I Want It Now!: Advances in MRI Acquisition, Reconstruction and the Use of Priors to Enable Fast Anatomic and Physiologic Imaging to Inform Guidance and Adaptation Decisions

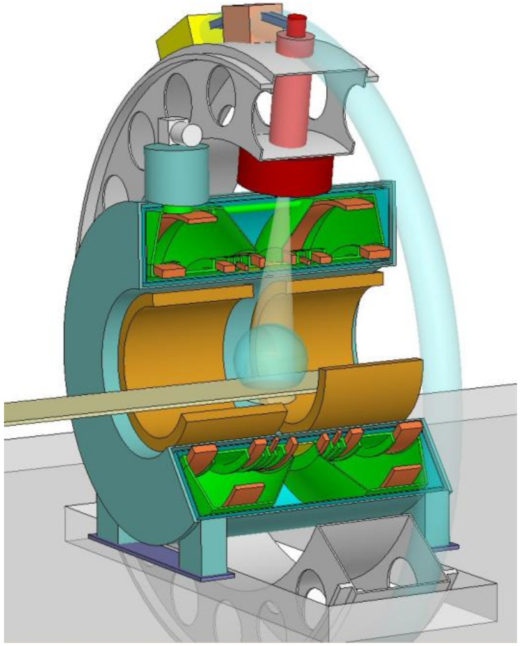
Yanle Hu

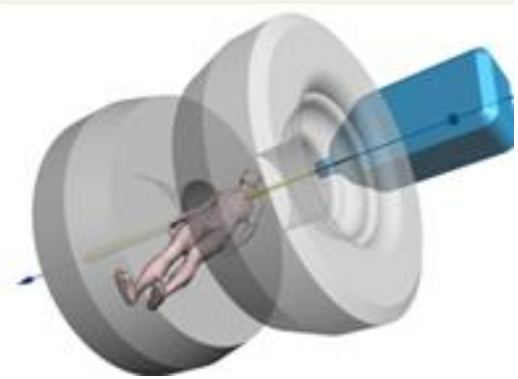
07/15/2015

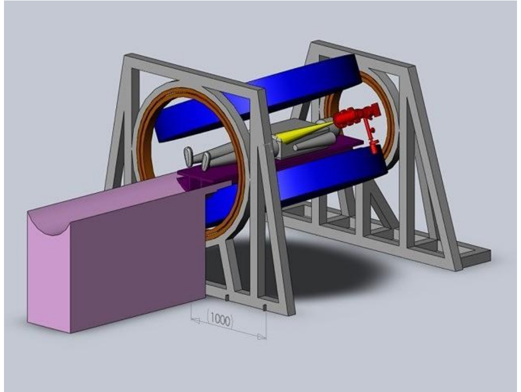
Conflict of interest: None

MR-guided radiation therapy

- **Provide real-time MR images during radiation therapy**



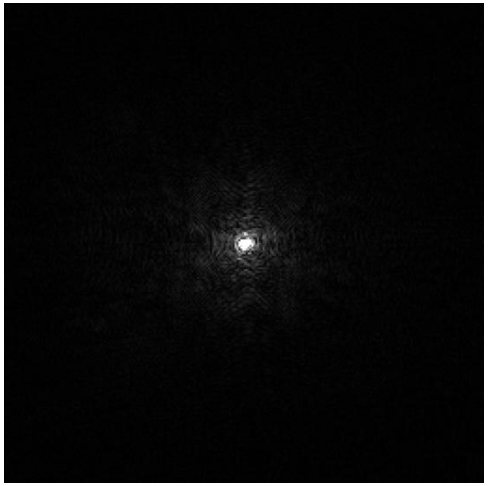




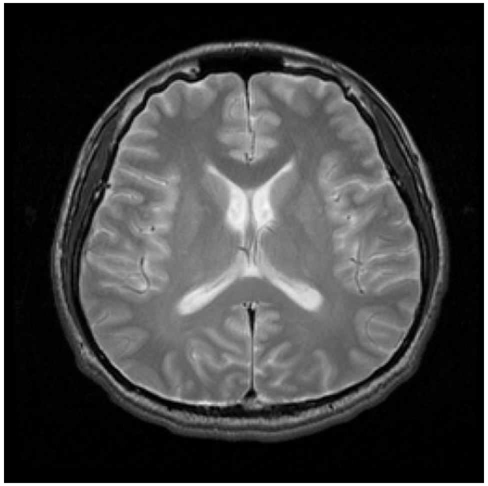
On-board MRI unit

- **Desired imaging capability**
  - Good temporal resolution for tracking and gating
  - Good spatial resolution for contouring
  - Good SNR and/or CNR
  - Functional capabilities for tumor response assessment

MRI image acquisition



$$\xrightarrow{\mathcal{F}^{-1}}$$

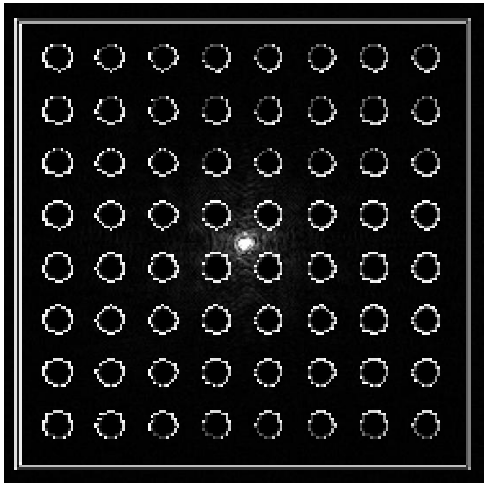


$$s(k_x, k_y, k_z) = \mathcal{F}\{m(x, y, z)\}$$

$$\hat{m}(x, y, z) = \mathcal{F}^{-1}\{s(k_z, k_y, k_z)$$

Where $k_j(t) = \frac{\gamma}{2\pi}\int_0^t G_j(\tau)d\tau \quad j = x,\ y,\ or\ z$

MRI image acquisition



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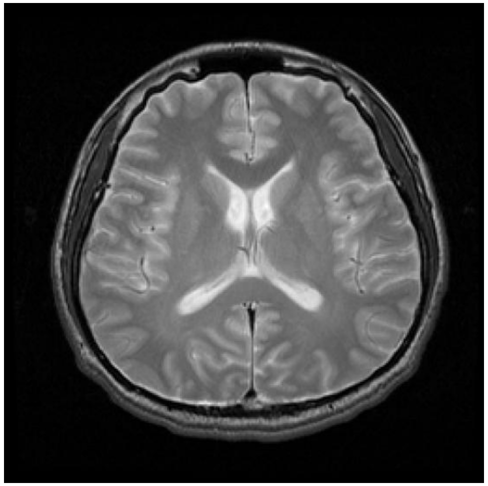

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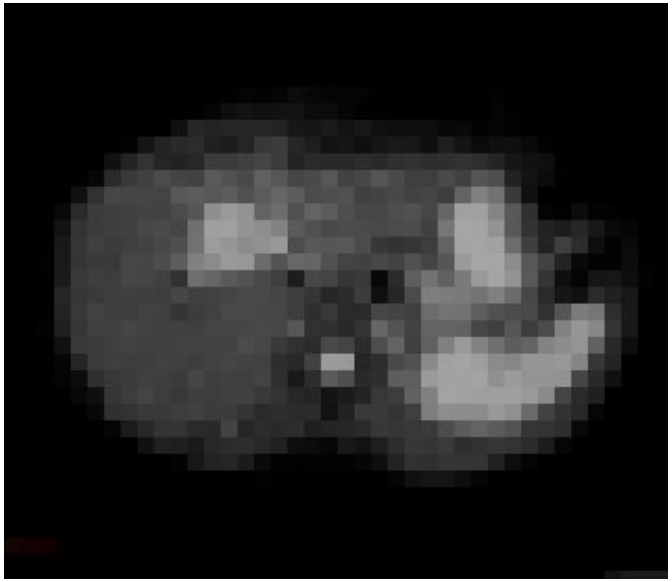
Balance between temporal and spatial resolutions

- **A tradeoff to be made for all MR-IGRT systems**
  - Tracking and gating require good temporal resolution.
  - Good temporal resolution -> Less time per frame.
  - MR data acquisition is in k-space. It depends on the range and rate of required k-space sampling.
  - Less time per frame -> smaller k-space coverage

    -> lower spatial resolution

Balance between temporal and spatial resolutions

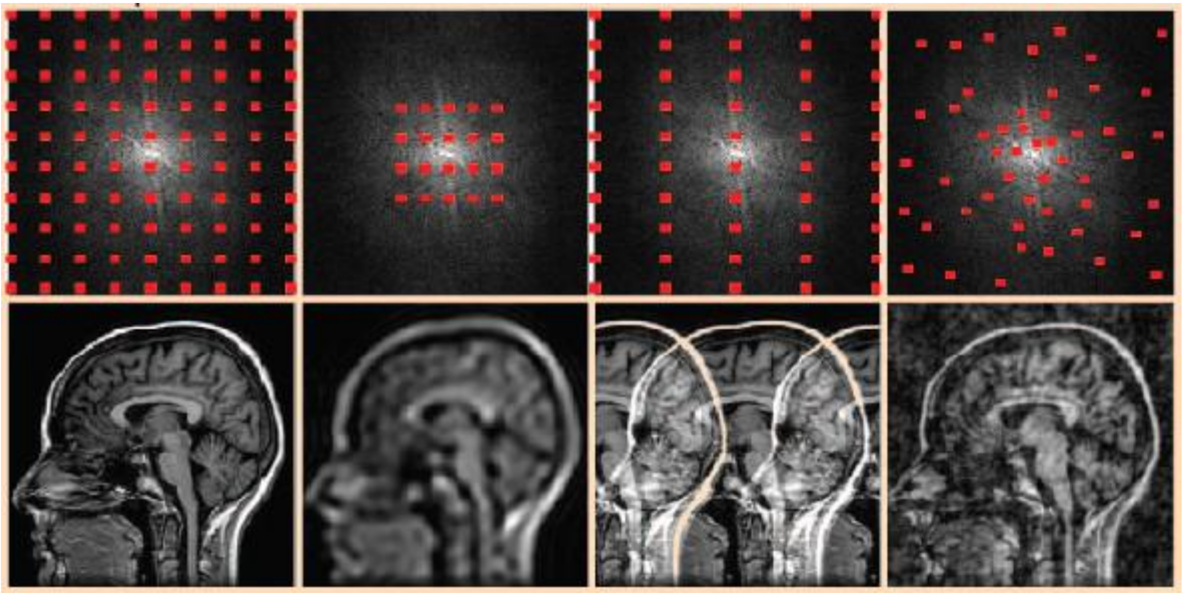


Balance between temporal and spatial resolutions

K-space under-sampling

- **Sampling a larger k-space in a given amount of time requires k-space under-sampling**
  - Only a portion of the k-space is sampled
  - Artifacts show in the reconstructed images
  - Additional algorithms are needed to remove artifacts
  - Given the same amount of time, a larger k-space is effectively covered. Good temporal and spatial resolution can be achieved simultaneously.

Balance between temporal and spatial resolutions



Lustig et al, IEEE signal processing magnizine 2008 25(2):72-82.

What is the tradeoff in the acquisition of real-time MRI images for guidance of radiation delivery?

83% A. Temporal resolution – Spatial resolution

6% B. SNR – contrast

1% C. Patient setup – patient comfort

9% D. Image distortion – image acquisition speed

1% E. Patient throughput – image acquisition speed

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A. Temporal resolution – Spatial resolution

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D. Image distortion – image acquisition speed

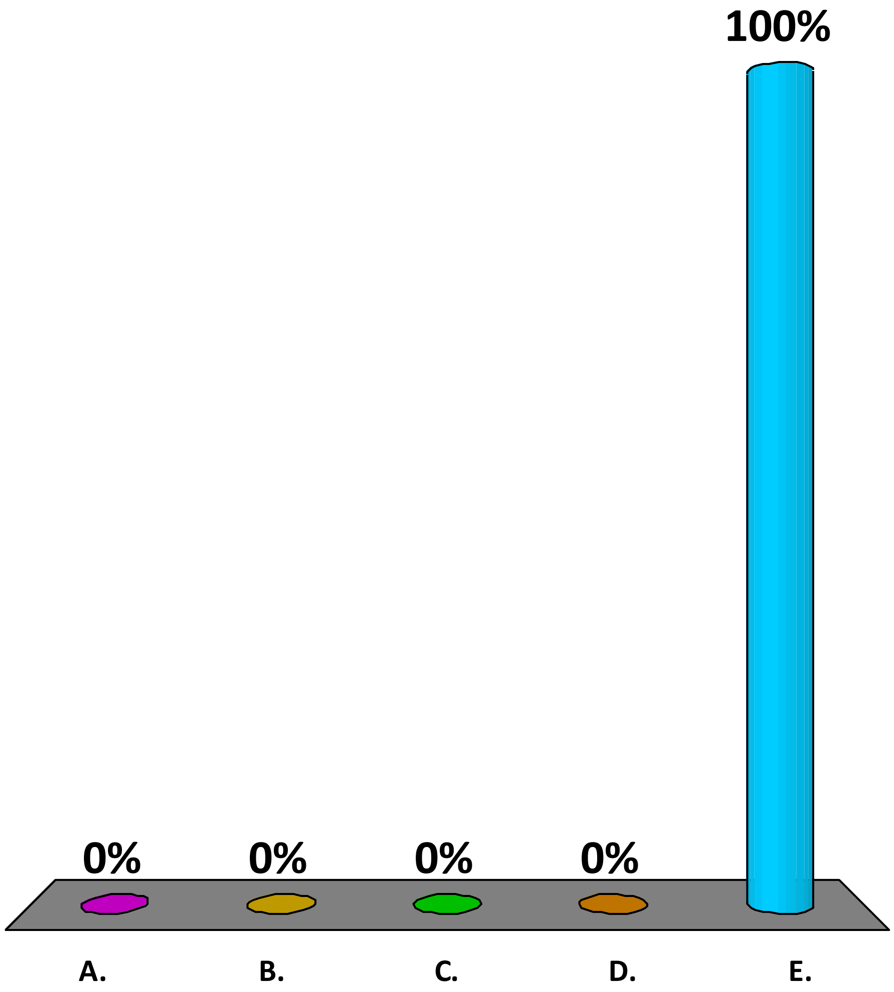
E. Patient throughput – image acquisition speed

Expedition of MRI acquisition

- **Methods to accelerate MR image acquisition**
  - Partial k-space acquisition
  - Parallel imaging
  - Compressed sensing

Which techniques can be used to expedite image acquisition?

A. Parallel imaging
B. Partial k-space acquisition
C. Compressed sensing
D. A & B
E. A, B & C



Which techniques can be used to expedite image acquisition?

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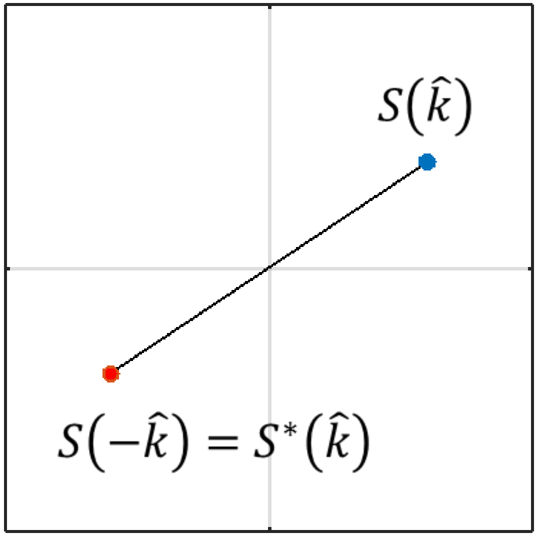
Fast MRI acquisition strategies

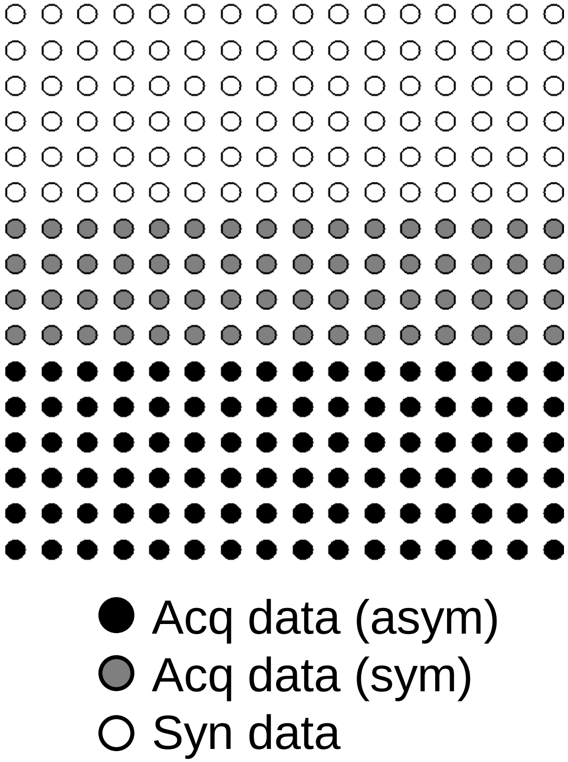
- **Partial k-space acquisition**
  - Based on conjugate symmetry
  - Spins are real in physical world

$$m(\hat{x})\ is\ real \quad \Rightarrow \quad S(-\hat{k}) = S^*(\hat{k})$$



Fast MRI acquisition strategies

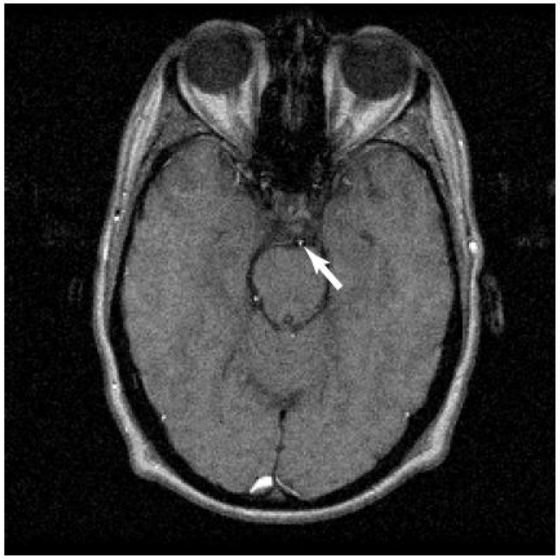
- **Partial k-space acquisition**
  - Theoretically half of k-space needs to be acquired
  - Max acceleration factor = 2
  - In reality, phase errors can void real-value assumption. phase correction is needed.



Fast MRI acquisition strategies

- **Partial k-space acquisition**

Full k-space recon



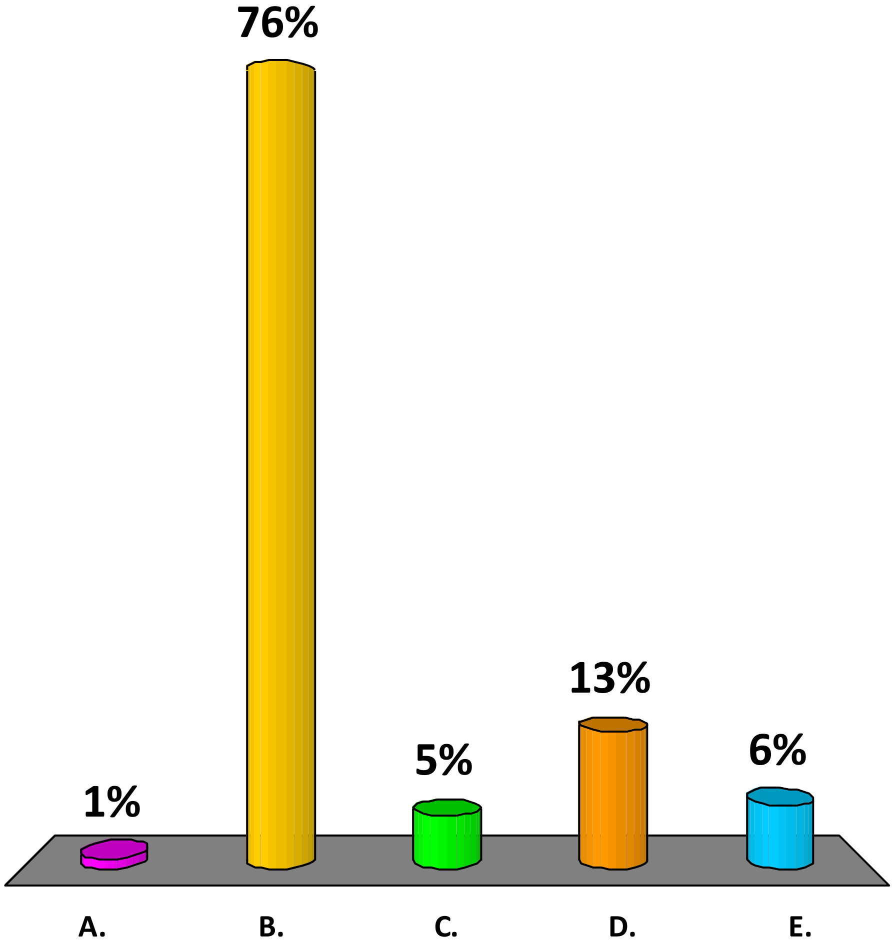
Half k-space recon (9/16)

John Pauly, Stanford University, EE369C class notes

SAMS Question

Which forms the basis of partial k-space acquisition

A. Coil sensitivity
B. Conjugate symmetry of the Fourier Transform of a real signal
C. Sparsity of a signal
D. A & C
E. None of the above



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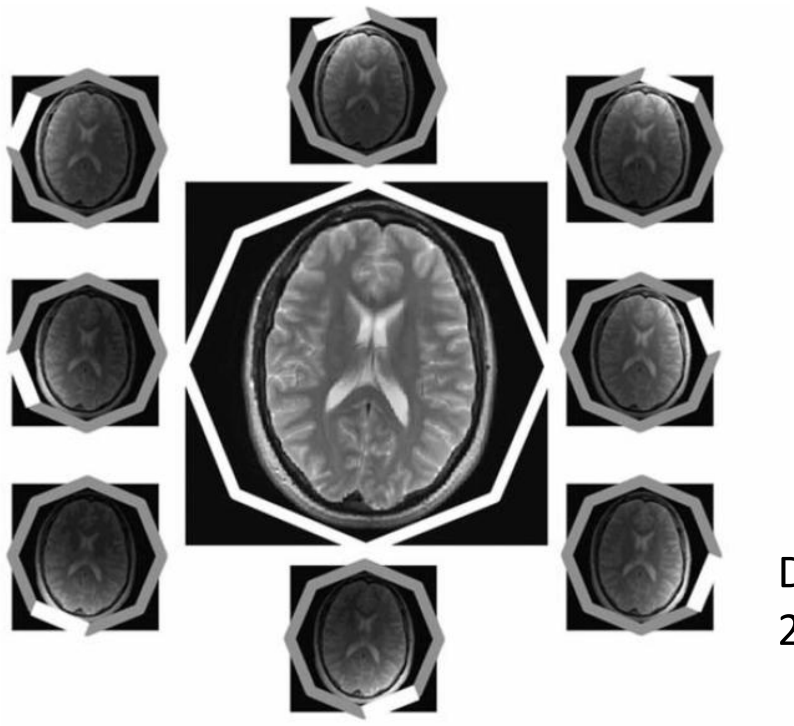
Ref: Feinberg DA, Hale JD, Watts JC, Kaufman L, Mark A. Halving MR imaging time by conjugation: demonstration at 3.5 kG. Radiology. 1986 Nov;161(2):527-31.

Fast MRI acquisition strategies

- **Parallel imaging**
  - Enabled by multi-channel receiver coil arrays



Deshmane et al. JMRI, 2012 36(1):55-72.

Fast MRI acquisition strategies

- **Parallel imaging**
  - Signal detected by the coil element is a function of distance to the coil element
  - Spins at a specific location create different signals in different coil element
  - Signal variation in coil elements can be used to get rid of artifacts.

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Fast MRI acquisition strategies

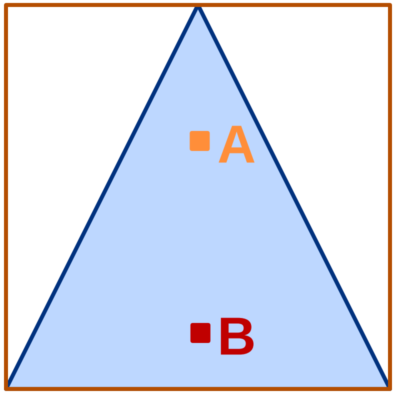
- **Parallel imaging**
  - SENSE (image space)

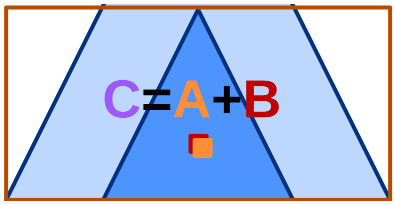
    SENSitivity Encoding
  - GRAPPA (k-space)

    Generalized Autocalibrating Partially Parallel Acquisition

Fast MRI acquisition strategies

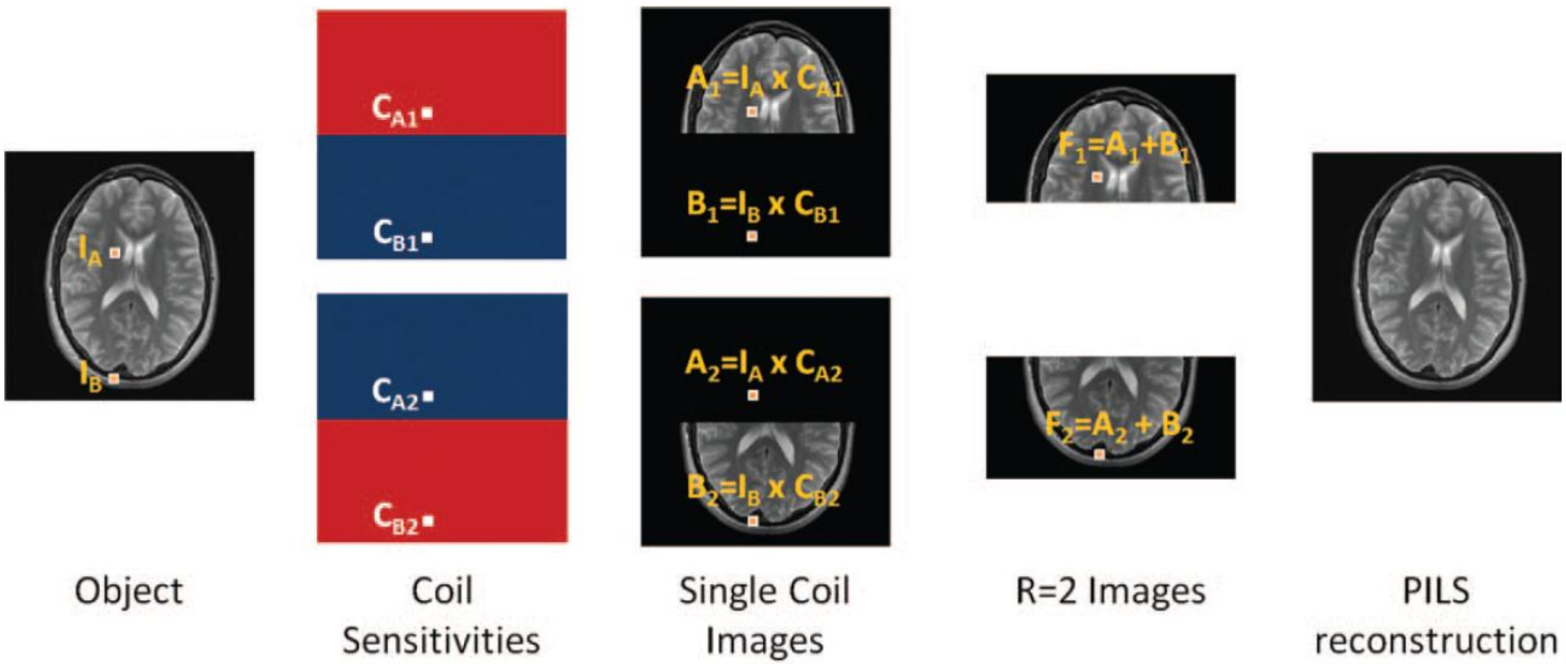
- **Parallel imaging – SENSE**





Fast MRI acquisition strategies

- **Parallel imaging – SENSE**



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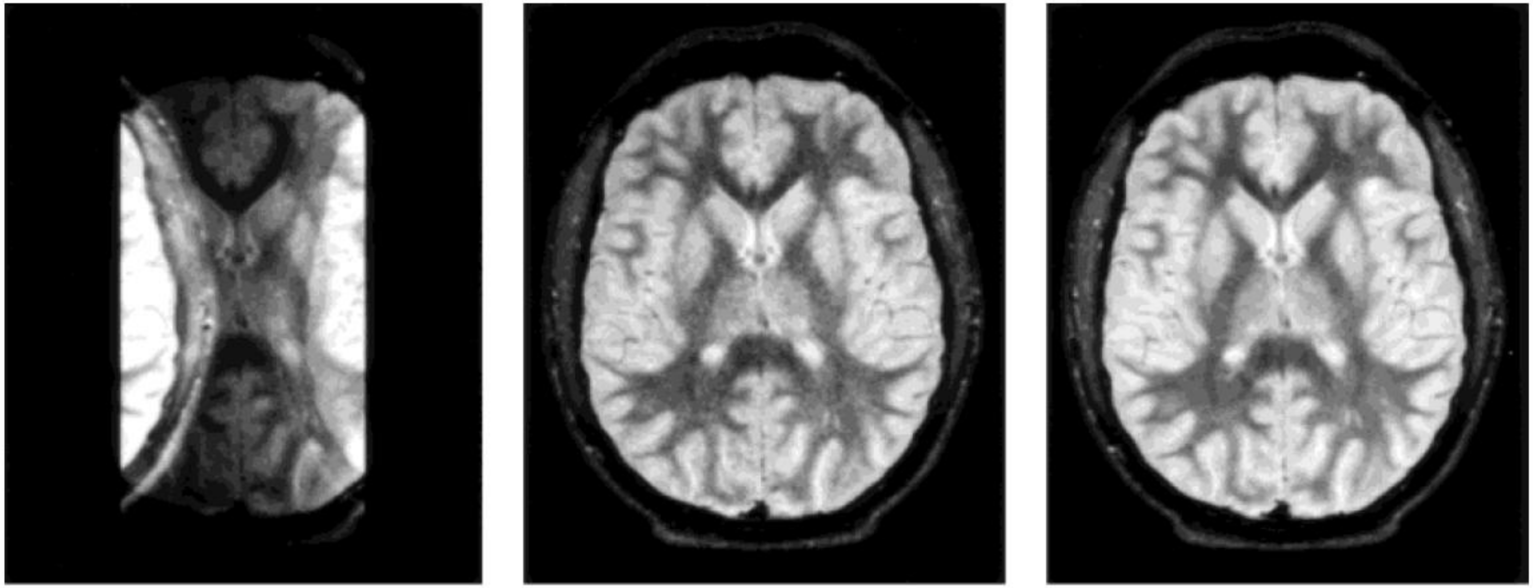
Fast MRI acquisition strategies

- **Parallel imaging – SENSE**

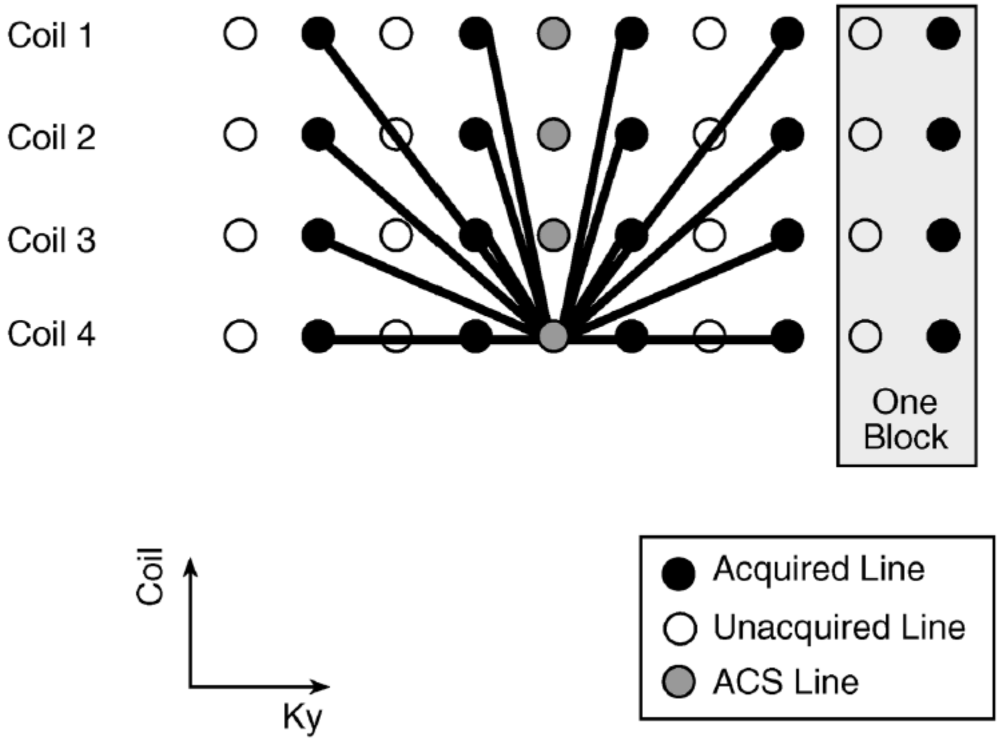


R=2, direct recon | R=2, SENSE recon | Full k-space recon

Pruessmann et al. MRM, 1999 42:952-962.

Fast MRI acquisition strategies

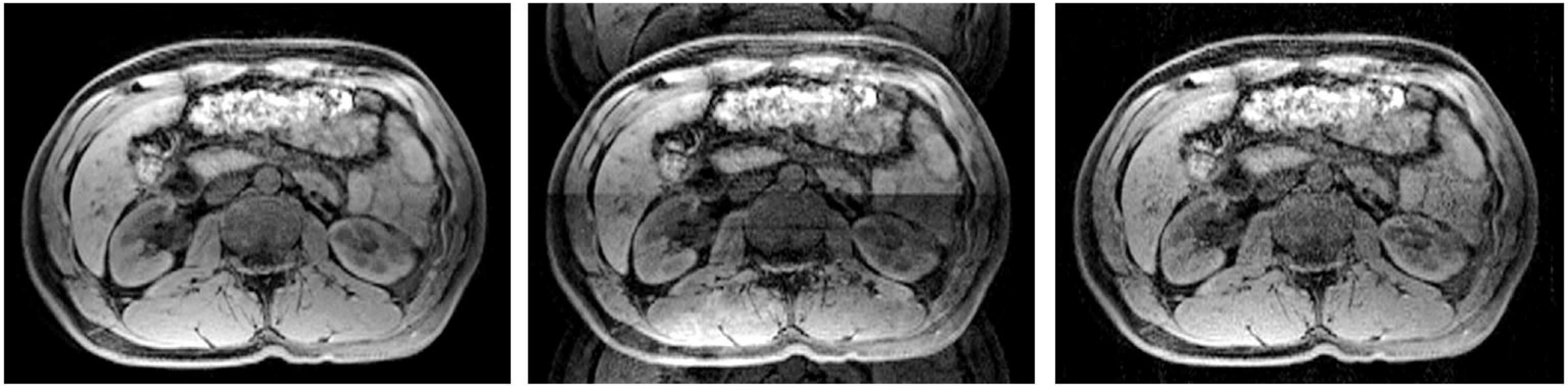
- **Parallel imaging – GRAPPA**



Griswold et al. MRM, 2002 47:1202-1210.

Fast MRI acquisition strategies

- **Parallel imaging – GRAPPA**



Full k-space recon R=2 direct recon R=2 GRAPPA recon

Griswold et al. MRM, 2002 47:1202-1210.

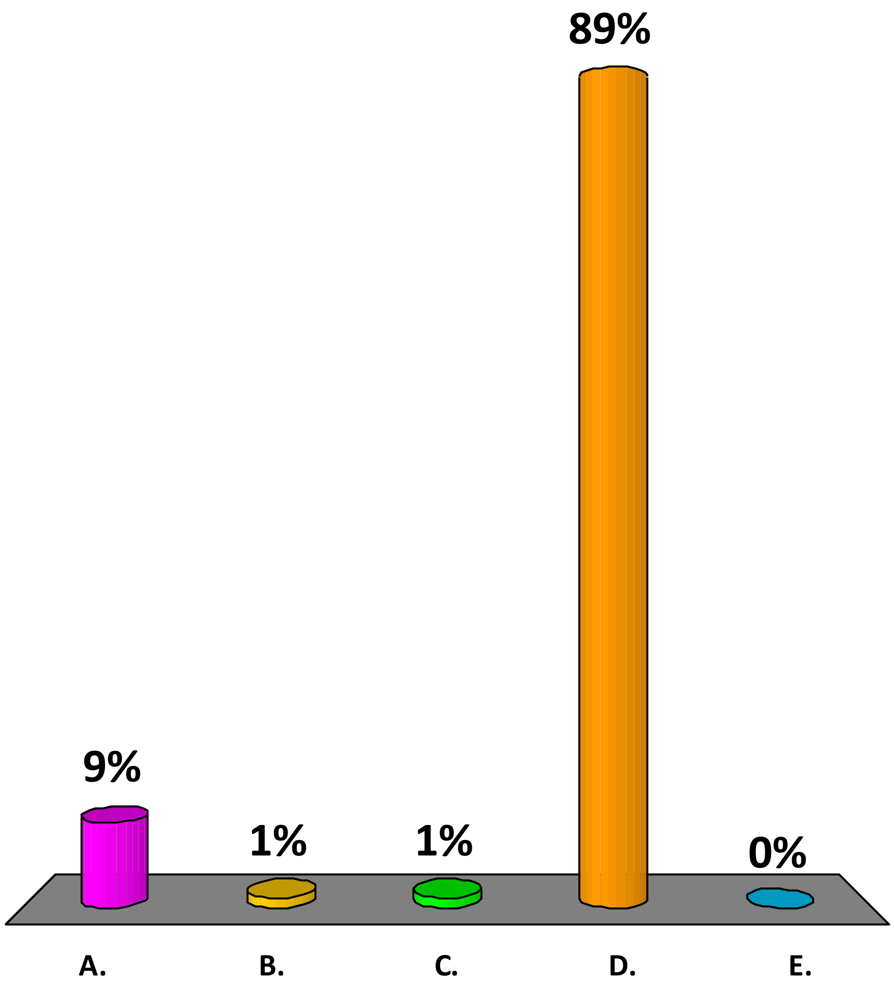
Fast MRI acquisition strategies

- **Parallel imaging – limitation**
  - Theoretical maximum acceleration factor = number of coil elements in the multi-channel coil arrays
  - Methods won't work if there are no sensitivity variation
  - Additional SNR drop due to geometric factor

SAMS Question

Which of the following coils enables the capability of parallel imaging?

A. Transmit/receive head coil
B. Body coil
C. Single channel surface coil
D. Multi-channel receiver coil arrays
E. None of the above



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Fast MRI acquisition strategies

- **Compressed sensing**
  - Natural images can often be compressed with little or no perceptible loss of information
  - Transform-based compression has been adopted in standards like JPEG and MPEG
  - Most MR images are sparse in an appropriate transform domain
  - Sparsity exists in not only still MR images but also dynamic MR images.

Fast MRI acquisition strategies

- **Compressed sensing**
  - Examples of sparsifying transforms
    - Finite difference
    - Discrete Cosine transform (JPEG)
    - Discrete wavelet transform (JPEG-2000)

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Fast MRI acquisition strategies

- **Compressed sensing**
  - Image reconstruction is to solve the constrained optimization problem

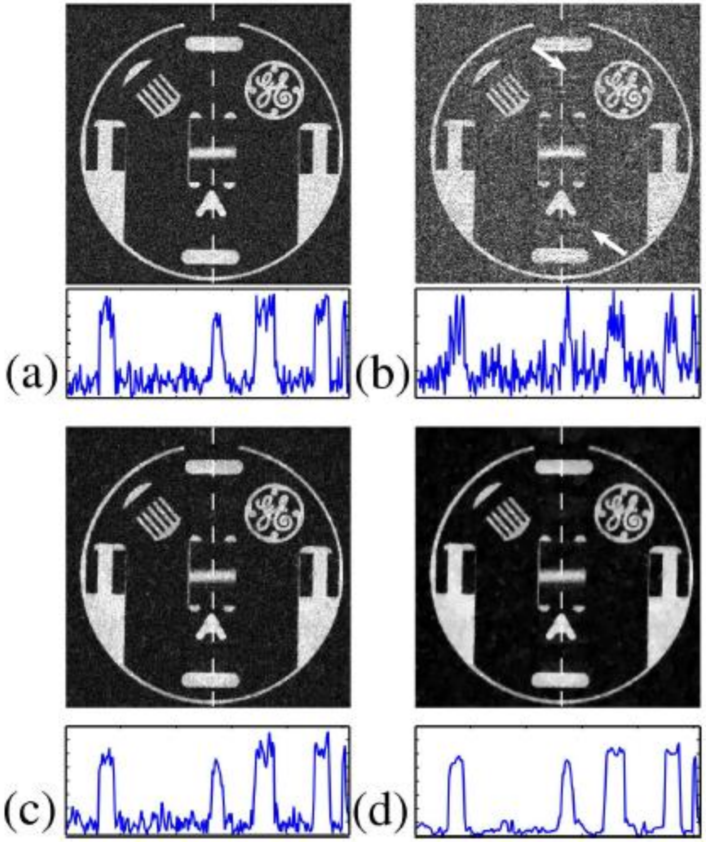
$$\begin{aligned} &\mathit{minimize} && \|\Psi m\|_1 \\ &s.t. && \|\mathcal{F}m - S\|_2 < \mathcal{E} \end{aligned}$$

  - Ψ sparsity can be traded with finite difference sparsity

$$\begin{aligned} &\mathit{minimize} && \|\Psi m\|_1 + \lambda TV(m) \\ &s.t. && \|\mathcal{F}m - S\|_2 < \mathcal{E} \end{aligned}$$

Fast MRI acquisition strategies

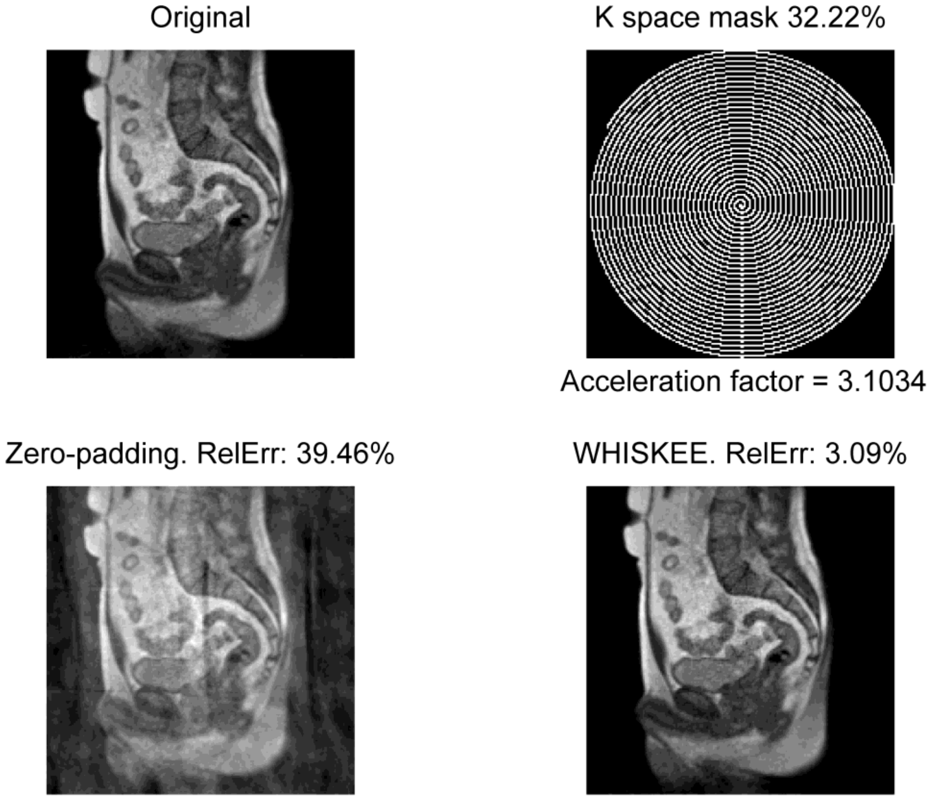
- **Compressed sensing**



Lustig et al, MRM, 2007 58(6):1182-95.

Fast MRI acquisition strategies

- **Compressed sensing**



SAMS Question

Which of the following statements is true regarding compressed sensing?

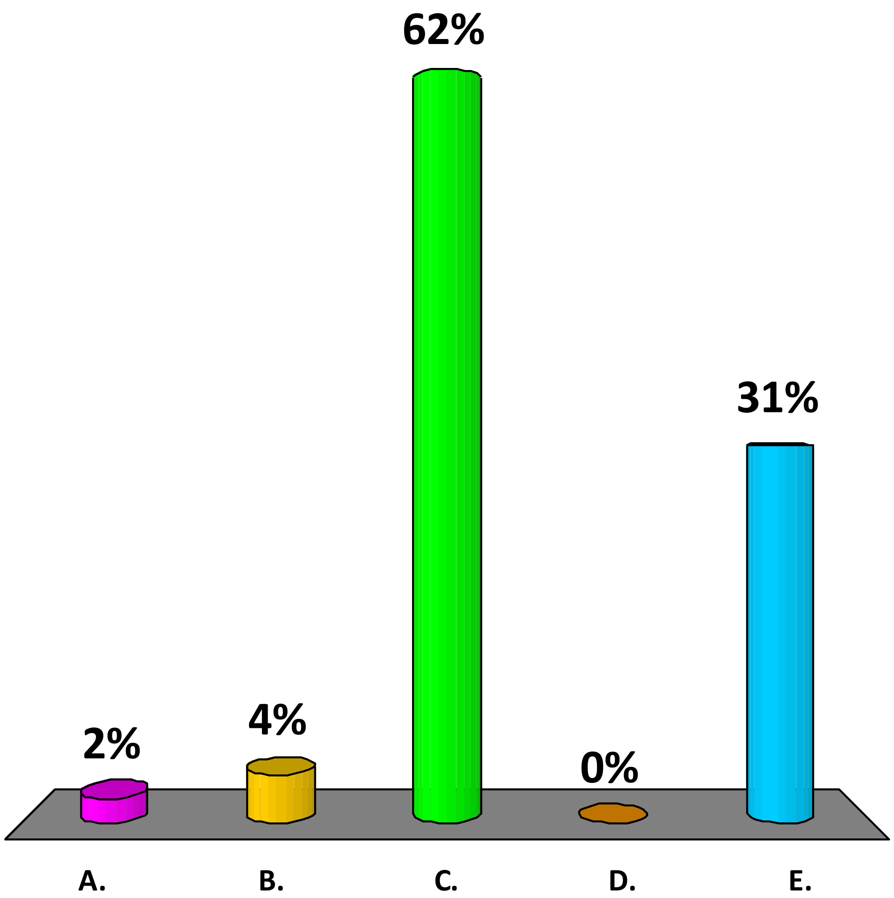
A. It requires multi-channel phase array coil

B. It is always accompanied by SNR drop

C. It exploits the sparsity which is implicit in MR images

D. It is widely available for clinical usage

E. All of the above



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SAMS Question

Among the techniques to expedite image acquisition, which one CAN NOT have a acceleration factor of above 2?

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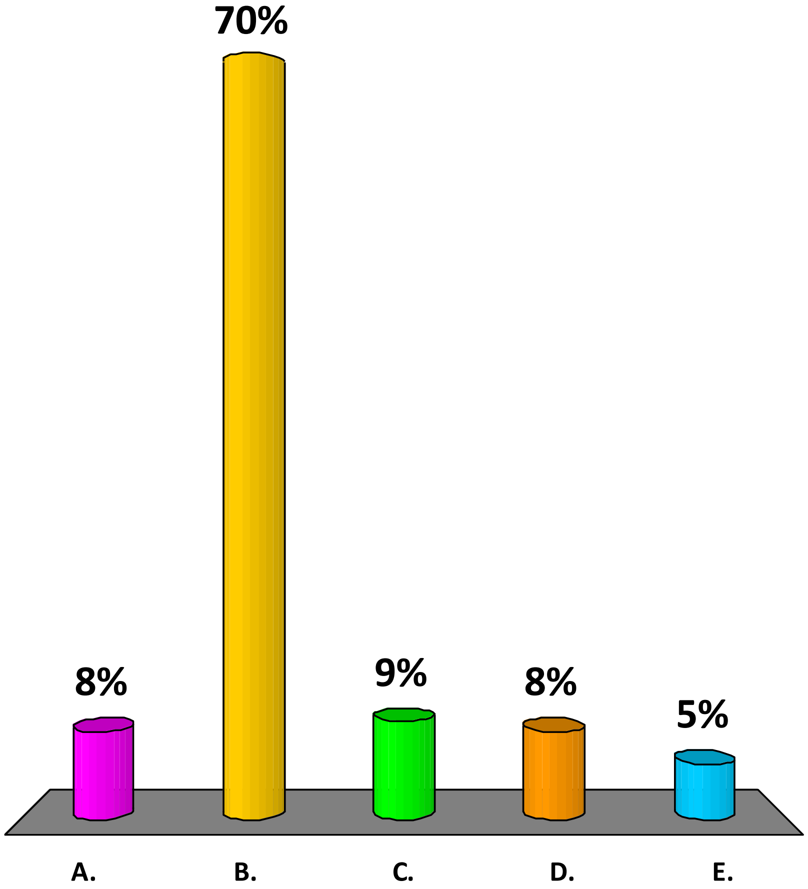

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