COST B21 Meeting, Lodz, 6-9 Oct. 2005

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The *SIMRI* project
A versatile and interactive MRI simulator *

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- ✓ 1. Context
- ✓ 2. *SIMRI* overview
- ✓ 3. Simulation results
- ✓ 4. Simulator implementation
- ✓ 5. Perspectives

1. Context

✓ **MR Imaging**

- Recent and complex technique
- Based on protons magnetization
- High static field + RF excitations
- Contrast imaging adapted to soft tissue

- Images +- artéfacts
  - Objects (Chemical shift, susceptibility, motion)
  - Imaging device (Field, RF inhomogeneity, gradient non linearity)

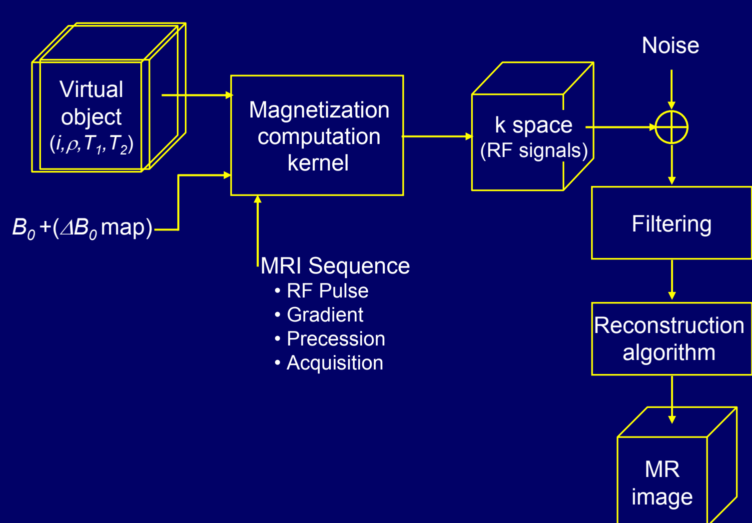
✓ **MRI simulation**

- Better understanding of MRI images
- Pedagogic purposes
- Conception, calibration and test of MRI sequences
- MRI Images with a « ground truth »
  - Artifacts impact and correction
  - Image processing assessment (segmentation, quantification)
- Main works
  - 1D MRI simulation [Bittoun-81]
  - 2D MRI simulation [Olsson-95]
  - Simulation with a distributed implementation [Brenner-97]
  - 3D brain MRI simulation [Kwan-99]
  - Susceptibility and MRI simulation [Yoder-02-04]

2. Simulator overview

- ✓ 2.1. *SIMRI* overview
- ✓ 2.2. Virtual object description
- ✓ 2.3. Static field and field inhomogeneity
- ✓ 2.4. MRI sequence
- ✓ 2.5. Magnetization kernel
- ✓ 2.6. T2* effect
- ✓ 2.7. Noise and filtering

✓ 2.1. *SIMRI* overview



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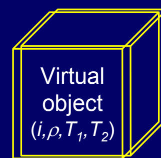
✓ 2.2. Virtual object description

- **3D volume of physical parameters**
  - ρ, proton density
  - *T1*, *T2*, spin relaxation constant
  - 1 to N components (Chem. Shift, partial volume effect)
  - Object dimension, component resonance frequency
  - ΔB_s : susceptibility associated field



- **Synthetic objects perfectly known**
  - Sphere, ellipse, cube …
  - Adapted McGill brain phantom 256^3
  - Real images ➢ segmentation + (T1,T2 maps) ➢ objects

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✓ 2.3. Static field and field inhomogeneity

$$\Delta B(\vec{r})\vec{z} = \Delta B_s(\vec{r})\vec{z} + \Delta B_0(\vec{r})\vec{z}$$

- $\Delta B_s(\vec{r})$ linked to the susceptibility variation
- $\Delta B_0(\vec{r})$ linked to the main field inhomogeneity
- ΔB_i linked to the intra-voxel inhomogeneity,
  It induces a T2* FID weighting

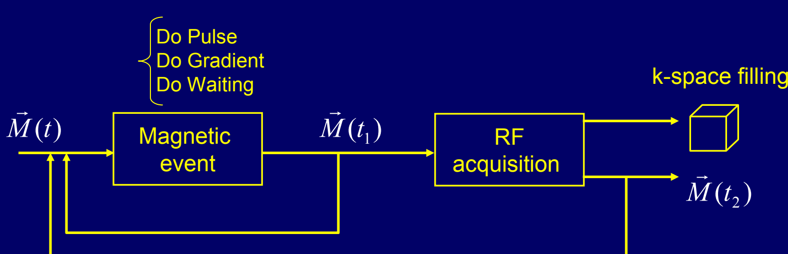
$$e^{-\gamma \Delta B_i t} \qquad \frac{1}{T_2 *} = \frac{1}{T_2} + \gamma \Delta B_i$$

✓ 2.4. MRI sequence

4 types of event within C language functions

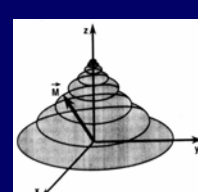
- Free precession (duration)
- Precession + gradient (x,y,z)
- RF pulse +- gradient
  - Constant pulse (duration, flip angle, rotation axis)
  - Sinc shaped pulse (duration, number of lobes, number of point)
  - User shaped pulse (file, constant pulse list)
- 1D signal acquisition step (number of points, bandwidth, readout gradient, k space position)

✓ 2.5. Magnetization kernel



Kernel is based on the Bloch Equation

$$\frac{d\vec{M}}{dt} = \gamma.(\vec{M} \times \vec{B}) - \begin{pmatrix} M_x / T_2 \\ M_y / T_2 \\ (M_z - M_0)/T_1 \end{pmatrix}$$



and on their discrete time solution

$$\vec{M}(\vec{r}, t + \Delta t) = Rot_z(\theta_g).Rot_z(\theta_i).R_{relax}.R_{RF}.\vec{M}(\vec{r}, t)$$

✓ 2.6. T2* effect, limited spin number

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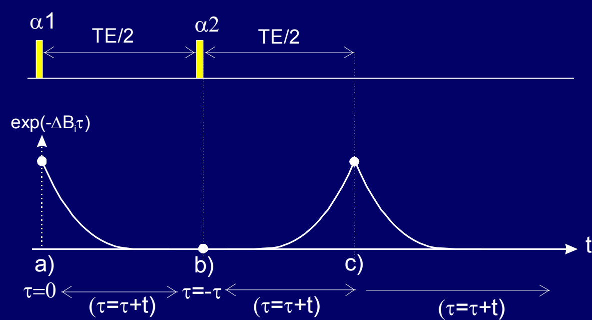
Lorenzian distribution of isochromats

- FID weighting $e^{-\gamma \Delta B_i t}$ ➢ $\frac{1}{T_2 *} = \frac{1}{T_2} + \gamma \Delta B_i$

- Spin refocusing, Spin Echo



✓ 2.7. Noise and filtering

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Thermal noise

- White Gaussian noise in the k-space

K-space filtering

- Hamming (or any digital filter), prevent ringing

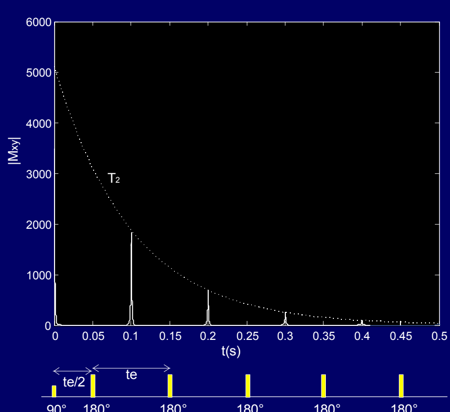
Reconstruction

- FFT

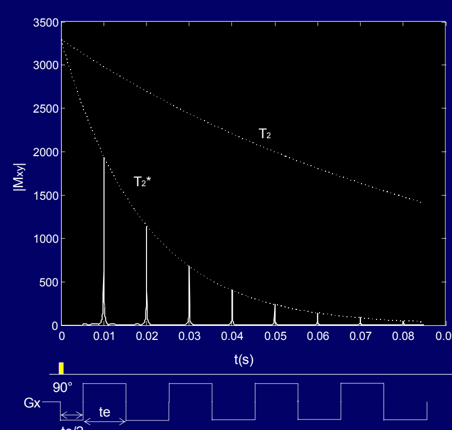
3. Simulation results

- ✓ 3.1. Echo train
- ✓ 3.2. Contrast in GE and SE imaging
- ✓ 3.3. True Fisp imaging
- ✓ 3.4. Chemical shift artifact
- ✓ 3.5. Susceptibility artifact

✓ 3.1. Echo train and T2*



Simulated signal obtained after a CPMG sequence. It is composed of a train of spin echoes T2 weighted. The intra-voxel inhomogeneity is set to 10-6 T and the main field to 1 T.



Simulated signal obtained after a gradient echo pulse sequence. It is composed of a train of T2* weighted gradient echoes. The intra-voxel inhomogeneity is set to 10-6 T and the main field to 1 T.

✓ 3.2. Contrast in SE and GE imaging

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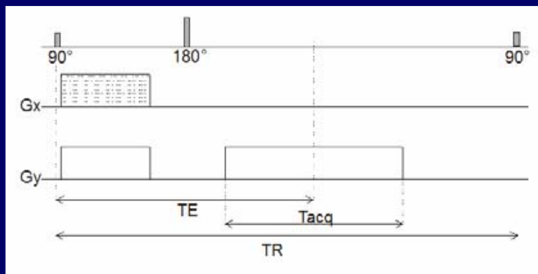
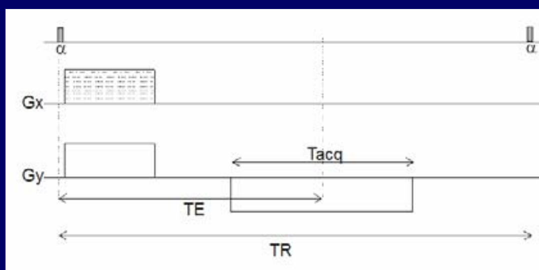


SE sequence



GE sequence

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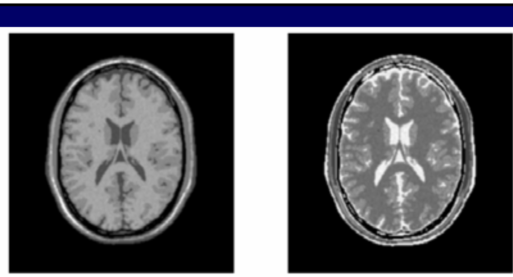
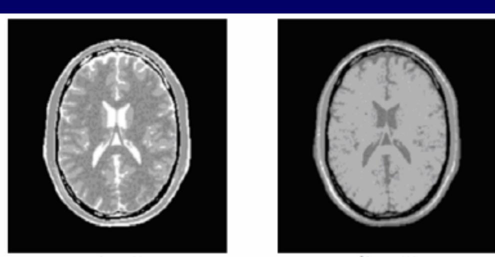


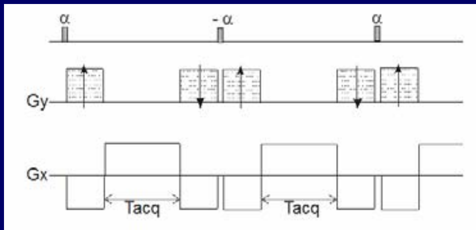
a) TE=25 ms TR=500 ms BW=25.6 kHz. *b) TE=100 ms TR=2000 ms BW=25.6 kHz.*
Contrast variation in Spin Echo imaging at 1.5 T on a 256x256 brain image.
a) T1 weighting. b)T2 weighting.

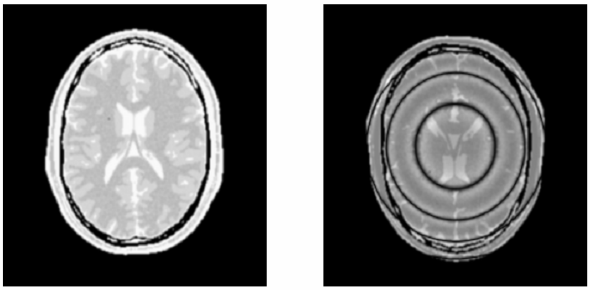


a) $\alpha = 2°$ *b) $\alpha = 60°$*
Impact of the RF flip angle α on the image contrast when using Gradient Echo imaging at 1.5 T on a 256x256 brain image with TE=4.25 ms, TR=25 ms, and a Bandwidth BW=256 kHz.

McGill Brain phantom
10 tissues profiles

✓ 3.3. True Fisp imaging

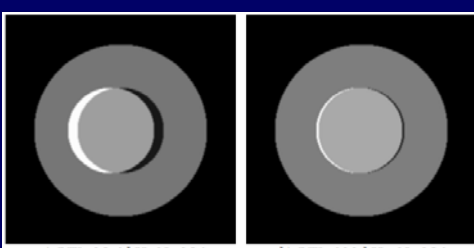




a) No static field default. *b) Parabolic static field default.*

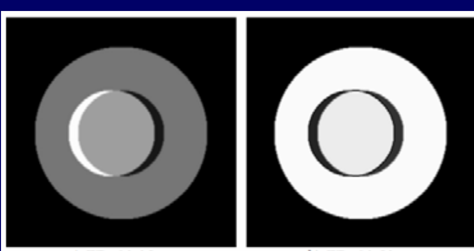
True FISP simulations with an RF pulse of 20 ° and 300 µs duration, a readout bandwidth BW=256 kHz, B_0=1.5 T and a TR=4 ms. a) Image simulated with no static field default. b) Image simulated with a parabolic static field default with a maximum intensity of 6.10^{-5} T.

✓ 3.4. Chemical shift artifact



a) BW=25.6 kHz N=256 *b) BW=128 kHz, N=256*

Impact of the bandwidth on the chemical shift using a Spin Echo sequence with TE=20 ms TR=2500 ms at B_0=7 T



a) TE=19.05 ms *b) TE=19.52 ms*

TE effect on the chemical shift in a gradient echo sequence with B_0=7 T, a flip angle of 60° and a bandwidth of 25.6 kHz.

$$2\pi \cdot \Delta f \cdot TE = (2k+1)\pi$$

Water and fat signals in phase opposition !

✓ 3.5. Susceptibility artifact

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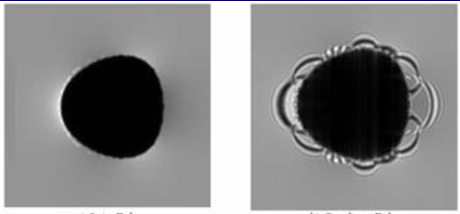
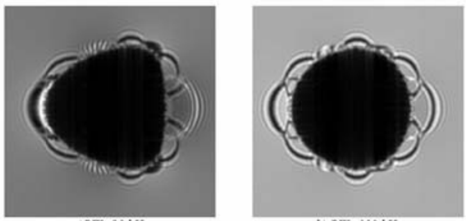


a) Spin Echo *b) Gradient Echo*

Illustration of the susceptibility artifact on an air bubble into water with a static field of 7T. Impact of the sequence type. a) Spin Echo sequence (TE=20 ms ,TR=1000 ms, BW=20 kHz). b) Gradient Echo sequence (TE=20 ms ,TR=1000 ms, BW=20 kHz, α=90°). 256x256 simulations.



a)BW=25 kHz *b) BW=100 kHz*

Illustration of the susceptibility artifact on an air bubble into water with a static field of 7T. Impact of the Bandwidth (BW) parameter using a Gradient Echo sequence (α=90° TE=20 ms TR=1500 ms). a) BW=25 kHz. b) BW=100 kHz. 256x256 simulations.

Geometric distortions
+ Intensity loss

4. Simulator implementation

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- ✓ 3.1. Code organization
- ✓ 3.2. Sequence programming
- ✓ 3.3. Acquisition programming
- ✓ 3.4. 1D interactive simulation
- ✓ 3.5. Distributed implementation

✓ 3.1. Code organization

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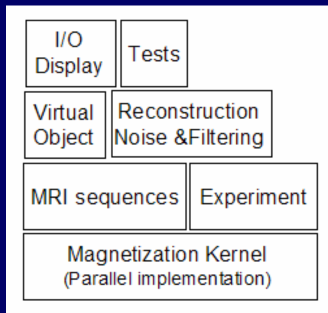

- ANSI C language
- Running on Linux and windows OS
- Independent module organization
- Linked in a dll wrapped for being used with python for the 1D interface
- Parallelized using MPI to run on grid, cluster, multiprocessors.

✓ 3.2. Sequence programming

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```
PPPVOLUME_COMPLEX_DOUBLE SeqSpinEcho2D(SEQPARAM *seqparam,EXPERIMENT3D *expr)
{
(…)
 timp=0.3;
 acq_delay = (te/2) - (tacq/2);
 tg = tacq/2.;
 gx = (ntx-1)/tacq/G_kHz_G/fovx;
 gy = (nty-1)/(tg/1000)/G_kHz_G/fovy;
 gz = 0.0;
 npz= 0;

 SetSpoilingFlag(entre,ACTIVE); /* XY Spoiling after acquisition */

 for (npy = 0; npy < expr->nty; npy++)
       {
           ResetToExperiment(expr);
           DoPulseRect(expr,entre, 90.,timp);

           gp = (gy) * (npy - (nty) / 2) / (nty);
           DoGradient(expr,entre,tg,gx,gp,gz);
           DoWaiting(expr,entre,acq_delay);

           DoPulseRect(expr,entre,180.,timp);
           DoWaiting(expr,entre,acq_delay);

           DoAcqFrequenceX( expr,entre, gx, npy, npz, 0, MOINS);

           DoWaiting(expr,entre,tr-te-tacq/2.0);
       }
     NormalizeRFSignal(expr);
 return(GetSignalRFComplexFromExperiment(expr));
}
```

✓ 3.3. Acquisition programming

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```
void TestSequence(int objsize,int imasize,int visu,
                  double tacq,double TE,double TR,double b0, double db0,
                  int flagres,int filter,char * fileout)
 {
 int x,y,z;
 int ntx, nty, ntz;          /* RF volume size */
 double fovx,fovy,fovz;      /* Fov in meter */
 OBJET3D *objet;
 EXPERIMENT3D *expr;
 SEQPARAM seqparam;
 (…)

 /* Object */
 x=objsize; y=x; z=1;
 objet=CreateObjectTest2D_CircleEllipse(x,y);
 SetSizeObject(objet,(float)0.2,(float)0.2,(float)0.002);
 SetDeltaB0Object(objet,db0);

 /* Experiment */
 expr=AllocExperiment();
 ntx=imasize; nty=ntx; ntz=z;
 fovx=0.20; fovy=0.20; fovz=0.0020;
 SetFovExperiment(expr,fovx,fovy,fovz,0.0,0.0,0.0);
 SetAcqExperiment(expr,ntx,nty,ntz,tacq*1e-3);
 SetResonanceExperiment(expr,flagres);
 SetB0Experiment(expr,b0);

 /* Sequence */
 SetSeqParamTE(&seqparam,TE);
 SetSeqParamTR(&seqparam,TR);
 volrf = RunSequence("SE2D",&seqparam,objet,expr);
 FreeObjet(objet);
 AddGaussianNoiseToRFVolume(volrf,0.001);
 if (filter==YES) VolRFFiltering(volrf,HAMMING);
 volrecmod = RecVolIFFTModuleFromVol(volrf);

 /* Output Result */
 if (visu==YES) DisplayVolXY((PPPVOLUME)volrecmod,0,"Recvol2D");
 WriteVolRF(volrf);
 WriteVolRecUchar(volrecmod,fileout);
 IdVolFree(volrecmod);IdVolFree(volrf);
}
```


✓ 3.4. 1D interactive simulation

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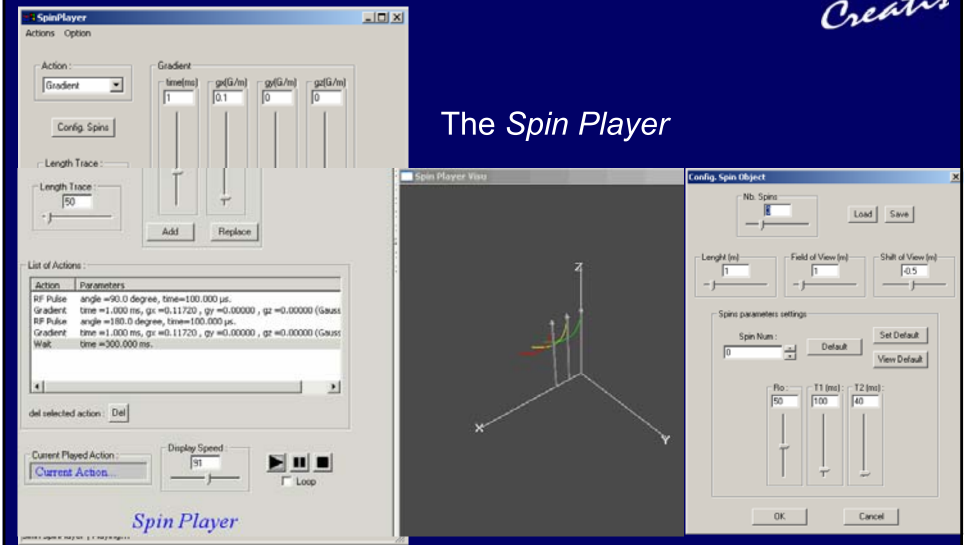
The *Spin Player*



✓ 3.5. Distributed implementation

Time is the enemy !

- Simulation time $T_s \approx Texc + Tacq = c.(X.Y.Z).[(M.N.P) + N_{ex}]$

- 2D Image (NxN)
  - Nx2 ➢ time x16
  - 1024^2 = 2.3 days
  - High resolution : *small cluster*

- 3D image(NxNxN)
  - Nx2 ➢ time x 64
  - 128^3 = 9.3 days / 512^3 = 104 years !
  - High resolution ➢ *large scale data grid*

- A “*Divide & Conquer* “ parallelisation scheme
- Based on the free library MPI, transparent at a user level
- Allowing run on single PC, PC cluster, grid architecture, massively parallel machine

Simulation web portal

- Work done in the context of European grid projects
  - DATAGRID Project (2001-03)
  - EGEE Project (2003-05)

5. Conlusion

✓ **An operational MRI simulator**

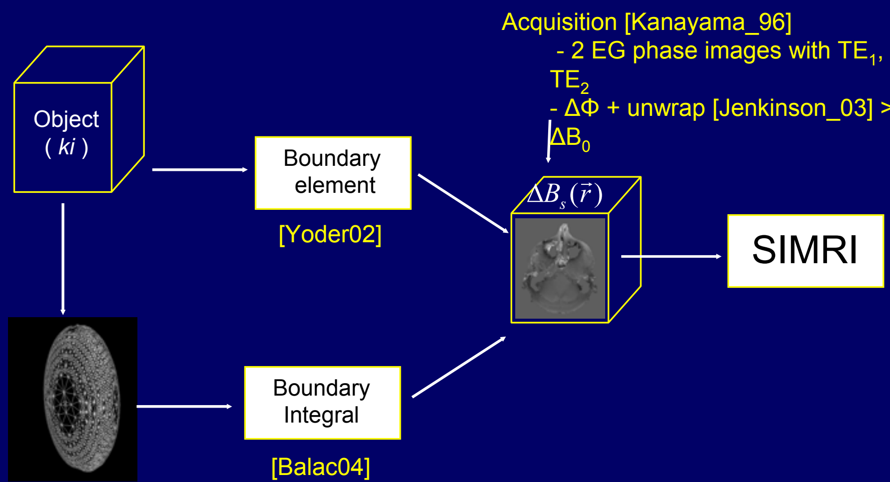
- 1D-2D-3D
- Sequences (SE, GE, Turbo, TFisp, STIR)
- Artifacts : Chemical shift, susceptibility, static field
- B_0 , T2*, Off-On resonance
- Versatile, Parallelized, Interactive and *GPL* !

6. Perspectives

✓ **Main perspectives**

- Anatomic object design ➢ Sequence tuning
  ➢ Image processing evaluation
- Molecular imaging ➢ susceptibility and Cell. Con. agent
- New sequences / Interface with ODIN project
- RF / Antennas
- Artifact correction
- Flow , Diffusion & Perfusion ?

✓ ΔB_s Field map estimation



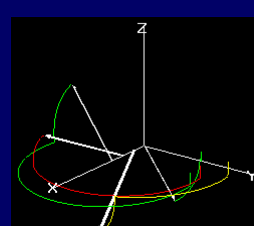
$$\vec{B}(P) = \vec{Bo}\ Xm(P)\ \delta\Omega(P) - \frac{1}{4\pi}\sum_{k=1}^{NbFace} \Delta Xm\ \vec{n} \left[\vec{Bo} \int_{Face\,k} \vec{C}(P,q)dsq \right]$$

$$\theta_g = \gamma.\vec{r}.\int_t^{t+\Delta t} \vec{G}(\tau)d\tau$$ gradient effect

$$Rot_z(\theta) = \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\theta_i = \gamma.\Delta B(\vec{r}).\Delta t$$ Inhomogeneity effect

$$R_{relax} = \begin{pmatrix} e^{-\frac{\Delta t}{T_2(\vec{r})}} & 0 & 0 \\ 0 & e^{-\frac{\Delta t}{T_2(\vec{r})}} & 0 \\ 0 & 0 & 1-e^{-\frac{\Delta t}{T_1(\vec{r})}} \end{pmatrix}$$ Relaxation effect



$$R_{RF} = Rot_z(\phi).Rot_x(\alpha).Rot_z(-\phi)$$ Pulse effect

$$\alpha' = -\tau.\sqrt{(\Delta\omega)^2 + \left(\frac{\alpha}{\tau}\right)^2}$$ Off-resonance effect

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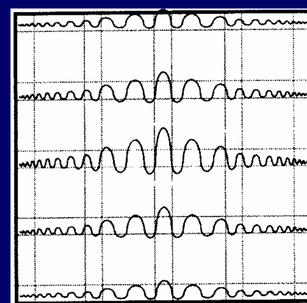
- K-space acquisition
  - One point is obtained by summation all over the object

$$s[t] = \sum_{\vec{r}} \vec{M}(\vec{r},t).\vec{x} + j\sum_{\vec{r}} \vec{M}(\vec{r},t).\vec{y}$$

  - Next point is obtained after a time step Δt, the sampling rate



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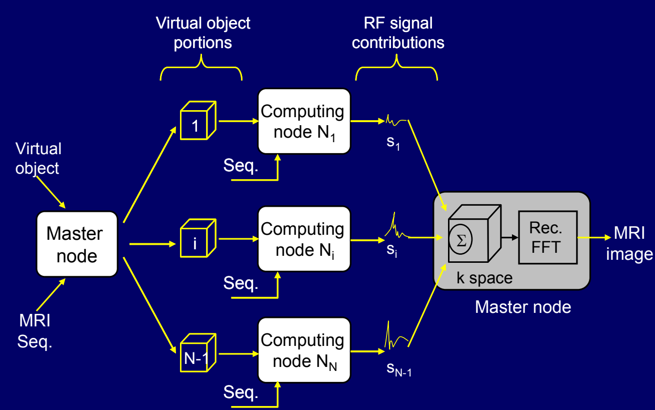

- Some test results :
  - PC cluster CREATIS : 8 (PIII-1Ghz) + 10 (PIV-2,6 Ghz)
  - CINES parallel machine : 64 to 128 nodes, RI 4000-500 Mhz
  - IN2P3 through EGEE grid interface : 9 AMD Opteron 2.2 Ghz

	Single PC PIV-3Ghz	EGEE, IN2P3 (9 Nodes)	CINES (9 Nodes)	CINES (64 Nodes)	Cluster CREATIS (8+10 Nodes)
Image 512^2	4h	68 m	1h56m	15 m	52m
Volume 64^3	4h	68 m	2h01m	13 m	61 m

- 128^3 : 8h30 on a 128 proc. CINES machine

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  - EGEE Project (2003-05)