Radiomics and Machine Learning for Prediction of Cavernous Sinus Invasion in Pituitary Adenomas

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Background

- Cavernous sinus invasion (CSI) is a major determinant of surgical approach, resectability, prognosis, and need for adjuvant therapy in pituitary adenomas.
- Conventional MRI grading (for example, Knosp) is limited by sequence dependence, interobserver variability, and reduced sensitivity for intermediate grades.
- Radiomics combined with machine learning (ML) provides a quantitative, reproducible approach to improve preoperative CSI prediction.

Methods

A PRISMA-based review identified **five studies (2020–2025)** evaluating radiomics and ML for preoperative CSI prediction.

Extracted data included imaging sequences, model architecture, diagnostic performance, interpretability methods, and clinical readiness.

Results

Performance: Radiomics-based ML models consistently outperformed conventional MRI grading, with reported AUCs ranging from **0.80–0.92**.

Integrated Models: Models combining radiomics with clinical variables (for example, Knosp grade, tumor lateral diameter, satellite morphology) achieved the highest accuracy and exceeded expert radiologist performance.

Imaging Correlates: Radiomic features reflecting texture heterogeneity, boundary sharpness, and shape deformation correlated with intraoperative medial cavernous sinus wall invasion.

Interpretability: Feature attribution methods (including SHAP) identified MRI-derived features most strongly driving CSI prediction, supporting clinical interpretability and trust.

Limitations: Most studies were retrospective and single-center, highlighting the need for prospective external validation.

Key Radiomic Features and Model Performance

- **Quantitative MRI features** (texture, boundary sharpness, shape deformation, lateral extension) capture CSI beyond conventional Knosp grading.
- **Radiomics–ML performance:** Consistent improvement over conventional MRI and expert reads, with **AUCs ~0.80–0.92**.
- **Hybrid models:** Combining radiomics with clinical variables (Knosp grade, tumor diameter) yields the **highest** accuracy and calibration.
- **Interpretability:** Feature-attribution methods (such as **SHAP**) identify which MRI features drive invasion predictions at the single-patient level.
  Evidence base: Five primary studies using multiple radiomics pipelines and ML architectures, supported by dedicated radiomics reviews.

Take-Home Messages

- Conventional MRI and Knosp grading alone are limited for detecting cavernous sinus invasion, particularly in intermediate cases
- Radiomics-based ML models provide **more accurate and reproducible CSI prediction** than expert visual assessment.
- Models integrating clinical and radiomic features most closely align with intraoperative findings of cavernous sinus invasion.
  Interpretable ML techniques translate model outputs into feature-based explanations that mirror surgical MRI reasoning.
- With prospective validation and PACS integration, automated CSI risk scores could be incorporated into MRI reports within **~3 years**, refining surgical planning and adjuvant therapy decisions.

Study (year, PMID)	Design / key features	AUC
Radiomics nomogram for CSI in Knosp 2–3 PAs (2019, 30255254)	Single-center; CE-T1/T2 radiomics + SVM nomogram	~0.84–0.89
Thin-slice MRI with DL-based reconstruction (2022, 34992127)	Prospective; 1-mm pituitary MRI + DL reconstruction; improved depiction of CSI	~0.86
Radiomics-based multiple ML approaches for CSI (2022, 1706895)	Single-center; T2 radiomics + multiple ML models	best models ~0.85–0.90
Clinical + radiomics LightGBM CSI model (2025, 12675217)	Clinical + MRI radiomics; LightGBM with SHAP attribution	train 0.90, test ~0.86
Radiomics in pituitary adenomas – CSI overview (2025, 41010799)	Systematic review of radiomics applications including CSI	many models report AUC ≥0.80

Conclusions

Radiomics and ML significantly enhance preoperative assessment of cavernous sinus invasion by providing automated, reproducible, and interpretable predictions. These models reduce diagnostic variability and support more precise surgical planning.

Clinical integration into radiology workflows within the next **~3 years** is anticipated, enabling CSI risk scores to accompany MRI reports and tumor board discussions.

Future Directions and Clinical Implications

- Prospective, multi-center validation using standardized MRI and segmentation protocols.
- Embedding automated CSI risk prediction and feature attribution into PACS and radiology reports.
- Integrating CSI risk with tumor consistency and other imaging biomarkers to tailor surgical and adjuvant strategies.
- Leveraging interpretable ML as a foundation for AI-informed navigation and robotic assistance in cavernous sinus surgery.

References:

1. Park YW, et al. Preoperative prediction of cavernous sinus invasion by pituitary adenomas using a radiomics method based on magnetic resonance images. Eur Radiol. 2019. PMID 30255254.
2. Thin-Slice Pituitary MRI with Deep Learning–Based Reconstruction for Preoperative Prediction of Cavernous Sinus Invasion by Pituitary Adenoma: A Prospective Study. AJNR Am J Neuroradiol. 2022. PMID 34992127.
3. Radiomics-based multiple machine learning approaches for preoperative prediction of cavernous sinus dural invasion in pituitary adenomas. 2022/2025. (Front Oncol, PMCID/PMID as in article).
4. The current state of MRI-based radiomics in pituitary adenoma: promising but challenging. Front Endocrinol. 2024. PMID 39371931.
5. Radiomics in pituitary adenomas: a systematic review of clinical applications. 2025. PMID 41010799.