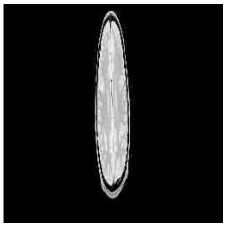
Part 4: Spin-Warp; 2D

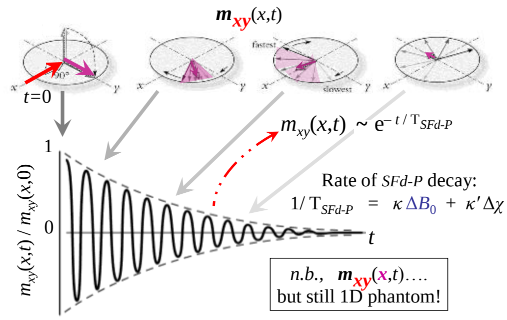


- Spin-Echo Pulse Sequence
- T2 Spin-Relaxation
- T1-*w*, T2-*w*, and PD-*w* S-E MR Imaging
- Spin-Echo / Spin-Warp in 2D

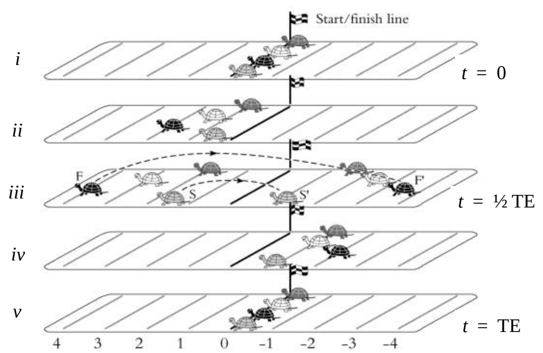
Static Field de-Phasing in ***x-y Plane*** of Spins in a Voxel

SFd-P from ***static***-field inhomogeneities & susceptibility effects

This de-phasing is ***REVERSABLE!!!!***



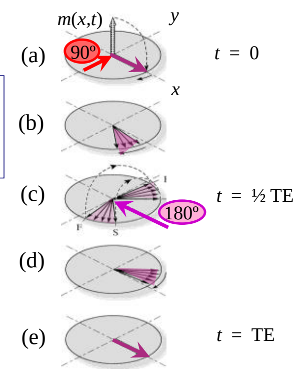
Creating the Spin-Echo: Kentucky Turtle-Teleportation Derby



Spin-Echo Generates an Echo *and* Eliminates *SFd-P* Effects

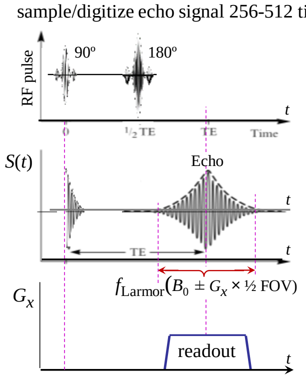
Local magnetic environment for each spin packet is ***static***. So ***this*** de-phasing **can be REVERSED*!!!***

(**T2** dephasing, by contrast, is **random** over time, and can ***NOT*** be un-done!!)



S-E Pulse Sequence

sample/digitize echo signal 256-512 times, *e.g.*



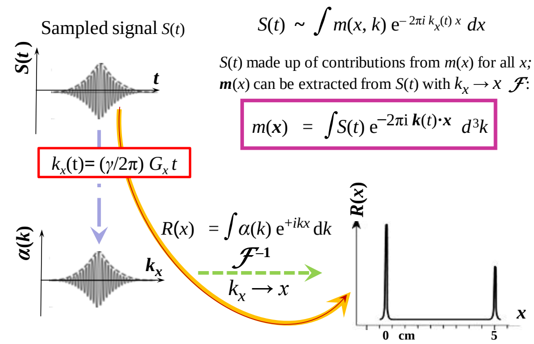
5

k-Space for S-E in 1D, 2-Voxel Phantom

$S(t) \sim \int m(x, k)\, e^{-2\pi i\, k_x(t)\, x}\, dx$

$S(t)$ made up of contributions from $m(x)$ for all x; $m(x)$ can be extracted from $S(t)$ with $k_x \to x$ $\mathcal{F}$:

$$m(\mathbf{x}) = \int S(t)\, e^{-2\pi i\, \mathbf{k}(t)\cdot \mathbf{x}}\, d^3k$$



During Readout, k_x Increases Linearly with t

$k(t)$ for all voxels increases linearly with t while the echo signal is being received and read:

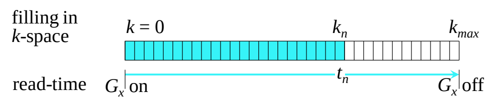
$$k_n = [G_x \gamma / 2\pi]\, t_n.$$

Larger k-values (greater sampled times) correspond to **greater spatial frequencies**!

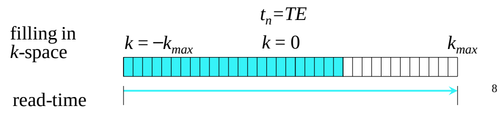
Signal is sampled sequentially at typically 256-512 times at Δt intervals; t_n is the exact n^{th} sampling time after G_x is turned on.

Filling in *k*-space in 1D

During ***FID***, readout direction filled from k_x=0 to k_x=k_{max}, (center to edge of *k*-space) as time progresses



With ***S-E***, readout direction filled from $k_x = -k_{max}$ to k=0 to k=k_{max} (one edge to center to opposite edge)



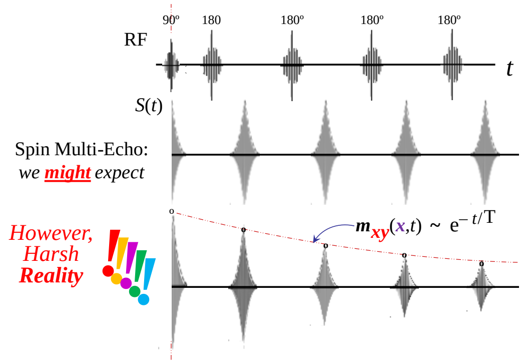
8

T2 Spin-Relaxation

T1-Events
and ***Non-Static, Random, Non-Reversible***
Proton-Proton Dipole Interactions
Both Contribute to 1/T2

Specifically,
any process that decreases either the number of transverse spins or their phase coherence will add to T2 relaxation.

Thus, Spin-Echo Signal ***Does*** Decay, and Much Faster than 1/T1!



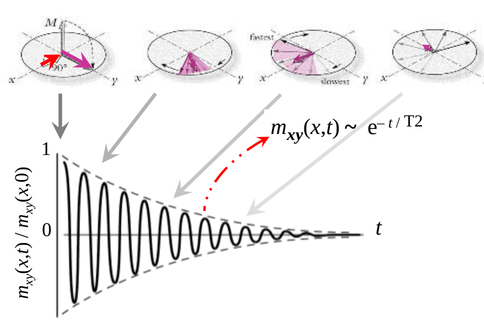
So…

SOMETHING *BIG*
MUST BE GOING ON
IN ADDITION **TO**
THE T1 PROCESS

Another Form of Relaxation, As Well !

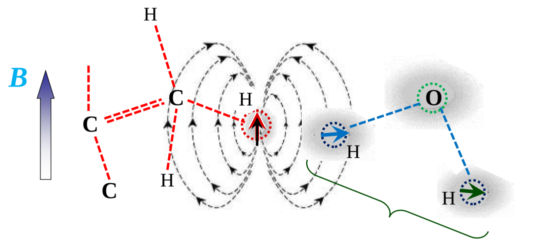
Call it **T2**!

Even with S-E, Spin De-Phasing Is Caused by T1 Events *and* by ***Non-Static***, ***Random***, Proton-Proton Dipole Interactions



Spin-Spin (Secular) De-Phasing in Bound *Water*

with *its* protons precessing in the *x*-*y* plane at different rates

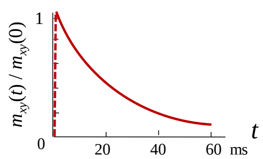


Quasi-static *spin-spin interactions*
do ***not*** involve exchange of energy!

$1/T2 \sim 10 \times (1/T1)$

Tissue	PD p⁺/mm³, rel.	T1, *1T* (ms)	T1, *1.5T* (ms)	T1, *3T* (ms)	T2 (ms)
pure H_2O	1	4000		4000	4000
brain					
CSF	0.95	2500	2500	2500	200
white matter	0.6	700	800	850	90
gray matter	0.7	800	900	1300	100
edema			1100		110
glioma		930	1000		110
liver			500		40
hepatoma			1100		85
muscle	0.9	700	900	1800	45
adipose	0.95	240	260		60

Exponential, T2-Caused De-Phasing of $\boldsymbol{m}_{xy}(x,t)$ in *x*-*y* Plane



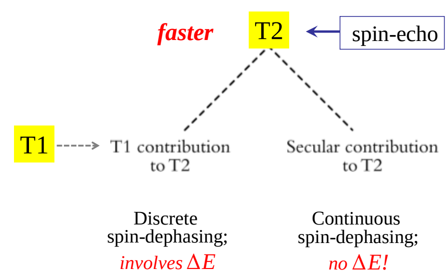
$$d\boldsymbol{m}_{xy}(t)/dt = -(\mathbf{1/T2})\, \boldsymbol{m}_{xy}(t)$$

$$m_{xy}(t)/m_{xy}(0) = e^{-t/T2}$$

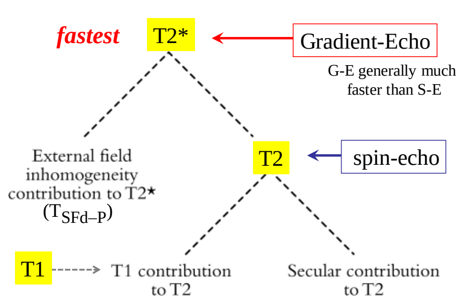
$$d\mathbf{m}(x,t)/dt = \gamma\, \mathbf{m}(x,t)\times \boldsymbol{B}_z(x) - \frac{[m(x,t) - m_0(x)]\hat{z}}{T1} - \frac{[m_x\hat{x} + m_y\hat{y}]}{T2}$$

classical Bloch Equation

$1/T2 = 1/(2\,T1) + 1/T2_{secular}$



One Last Member of the Spin-Relaxation Family Tree: T2*



SAMs Q:

IV-8 T2 relaxation refers to:

a) the rate at which longitudinal magnetization recovers.
b) the rate at which longitudinal magnetization disappears.
c) the rate at which transverse magnetization recovers.
d) the rate at which transverse magnetization disappears.
e) the rate at which tissue is magnetized.

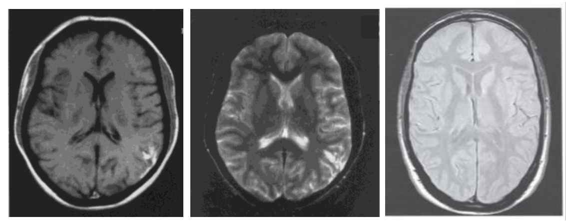
Answer: (d).

Ref: "Medical Imaging", A.B. Wolbarst *et al.*, Wiley-Blackwell (2013), p. 364.

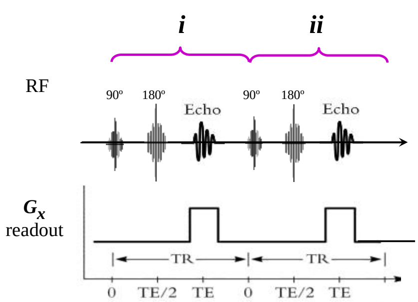
T1-*w*, T2-*w*, and PD-*w* S-E MRI

Three Different Forms of MRI Contrast

created by, and reflecting, three quite different physical processes



Multiple Spin-Echo Pulse Sequence



MRI Signal Strength at t = TE Depends on….

Inherent Parameters	Operator Settings
T1	TR ← time since previous S-E sequence
T2	TE
PD	

$$S(t = \text{TE}) \sim \text{PD}\,(1 - e^{-\text{TR}/\text{T1}})\, e^{-\text{TE}/\text{T2}}$$

PD: proton density; $(1 - e^{-\text{TR}/\text{T1}})$: prior regrowth along z-axis; $e^{-\text{TE}/\text{T2}}$: current dephasing in x-y plane

bright **regions:**
m_{xy} large at t = TE

SAMs Q:

IV-9 $S(t = \text{TE}) \sim \text{PD}\,(1 - e^{-\text{TR}/\text{T1}})\, e^{-\text{TE}/\text{T2}}$. Therefore, in a spin-echo pulse sequence, a short TE will:

(a) Minimize T1 image contrast
(b) Eliminate T2 effects
(c) Result in a lower SNR
(d) Increase the effects of static-field dephasing
(e) Enhance tissue susceptibility differences

Answer: (b).

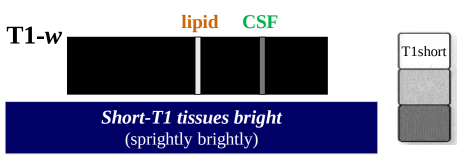
Ref: "Medical Imaging", A.B. Wolbarst *et al.*, Wiley-Blackwell (2013), p. 368.

T1-*weighted* – Short TE to Eliminate T2 Contribution

TR ~ $T1_{av}$ to maximize contrast; Short TE to minimize T2 impact

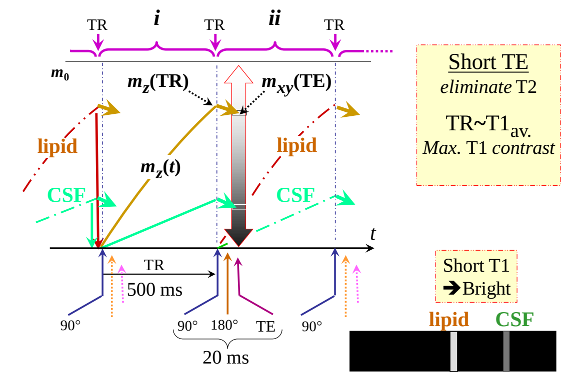
$$S(t \sim \text{TE}) \sim \text{PD}\,(1 - e^{-\text{TR}/\text{T1}})\, \cancel{e^{-\text{TE}/\text{T2}}}$$

PD: proton density; $(1 - e^{-\text{TR}/\text{T1}})$: prior regrowth along z-axis; $e^{-\text{TE}/\text{T2}}$: current de-phasing in x-y plane



Short-T1 tissues bright
(sprightly brightly)

T1-w – Short TE to *Eliminate* T2 Contribution



T2-w – Long TR to Eliminate T1 Contribution

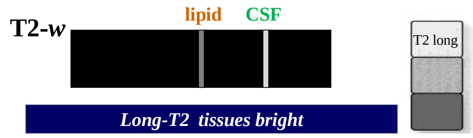
For T2-*w* imaging

Long TR: eliminate T1 impact

TE at mid-T2: maximize contrast

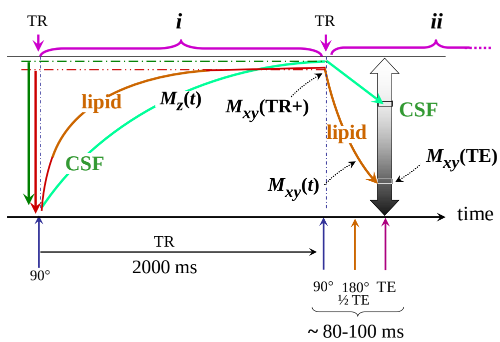
$$S(t\sim TE) \sim PD\,(1 - \cancel{e^{-TR/T1}})\,e^{-TE/T2}$$

proton density; prior regrowth along *z*-axis; current de-phasing in *x*-*y* plane

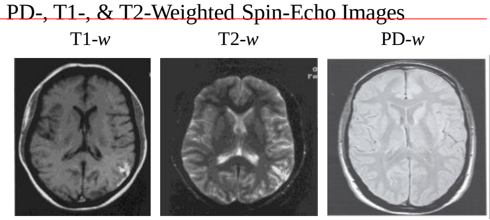


T2-w – Long TR to Eliminate T1 Contribution

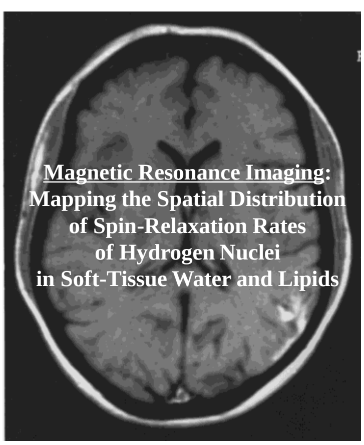
TE ~ mid-T2 to maximize T2 contrast



PD-, T1-, & T2-Weighted Spin-Echo Images



	T1-w	T2-w	PD-w
TR (ms)	mid- (~$T1_{av}$) 300 – 700	long 1,500 – 3,500	long 1,500 – 3,500
TE (ms)	short 0 – 25	mid- (~$T2_{av}$) 60 – 150	short 10 – 25
Bright	short T1	long T2	high PD
SNR	good	lower	best



SAMs Q:

IV-10. Which of the following would appear bright on a T2-weighted image of the brain?

(a) CSF
(b) Fat
(c) Bone
(d) White matter
(e) Air

Answer: (a) cerebral spinal fluid.

Ref: "Medical Imaging", A.B. Wolbarst *et al.*, Wiley-Blackwell (2013), p. 368.

Spin-Echo / Spin-Warp in 2D

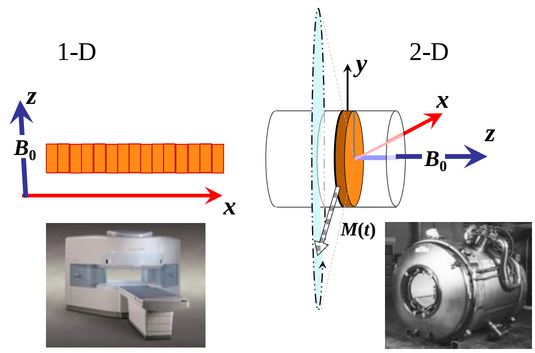
Sensitive Point (Earliest) Reconstruction

Oscillating Gradient Fields

net field stable in one voxel at a time;
move sensitive point around.

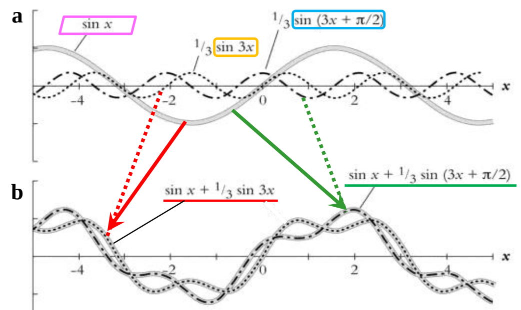
cannot be done with CT.

Open Magnet, 1D Phantom *vs.* Supercon, 2D Phantom



In 2-D MRI, Phase Is Every Bit As Critical as Frequency

2 possible phases for the higher-frequency components

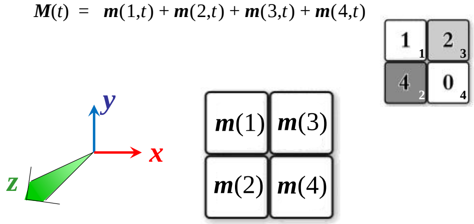


2 different superimpositions with the longer-λ wave

PD Map of Thin-Slice 2D, 4-Voxel Patient

after 90º pulse drives $M(t)$ into x-y plane…

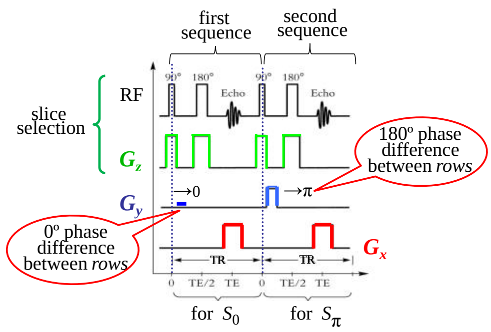
$\boldsymbol{M}(t) = \boldsymbol{m}(1,t) + \boldsymbol{m}(2,t) + \boldsymbol{m}(3,t) + \boldsymbol{m}(4,t)$



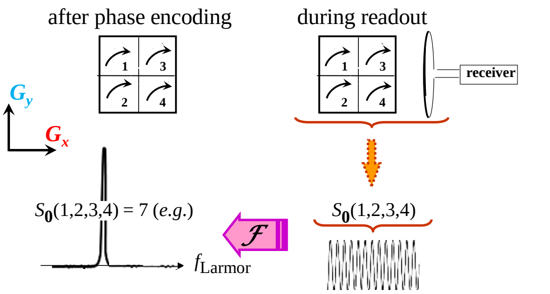
viewed from feet to head

Spin-Echo, Spin-Warp Sequence for 2×2 Matrix

involves 2 spin-echo pulse sequences

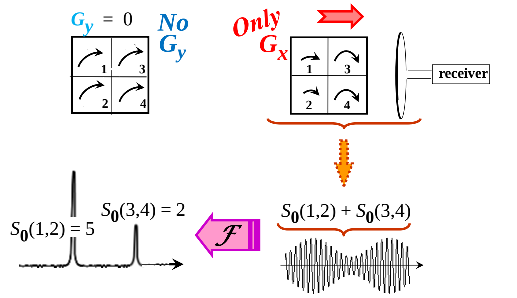


No x- or y-Gradients: $G_y = G_x = 0$



$\mathcal{F}[S_0(1,2,3,4)] \rightarrow$ $7 = m(1) + m(2) + m(3) + m(4)$

1st S-E Sequence: *x*-Gradient Only, On During Readout



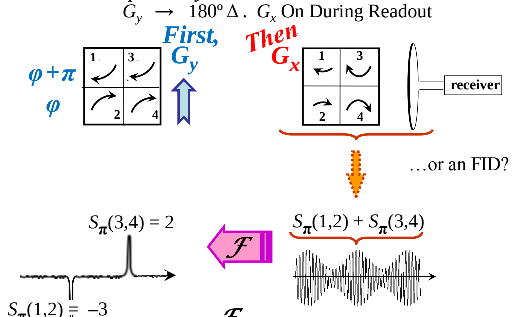
$\mathcal{F}[S_0(1,2) + S_0(3,4)]$ <

$S_0(1,2) = 5 = m(1) + m(2)$

$S_0(3,4) = 2 = m(3) + m(4)$

2nd S-E Sequence: *y*-Gradient, then *x*-Gradient

$G_y \rightarrow 180^\circ\,\Delta$. G_x On During Readout



$S_\pi(1,2) + S_\pi(3,4)$ $\mathcal{F}$ <

$S_\pi(1,2) = -3 = m(1) - m(2)$

$S_\pi(3,4) = 2 = m(3) - m(4)$

4 Equations in 4 Unknowns

in phase: add

$S_0(1,2) + S_0(3,4)$ $\mathcal{F}$ <

$S_0(1,2) = 5 = m(1) + m(2)$

$S_0(3,4) = 2 = m(3) + m(4)$

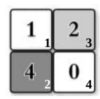
180° out of phase: subtract

$S_\pi(1,2) + S_\pi(3,4)$ $\mathcal{F}$ <

$S_\pi(1,2) = -3 = m(1) - m(2)$

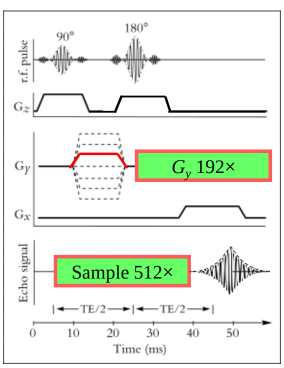
$S_\pi(3,4) = 2 = m(3) - m(4)$

Solution:
$m(1) = 1$
$m(2) = 4$
$m(3) = 2$
$m(4) = 0$



check: $S_0(1,2,3,4) \xrightarrow{\mathcal{F}} 7 = m(1) + m(2) + m(3) + m(4)$!

Spin-Echo, Spin-Warp…. (*e.g.*, 256×192 matrix)



90° pulse with G_z on selects z-plane and initiates spin-echo

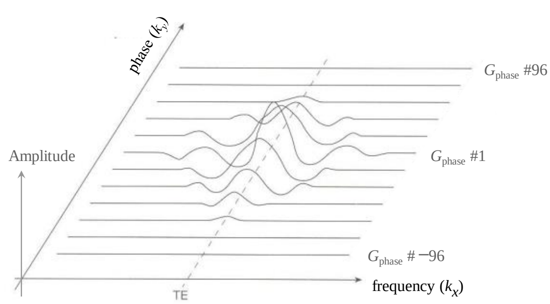
Free precession with G_y on phase-encodes y-position for current n, $G_y(n) = n \times G_y(1)$

Reading NMR signal with G_x on frequency-encodes x-position

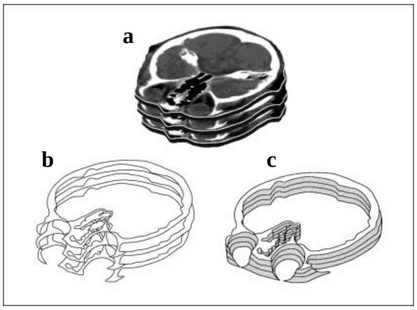
Repeat, but with $G_y(n+1)$, $n = 1, 2, \ldots, 192$

Creation of an MRI 'Image' in 2D *k*-Space

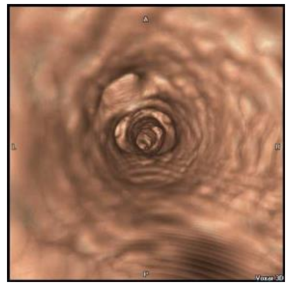
each line in *k*-space from data obtained during one M_{xy}(TE) readout; different lines for different phase-encode gradient strength



Creating a 3D Image



Interior of Bronchus



Some Important Topics Not Covered Today

Some Important Topics Not Addressed Here

2D, 3D, 4D Imaging
Inversion Recovery (STIR and FLAIR)
Fast S-E; Gradient Recovery Imaging (GRE, *e.g.*, EPI)
Dynamic Contrast-Agent Enhancement (DCE)
Magnetization Transfer
CNR and Other Quantitative Measures of Image Quality
Parallel-Coil Receive, Transmit; Shim Coils
Magnetic Resonance Angiography (MRA)
Perfusion Imaging
Diffusion Tensor Imaging (DTI)
Functional MRI (*f* MRI)
Image QA, and ACR Accreditation
MRI/PET, MRI-Elastography, MRI/DSA, MRI/US
Highly Mobile MRI (*e.g.*, for strokes)
Zero-Quantum Imaging
Artificial Intelligence Diagnosis
MRI-Guided Radiation Therapy: Tomorrow!