EUROVIS ZURICH 21

Uncertainty-aware Visualization in Medical Imaging – A Survey

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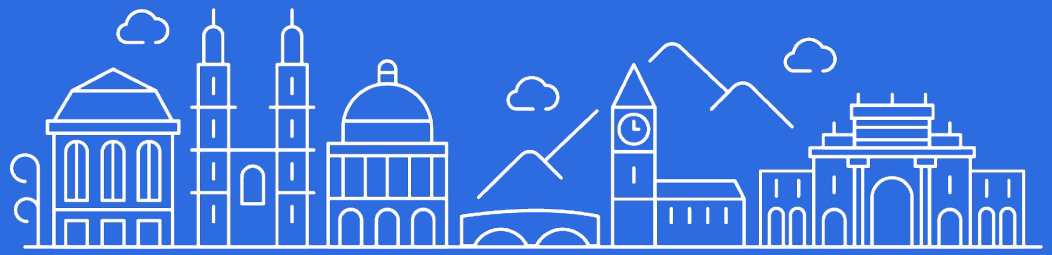
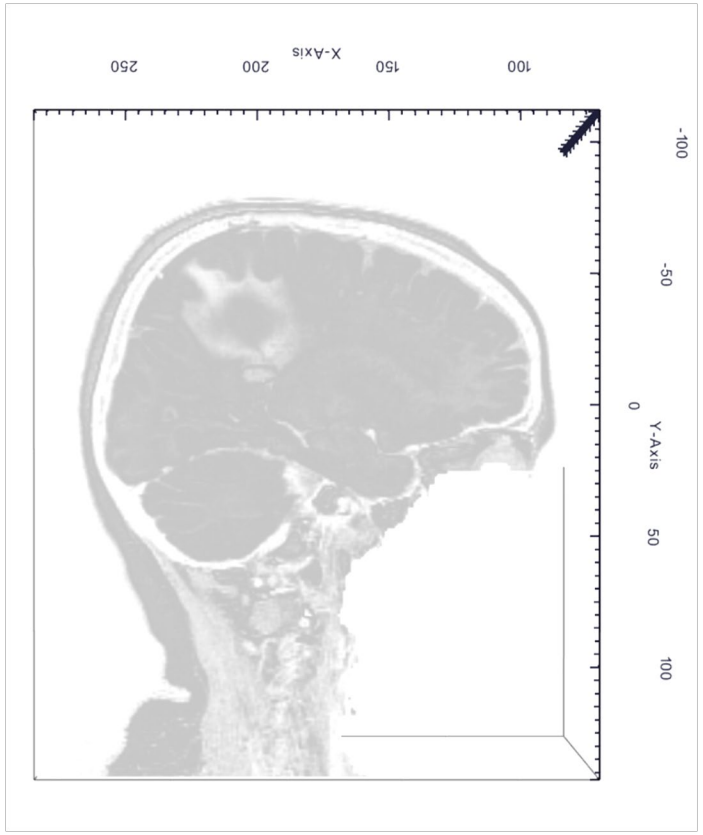


Why This survey?

- Medical Imaging:
  - Is a popular application of visualization
  - Provides unique and complicated data
  - Is affected by uncertainty in various manners



Which uncertainty-aware visualization approaches exist that fit medical imaging?

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1. What is Medical Imaging?
2. Definition of Uncertainty
3. Types of Uncertainties in Medical Imaging
4. Requirements of uncertainty-aware Visualization in Medical Imaging
5. Paper Selection Criteria
6. State of the Art Analysis
7. Creation of Medical Imaging Pipelines
8. Open Problems

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1. **What is Medical Imaging?**
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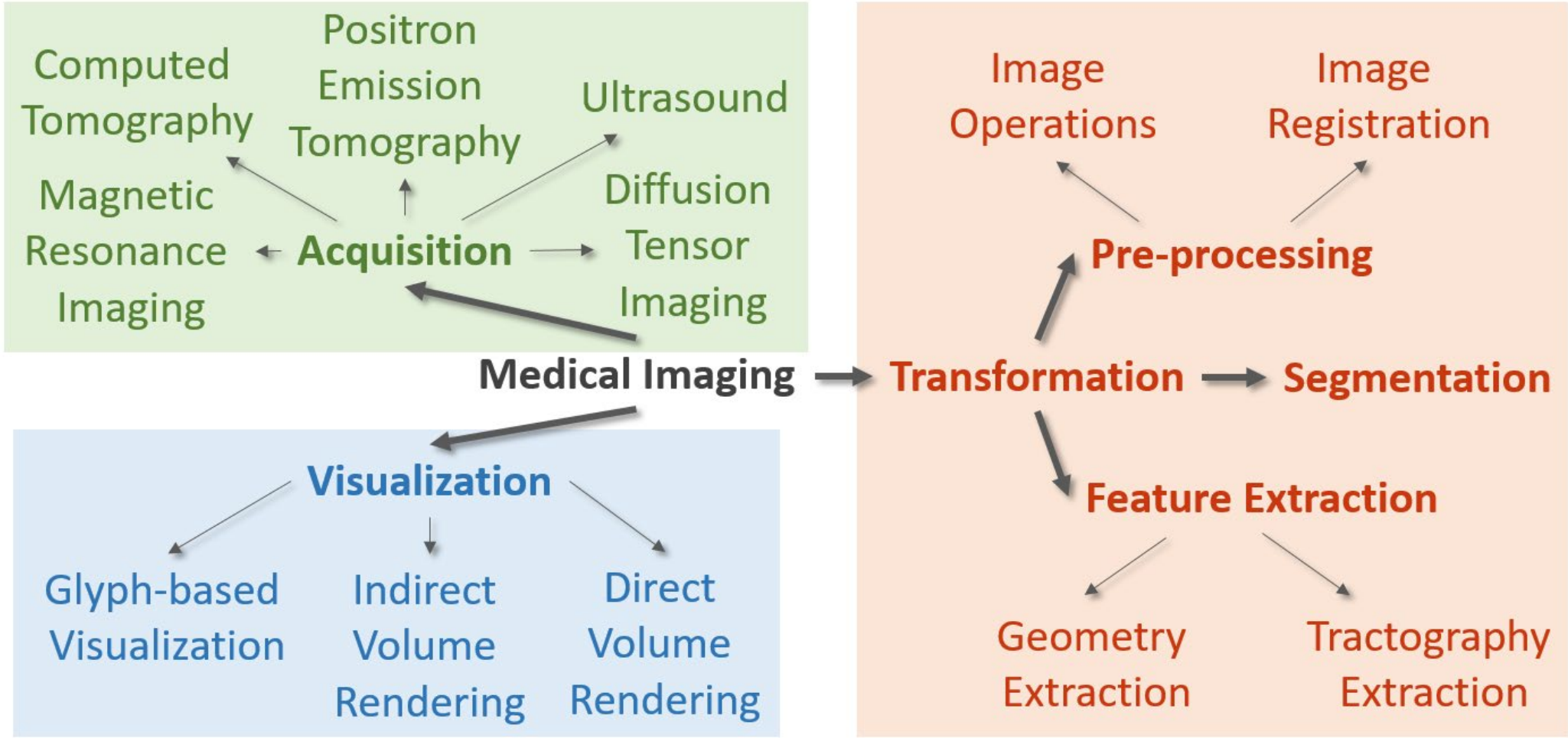
1. What is Medical Imaging?

„Medical imaging is concerned with the analysis, visualization, and exploration of medical images“

Acquisition:	Generation of medical images
Transformation:	Analysis and processing of images
Visualization:	Visual representation of medical images
Applications:	Diagnosis, Treatment Planning, Intraoperative Support, Education

1. What is Medical Imaging?



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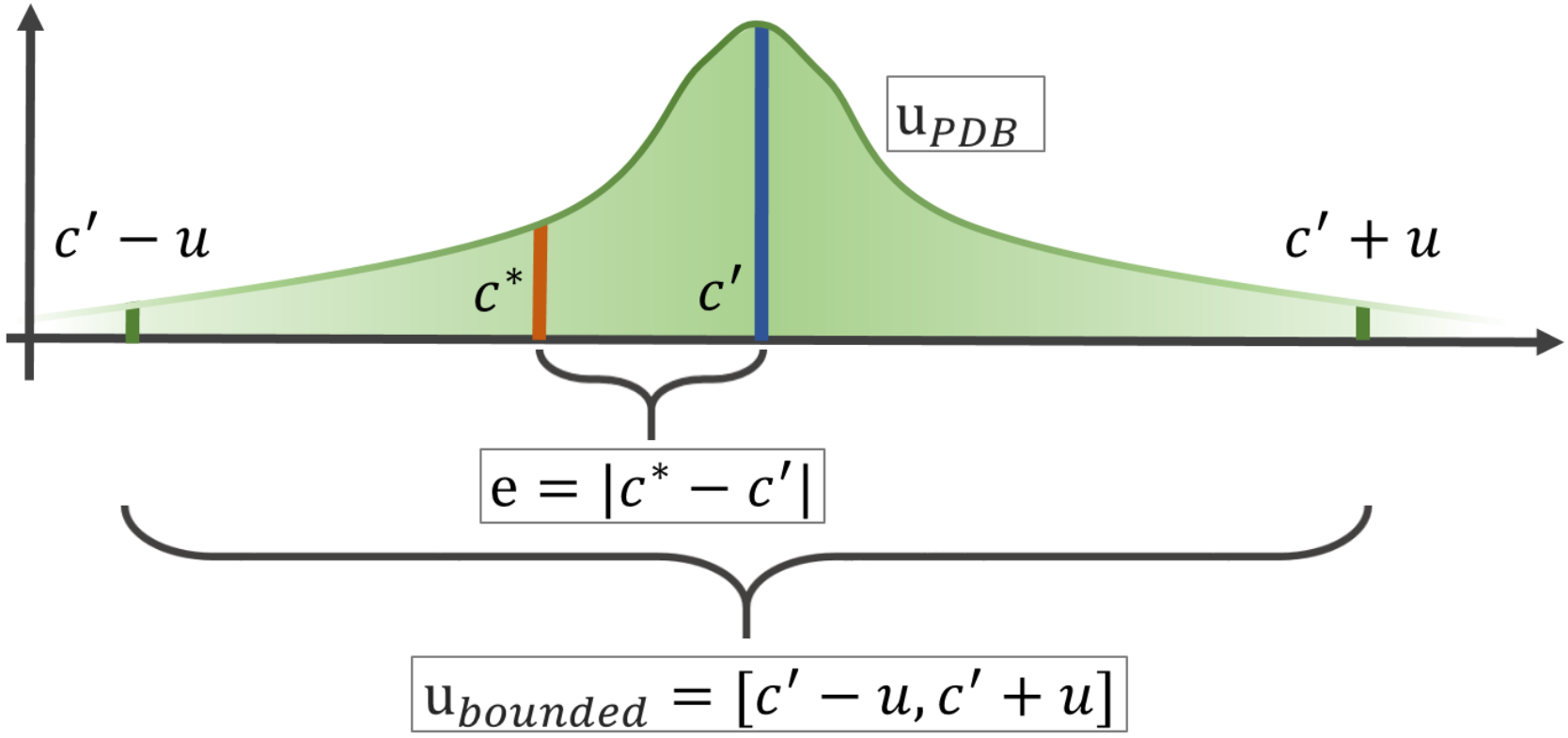
2. Definition of Uncertainty



2. Definition of Uncertainty

Uncertainties can be descriped by:

- Type
  - Aleatoric (uncertainty arising from the data)
  - Epistemic (uncertainty arising from the computational model)
- Dimensionality of Event
- Category (numerical, spatial, binary…)
- Description (discrete or continous)

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3. Types of Uncertainties in Medical Imaging

Sources of Uncertainty	Type	Dimensionality of Event	Category	Description of Event
Positional uncertainty	a	3D	numerical	discrete
Pixel/voxel value uncertainty	a	nD	numerical	discrete
Incompleteness of Data	a	nD	numerical	discrete
Model inaccuracy	e	3D	spatial/volumetric/numeric	discrete/continuous
Model incompleteness	e	3D	spatial/volumetric/numeric	discrete/continuous
Parameter/boundary condition uncertainty	a/e	nD	numerical	discrete
Rasterization uncertainty	e	2D/3D	numerical	continuous
Perceptual and cognitive uncertainty	e/a	3D	binary	continuous
Decision making bias	e/a	3D	binary	continuous

Goal: Capture at least of one these uncertainties in a visualization

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4. Requirements of uncertainty-aware Visualization in Medical Imaging

- Discussion with collaborators
- Based on requirements known for medical imaging
- Rating of experts
- Reduction to high-level requirements

1. Show the original dataset
2. Show the related uncertainty
3. Keep the cognitive load minimal

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5. Paper Selection Criteria

- Search Platforms
  - IEEE Transactions on Visualization and Computer Graphics
  - IEEE Transactions on Medical Imaging
  - Computers & Graphics
  - Eurographics Digital Library
  - Computer Graphics Forum
  - Uncertainty Quantification in Scientific Computing
  - Google Scholar
  - Springer Link

5. Paper Selection Criteria

- Keywords

  1. Part:

  Uncertainty-aware Visualization | Uncertainty Visualization | Uncertainty Analysis | Sensitivity Analysis |Ambiguity Analysis| Variability | Variation

  2. Part:

  Medical Imaging | Medical Imaging subcategories | Diagnosis | Intraoperative Support | Treatment Planning | Education

- Criteria of inclusion in this STAR
  - At least one example from medical imaging
  - Uncertainty visualization

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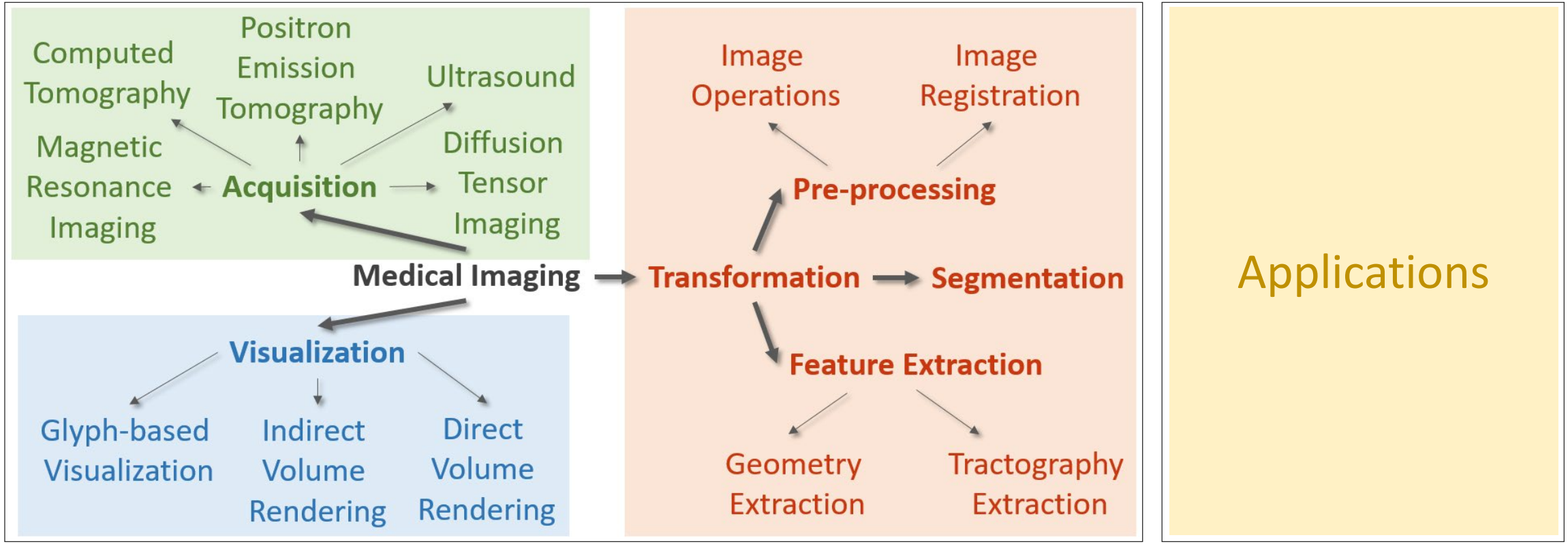
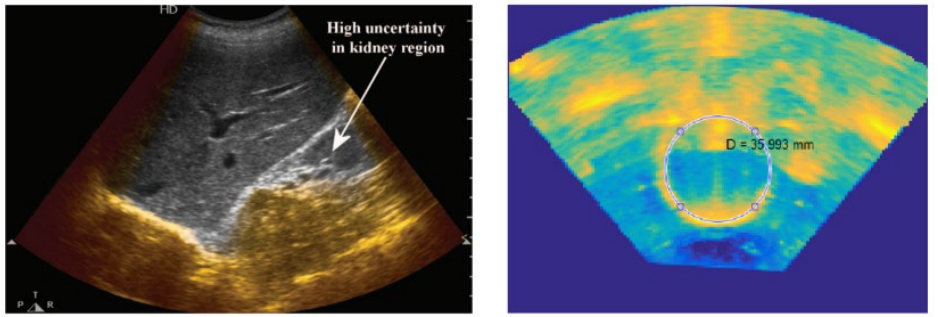
6.State of the art analysis

- Structured along the medical imaging pipeline

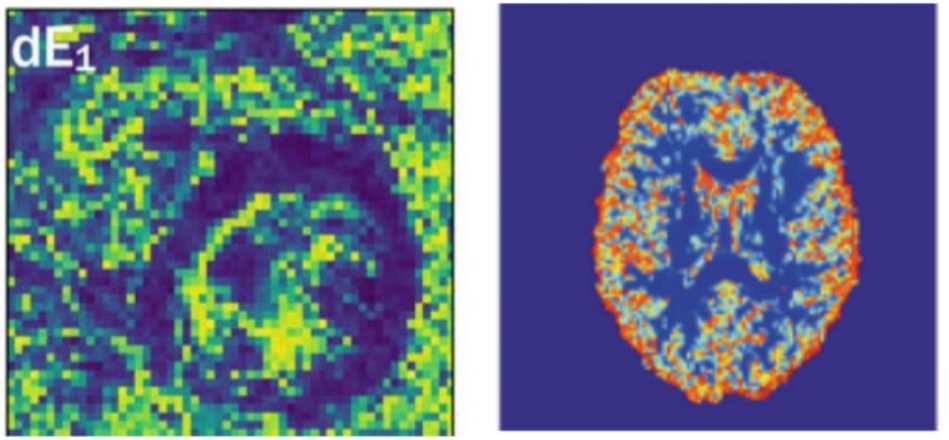


6.State of the art analysis (Acqusition)

- Ultrasound, Computed Tomography, Magnetic Resonance Tomography, Diffusion Tensor Imaging, Positron Emission Imaging
- Further imaging available, but not as popular



(a) Ultrasound (b)



(a) (b)

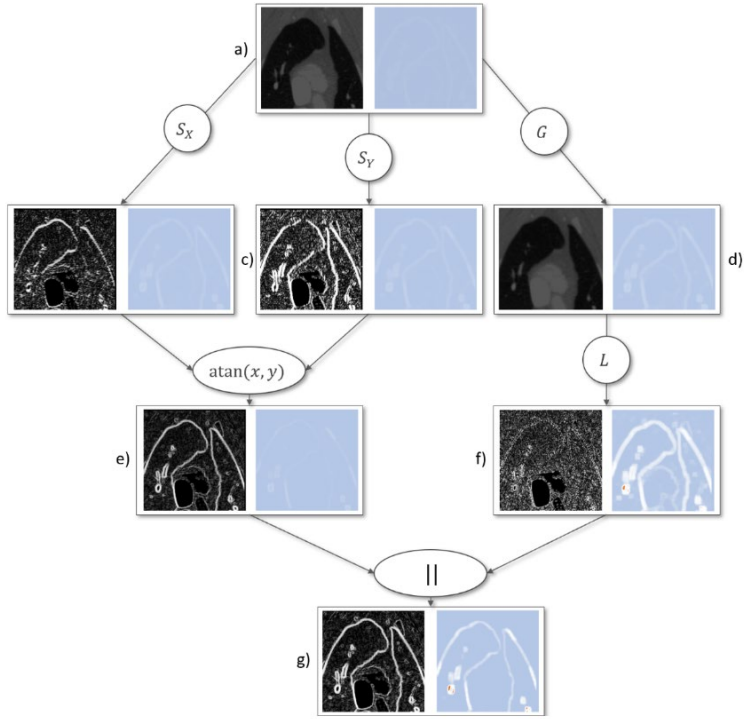
Diffusion Tensor Imaging

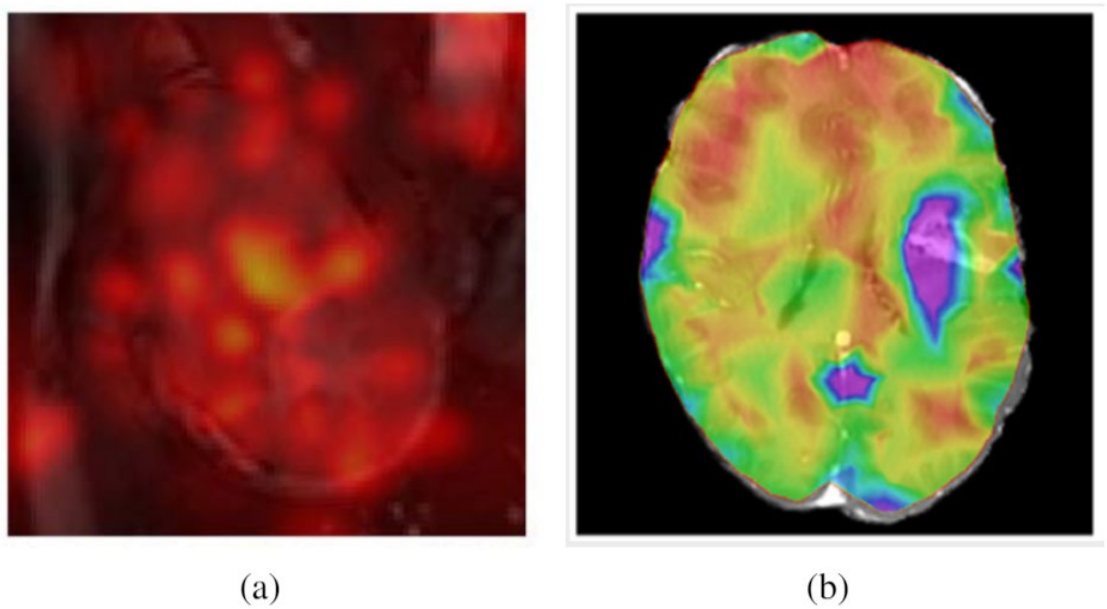
6.State of the art analysis (Acqusition)

Acquisition	Work	R1	R2	R3
Ultrasound	[HCMC10]	✓	✗	✓
	[ZBDH*15]	✓	✓	✓
	[KWKN12]	✓	✓	✓
	[LBdJ18]	✗	✓	✓
	[GML14]	✗	✓	✓
Computed Tomography	[HLF14]	✗	✓	✓
	[TS16]	✗	✓	✓
	[RHH*20]	✗	✓	✓
	[GAH*17]	✓	✓	✓
Magnetic Resonance Imaging	[EMVP19]	✗	✓	✓
	[GDP*20]	✗	✓	✓
	[CVR19]	✓	✓	✗
Diffusion Tensor Imaging	[AMME18]	✗	✓	✓
	[WTW*08]	✗	✓	✓
	[BWJ*03]	✗	✓	✓
Positron Emission Imaging	[SSHM07]	✗	✓	✓
	[HBG*15]	✗	✓	✓
	[NBYR12]	✓	✓	✗

6.State of the art analysis (Transformation, preprocessing)

- Image pre-processing and image registration covered





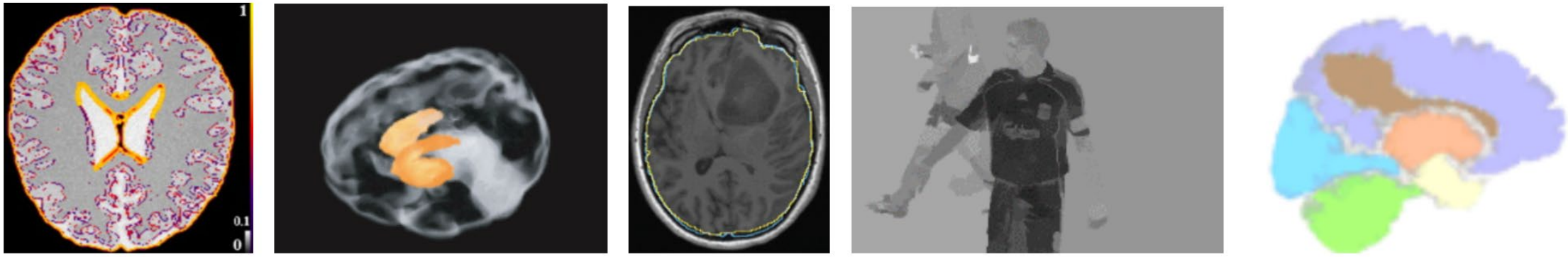
(a) (b)

6.State of the Art Analysis (Transformation, Preprocessing)

Transformation		Work	R1	R2	R3
Pre-Processing	Image Operations	[PAL01]	✓	✗	✗
		[MRSS08]	✓	✗	✗
		[JH01]	✓	✗	✗
		[LTAH13]	✓	✓	✗
		[FCC15]	✓	✗	✗
		[GPW*19]	✓	✓	✓
		[Cha15]	✓	✗	✗
	Image Registration	[LTAH13]	✗	✓	✓
		[BYW*20]	✗	✓	✓
		[LDCA17]	✗	✓	✓
		[RPSW10]	✓	✓	✓
		[YN15]	✓	✓	✓
		[SFJ*16]	✓	✓	✓

6. State of the Art Analysis (Transformation, Segmentation)

- Image Segmentation is involved in nearly any medical imaging process
- Machine learning on the rise



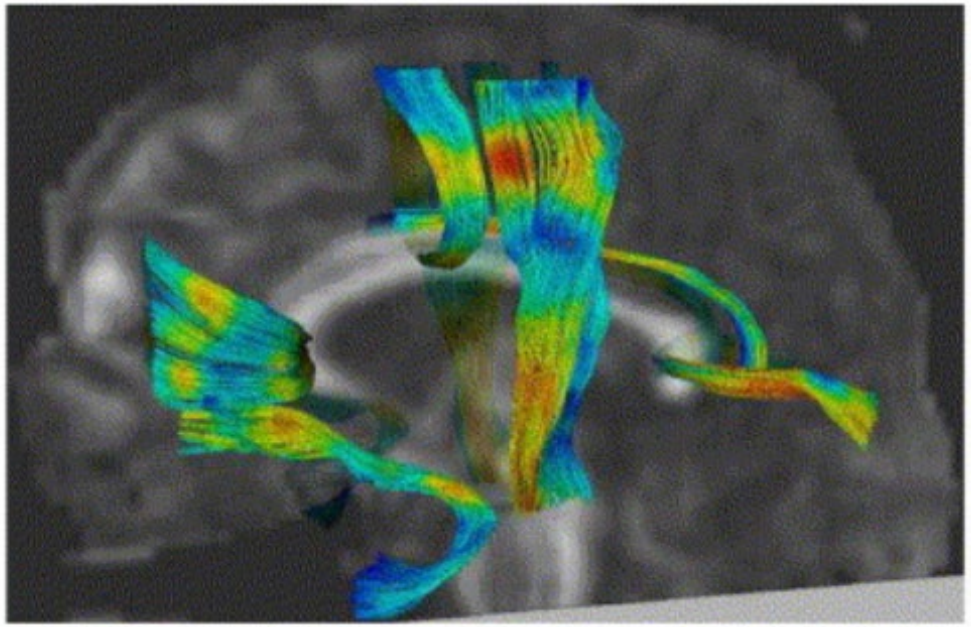
(a) (b) (c) (d) (e)

6. State of the Art Analysis (Transformation, Segmentation)

Transformation	Work	R1	R2	R3
Segmentation	[BS09]	✓	✗	✗
	[CCZ07]	✓	✗	✗
	[AVvO*04]	✓	✗	✗
	[KT08]	✗	✓	✓
	[Ada12]	✗	✓	✓
	[HR18]	✓	✓	✓
	[LGM*14]	✗	✓	✓
	[ATHL14]	✗	✓	✓
	[SHM10]	✗	✓	✗
	[PRH10]	✓	✓	✓
	[BUK*10]	✗	✓	✓
	[ATHL15]	✓	✓	✗
	[GPW*19]	✗	✓	✓
	[KWKP20]	✓	✓	✓
	[NPAA20]	✓	✓	✓

6. State of the Art Analysis (Transformation, Feature Extraction)

- Geometry extraction and tractography covered



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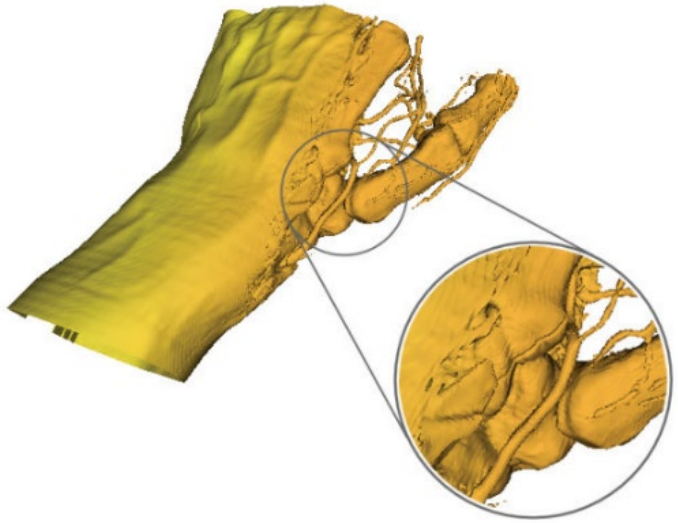


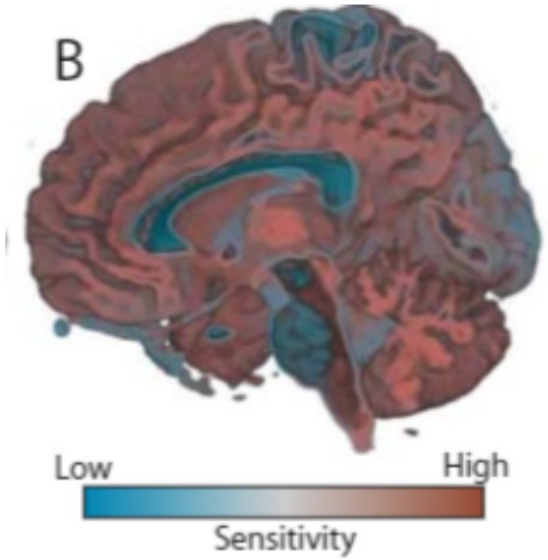
(a)

6. State of the Art Analysis (Transformation, Feature Extraction)

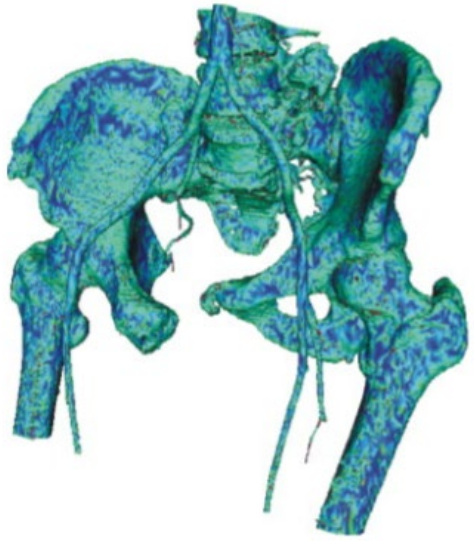
Transformation		Work	R1	R2	R3
Feature Extraction	Surface Extraction	[GMG09]	✓	✗	✗
		[DSS*09]	✓	✗	✗
		[PWH11]	✓	✗	✗
		[HMH*15]	✓	✓	✗
		[GWHA18]	✓	✓	✗
	Tracto-Graphy	[BBKW02]	✓	✓	✓
		[FFW06]	✓	✓	✓
		[CLH06]	✓	✓	✓
		[BBJ*07]	✓	✓	✓
		[BPVHR12]	✓	✓	✓

6. State of the Art Analysis (Visualization)

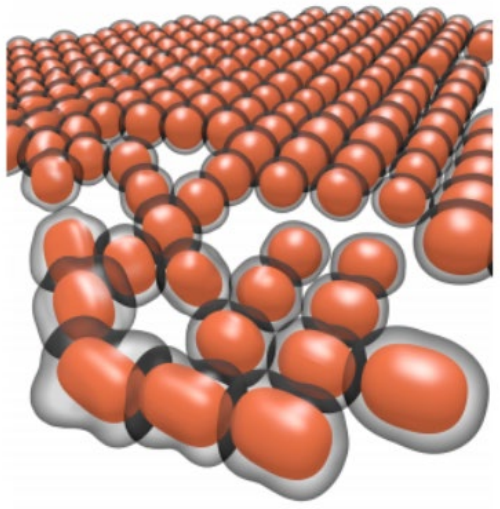
- Direct volume rendering, indirect volume rendering and glyph visualization
- Often lack the ability to relate to the original dataset



(a)



(b)



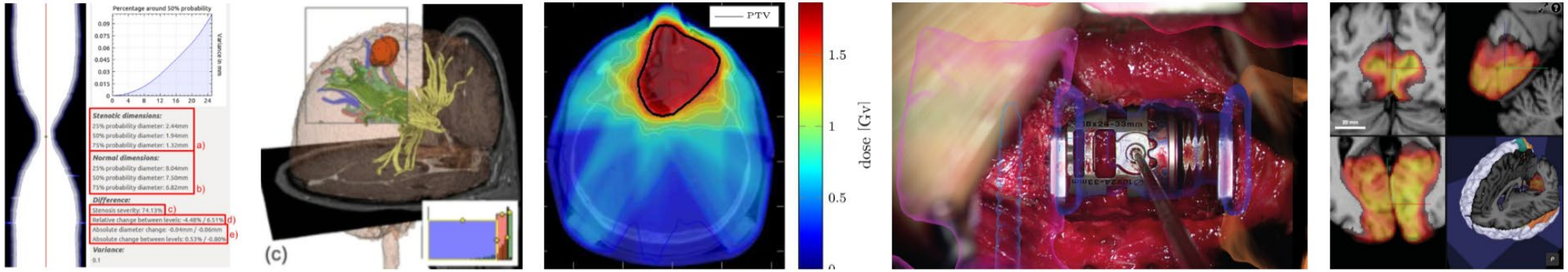
(b)

6. State of the Art Analysis (Visualization)

Visualization	Work	R1	R2	R3
Direct Volume Rendering	[Kni08]	✓	✓	✗
	[LLPY07]	✓	✓	✓
	[MCC*20]	✓	✓	✗
	[KSE16]	✓	✓	✓
Indirect Volume Rendering	[RLBS03]	✓	✓	✗
	[GR04]	✓	✓	✗
	[Dra08]	✓	✓	✗
	[GWHA18]	✓	✓	✗
Glyph-based Visualization	[Jon03]	✓	✓	✗
	[ZSL*16]	✓	✓	✗
	[GRT19]	✓	✓	✗
	[AWHS16]	✓	✓	✗
	[RGH*19]	✓	✓	✗

6. State of the Art Analysis (Applications)

- Diagnosis, treatment Planning, Intraoperative Support and Education
- Visual Analytics approaches
- Interactive approaches
- Multi-modal visualization



(a) (b) (c) (d) (e)

6. State of the Art Analysis (Applications)

Application	Work	R1	R2	R3
Diagnosis	[SSHM07]	✓	✓	✗
	[GSW*20]	✗	✓	✓
	[BPtHRV13]	✓	✓	✓
	[RMW*17]	✗	✓	✓
	[GMHW18]	✓	✓	✓
Treatment Planning	[WCW*17]	✓	✓	✗
	[MUO06]	✗	✓	✓
	[CST*18]	✓	✓	✓
	[AMBZ20]	✗	✓	✗
	[Fox18]	✓	✓	✓
Intraoperative Support	[SMC*06]	✓	✓	✓
	[CBS*19]	✓	✓	✓
	[SMV*14]	✓	✓	✓
	[GMP*18]	✗	✓	✓
Education	-	-	-	-

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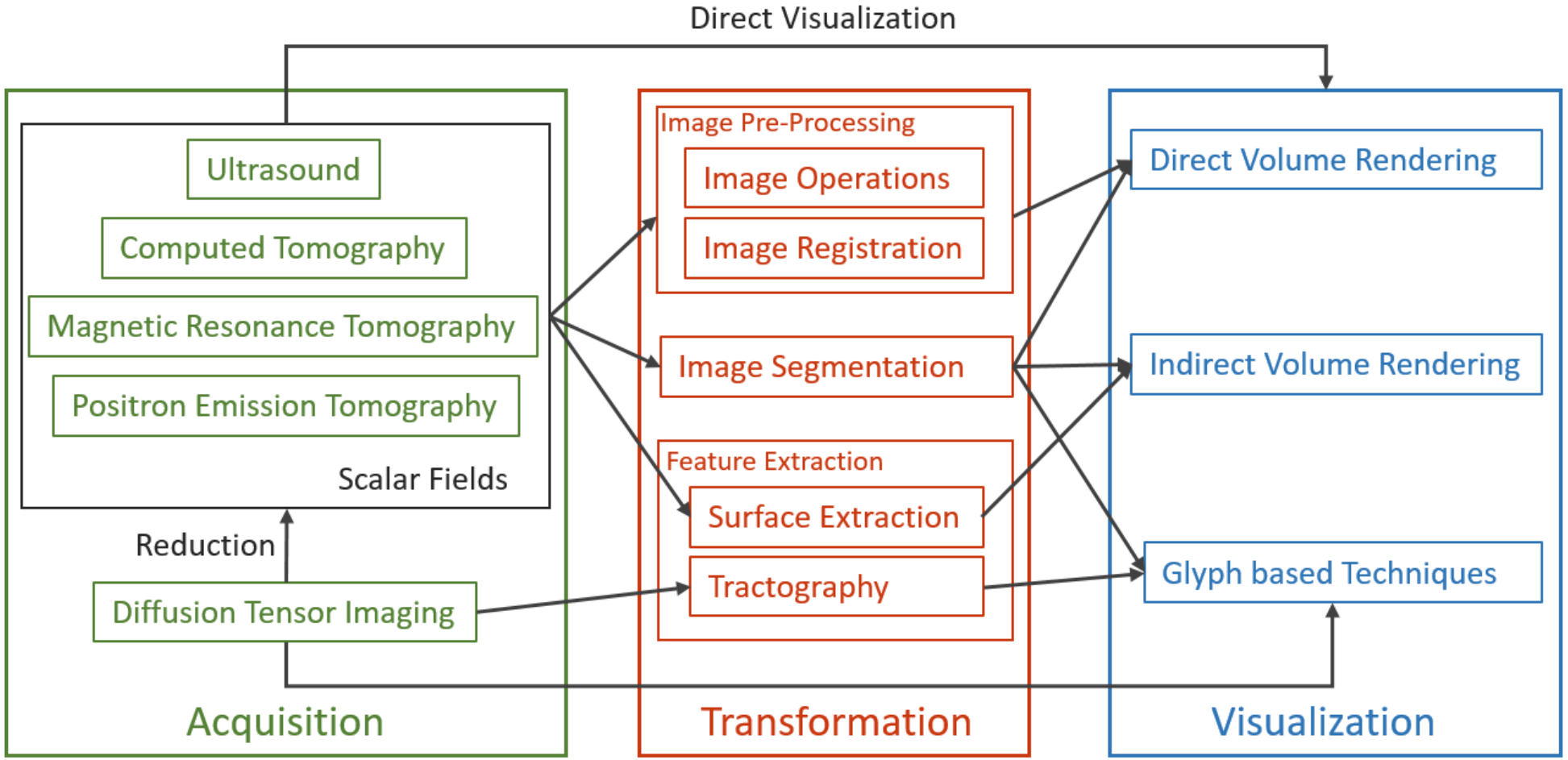
7. Creation of Medical Imaging Pipelines



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8. Open Problems

- Identification of proper Uncertainty Quantification Approaches
- Uncertainty in Clinical Studies
- Exploration Tools for Uncertainty in Medical Image Data
- Knowledge from other Applications
- Provenance Visualization of Uncertainty
- Teaching of uncertainty-aware Medical Imaging
- Connection to Sensitivity and Ensemble Visualization
- Further use of Machine Learning
- Visual Analytics Approaches in Medical Imaging
- Ready to use Framework

Thank you!

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