

OMA workshop – Mar 12, 2018

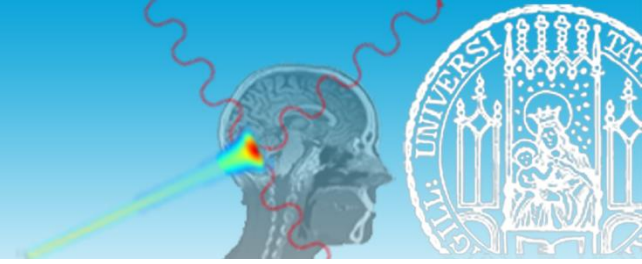
3D motion detection in medical applications

Marco Riboldi

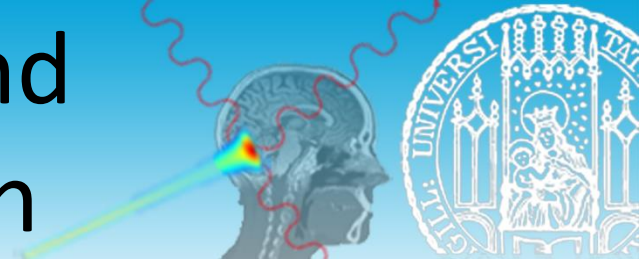
Ludwig-Maximilians-Universität München (LMU Munich)

Department of Experimental Physics - Medical Physics

Outline



- Intro on 3D localization
- From 3D localization to motion detection
- Motion detection in external beam therapy
 - External surface
 - Internal anatomy
 - Combined approaches

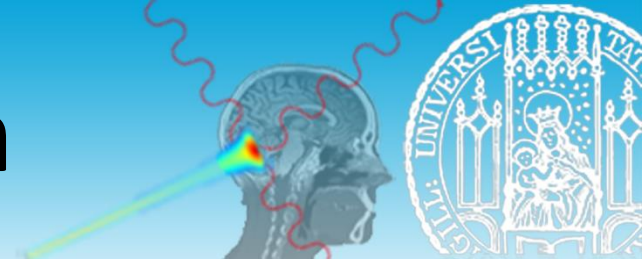


3D motion detection:

- **External surface**
 - Point-based localization
 - Surface imaging
- **Internal anatomy**
 - Implanted landmarks
 - Imaging

**Combined
approaches**

3D localization

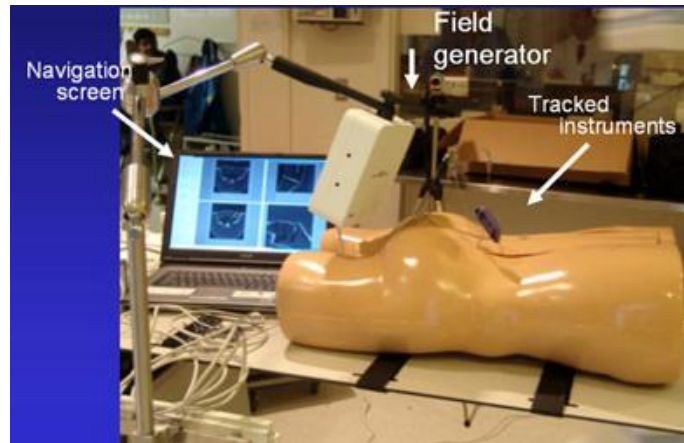


✓ **3D localization systems:**

- measure specific surface markers (landmarks)
- 3 basic technologies



**Mechanical
(digitizer)**



**Electromagnetic
(EM)**

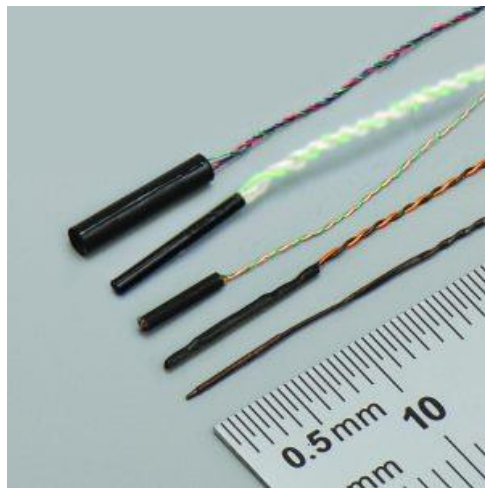


**Optical
(active/passive markers)**

EM tracking



The **Field Generator** emits a **low-intensity, varying electromagnetic field** and establishes the **position of the tracking volume**



Sensors: induced coil voltage is readout to determine the **sensor spatial location** based on the prior knowledge of strength and phase of the exciting field.



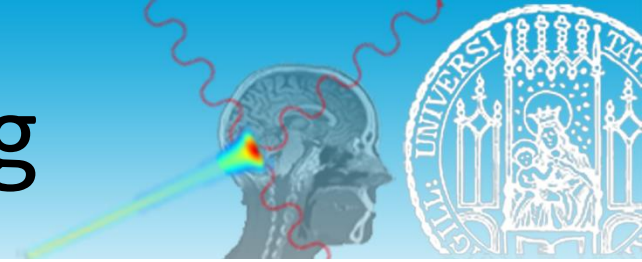
EM performance



	Cube Volume		Dome Volume	
	RMS	95% CI	RMS	95% CI
Accuracy – 5DOF Sensors*				
Position	0.70 mm	1.40 mm	1.10 mm	2.00 mm
Orientation	0.20°	0.35°	0.20°	0.40°
Accuracy – 6DOF Sensors*				
Position	0.48 mm	0.88 mm	0.70 mm	1.40 mm
Orientation	0.30°	0.48°	0.30°	0.55°

*All data collected with the Aurora V2 System in an environment free of electromagnetic disturbances. Accuracy depends on tool design and the presence of metal.

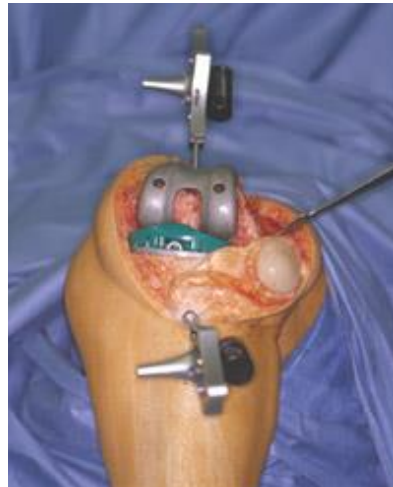
Optical tracking



- ✓ **Optical** (infrared, IR) system for motion tracking
 - actual **standard in medical applications**
 - computer vision techniques are applied for point (**marker**) localization
 - **accurate, real-time, 3D**
 - **visibility** needs to be ensured for reconstruction



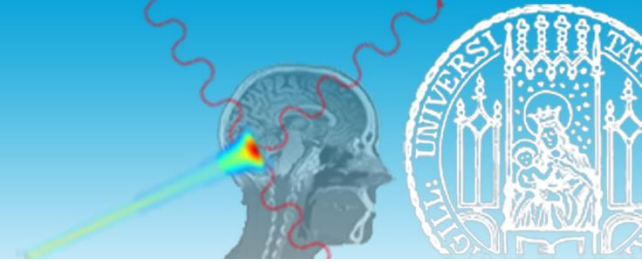
*Active markers
(cabled)*



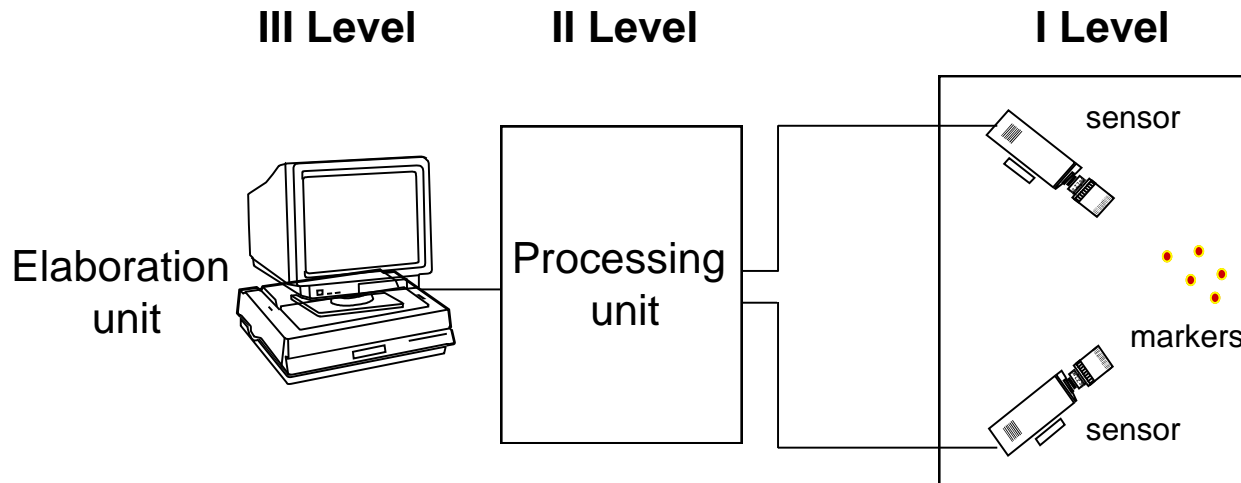
*Active markers
(wireless)*



Passive markers



✓ *IR optical tracker*



- optical component: **CCD TV cameras** (high frequency)
- image processing (**marker recognition**)
- marker **classification** and **tracking**
- **3D reconstruction**

Optical sensors



✓ IR *optical tracker*:

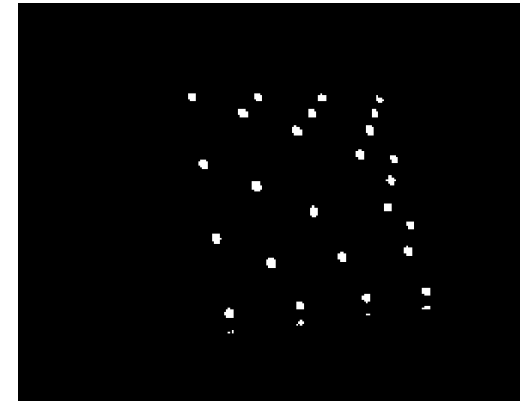
- optical component:
 - CCD TV cameras CCD (frequency 50-100 Hz)
 - IR illumination (760 nm) for passive markers
 - passive markers: plastic spheres /emispheres covered with reflective coating (3M Scotchlite™)
 - different size (2-20 mm radius)
 - self-adhesive or through support



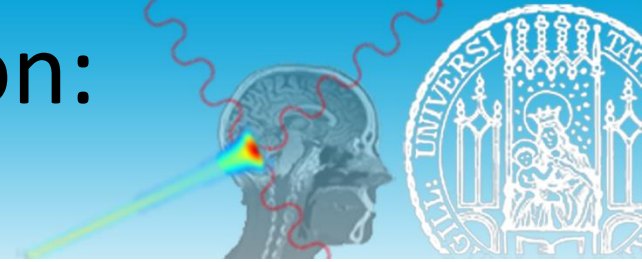
Marker recognition: threshold



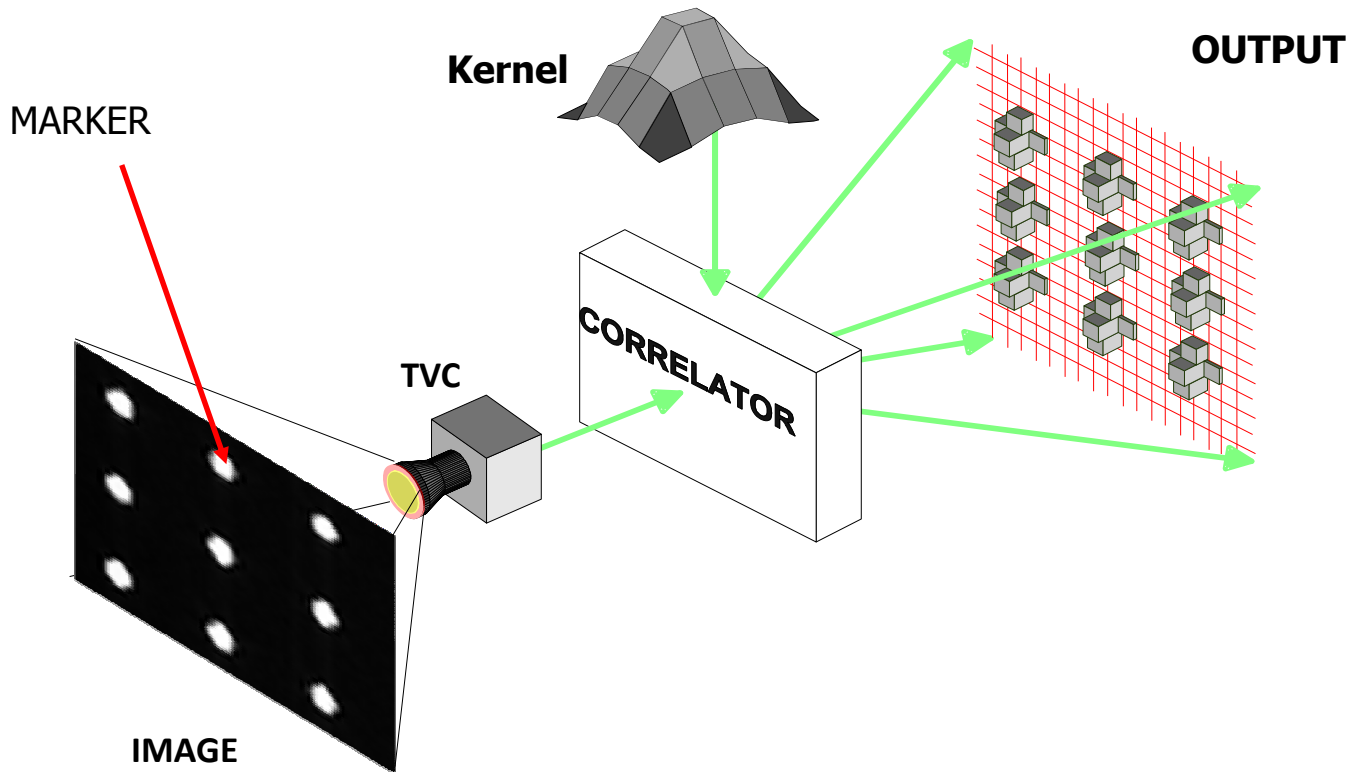
✓ IR *optical tracker*: threshold recognition (binarization)



Marker recognition: shape



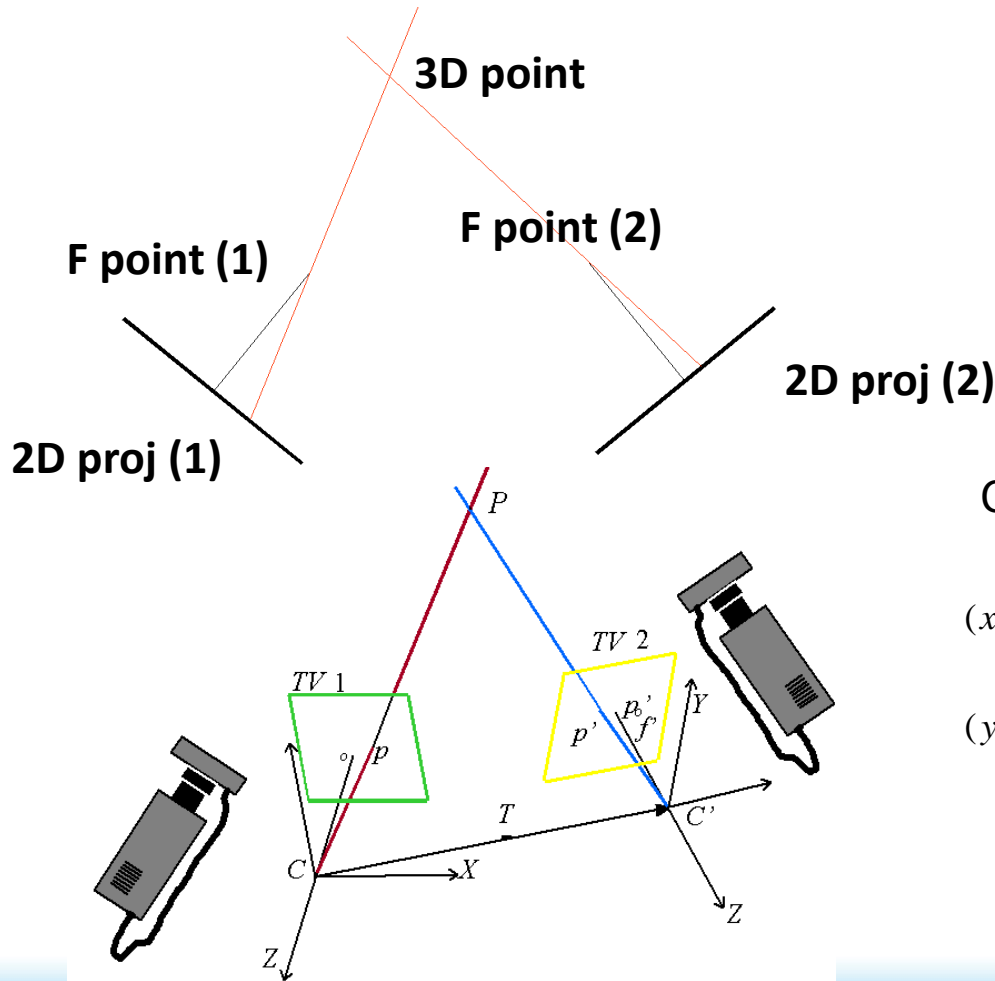
- ✓ IR *optical tracker*: shape recognition (correlation)
 - *output*: local correlation value with the kernel
(above threshold)



3D reconstruction



✓ IR *optical tracker*: stereometric 3D reconstruction

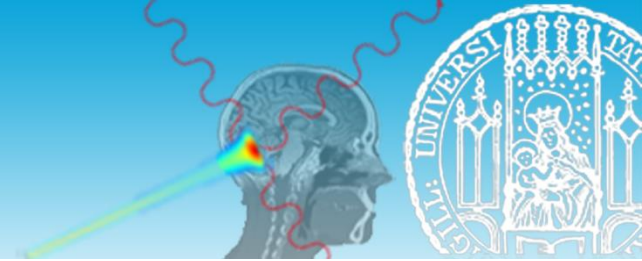


Colinearity equation: projective model

$$(x - x_0) = -c \frac{m_{11}(X - X_0) + m_{12}(Y - Y_0) + m_{13}(Z - Z_0)}{m_{31}(X - X_0) + m_{32}(Y - Y_0) + m_{33}(Z - Z_0)};$$

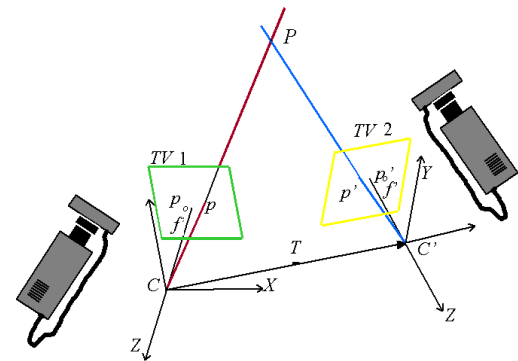
$$(y - y_0) = -c \frac{m_{21}(X - X_0) + m_{22}(Y - Y_0) + m_{23}(Z - Z_0)}{m_{31}(X - X_0) + m_{32}(Y - Y_0) + m_{33}(Z - Z_0)};$$

Model for 3D reconstruction



✓ Stereo-photogrammetry concepts:

- 9 parameters for each TVC:
 - X_0, Y_0, Z_0 : TVC position
 - $m_{11} \dots m_{33}$ TVC orientation matrix
(3 free parameters, i.e. angles)
 - c (f in figure): focal length
 - x_0, y_0 , principal point (projection of focal point on the sensor plane)



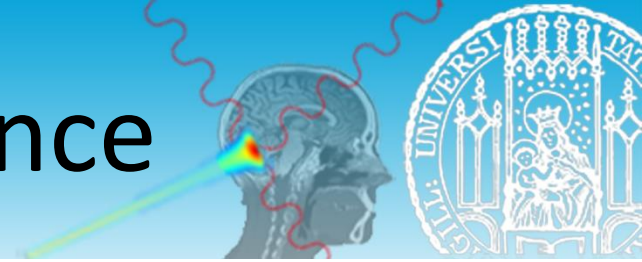
$$(x - x_0) = -c \frac{m_{11}(X - X_0) + m_{12}(Y - Y_0) + m_{13}(Z - Z_0)}{m_{31}(X - X_0) + m_{32}(Y - Y_0) + m_{33}(Z - Z_0)};$$

$$(y - y_0) = -c \frac{m_{21}(X - X_0) + m_{22}(Y - Y_0) + m_{23}(Z - Z_0)}{m_{31}(X - X_0) + m_{32}(Y - Y_0) + m_{33}(Z - Z_0)};$$



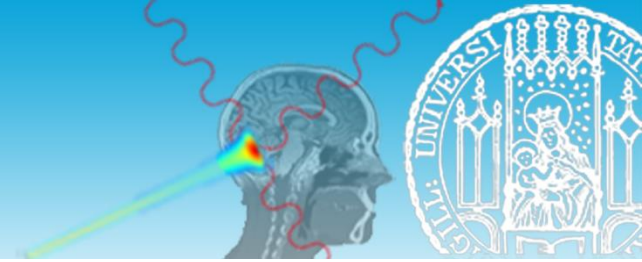
LUDWIG-
MAXIMILIANS-
UNIVERSITÄT
MÜNCHEN

Optical performance



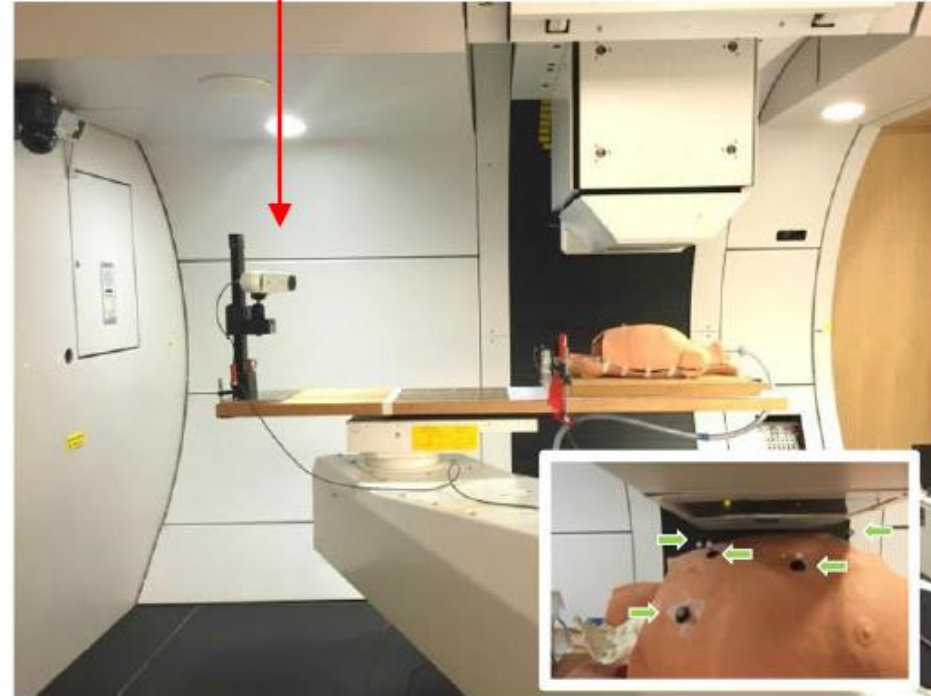
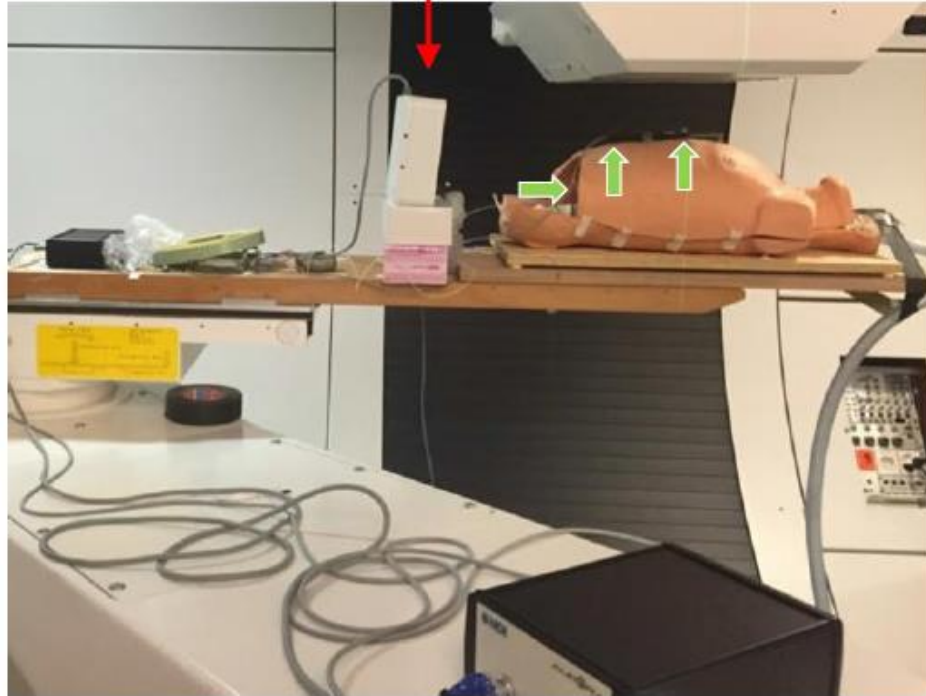
	Hybrid Polaris Spectra [®]	Passive Polaris Spectra [®]	Polaris Vicra [®]
Performance			
Accuracy:			
Volumetric ^{1,2}	Pyramid: 0.25 mm RMS Extended Pyramid: 0.30 mm RMS ²		0.25 mm RMS
AAK	0.35 mm RMS		0.35 mm RMS
95% Confidence Interval	Pyramid: 0.5 mm Extended Pyramid: 0.6 mm		0.5 mm
Maximum Update Rate ³	60 Hz		20 Hz
Operating Temperature ⁴	10C° to 40°C		10°C to 30°C
Measurement Volume	Pyramid and Extended Pyramid		Vicra Volume

EM / optical comparison

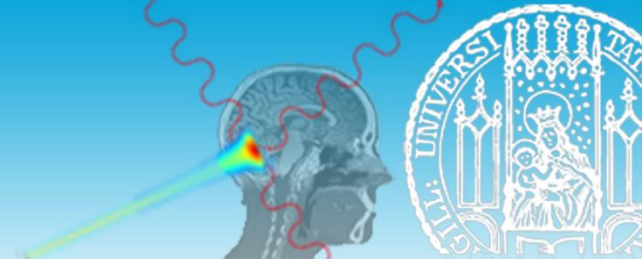


EMTS EM
generator

OTS
sensor

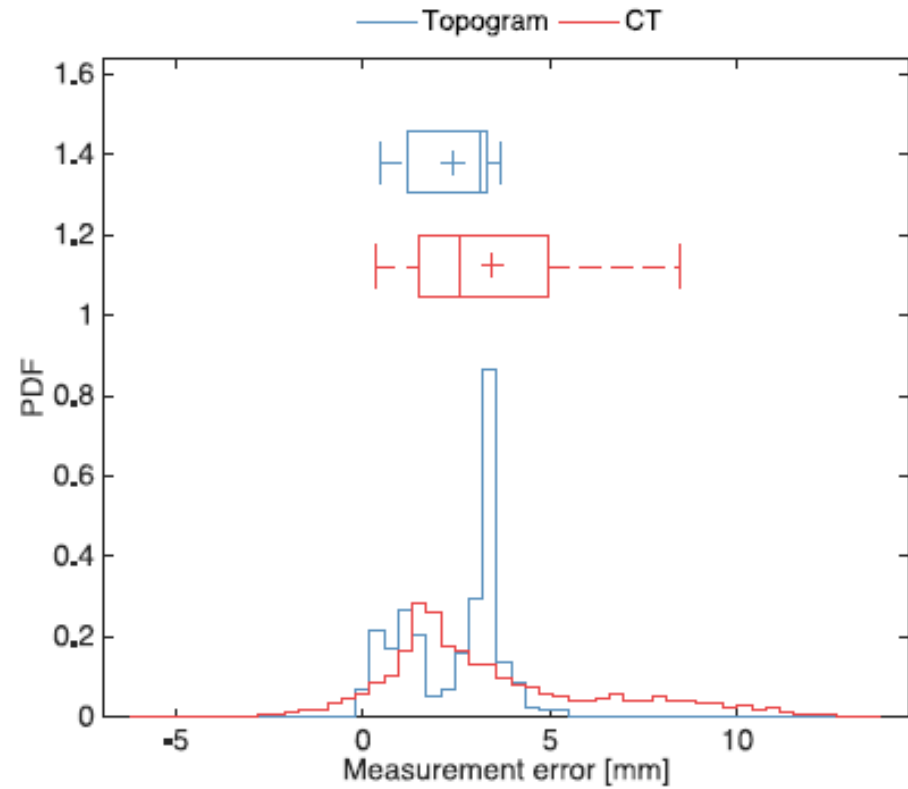
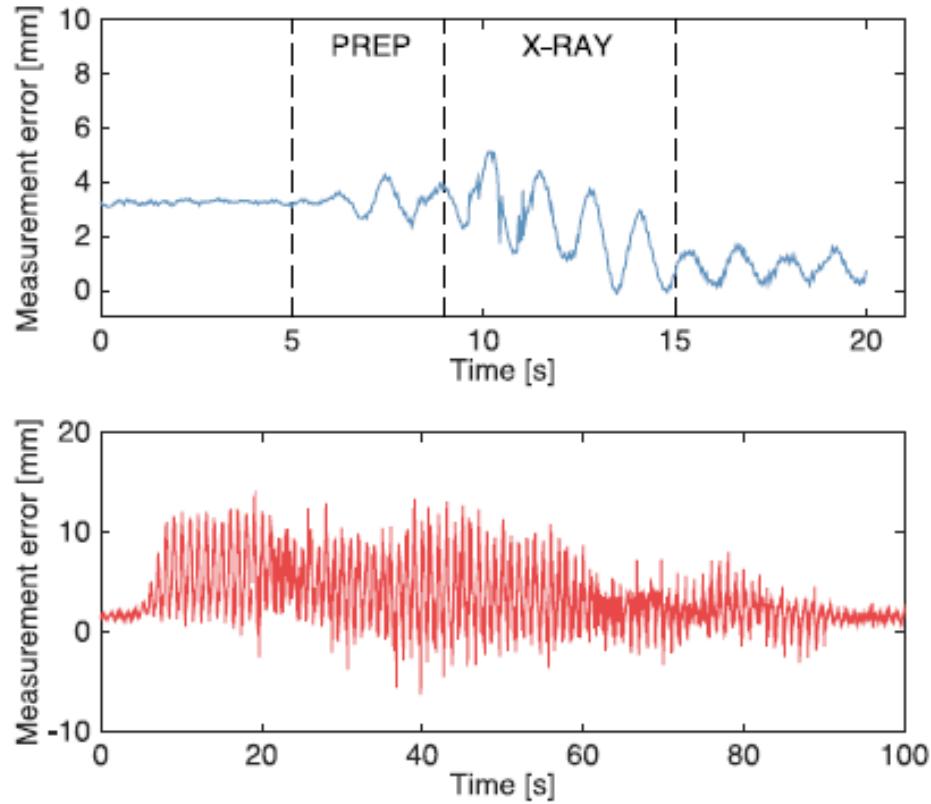
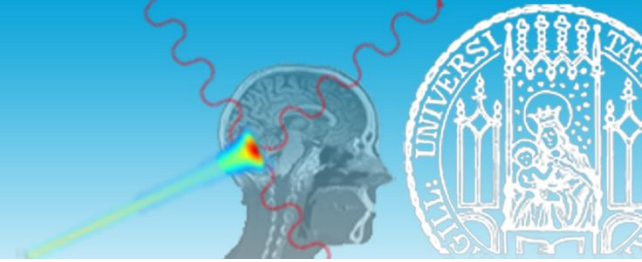


EM / optical comparison

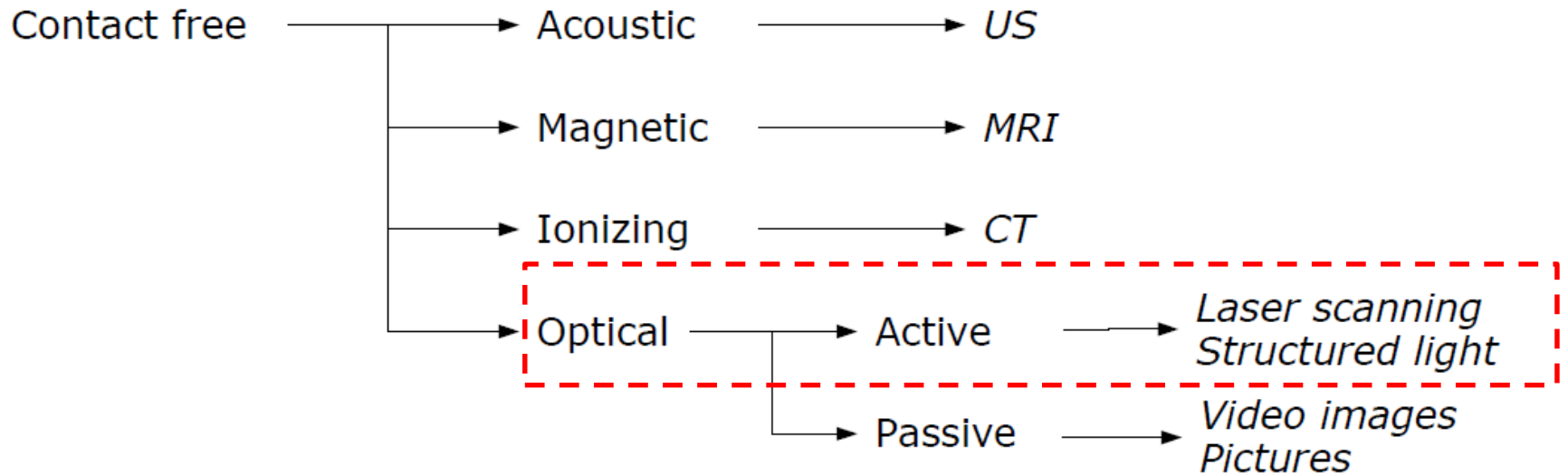
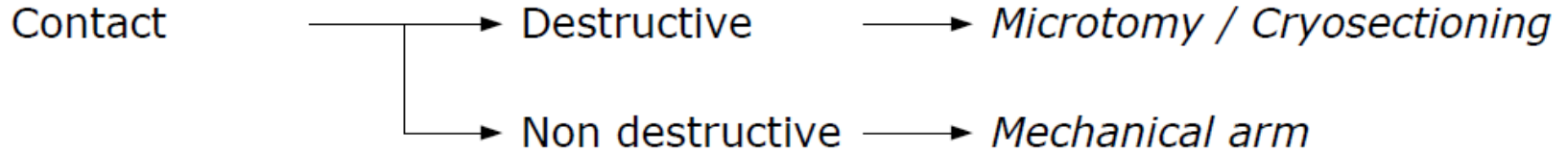
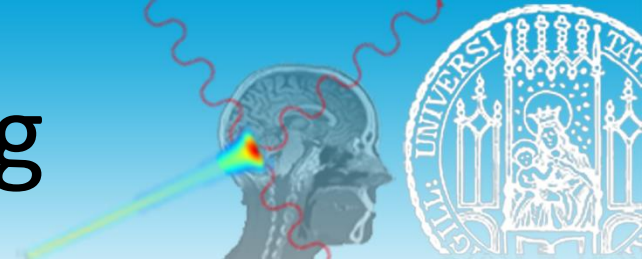


- **Sub-mm accuracy** in controlled lab conditions.
- The measurement error in case of **close proximity to a CT scanner** is up to 10.5 mm and precludes its use for the monitoring of respiratory motion during 4DCT acquisitions.
- Similarly, the **motion of the treatment gantry** distorts up to 22 mm the tracking result.

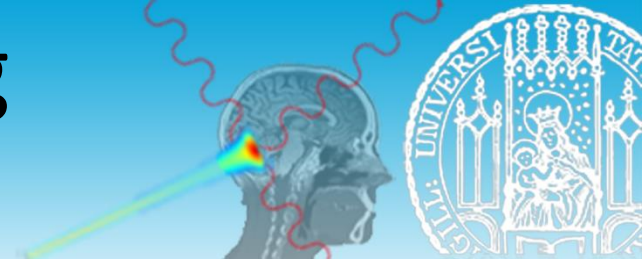
EM / optical comparison



Surface imaging



Surface imaging applications



Manufacturing

- Quality control
- Virtual reality
- Reverse engineering
- Custom prototyping
- ...

Arts

- Virtual databases
- Statue replicas
- ...

Biomedical Applications

- Planning and simulation of the surgical intervention
- Surgical outcome assessment
- Custom prosthesis and orthosis
- 3D morphologic analysis
- 3D antropometry
- ...

Forensic pathology

- Wounds reconstruction
- Face reconstruction
- 3D crime scene analysis
- ...

- ...
- ...
- ...

Example: reconstructive surgery

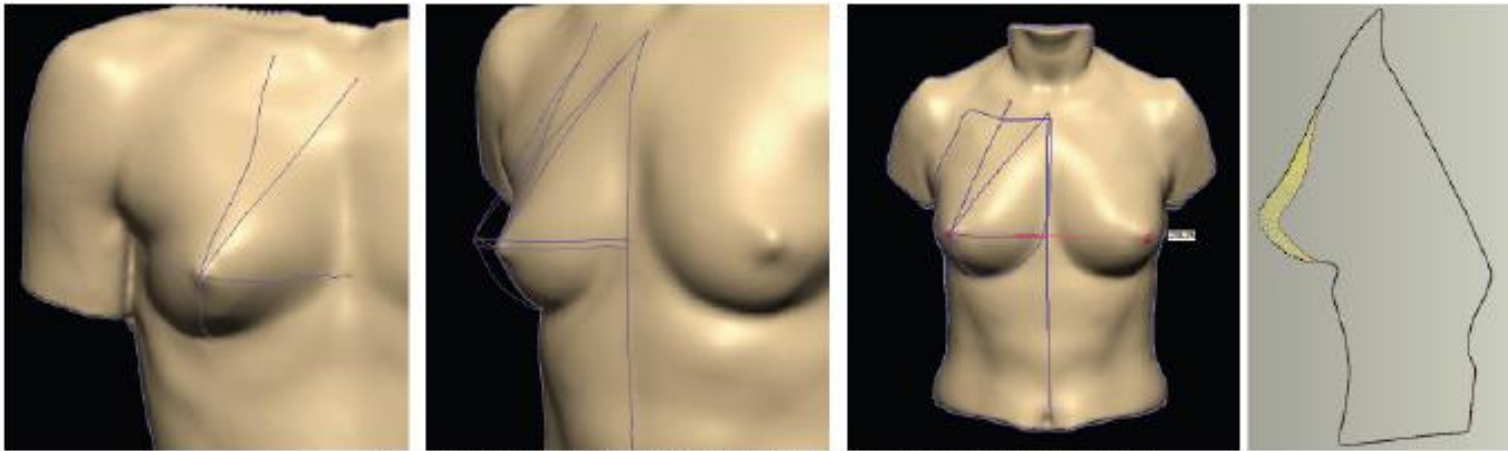
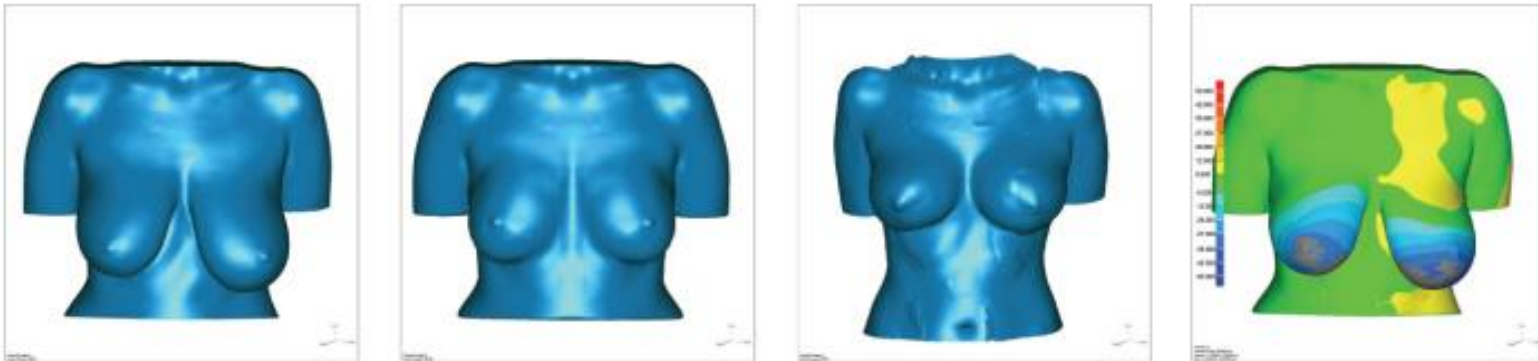


Fig. 2 3-D virtual planning of breast augmentation surgery



Laser scanners



Pros:

- Speed: complete scan in $\sim 2.5s$
- Accuracy: 3D error $\sim 0.01mm$

Cons:

- Multiple scans needed



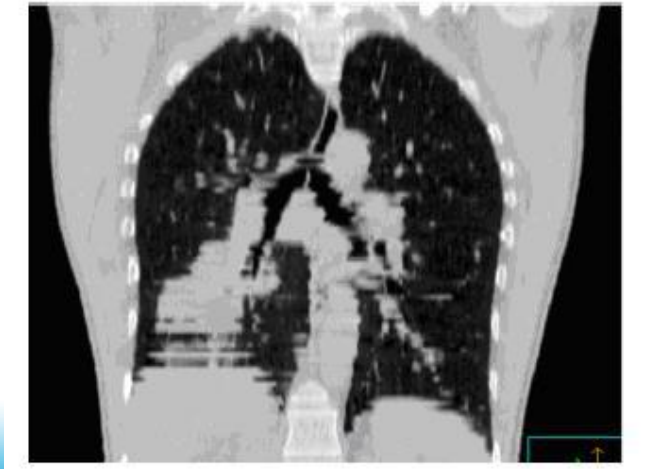
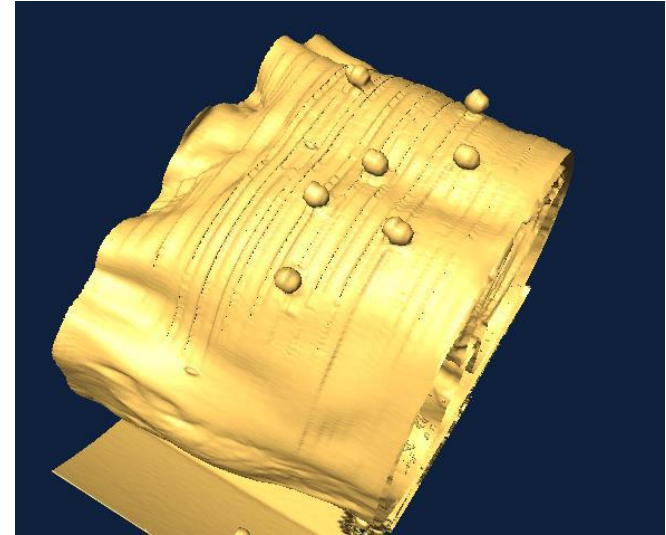
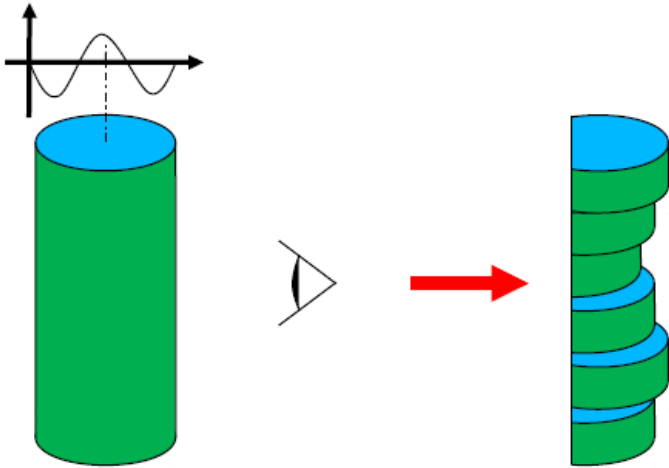
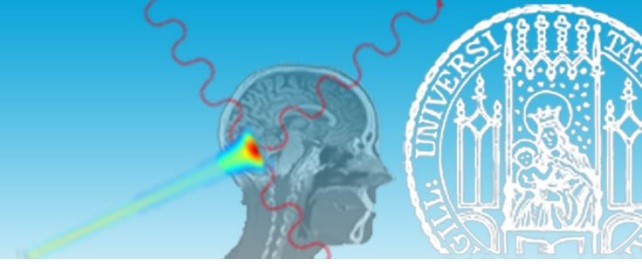
Pros:

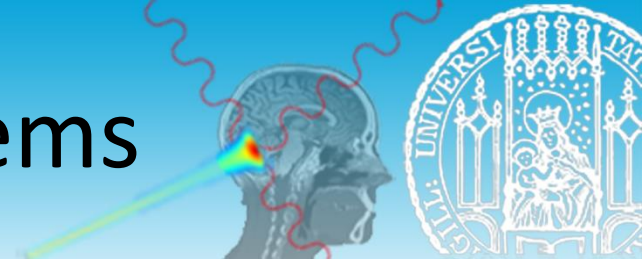
- Single scan
- Accuracy: 3D error $\sim 0.01mm$

Cons:

- Tracking of the scanning system
- Long acquisitions

Motion issues





Interferometry

Structured light

Pros:

- Speed
- Precision
- Accuracy (0.1 mm)

Cons:

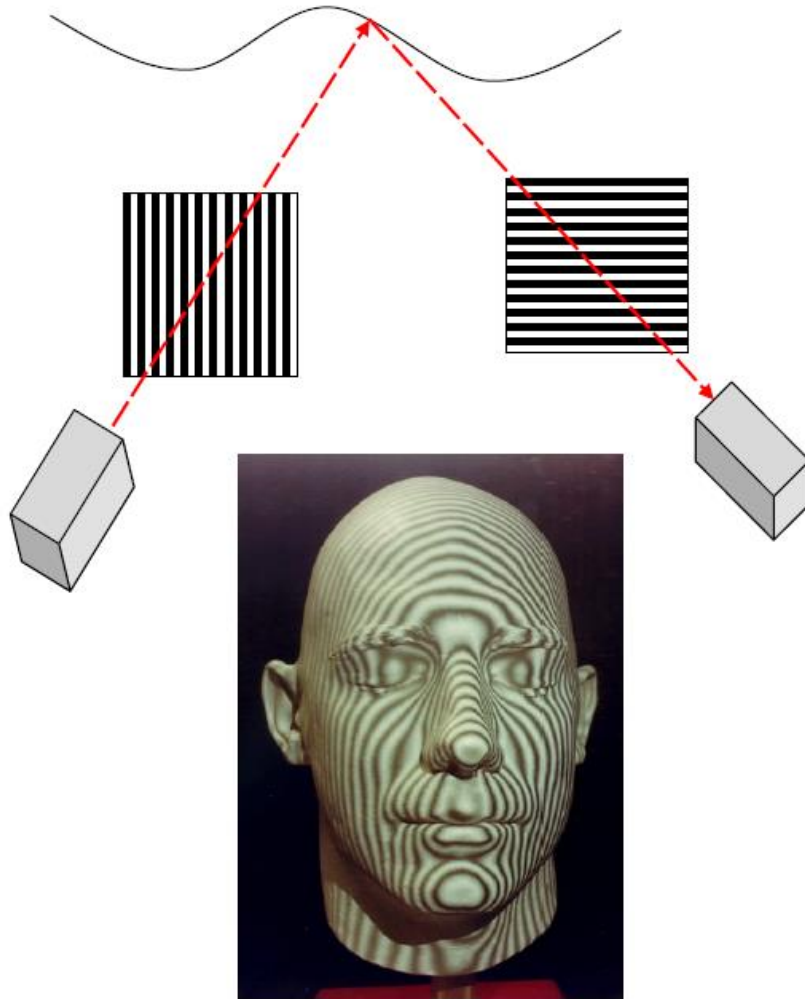
- Illumination and color sensitivity
- *Cost!!!*



Light patterns



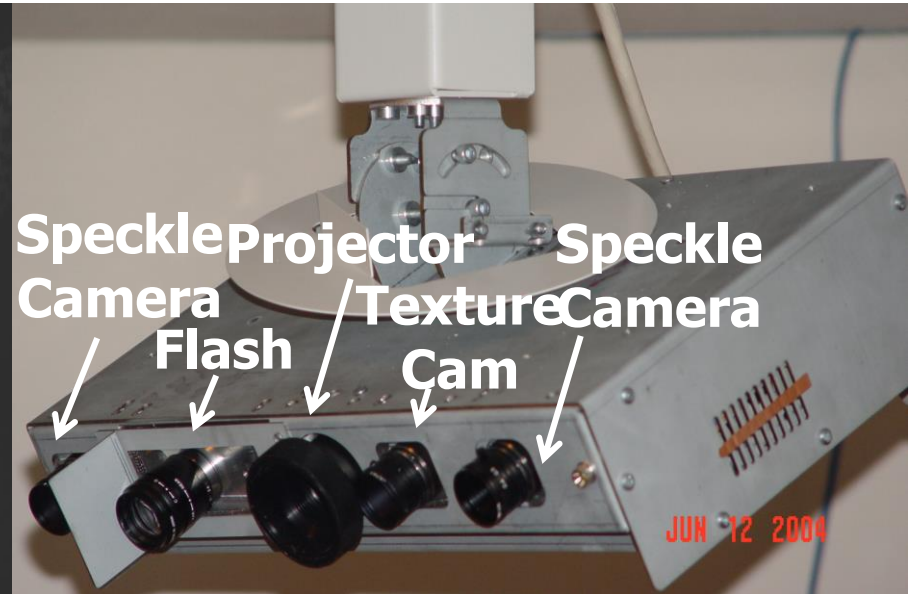
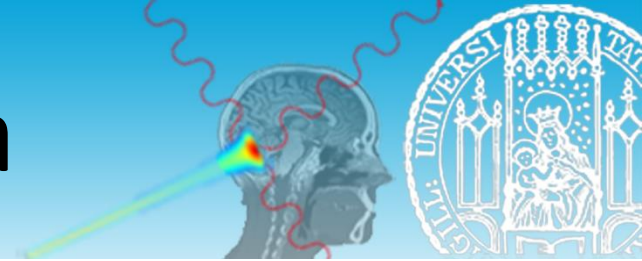
Interferometry



Structured light



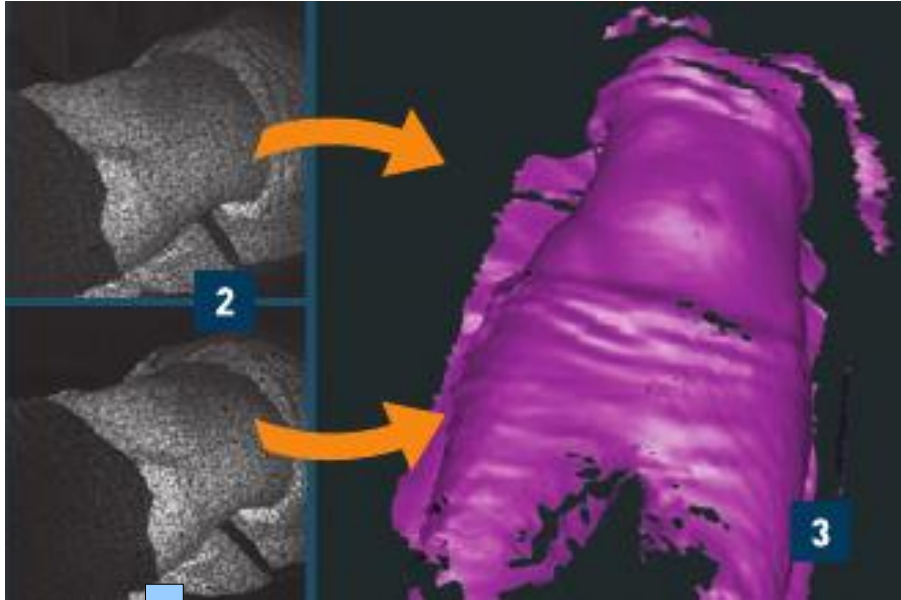
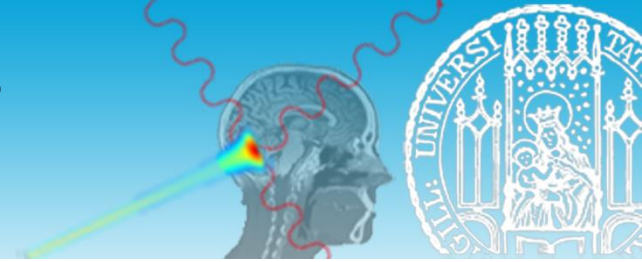
Stereo-camera



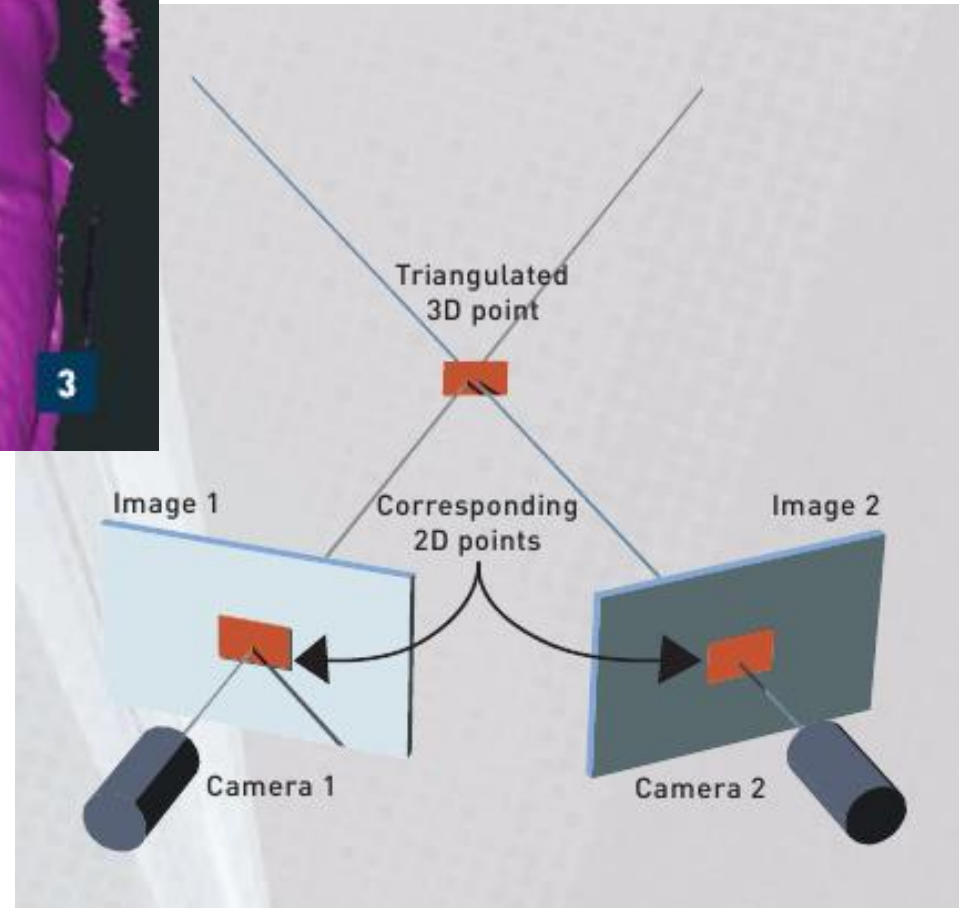
Operational modes:

- visible light (flash)
- near infrared (no flash)

Stereo-cameras reconstruction



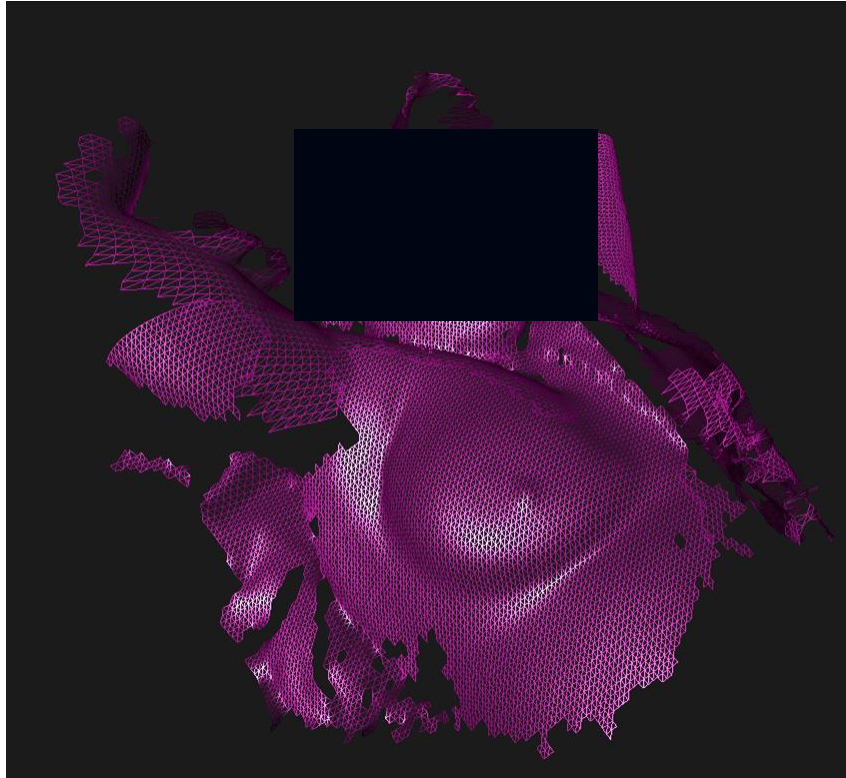
- Correspondent points on speckle cameras
- 3D stereo-photogrammetry



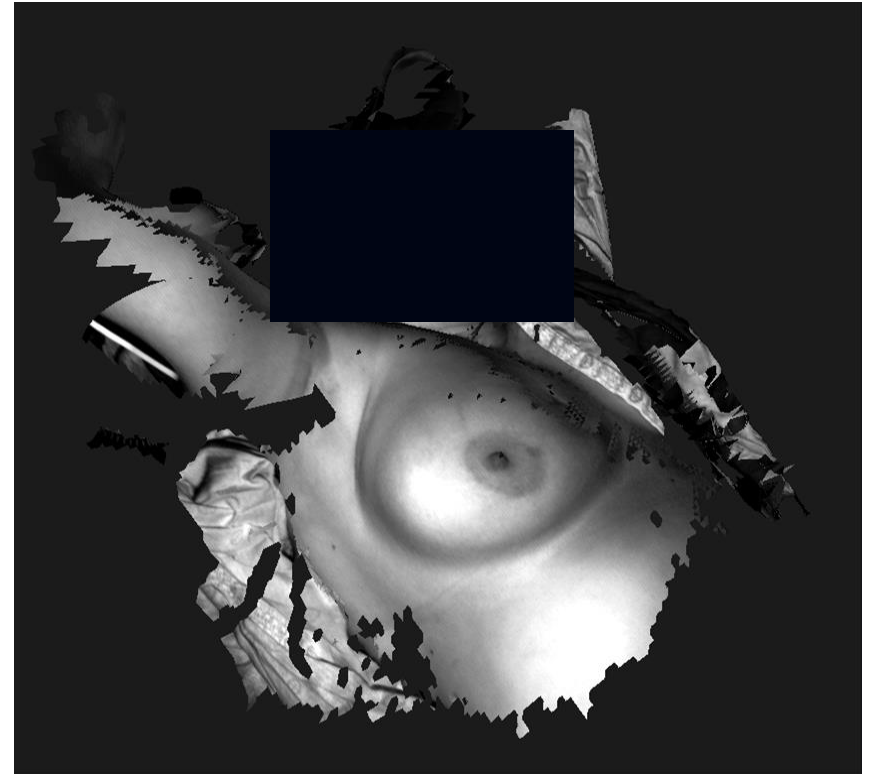
Surface representation



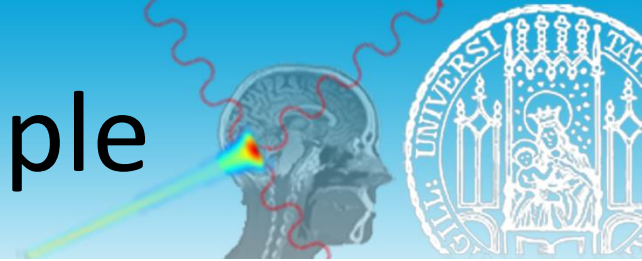
Wire-frame



Textured surface



Application example



visionrt 10/08/2007 08:07 ? ↓

Mode Evaluate functions

alignrt Record Verify

Mr

Patient notes: Mid Skintone

B5
DFP: 89.5
VERT.10.6

Treatment site: Other Date-time stamp: 070706 113503

Page 1 2

Couch Deltas → ↔

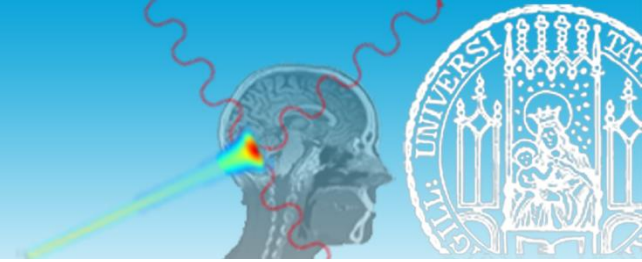
Couch Coordinates		Posture Rotations	
Δ VRT:	0.27 cm		
Δ ALNG:	0.38 cm	0.18°	
Δ LAT:	-0.09 cm	0.60°	
Δ RTN:	-0.30°		
RTN:	0.0°		

OPTIMISE

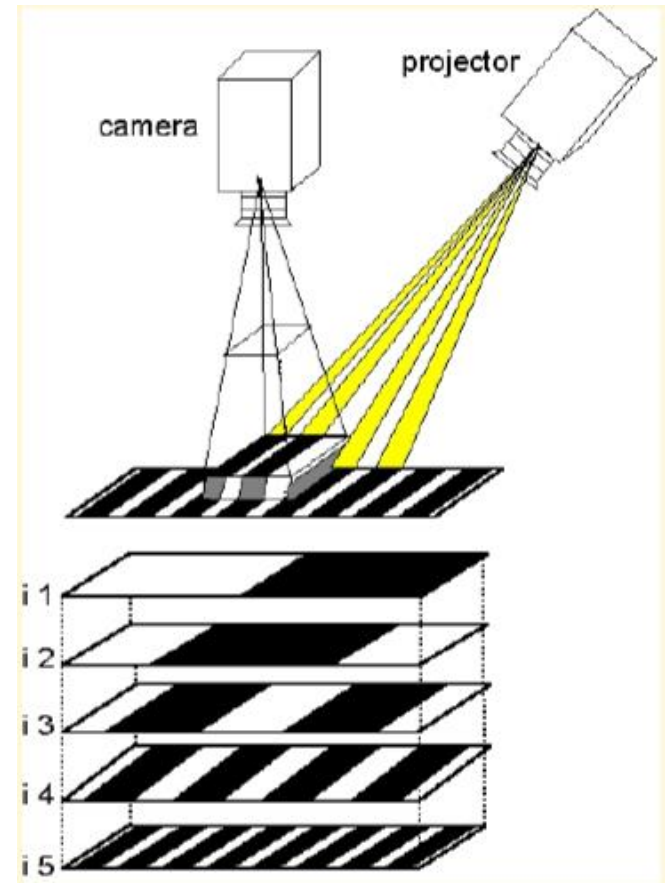
3D Display

IEC 60601-2-1

Single camera



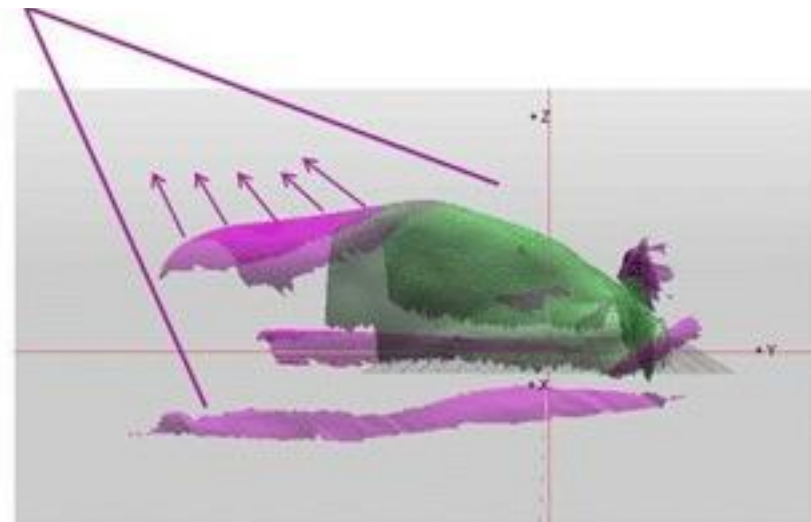
- **Patterns of light** are projected onto an object
- With knowledge of relevant camera and projector geometry, depth can be calculated by triangulation
- The challenge in optical triangulation is **obtaining correspondence** between points in the projected pattern and pixels in the image



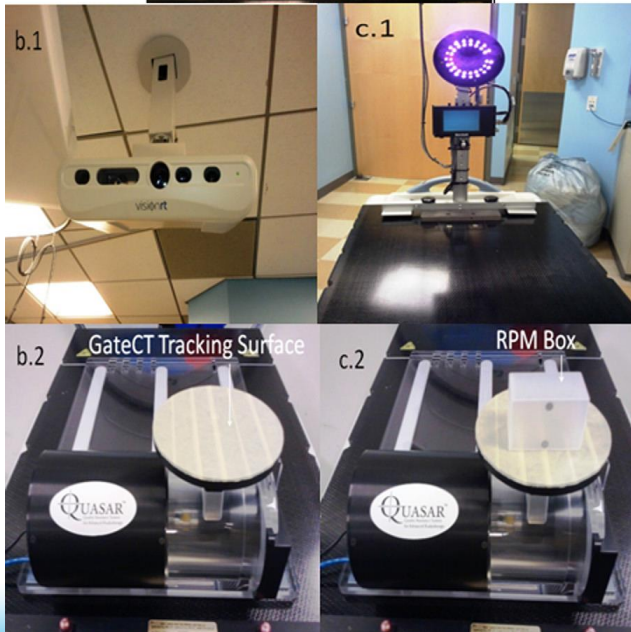
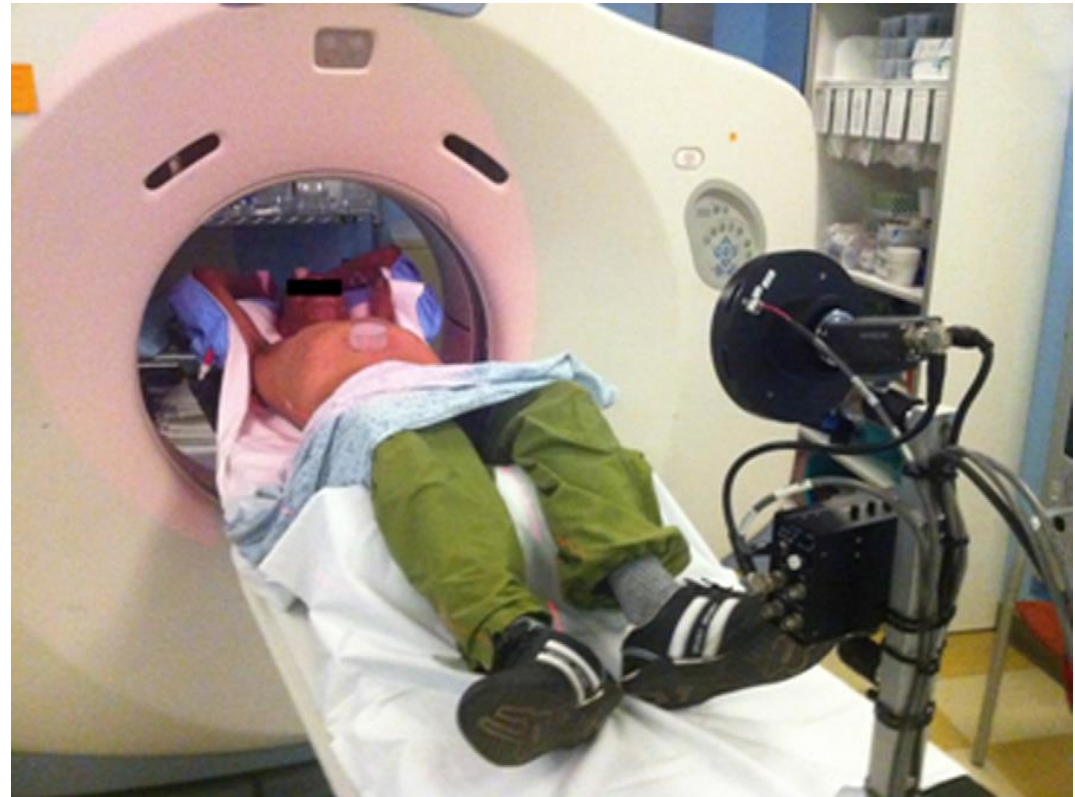
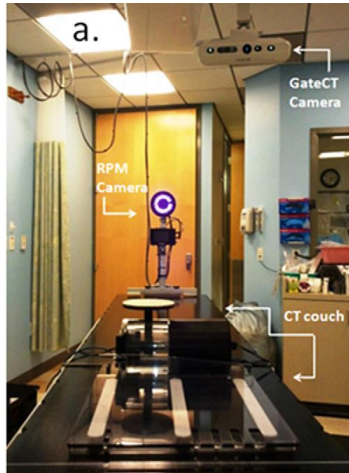
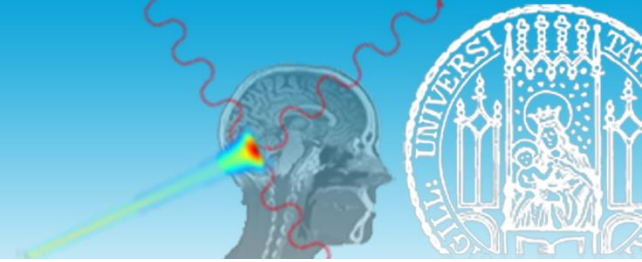
Single camera



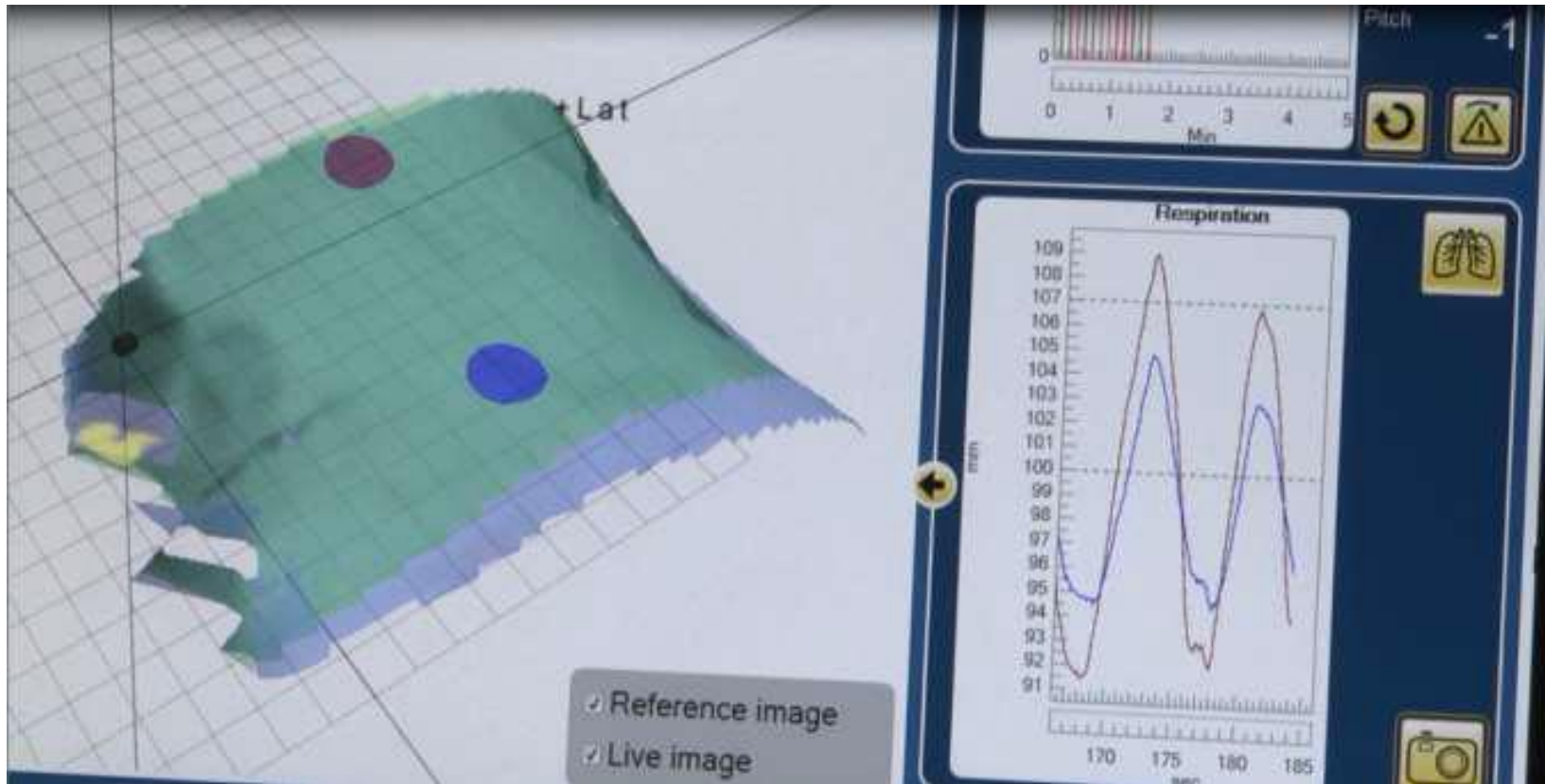
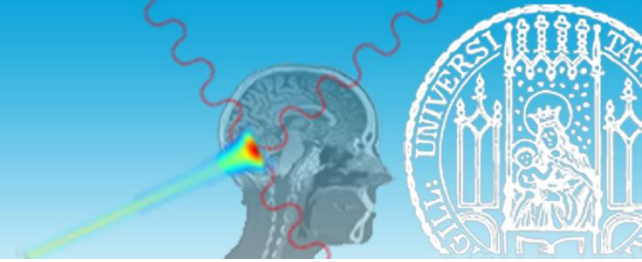
The patient's position in the room is determined by means of optical triangulation of the reflected light and the Catalyst™ software calculates the patient's surface using a non-rigid registration algorithm.



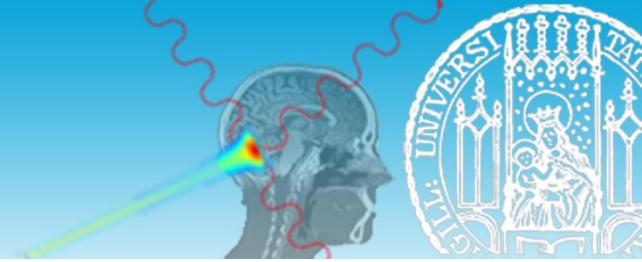
Surface motion detection



Surface motion detection



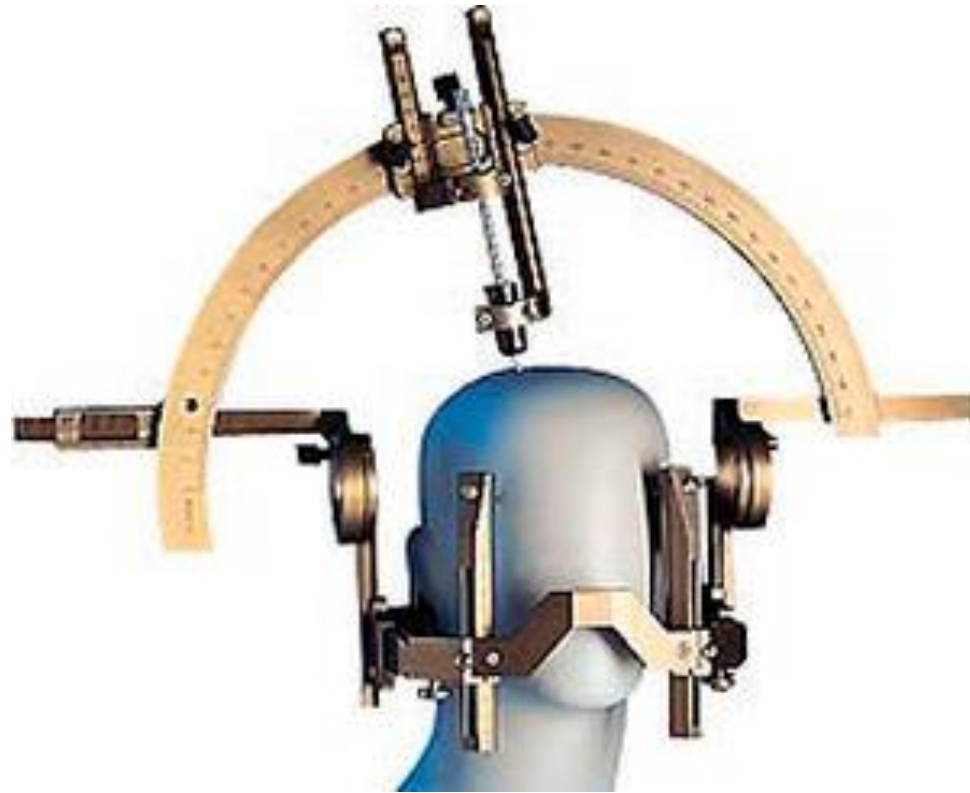
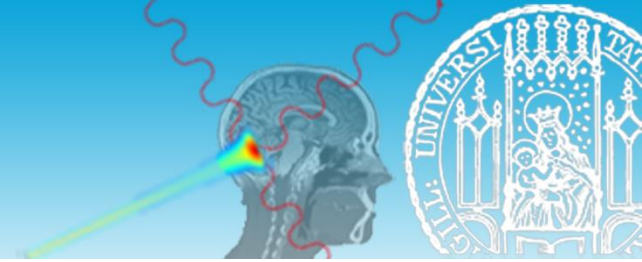
Monitoring of a **small surface patch** (few cm^2) is feasible at frequencies compatible with motion



From external surface to internal anatomy:

- Verification of rigid-body assumption
 - Stereotactic localization
 - Correlation model
- Direct localization:
 - Imaging
 - Localization w/wo implanted landmarks

Stereotaxis



from Greek: **stereo-** three-dimensional
+
taxis 'orientation'

- Concept taken from **neurosurgery applications**
- The use of a **reference system** (real / virtual) built on external landmarks helps in localizing internal anatomy

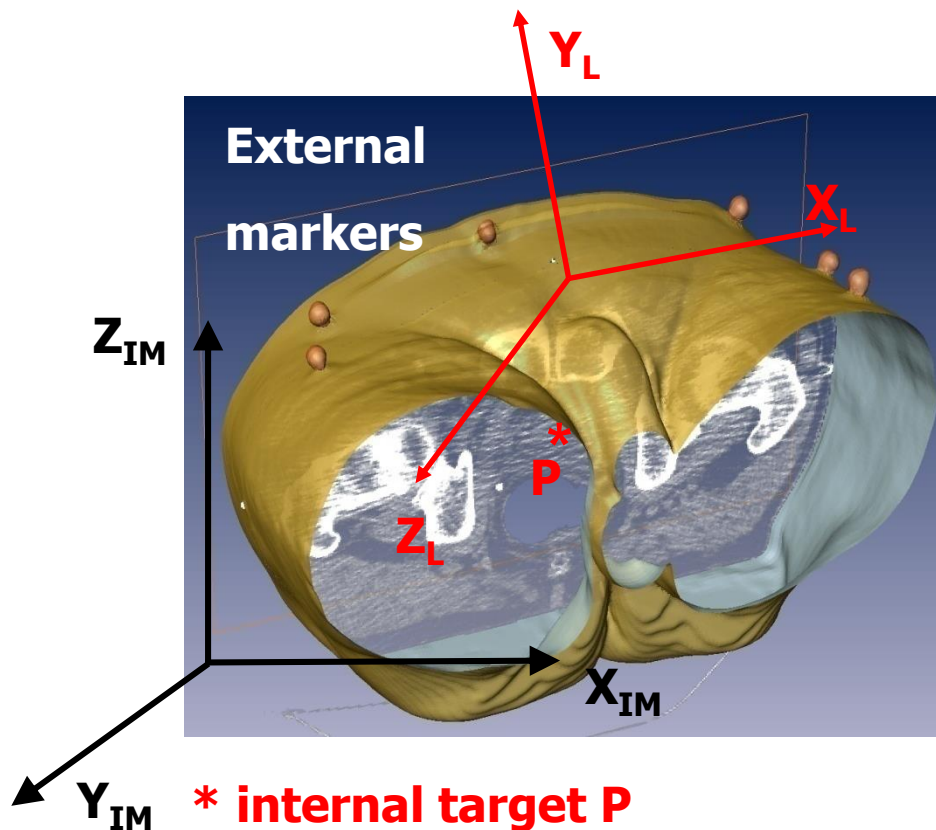


RIGID BODY

Stereotaxis



- ✓ Rigid body approach
 - Measuring inner target points



The following applies:

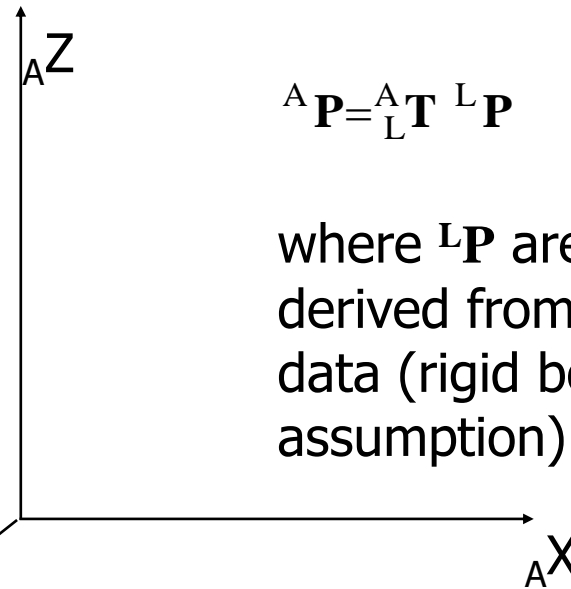
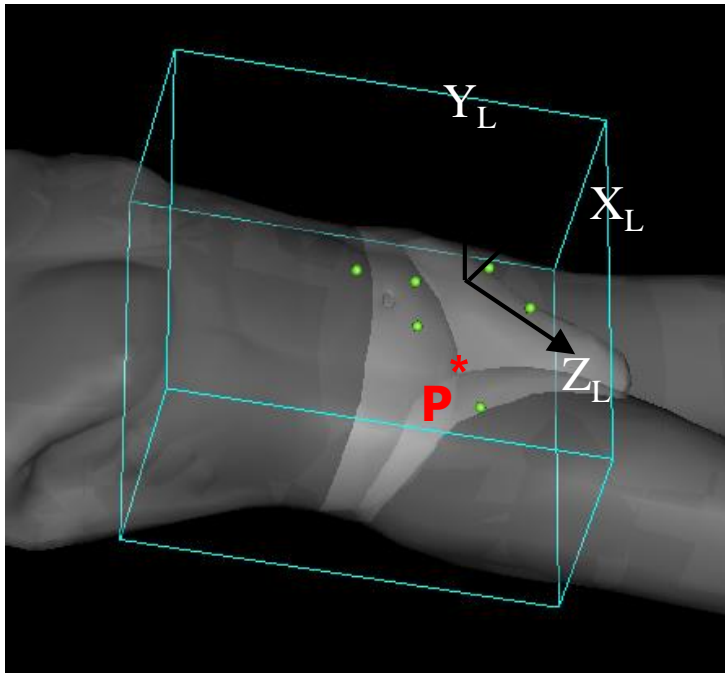
$${}^L P = {}^L T_{IM} {}^{IM} P$$

Local (stereotactic) target coordinates are derived from imaging (e.g. CT)

Stereotaxis



- ✓ Rigid body approach
 - Measuring inner target points



$${}^A\mathbf{P} = {}^A\mathbf{T}_L {}^L\mathbf{P}$$

where ${}^L\mathbf{P}$ are the same derived from imaging data (rigid body assumption)

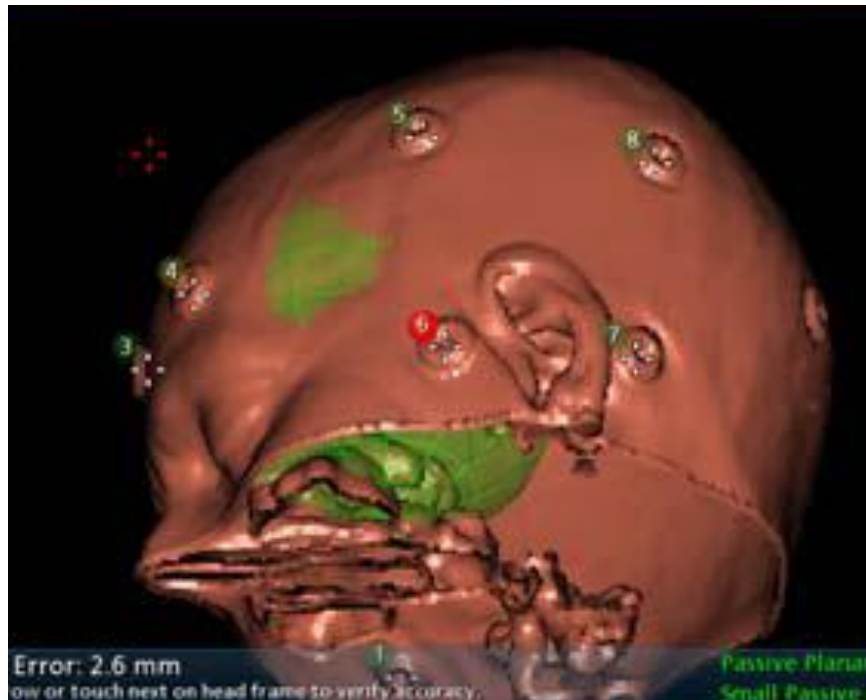
A_Y

The internal target can be localized even in absence of imaging

Surgical navigation



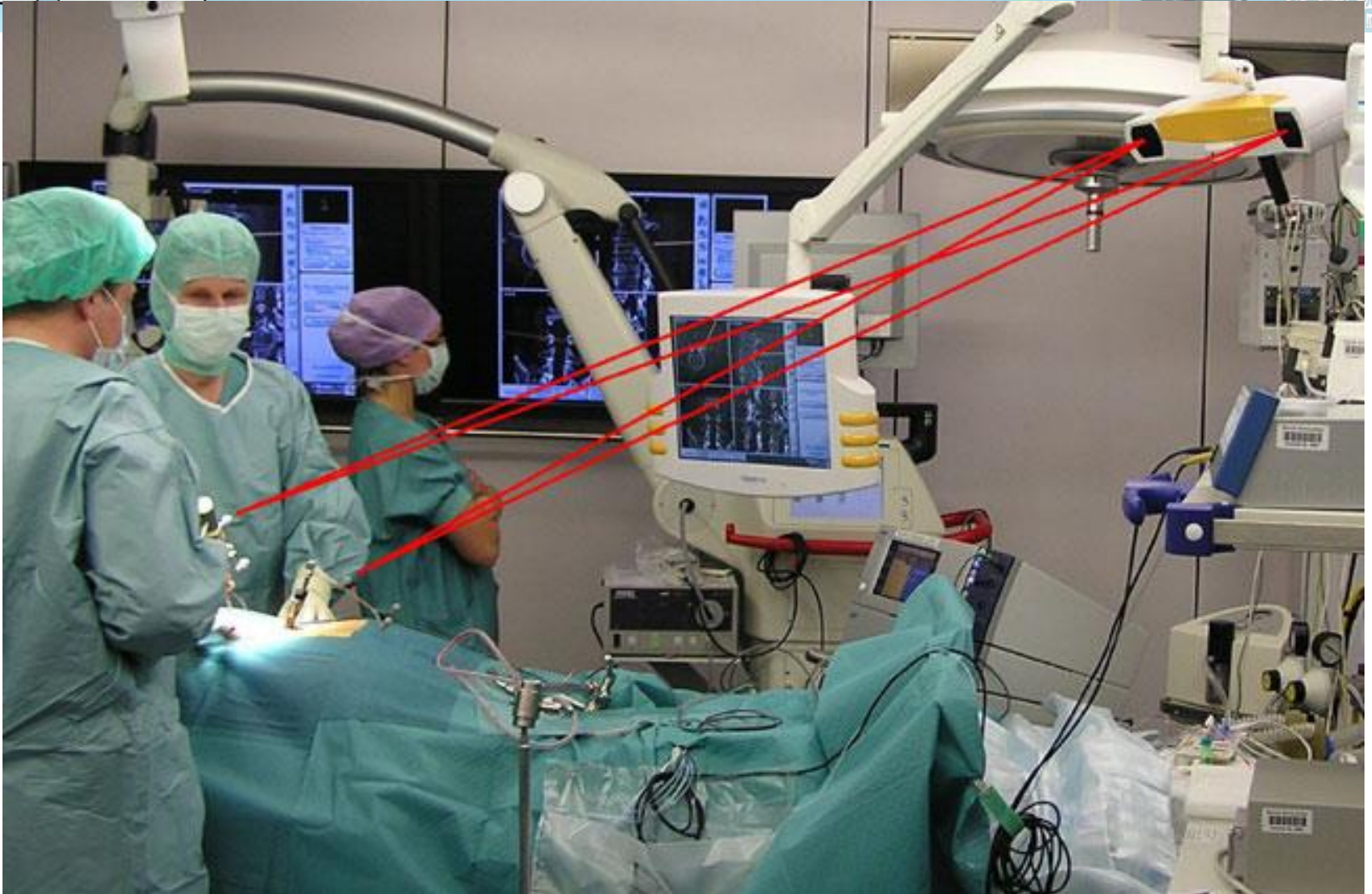
Planning



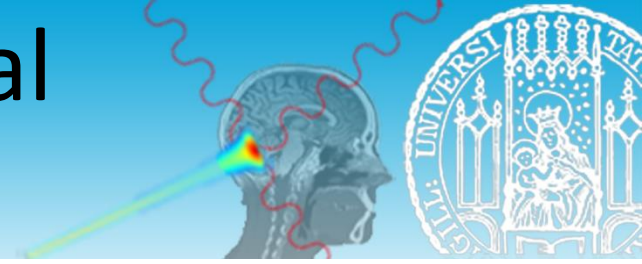
Execution: registration



Surgical navigation

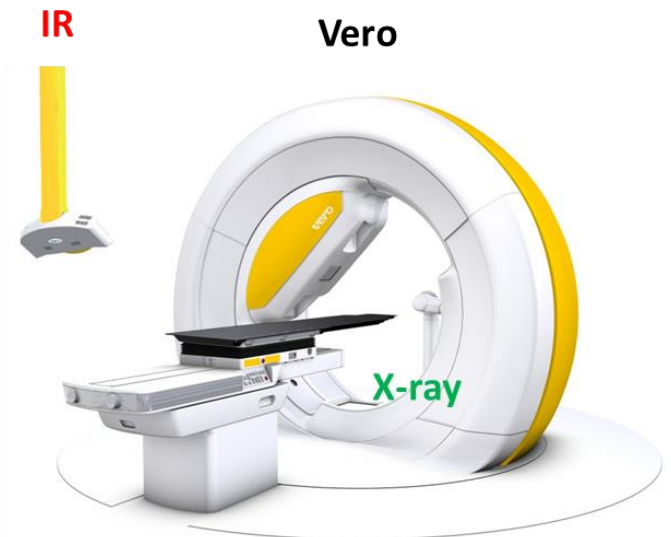
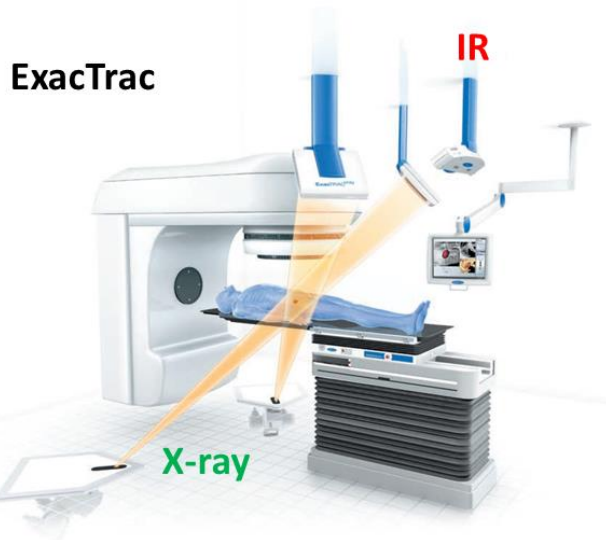


Managing internal motion

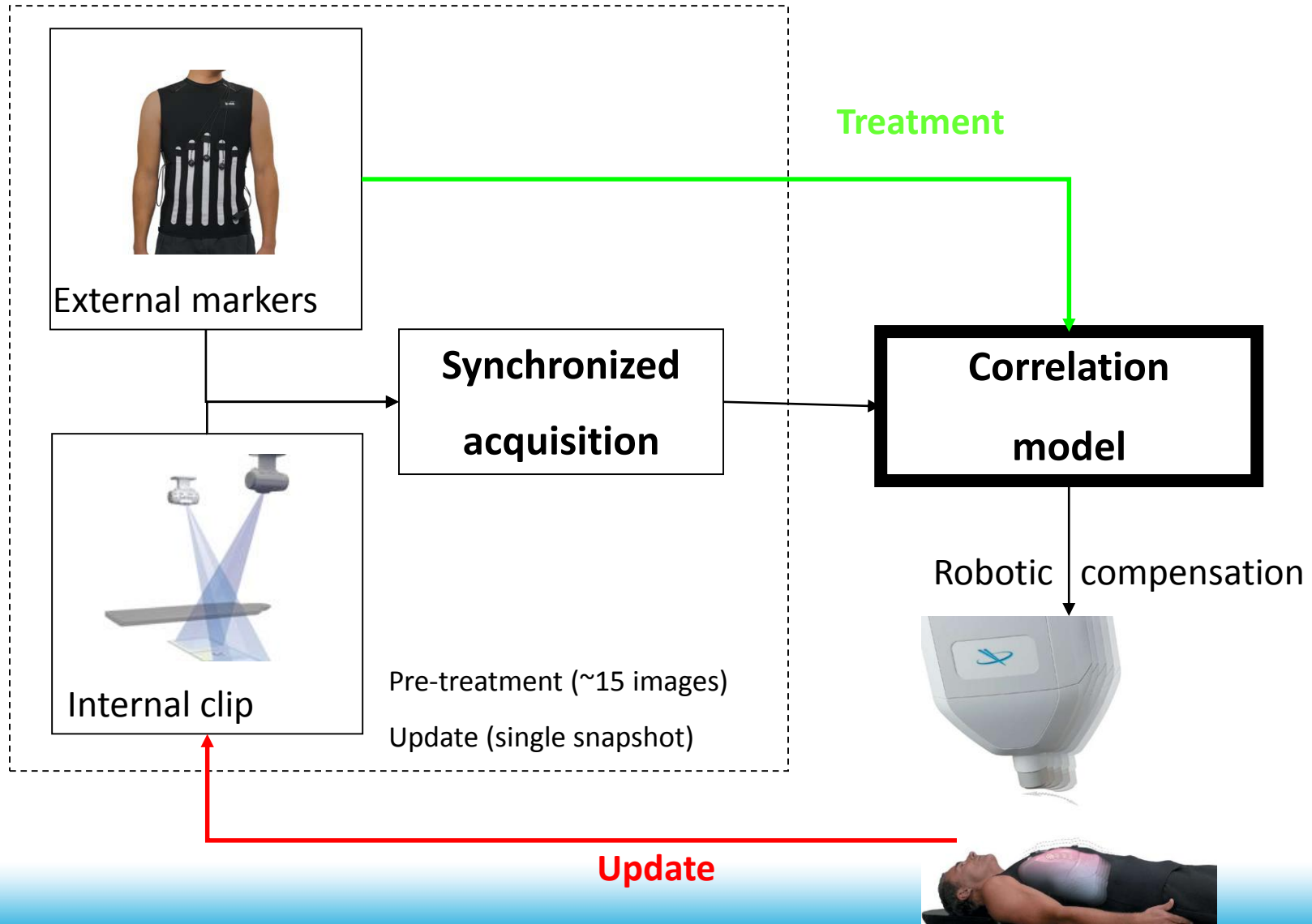
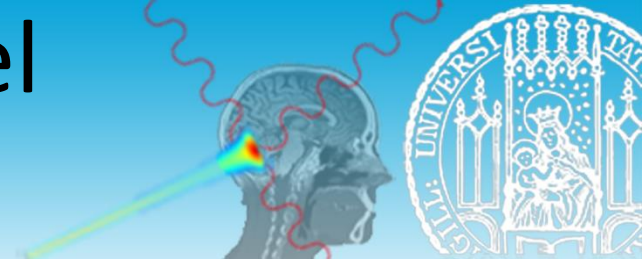


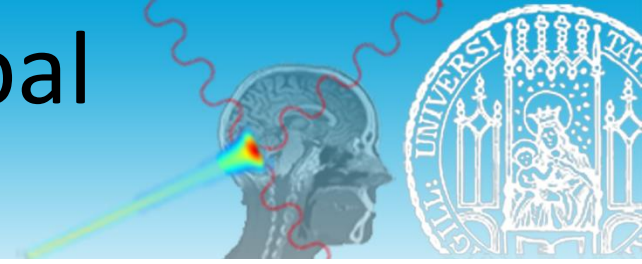
Extend beyond the **rigid body assumption**:

- Real-time tumor tracking based on **correlation models**
- Trade-off between **accuracy / imaging dose**



Correlation model strategy

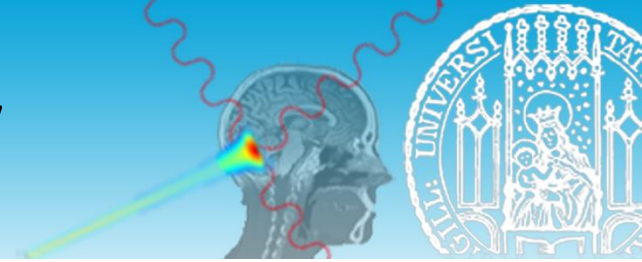




Respiratory motion model = mathematical description of anatomical motion due to breathing in a certain region of interest (ROI)

- Provide tools for **computer simulations**
 - Treatment planning studies
- **Facilitate motion estimation**
 - Motion management

Comprehensive
evaluation of motion



Model initialization (Treatment planning)

Deformable registration of
4D-CT(MRI) images

Parameterize vector field

-PCA*

-Amplitude/phase/baseline**

Extract breathing surrogate

Image-based*

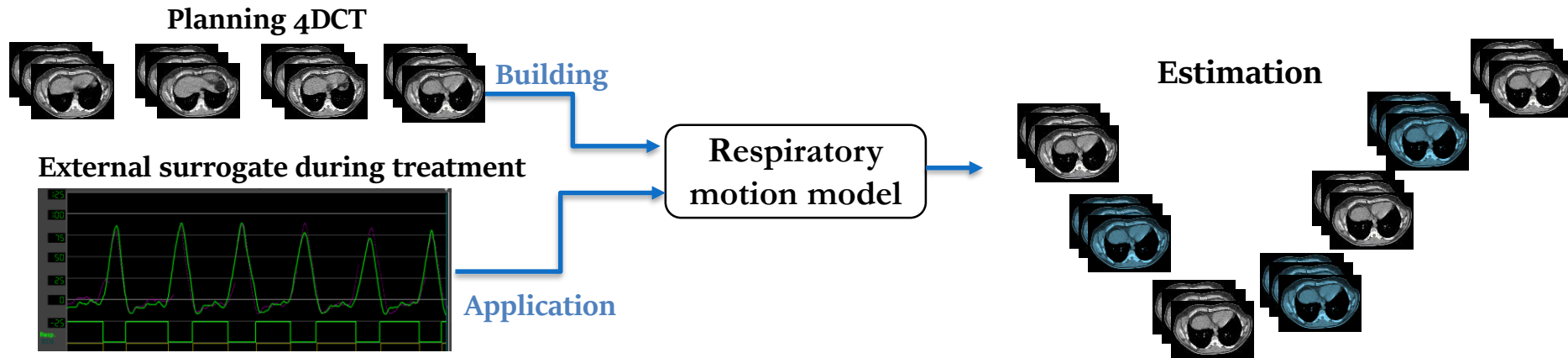
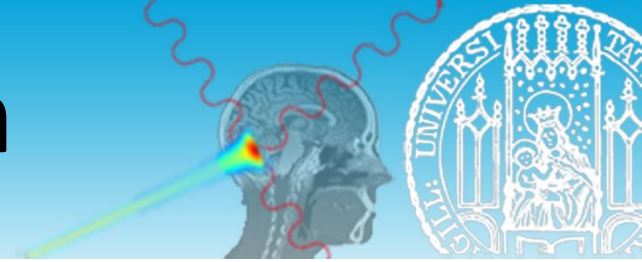
External surrogate**

Apply model

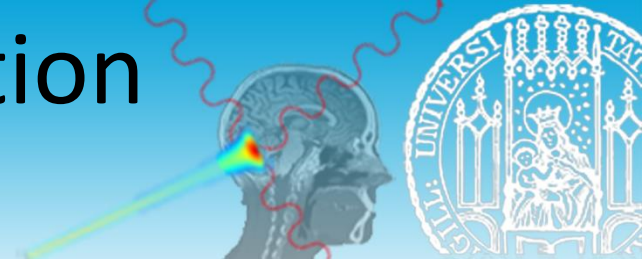
Virtual «4D-CT of the day»

*Zhang Y *et al*, Phys. Med Biol. 2013;58:8621–8645

**Fassi A *et al*, IJROBP 2014;88:182–188



- Estimate **CT volumes at arbitrary respiratory phases**
- Once the model is built, only the surrogate is required (**no imaging!**)
- **Validation issues**



✓ Direct internal localization

✓ Marker-based methods

✓ X-ray [Shirato et al. *Cancer Sci* 2012;103:1–6]

✓ EM (Calypso™) [Balter et al. *IJROBP* 2005;61:933–37]

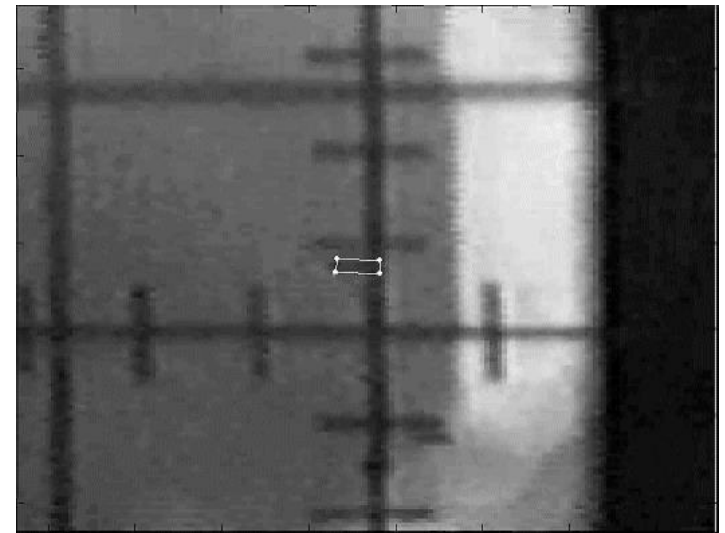
✓ Markerless

✓ Ultrasound [Schlosser et al *Med Phys* 2010;37:6357–67]

✓ Real-time X-ray image registration

[Gendrin et al *Radiother Oncol* 2012; 102:274–80]

✓ MRI [Fallone et al *Med Phys* 2009;36:2084–88]

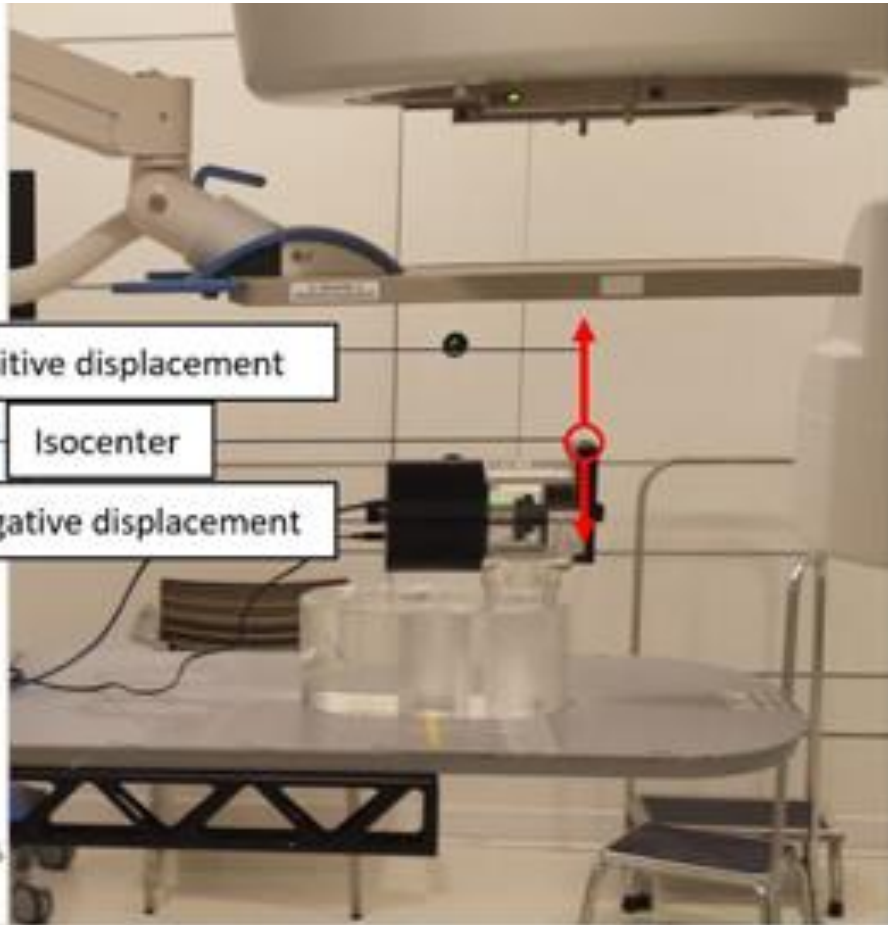
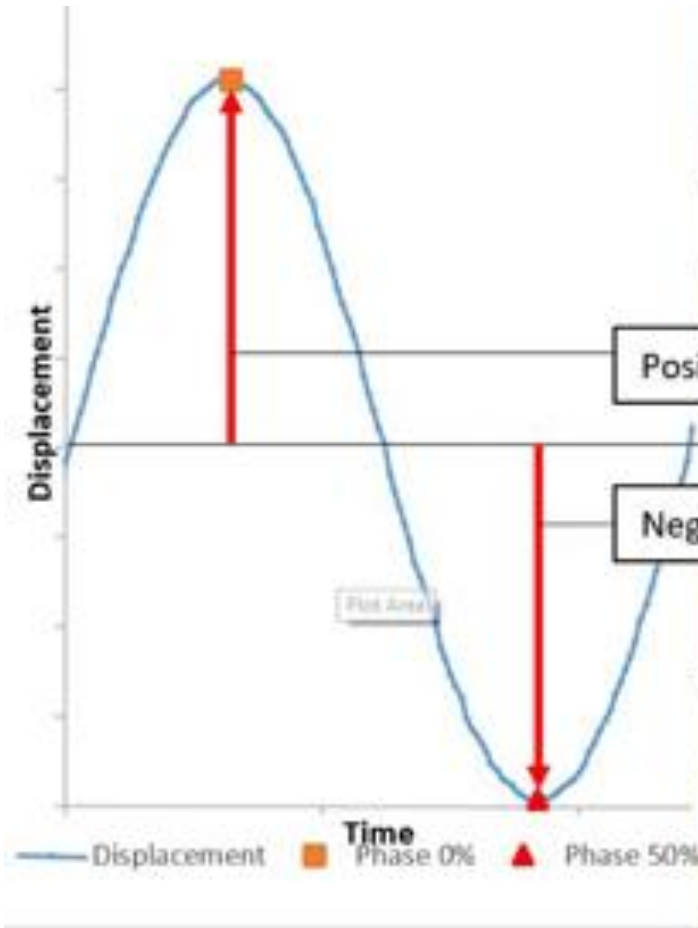
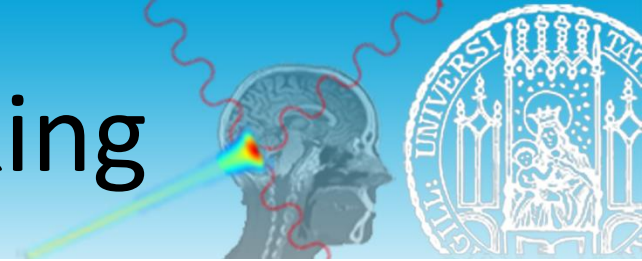


EM internal tracking

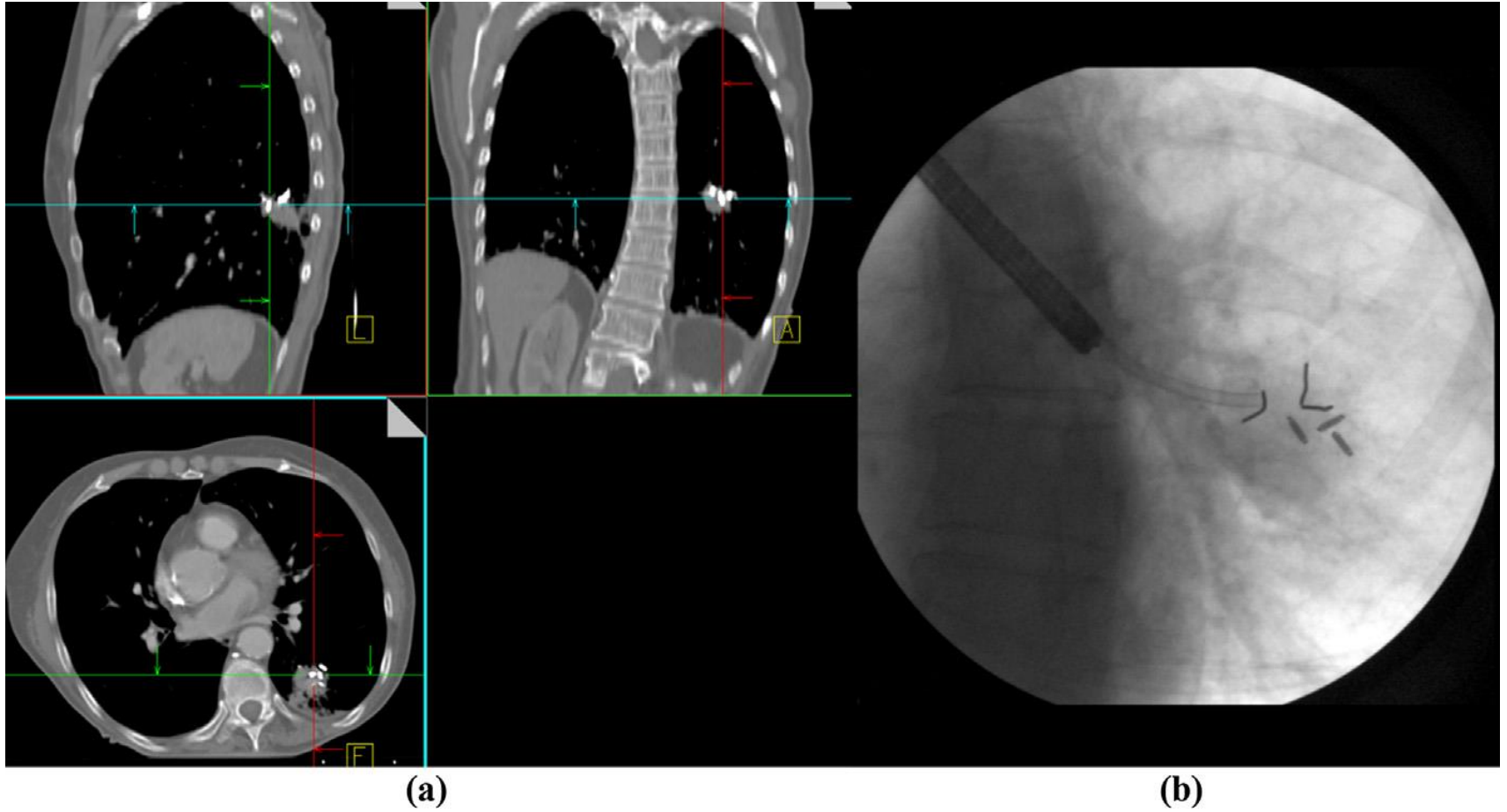


- **Implanted EM transponders:** powered by resonant frequencies of 300, 400, or 500 kHz from a source array.
- When energized, the transponder emits a response signal which may be **localized relative to an array of sensor coils** located in an electromagnetic array placed above isocenter.

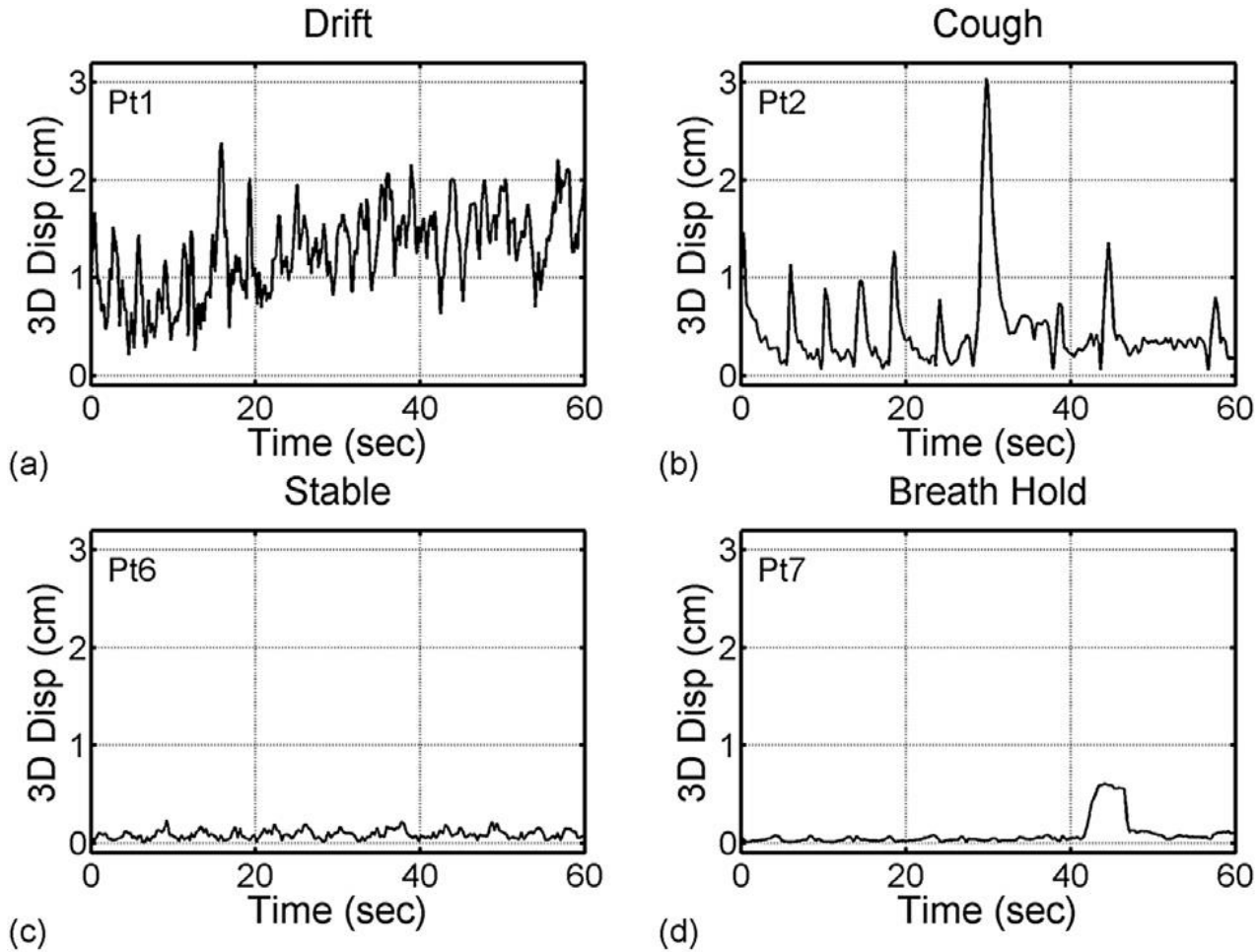
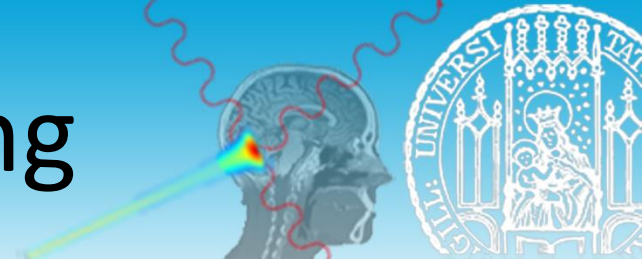
EM internal tracking

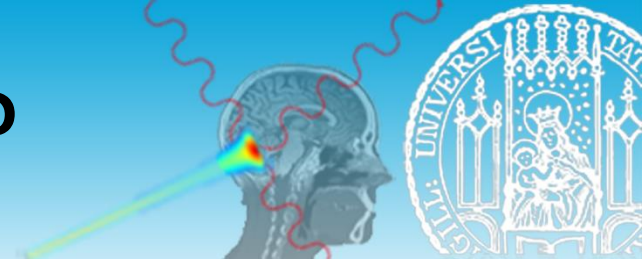


Lung EM tracking



Lung EM tracking

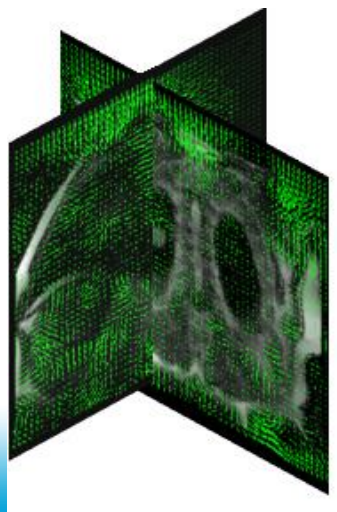
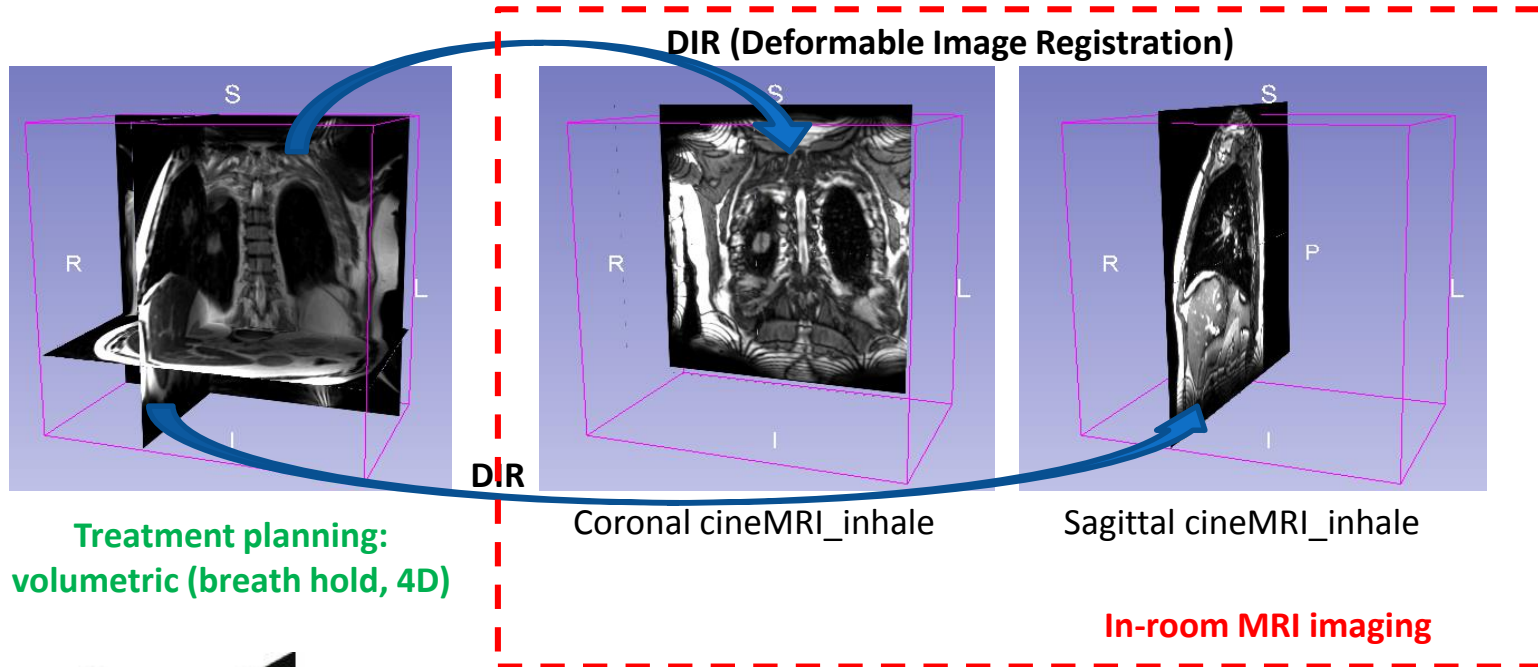
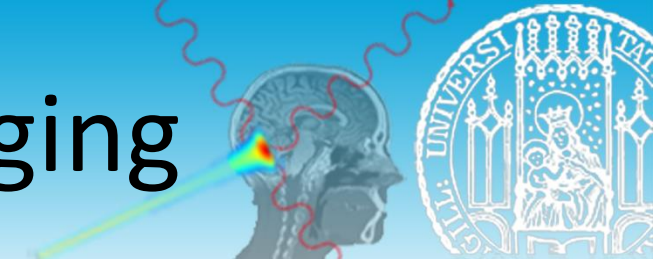




A Monte-Carlo study to assess the effect of 1.5 T magnetic fields on the overall robustness of pencil-beam scanning proton radiotherapy plans for prostate cancer

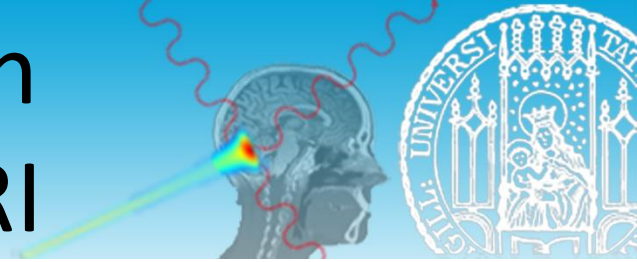
Christopher Kurz¹, Guillaume Landry², Andreas F Resch^{2,3},
George Dedes², Florian Kamp⁴, Ute Ganswindt⁴,
Claus Belka^{4,5}, Bas W Raaymakers¹ and Katia Parodi²

In-room MRI imaging



Motion tracking in MRI limited by spatial/temporal resolution trade-off:

- **2D sagittal/coronal cineMRI images** at ≈ 200 ms sampling



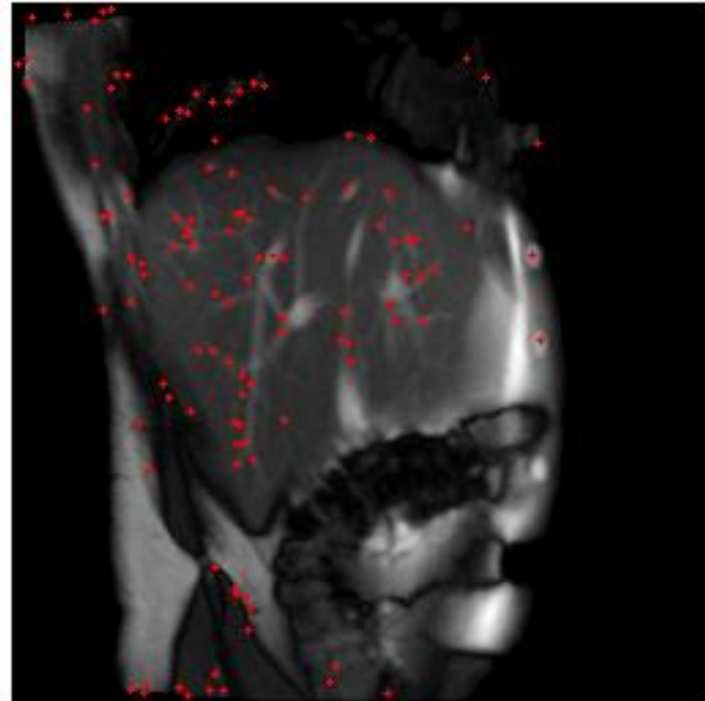
Real-time motion tracking with MRI-linac
requires:

- **Fast image processing**
- **Motion prediction** (≈ 200 ms acquisition time + image processing time)



Real time tracking:

- based on **optical flow registration**
- **Speed-up** relying on image similarity matching

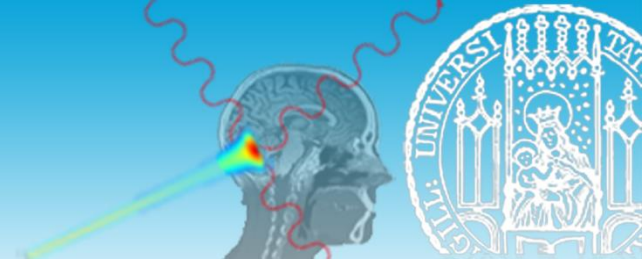




- Motion tracking of the external surface:
 - optical technologies are established (point / surface localization)
 - Correlation with anatomical motion can be measured through imaging
- Motion detection of internal anatomy
 - EM tracking available, requires marker implantation
 - MRI imaging is promising, need extension to real-time 3D



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Thank you