Integrating Bayesian Deep Learning Uncertainties in Medical Image Analysis

Raghav Mehta

Supervisor: Prof. Tal Arbel

External Member: Prof. Julien Cohen-Adad

Internal Examiner: Prof. Derek Nowrouzezahrai

Internal Member: Prof. James. J. Clark

Chair Representative: Prof. Benoit Champagne

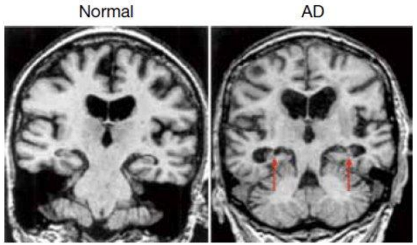
Pro-Dean: Prof. Massimo Avoli

Thesis

CENTRE FOR INTELLIGENT MACHINES

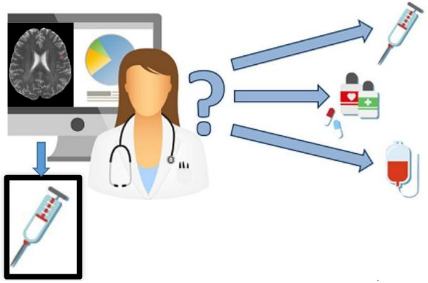
Machine Learning and Medical Imaging

Machine learning (ML) in medical imaging has HUGE potential for assisting in:



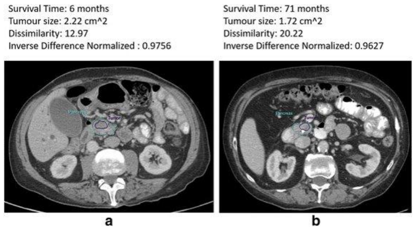
Compliment of Scanning Department, St. Teresa's Hospital

Disease Development



Personalized Medicine

Patient diagnosis



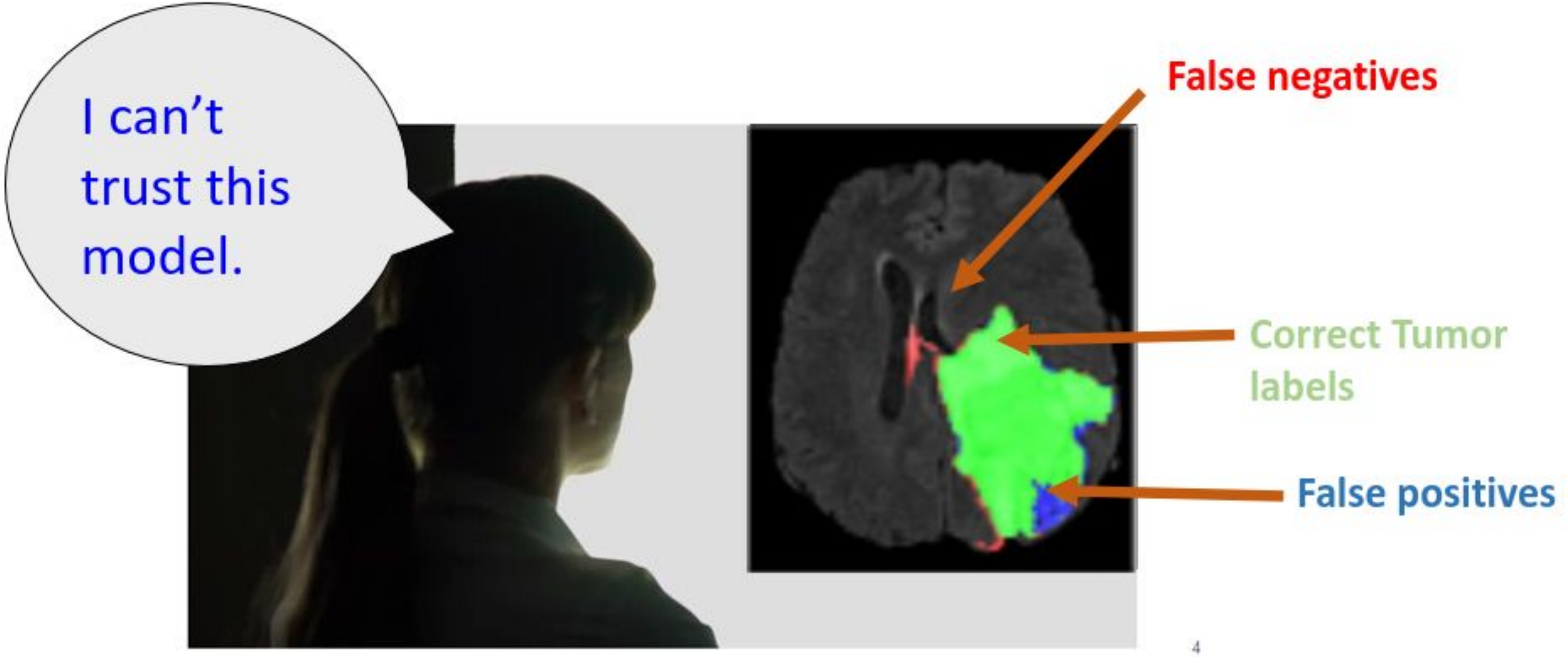
Outcome Prediction

Machine Learning and Medical Imaging

- Wide variety of successful ML frameworks for segmentation, classification in medical imaging
- However, resulting approaches have not yet been widely integrated into real clinical practice!
    - Why is that?

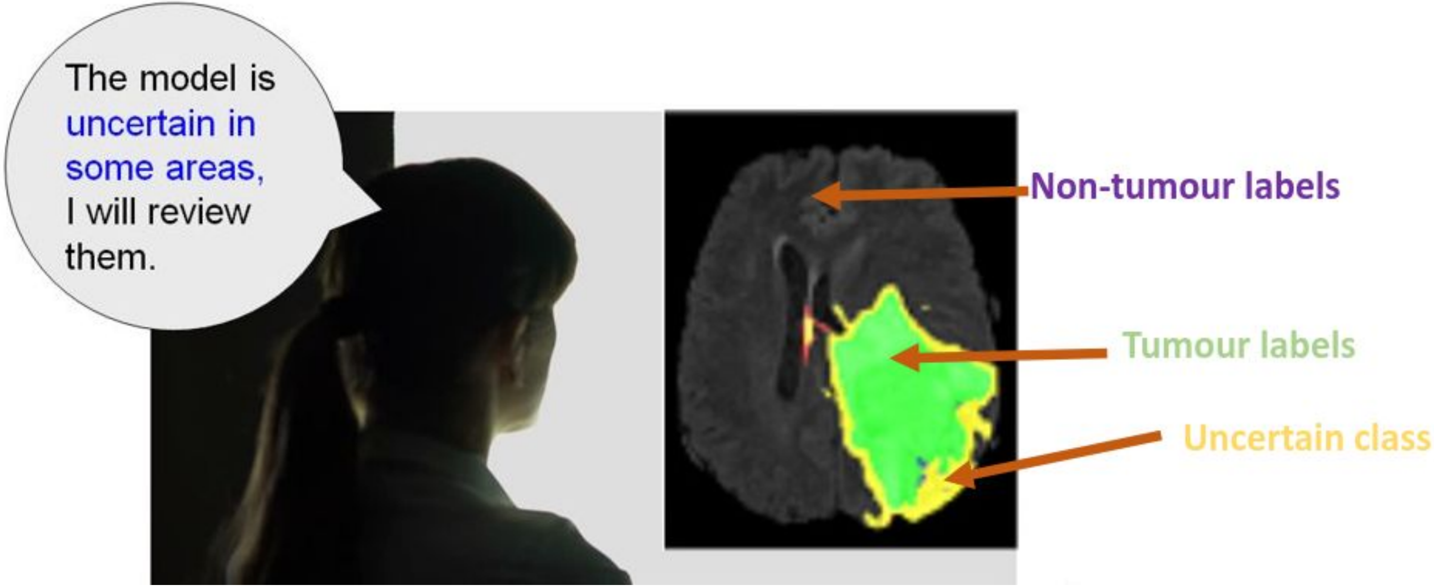
Open Problem: ML in Medical Imaging

- Most ML models can make mistakes



Solution: ML in Medical Imaging

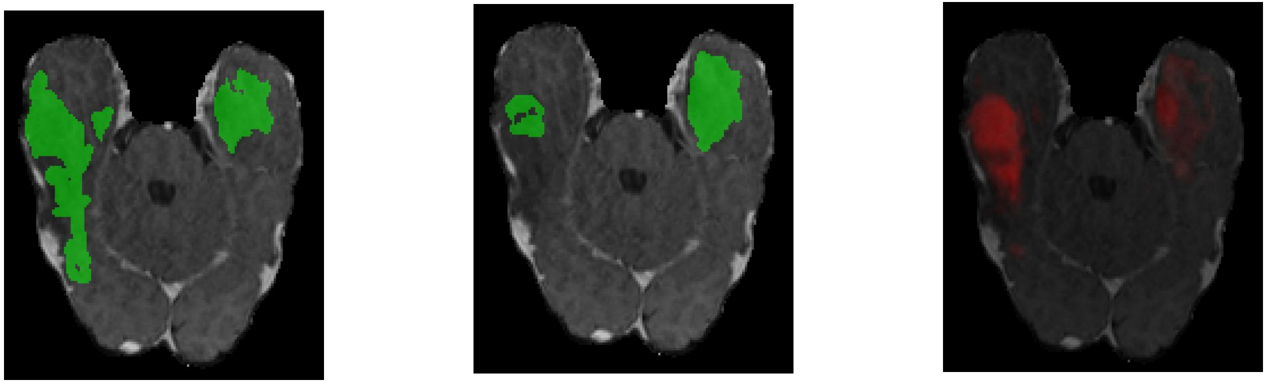
- Trust can be build with the notion of uncertainties associated with the model output



Thesis Contributions

- Uncertainty aware medical image analysis framework
  - Uncertainty Evaluation Score

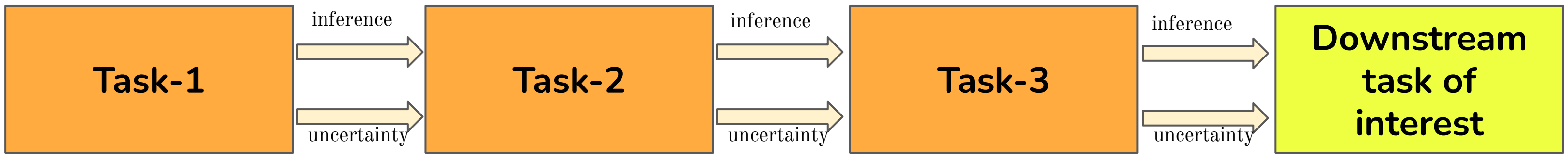
Ground Truth Prediction Uncertainty



Mehta et al. “*QU-BraTS: MICCAI BraTS 2020 Challenge on Quantifying Uncertainty in Brain Tumor Segmentation - Analysis of Ranking Scores and Benchmarking Results*”, **Journal of Machine Learning for Biomedical Imaging (MELBA) 2022**.

Thesis Contributions

- Uncertainty aware medical image analysis framework
  - Uncertainty propagation across cascade of inference task



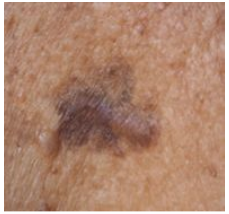
Mehta et al. “*Propagating Uncertainty Across Cascaded Medical Imaging Tasks for Improved Deep Learning Inference*”, **IEEE Transactions on Medical Imaging (TMI) journal 2022**.

Thesis Contributions

- Uncertainty aware medical image analysis framework
  - Fairness and Uncertainty

AI skin cancer diagnoses risk being less accurate for dark skin – study

Research finds few image databases available to develop technology contain details on ethnicity or skin type



BRIEF REPORT | APPLIED MATHEMATICS

Gender imbalance in medical imaging datasets produces biased classifiers for computer-aided diagnosis

Agostina J. Larrazabal, Nicolás Nieto, Victoria Peterson, +1, and Enzo Ferrante Authors Info & Affiliations

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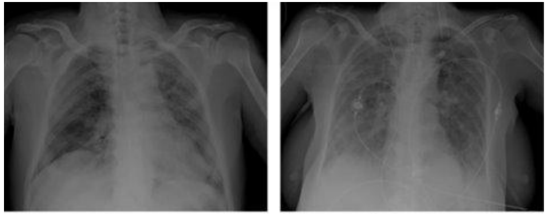
May 26, 2020 | 117 (23) 12592-12594 | https://doi.org/10.1073/pnas.1919012117

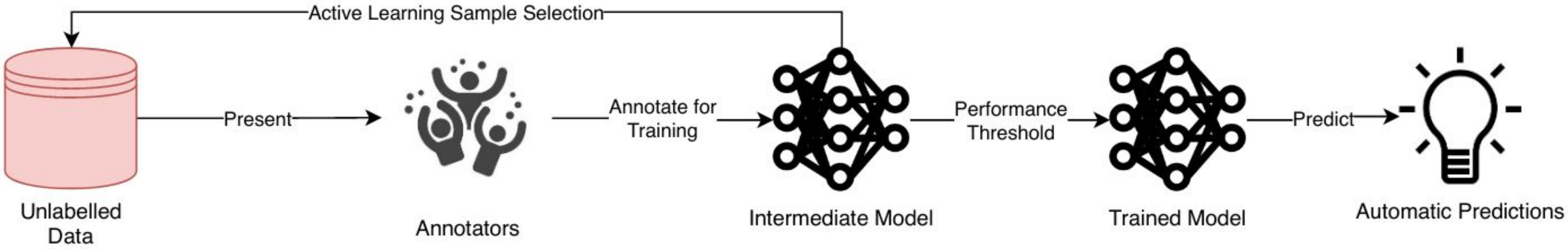


(a) Male (b) Female

Mehta et al. "*Evaluating the Fairness of Deep Learning Uncertainty Estimates in Medical Image Analysis*", **Medical Imaging and Deep Learning (MIDL) conference 2023**.

Thesis Contributions

- Uncertainty aware medical image analysis framework
    - Information Gain Active Learning



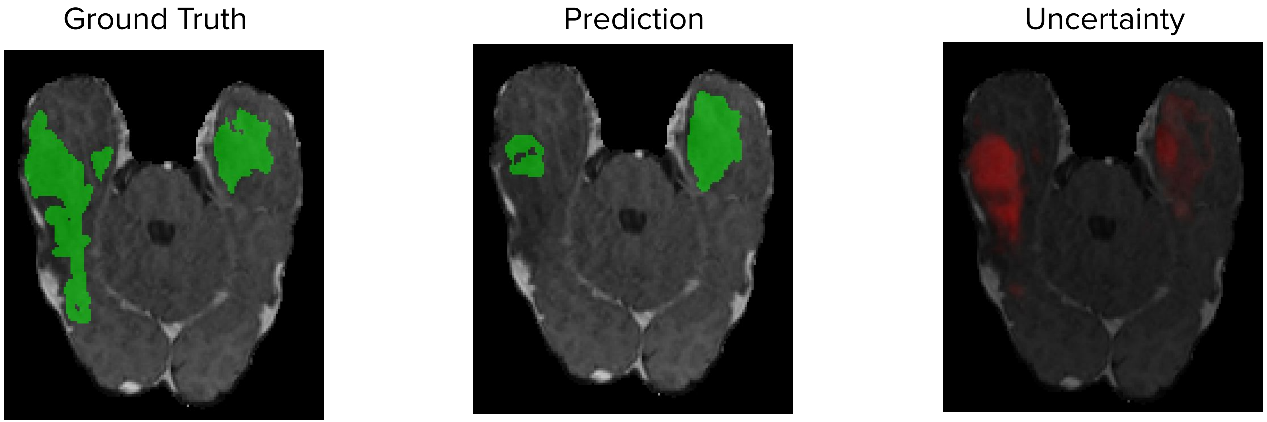
Mehta et al. "*Information Gain Sampling for Active Learning in Medical Image Classification*", **Uncertainty and Safe Utilization (UNSURE) workshop at International conference on Medical Image Computing and Computer Assisted Intervention (MICCAI) 2022.**

Uncertainty Evaluation

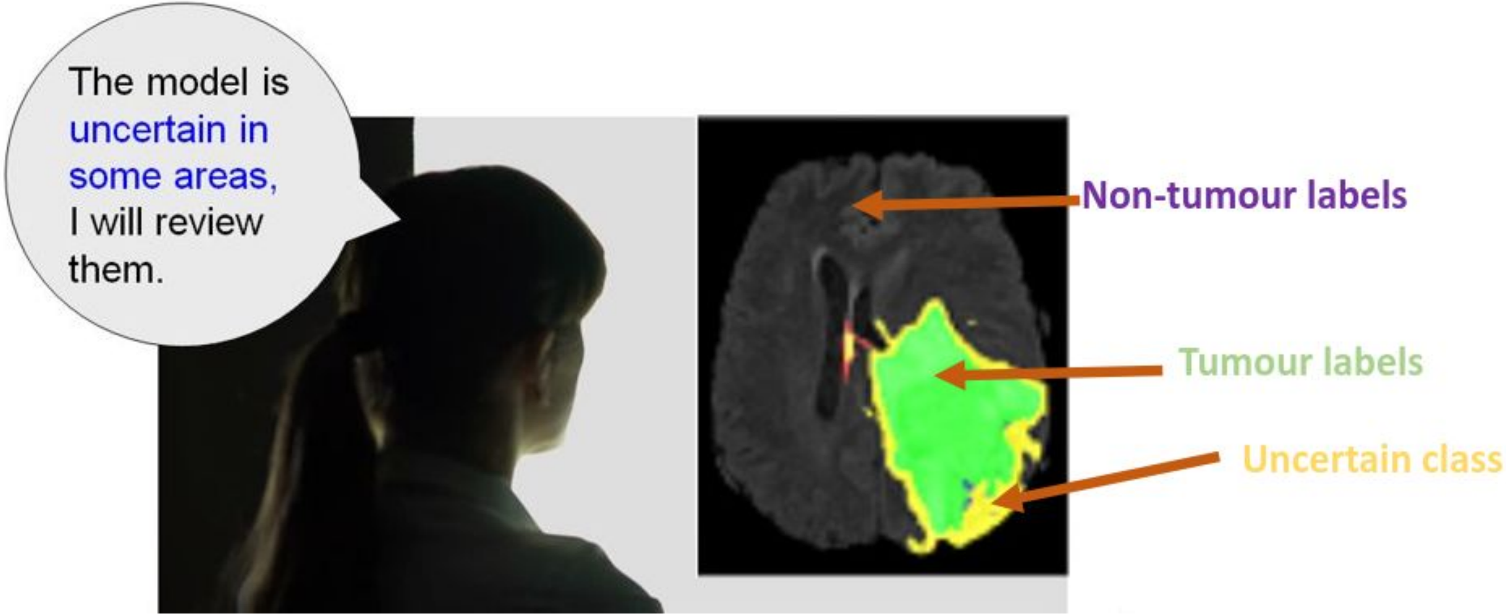
     

Mehta et al. "*QU-BraTS: MICCAI BraTS 2020 Challenge on Quantifying Uncertainty in Brain Tumor Segmentation - Analysis of Ranking Scores and Benchmarking Results*", **Journal MELBA 2022**.

Brain Tumour Segmentation

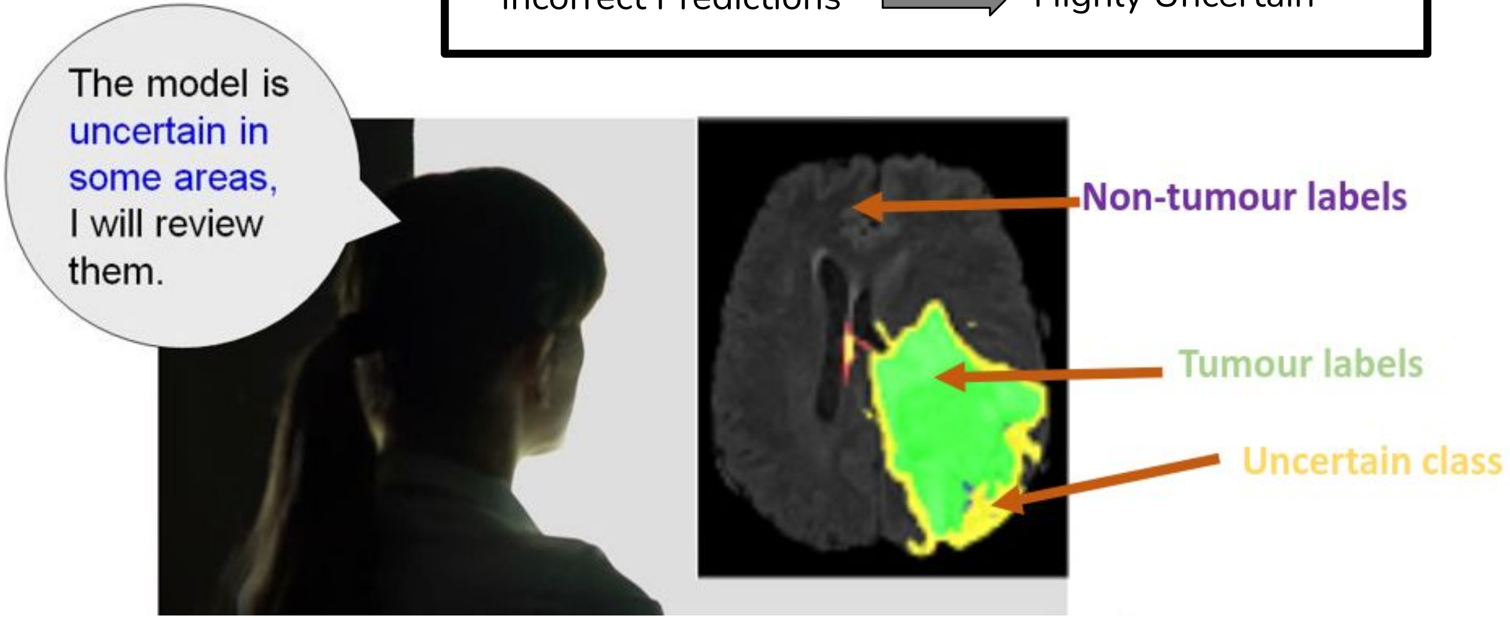


Brain Tumour Segmentation



Brain Tumour Segmentation

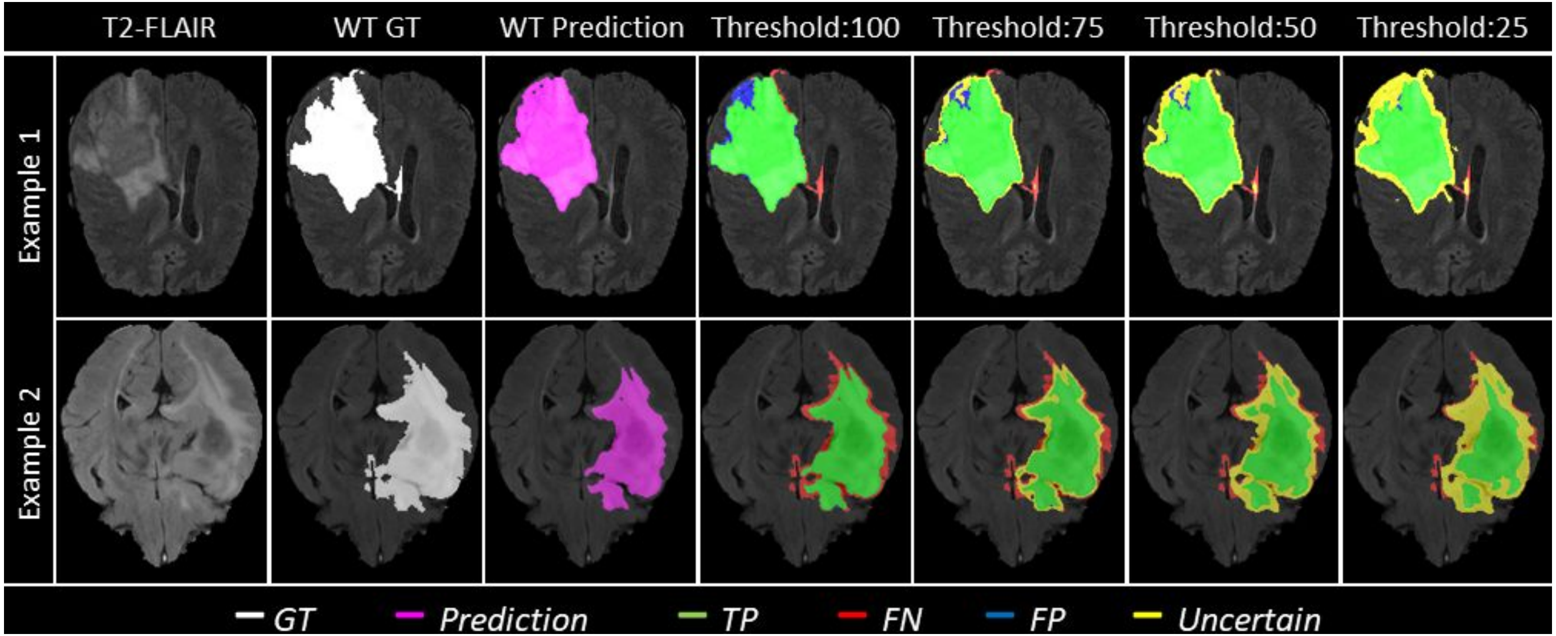
Confident Predictions	→	Correct Predictions
Incorrect Predictions	→	Highly Uncertain



QU-BraTS

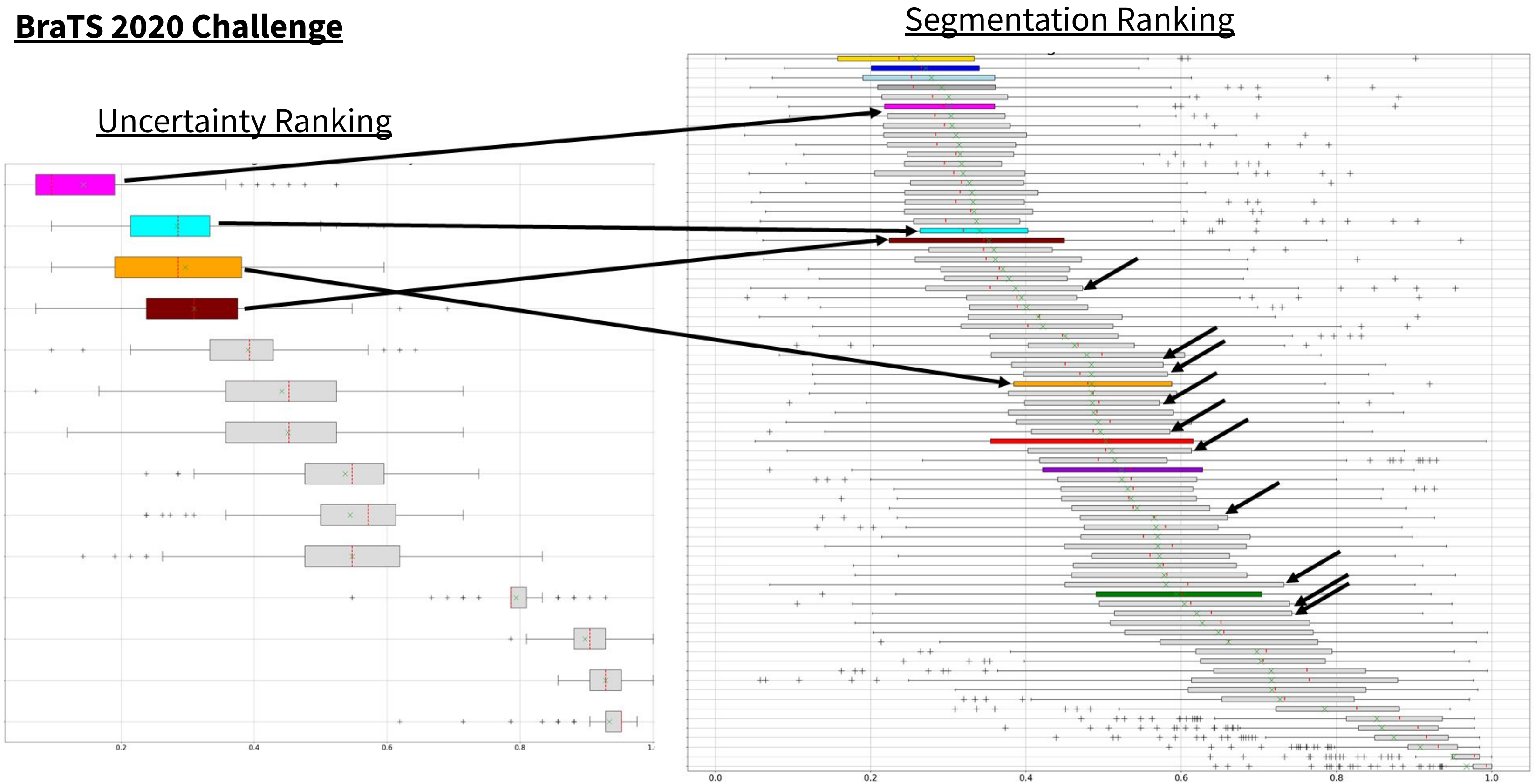
Increased
Metric of Interest (Dice)

Dice = 2 * (■) / [2 * (■) + ■ + ■]



QU-BraTS

- **BraTS 2020 Challenge**

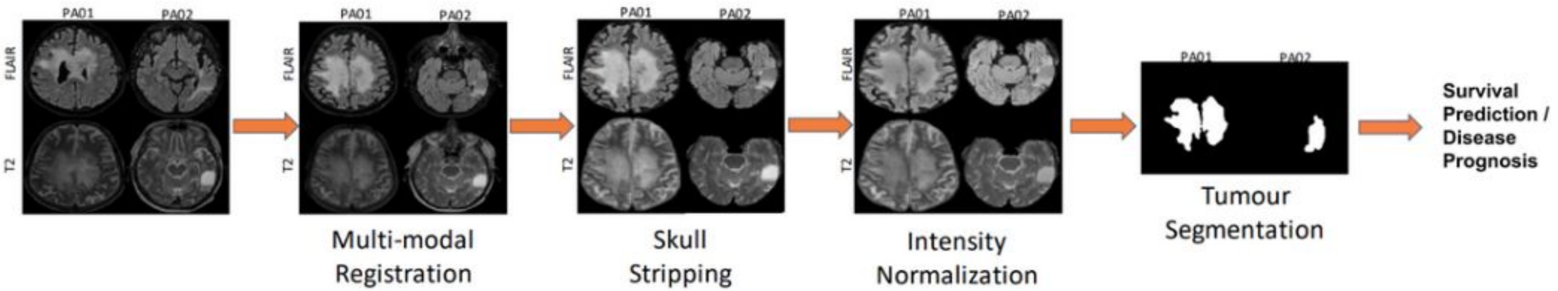


Uncertainty Propagation

Mehta et al. “*Propagating Uncertainty Across Cascaded Medical Imaging Tasks for Improved Deep Learning Inference*”, **IEEE Transactions on Medical Imaging (TMI) journal 2022**.

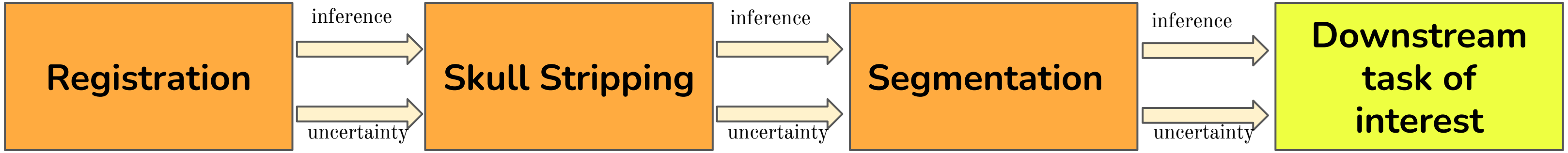
Uncertainty Propagation

- Medical Image Analysis Pipeline



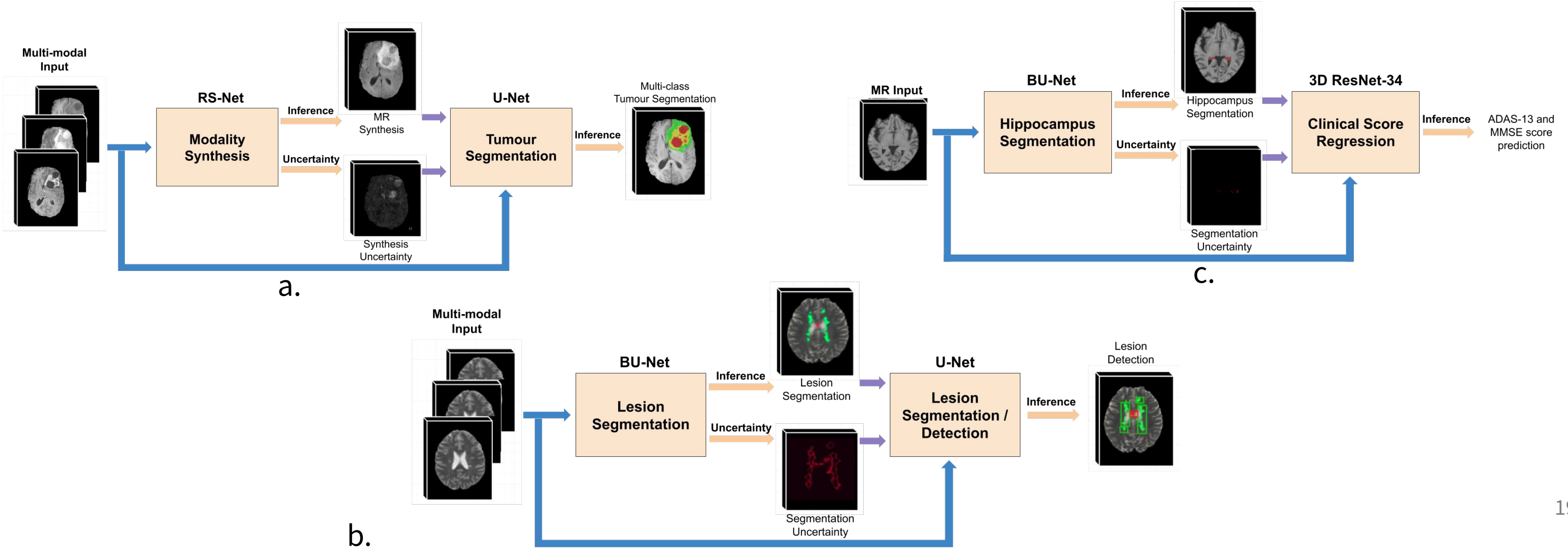
Uncertainty Propagation

- Hypothesis: We can improve inference on the downstream task of interest by propagating uncertainty estimated for the prior tasks



Uncertainty Propagation

- **Experimentation:**
  a. Brain Tumour Segmentation Pipeline
  b. MS T2 Lesion Segmentation/Detection Pipeline
  c. Alzheimer's Disease Clinical Score Prediction Pipeline



Uncertainty Propagation

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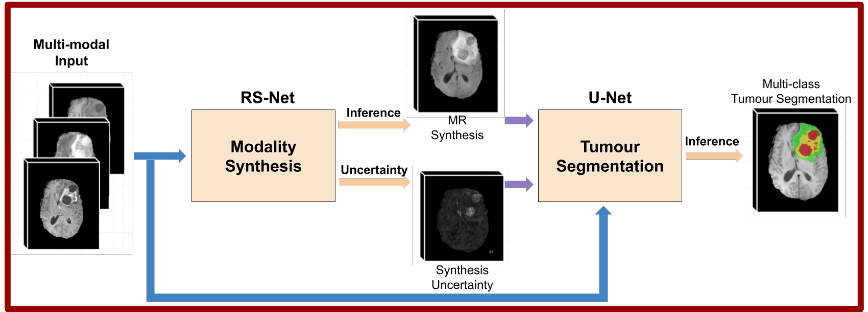
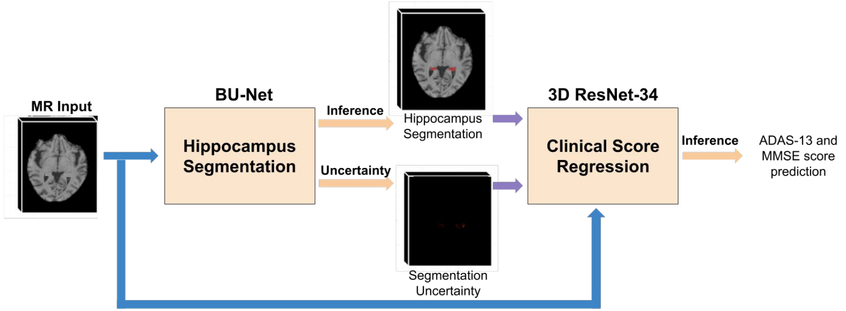
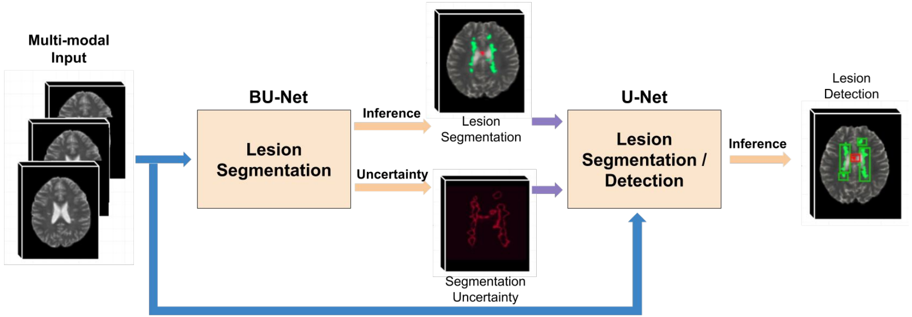


a.



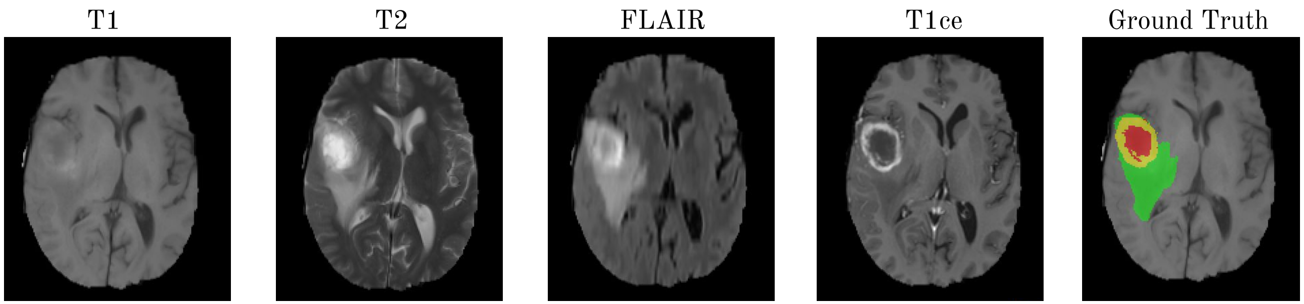
c.



b.

Uncertainty Propagation

- **Brain Tumour Segmentation**
  - Availability of different MR sequences improve tumour segmentation [25]



[25] Havaei et al. “HeMIS: Hetero-modal image segmentation.”, MICCAI 2016

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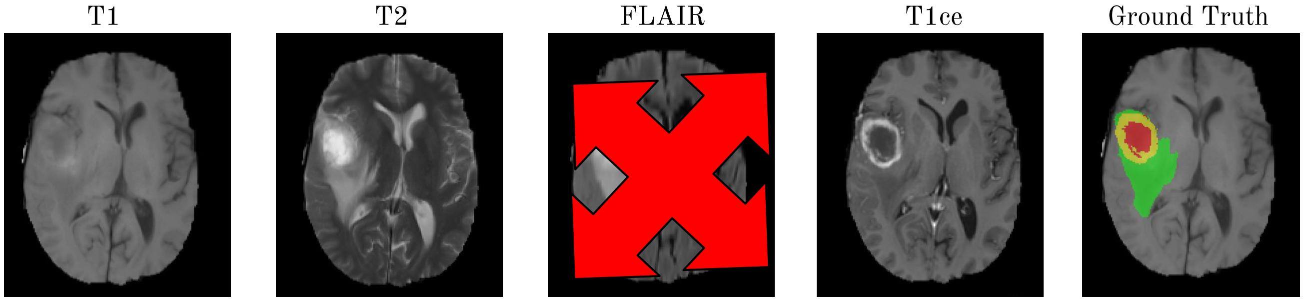
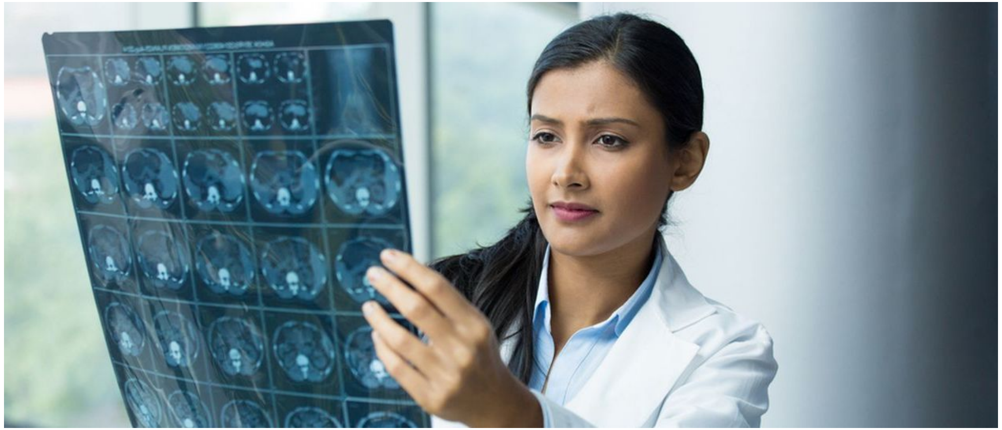


[25] Havaei et al. “HeMIS: Hetero-modal image segmentation.”, MICCAI 2016

Uncertainty Propagation

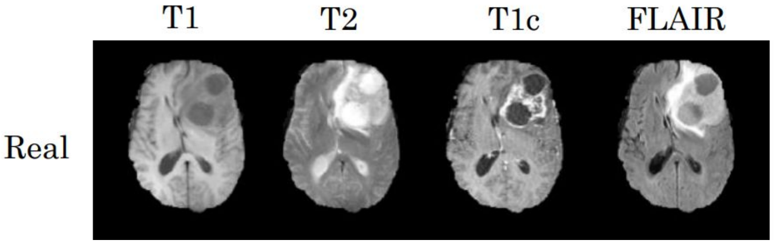
- **Brain Tumour Segmentation**
  - Synthesizing missing (unavailable) sequence can help
    - Clinicians to review
    - Improve downstream tumour segmentation task [26]



[26] van Tulder et al. “Why does synthesized data improve multi-sequence classification?.”, MICCAI 2016

Uncertainty Propagation

- Brain Tumour Segmentation



Uncertainty Propagation

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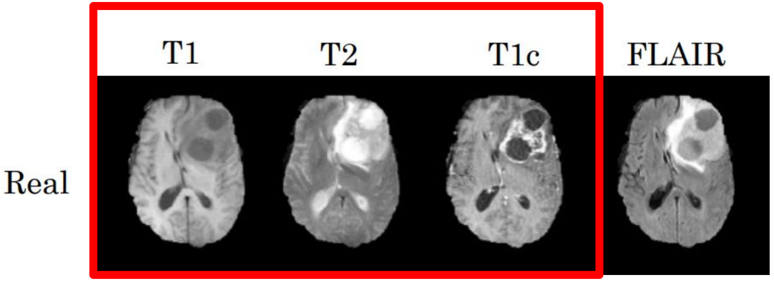

Uncertainty Propagation

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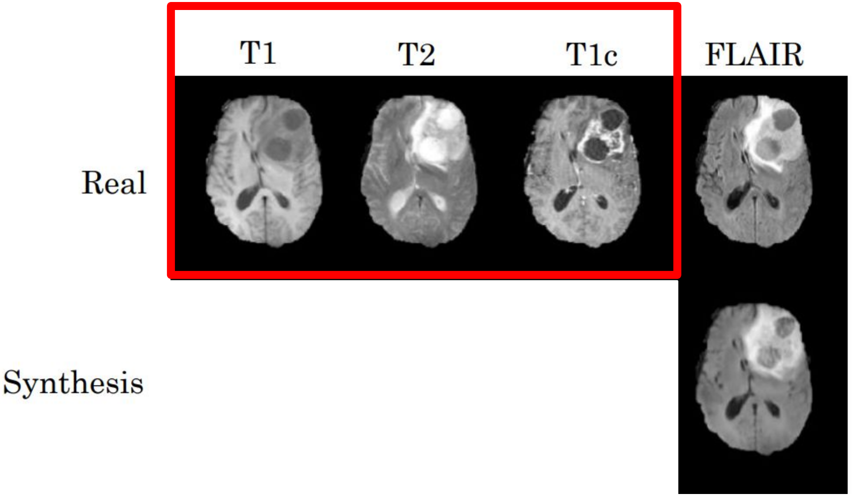

Uncertainty Propagation

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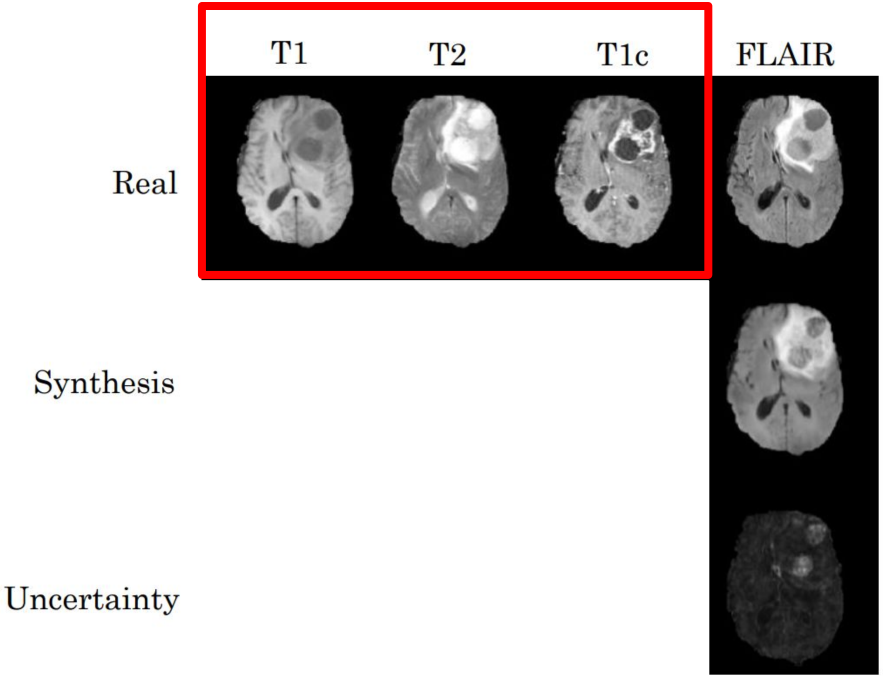

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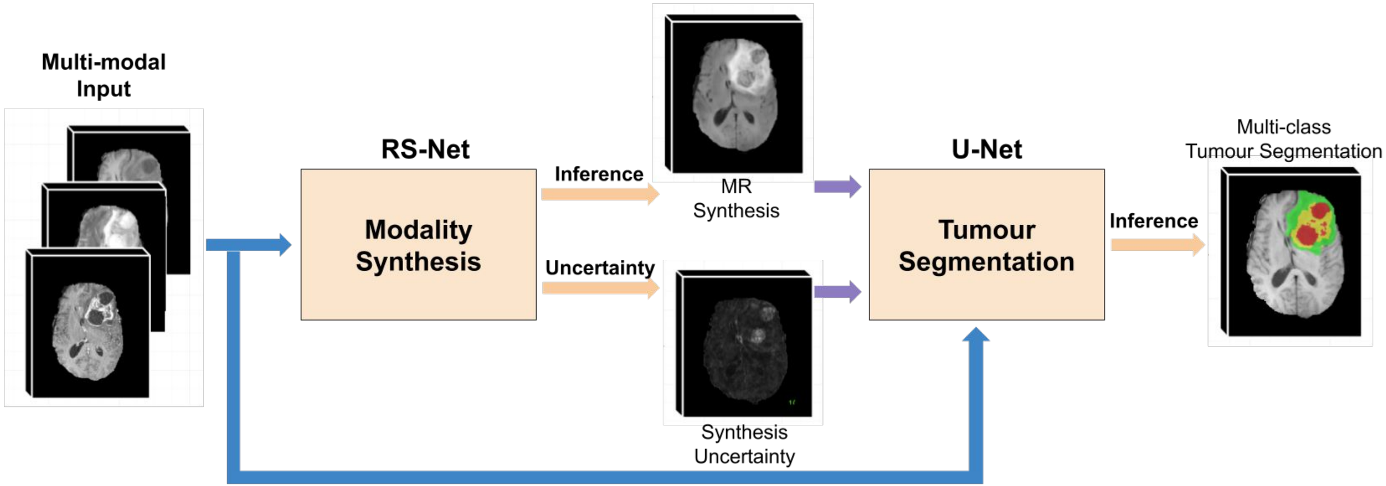
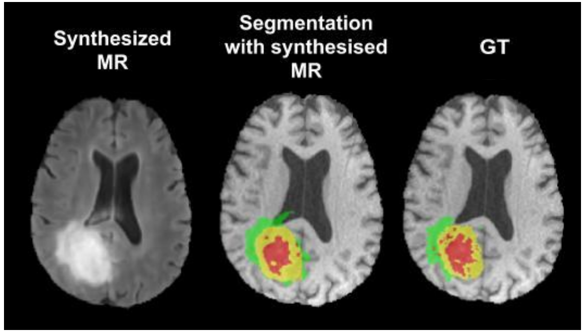


Uncertainty Propagation

- Brain Tumour Segmentation
  - Edema
  - Enhancing Tumour
  - Necrotic Core + Non-Enhancing Tumour



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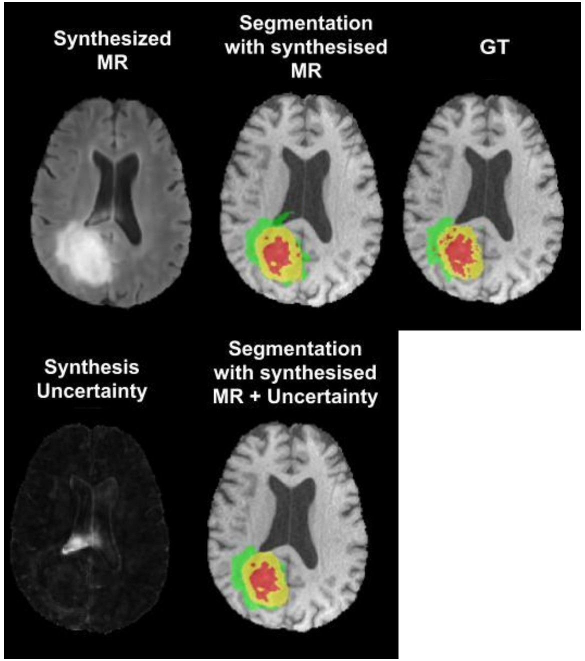

Fairness and Uncertainty

  

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Fairness and Uncertainty

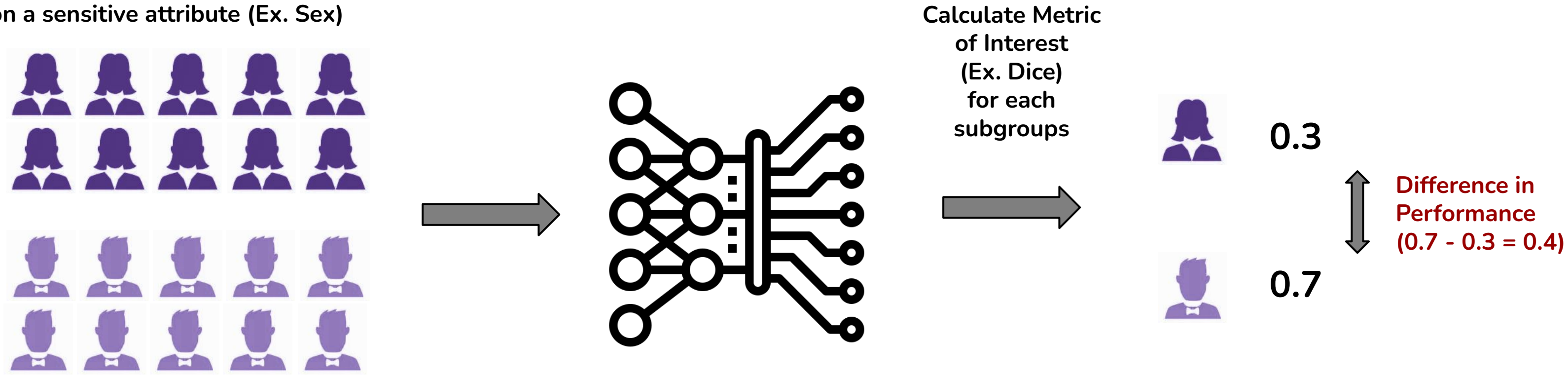
1. Brain Tumour Segmentation
2. Skin Lesion Classification
3. Alzheimer's Disease Clinical Score Regression

Fairness and Uncertainty

1. **Brain Tumour Segmentation**
2. Skin Lesion Classification
3. Alzheimer’s Disease Clinical Score Regression

Fairness

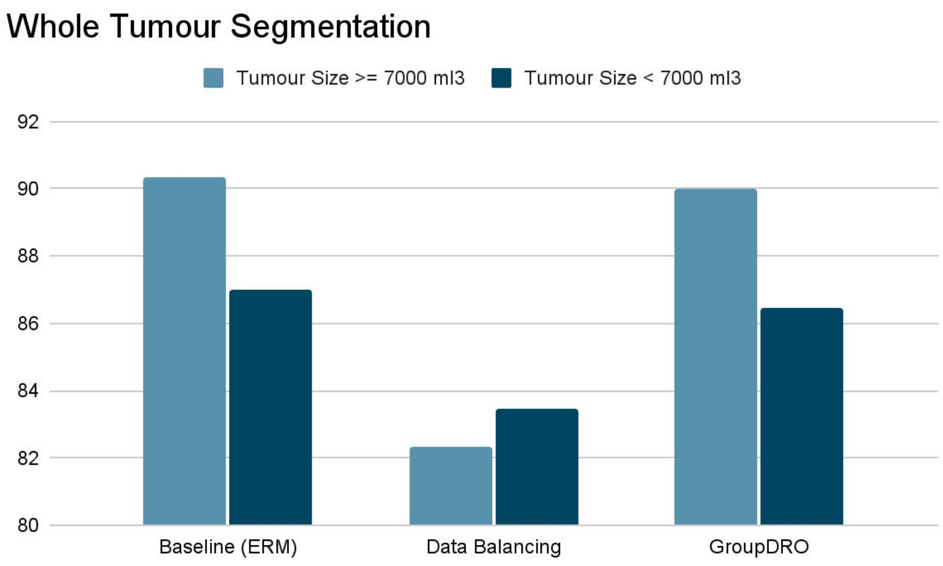
Partition dataset into subgroups based on a sensitive attribute (Ex. Sex)



Fairness - Brain Tumour Segmentation

- **Network:**
  - U-Net
- **Sensitive Attribute**: Tumour Size
  - Divide into two subgroups
    - >= 7000 ml^3
    - < 7000 ml3

- **Popular Fairness mitigation ML Methods:**
  - Baseline (ERM)
  - Data balancing
  - GroupDRO



Fairness and Uncertainty

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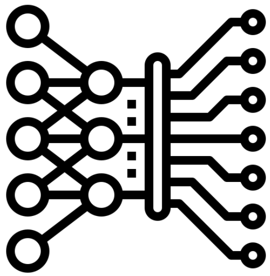
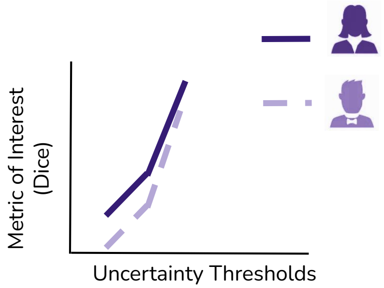
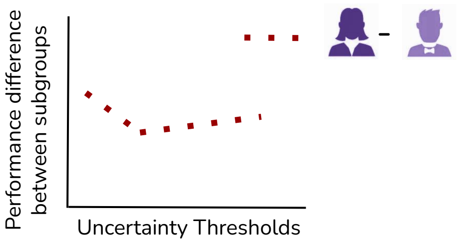


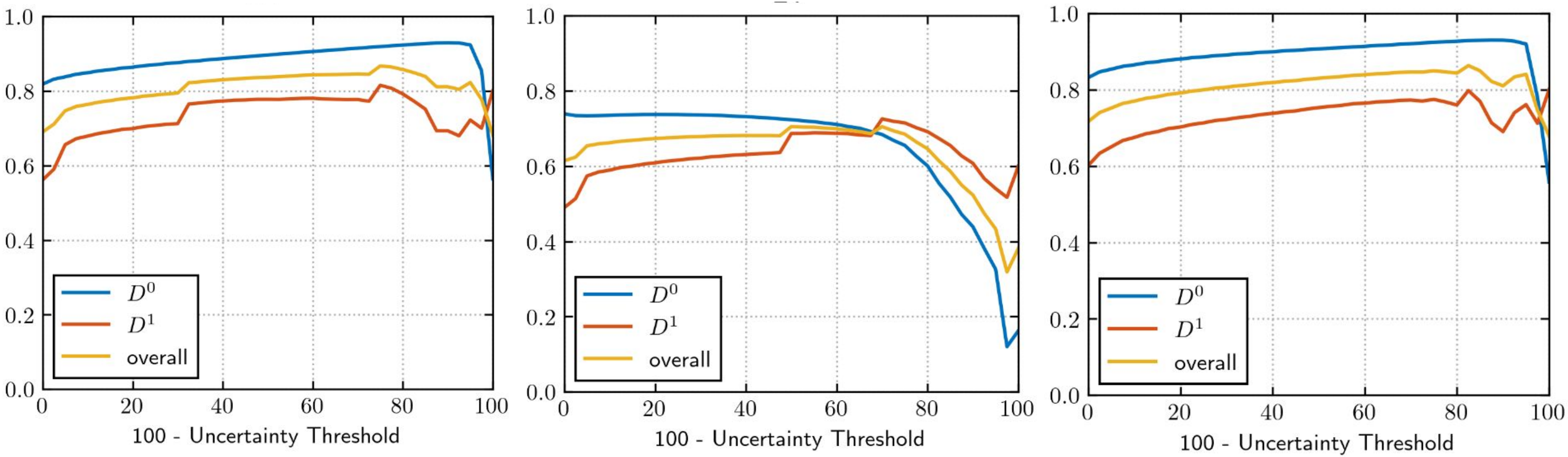
Calculate Metric of Interest (Ex. Dice) for each subgroups At different uncertainty threshold





Fairness and Uncertainty

- Brain Tumour Segmentation



(a) Baseline-Model (b) Balanced-Model (c) GroupDRO-Model

Active Learning

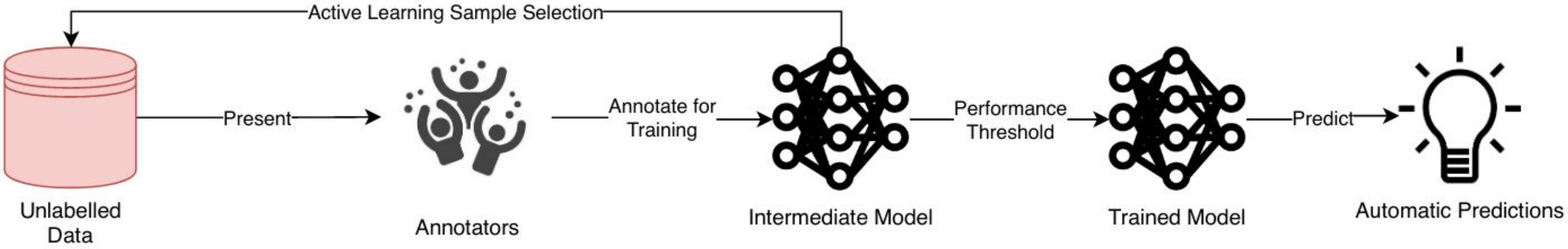
   

Mehta et al. “*Information Gain Sampling for Active Learning in Medical Image Classification*”, **Uncertainty and Safe Utilization (UNSURE) workshop at International conference on Medical Image Computing and Computer Assisted Intervention (MICCAI) 2022.**

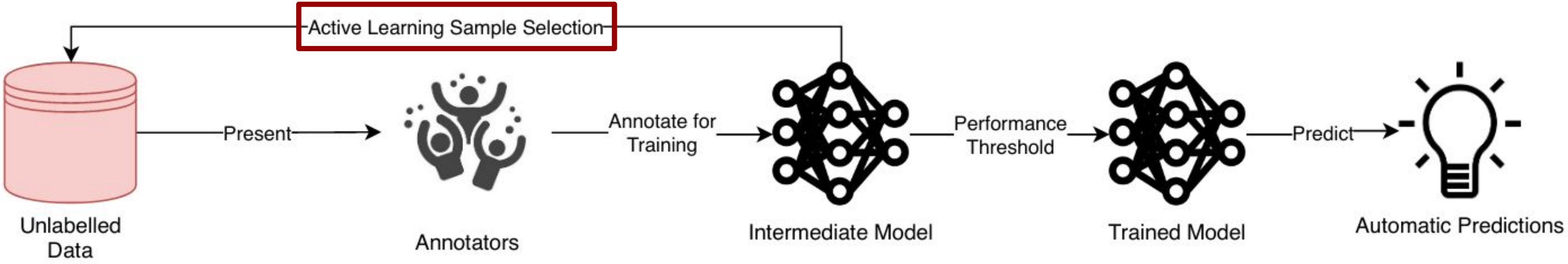
Challenges: ML in Medical Imaging

- Medical Image Analysis
    - Requires access to clinicians for data annotation

Active Learning

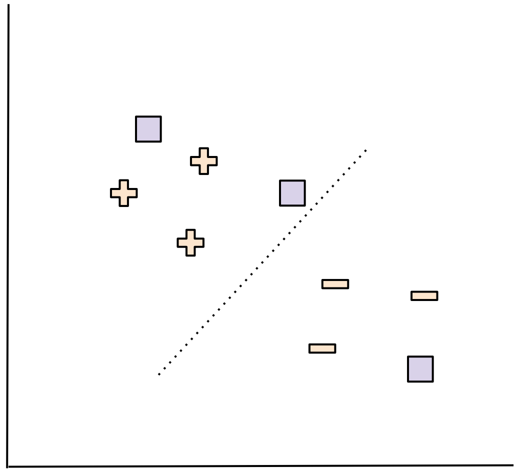


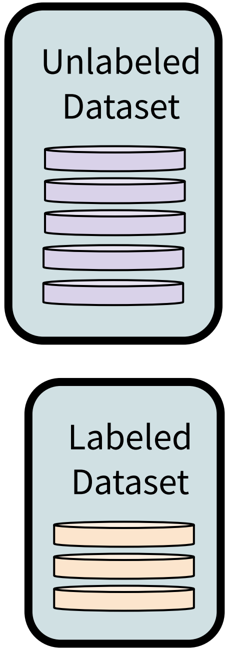
Active Learning



Active Learning

Uncertainty Based Sample Selection





Active Learning

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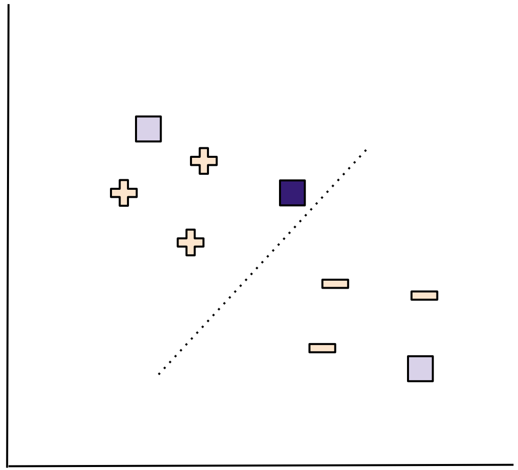

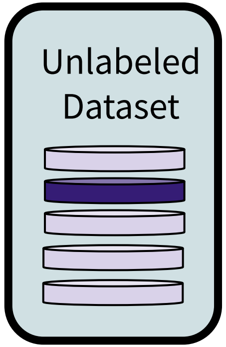

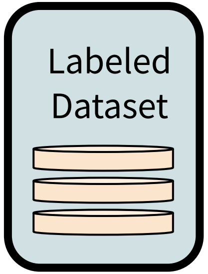

Active Learning

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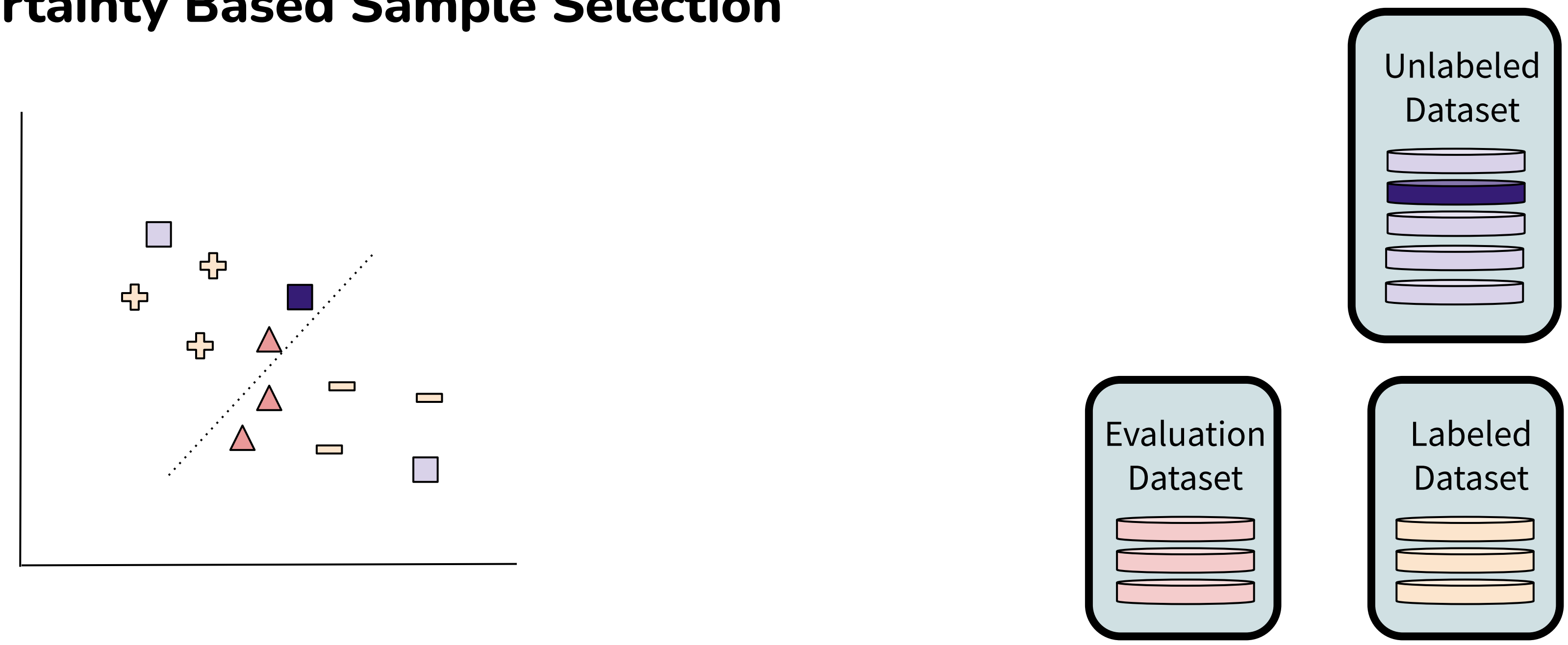


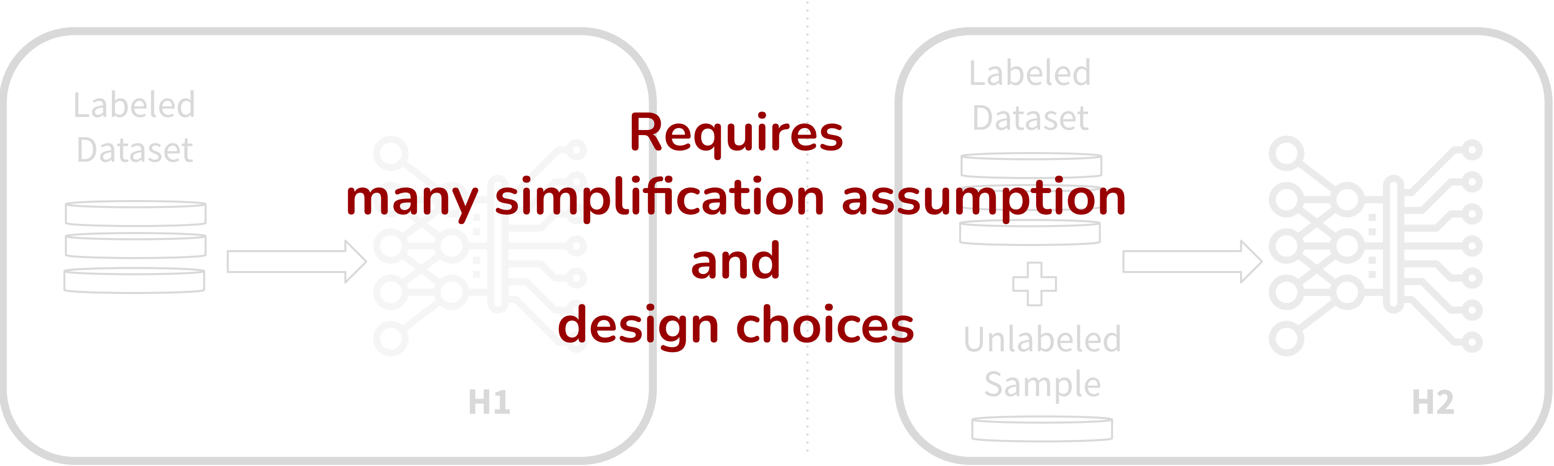
Active Learning

- Information Gain (IG)
  - IG (X; Y=y) = H(X) - H(X|Y=y)

Active Learning

Information Gain Sampling for AL

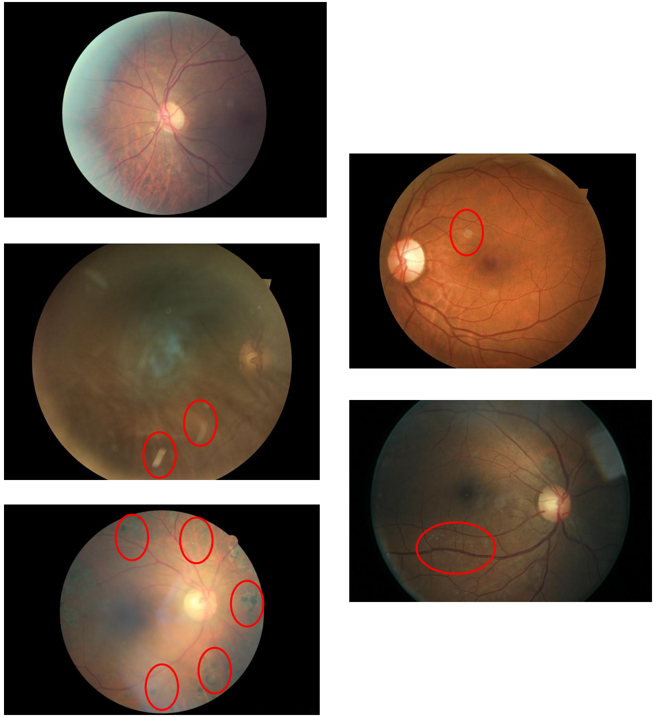
- Select samples with maximum IG = H1 - H2



Requires
many simplification assumption
and
design choices

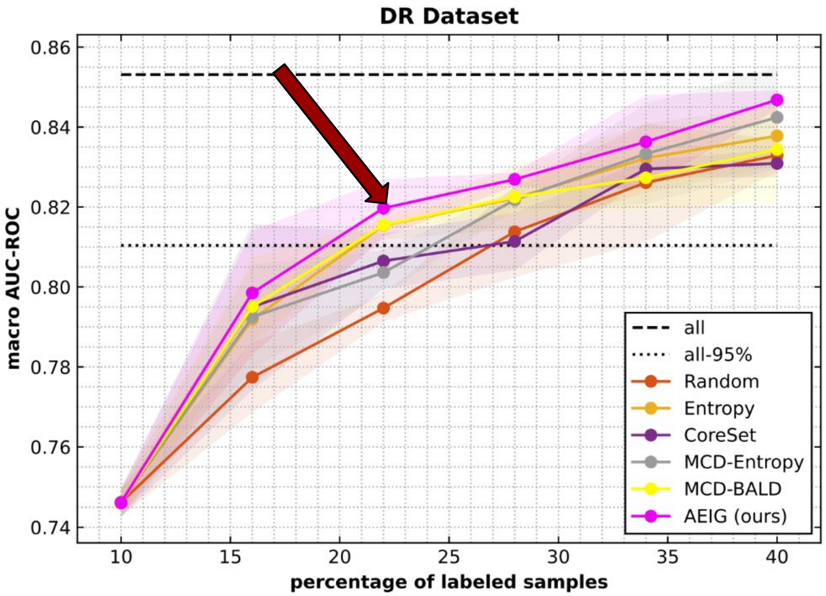
Active Learning

- <u>**Datasets:**</u>
  - Multi-class Diabetic Retinopathy (DR) disease classification
- <u>**Evaluation Metric:**</u>
  - ‘macro’ Area Under the Receiver Operating Characteristic Curve (ROC AUC)

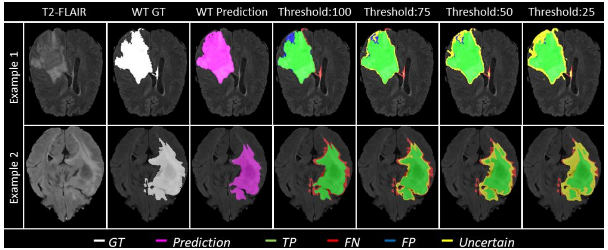


Active Learning

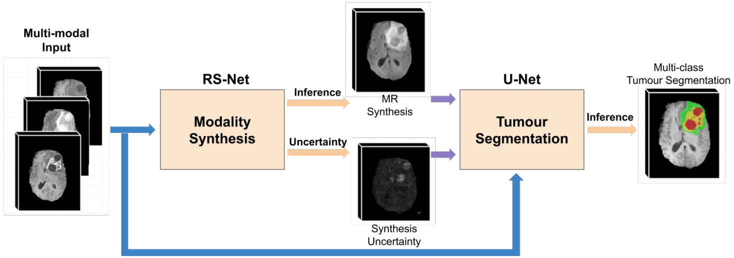
- <u>Results</u>



Summary

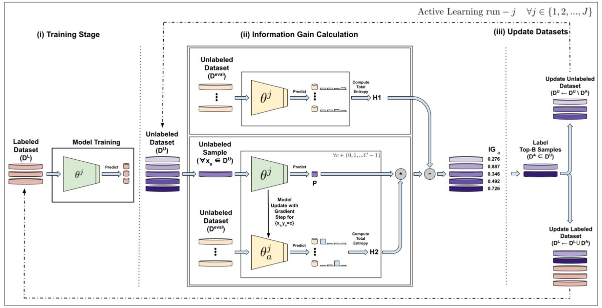


Uncertainty Evaluation Score

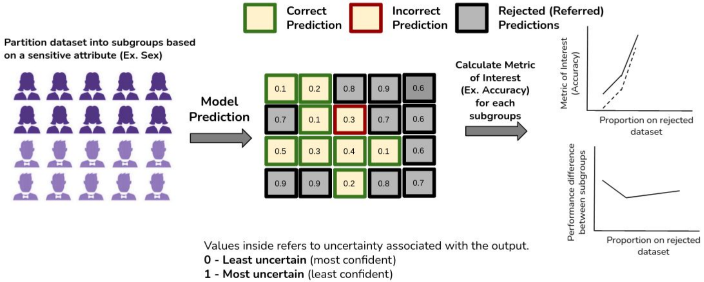


Uncertainty Propagation

Integrating Bayesian Deep Learning Uncertainties



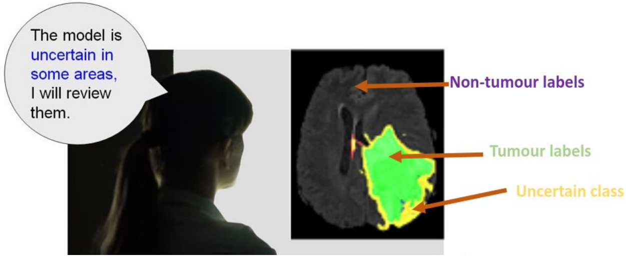
Active Learning



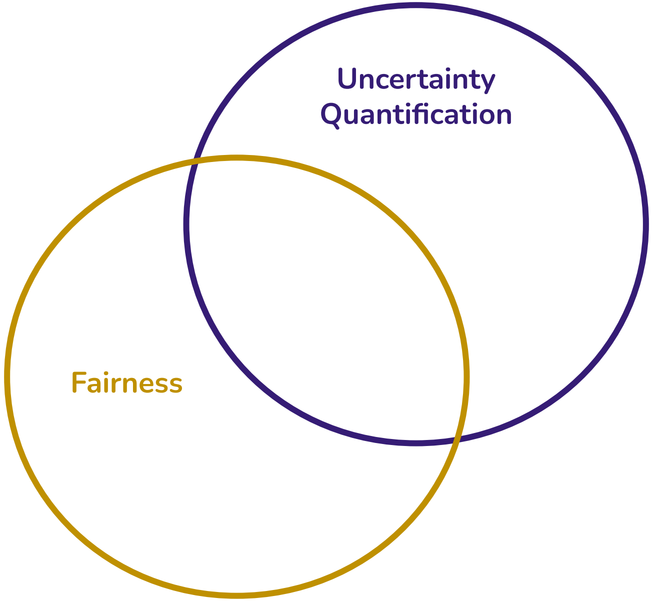
Fairness and Uncertainty

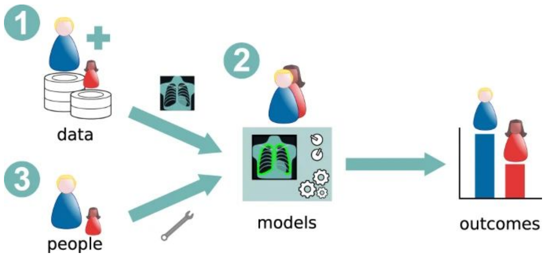
Trustworthy Models

Uncertainty Quantification

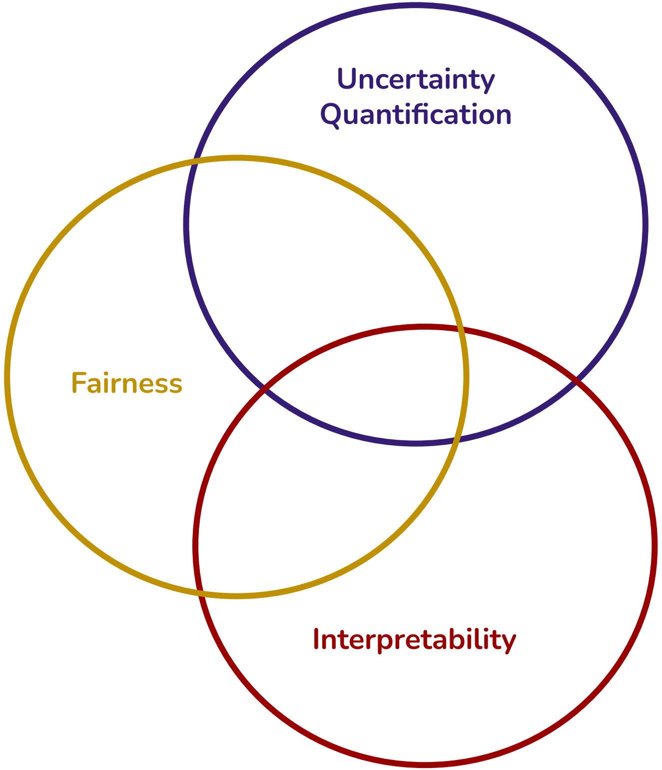


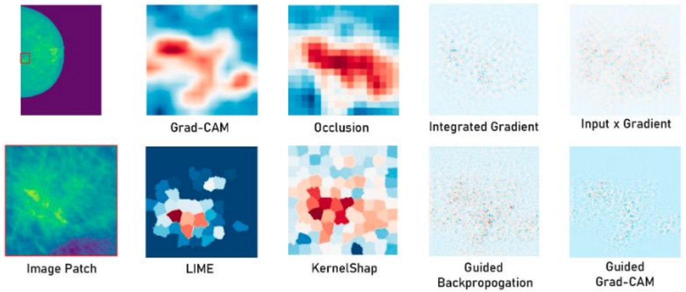
Trustworthy Models



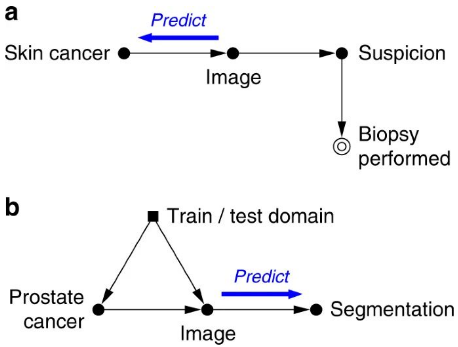


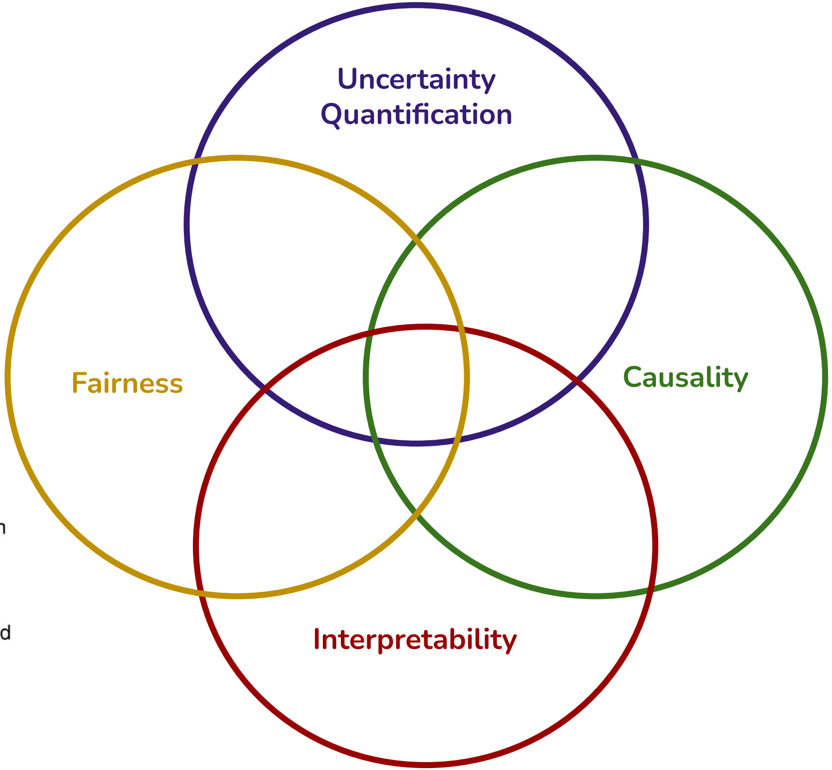
Future Work: Trustworthy Models

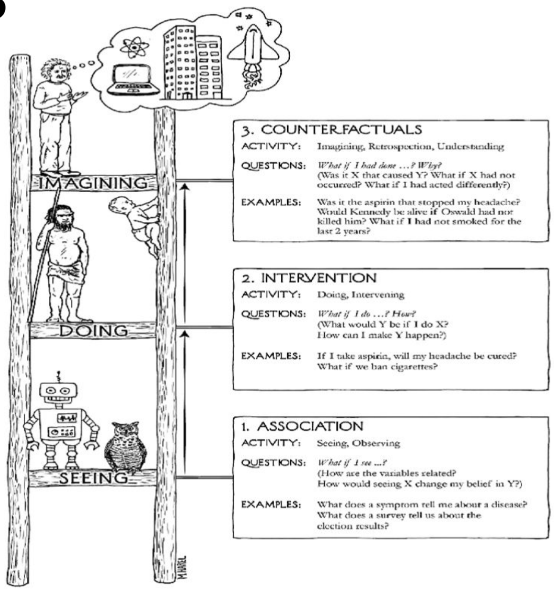




Future Work: Trustworthy Models







Related publications

<u>Journals:</u>

1. <u>R. Mehta</u>, A. Filos, U. Baid, ..., S. Bakas, Y. Gal, T. Arbel, "QU-BraTS: MICCAI BraTS 2020 Challenge on Quantifying Uncertainty in Brain Tumor Segmentation - Analysis of Ranking Scores and Benchmarking Results", **The Journal of Machine Learning for Biomedical Imaging (MELBA), August 2022.**
2. **<u>R. Mehta</u>, T. Christinck, T. Nair, A. Bussy, S. Premasiri, M. Costantino, M. Chakravarty, D. L. Arnold, Y. Gal, T. Arbel,** "Propagating Uncertainty Across Cascaded Medical Imaging Tasks for Improved Deep Learning Inference", **IEEE Transactions on Medical Imaging (TMI), Volume: 41, Issue: 2, February 2022**

<u>Peer-reviewed conferences and workshops:</u>

1. <u>R. Mehta</u>, C. Shui, T. Arbel "Evaluating the Fairness of Deep Learning Uncertainty Estimates in Medical Image Analysis", **Medical Imaging and Deep Learning (MIDL) conference 2023.**
2. <u>R. Mehta</u>, C. Shui, B. Nichyporuk, T. Arbel, "Information Gain Sampling for Active Learning in Medical Image Classification", **Uncertainty for Safe Utilization of Machine Learning in Medical Imaging (UNSURE) Workshop held in conjunction with 25th International Conference on Medical Image Computing and Computer Assisted Intervention (MICCAI) 2022.**
3. <u>R. Mehta</u>, A. Filos, Y. Gal, T. Arbel, "Uncertainty Evaluation Metrics for Brain Tumour Segmentation", **Medical Imaging with Deep Learning (MIDL) 2020 short paper**
4. <u>R. Mehta</u>*, T. Christinck*, T. Nair, P. Lemaitre, D. Arnold, T. Arbel, "Propagating Uncertainty Across Cascaded Medical Imaging Tasks for Improved Deep Learning Inference", **Uncertainty for Safe Utilization of Machine Learning in Medical Imaging (UNSURE) Workshop held in conjunction with 22nd International Conference on Medical Image Computing and Computer Assisted Intervention (MICCAI) 2019, (*<u>Best Paper Award</u>*) .**

Other Publications

Published:

1. C. Shui*, J. Szeto*, R. Mehta, D. L. Arnold, T. Arbel, "Mitigating Calibration Bias Without Fixed Attribute Grouping for Improved Fairness in Medical Imaging Analysis", 26th International Conference on Medical Image Computing and Computer Assisted Intervention (MICCAI) 2023.
2. J. Durso-Finley, J. P. Falet, R. Mehta, D. L. Arnold, N. Pawlowski, T. Arbel, "Improving Image-Based Precision Medicine with Uncertainty-Aware Causal Models", 26th International Conference on Medical Image Computing and Computer Assisted Intervention (MICCAI) 2023.
3. R. Mehta, Vitor Albiero, Li Chen, Ivan Evtimov, Tamar Glaser, Zhiheng Li, Tal Hassner, "You Only Need a Good Embeddings Extractor to Fix Spurious Correlations", Responsible Computer Vision (RCV) Workshop, European Conference on Computer Vision (ECCV) 2022.
4. B. Nichyporuk* J. Cardinell*, J. Szeto, R. Mehta, J.P. Falet, D. Arnold, S. Tsaftaris, T. Arbel, "Rethinking Generalization: The Impact of Annotation Style on Medical Image Segmentation", The Journal of Machine Learning for Biomedical Imaging (MELBA), October 2022.
5. B. Nichyporuk, J. Cardinell, J. Szeto, R. Mehta, D. Arnold, S. Tsaftaris, T. Arbel, "Cohort Bias Adaptation in Federated Datasets for Lesion Segmentation", Domain Adaptation and Representation Transfer (DART) 2021 workshop held in conjunction with 24th International Conference on Medical Image Computing and Computer Assisted Intervention (MICCAI) 2021, Lecture Notes in Computer Science, Springer, LNCS 12968, pp. 101-111, 2021.
6. S. Vadacchino, R. Mehta, N. M. Sepahvand, B. Nichyporuk, J. J. Clark, T. Arbel, "HAD-Net: A Hierarchical Adversarial Knowledge Distillation Network for Improved Enhanced Tumour Segmentation Without Post-Contrast Images", Medical Imaging with Deep Learning (MIDL) 2021.
7. B. Kaur, P. Lemaitre, R. Mehta, N.M. Sepahvand, D. Precup, D. Arnold, T. Arbel, "Improving Pathological Structure Segmentation Via Transfer Learning Across Diseases", Domain Adaptation and Representation Transfer (DART): Learning Transferable, Interpretable, and Robust Representation Workshop held in conjunction with 22nd International Conference on Medical Image Computing and Computer Assisted Intervention (MICCAI) 2019, Lecture Notes in Computer Science, Springer, LNCS 11795, pp. 90-98, 2019.
8. S. Bakas, M. Reyes, ..., T. Arbel, ..., R. Mehta, ..., B. Menze, "Identifying the Best Machine Learning Algorithms for Brain Tumor Segmentation, Progression Assessment, and Overall Survival Prediction in the BRATS Challenge", arXiv preprint arXiv:1811.02629, 2018.
9. R. Mehta, T. Arbel, "3D U-net for Brain Tumour Segmentation", Multimodal Brain Tumour Segmentation (BraTS) challenge 2018 held in conjunction with 21st International Conference on Medical Image Computing and Computer Assisted Intervention (MICCAI) 2018, Lecture Notes in Computer Science, Springer, LNCS 11384, pp. 254-266, 2018.
10. R. Mehta, T. Arbel, "RS-Net: Regression-Segmentation 3D CNN for Synthesis of Full Resolution Missing Brain MRI in the Presence of Tumours", Simulation and Synthesis in Medical Imaging (SASHIMI) workshop held in conjunction with 21st International Conference on Medical Image Computing and Computer Assisted Intervention (MICCAI) 2018, Lecture Notes in Computer Science, Springer, Vol. 11037, pp. 119-129.

Thank You