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Research Progress of Radiomics and Deep Learning in Prognosis and Efficacy Prediction of Laryngeal Cancer

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Abstract

In recent years, the rapid development of radiomics and deep learning (DL) technologies has provided new research directions for the precision diagnosis and treatment of laryngeal cancer. This article introduces the concepts of radiomics and DL, and reviews the applications in predicting the prognosis and treatment efficacy of laryngeal cancer. The article highlights the limitations and challenges of radiomics and DL in laryngeal cancer, and suggests future directions such as multi-center collaboration, the establishment of standardized processes, and the integration of multi-omics approaches.

Keywords: radiomics, deep learning, laryngeal cancer, prognosis prediction, efficacy prediction

1. Introduction

Laryngeal cancer, a highly invasive malignancy of the head and neck, accounts for over 268,000 new cases globally each year, resulting in approximately 138,000 deaths (Siegel R L, Miller K D, Fuchs H E, et al., 2022). Despite significant advances in treatment techniques, the recurrence rate remains as high as 30%, and the 5-year overall survival rate is approximately 54-61% (Keek S A, Wesseling F W R, Woodruff H C, et al., 2021). Currently, the prognosis of laryngeal cancer primarily relies on the tumor-node-metastasis (TNM) staging system. However, the TNM system is mainly based on anatomical information and cannot fully reflect the biological heterogeneity of tumors, nor does it adequately evaluate the tumor microenvironment and molecular characteristics. As a result, patients with the same stage may have significantly different prognostic outcomes, thus limiting its application in personalized treatment (Liu Y, He S, Wang X L, et al., 2021). Common clinical methods for assessing laryngeal cancer prognosis and efficacy include laryngoscopy, CT, and MRI; however, the analysis of these images heavily depends on the physician's experience and subjective judgment, making it a time-consuming and labor-intensive process with uncertain accuracy.

In recent years, imaging-based artificial intelligence research has become a hotspot in the medical field (Bera K, Braman N, Gupta A, et al., 2022). Radiomics and deep learning (DL), important branches of machine learning, enable the identification of features not visible to the human eye and quantify the temporal and spatial heterogeneity of tumor tissues. These technologies have shown great potential in tumor prognosis prediction and efficacy evaluation (Sahoo P K, Mishra S, Panigrahi R, et al., 2022; Qi M, Zhou W, Yuan Y, et al., 2024; Gu J, Wang A, Lin Q, et al., 2021). The basic workflow of radiomics includes image acquisition and preprocessing, region of interest segmentation, feature extraction and selection, and model construction and validation (Peng Z, Wang Y, Wang Y, et al., 2021). Radiomic features include first-order statistical features (e.g., mean, variance), spatial geometric features (e.g., shape, size), texture features (e.g., gray-level co-occurrence matrix), and frequency domain features (e.g., wavelet features). DL, inspired by the structure of the brain's neural network, generates various models using deep neural networks to analyze data and output predictions (Akay A & Hess H., 2019). Convolutional neural networks (CNNs), one of the most commonly used DL models in medical image analysis, automatically detect and segment lesions from images, extract and learn representative features, and construct end-to-end predictive models with layers including the input layer, hidden layers, and output layer (Avanzo M, Wei L, Stancanello J, et al., 2020). Compared to radiomics, DL models do not require predefined features and can automatically analyze complex information in medical images, significantly improving the efficiency and accuracy of image analysis. Additionally, deep learning-based radiomics (DLR) models have emerged, further exploring and identifying complex tumor characteristics, offering broader application prospects (Gu B, Meng M, Xu M, et al., 2023; Wei Z, Xv Y, Liu H, et al., 2024). This paper systematically reviews the research progress of radiomics and DL technologies in predicting the prognosis and treatment efficacy of laryngeal cancer, analyzes the challenges, and prospects future development directions to provide theoretical support for precision medicine in this field.

2. Applications of Radiomics and DL in Prognostic and Efficacy Prediction of Laryngeal Cancer

2.1 Survival Prediction

Accurate survival prediction is critical in clinical decision-making and treatment planning. CT imaging is one of the key methods in the imaging follow-up of laryngeal cancer patients, and the value of CT-based radiomics in predicting survival has been demonstrated in multiple studies (Rajgor A D, Kui C, Mcqueen A, et al., 2024; Agarwal J P, Sinha S, Goda J S, et al., 2020). Chen et al. extracted and selected texture features from enhanced CT images of 136 surgically treated laryngeal cancer patients, constructed a radiomics nomogram, and combined it with clinical and pathological factors to assess overall survival (OS). The results showed that the nomogram's C-index was significantly higher than that of the TNM staging system (0.913 vs. 0.699), and Cox proportional hazards regression analysis suggested that radiomics features were potential prognostic biomarkers for laryngeal cancer (Chen L, Wang H, Zeng H, et al., 2020). Li et al. focused on dual-energy CT images of 118 early-stage glottic laryngeal cancer patients, extracting radiomics features and using Cox and LASSO regression analysis to select the five best features for radiomics scoring, which predicted progression-free survival (PFS). The radiomics model demonstrated the best performance in the validation set, with AUCs of 0.714 and 0.671 for 1-year and 3-year PFS, respectively, surpassing those of the T-stage clinical model (AUCs of 0.607 and 0.665) (Li W, Zhang H, Ren L, et al., 2022). Notably, not only tumor-related radiomics features but also those from the surrounding environment contain valuable prognostic information. Lin et al. enrolled 92 laryngeal and hypopharyngeal cancer patients receiving radiation therapy, extracting radiomics features from pre-treatment and on-treatment CT images of both the tumor and peritumoral region (5mm beyond the primary tumor). They constructed models using LASSO-Cox regression to predict OS. The results demonstrated that the radiomics models for both the peritumoral and intratumoral regions during radiation therapy offered the best prediction performance, with AUC values of 0.77 and 0.79, respectively, both exceeding the TNM staging (AUC = 0.52) (Lin C H, Yan J L, Yap W K, et al., 2023). MRI, alongside CT, plays a crucial role in laryngeal cancer prognosis. Yuan et al. extracted radiomics features from T2-weighted MRI images of 170 head and neck squamous cell carcinoma (HNSCC) patients. By combining these features with clinical data, they developed a nomogram to predict OS and risk stratification in laryngeal cancer patients. The fusion model exhibited a higher C-index than the TNM staging system (0.72 vs 0.61) (Yuan Y, Ren J, Shi Y, et al., 2019). Functional MRI, such as diffusion-weighted imaging (DWI), transcends the limitations of traditional MRI by providing additional information about tissue cellular function. DWI reflects the diffusion of free water at the molecular level and quantifies it using the apparent diffusion coefficient (ADC), which has shown preliminary applications in predicting the prognosis of laryngeal cancer. Tomita et al. utilized a DL model based on DWI and ADC to predict PFS in 70 laryngeal and hypopharyngeal cancer patients undergoing radiation therapy. The study revealed that the DWI-based DL model during treatment was significantly associated with PFS, and multivariable Cox analysis confirmed it as an independent prognostic factor (Tomita H, Kobayashi T, Takaya E, et al., 2022). These studies highlight the significant role of radiomics and DL in predicting the survival of laryngeal cancer patients, offering more accurate prognostic assessments compared to traditional TNM staging systems. When combined with clinical independent risk factors, they enhance predictive performance, thereby furnishing more effective tools for clinical diagnosis and treatment.

2.2 Lymph Node Metastasis Prediction

Lymph node metastasis (LNM) status serves as a critical determinant not only for optimizing treatment strategies in laryngeal cancer patients but also as a pivotal prognostic indicator affecting survival and postoperative recurrence (Le H, Chen S, Li Y, et al., 2019). Conventional imaging-based LNM diagnosis primarily depends on morphological features such as short diameter, shape, necrosis, and enhancement patterns (Valizadeh P, Jannatdoust P, Pahlevan-Fallahy M T, et al., 2024). However, these methods' accuracy often fluctuates due to inter-observer variability and subjective interpretation limitations. Radiomics and DL methodologies offer transformative potential through non-invasive, objective, and quantitative extraction of multi-dimensional imaging data, significantly enhancing predictive capabilities. Zhao et al. developed a nomogram by integrating radiomics features from venous-phase CT images of 464 laryngeal cancer patients with tumor location and lymph node status from CT reports, achieving superior predictive performance compared to radiologists' manual assessments (AUC = 0.89 vs. 0.70). Decision curve analysis further validated its clinical utility in cervical LNM prediction (Zhao X, Li W, Zhang J, et al., 2023). Jia et al. advanced this approach by manually segmenting primary tumors from enhanced T1WI and T2WI MRI sequences in 117 laryngeal cancer patients to generate radiomics signatures. When combined with MR-reported lymph node status, their nomogram demonstrated enhanced predictive accuracy over manual interpretation in both training (AUC = 0.930 vs. 0.824) and testing cohorts (AUC = 0.883 vs. 0.772) (Jia C, Cao Y, Song Q, et al., 2020). Not only can radiomics features derived from the primary tumor predict cervical LNM, but features can also be directly extracted from the lymph nodes for modeling. Wang et al. constructed a predictive model using radiomics features extracted from preoperative enhanced T1WI and DWI images of cervical lymph nodes in 120 HNSCC patients, alongside ADC values and short-axis diameters. This model achieved robust predictive performance (AUC = 0.83), surpassing ADC-alone (AUC = 0.560) and short-axis diameter-based models (AUC = 0.731) (Wang Y, Yu T, Yang Z, et al., 2022).

In addition, for laryngeal cancer patients with clinically undetected cervical LNM on preoperative imaging, there remains a risk of occult cervical LNM. Clinically, these patients are often treated with prophylactic selective neck dissection. However, compared to a conservative observation strategy, this method has not significantly improved survival rates and may lead to complications that impact quality of life (Patel T R, Eggerstedt M, Toor J, et al., 2021). Therefore, accurately predicting occult LNM preoperatively is crucial for laryngeal cancer prognosis. Wang et al. enrolled 553 clinically N0-staged laryngeal cancer patients and constructed various models, including 2D and 3D DL models, as well as a DLR model, based on primary tumor venous phase CT images to predict occult LNM. The results showed that the decision fusion-based DLR model achieved the highest AUC (0.89-0.90) across all test sets (Wang W, Liang H, Zhang Z, et al., 2024). These studies highlight the promising role of radiomics and DL in predicting cervical LNM in laryngeal cancer, not only improving accuracy but also providing more objective evidence for clinical decision-making, thus avoiding unnecessary surgeries.

2.3 Tumor Recurrence Prediction

Despite advances in treatment, the recurrence rate of laryngeal cancer remains high, especially within the first three years after curative treatment, with approximately 30% of patients facing recurrence, which poses a major obstacle to long-term survival (Pfister D G, Spencer S, Adelstein D, et al., 2020). Therefore, accurately identifying laryngeal cancer patients at risk of recurrence and implementing early intervention is crucial. Yao et al. constructed a radiomics model using enhanced CT images from 140 laryngeal cancer patients before surgery and combined it with relevant clinical factors to develop a nomogram to predict early postoperative recurrence risk. The results showed that the nomogram's AUC was significantly higher than the clinical model (0.939 vs. 0.817) (Yao Y, Jia C, Zhang H, et al., 2023). Cong et al. extracted radiomics features from PET/CT images of 298 HNSCC patients (including 45 laryngeal cancer patients) before treatment and built a fusion model combining age, tumor location, and N-stage to predict local recurrence. The fusion model performed the best with an AUC and C-index of 0.70 (Cong H, Peng W, Tian Z, et al., 2021). Tomita et al. employed an Xception-based DL model to analyze DWI and ADC images from 70 laryngeal and hypopharyngeal cancer patients before and during treatment to predict local recurrence. The DWI-based DL model outperformed clinical staging models in predicting local recurrence, yielding an AUC of 0.767 and 81.0% accuracy in the validation cohort, compared to clinical models with AUC = 0.544 and 47.6% accuracy (Tomita H, Kobayashi T, Takaya E, et al., 2022). Collectively, radiomics and DL models exhibit substantial advantages over clinical models in post-treatment recurrence prediction. However, further validation in larger, external cohorts is warranted to enhance generalizability.

2.4 Prediction of Prognostic Tumor Molecular Markers

In recent years, radiomics and DL have attracted considerable attention in predicting prognostic tumor molecular markers in laryngeal cancer. Traditional detection methods often rely on invasive tissue samples for analysis, but artificial intelligence provides a non-invasive solution for predicting tumor molecular markers. Several studies have demonstrated that radiomics and DL can effectively predict molecular markers related to laryngeal cancer prognosis, such as Ki-67, TP53, and EGFR. Zheng et al. collected enhanced CT and Ki-67 immunohistochemical data from 217 HNSCC patients (including 66 laryngeal cancer patients) and extracted radiomics features to construct a nomogram to predict Ki-67 expression in HNSCC. The results showed that the nomogram's performance was superior to clinical models (AUC = 0.832 vs. 0.685), highlighting the added value of radiomics in model enhancement (Zheng Y M, Chen J, Zhang M, et al., 2023). Tian et al. established a radiomics model using multi-phase CT images from 96 laryngeal cancer patients to predict TP53 status. Using ANOVA and LASSO regression analysis, they identified 22 features related to TP53 status and built models using five machine learning methods, with the linear SVM radiomics model showing the best performance (AUC = 0.797) (Tian R, Li Y, Jia C, et al., 2022). Another study by Zheng et al. constructed a DLR nomogram from venous phase CT images of 300 HNSCC patients (including 97 laryngeal cancer patients) to predict EGFR mutation status. The nomogram integrated five radiomics features, six DL features, and two clinical factors (gender and necrosis area) and performed optimally in the testing set with an AUC of 0.875, demonstrating the advantages of combining radiomics and DL features (Zheng Y M, Pang J, Liu Z J, et al., 2024).

Although DL applications in predicting molecular markers for laryngeal cancer are not yet widespread, its potential and advantages have already been shown in other tumors of the head and neck, such as thyroid cancer, glioblastoma, and meningioma (Wang C W, Muzakky H, Lee Y C, et al., 2023; El Nahhas O S M, Loeffler C M L, Carrero Z I, et al., 2024; Chen J, Xue Y, Ren L, et al., 2024). In the future, as radiomics and DL technologies continue to develop and optimize, and as the quality and quantity of imaging data improve, their application in predicting molecular markers in laryngeal cancer will likely have broader prospects.

2.5 Prediction of Efficacy Prediction

Radiation therapy and chemotherapy are key treatments for laryngeal cancer patients, but the efficacy varies across individuals. Identifying robust biomarkers to predict treatment sensitivity is therefore crucial for enabling personalized therapeutic strategies and optimizing clinical outcomes. Current clinical evaluations primarily depend on post-treatment imaging or histopathological assessments categorized as complete response, partial response, stable disease, or progressive disease. However, these conventional methods inherently suffer from temporal delays due to their reliance on post-intervention data acquisition. By contrast, radiomics and DL methodologies enable non-invasive pre-treatment prediction of therapeutic response, offering actionable insights for treatment customization. The NCCN guidelines advocate induction chemotherapy prior to total laryngectomy for advanced-stage patients to improve laryngeal preservation rates (Pfister D G, Spencer S, Adelstein D, et al., 2020). However, this approach risks cumulative toxicities, underscoring the need for precise identification of non-responders. Kang et al. constructed a radiomics model using contrast-enhanced CT images to predict pathological response (complete or partial response) in 114 advanced laryngeal cancer patients undergoing induction chemotherapy. The model achieved AUCs of 0.87 and 0.79 in the training and validation sets, respectively, and multivariate logistic regression analysis identified that only radiomics scores were significantly associated with pathological response. Furthermore, they combined radiomics scores, tumor volume, and N-stage to construct a nomogram for predicting 1-year OS, with a C-index of 0.735 in the validation set, higher than T-stage (C-index = 0.543) and N-stage (C-index = 0.561) (Kang C, Sun P, Yang R, et al., 2023). In the immunotherapy realm, PD-1 expression critically guides treatment decisions. Zandberg et al. extracted radiomics features from pre-treatment CT images of 61 HNSCC patients (including 12 laryngeal cancer patients) receiving anti-PD-1 treatment and used the XGBoost machine learning algorithm to construct a radiomics model for predicting disease control rate (complete response, partial response, or stable disease). The radiomics model outperformed clinical models based on neutrophil-to-lymphocyte ratio and HPV status, with AUCs of 71.21%, 50.03%, and 46.97%, respectively (Zandberg D P, Zenkin S, Ak M, et al., 2025). For locally advanced HNSCC patients, combining PD-1 inhibitors with chemotherapy can improve the response rate of neoadjuvant therapy (Vos J L, Elbers J B W, Krijgsman O, et al., 2021). Lin et al. included 172 HNSCC patients from three hospitals who underwent surgery after receiving neoadjuvant chemoradiotherapy, extracting radiomics features from both the tumor and surrounding regions in MRI images. They constructed corresponding radiomics scores for these regions and combined them with clinical pathological features to develop a nomogram for predicting pathological complete response. The nomogram demonstrated the highest predictive accuracy, with AUCs of 0.860 and 0.849 in the internal and external validation groups (Lin P, Xie W, Li Y, et al., 2024). In guiding post-operative adjuvant chemoradiotherapy for laryngeal cancer patients, Howard et al. constructed three machine learning models, including DeepSurv, to predict treatment benefit in 33,527 HNSCC patients, of whom 5,631 had laryngeal cancer. The results demonstrated that patients who followed the machine learning model recommendations for post-operative radiotherapy had significant survival advantages, with a risk ratio of 0.79-0.90 and C-indexes of 0.691-0.695 (Howard F M, Kochanny S, Koshy M, et al., 2020). These studies suggest that radiomics and DL offer new perspectives and methods for predicting treatment response in laryngeal cancer patients, enabling earlier non-invasive efficacy evaluation and exhibiting higher accuracy compared to clinical models.

3. Limitations and Future Outlook

Despite the significant potential of radiomics and DL methodologies in predicting laryngeal cancer prognosis and treatment efficacy, several challenges persist: (1) Most studies rely on single-center cohorts with limited sample sizes and retrospective designs, which inherently compromise the generalizability and robustness of their conclusions. Future investigations should prioritize multicenter collaborations, expanded prospective cohorts, and standardized study protocols to enhance model transferability. (2) The lack of standardized image acquisition parameters, the complexity and subjectivity of manual segmentation, as well as differences in parameter settings and algorithm selection, all contribute to poor accuracy and reproducibility of the research results. Therefore, it is essential to establish unified and standardized imaging data collection methods and precise automatic image segmentation techniques to ensure the reliability of the models. (3) The "black-box" issue of DL limits the interpretability of the results and hinders its clinical application. Thus, increasing model transparency and interpretability should be a key direction for future research. (4) Currently, most radiomics research is focused on single-modal and single-omics studies, with relatively few studies combining multiple modalities or multi-omics. Pathology, metabolomics, and proteomics also contain valuable micro-information related to prognosis. Future studies should integrate multi-omics to uncover the systemic regulatory relationships in tumorigenesis and development from a molecular mechanism perspective, offering new insights and methods for precision treatment and prognosis prediction in laryngeal cancer.

4. Conclusion

In conclusion, radiomics and DL technologies demonstrate significant potential in predicting laryngeal cancer outcomes, including survival, recurrence, metastasis, treatment responses, and molecular biomarkers. They offer preoperative, non-invasive tools to assess prognosis and treatment efficacy. Future advancements will rely on multi-center collaborations to establish standardized analytical pipelines and validation datasets, enhancing model generalizability and robustness. Integration of multi-dimensional data (clinical, imaging, pathological, genetic) will further refine predictive accuracy, enabling personalized treatment strategies. As these technologies mature, they are poised to become pivotal in laryngeal cancer management, driving precision medicine forward.

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