Rigid vs. Deformable Image Registration in Surface Guided Radiation Therapy (SGRT): Applications, Limitations, and Clinical Relevance

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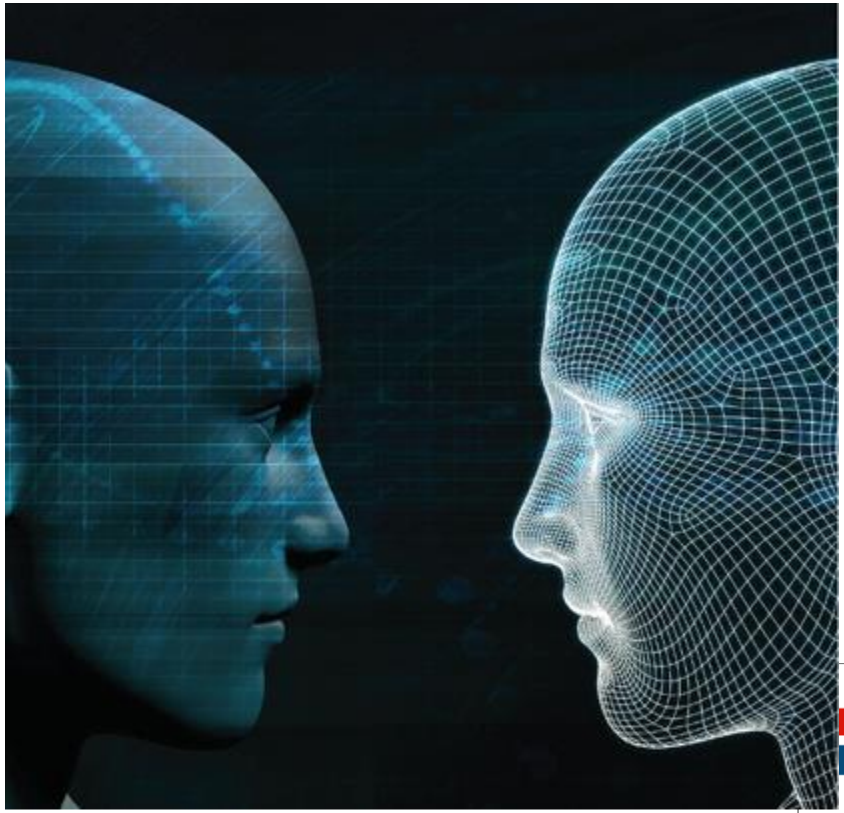

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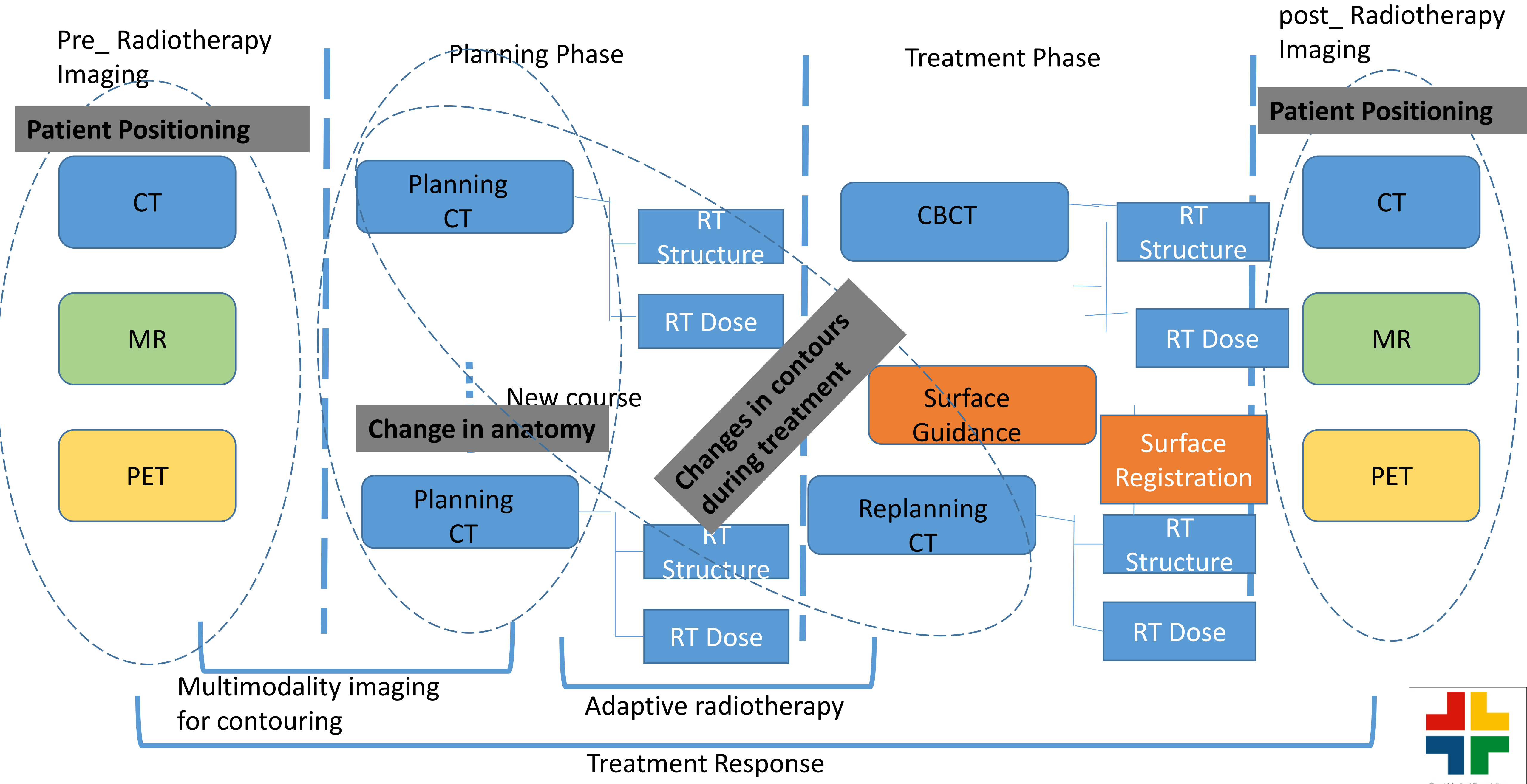
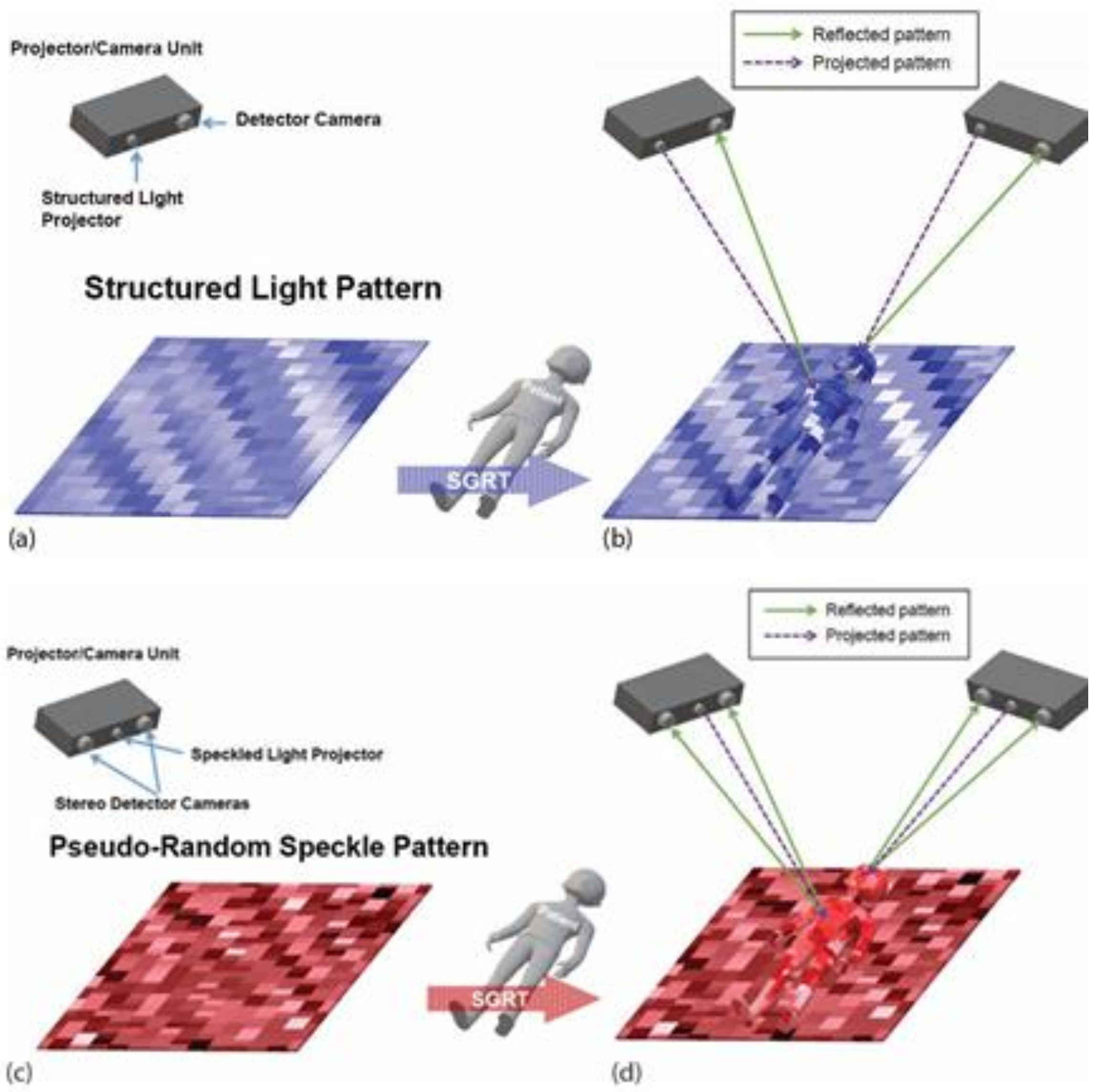


Pre_ Radiotherapy Imaging
Planning Phase
Treatment Phase
post_ Radiotherapy Imaging
Patient Positioning
CT
MR
PET
Planning CT
RT Structure
RT Dose
New course
Change in anatomy
Planning CT
RT Structure
RT Dose
Changes in contours during treatment
CBCT
RT Structure
RT Dose
Surface Guidance
Surface Registration
Replanning CT
RT Structure
RT Dose
Patient Positioning
CT
MR
PET
Multimodality imaging for contouring
Adaptive radiotherapy
Treatment Response



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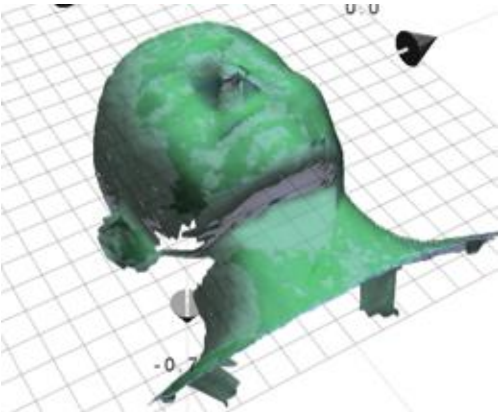

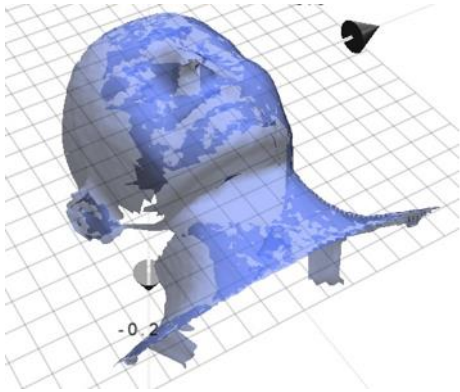

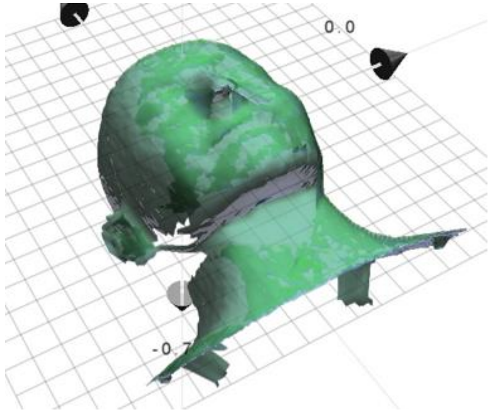

TPS Body contour taken as reference Image with information of Isocenter

→

Live Position is matched with reference

→

Patient is monitored for whole treatment

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Problem of registering two surfaces

- It is a fundamental problem in computer vision, medical Imaging, Robotics and 3D modelling
- The goal is to align two surfaces
- First Create the surface and then register

Algorithms in Registration

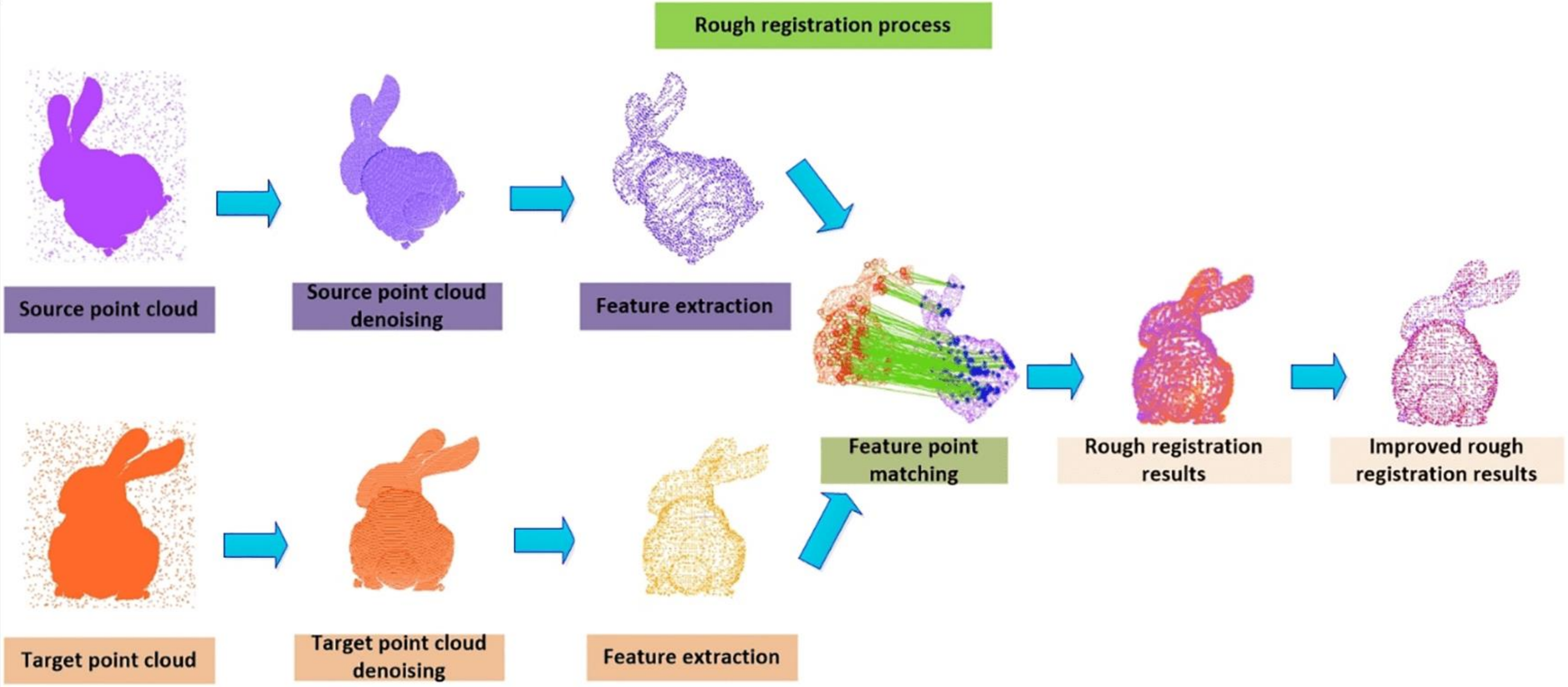
- **Iterative Closest Point (ICP) and Variants**
- ICP (Classic) – Iteratively minimizes the distance between corresponding points.

  Point-to-Point ICP

  Point-to-Plane ICP

  Generalized ICP (GICP) – Combines point-to-point and point-to-plane.

  Color ICP – Uses color information in correspondence matching.



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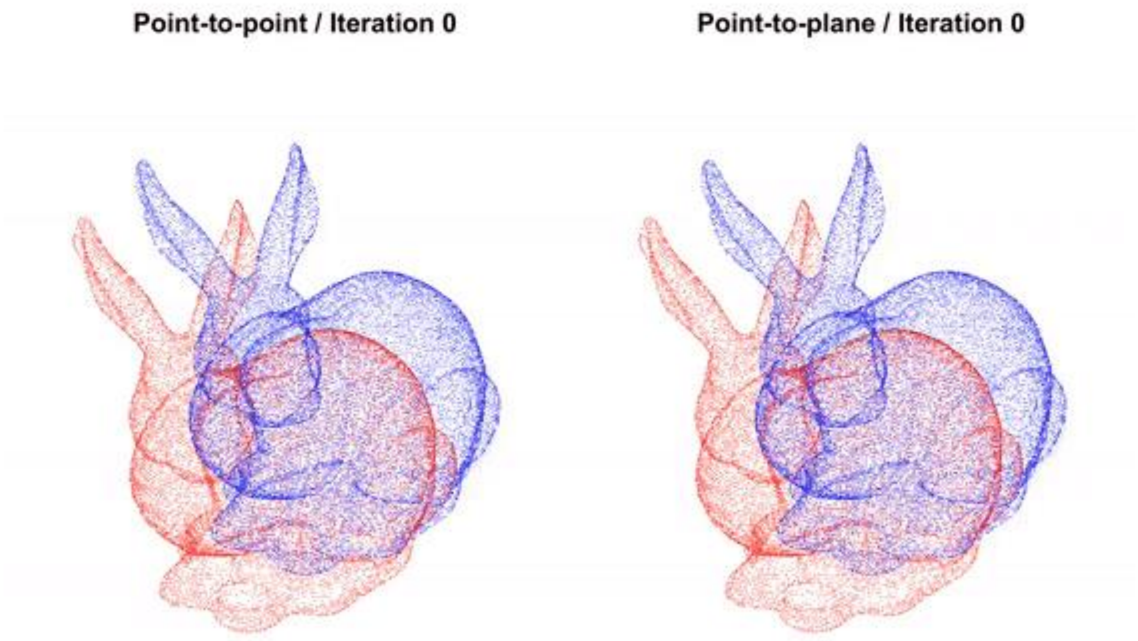
Iterations



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Other Registration Algorithms

- **Feature-Based Registration**

SIFT-3D, Spin Images, SHOT descriptors, FPFH (Fast Point Feature Histograms) – Extract local features and match them.

RANSAC-based alignment – Uses feature correspondences and random sampling for robust alignment.

- **Probabilistic Approaches**

Coherent Point Drift (CPD) – Uses probabilistic models to align points.

Gaussian Mixture Models (GMM) – e.g., EM-ICP.

- **Global Registration**

Go-ICP – Global optimal ICP using a branch-and-bound strategy.

Super4PCS – Fast global registration based on 4-point congruent sets.

TEASER++ – Robust, certifiable registration framework for extreme outlier conditions.

Non-Rigid Registration Algorithms

- **Non-rigid ICP (N-ICP)**

  Extends ICP by allowing local transformations.
- **Coherent Point Drift (Non-rigid mode)**
  Thin Plate Spline (TPS)

  Fits a smooth deformation field using sparse correspondences.
- **Gaussian Process Morphable Models (GPMM)**
- **Embedded Deformation Graphs**

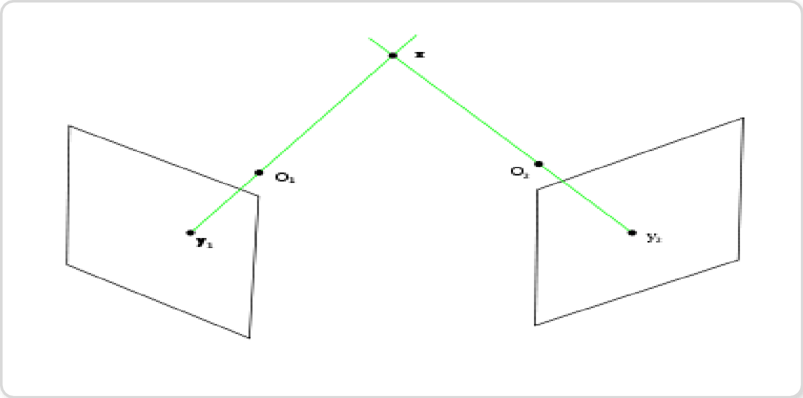
  Often used in real-time applications like Dynamic Fusion.

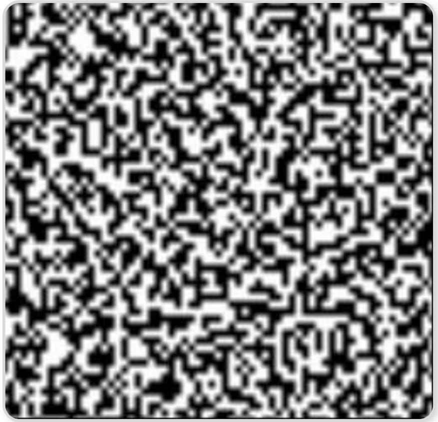
DEVICE OVERVIEW - HOW DOES IT WORK?

Calibration

Active Stereo

- **Projects near infrared light* and pseudo-random optical speckle pattern on the subject**
- **The pattern adds texture and is used for 3D reconstruction**





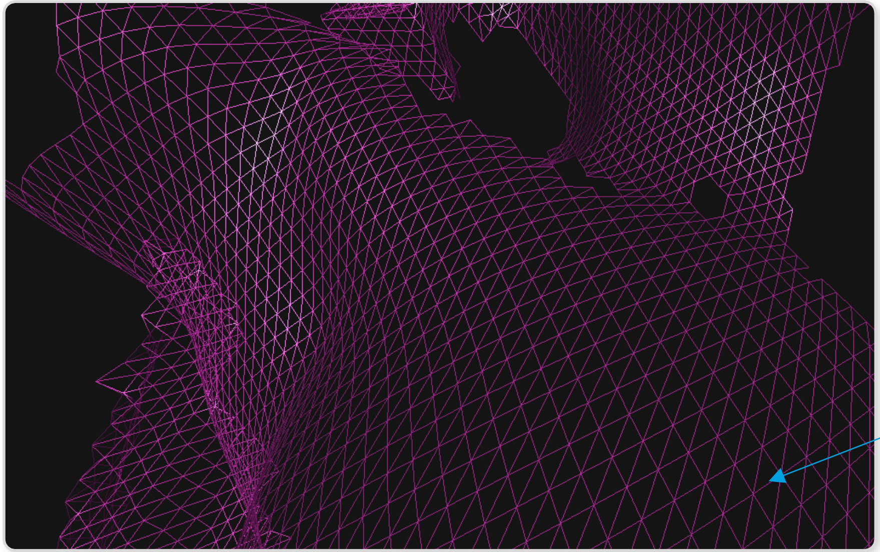
***Refer to 1016-0281 Vision RT Why Red document for more information**

DEVICE OVERVIEW - HOW DOES IT WORK?

Vertices are created and triangulated

- Each vertex comprises (x, y, z) values
- Each triangle consists of 3 corresponding vertices

The system creates a 3D surface model of up to 20,000 points



Wireframe rendering

Vertices, triangles

Smooth rendering

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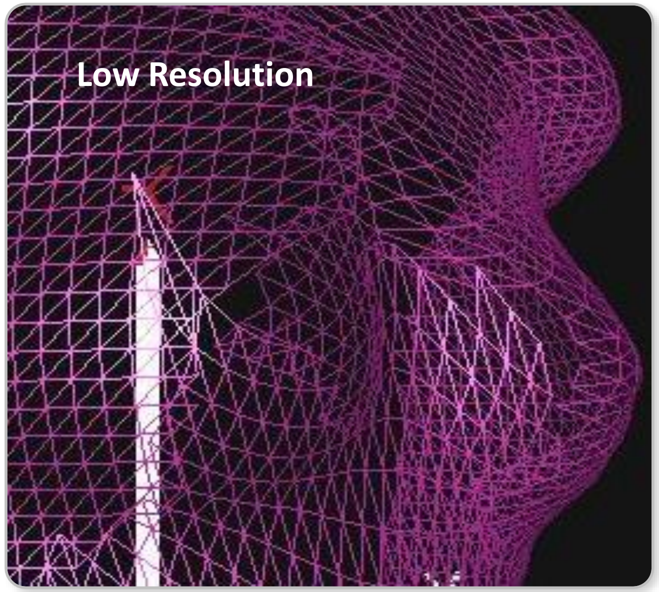
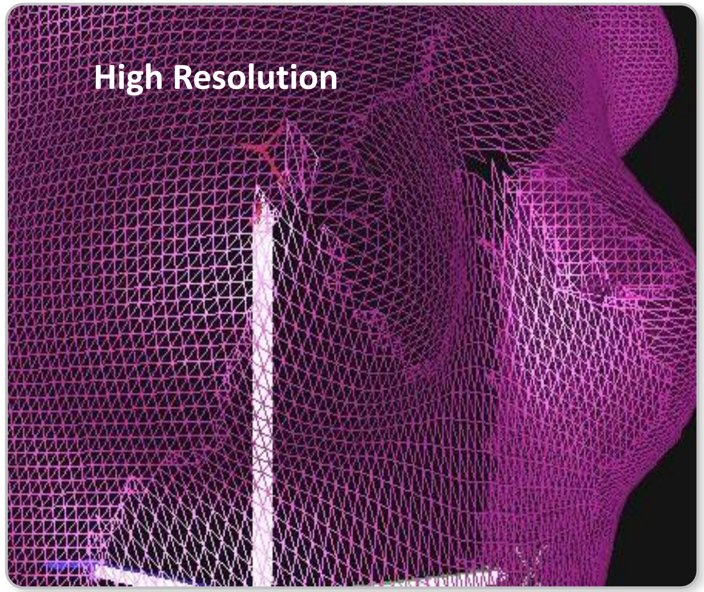
3D SURFACE DATA

- Surface data is composed of a number of triangles
- The greater the number of triangles, the higher the surface resolution
- Choosing Brain, Head and Neck or Intracranial SRS treatment protocols gives higher resolution data
- High resolution data is required for more complex treatment surfaces such as SRS

Site	Resolution	Frame Rate	Default Translational Threshold	Default Translational Bounds	Default Rotational Threshold	Default Rotational Bound	Default Translational Display Unit	Default Precision/ No. of Decimal Places)
Intracranial SRS	High	Low	0.1cm	0.5cm	1.0°	6.0°	cm	2
Head and Neck	High		0.2cm	1.0cm	2.0°	12°	cm	2
Brain	High		0.2cm	1.0cm	2.0°	12°	cm	2
Spine	Med		0.3cm	1.5cm	3.0°	12°	cm	2
SCF	Med		0.3cm	1.5cm	3.0°	12°	cm	2
Abdomen	Med		0.3cm	1.5cm	3.0°	12°	cm	2
Chest Wall	Med		0.3cm	1.5cm	3.0°	12°	cm	2
Pelvis	Med		0.3cm	1.5cm	3.0°	12°	cm	2
SBRT	Med		0.3cm	1.5cm	3.0°	12°	cm	2
Breast	Med		0.3cm	1.5cm	3.0°	12°	cm	2
Chest	Med		0.3cm	1.5cm	3.0°	12°	cm	2
Chest Wall DIBH	Med		0.3cm	1.5cm	3.0°	12°	cm	2
Breast DIBH	Med		0.3cm	1.5cm	3.0°	12°	cm	2
Extremities	Med		0.3cm	1.5cm	3.0°	12°	cm	2
Other	Low	High	0.3cm	1.5cm	3.0°	12°	cm	2





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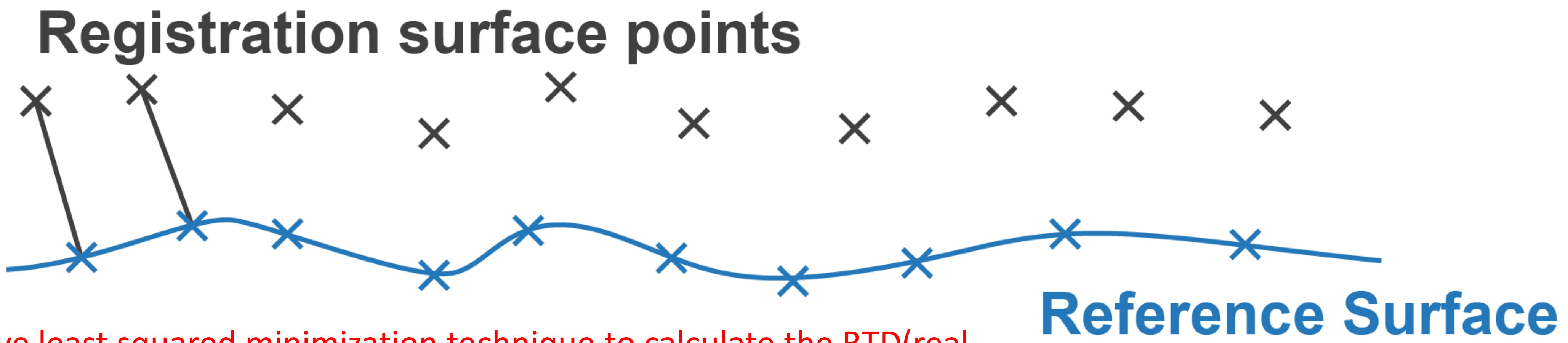
SURFACE REGISTRATION

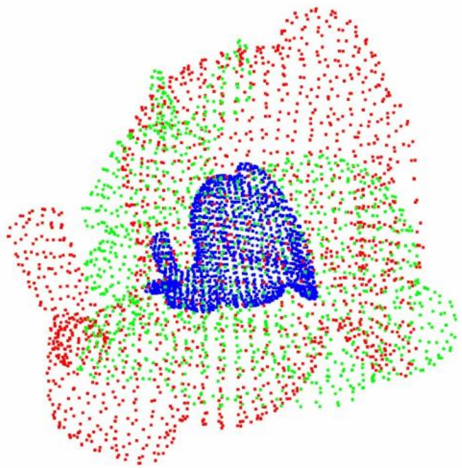
- **During treatment capture or monitoring, the surface is automatically registered to the reference ROI to determine patient misalignment**
- **The registration process assumes that patient motion is rigid**
- **Iterative Closest Point match**



Iterative least squared minimization technique to calculate the RTD(real time delta)

What is non rigid image registration (DIR)

- DIR is the **nonaffine/non linear** process of mapping voxels from one image to another where the individual vectors that describe the mapping may vary in both ***magnitude and direction from their neighbors***. The entire process is encompassed by the deformation vector field (DVF), which aggregates the individual vectors into a single map and specifies the coordinate transformation between the two datasets.



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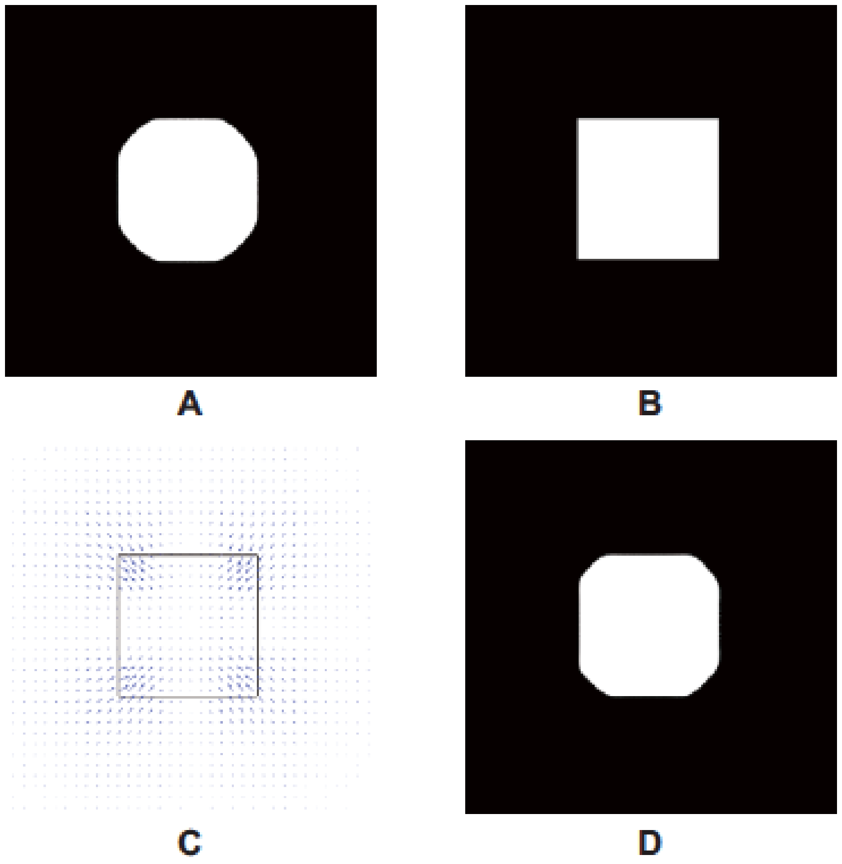
Non rigid image registration

- Two image sets, a fixed image (A) and a moving image (B)
- Rigid image registration could not register the four sharp corners of the rectangle in the moving image into the rounded boundary in the fixed image.
- Deformable image registration locally deformed the four sharp corners with a different amount of deformation (or displacement).
- (C) The 2D deformation vector field (DVF) was displayed as blue arrows with the edge of the moving image object.
- The size and direction of the arrows represent the magnitude and direction of DVF.
- The magnitude of deformation is the largest at the corners and gradually decreases.
- (D) The deformed results with DVF.



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pISSN 2234-1900 . eISSN 2234-3156

Rigid Vs Deformation

- Rigid:

Assume static or minimal deformations of the subject and determine the radiation isocentre based on global rigid surface alignment.

- Non-Rigid:

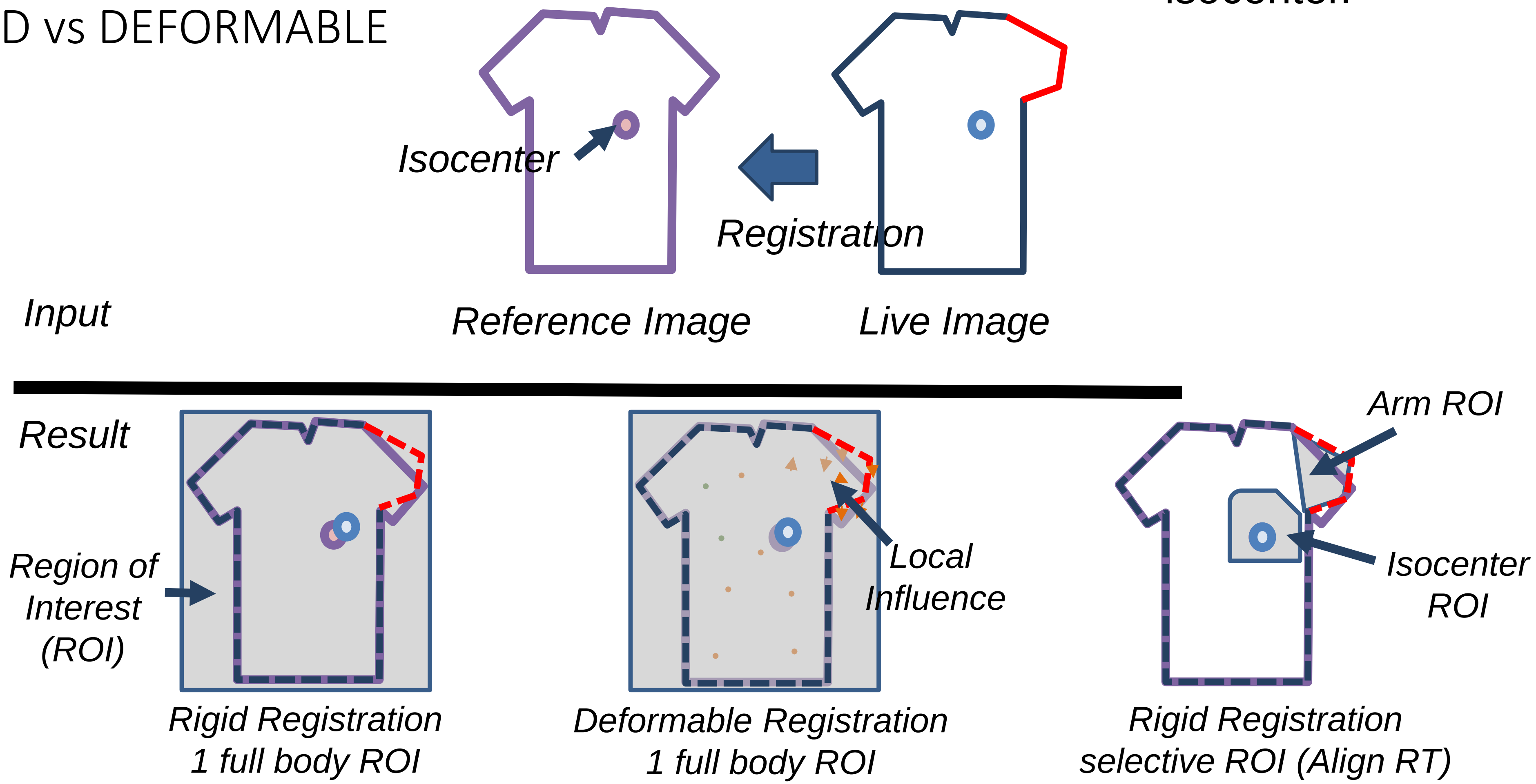
Account for deformations of the subject and determine the radiation isocenter based on global non-rigid surface alignment.

How to deal with patient deformation?

- Rigid algorithm: Use small and multiple ROIs to exclude deformations. Accuracy is depended on the ROI definition and selection by user
- Non-Rigid algorithm: Accounted for by deformable registration. Accuracy provided by the algorithm automatically adjusting to level of deformation without user input.

isocenter.

RIGID vs DEFORMABLE



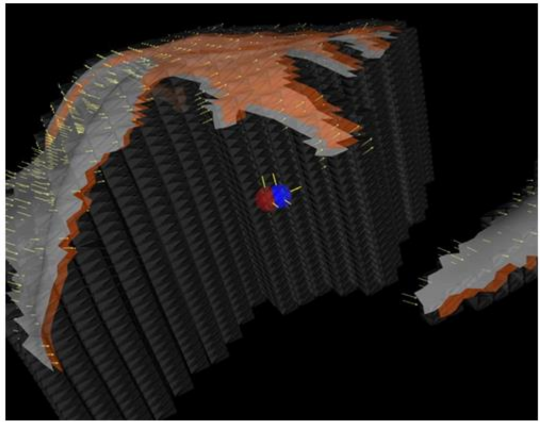
No distance weighting: ***larger error***

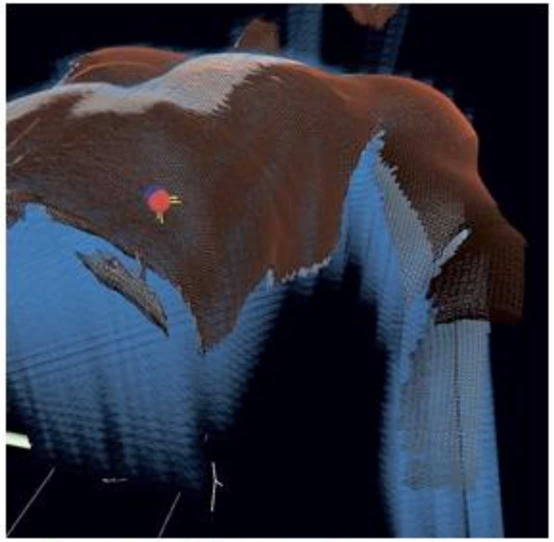
Distance weighted algorithm: ***smaller error***

No change in Isocenter ROI: ***NO error from arm movement***

How is non rigid implemented?

- Starts with rigid matching then lets the surface deforms if needed
- The level of allowed deformation can be adjusted to fit the expected target
- The algorithm has two steps
- Surface displacement by the Non-Rigid Image registration
- calculate isocenter displacement by volumetric calculat



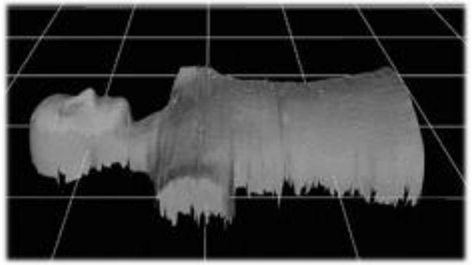


Non rigid registration

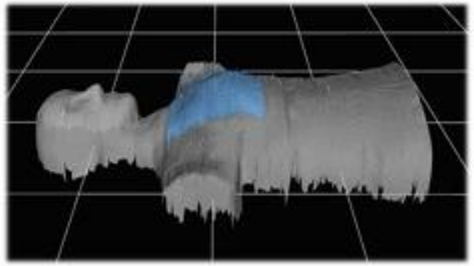
Process of Deformation

Illustrated Example:

1. Live Image With Surface Discrepancy (Blue) and Whole Body Misalignment

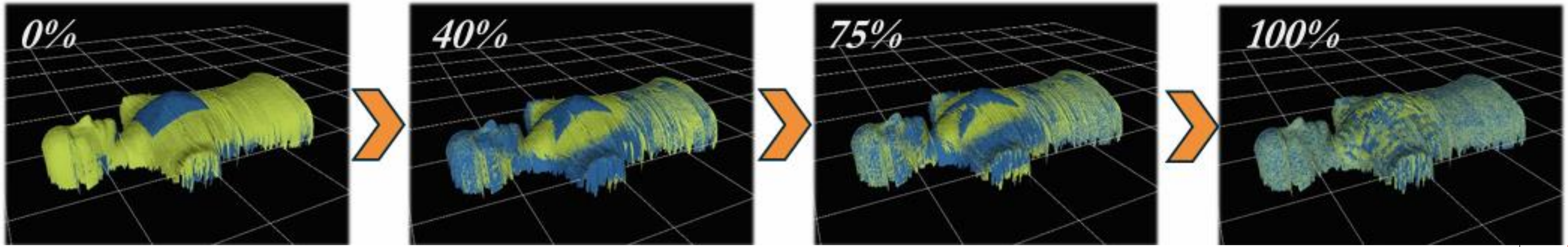


Reference Image



Live Image

2. Deformable Iterative Process for Surface Matching (0% -100%)



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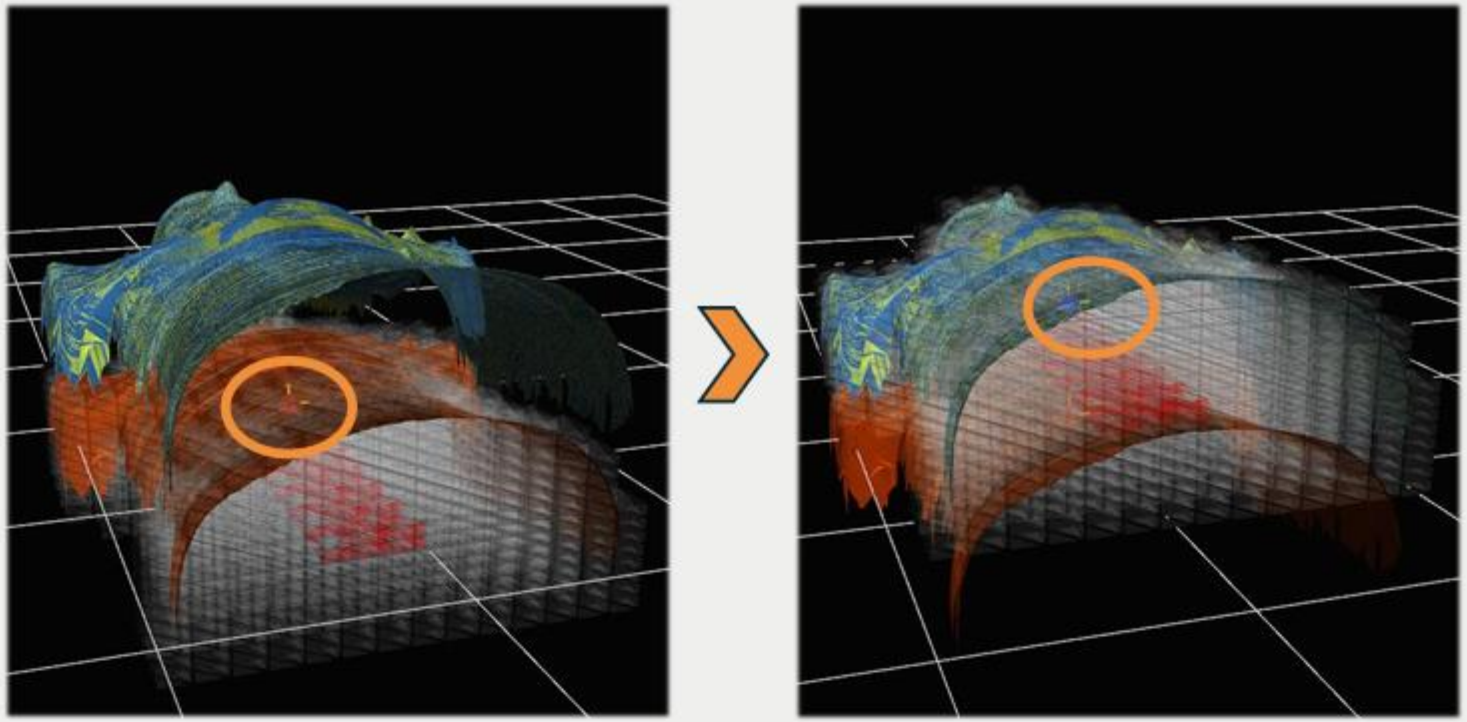
Algorithm process - isocenter displacement

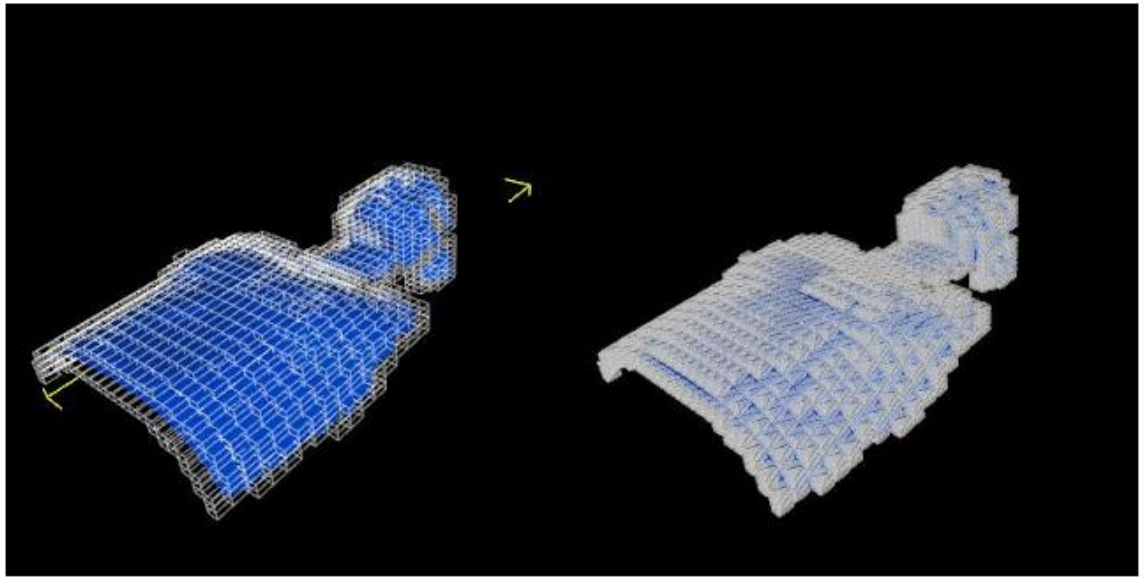
Volumetric Calculations for Isocenter Displacement and Correction



Initial Refence Volume (Isocenter Highlighted)

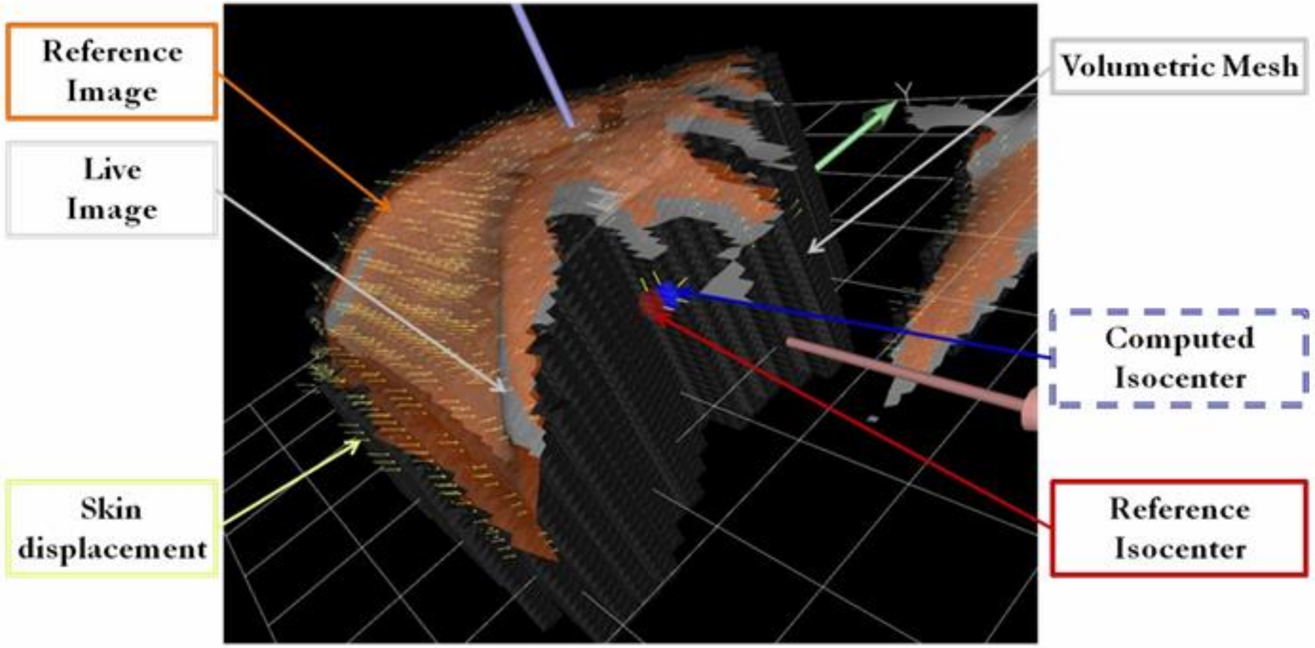
Live Volume (Isocenter Highlighted)

- Generate a volumetric mesh from the reference surface.
- The isocenter is included in the volumetric mesh to be used for the calculated shift



Left: triangulated surface embedded in voxels. Right: Surface embedded in tetrahedron

- Apply the vector field from the surface displacement to the volumetric mesh
- Compute the volumetric mesh displacement from applied vector field that minimize the structure’s energy state (FEM, conjugate gradient algorithm)
- Calculate the isocenter displacement by using the information of the volumetric mesh displacement



> J Appl Clin Med Phys. 2022 Mar;23(3):e13493. doi: 10.1002/acm2.13493. Epub 2022 Jan 25.

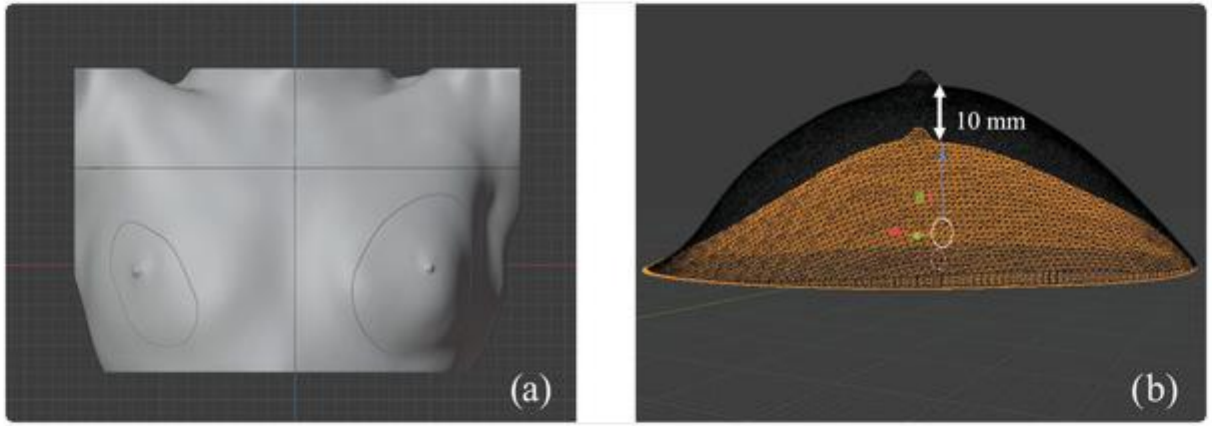
Accuracy of patient setup positioning using surface-guided radiotherapy with deformable registration in cases of surface deformation

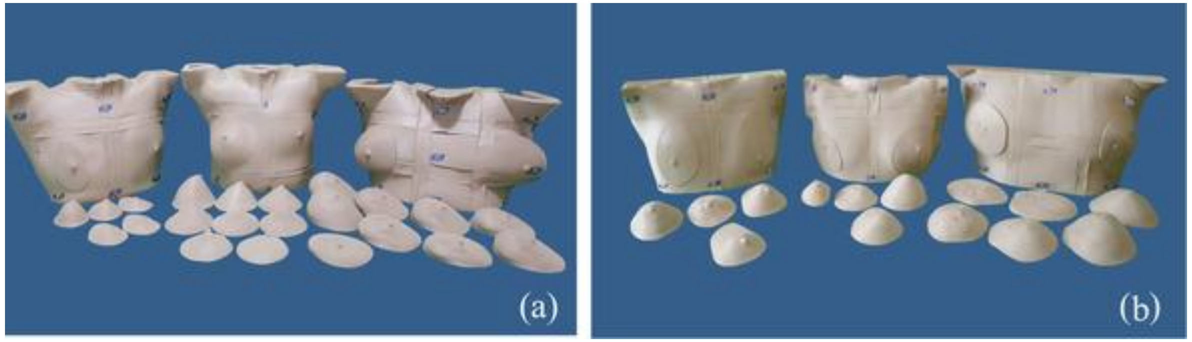
Boriphat Kadman [1], Akihiro Takemura [2], Tatsuya Ito [3], Naoki Okada [1], Hironori Kojima [4], Shinichi Ueda [4]

Affiliations + expand

PMID: 35077004 PMCID: PMC9398221 DOI: 10.1002/acm2.13493

Abstract





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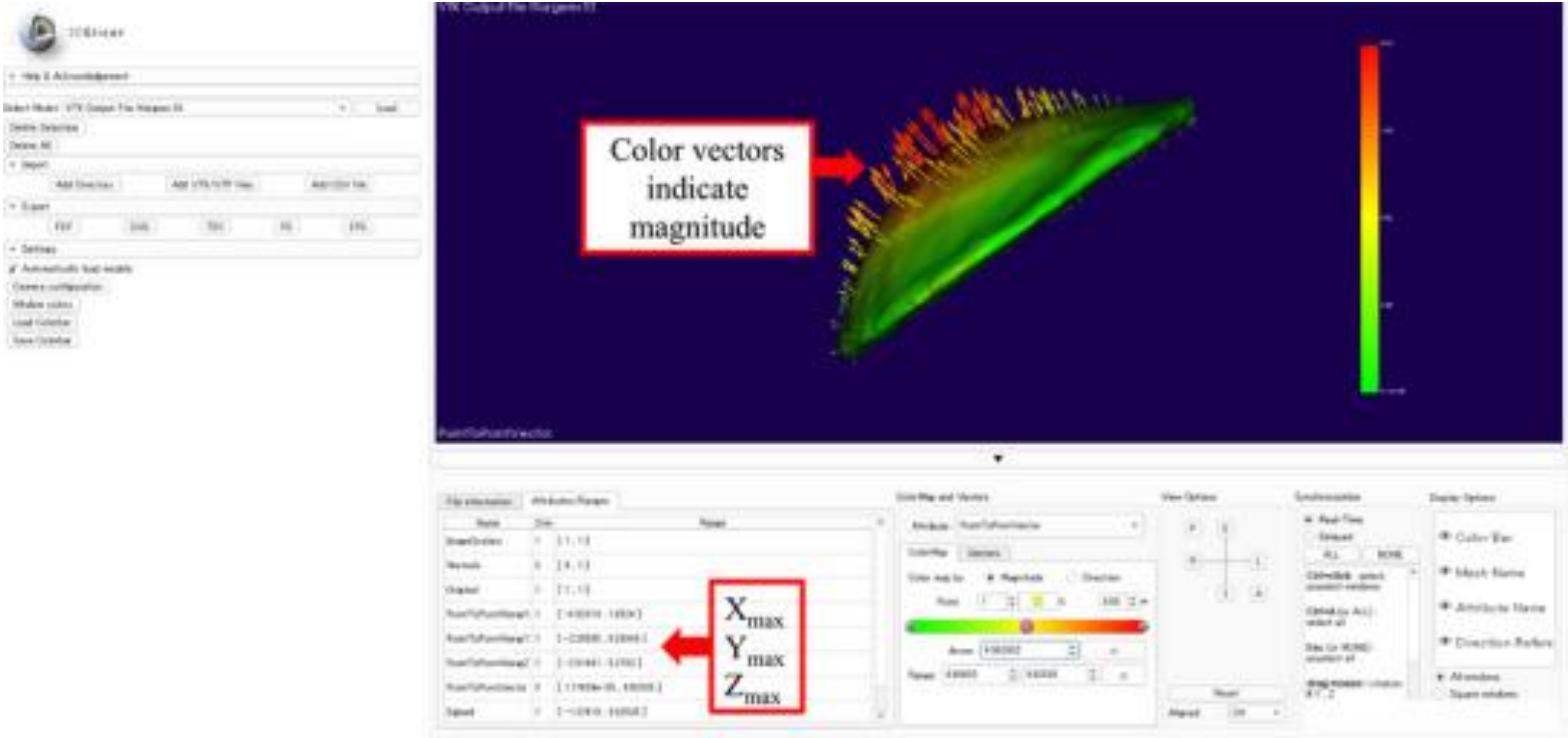

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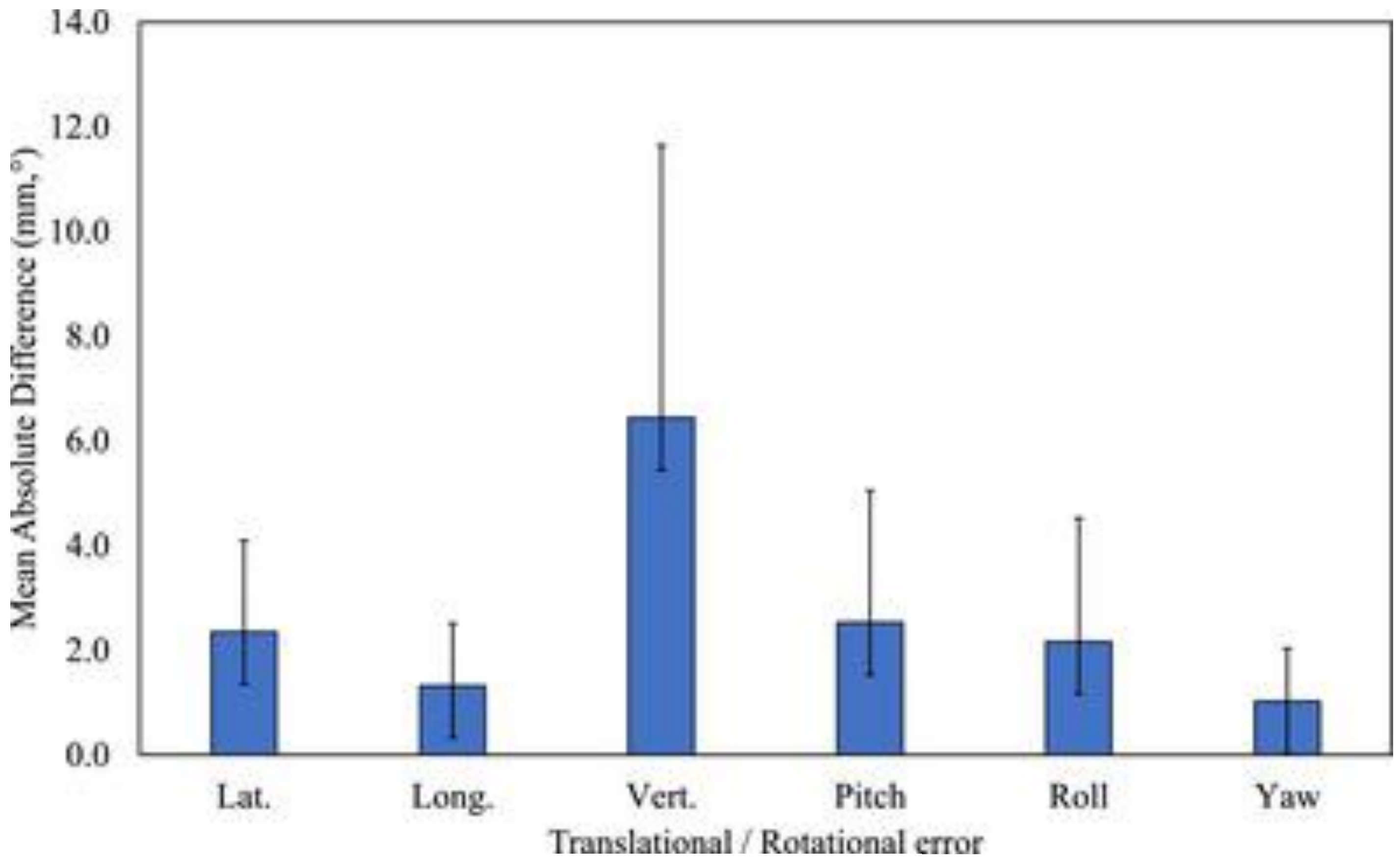
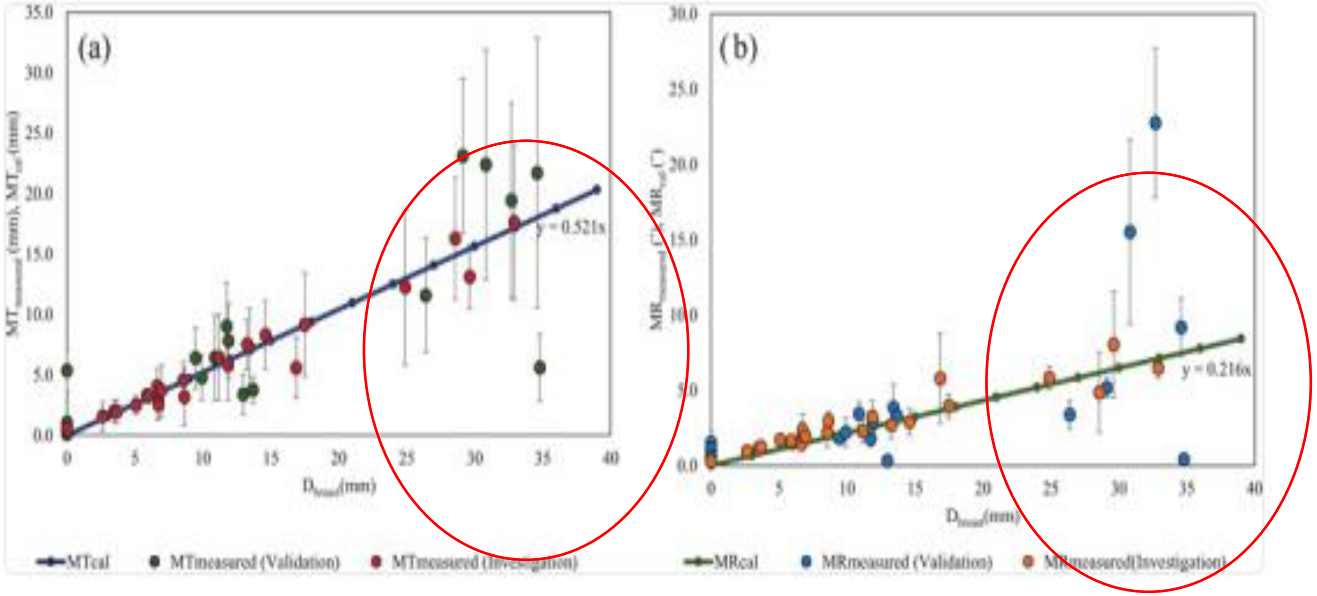


$$MT_{measured} = \sqrt{la\,t^2 + ln\,g^2 + vr\,t^2},$$

$$MR_{measured} = \sqrt{pitc\,h^2 + rol\,l^2 + ya\,w^2},$$



Correlations between (a) $MT_{measured}$ (mm)/MT_{cal} (mm), (b) $MR_{measured}$ (°)/MR_{cal} (°), and deformation of the breast part

The magnitude of breast deformation affects the positioning accuracy of SGRT system

- Although deformable registrations can play a valuable role in certain areas of radiation oncology, including adaptive RT and automatic segmentation methods, during treatment, it is important to be able to evaluate surface contours without altering the shape and to provide meaningful shift information that can be performed by the 6DOF treatment couch system.
- Rigid registration is the means used for patient positioning in other situations, for example, cone-beam CT (CBCT) matching.
- There is no time for quality assurance of the deformation field that contributes to the final registration

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	Rigid Registration	Non-Rigid Registration
Definition	Aligns surfaces using only rotation and translation	Allows local deformations (e.g. stretching, bending)
Pros	– Fast and computational efficient – Simple to implement – Good for bony structures and minimal deformation areas – Stable and repeatable	– Can model anatomial deformation – More accurate alignment in soft tissue areas (e.g., breast, abdomen) – Better at accounting for posture changes or respiratory motion
Cons	– Cannot account for soft tissue deformation – Inaccuracte if patient posture differs between sessions – Misalignment in flexible regions	– Higher computational cost – Risk of overfitting or urrelistic deformation – May require regularization and more complex validation – Less reproducible across timepints
Use Cases in SGRT	Head & Neck positioning with rigid masks Spine and pelvis alignment Initial setup verification	Breast radiotherapy where tissue moves and deforms Abdominal or thoraric treatments affected by respiration
Sensitivity to Surface Quality	Widely adopted duo simplicity and speed	Limited but growing, especially in research and adaptive worrkflows

Conclusion

- Surface imaging provides intra-fraction motion monitoring, with both high temporal and spatial resolution but without any added dose from ionizing radiation, which has considerable safety and quality implications
- The role of SGRT is still evolving as the RT community continues to learn how to fully exploit the unique information provided by sur face imaging.
- SGRT is more than just a technological upgrade. It’s a bold step forward in our commitment to treat the disease without compromising the patient. It reflects our dedication to safety, accuracy, and innovation—and fuels our vision of a future where every beam of radiation hits its mark.

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Thank you