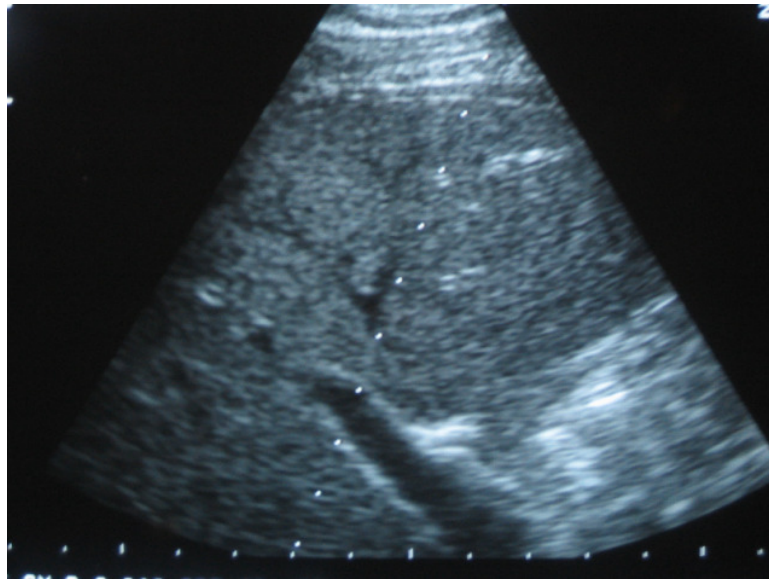


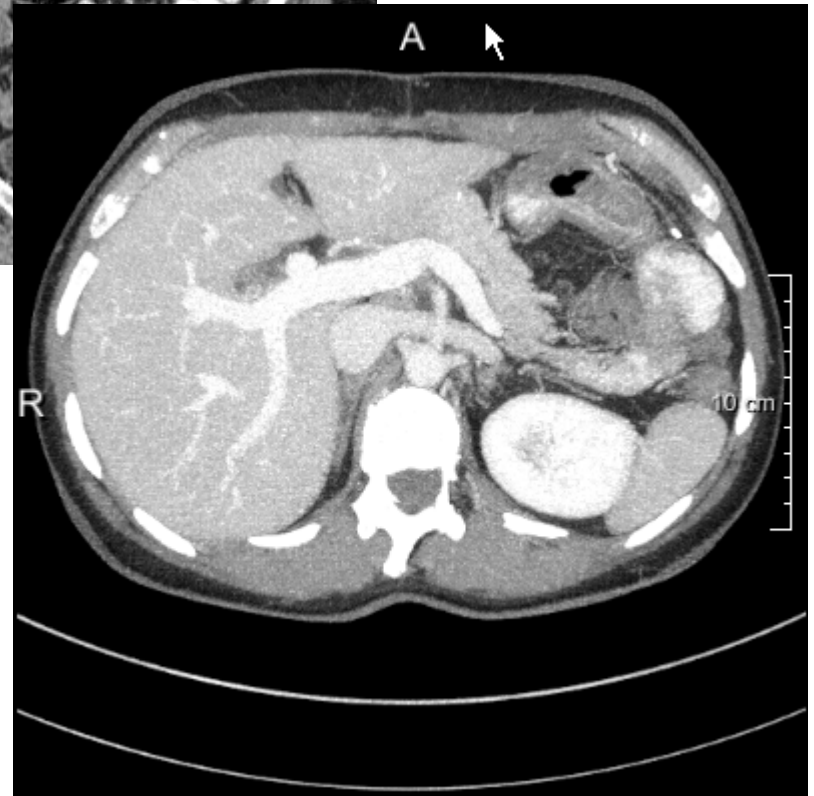
Image registration in image-guided interventions

Stefan Klein
Erasmus MC, the Netherlands
Biomedical Imaging Group Rotterdam (BIGR)

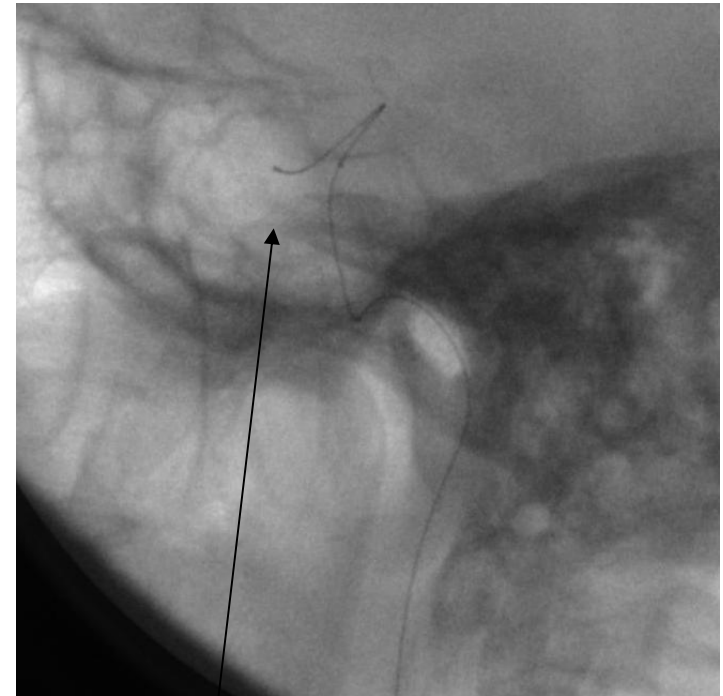
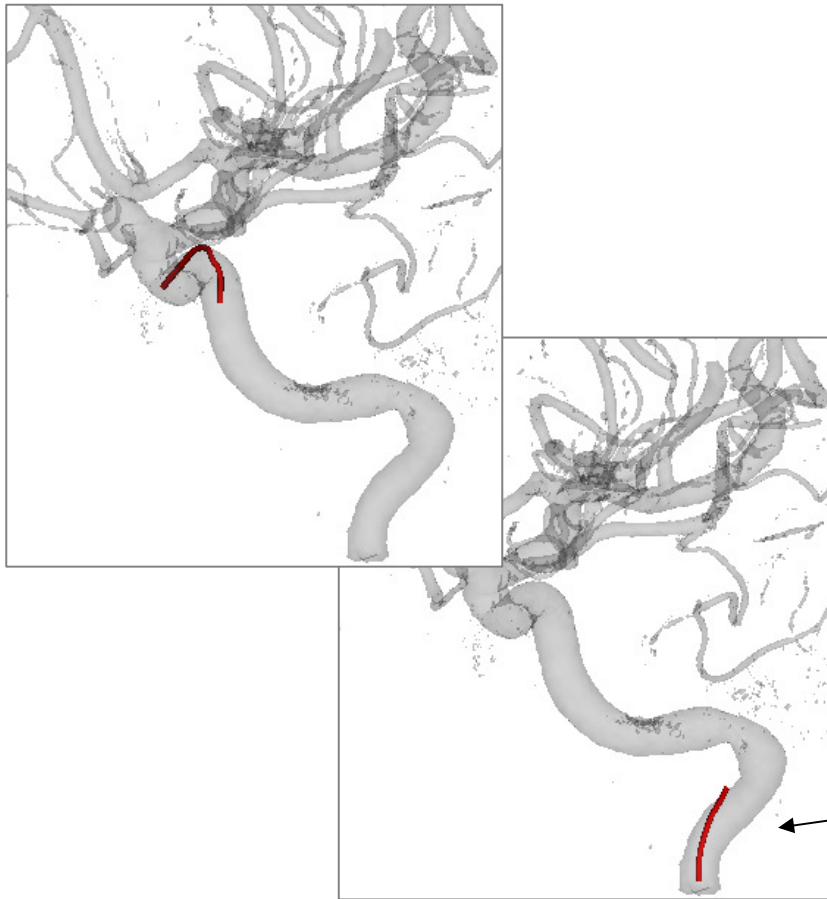
Intraoperative images



Diagnostic images

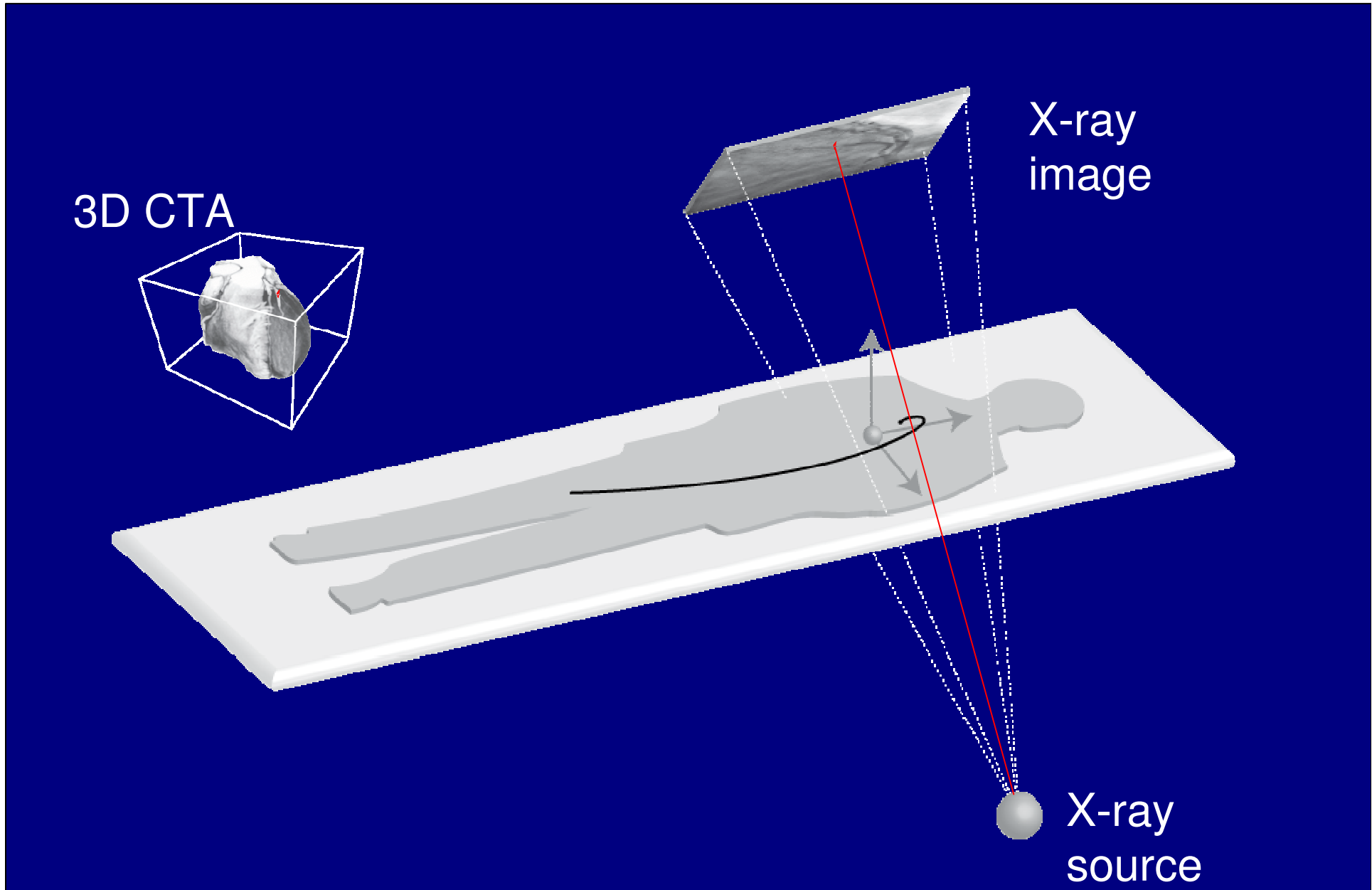


Registration in IGI: fuse information!

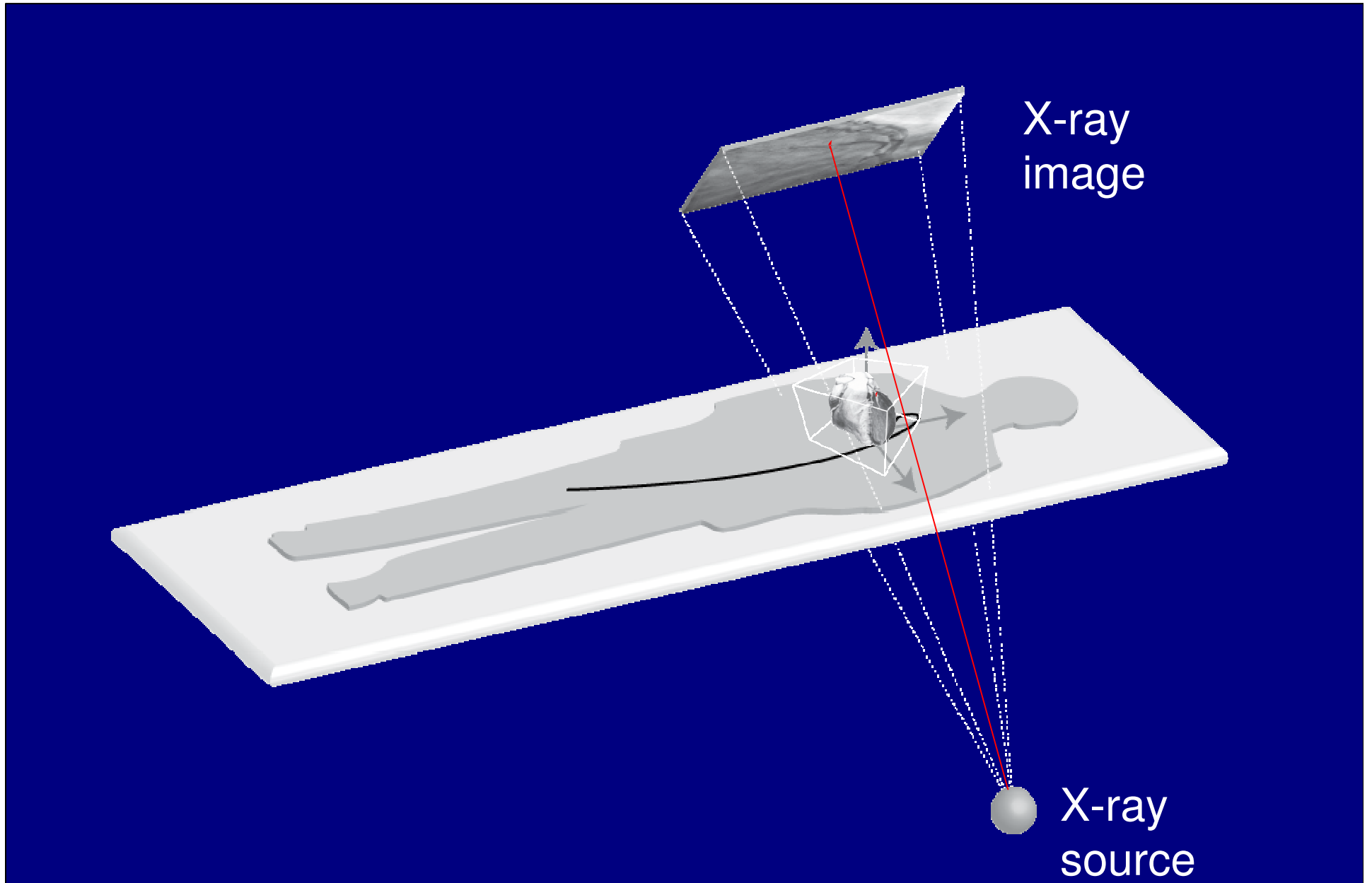


Guide-wire

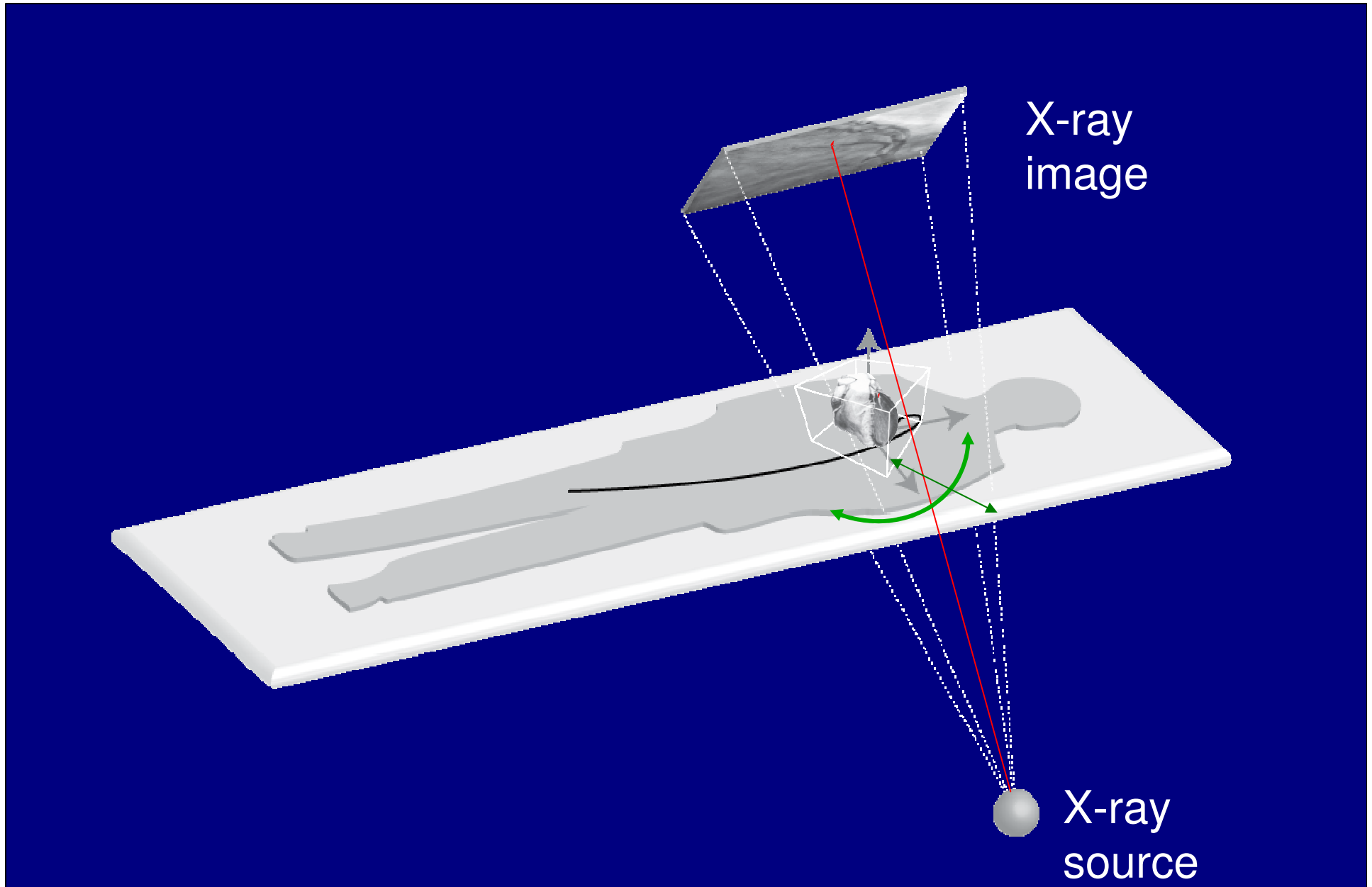
Registration in IGI: fuse information!



Registration in IGI: fuse information!



Registration in IGI: fuse information!



Registration in IGI: examples

2D – 3D : X-ray with CT

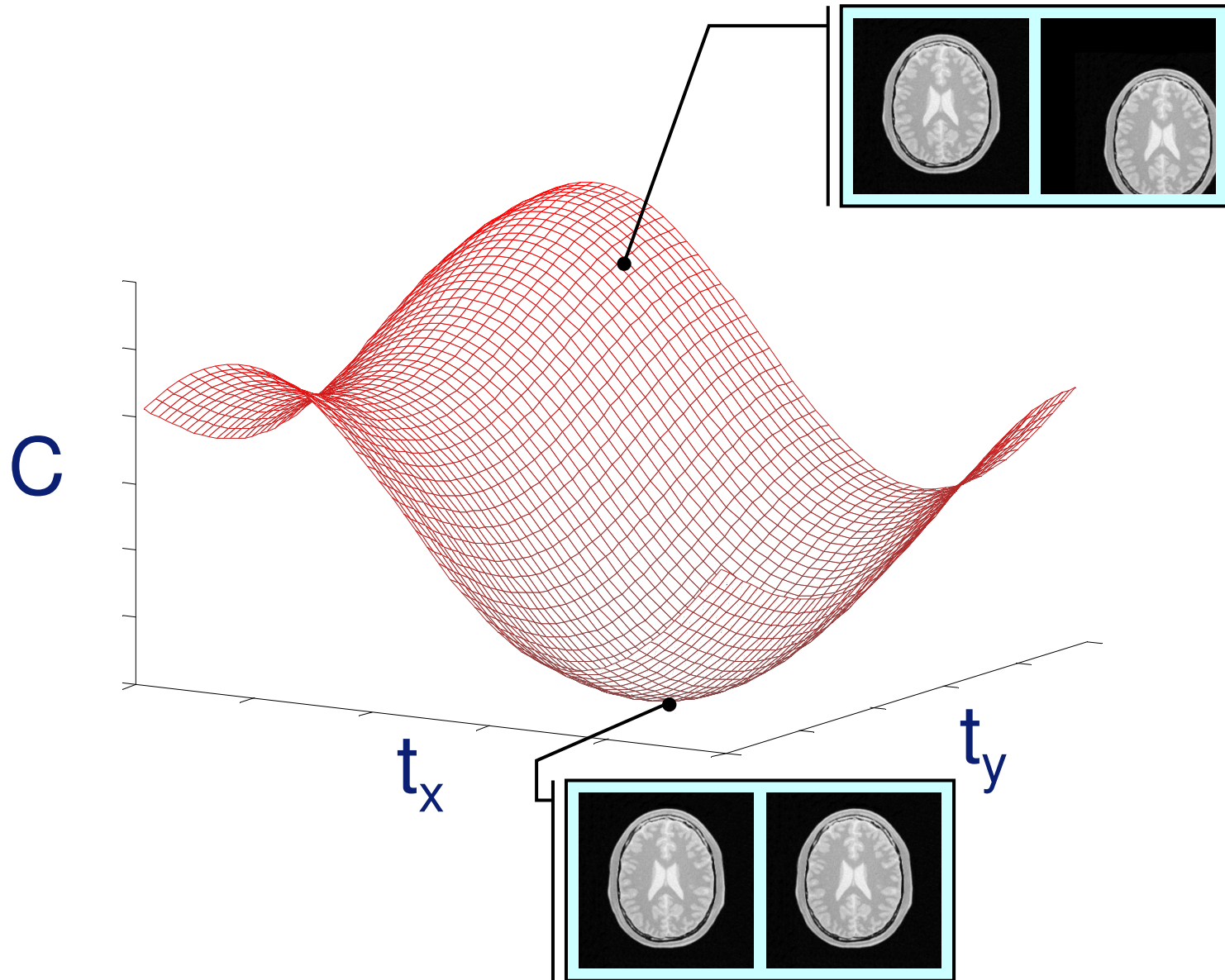
3D – 3D : intraoperative MRI with preoperative MRI

2D+t – 3D : US with MRI/CT

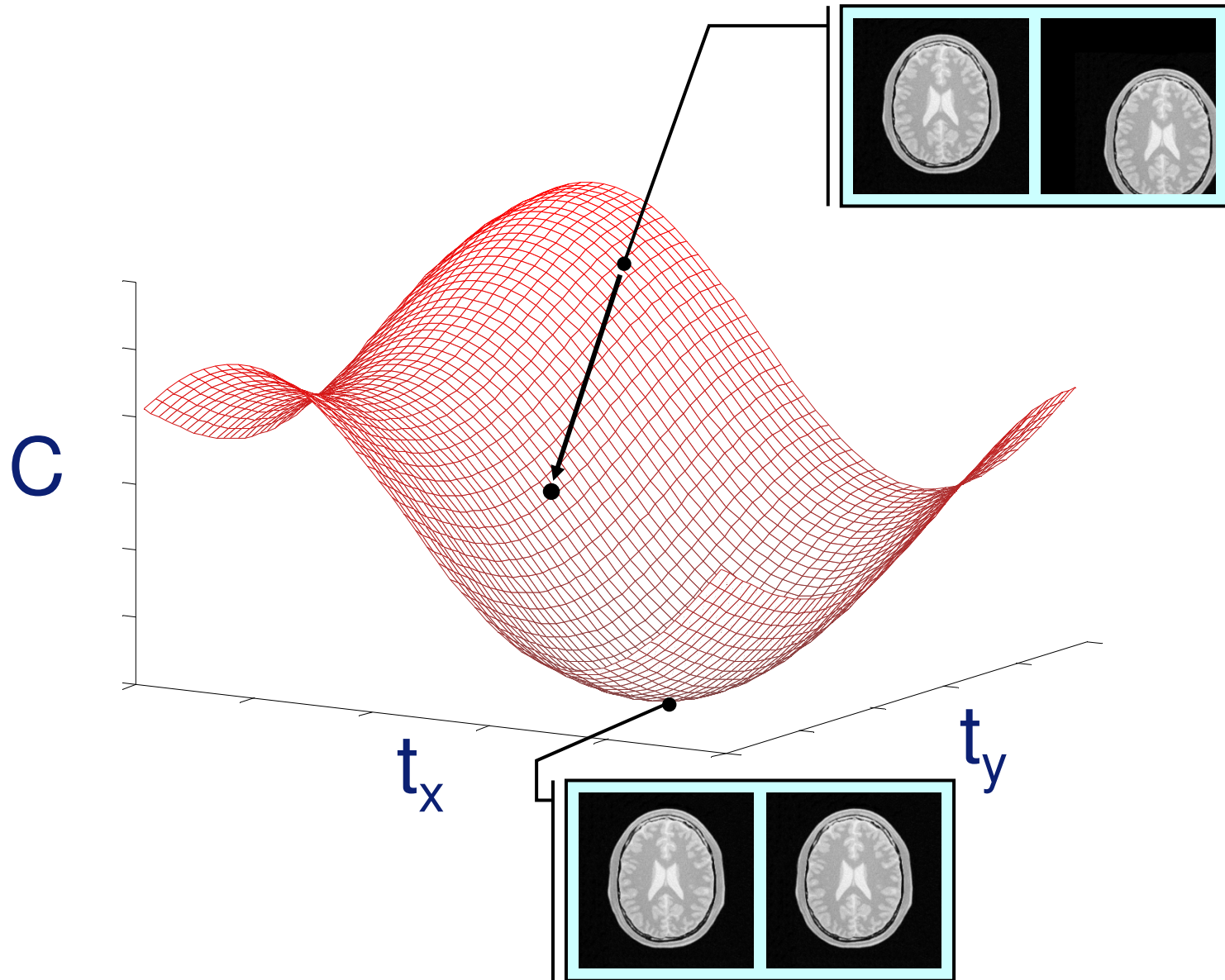
2D+t – 3D+t : X-ray sequence with dynamic CT

registration = optimisation

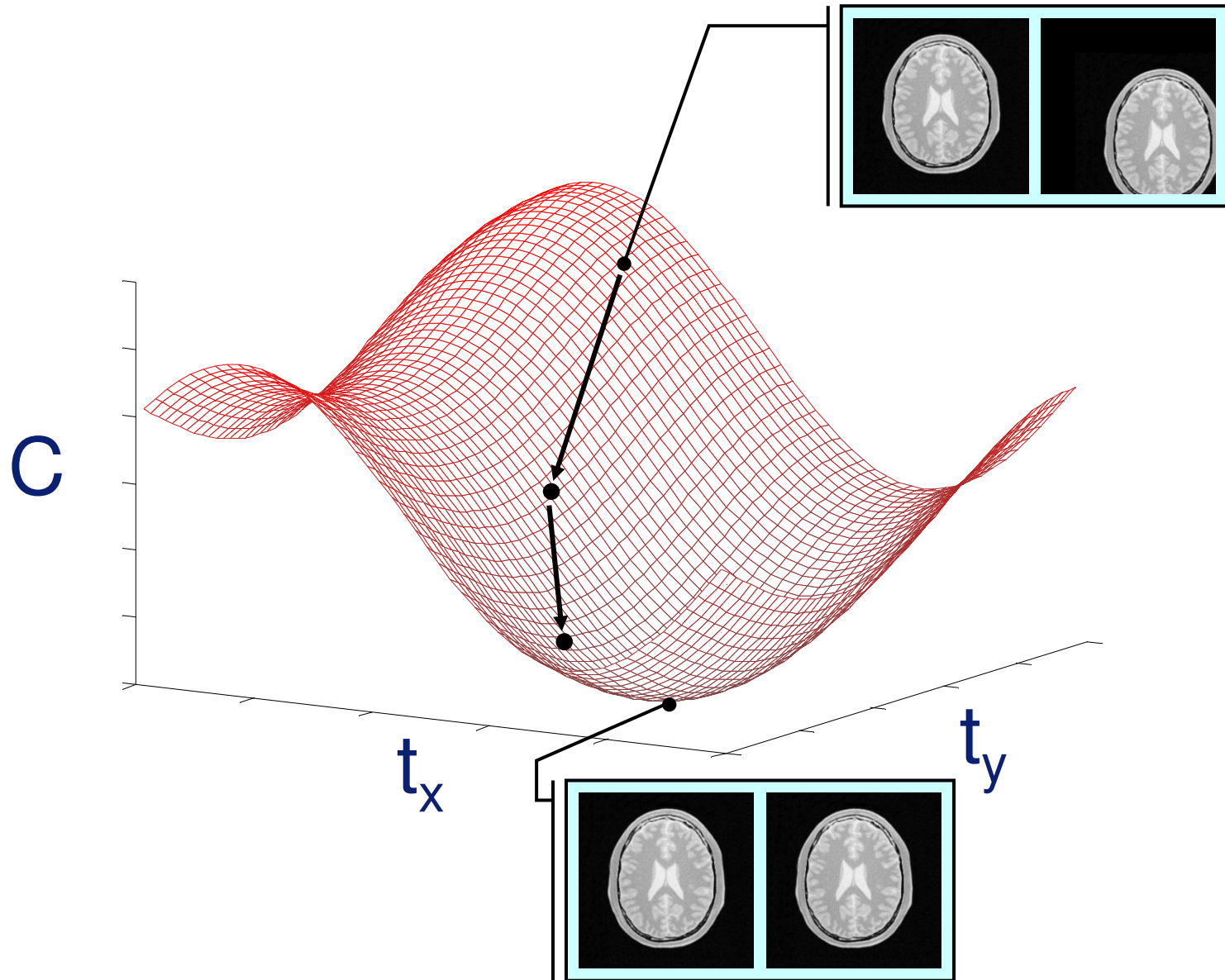
Registration = optimisation



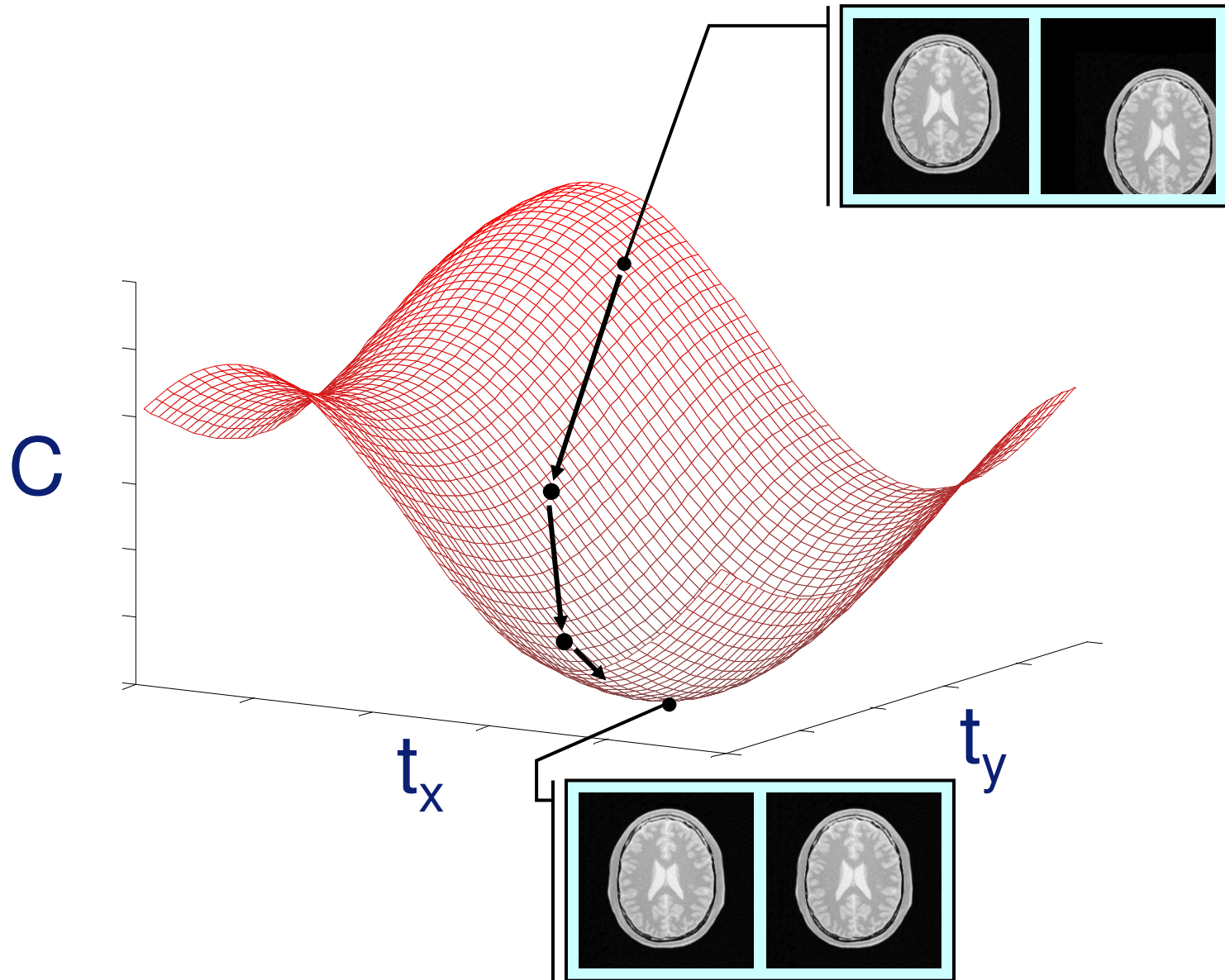
Registration = optimisation



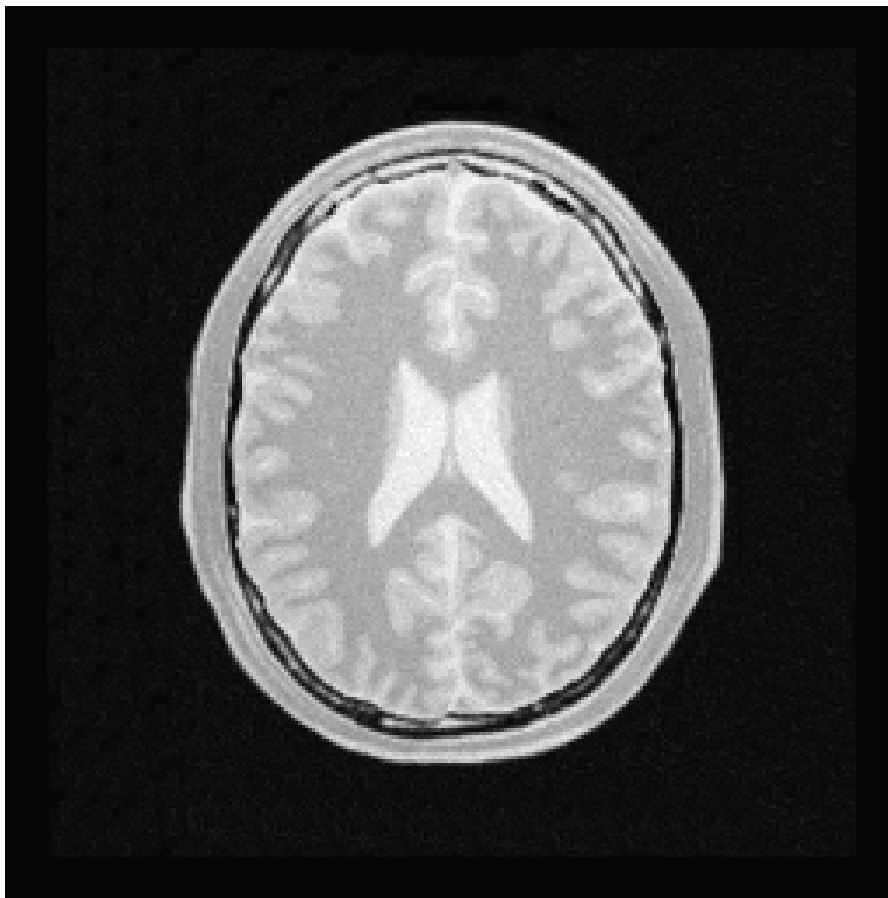
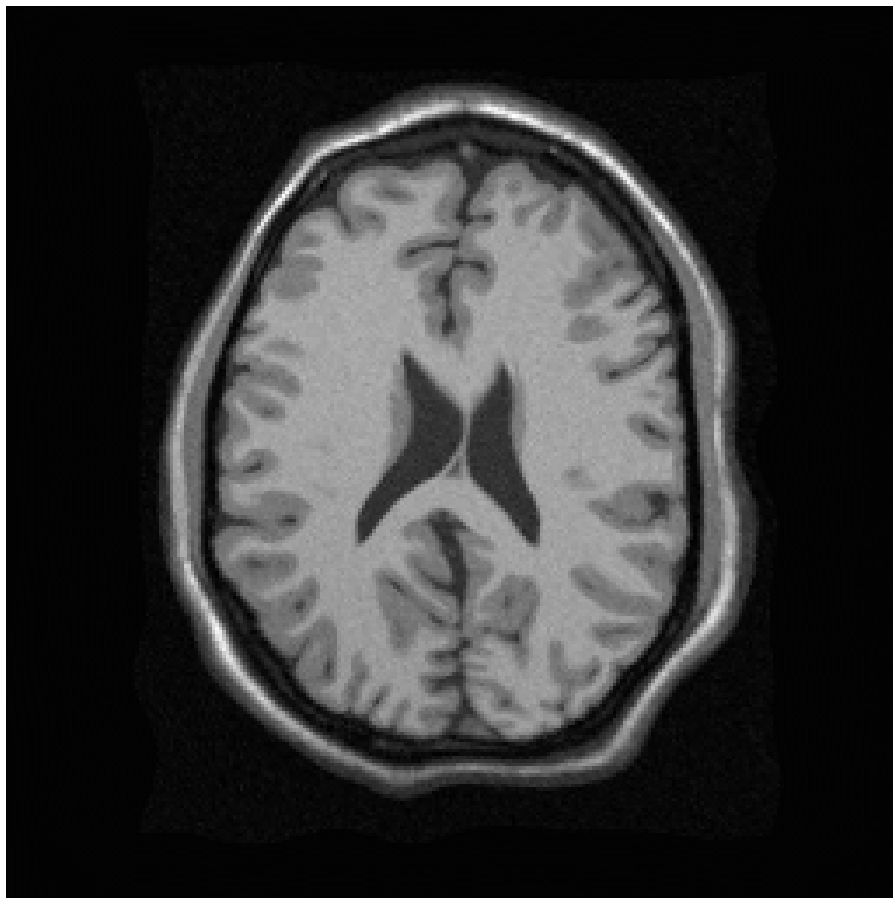
Registration = optimisation



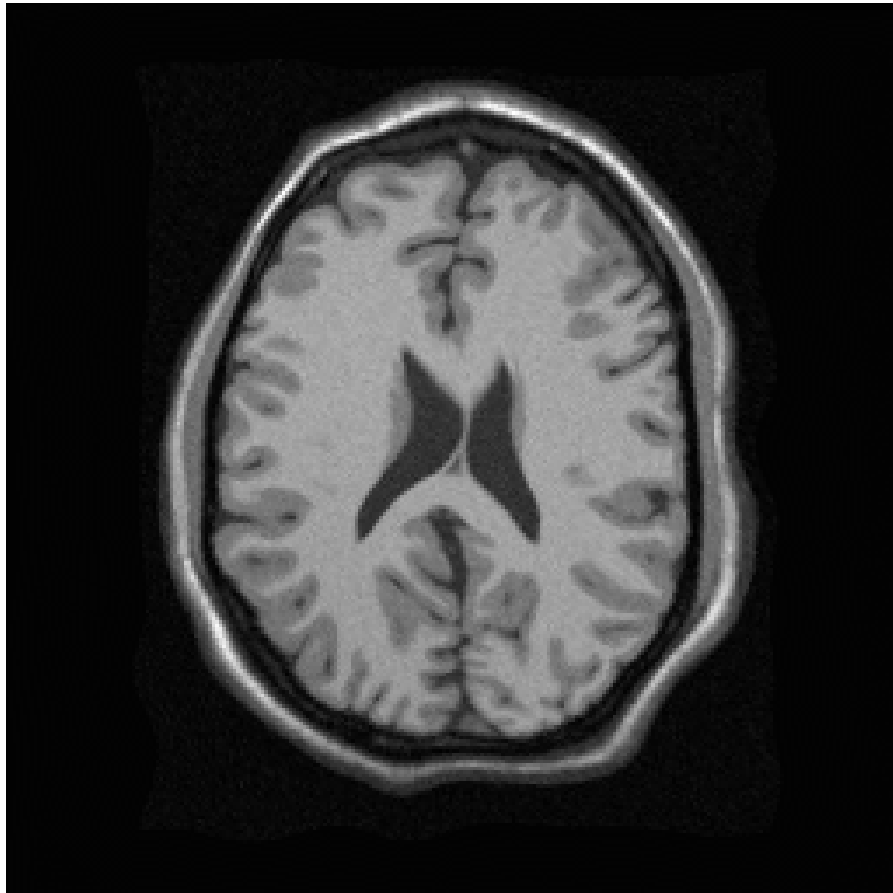
Registration = optimisation



Example



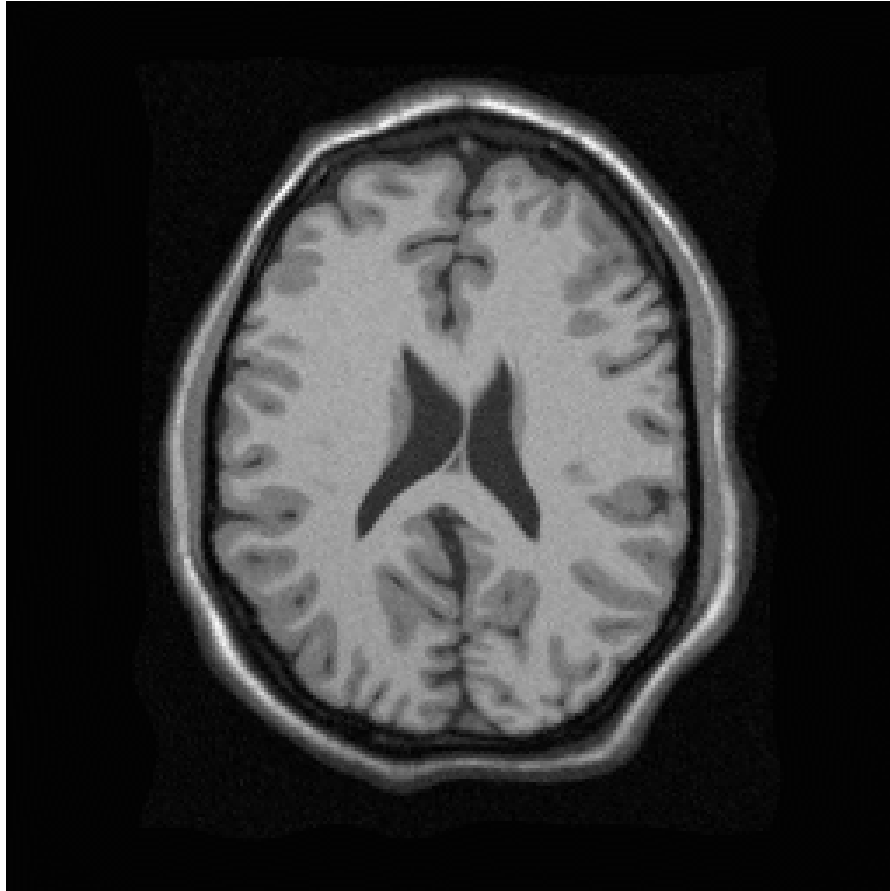
Example



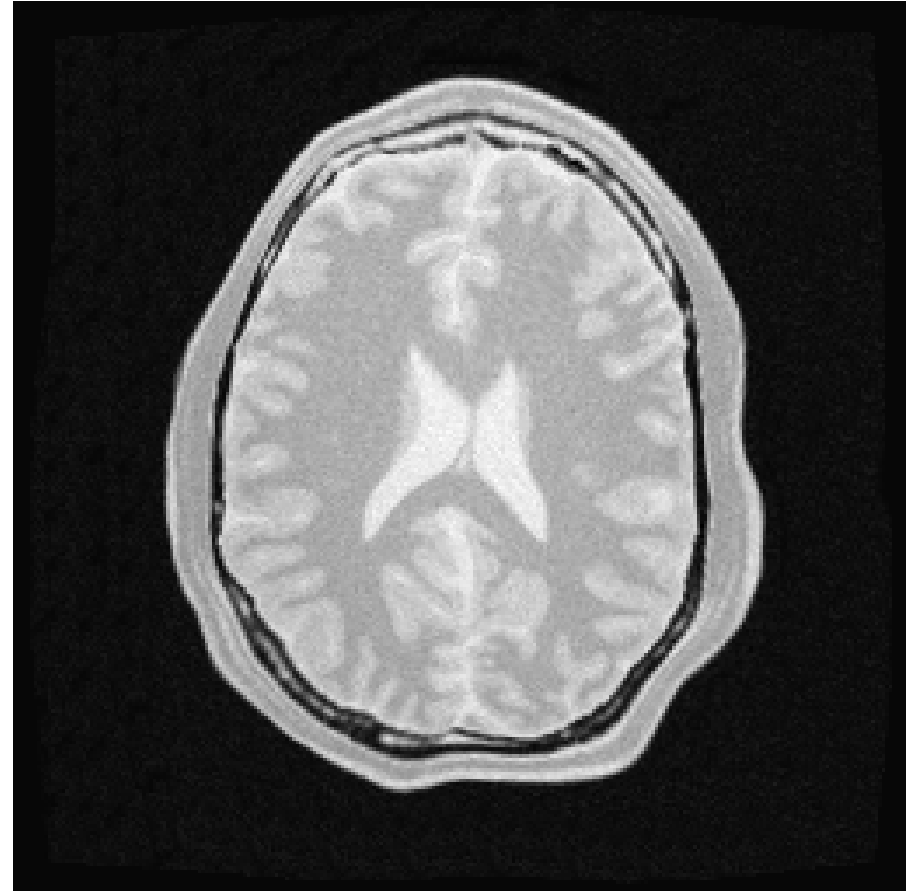
fixed image

moving image

Example

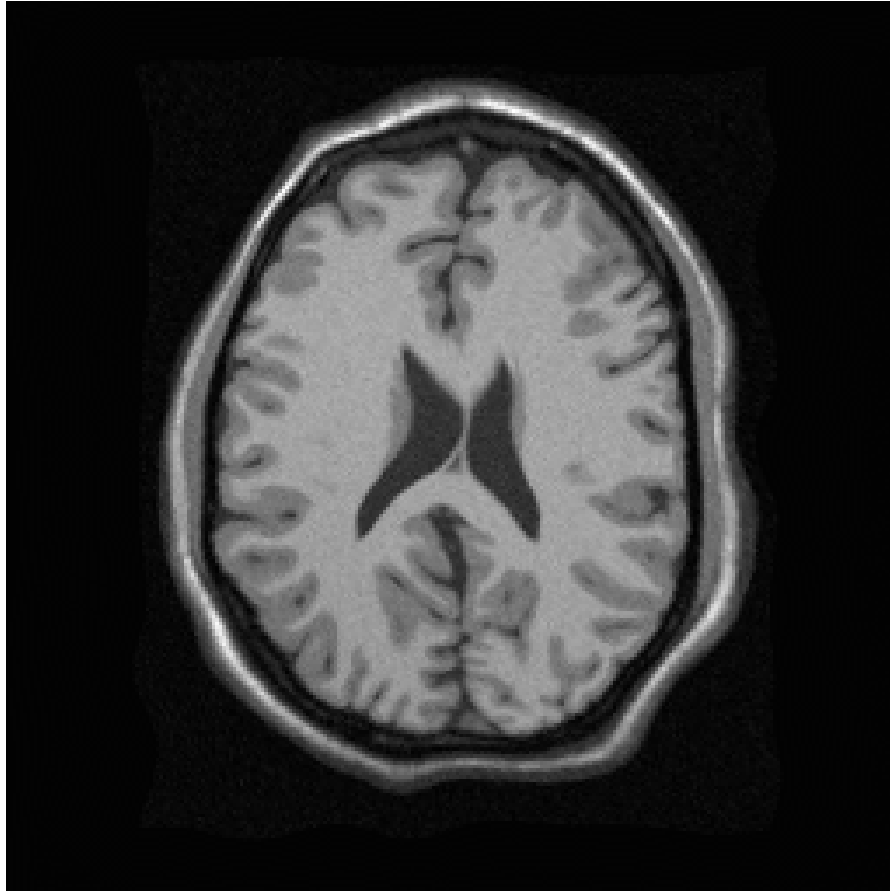


fixed image

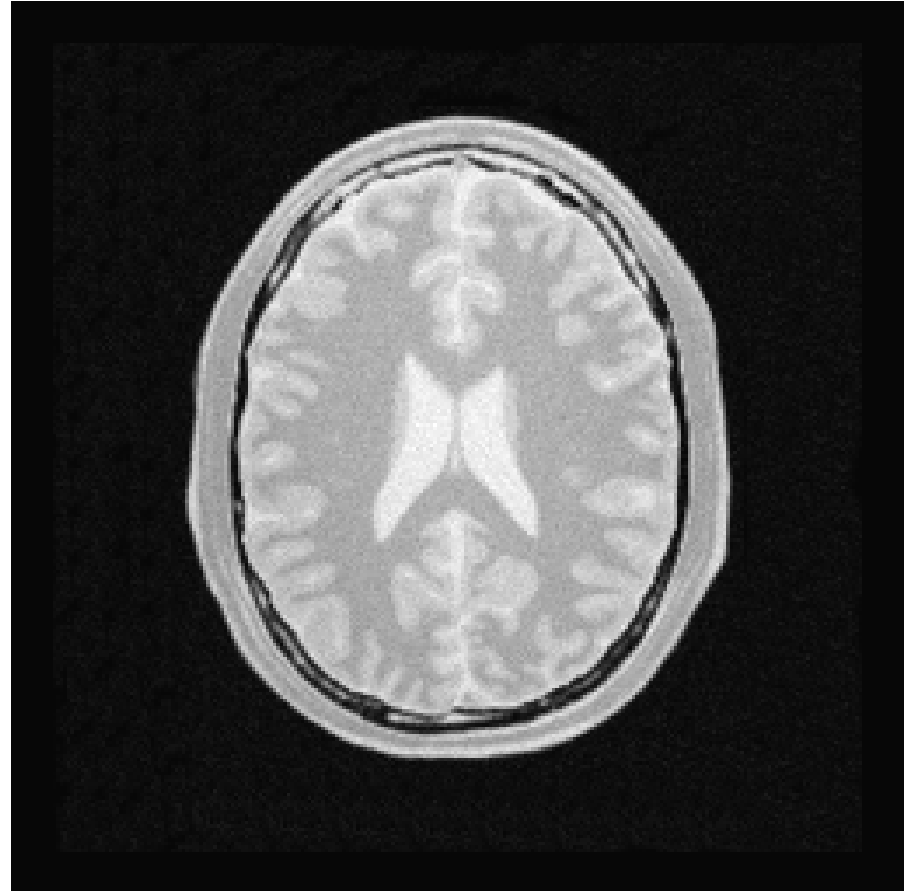


moving image

Example



fixed image



moving image

Math

- $F(\mathbf{x})$ = fixed image, $M(\mathbf{x})$ = moving image
 \mathbf{x} = voxel coordinate
- Transformation function: $T(\mathbf{x}; \mathbf{p})$
 \mathbf{p} = vector of transformation parameters
- Cost function: $C(\mathbf{p})$
measures similarity of fixed image $F(\mathbf{x})$ and
deformed moving image $M(T(\mathbf{x}; \mathbf{p}))$
- Find \mathbf{p} that minimises C

Iterative optimisation

$$\mathbf{p}_{k+1} = \mathbf{p}_k + a_k \cdot \mathbf{d}_k$$

\mathbf{d}_k = search direction

a_k = step size

gradient descent: $\mathbf{d}_k = -\frac{\partial C}{\partial \mathbf{p}}(\mathbf{p}_k) \equiv -\mathbf{g}_k$

Cost function derivative

Example for mean of squared differences:

$$\begin{aligned} C(\mathbf{p}) &= \frac{1}{N} \sum_{\mathbf{x}} (F(\mathbf{x}) - M(\mathbf{T}(\mathbf{x}; \mathbf{p})))^2 \\ \frac{\partial C}{\partial \mathbf{p}} &= -\frac{2}{N} \sum_{\mathbf{x}} (F(\mathbf{x}) - M(\mathbf{T}(\mathbf{x}; \mathbf{p}))) \frac{\partial M}{\partial \mathbf{p}} \\ &= -\frac{2}{N} \sum_{\mathbf{x}} (F(\mathbf{x}) - M(\mathbf{T}(\mathbf{x}; \mathbf{p}))) \left(\frac{\partial \mathbf{T}}{\partial \mathbf{p}} \right)^t \frac{\partial M}{\partial \mathbf{x}} \end{aligned}$$

Cost function derivative

Example for mean of squared differences, with projection step (2D-3D):

$$\begin{aligned} C(\mathbf{p}) &= \frac{1}{N} \sum_{\mathbf{x}} \left(F(\mathbf{x}) - \int_{\mathbf{r} \in \text{RAY}[\mathbf{x}]} M(\mathbf{T}(\mathbf{r}; \mathbf{p})) d\mathbf{r} \right)^2 \\ \frac{\partial C}{\partial \mathbf{p}} &= -\frac{2}{N} \sum_{\mathbf{x}} \left(F(\mathbf{x}) - \int_{\mathbf{r} \in \text{RAY}[\mathbf{x}]} M(\mathbf{T}(\mathbf{r}; \mathbf{p})) d\mathbf{r} \right) \int_{\mathbf{r} \in \text{RAY}[\mathbf{x}]} \frac{\partial M}{\partial \mathbf{p}} d\mathbf{r} \\ &= -\frac{2}{N} \sum_{\mathbf{x}} \left(F(\mathbf{x}) - \int_{\mathbf{r} \in \text{RAY}[\mathbf{x}]} M(\mathbf{T}(\mathbf{r}; \mathbf{p})) d\mathbf{r} \right) \int_{\mathbf{r} \in \text{RAY}[\mathbf{x}]} \left(\frac{\partial \mathbf{T}}{\partial \mathbf{p}} \right)^t \frac{\partial M}{\partial \mathbf{x}} d\mathbf{r} \end{aligned}$$

Choice of d_k

$$\mathbf{p}_{k+1} = \mathbf{p}_k + a_k \cdot \mathbf{d}_k$$

gradient descent: $\mathbf{d}_k = -\mathbf{g}_k$

Newton: $\mathbf{d}_k = -[\mathbf{H}_k]^{-1} \mathbf{g}_k$

quasi-Newton: $\mathbf{d}_k = -\mathbf{B}_k \mathbf{g}_k$

conjugate gradient: $\mathbf{d}_k = -\mathbf{g}_k + \beta_k \mathbf{d}_{k-1}$

stochastic gradient: $\mathbf{d}_k \approx -\mathbf{g}_k$

} smarter steps

→ cheaper steps

Choice of a_k

$$\mathbf{p}_{k+1} = \mathbf{p}_k + a_k \cdot \mathbf{d}_k$$

constant: $a_k = a$

slowly decaying: $a_k = f(k) = a / (A + k)^\alpha$

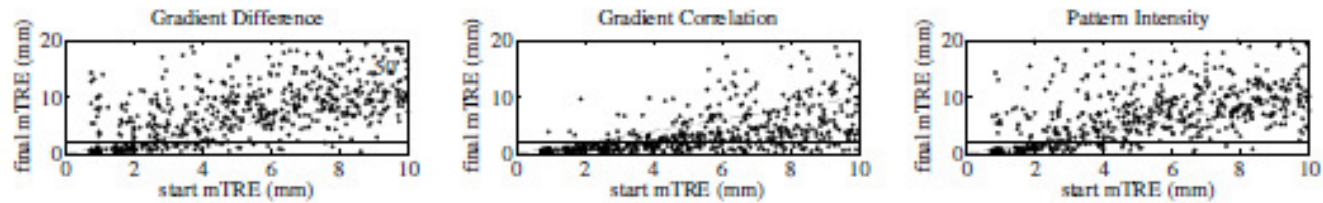
exact line search: $a_k = \operatorname{argmin}_a C(\mathbf{p}_k + a \mathbf{d}_k)$

inexact line search: $a_k \approx \operatorname{argmin}_a C(\mathbf{p}_k + a \mathbf{d}_k)$ *[Wolfe conditions]*

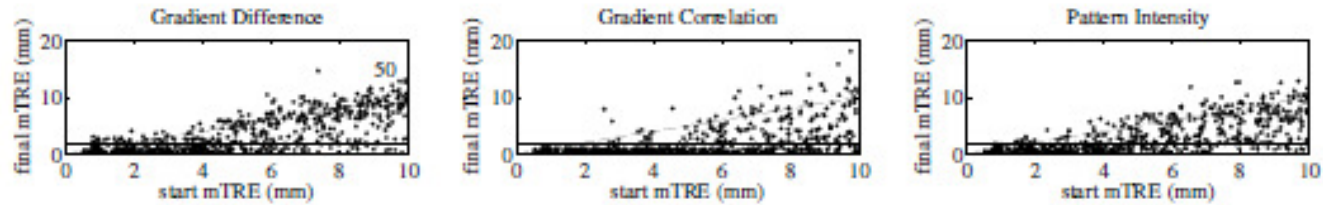
adaptive: $a_k = F(\text{progress in previous iterations})$

Literature

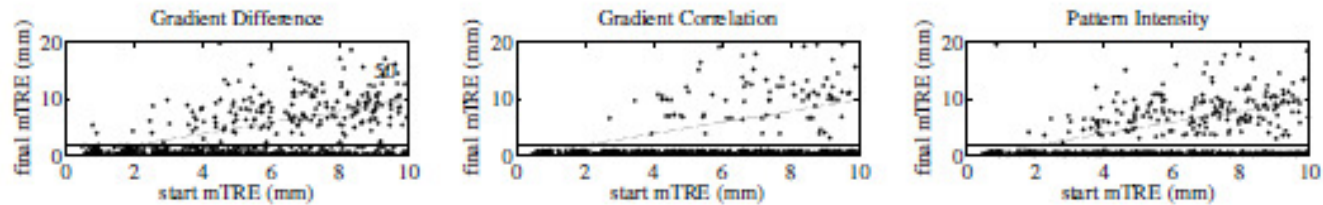
- Nocedal & Wright: Numerical Optimization
- IEEE Trans. Image Processing 2007 - Klein, Staring, Pluim
Evaluation of optimization methods for nonrigid medical image registration using mutual information and B-splines
- IEEE Trans. Image Processing 2000 - Thevenaz, Unser
Optimization of mutual information for multiresolution image registration
- SPIE2011 – van der Bom, Klein, Staring, Homan, Bartels Pluim
Evaluation of optimization methods for intensity-based 2-D-3D registration in X-ray guided interventions



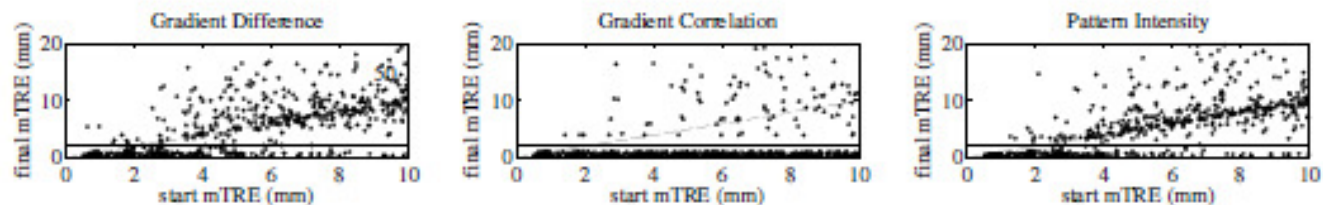
(a) Gradient descent ($o_{GD} = 18, o_{GC} = 3, o_{PI} = 15$)



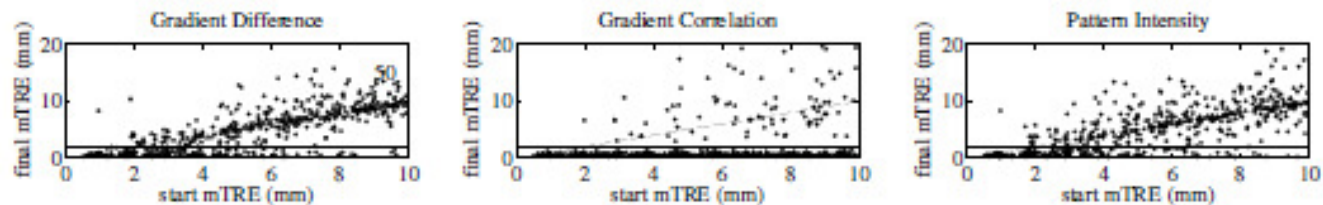
(b) Nelder-Mead ($o_{GD} = 0, o_{GC} = 0, o_{PI} = 0$)



(c) Powell-Brent ($o_{GD} = 9, o_{GC} = 11, o_{PI} = 8$)



(d) Quasi-Newton ($o_{GD} = 9, o_{GC} = 18, o_{PI} = 4$)



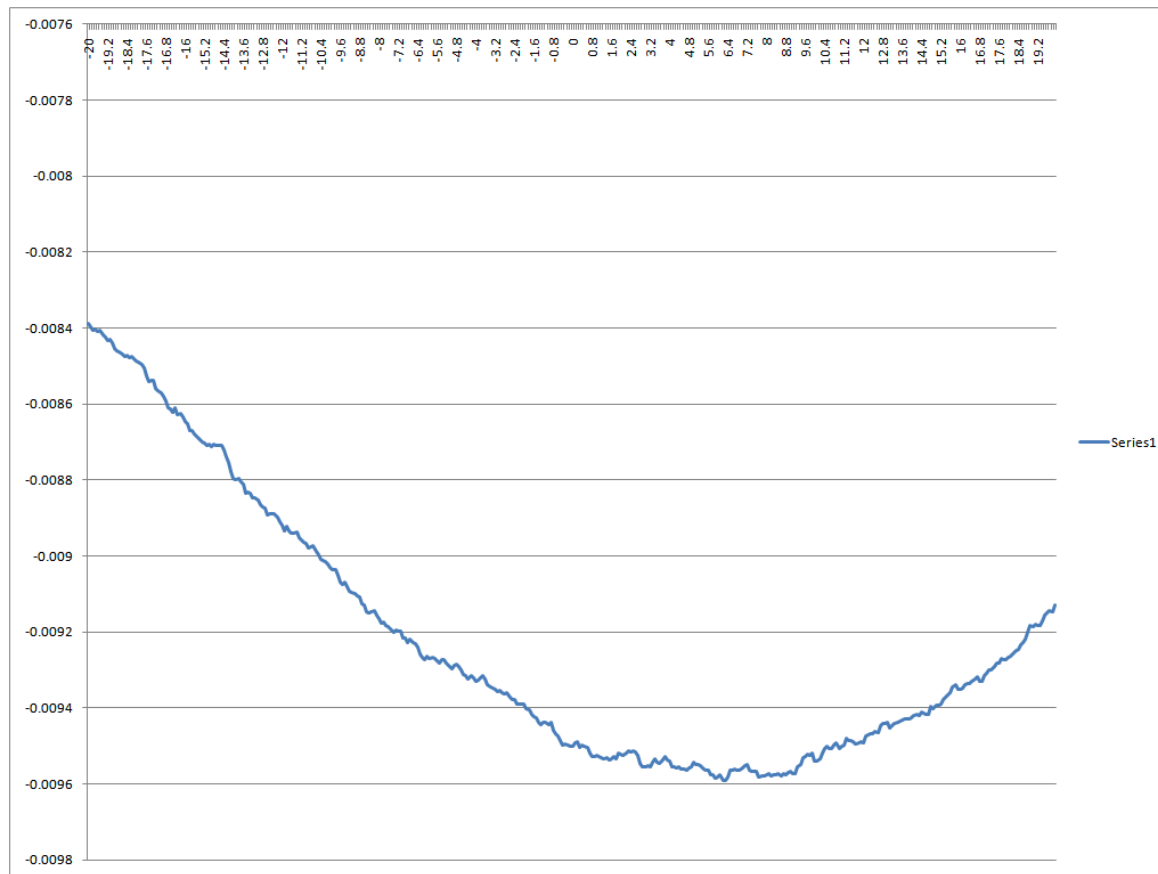
(e) Nonlinear conjugate gradient ($o_{GD} = 11, o_{GC} = 31, o_{PI} = 9$)

Pitfalls

- Cost function is not smooth
- Cost function is badly scaled
- Capture range too small

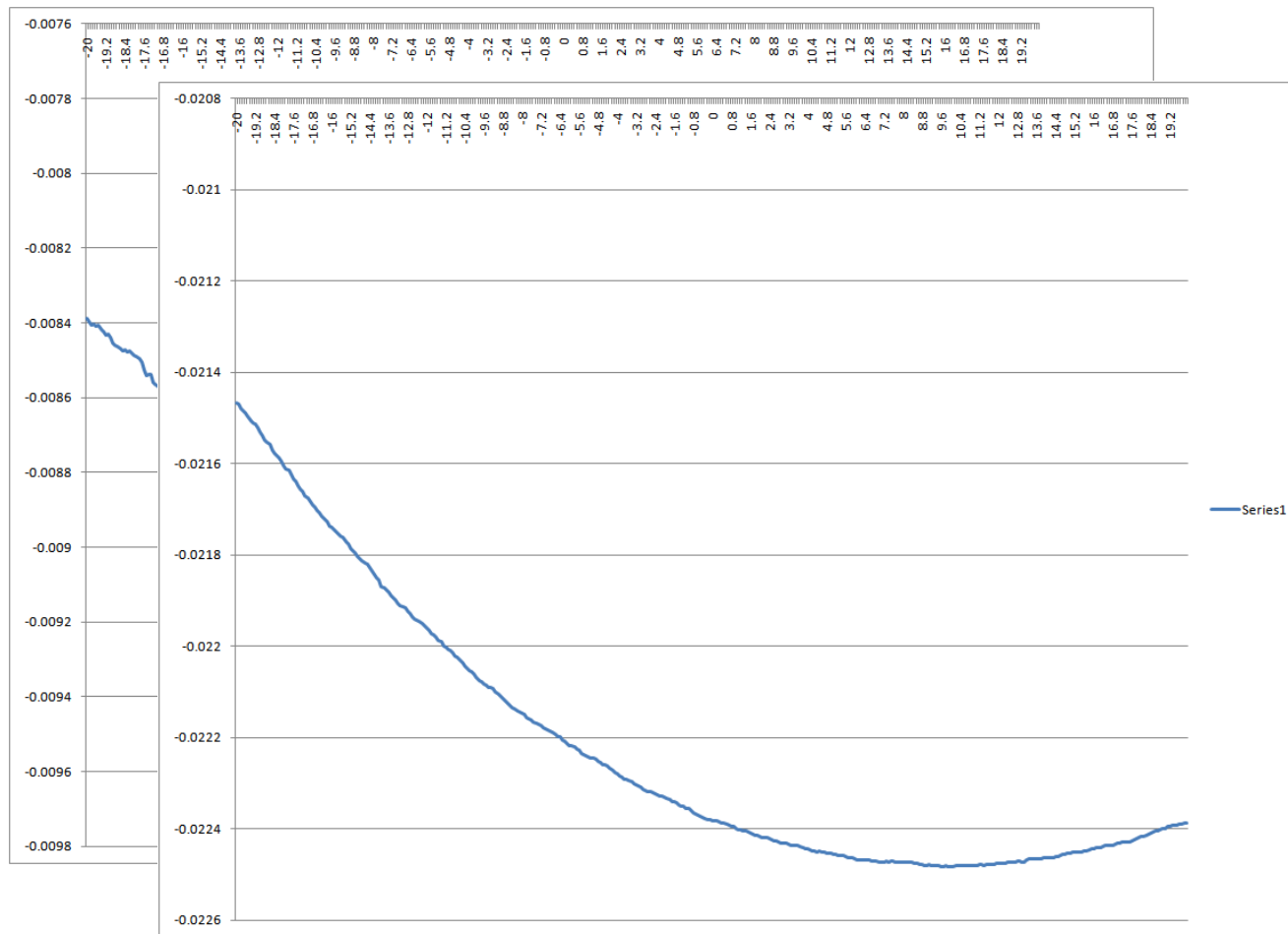
Pitfalls

- Cost function is not smooth



Pitfalls

- Cost function is not smooth



Pitfalls

- Cost function is not smooth
 - Cost function is badly scaled
 - Capture range too small
-

Pitfalls

- Cost function is not smooth
- Cost function is badly scaled
 - Use Hessian (Newton-like algorithm)
 - Scale parameters such that average $\| d\mathbf{T} / d\mathbf{p}_i \|$ is equal for all i
- Capture range too small

Pitfalls

- Cost function is not smooth
- Cost function is badly scaled
- Capture range too small

Pitfalls

- Cost function is not smooth
- Cost function is badly scaled
- Capture range too small
 - Add information: prior motion model, additional images (bi-plane x-ray), landmarks, regularisation...
 - Multiresolution strategies
 - Global optimisation methods? (usually less time-efficient)

Example

2D+t X-ray time sequence

3D+t coronary motion model
from dynamic CTA

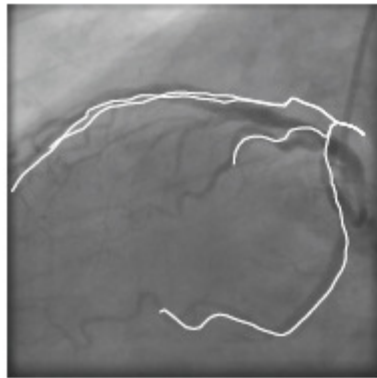


p0005x.avi

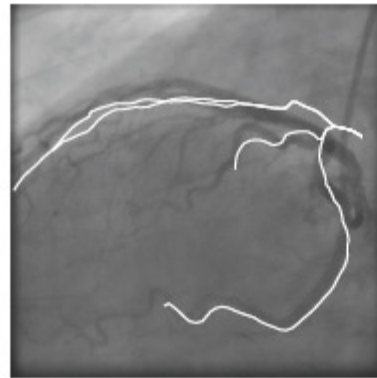


p0005.avi

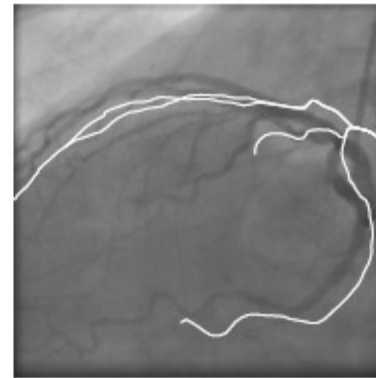
Example



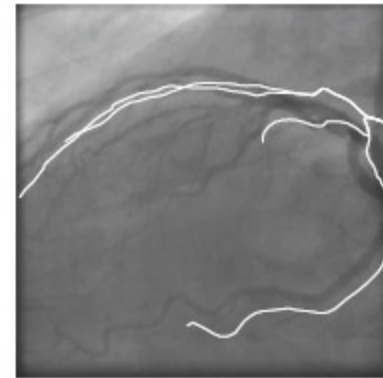
(a) 3-2 (L), 25%, before



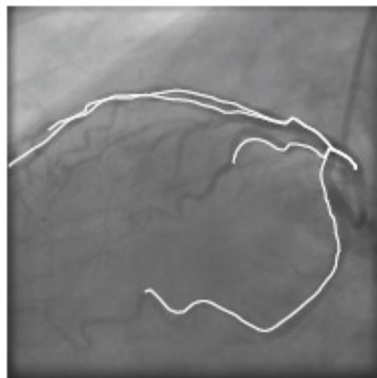
(b) 3-2 (L), 50%, before



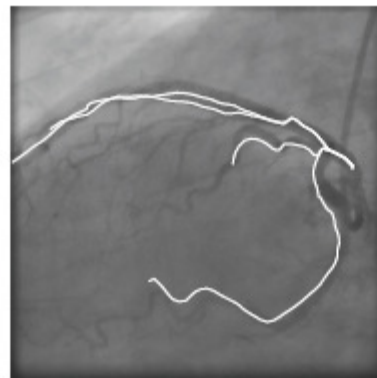
(c) 3-2 (L), 75%, before



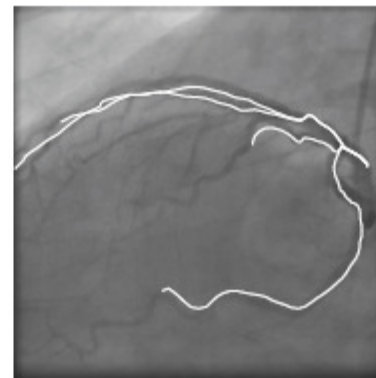
(d) 3-2 (L), 100%, before



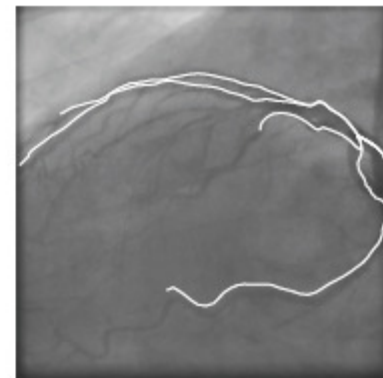
(e) 3-2 (L), 25%, after



(f) 3-2 (L), 50%, after



(g) 3-2 (L), 75%, after



(h) 3-2 (L), 100%, after

For more details:

- Augmented Environments for Computer Assisted Interventions
 - Oral presentation session III.
 - September 22 2.45 - 3pm
 - Alignment of 4D Coronary CTA with Monoplane X-Ray Angiography
 - Coert Metz, Michiel Schaap, Stefan Klein, Peter Rijnbeek, Lisan Neefjes, Nico Mollet, Carl Schultz, Patrick Serruys, Wiro Niessen and Theo van Walsum
-

elasti



- Rigid and nonrigid registration
 - Various cost functions, transformation models, multiresolution strategies etc.
 - Many optimisation algorithms implemented
 - Free: <http://elastix.isi.uu.nl>
 - Based on Insight ToolKit (ITK): <http://www.itk.org>
 - IEEE Trans. Medical Imaging 2010 - Klein, Staring, Murphy, Viergever, Pluim — elastix: a toolbox for intensity based medical image registration
-

Experimental comparison

- gradient descent
- quasi-Newton
- conjugate gradient
- stochastic gradient

