Adaptive Acquisition in Real-Time Cardiac MRI

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Cardiac MRI : Applications and Challenges

Applications :

1. Vascular disease and tissue characterization
   a. Visualization of coronary arteries
   b. Coronary plaque characterization
2. Functional assessment of the ventricles
3. Myocardial dynamics, perfusion, and viability
4. Valvular function

➔ Needs :

- Higher spatial resolution in 3D
- Higher temporal resolution
- Imaging without breathholding
- Real-time
- Spectroscopic, diffusion imaging

Grand Challenge : 4D (5-6D?!) cardiac imaging

Cardiac MRI : Problems & “Solutions”

Problems :

- Insufficient MR data acquisition speed for Nyquist sampling
- Difficult to account for two distinct motion processes :
  - ➢ Heartbeat ➢ Respiration

Approaches:

- Faster data acquisition sequences ➔ limited speed-ups:
  - – Hardware (gradients, field strength)
  - – Energy deposition and peripheral nervous stimulation
  - – MR physics
- Cardio-respiratory gating ➔ time-averaged snapshots; long
- Breathholding ➔ patient cooperation; limited time-window
- Reduced data acquisition methods (Keyhole, Rigr, Dime, etc.)

Overview

Aim:

- Produce a real-time, time-resolved cardiac cine
  - No breath holding
  - No cardio-respiratory gating

Approach:

- **Model-based, minimum-redundancy**

To Model or Not to Model?

- The truth, only the truth, and all the truth.
- But, a finite number of k-t space samples tells nothing at all!

- Dynamic Imaging is an ill-posed inverse problem
- Modeling in dynamic imaging is unavoidable
- Everyone models -- whether they admit it or not

Rules for Safe® Modeling

- Don’t overdo
- Be explicit
- Analyze robustness to deviation from modeling assumptions
- Learn model from the imaged subject data

Overview

Aim:

Produce a time-resolved cardiac cine without breathholding or cardio-respiratory gating

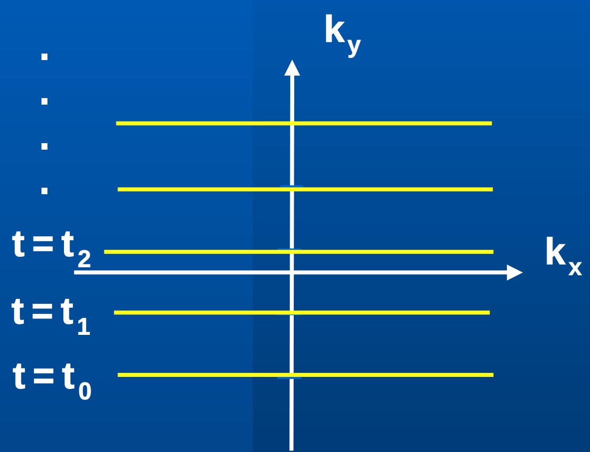
Approach:

A. Use spatio-temporal (2D+t, 3D+t) formulation
B. Model both respiratory and cardiac motion
C. Adapt model to imaged subject
D. Adapt MR data acquisition to model
E. Tailor reconstruction to A - D

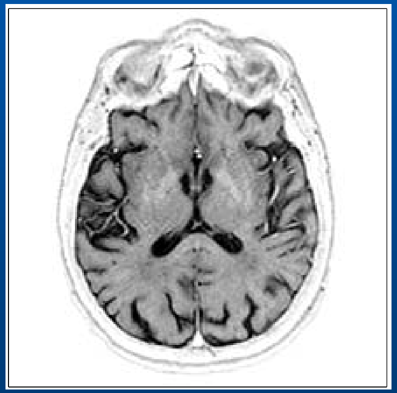
MR Imaging (Cartesian) and TSS

Imaging Equation : $$s(\mathbf{k}(t)) = \int_{FOV} I(\mathbf{r},t)\, e^{-i\mathbf{k}(t)\cdot\mathbf{r}}\, d\mathbf{r}$$

MR Data ⟷ Spatial Fourier Transform ⟷ Object



Spatial Fourier Transform ⟷

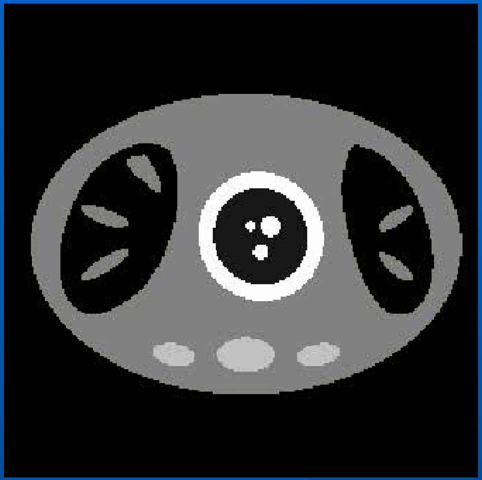


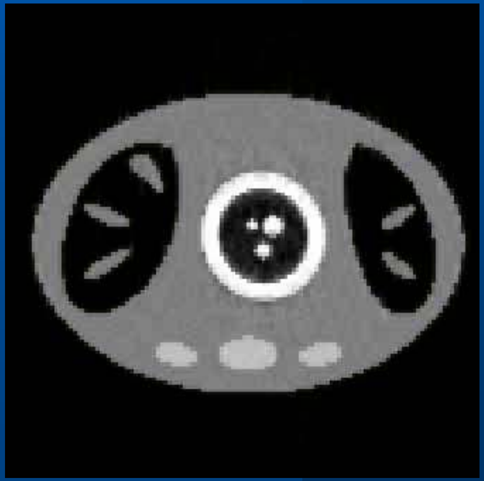
k- space sampling

MR image
(static object)

Time-Sequential (TS) Constraint :
Only 1 k-space line can be acquired at a time

MR Imaging : Dynamic Object





Conventional Imaging
(T_R=2ms)

Desired image size = 128*128
Max. temporal frequency = 10 Hz
→ Nyquist sampling rate = 2560 lines/s
i.e. $T_R \approx 0.4$ ms

- Artifacts are due to temporal undersampling
- Correct mathematical formulation is in the spatio-temporal domain
  - Objects are functions in (**r**,t) domain
  - Sampling occurs in (**k**,t) domain
  - Sampling can be analyzed in the dual (**r**,f) domain
- For unique reconstruction, object I(**r**,t) must be restricted to a model class, $\mathcal{M}$

Dynamic Imaging: Definition

➢ **Given a class $\mathcal{M}$ of spatio-temporal signals $g(y,t) \in \mathcal{M}$ with :**

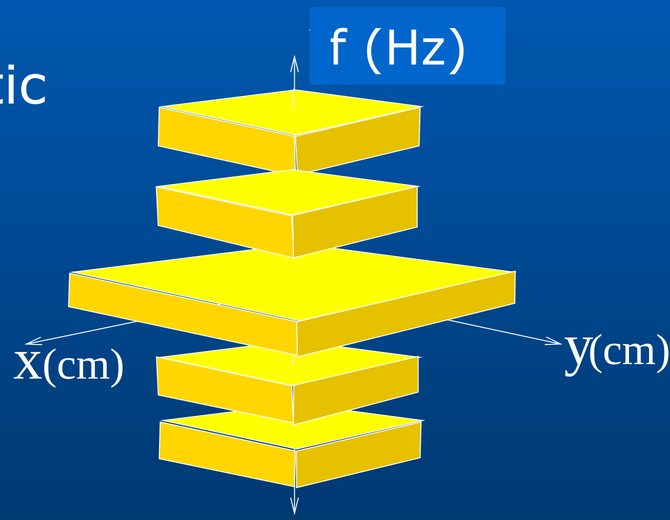
- **Spatial ROI : $\{y \in \mathcal{S}\}$ & Temporal ROI : $\{t \in \mathcal{T}\}$**
- **Dual k-t (D-k-t) Support (essential) :** $\mathcal{B} = \mathrm{supp}\left\{ \int_{\mathcal{S}} \int_{\mathcal{T}} g(y,t)\, e^{-j2\pi(k_y y + ft)}\, dy\,dt \right\}$

➢ **Find a sampling schedule $\Psi = \{k_n, t_n\}$ so that $\{g(y,t), y \in \mathcal{S}, t \in \mathcal{T}\}$ is recoverable from the corresponding samples.**

Cardiac Image models (Phenomenological)

Characteristics :

- The (highly) dynamic portion of the object (i.e heart) is spatially localized within the field-of-view.
- The cardiac motion is quasi-periodic
- Even with breathhold thorax is not static



Model :

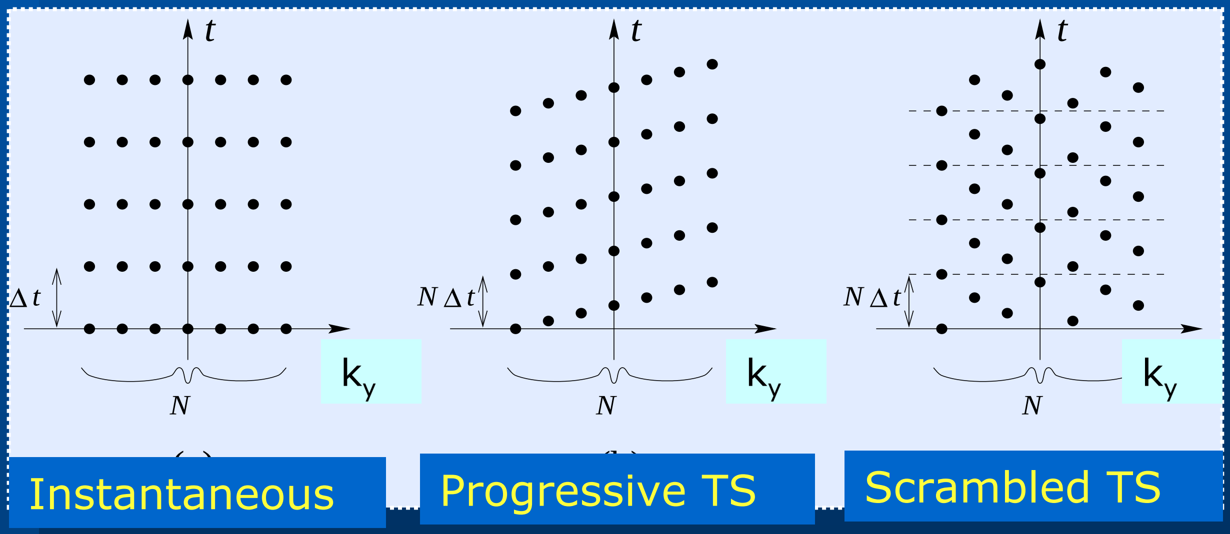
Object to be imaged : $I(\mathbf{r},t)$

Spatio-temporal spectrum : $I(\mathbf{r},f)=\int I(\mathbf{r},t)e^{-i2\pi f t}dt$

Dual k-t (D-k-t) support : $\mathcal{B} \triangleq \mathrm{supp}\{I(\mathbf{r},f)\}$

TSS Problem

Given model class (= D-k-t support) find a time-sequential sampling schedule from which I(r,t) can be reconstructed to prescribed resolution.



TSS Problem

Questions :

- Design of sampling schedule Ψ?
- Conditions on sampling rate ?
- Reconstruction from acquired samples ?

Properties :

- Aliasing in TSS determined not only by density of points (sampling rate) in Ψ, but also by the temporal order in which points are visited [Allebach,1987]
- Order of acquisition need not be determined by the adjacency of k-space sample locations
- Optimization of Ψ is a very difficult combinatorial problem. Need to explore 256! possible orderings for 256 sample locations.
- Solution: Unified TSS theory (Willis & Bresler, IEEE Trans. IT,1997)

Time-Sequential Sampling Theory

TSS Theory (Willis & Bresler, 1992, 1997)

Key Idea : Consider TSS schedules that lie on a lattice

Results:

- Sampling pattern design through constrained geometric packing of $\mathcal{B}$, $\mathcal{S}$.
- Reconstruction of g(y,t) through linear filtering
- Bounds on achievable TS sampling rates

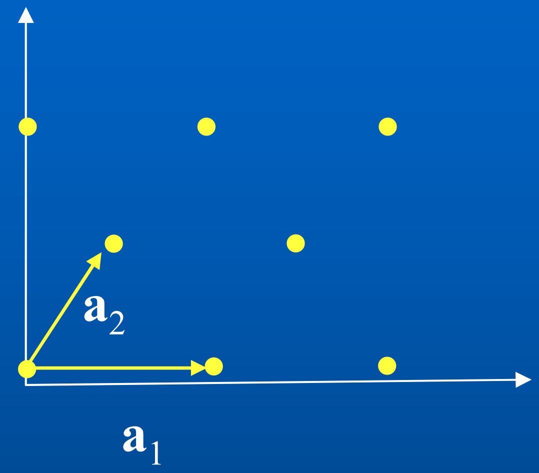
- In practice, sampling rate reduced by large factor compared to conventional sampling schemes

Lattice Theory

Lattice : A lattice Λ_A is the set :

$$\Lambda_{\mathbf{A}} = \{\sum_{i=1}^{n} m_i \mathbf{a}_i : m_i \in \mathbb{Z}\}$$

where $\mathbf{a}_i$ (in $\mathbb{R}^n$) are linearly independent



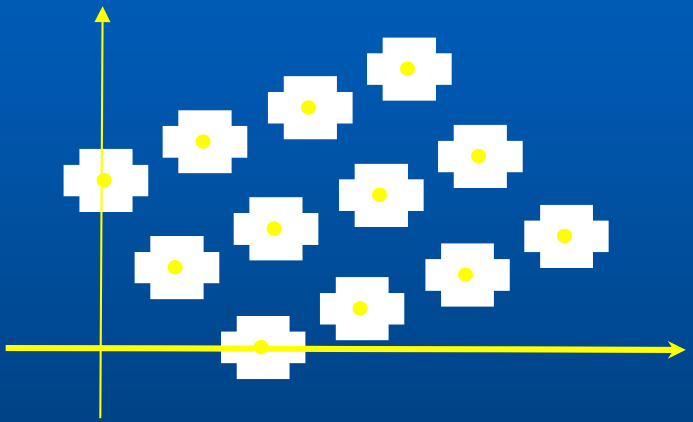
Basis Matrix : A basis matrix of Λ_A is $A = [a_1, a_2, \ldots]$

Fact : Every (rational) lattice has a basis matrix of the form $\mathbf{A} = \begin{pmatrix} D & s \\ 0 & T_R \end{pmatrix}$

Polar Lattice : The polar lattice of a lattice Λ_A is a lattice Λ_{A*} with basis matrix $A^* = A^{-T}$

Multidimensional Sampling Theory

Fact : If signal *g* is sampled on lattice Λ_A then it's spectrum is replicated in the frequency domain on the polar lattice Λ_{A*}



→ Signal *g* can be recovered from it's samples iff the replicas do not overlap

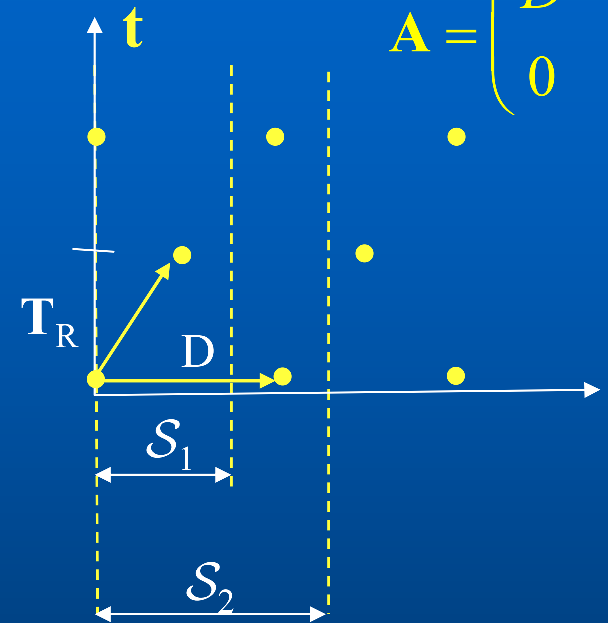
→ Lattice Λ_{A*} *packs* the spectral support $\mathcal{B}$ of *g*

Notation : $\Lambda_A \varepsilon \mathcal{R}(\mathcal{B})$

Time-Sequential Sampling on a Lattice

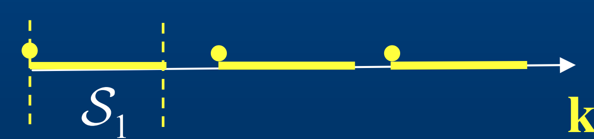
$$\mathbf{A} = \begin{pmatrix} D & s \\ 0 & T_R \end{pmatrix}$$

If sample points (k_n, t_n) are chosen to lie on a lattice Λ_A, in general, the time-sequential constraint will not be met.



However there may be *only one sample point in* $\mathcal{S}$ at any given sampling time instant, i.e Λ_A is time-sequential w.r.t. $\mathcal{S}$

Notation : $\Lambda_A \ \varepsilon \ \mathcal{T}(\mathcal{S})$



Result : $\Lambda_A \ \varepsilon \ \mathcal{T}(\mathcal{S})$ if lattice spanned by D (i.e. Λ_D), packs $\mathcal{S}$

$$\Lambda_D + \mathcal{S}_1$$

Sampling Schedule Design

Find : Lattice sampling schedule $\Lambda_A = \{k_n, t_n\}_n$ such that :

1. Any signal in $\mathcal{M}$ can be recovered from the samples
2. Schedule is time-sequential and temporally uniform w.r.t $\mathcal{S}$ (with time period T_R),
3. T_R is maximized

Solution:

$$\arg\max T_R$$
$$\mathbf{A} = \begin{pmatrix} D & s \\ 0 & T_R \end{pmatrix}; \Lambda_{\mathbf{A}} \in \mathcal{R}(\mathcal{B}) \cap \mathcal{T}(\mathcal{S}) \cap \mathcal{U}(\mathcal{S})$$

Solution computed by searching for lattices subject to the “dual” packing constraints :

1. **Λ_{A^*} packs the dual k-t support $\mathcal{B}$**
2. **$(\Lambda_D , \mathcal{S})$ tiles $\mathbb{R}$**

Reconstruction and Results

Reconstruction method :

Filter the samples with filter with frequency response $H\left(y, f_t\right) = \chi_{\mathcal{B}}\left(y, f\right)$

Performance bounds for TSS :

$$\text{Speed Gain factor} = \text{G} = \frac{\text{T}_{\text{opt}}}{\text{T}_{\text{prog}}} \leq \frac{volume(bounding\ box(\mathcal{B}))}{volume(\mathcal{B})}$$

$$T_R(\Lambda, \mathcal{S}) \leq \frac{1}{d(\Lambda_{crit}(\mathcal{B})) \cdot volume(\mathcal{S})} \leq \frac{1}{volume(\mathcal{B}) \cdot volume(\mathcal{S})}$$

Asymptotically and in practice – for optimum schedule :

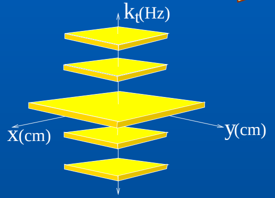
- Bounds achievable
- No penalty for restriction to lattice patterns !
- No penalty for time-sequential constraint !

Adaptive Imaging Scheme

Pre-Imaging

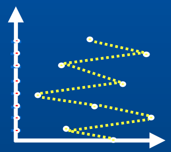
Pilot-scan Acquisition → Spectral Analysis

Dual-k-t support



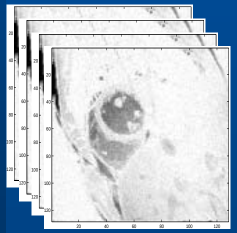
Adaptation of TS Sampling Pattern

TS Sampling pattern



Imaging Acquisition

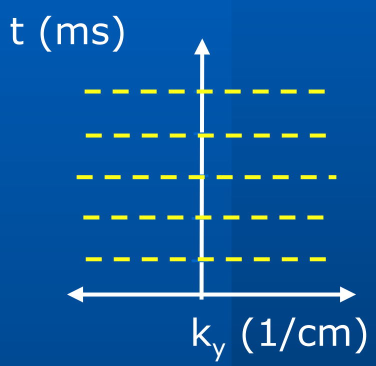
→ Image Reconstruction → cine



A. Pre-imaging Acquisition

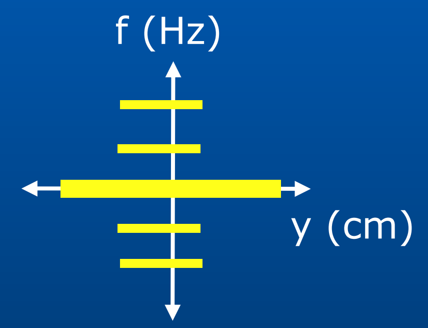
Aim : estimate the D-k-t support

Method : For each k_x …



$I(k_x,k_y,t)$

Spectral Analysis



Support of $I(k_x,y,k_t)$

k_x – phase-encode
k_y - readout

$$\mathcal{B} = \bigcup_{k_x} supp\{I(k_x, y, k_t)\}$$

- **Acquisition of D-k-t support is easy!**

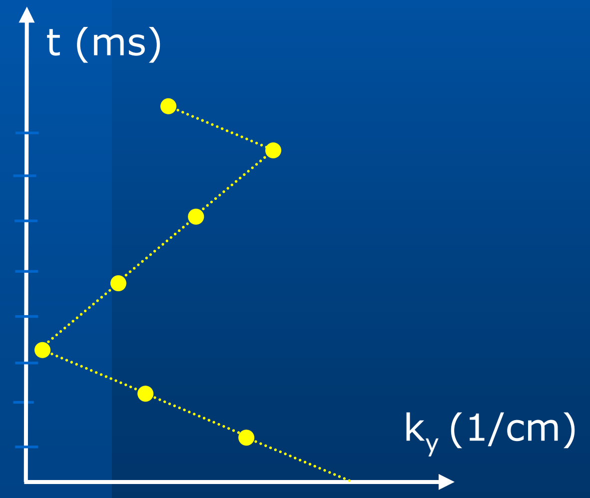
B. Adptation of TS Imaging

Given :

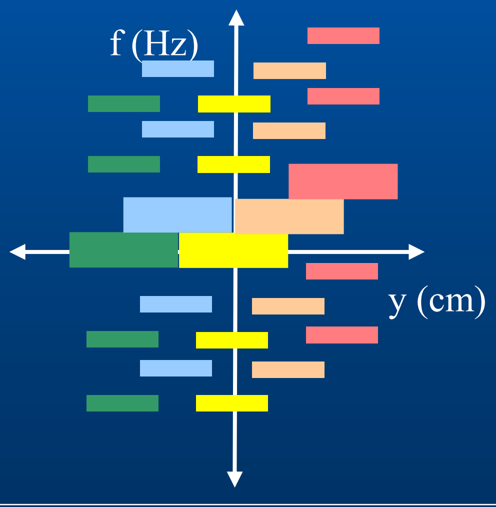
- D-k-t support $\mathcal{B}$
- Desired spatial resolution (k_{max})

Find :

Minimum rate TS sampling pattern $\Psi = \{k(n), nT_R\}_n$ from which I(r,t) can be reconstructed



Lattice TS Sampling Pattern



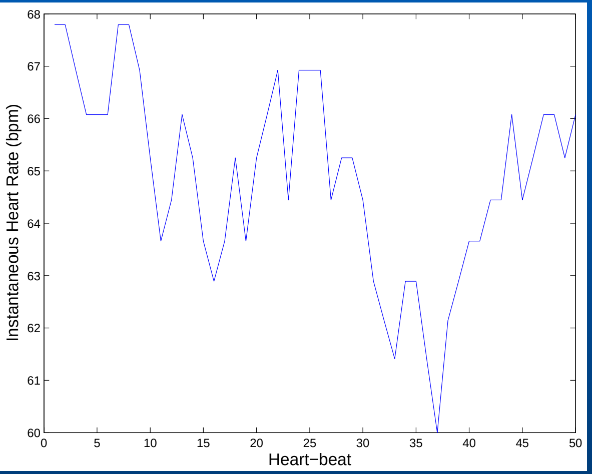
Lattice Packing of $\mathcal{B}$ Subject to TSS Constraint

MRI Experiment

Object: Gel phantom moved by a stepping motor.

Motion:

- Driven by phase of ECG. HRV = 63-68 BPM
- Fundamental frequency scaled to about 0.2Hz



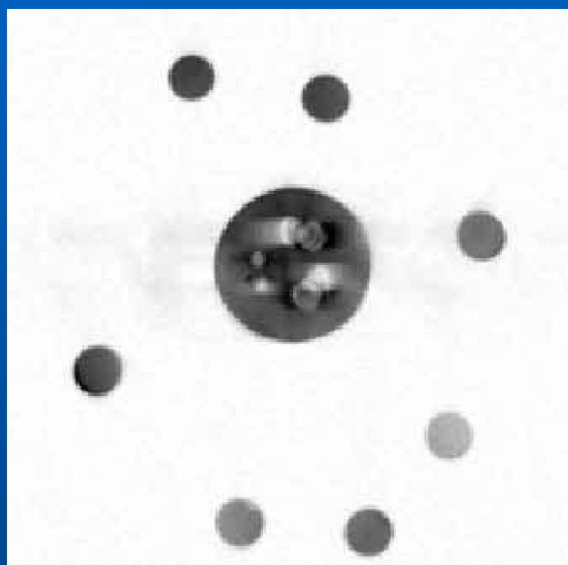
STS Model:

- 10 harmonics, bandwidth 1/20 f_0
- Nyquist sampling period = 1ms

Acquisition: VARIAN/SISCO 4.7T imaging spectrometer

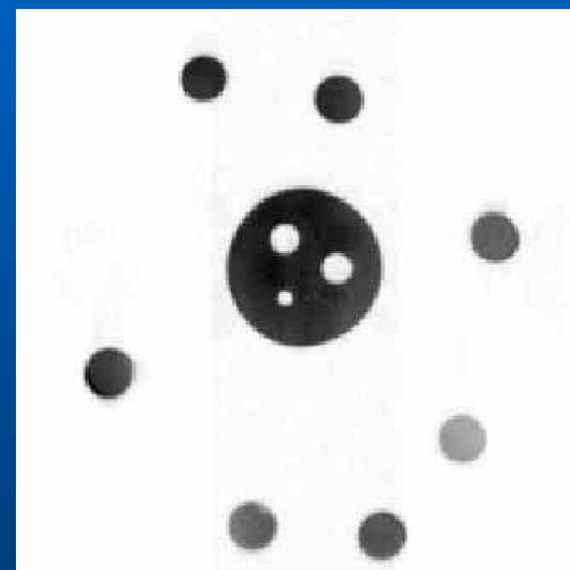
- 146 sec acquisition interval (29 “heart beats”)
- TSS Acquisition: Tr= 17.8 ms
- Progressive Acquisition: Tr=8 ms

Experimental Result



Progressive sampling

(Tr=8 ms)



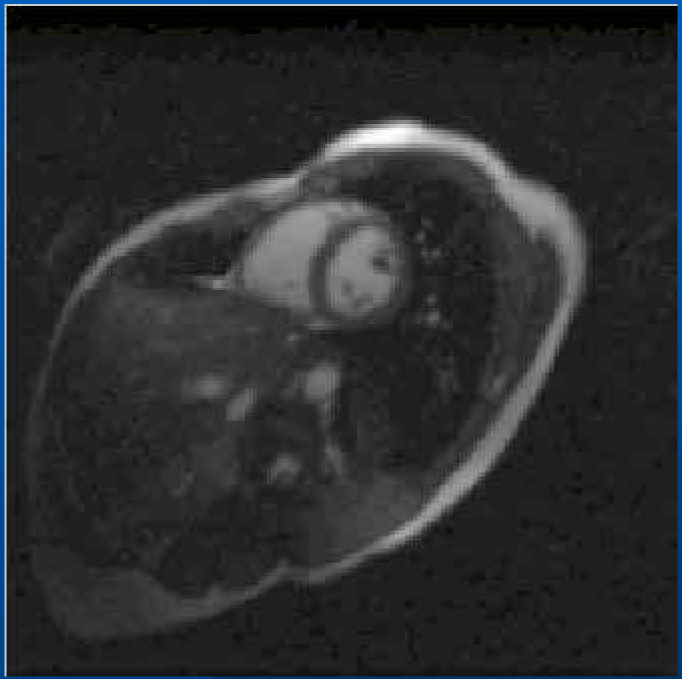
TS Lattice Sampling

(Tr=18 ms)

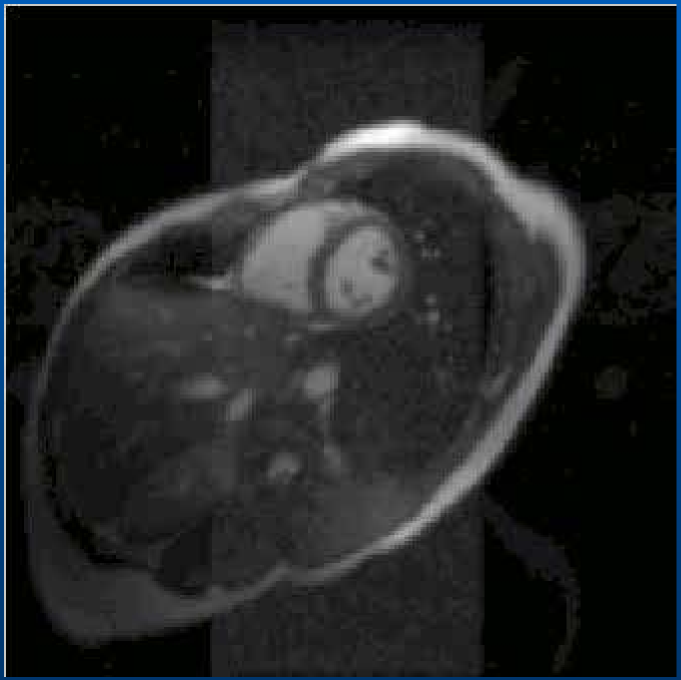
Resolution: 256 x 256 (0.4x0.4 mm)

In Vivo MR Experiment (Preliminary)

Ungated Acquisition



Conventional Imaging
(T_R=3.5ms)

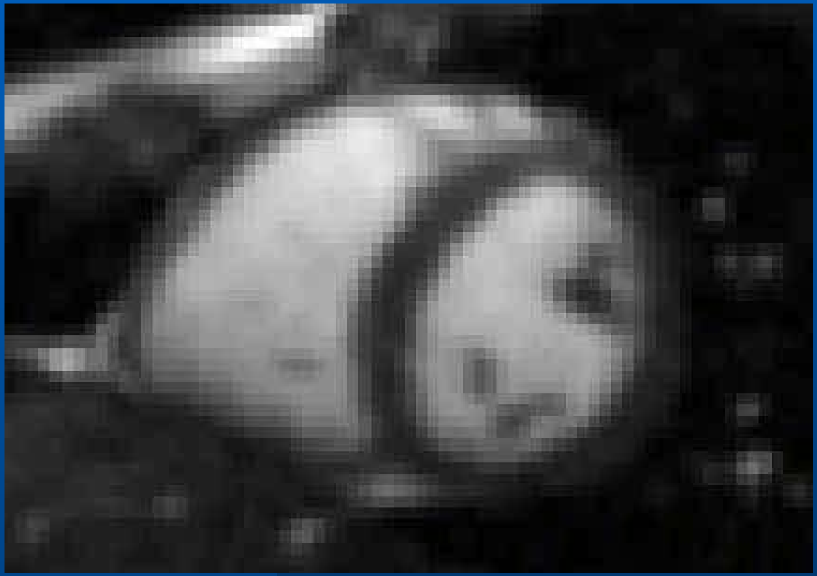


Time-Sequential Imaging
(T_R=3.5ms)

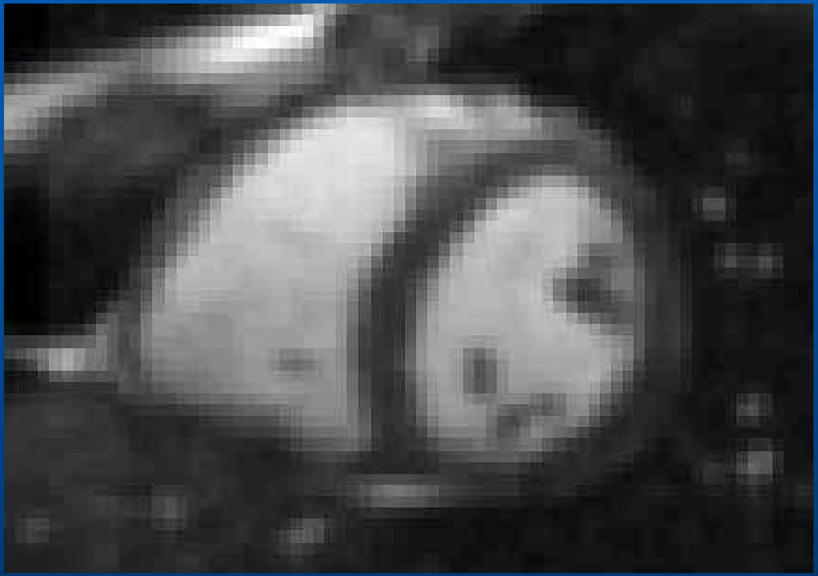
$(T_R^{\mathrm{Nyq}} \approx 0.7\,\mathrm{ms})$

In Vivo MR Experiment (Preliminary)

- Ungated Acquisition



Conventional Imaging
(T_R=3.5ms)



Time-Sequential Imaging
(T_R=3.5ms)

$(T_R^{\mathrm{Nyq}} \approx 0.7\,\mathrm{ms})$

Discussion

- Imaging scheme compatible with:
  - Cartesian (Zhao *et al* 2001, Bresler 2002, Aggarwal *et al* 2002), radial k-space sampling (*Willis & Bresler, 1995*)
  - 3D
- Reconstruction method :
  - Filtering with interpolating LSI filter (ibid)
  - Fitting of a parametric spatio-temporal model (Zhao *et al* 2002)
- Lattice optimality criterion can be modified to consider :
  - T_R,
  - SNR or CNR,
  - Hardware or physiological constraints

Respiratory Motion

Effect of Respiratory Motion: Analysis

- **Model as smooth spatial co-ordinate warp:**

$$G(y,t) = I(\Delta(y,t),t) \approx I(y,t) + \frac{\partial I(y,t)}{\partial y}\Delta(y,t)$$

$$G(y,f) \approx I(y,f) + \frac{\partial I(y,f)}{\partial y} \otimes_f \Delta(y,f)$$

- **Δ(·,t) lowpass (respiratory drift in breathhold) :**

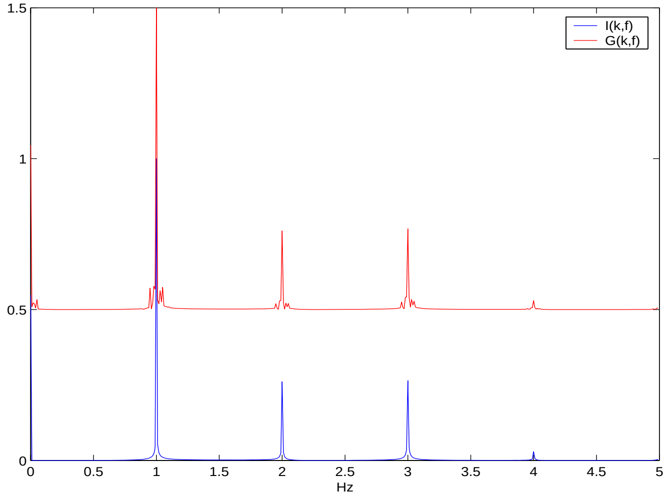
  ➔ broadening of temporal harmonic bands around nf_0

- **Δ(·,t) periodic (free-breathing)**

  ➔ creation of new (temporal) spectral bands around nf_0+mf_m

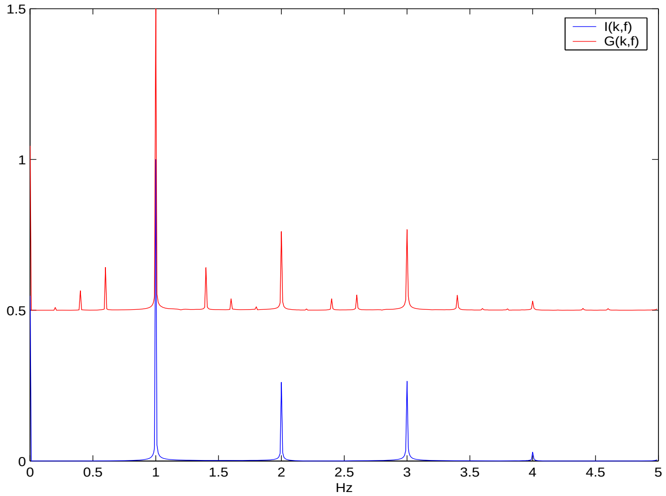
f_0: fundamental frequency of cardiac motion ; f_m: fundamental frequency of respiratory motion

Effect of Respiratory Motion: Confirmation



$I(k_y^0, f)$ and $G(k_y^0, f)$

for low-pass Δ(f)



$I(k_y^0, f)$ and $G(k_y^0, f)$

for periodic Δ(f)

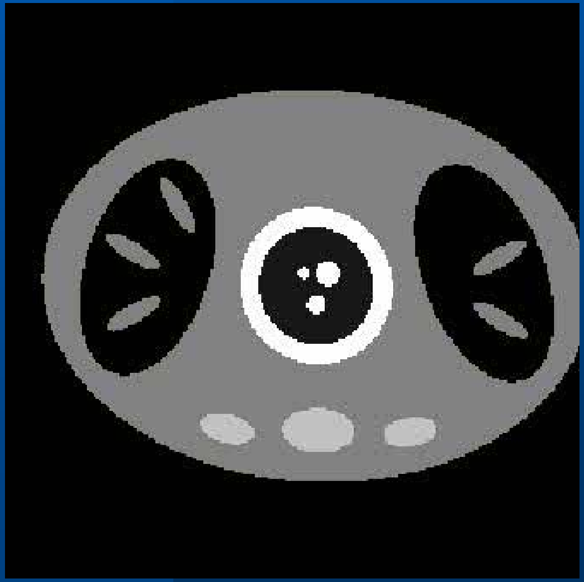
Effect on TS Imaging

Respiratory motion increases the D-k-t support

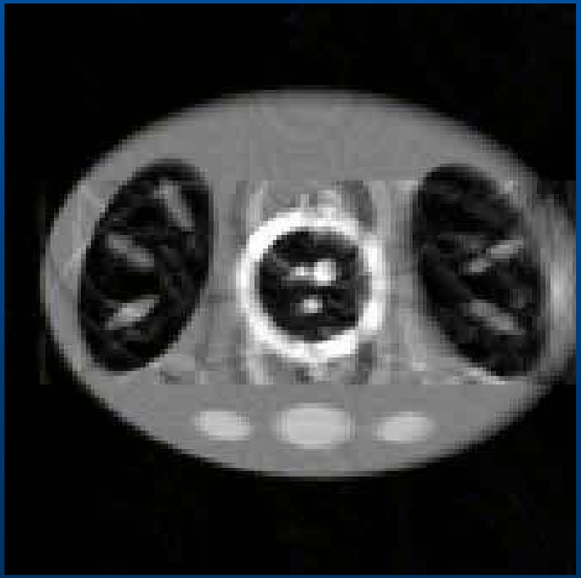
→ Required sampling rate increases

-- OR --

→ Respiratory motion artifacts created



Ground Truth



Uncorrected TS Imaging

Affine Respiratory Motion Model

$$G(\mathrm{r},t) = I[\,\mathrm{P}(t)\mathrm{r} + q(t), t\,]$$

G(r,t) : Actual cardiac time-varying image

I(r,t) : Respiration-free cardiac image
Modeled by D-k-t Model

$\mathrm{P}(t) \in \mathbb{R}^{3\times 3}$: Time-varying scaling and rotation matrix

$q(t) \in \mathbb{R}^{3\times 1}$: Time-varying displacement vector

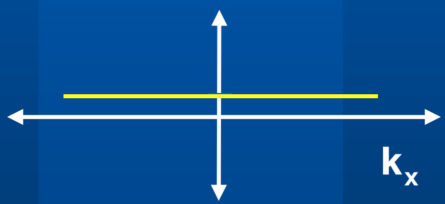
Properties :

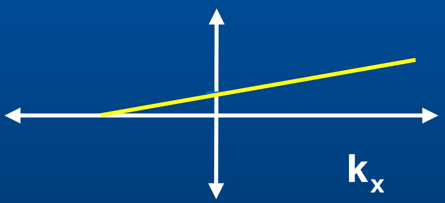
- Dominates respiratory motion of heart walls, arteries and adjoining tissue
- Subsumes translation, expansion and rotation

Affine Corrected Sampling Pattern

- Measurement Equation : $G(k,t) = \frac{1}{|P(t)|} e^{j2\pi k^T q(t)} I[P^{-T}(t)k,t]$
- Reconstruction Equation :

$$I(k,t) = \overbrace{|P(t)|}^{\text{Amplitude Correction}} \bullet \overbrace{e^{-j2\pi k^T q(t)}}^{\text{Phase Correction}} \bullet G[P^T(t)k,t]$$



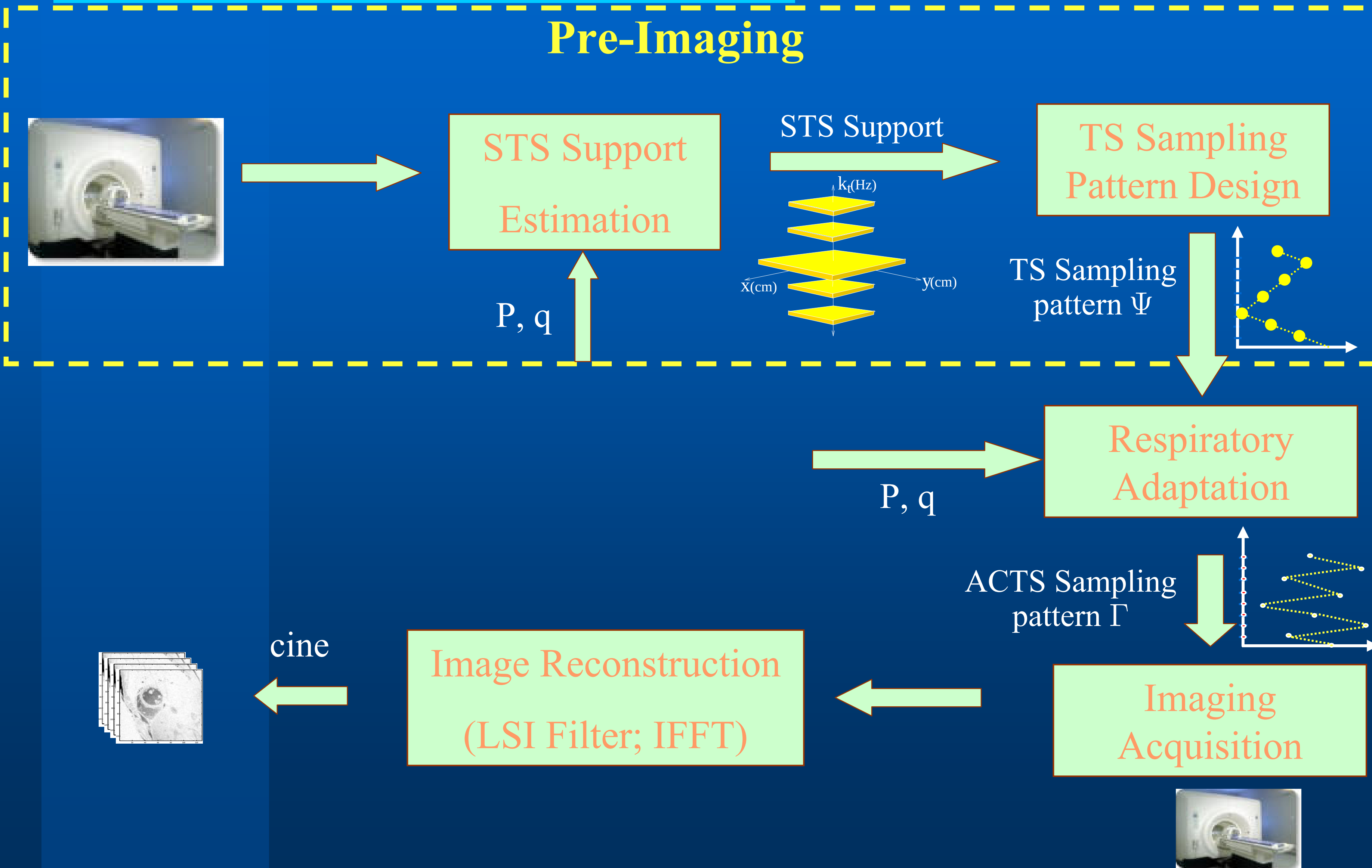


- I(r,t) can be reconstructed from samples at $\Psi = \{k^{TS}(n), nT_R\}_n$

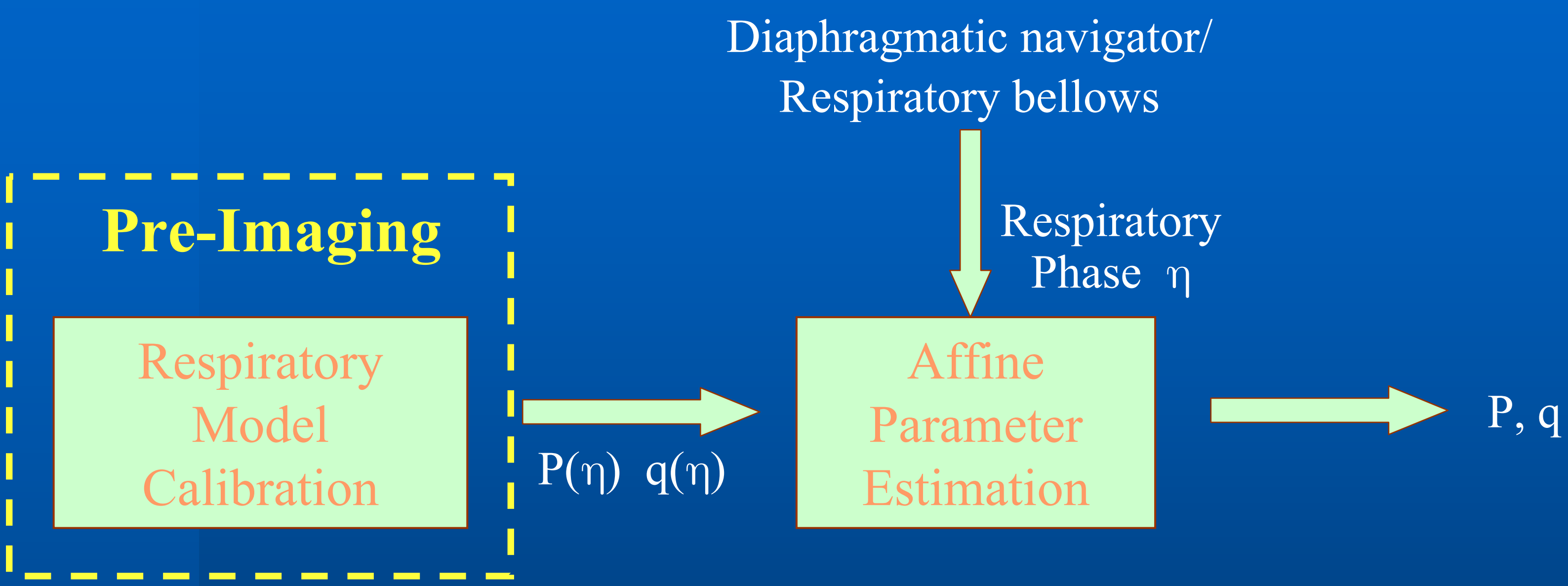
➔ I(r,t) can be reconstructed from samples of G(k,t) at

$$\Gamma = \{P^T(nT_R)k^{TS}(n), nT_R\}_n$$

Imaging Scheme



Estimation of Affine Motion



Respiratory Model Calibration [Manke:2002]:

Estimate the subject-specific relationship between affine motion parameters (P,q) and the respiratory phase η

Simulation : Affine Respiratory Motion

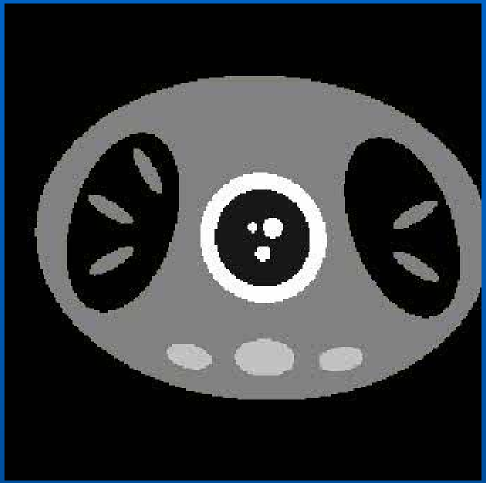
Simulation Parameters :

- Respiratory Motion : Affine[†]
- Respiratory rate = 16 breaths/min
- Cardiac rate = 60 beats/min
- Optimal T_R = 7.1 ms
- Total acquisition time = 30s

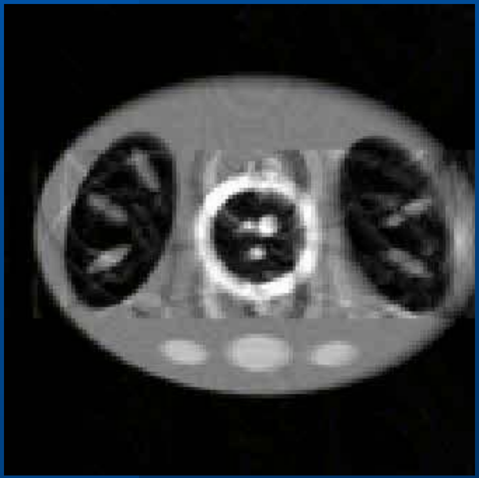
Affine Respiratory Motion

† : Parameters adapted from Manke:2002

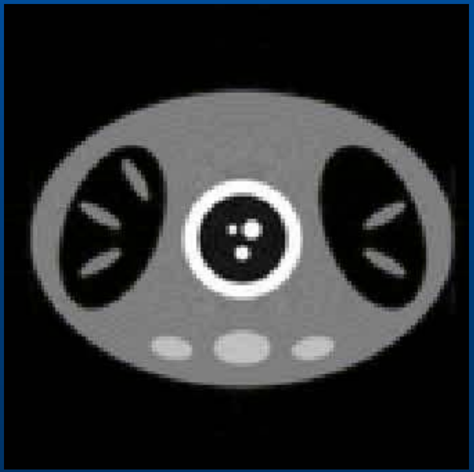
Simulation : Cardiac + Affine Respiratory Motion



Ground Truth



Uncorrected
TS Imaging

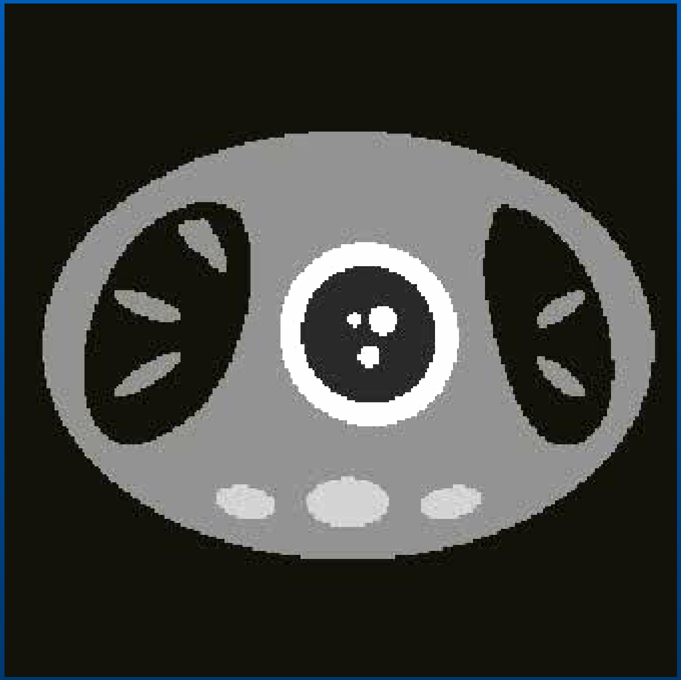


Affine-Corrected
TS Imaging

Modeling Robustness: Non-Affine Respiratory Motion

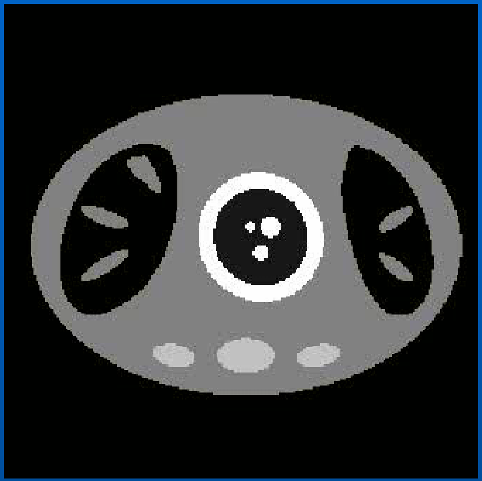
Simulation Parameters :

- Respiratory Motion :
  - Spine is stationary
  - Expansion motion for rib-cage
  - Affine motion for region surrounding the heart
- Respiratory rate = 16 breaths/min
- Cardiac rate = 60 beats/min
- Optimal T_R = 7.1 ms
- Total acquisition time = 30s

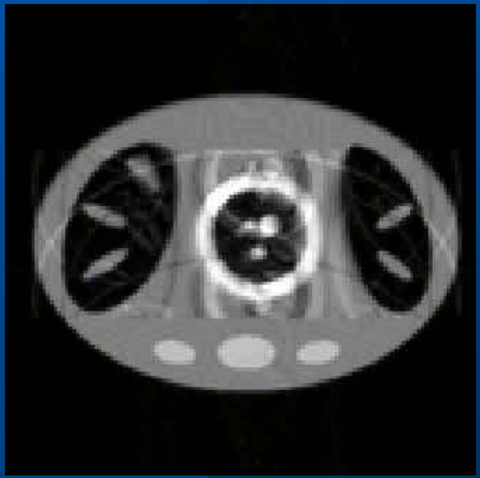


Non-Affine Respiratory Motion

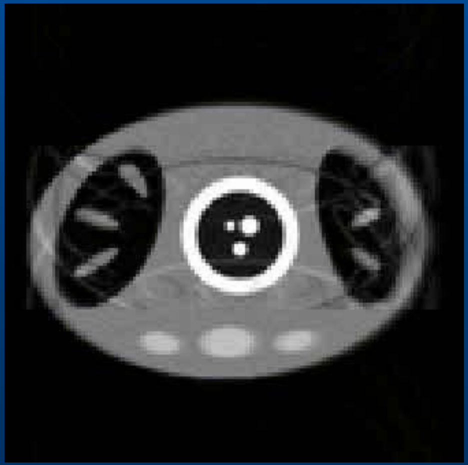
Simulation :
Cardiac + Non-Affine Respiratory Motion



Ground Truth

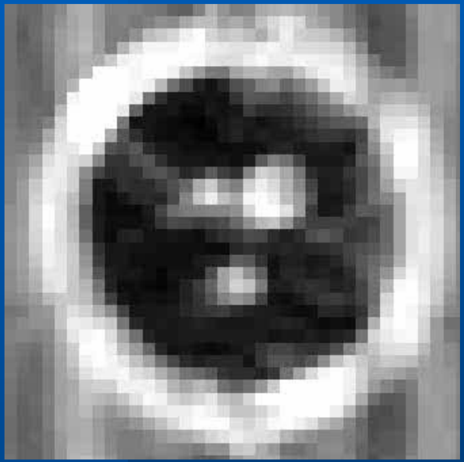


Uncorrected
TS Imaging

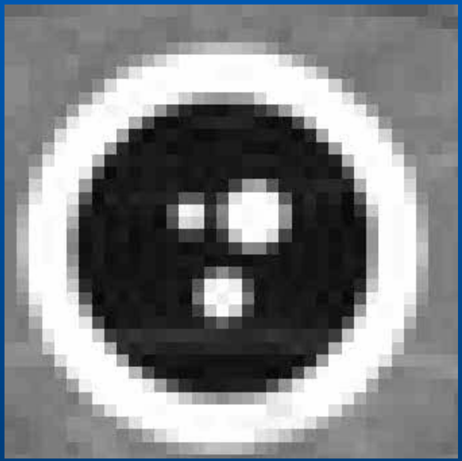


Affine-Corrected
TS Imaging

Simulation : Cardiac + Non-Affine Respiratory Motion



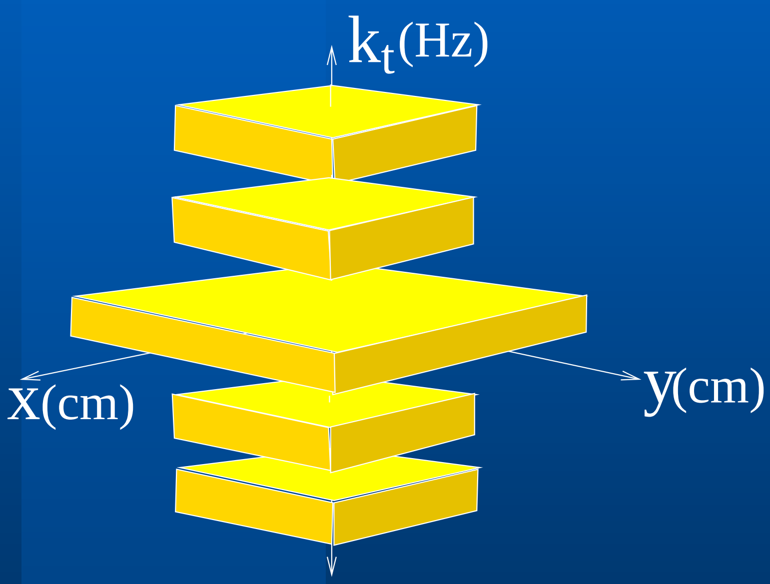
Uncorrected
TS Imaging



Affine-Corrected
TS Imaging

Heart Rate Variation:
Cardiac Aperiodicity

Spatio-Temporal Spectrum Model and Aperiodicity



- Regions with significant temporal variation spatially localized
- Cardiac motion is quasi-periodic

➡ Spectral bands

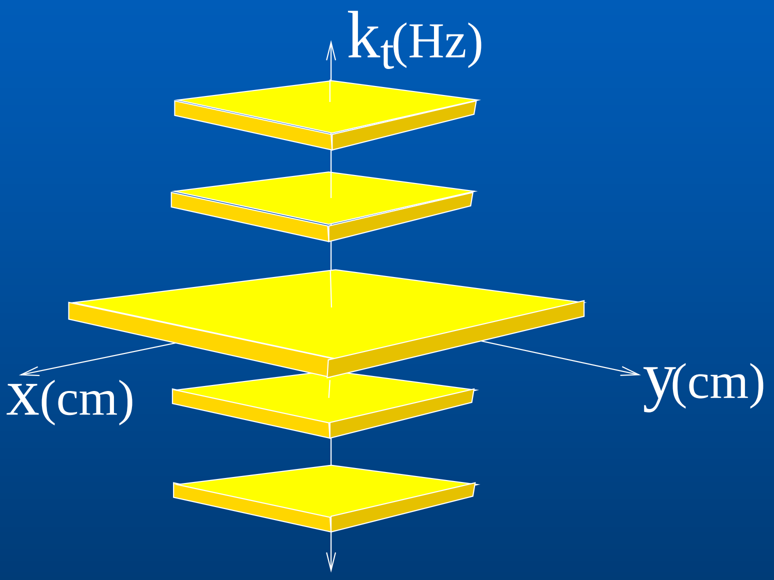
- Spectral bands broadened due to aperiodicity of dynamics

➡ Higher sampling rate required

Time-Warp & HRV

Time-Warp Model :

$$I(x,y,t) = G(x,y,\Phi(t))$$



I(x,y,t) : Time-varying cardiac image

G(x,y,t) : Idealized time-varying cardiac image with narrow-banded D-k-t support

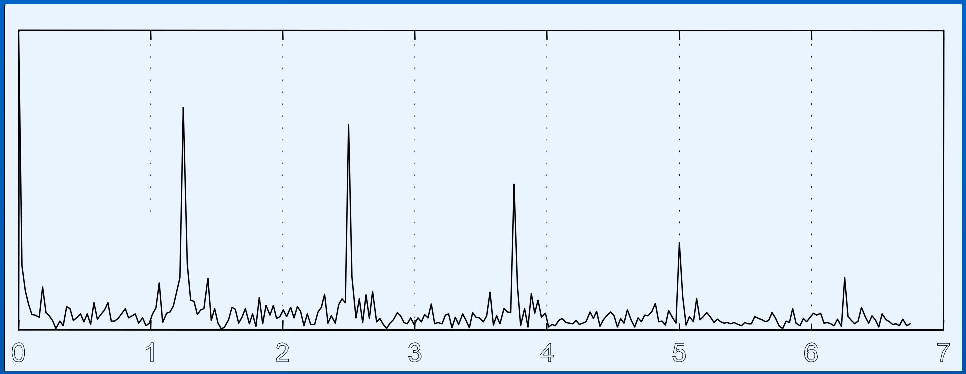
Φ(t) : Time-warp; assumed monotonic, slowly varying

Explicitly accounting for time-warp narrows D-k-t support

➔ Lowers sampling rate required

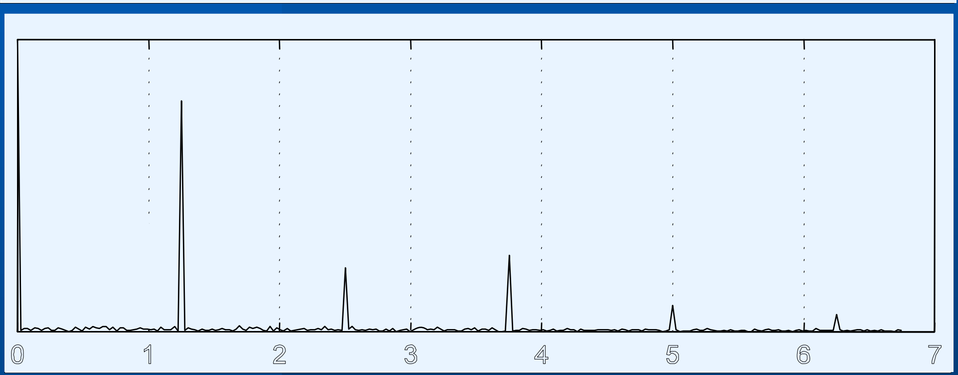
Time-Warp in Action

ECG



Temporal Spectrum

(before de-warping)



Temporal Spectrum

(after de-warping)

- **Dewarping uses dynamic programming**

- **Dewarp spectral analysis**
- **Adapt sampling to dewarped signal**
- **Dewarp acquired signal**
- **Reconstruct from nonuniform samples**

Discussion

- Real-time free-breathing cardiac MR imaging scheme **without** ECG or respiratory gating (Aggarwal *et al* 2004.)
- Method robust to respiratory motion modeling inaccuracies.
- Adaptive scheme is tolerant of aperiodicity & heart rate variability (Aggarwal *et al* 2002, Zhao *et al* 2002.)
- About 5x-20x reduction in sampling rate vs. Nyquist
- Improvements in sampling rate can be traded for increased spatial/temporal resolution, 3D, or SNR/CNR
- Generalizable to higher-dimensions, alternate k-space sampling trajectories
- Complementary to fast acquisition sequences or parallel MR imaging
- Similar techniques for other dynamic imaging applications

Conclusion

- Study sampling theory
- Model the data
- Be adaptive in
  - Modeling
  - Acquisition
  - Reconstruction
- Analyze & predict performance

Thank you for your attention!