先端科学技術研究科　修士論文要旨

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要旨

Urolithiasis is a clinically important urinary disease with a substantial risk of recurrence. Computed tomography (CT) provides detailed information about urinary stones and the surrounding urinary anatomy; however, manual review of volumetric CT images, delineation of small stones, and assessment of complex renal structures are time-consuming and may be affected by observer variability. The objective of this thesis is to construct a deep learning framework for analyzing CT images of patients with urolithiasis. The framework consists of two automated segmentation components—one for urinary stones and the other for renal structures of the urinary tract—followed by anatomical feature extraction for preliminary recurrence-risk assessment. Ultimately, this framework is intended to support quantitative image analysis, improve the efficiency of clinical workflows, and provide structured imaging features that may be integrated with clinical history for personalized recurrence-risk prediction.

The first component is a binary urinary stone segmentation model. Eight CT cases comprising 825 axial slices were analyzed, of which 67 slices contained stone pixels. Seven cases were used for training and one case was held out for validation. Three adjacent axial slices were stacked to form a 2.5-dimensional input to an ImageNet-pretrained VGG11 U-Net. To restrict the search area to clinically plausible regions, a urinary-system region of interest was constructed from TotalSegmentator masks of the kidneys, ureters, and urinary bladder, followed by a 10 mm dilation. Class-aware sampling and a combined ROI-weighted generalized Dice-focal loss and Boundary Difference over Union loss were used to address severe foreground-background imbalance and the small size of urinary stones. On the held-out case, the selected model achieved a Dice coefficient of 0.9358 and an intersection over union of 0.8804 at a probability threshold of 0.15.

The second component performs three-class segmentation of background, renal parenchyma, and the collecting system. Twenty CT cases containing 5,276 slices were used, with one case held out and the remaining 19 cases used for training. A 2.5-dimensional VGG11 U-Net served as the baseline. The anatomy-guided configuration incorporated a global anatomical prior derived exclusively from training masks, RegionFiLM-based feature modulation, and collecting-system-guided local cross-attention at one encoder stage and one decoder stage. Compared with the baseline, the anatomy-guided configuration increased the macro Dice score from 0.8407 to 0.8519, the macro intersection over union from 0.7287 to 0.7445, and the collecting-system Dice score from 0.7883 to 0.8093. Recall increased from 0.8193 to 0.8459, indicating improved sensitivity to small anatomical structures.

The third component investigates the extraction of patient-level anatomical features for preliminary postoperative recurrence-risk assessment. Bilateral renal landmarks were standardized in kidney-specific coordinate systems and represented using three graph formulations: a simple anatomical graph, an anatomy-strict enriched graph, and a simplified edge-feature graph. GINEConv and GATv2 models were compared with multilayer perceptron baselines that used the same graph-derived node features without explicit connectivity. In leave-one-negative-out evaluation, the multilayer perceptron baselines produced slightly lower mean held-out negative probabilities than the graph neural networks. In the final Graph C experiment, GATv2 and the multilayer perceptron each correctly classified three of four held-out non-recurrent cases, while M14 was consistently misclassified as recurrent. Gradient saliency, single-node occlusion, and anatomical-group occlusion further indicated that the predictions were associated with patient-specific combinations of collecting-system and parenchymal features. Because the current dataset contains only one recurrent case, this experiment should be regarded at this stage as a feasibility study. As additional cases become available, more systematic training and validation can be conducted on a larger and more balanced cohort, enabling the development and evaluation of a more complete recurrence-prediction model suitable for subsequent clinical validation.

Overall, this thesis demonstrates three complementary uses of anatomical information in CT-based urolithiasis analysis: restricting the search space for urinary stone segmentation, guiding fine-grained renal structure segmentation, and constructing structured patient-level representations for recurrence-risk analysis. The proposed framework provides a technical foundation for extracting reproducible imaging features that may subsequently be combined with clinical history and other patient information. With larger and more balanced datasets, controlled validation, and multimodal feature integration, this approach may contribute to more reliable recurrence-risk assessment, preventive management, and individualized treatment planning.