Enhancing Pancreatic Cancer Diagnosis with Lesion-Aware Graph Reasoning and Deep Feature Integration

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Abstract: Detecting pancreatic cancer early enough is still a tuff challenge because the tumors are usually small, have low contrast, and can hardly be distinguished from the surrounding anatomical structures in CT images. In this paper, the authors present a lesion-aware graph-augmented deep learning system that integrates physics-guided preprocessing, hybrid U-Net segmentation, radiomic feature extraction, MobileViT-based representation learning, graph reasoning, feature fusion, and probability calibration for pancreatic cancer detection. The system was tested with 1,418 high-resolution CT slices from the Pancreatic CT Images dataset. The proposed method has demonstrated a 94.2% accuracy at the slice level, 93.6% macro-F1 score, AUROC of 0.972, and AUPRC of 0.969. At the patient level, the results were further enhanced, reaching 96.0% accuracy, 95.7% macro-F1, 0.986 AUROC, and 0.983 AUPRC. Temperature scaling has decreased the Expected Calibration Error from 0.031 to 0.009, This way making the prediction more reliable. The segmentation network was scored by Dice at 0.82 0.09 and HD95 at 7.3 mm. Ablations have established that lesion-aware attention, graph learning, and radiomic features are very important to the performance. The system was also tested for strength when it comes to imaging artifacts and cross-site variations, and it performed outstandingly with AUROC values consistently higher than 0.94. Besides, the system achieved efficient deployment with an average inference time of 28 ms per slice and 1.48 s per study. Such results indicate that the combination of lesion-aware attention, graph-based contextual learning, and calibrated deep representations can give an accurate, reliable, and computationally efficient solution to the problem of pancreatic cancer detection from CT images. Keywords: Pancreatic cancer; Temperature scaling; Lightweight graph head; Lesion-aware feature fusion; post-hoc probability calibration.

Introduction

Pancreatic cancer is one of the most deadly cancers and one of the reasons for its poor survival rate is mainly because the disease is detected at a late stage. The use of contrast-enhanced computed tomography (CT) is still the main method of imaging for detecting, staging, and planning treatment. Still, finding very early tumors is difficult as these tumors are usually small and can be of low contrast or iso-attenuating with the normal pancreatic tissue. Thanks to recent developments in artificial intelligence, medical image analysis has seen tremendous advancements, mainly through deep learning, radiomics and graph-based learning. Still, even the best methods still struggle to some extent with lesions that have unclear boundaries, very small tumors, imaging artifacts, inter-site variability, and unreliable probability estimates. All these can bring decreased diagnostic accuracy and may even influence a physician's decision-making process.

To this end this paper presents a lesion-aware graph-augmented deep learning system for detection of pancreatic cancer from CT images. The system uses physics-guided preprocessing, hybrid U-Net-based tumor segmentation, radiomic texture analysis, MobileViT feature extraction, graph-based relational modeling, lesion-aware feature fusion, and probability calibration. The experiments were carried out using Pancreatic CT Images data set which is publicly available and it consists of 1,418 high-resolution DICOM slices.

The suggested method is tested using classification segmentation calibration, robustness, and deployment-oriented metrics. Besides, ablation experiments are carried out to analyze the separate impact of lesion-aware attention, graph reasoning, radiomics, and loss function units. The experimentation results verified the capability of the structure in the accurate, robust and clinically reliable pancreatic cancer detection task..

Related work

Various strategies of artificial intelligence for pancreatic cancer detection have been explored in recent studies. Nadeem et al. [12] designed a multi-stage computer-aided diagnosis system which through image preprocessing segmentation texture analysis, and deep learning classification stages, managed to obtain a very high level of diagnostic accuracy alongside very low computational delay.

Alaca [13] proposed a graph-based learning technique that strongly combines structural representations obtained from Harris-corner detections with the MobileViT architectural features which have been optimized through differentiable architecture search, Because of this resulting in Really better classification accuracy and computational performance. Considering aspects other than imaging, Lee et al. [14] focused on extracellular vesicle microbiome biomarkers and found that deep neural network models, when trained on the most representative microbial signatures, showed excellent diagnostic results. Almisned et al. [15] in a similar vein, used clinical and urine-based biomarkers and combined ensemble machine learning models with SHAP-based interpretability to provide support for early detection of pancreatic cancer.

Mostly, the discussed works represent different approaches which cover deep learning, graph-based representations, biomarker-guided diagnostics, ensemble learning, and calibration methods to pancreatic cancer detection. Still, the issues linked to lesion visibility, making models resilient to different imaging conditions, and trustworthy confidence estimation call for more integrated and clinically reliable diagnostic systems to be developed.

Key Contribution

This work describes a lesion-aware graph-augmented deep learning structure for pancreatic cancer diagnosis on CT images, which combines physics-guided preprocessing, hybrid U-Net-based tumor segmentation, radiomic texture analysis, MobileViT feature extraction, graph-based relational learning, and lesion-aware feature fusion. In addition, the setup makes use of probability calibration by temperature scaling to make diagnostic predictions more reliable. Significant tests have shown strong performance even after switching sites or encountering image artifacts, among others, while stand-alone experiments have helped to identify lesion-aware attention, graph reasoning, and radiomic features as main contributors. The new method is both highly accurate in making diagnoses and very efficient for computational resources which in turn, makes it viable for real-world clinical applications and early screening of pancreatic cancer.

Method, Experiments and Results

This study proposes a lesion-aware graph-augmented deep learning framework for pancreatic cancer detection from CT images. The overall workflow consists of physics-guided preprocessing, hybrid U-Net-based tumor segmentation, radiomic feature extraction, graph-based relational learning, lesion-aware feature fusion, and calibrated classification. Initially, CT images undergo Hounsfield-unit windowing, normalization, anisotropic diffusion filtering, and resizing to enhance lesion visibility and reduce inter-scanner variability. A hybrid U-Net generates tumor probability maps, which are subsequently used for radiomic texture analysis and lesion-guided attention. Deep semantic features are extracted using a MobileViT backbone, while graph-based descriptors model anatomical relationships within pancreatic regions. These complementary features are fused through a lesion-aware attention mechanism and classified using a calibrated prediction module.

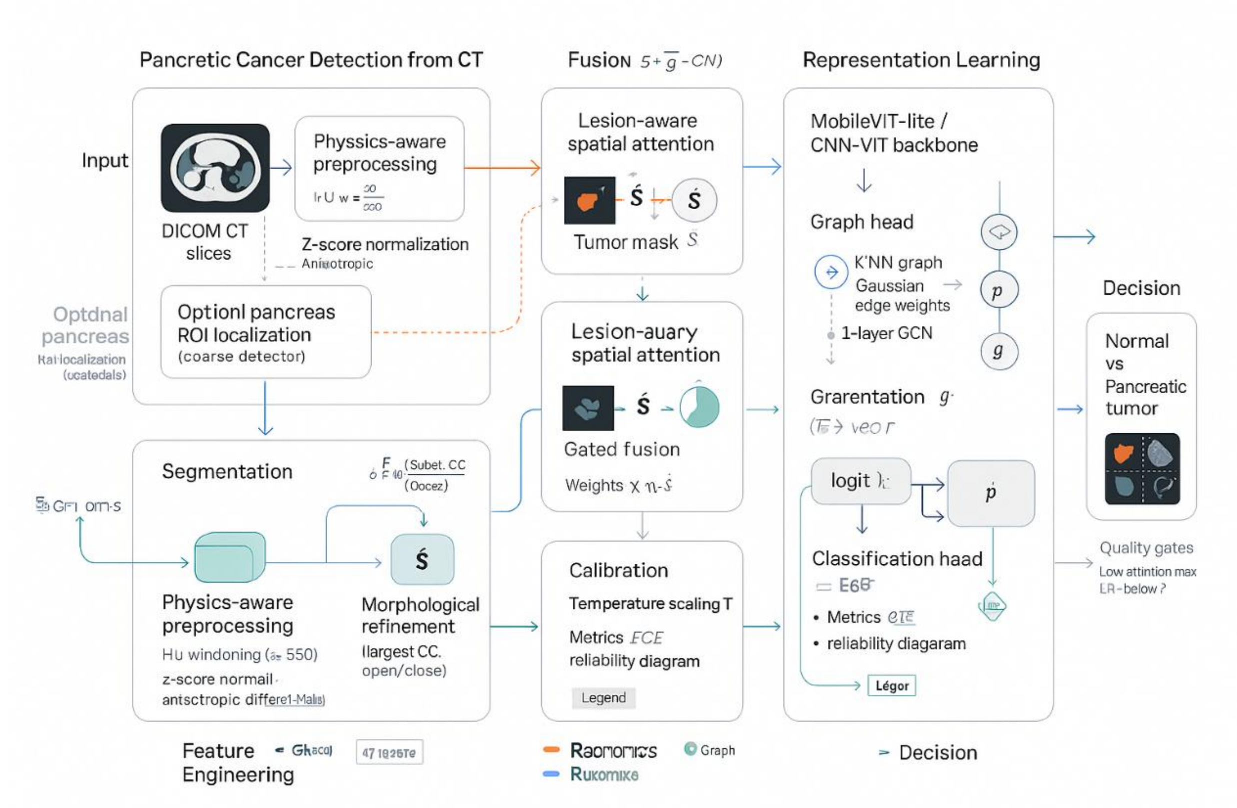

Figure 1: Workflow of the proposed model

We performed experiments on the Pancreatic CT Images dataset, which contained a total of 1,418 slices of high-resolution DICOM CT scans. To measure performance, several metrics like Accuracy, Macro-F1 AUROC AUPRC, Dice score, and calibration metrics were used plus analysis of robustness. At the level of individual slices, trials indicated the proposed system was very accurate with a score of 0.942, Macro-F1 was 0.936, AUROC reached 0.972, and AUPRC was 0.969. When results were averaged at the patient level, not only was there a significant enhancement in the performance with an accuracy of 0.960, Macro-F1 of 0.957, AUROC of 0.986, and AUPRC of 0.983, but it was also accompanied by satisfaction from the per-patient aggregation aspect Temperature scaling. Segmentation accomplished a Dice score of 0.82. Robustness tests revealed that the method maintained high-level operation even when subjected to noise, motion artifacts, and changes in the site of the experiment, strongly supporting the viability of the developed system in dependable pancreatic cancer detection.

Discussions

Experimental results show that the combination of lesion-attention mechanism, radiomic texture features, graph-based relational learning, and deep semantic features can greatly improve pancreatic cancer detection capability. Different from that we by running ablation experiments, realized that lesion-attention was mainly responsible for the increase in performance, while graph reasoning and radiomics gave extra diagnostic information. The calibration output showed that temperature scaling could eliminate the gap between prediction confidence and actual results, thereby rendering the model more trustworthy and suitable for clinical use. The approach we put forward not only performed well under normal conditions, but also presented strong performance when switched to unfamiliar domains and exposed to image noise, which implies that the model holds good generalization capability. Also, the very short time for producing inferences and relatively high coverage levels are indications that the presented system is practical as a computer-aided diagnostic tool for early pancreatic cancer detection and clinical decision support.

Conclusions

This research proposes a lesion-aware, graph-augmented library system for diagnosing pancreatic cancer using CT images. The diagnostic accuracies attained by the proposed model were impressively high at both slice and patient levels, with AUROC values of 0.972 and 0.986 respectively after combining segmentation radiomics graph learning, and probability calibration. On top of that, the research demonstrated that the network model is reliable in providing probability estimates, tumor localization is precise, and the approach is resistant to image artifacts and inter-site variations. High sensitivity, specificity, and low inference time highlight even more the usefulness of the system for clinical screening and decision support. Future research directions will be developing the system for 3D CT analysis, using self-supervised and domain-adaptive learnings for better generalization, and also using semi-supervised methods to harness unlabeled data. Besides, multimodal integration of clinical information, computational optimization for faster deployment, and prospective clinical studies to assess the system's impact on early diagnosis and patient management will be conducted in the future.

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