POLITECNICO DI MILANO

CartCasLab

Computer Aided RadioTherapy & Computer Aided Surgery

Robotic technologies for image guidance in particle therapy

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High-precision radiotherapy
A “*computer assisted – robotic surgery*” paradigm

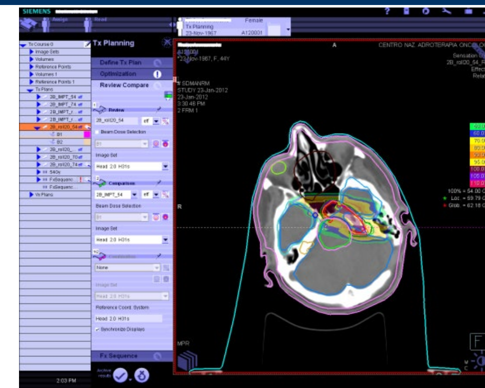
✓ *Planning stage*:

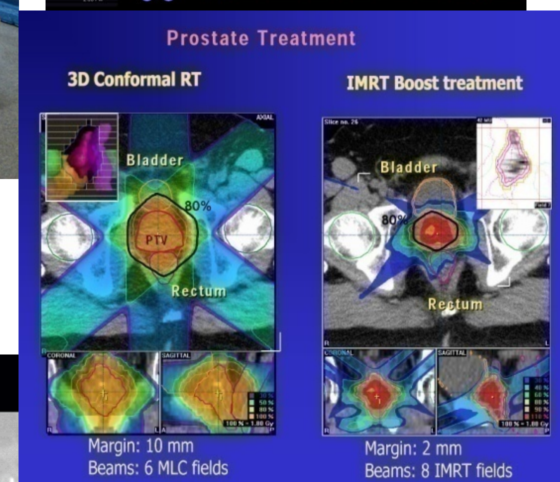
- X-ray volumetric imaging (3D/4D-CT)
- Functional imaging (PET , fMRI)
- Contouring (semi-automatic)
- Definition of treatment physical and geometry parameters
- Dose distribution simulation / optimization / evaluation

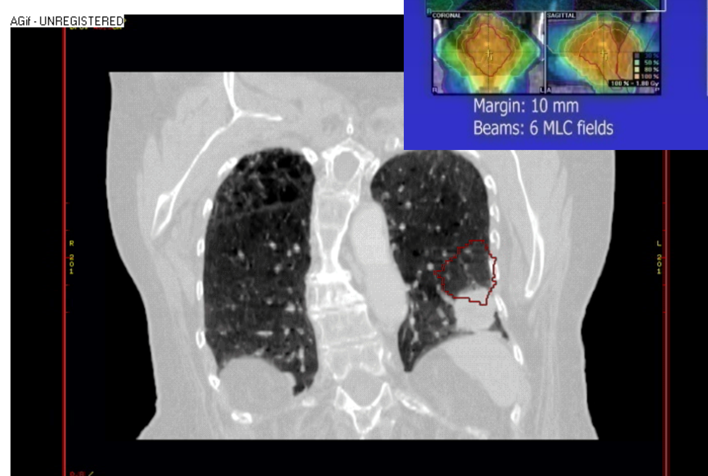
Uncertainties

✓ ***Delivery/treatment stage***:

- Patient set-up
- Geometry verification (Image Guidance)
- Compensation of inter-fractional patient deviations
- Dose delivery with compensation of intra-fractional patient deviations

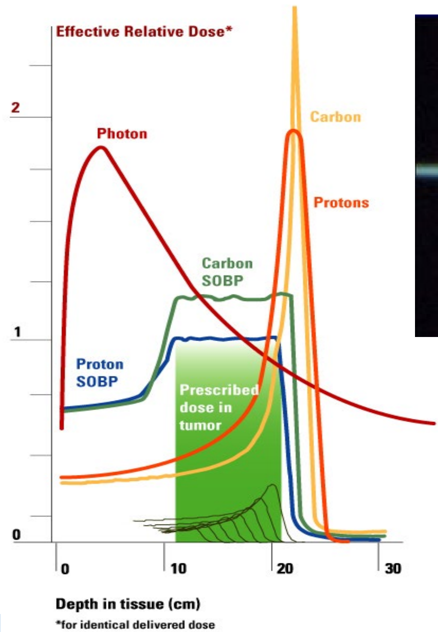


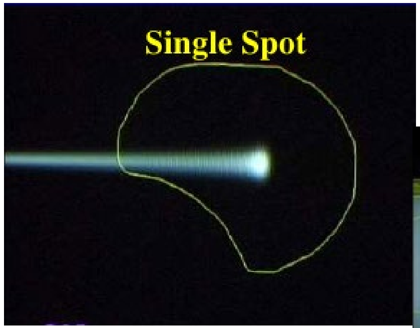


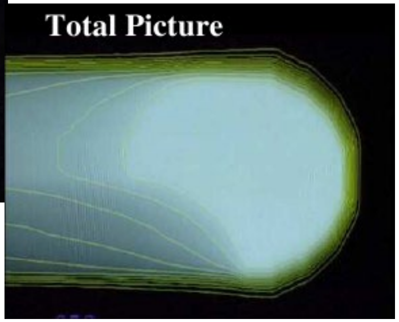


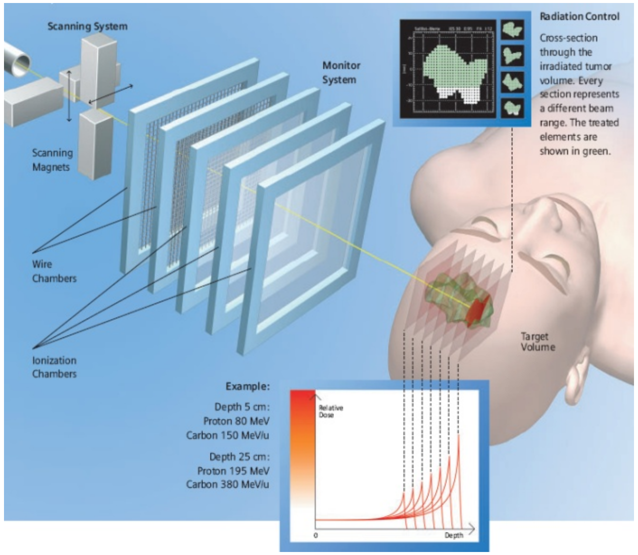
High-precision radiotherapy: New techniques
Particle therapy

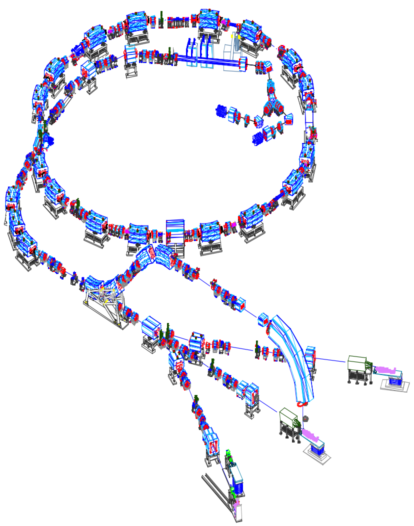
- ✓ Proton and heavy ions (C^{14})
- ✓ Higher biological effectiveness
- ✓ Higher geometrical selectivity
- ✓ Spot scanning delivery techniques for "*dose–sculpting*"
- ✓ Cyclotron (proton) or Synchrotron needed

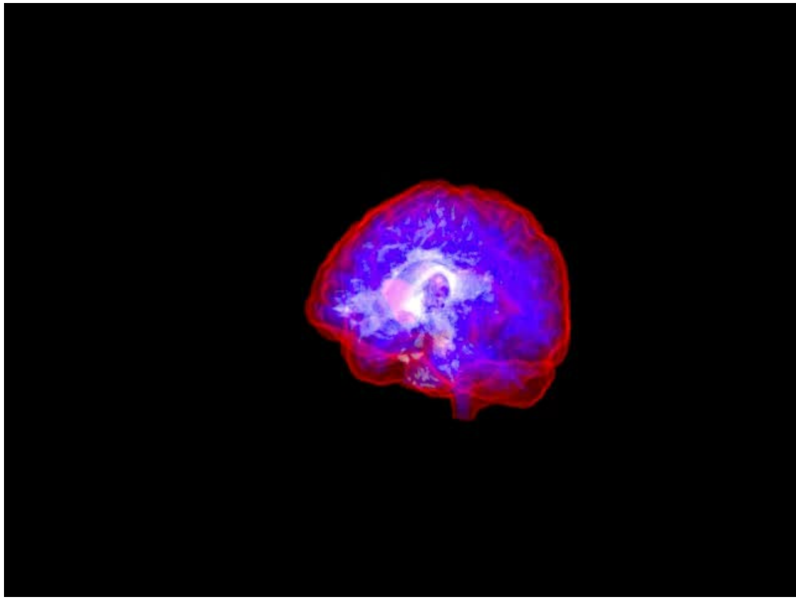






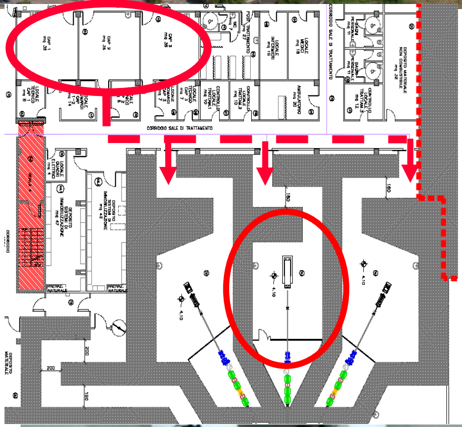


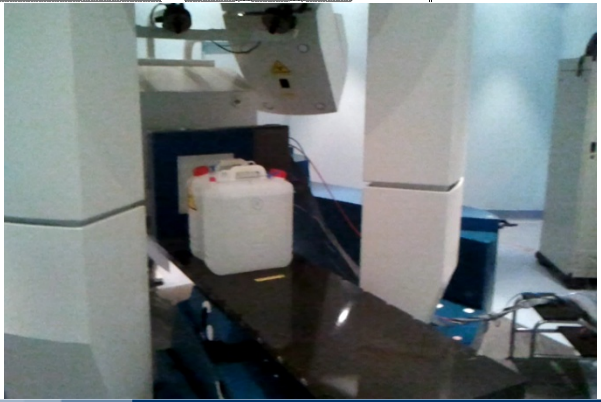




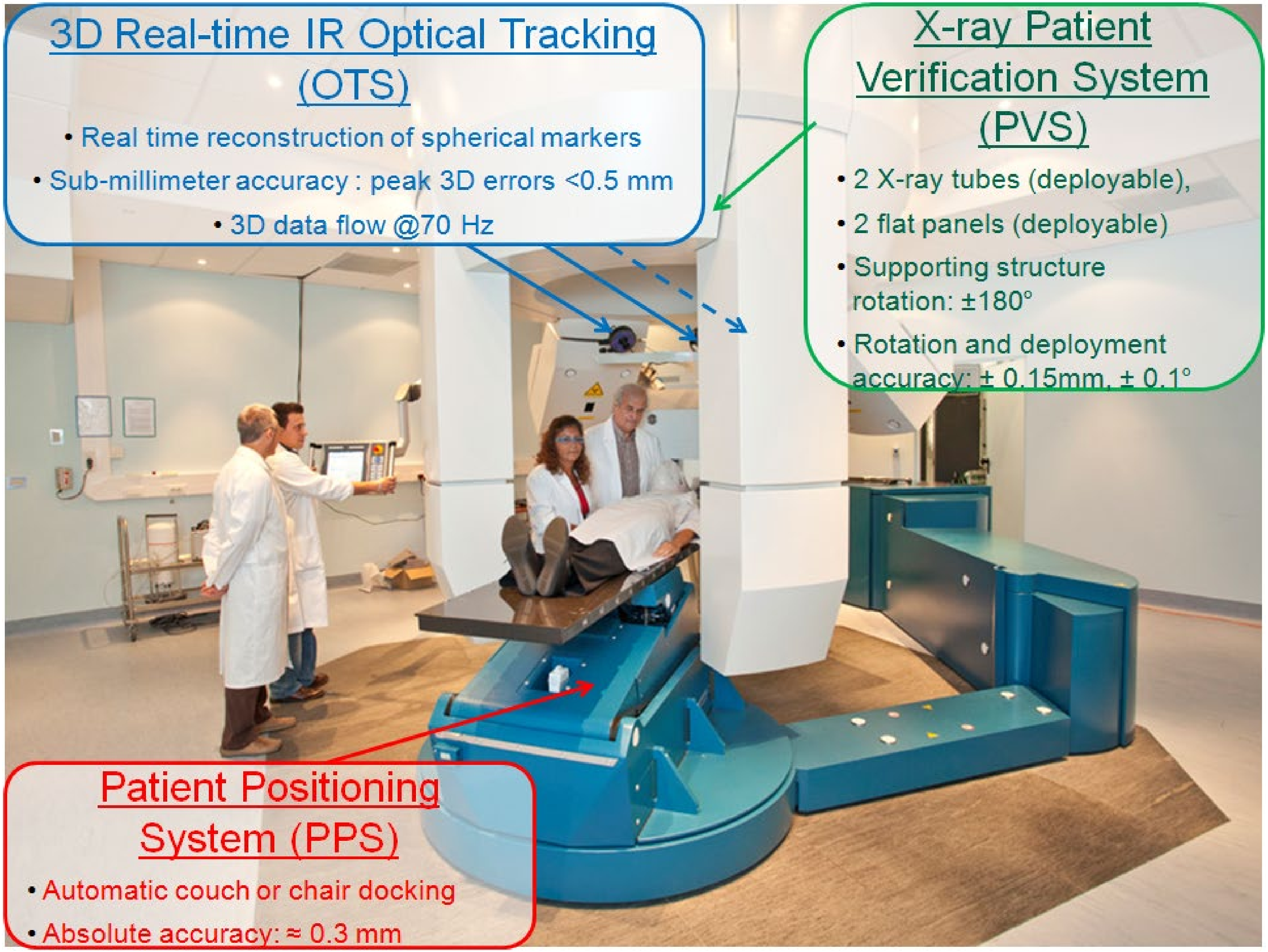
High-precision radiotherapy: IGRT in particle therapy in the CNAO facility

- ✓ Centro Nazionale di Adroterapia Oncologica (www.cnao.it)
  - ✓ first center in Italy (2nd in Europe; 5th worldwide) for active scanning proton and carbon-ion therapy
  - ✓ 3 treatment rooms with fixed beamline
- ✓ State of the art technologies for in-room image guidance
  - ✓ 6 dof patient positioning system
  - ✓ IR optical tracking for set-up and immobility verification
  - ✓ double X-ray projection systems for 2D-3D registration
  - ✓ under clinical exploitation since September 2011
  - ✓ Thousands of patient treated



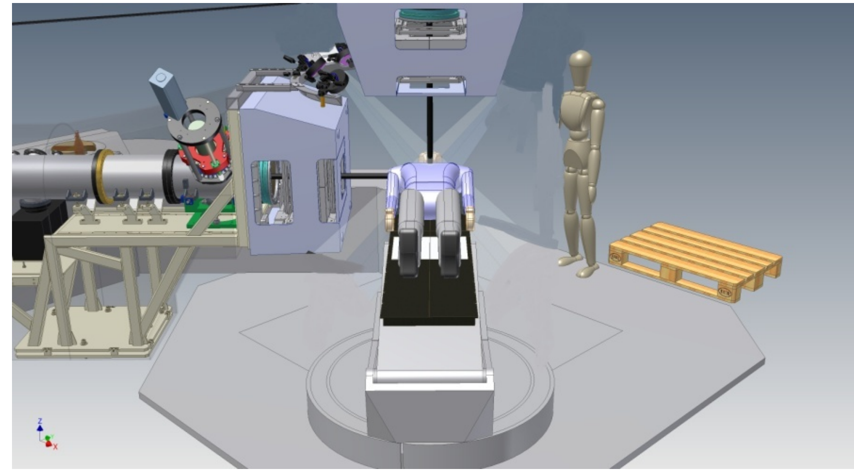


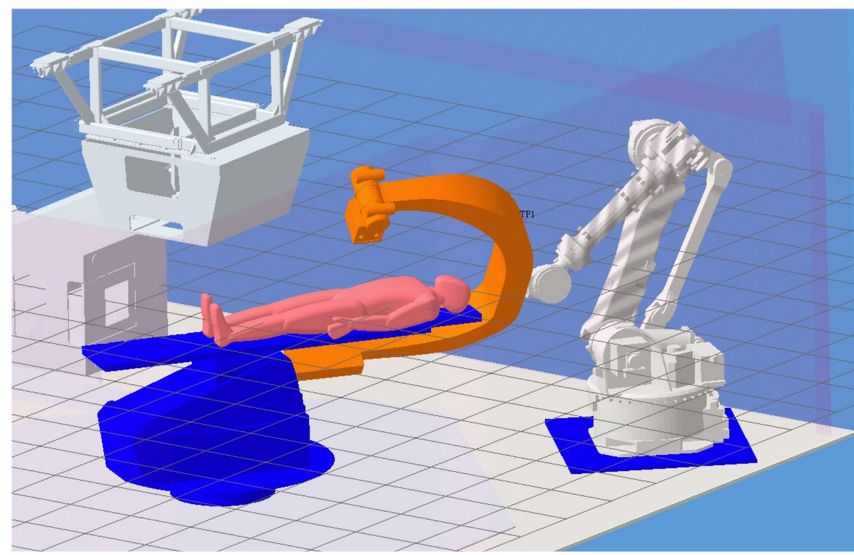
Patient Positioning and Verification strategy at CNAO
Integrated robotic, X-ray and IR localization system



High-precision radiotherapy: Robotics imaging in CNAO central room

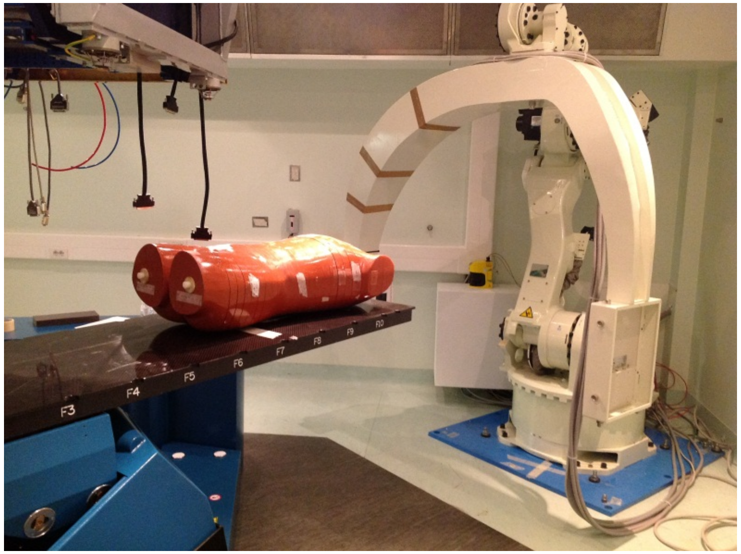
- ✓ H and V beamlines hinder suspended in-room imaging device (as in lateral rooms)
- ✓ Clinical requirement of multiple projections (2D-3D registration) and volumetric imaging (CBCT) for 3D-3D registration with soft tissue visualization (peak error <1mm)
- ✓ Industry-derived serial kinematic manipulator for static and dynamic patient imaging
- ✓ C-arm with kV X-ray tube and flat panel mounted on a 6-dofs robotic serial manipulator
- ✓ Dedicated SW for:
  - ✓ multiple imaging and 2D-3D image registration
  - ✓ cone-beam CT and 3D-3D registration
- ✓ Selected robot: Kawasaki ZX300-S:
  - ✓ 300 kg load capability
  - ✓ 0.3 mm repeatability
- ✓ Selected imaging componens:
  - ✓ Varian A277 X-ray tube with fluoroscopy capabilities
  - ✓ Varial 4030D flat panel (2048x1536 pixels)
  - ✓ Sample rate up to 30 Hz





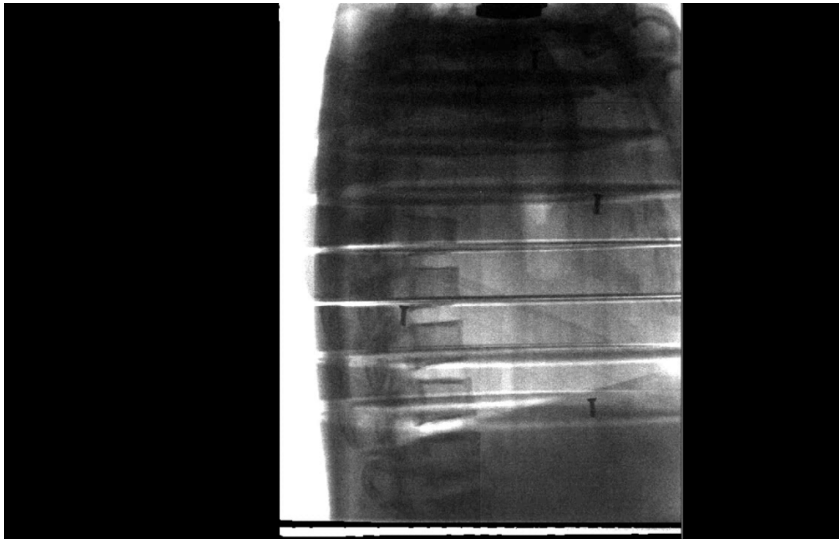
High-precision radiotherapy: IGHT
Robotic imaging in CNAO central room

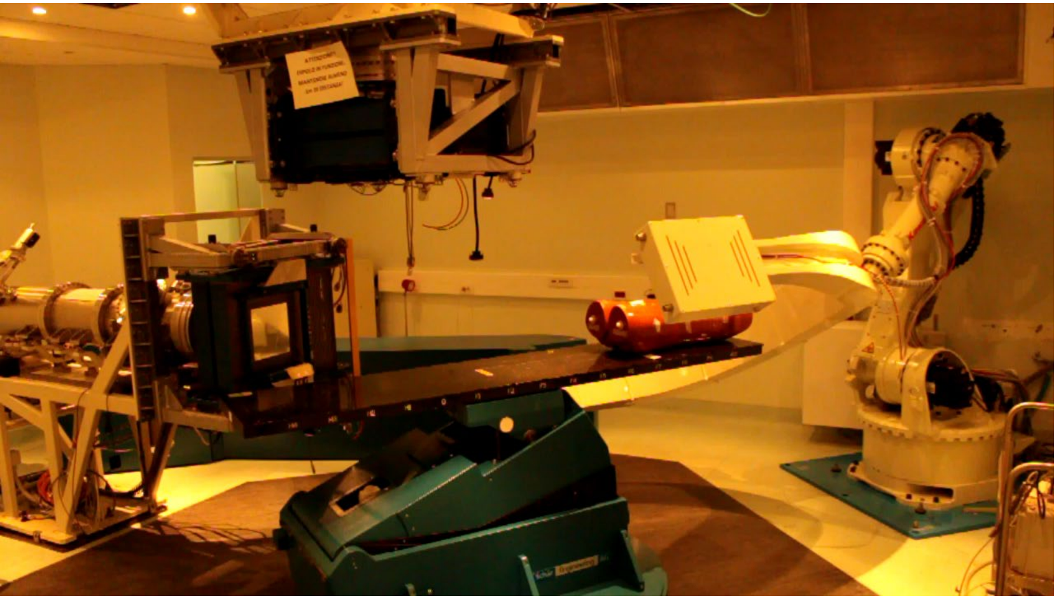
- ✓ 2D-3D image registration between DRR from TPS and acquired multiple projections
- ✓ 3D-3D registration between in-room CBCT and planning CT
- ✓ Under clinical application since March 2013

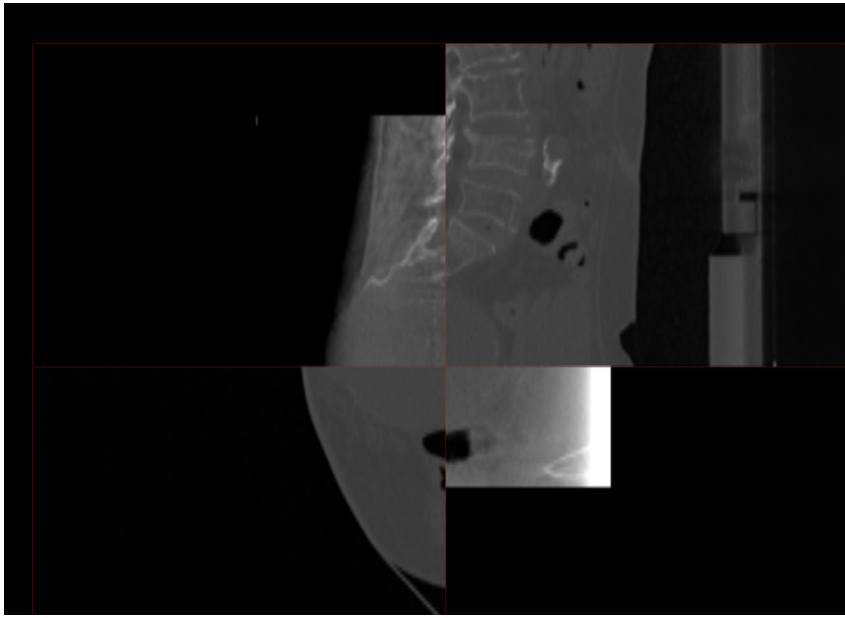


High-precision radiotherapy: IGHT
Localization technologies: Image-based

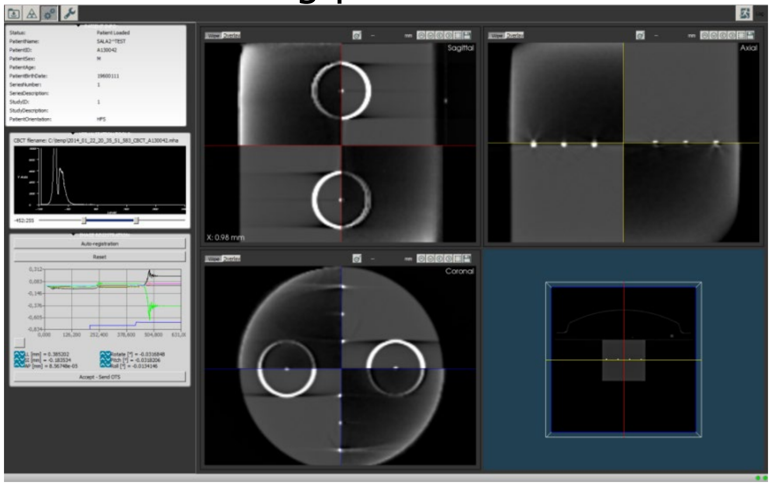
- ✓ 3D-3D registration between CBCT and planning CT
  - ✓ 615 projections over 220° ROM acquisiton time <40 sec
  - ✓ Recostruction time (GPU parallelized FDK) < 20 sec (depends on desired resolution)
  - ✓ 256x256x2.5 mm voxel dimension
  - ✓ 3D-3D registration time <60 sec
  - ✓ Dose to patient <20 mGy
  - ✓ Clinical application ongoing since summer 2014

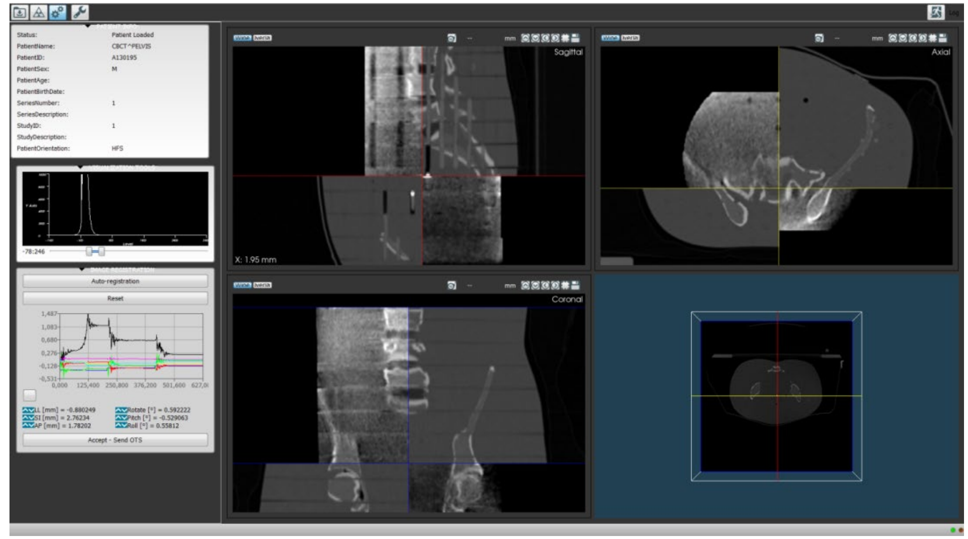






✓ Commissioning phase





Imposed error

	RL rotation [°]	SI rotation [°]	AP rotation [°]	RL [mm]	SI [mm]	AP [mm]
1	0	0	0	-1	-2	3
2	-2	-2,5	1,5	0	0	0
3	-1	-1,5	0,5	3	2	5
4	0,5	1,5	2	-2	-5	-4

Correction parameters

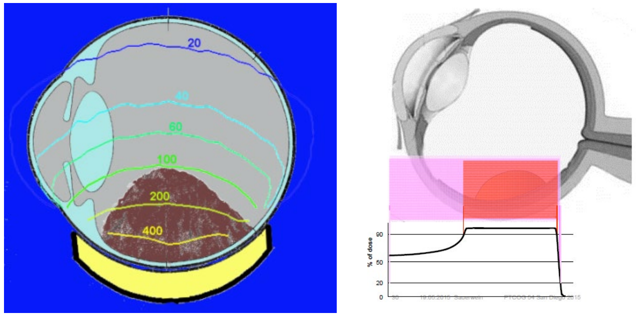
	RL rotation [°]	SI rotation [°]	AP rotation [°]	RL [mm]	SI [mm]	AP [mm]
1	-0,50	-0,26	-0,39	-1,25	-1,80	2,37
2	-1,86	-2,54	1,02	-0,06	0,54	-0,26
3	-1,41	-1,29	0,35	3,00	2,24	4,45
4	-0,17	1,59	1,56	-2,80	-4,64	-4,87

Robotic assisted eye treatment with protons

Ophtalmic tumours

- ENUCLEATION (before 1980s)
- RADIATION THERAPY (1980- present)
  - Brachytherapy

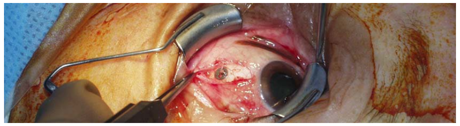
[Kacperek, Appl. Radiat. Isot., 2009]

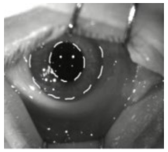


Dose distribution of a ^{125}I plaque (left) and proton beam (right)

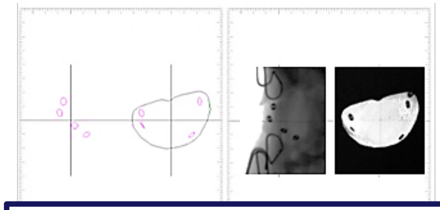
- **Proton Therapy** **14 dedicated beam line in operation worldwide**
  Over 20,000 treated patients

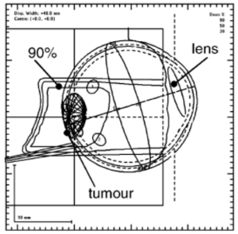
Radiopaque fiducials markers implantation → Treatment simulation → Treatment Plan





In-room orthogonal X-ray imaging system





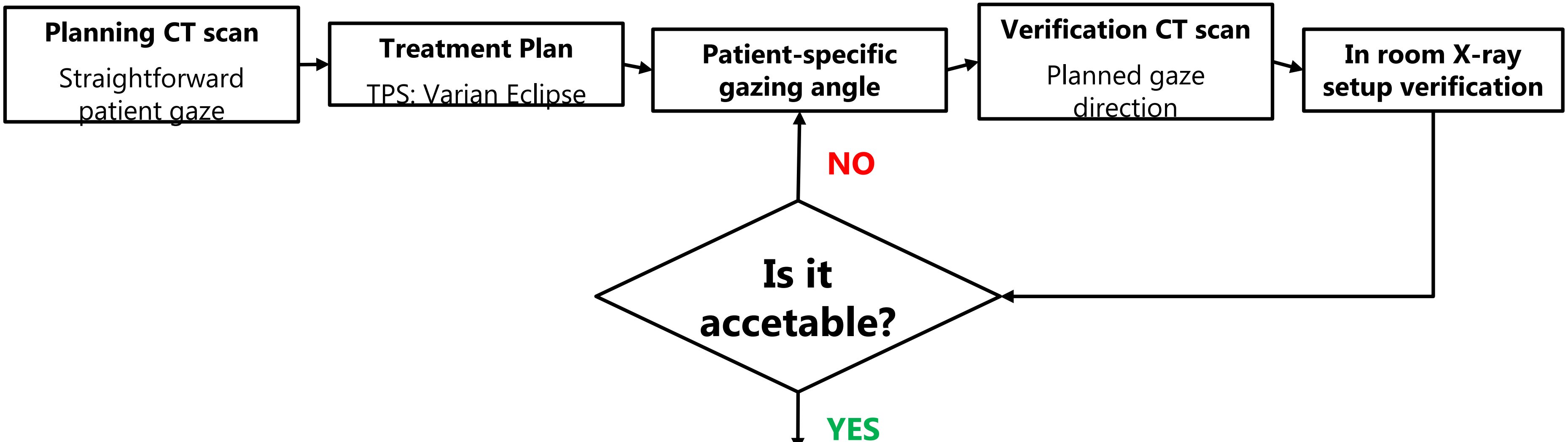
Active patient fixation of a red diode with planned position (Az, Pol)

Dose delivery ← X-ray Setup verification ← Treatment Setup

Clinical implementation @ CNAO

In August 2016 intraocular lesions treatments with proton beams started at CNAO

N.B: Non-dedicated beam line
- Active scanning
- Non orthogonal in-room imaging system



✓ **Set-up correction (treatment chair adjustment)**
✓ **Irradiation**

The requirement of a gaze stabilization and eye motion monitoring device during CT scans and irradiation was fulfilled by means of a compact and portable Eye Tracking System conceived for 3D real-time video oculography

CNAO-EyeTrackingSystem (ETS)

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Requirements

- CT compatibility
- Clinically suited design
- In-room localization

Mirror configuration

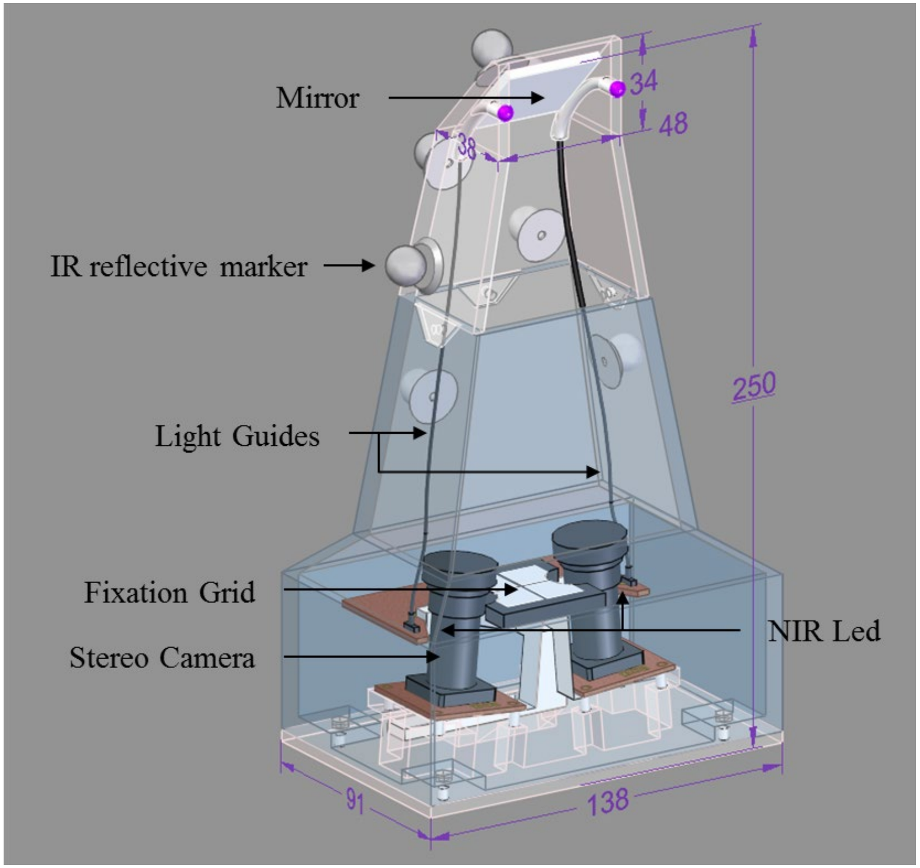
- Removal of electronic components from the CT FOV
- Miniaturization

Components

- IDS UI-1241-LE-NIR camera.
- Präzisions Glas & Optik: SEA-NIR Front surface Mirror.
- OSRAM LED SFH486 IR Led.
- ABS for device casing.

Additional features

- Passive markers configuration (identifiable by the CNAO optical tracking system attached to outer case
- Marker configuration calibrated w.r.t. fixation point



[Via et al, Med Phys, 2015]

Robotic ETS positioning

Requirements

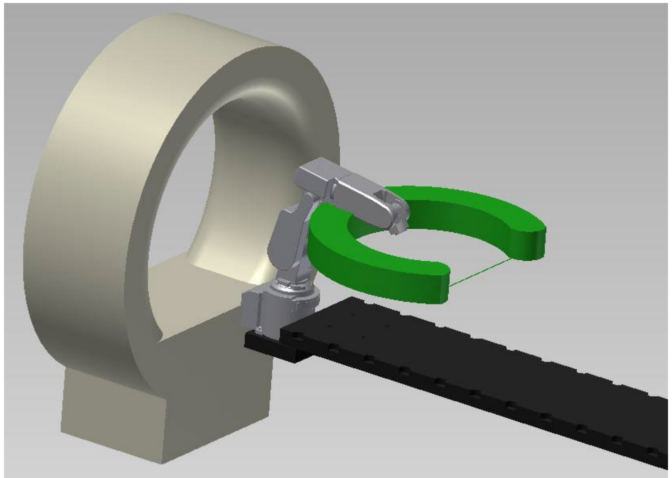
- Exploit high geometrical repeatability of mechanical serial manipulators for ETS positioning in CT room and treatment room
- Co-operative modality of robot activation (safety redundant PLC)

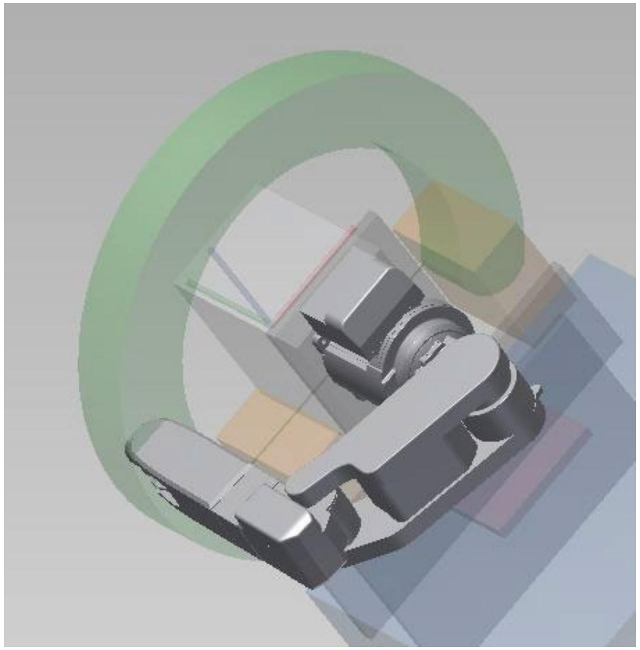
Technology

- MITSUBISHI Serie F; Model RV-4FL-D for Treatment Chair
- MITSUBISHI Serie F; Model RV-2F-D for CT Couch

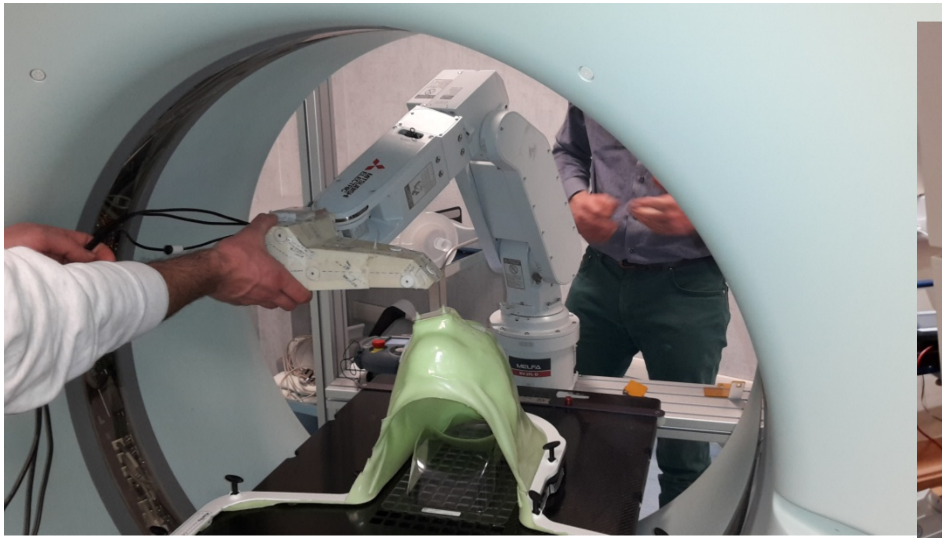
Design

- Mechanical support
- Feasibility of common ETS position and orientations
- Robot singularities
- SW application (GUI)





Robotic ETS positioning



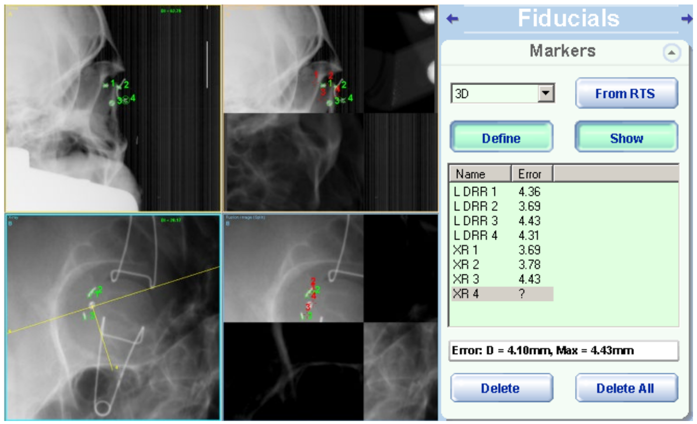
ETS application in CNAO workflow

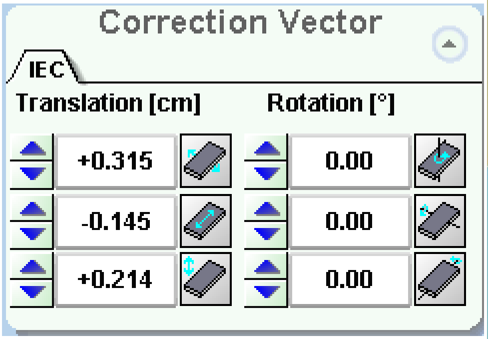
Irradiation

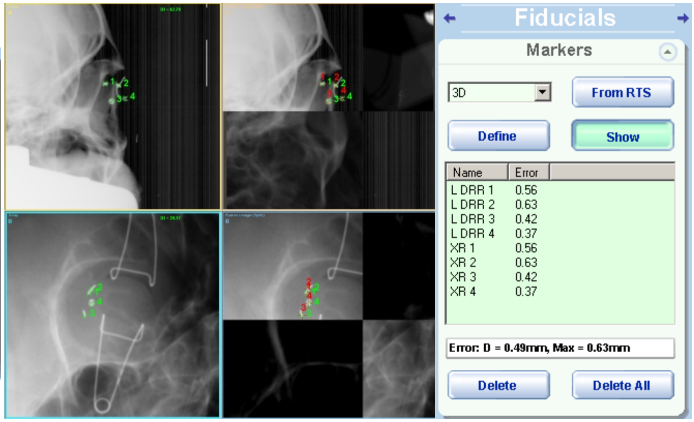
X-ray imaging

Point-based registration on clips

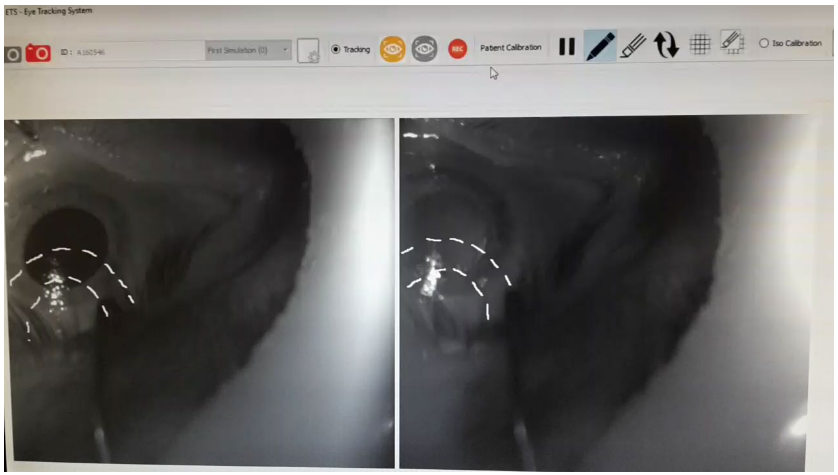
Residuals ≤1mm

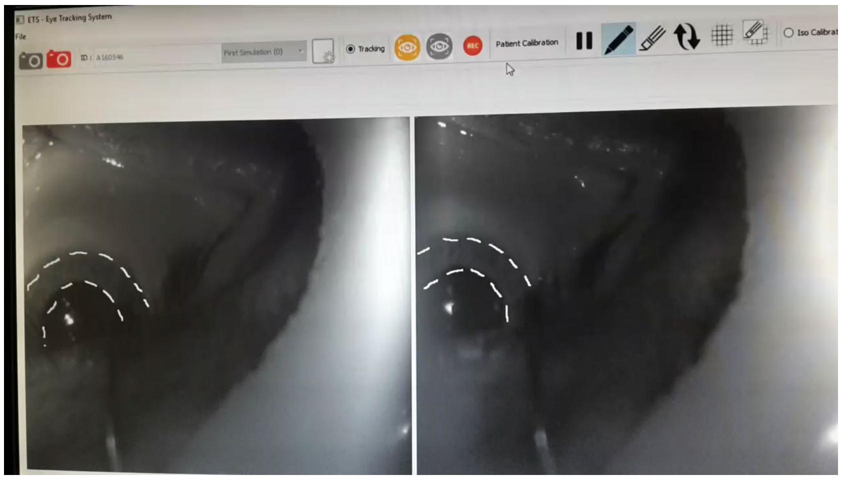






Dose delivery

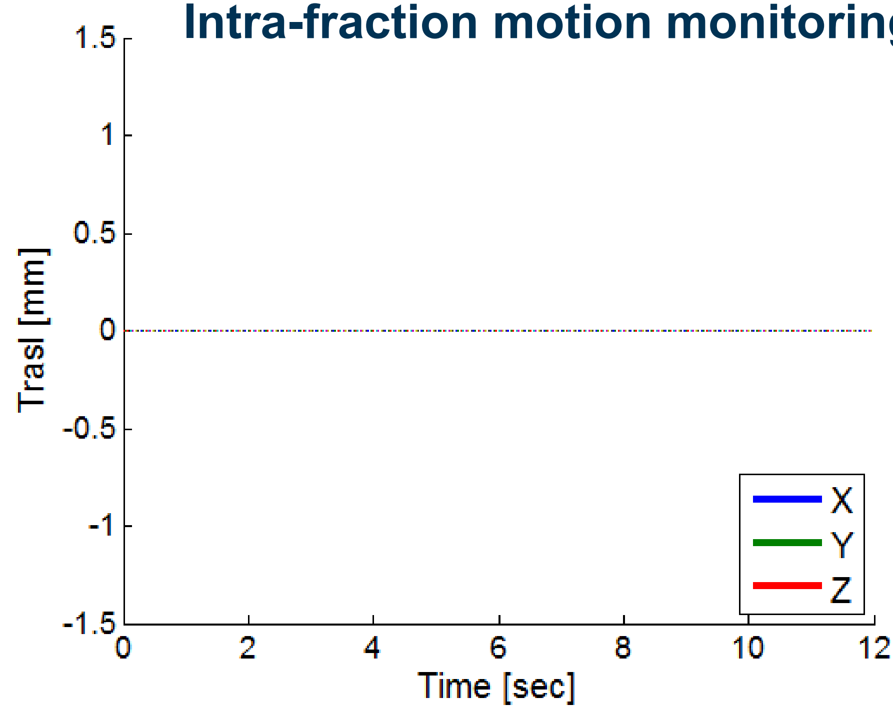




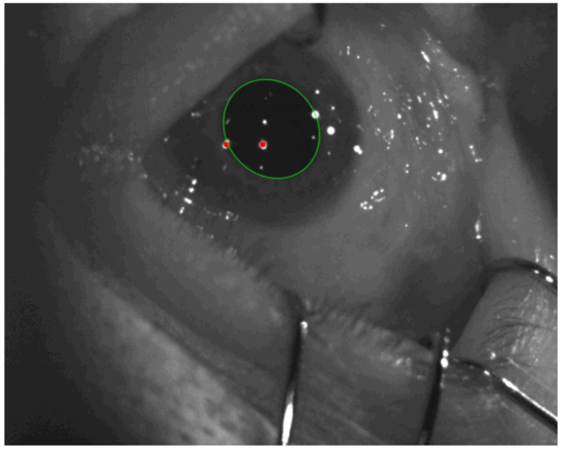
Robotic-assisted eye tracking

	Implanted markers		Set-up errors (mm) LL $_{M(\sigma)}$	SI $_{M(\sigma)}$	AP $_{M(\sigma)}$
Patient 1	**4**	**X-Ray**	0.01 (0.26)	-0.17 (0.16)	3.47 (1.05)
		ETS	0.11 (0.43)	-0.10 (0.23)	3.71 (1.50)
Patient 2	**6**	**X-Ray**	0.28 (0.29)	0.12 (0.16)	1.15 (1.50)
		ETS	0.11 (0.42)	0.36 (0.47)	0.94 (0.96)

Intra-fraction motion monitoring



Patient	Mean [mm]	σ [mm]
1	0.93	0.75
2	0.16	0.10



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