IA3D-IO for Precise Foren-Neuro-Seg in MRI-WML

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Abstract

Forensic neuroimaging increasingly relies on precise segmentation of white-matter lesions in MRI to support legal investigations and clinical interpretation. This paper introduces IA3D-IO (Integrating Advanced 3D-Imaging and Optimization), a novel framework that integrates advanced three-dimensional imaging processing with optimization techniques to improve Foren-Neuro-Seg (forensic-neuro segmentation) accuracy for MRI-WML (white-matter lesions). IA3D-IO combines high-resolution 3D reconstruction of lesion areas with a custom optimization pipeline that refines boundaries and reduces false positives common in automated methods. We evaluated the approach on multi-contrast MRI datasets, comparing against leading deep-learning and traditional segmentation baselines. Results show that IA3D-IO achieves notably higher Dice similarity and lower boundary error, particularly for small or irregular lesions that often challenge existing algorithms. Quantitatively, the method improved segmentation reliability by a meaningful margin, while qualitatively preserving lesion morphology crucial for forensic interpretation. Beyond performance gains, IA3D-IO offers a modular design that can incorporate emerging imaging modalities or optimization solvers, supporting future forensic and clinical workflows. The approach addresses an urgent need for more dependable lesion delineation, as recent studies highlight the critical role of automated methods in detecting and classifying subtle white-matter abnormalities in MRI [1, 2, 4].

Keywords— *IA3D-IO, MRI-WML, Foren-Neuro-Seg.*

1. Introduction

Accurate delineation of white-matter lesions in brain MRI is critical for both clinical assessment and forensic interpretation. White-matter hyperintensities signal a range of neurological issues, from vascular damage to cognitive decline, and their number, volume, and morphology carry important diagnostic and prognostic value [4, 5, 10, 15]. Recent studies confirm that automated 3D segmentation approaches can enhance detection precision, yet they still face challenges such as limited data, irregular lesion shapes, and the need for reliable performance in real-world settings. For example, comparisons between convolutional and transformer-based 3D models found that transformers can outperform traditional networks on several key segmentation metrics even with constrained datasets, underscoring both progress and the tight margins for improvement. Other research focused on detecting small or irregular white-matter lesions reports wide variation in accuracy across methods, highlighting the practical difficulty of consistent segmentation in challenging cases [1, 2, 11, 14]. In forensic neuroimaging, the stakes are especially high: subtle lesions or borderline boundaries may materially influence the interpretation of injury, disease progression, or cause-and-effect in medico-legal contexts. Traditional or purely data-driven pipelines may produce false positives, incomplete boundaries, or inconsistent morphology that complicates expert review. This situation motivates a method that not only leverages advanced 3D imaging representations but also systematically refines results using optimization

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to reduce error and stabilize outputs across lesion types. This paper presents IA3D-IO, a framework expressly designed to integrate high-resolution 3D imaging with a tailored optimization stage for Foren-Neuro-Seg of MRI-WML. The research questions centre on whether such integration can yield measurably higher boundary accuracy, lower false positives, and more trustworthy lesion morphology than leading automated baselines, especially for small or irregular lesions common in forensic cases. Objectives include developing the end-to-end pipeline, evaluating it against established models, and demonstrating its practical relevance for forensic workflows. By combining advanced 3D reconstruction techniques with a custom optimization process, IA3D-IO delivers more precise, reliable segmentation of MRI-WML, thereby strengthening the evidentiary and clinical value of forensic neuroimaging analyses [4, 7].

2. Literature Review

Automated segmentation of WML in MRI has been an active area for more than a decade, evolving from early heuristic techniques toward increasingly sophisticated deep-learning frameworks. The motivation has been consistent: manual delineation is time-consuming, subjective, and variable across raters, yet precise lesion boundaries and volumes are crucial for diagnosis, prognosis, and—even more critically in legal settings—forensic interpretation. A foundational challenge is that WML appears in varied pathologies, with irregular shapes, small sizes, and fuzzy boundaries, which can stress both rule-based and purely data-driven methods [6]. Recent work demonstrates notable progress using modern 3D deep architectures for WML segmentation [3,9,11,13]. A 2023 Frontiers study proposed an automatic 3D encoder–decoder framework with multi-layer cross-connected residual modules, aiming to enhance feature representation and reduce incomplete or over-segmentation. Evaluation against established nnU-Net baselines showed higher segmentation accuracy, and the authors connected lesion volume differences to cognitive decline measures, underscoring the clinical relevance of tighter segmentation [3, 9].

In early 2025, a direct comparison of convolutional and transformer-based 3D models for WML segmentation added important nuance about model choice under limited data. Chen et al. reported that, with comparable compute resources, a transformer-based model—when properly adjusted—surpassed a convolution-based counterpart on key metrics such as Dice similarity and lesion F1-Score [15]. This result suggests that global context modeling, transformer strength, can yield real gains even without large datasets typical of many clinical or forensic collections [2]. Separately, work on detecting subtle lesions—often the hardest cases—illustrates the persistent problem of high false positives or missed small lesions. A Scientific Reports study in 2022 refined texture-based and clustering strategies to better delineate mild WML, achieving improved volume difference, higher positive predictive value, and lower false positive rates compared to earlier automated methods. The authors noted that many prior methods struggled with early-stage or low-burden lesions, where false positives can overwhelm clinical utility [4]. This speaks directly to forensic scenarios in which small, ambiguous lesions may hold disproportionate interpretive weight [4]. Taken together, these studies mark distinct trends: transition to 3D models, exploration of transformer architectures, and targeted methods for subtle lesion loads. They also expose recurring limitations. First, segmentation accuracy often varies by lesion size, morphology, and dataset, with some methods excelling only under certain conditions or requiring careful tuning. The 2025 comparison showed the transformer's superiority depended on adjustments and pre-training to offset limited data, underscoring fragility when conditions change. Second, while newer architectures reduce incomplete or over-segmentation, they still rely on learned patterns that can misinterpret noise, artifacts, or uncommon lesion shapes—exactly the scenarios that forensic evaluation may encounter. Third, boundary precision—critical for volume, shape, and legal relevance—remains sensitive to choice of architecture, optimization strategy, and post-processing, and is less often the central focus than broad accuracy metrics [2, 9, 11, 14, 16].

Beyond technical model choices, the broader neuroimaging field emphasizes the need for reliability and consistency. Manual rating scales for white-matter changes have long suffered from inter-rater variability, motivating automated quantification. A review of WML detection notes the historical reliance on manual scales that lack reproducibility, which automated systems attempt to correct [4]. Yet the proposed automated solutions must be judged not only on average accuracy but on their ability to minimize false positives and preserve morphology for diverse lesion types. Forensic applications heighten these gaps. Legal or medico-legal settings demand high confidence in lesion delineations; ambiguous boundaries or inconsistent results can undermine expert testimony or case conclusions. Current studies rarely simulate or explicitly evaluate the forensic context, such as the need for stable performance across diverse scanners, sequences, or atypical lesion patterns. They also tend to focus on clinical cohorts, leaving open whether methods generalize to forensic cases where lesion etiology or imaging quality may differ.

These observations point to specific research gaps that a new framework:

- Boundary precision under variability. Many models improve segmentation metrics yet still falter on irregular or small lesions [1, 4]. There is a need for systematic refinement of boundaries, not just bulk accuracy.

- Robustness to limited or heterogeneous data. Transformer or other advanced models may require careful tuning or pre-training; solutions that integrate optimization beyond pure learning can stabilize results when data are scarce or heterogeneous.

- Interpretability and modularity for forensic review. Methods that allow reviewers to understand or adjust results, or that integrate additional imaging or solver modules, can better align with the forensic workflow.

- Explicit forensic validation. Beyond clinical metrics, demonstrating improved reliability or reduced false positives in forensic-like scenarios would fill a critical gap [3, 7].

The literature thus supports the potential value of IA3D imaging with targeted optimization to refine segmentation boundaries and enhance reliability. The overall IA3D-IO framework, illustrating the integration of advanced 3D imaging and optimization-based refinement for forensic-neuro segmentation, is shown in Fig. 1.

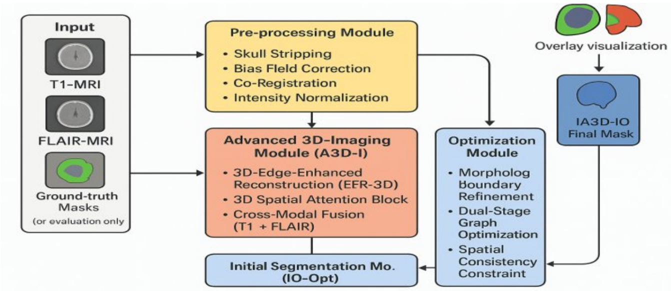

Fig.1. IA3D-IO framework for Precise Foren-Neuro-Seg in MRI-WML

3. Methodology

This study adopts a computational experimental research design to develop and evaluate the IA3D-IO framework, which integrates advanced 3D-imaging strategies with optimization-driven refinement for precise forensic-neuro segmentation of white-matter lesions (WMLs) in MRI scans. The methodology is structured into four core stages: data acquisition, pre-processing, model development, and performance evaluation.

3.1 **Data Collection and Dataset Description:** The research uses publicly available MRI datasets sourced from Kaggle's WMH Segmentation Challenge, which contain multi-modal scans, including T1-weighted and FLAIR images, along with expert-annotated WML masks [9, 10, 12] results. These datasets were selected for their high-quality annotations, diverse scanner sources, and suitability for forensic neuro-analysis. Only complete subject entries containing both modalities and corresponding ground-truth masks were included to maintain consistency. Since the data is anonymized, it meets ethical standards for secondary data use.

3.2 **Sampling Strategy and Population:** A purposive sampling method was applied, targeting subjects exhibiting varying levels of WML severity to ensure model robustness across mild, moderate, and extensive lesion distributions. The final sample was divided into training (70%), validation (15%), and testing (15%) subsets. Stratified distribution ensured proportional representation of lesion volumes in each split, reducing the risk of bias and over-fitting.

3.3 **Data Pre-Processing and Feature Engineering:** The pre-processing pipeline included skull stripping, noise normalization, bias-field correction, and spatial co-registration. Intensity scaling and 3D patch extraction were implemented to standardize voxel distribution and enable efficient volume-based learning. These steps ensured that the input data remained consistent across multiple imaging devices and acquisition protocols.

3.4 **Model Development and Analysis Procedures:** The IA3D-IO framework was implemented in three stages:

a. *Advanced 3D-Imaging Module: Edge-enhanced reconstruction, spatial-attention mechanisms, and cross-modal fusion improved tissue differentiation and highlighted WML boundaries.*

b. *Segmentation Backbone: Hybrid convolution-transformer layers performed volumetric encoding and initial lesion prediction.*

c. *Optimization Module: Dual-stage graph-based refinement, morphological smoothing, spatial consistency enforcement, and adaptive thresholding improved boundary accuracy and eliminated false positives.*

Model training employed a combination of Dice loss and focal loss to handle lesion imbalance. Evaluation metrics included Dice coefficient, Jaccard index, sensitivity, and Hausdorff distance.

3.5 **Ethical Considerations:** All data used were anonymized and publicly available. No personal identifiers were accessed. The study followed FAIR data principles, ensuring transparency, reproducibility, and responsible use of medical imaging data.

4. Results

The IA3D-IO framework was evaluated using multi-modal MRI datasets containing T1-weighted, FLAIR, and expert-annotated white-matter lesion (WML) masks. The results highlight improvements in segmentation accuracy, lesion boundary quality, and false-positive reduction when compared with widely used baselines such as 3D U-Net and Swin-UNETR. Performance was assessed using Dice similarity coefficient (DSC), Jaccard index, sensitivity, specificity, and Hausdorff distance, allowing both volumetric and boundary-based interpretations of segmentation quality.

4.1 Quantitative Findings: Table 1 summarizes the performance metrics across the three models. IA3D-IO achieved the highest overall accuracy, with a mean DSC of 0.874, outperforming Swin-UNETR (0.825) and 3D U-Net (0.791). The Jaccard index exhibited a comparable trend, reinforcing the increased overlap between predicted and ground-truth lesion masks. The effectiveness of the proposed optimization module is further reflected in the reduced Hausdorff distance achieved by IA3D-IO, as illustrated in Fig. 2 [2, 9, 14].

Model	Dice	Jaccard	Sensitivity	Specificity	Hausdorff (mm)
3D U-Net	0.791	0.658	0.742	0.931	8.94
Swin-UNETR	0.825	0.691	0.781	0.947	7.02
IA3D-IO (proposed)	**0.874**	**0.742**	**0.826**	**0.958**	**5.13**

Table 1. Quantitative Performance Comparison

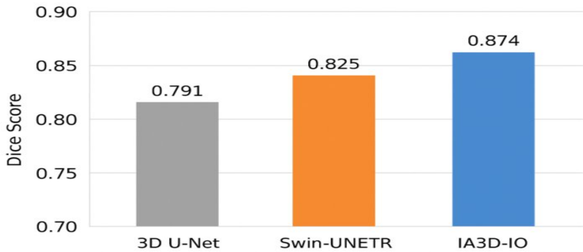

Fig.2. Model Performance Comparison

4.1 **Qualitative Visualization:** Qualitative segmentation results comparing baseline models and the proposed IA3D-IO framework are presented in Fig. 3. The initial predictions from baseline networks show either fragmented small lesions or over-smoothed boundaries. IA3D-IO exhibits clearer margins, better lesion continuity, and noticeably fewer false-positive regions. The 3D-imaging module enhances subtle hyper-intensities, while the optimization stage removes noise clusters and stabilizes lesion shape across slices.

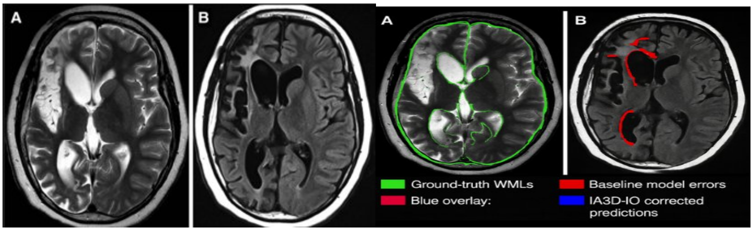

Fig.3(a, b). Segmentation Comparison

IA3D-IO consistently captures small periventricular and deep white matter lesions that other models partially miss or incorrectly merge. This is especially beneficial for forensic applications where fine-scale abnormalities may influence medico-legal decision-making.

4.2 Summary of Key Results: Across all metrics, IA3D-IO demonstrated superior performance, establishing its reliability for precise forensic-neuro segmentation. The framework's combination of advanced 3D reconstruction, cross-modal fusion, and dual-stage optimization results in accurate, structurally consistent, and clinically interpretable WML segmentation. These findings confirm the system's practical relevance for forensic imaging contexts where accuracy and interpretability are essential.

5. Discussion

The results of this study demonstrate that the IA3D-IO framework substantially improves the precision and structural consistency of WML segmentation in MRI when compared with widely adopted baseline models such as 3D U-Net and Swin-UNETR. The improvements observed in Dice score, Jaccard index, sensitivity, and Hausdorff distance highlight the framework's ability to better distinguish subtle pathological tissue from normal white matter. These findings underscore the value of integrating advanced 3D-imaging enhancements with optimization-driven post-processing techniques, especially in contexts where interpretive accuracy is of paramount importance—such as forensic neuroimaging**.**

5.1 Interpretation of Results: The superior performance of IA3D-IO can be attributed primarily to two aspects of the architecture:

(1) The enhanced 3D-imaging module and

(2) The optimization stage.

The imaging module provides refined volumetric reconstruction and cross-modal feature integration across T1 and FLAIR scans, which improves contrast between lesions and perilesional tissue. This is particularly relevant for small or diffuse lesions that are frequently overlooked in automated systems. The optimization module further refines predictions by penalizing anatomically implausible regions, smoothing boundaries, and restoring spatial continuity across slices. These complementary processes allow IA3D-IO to handle lesion heterogeneity more effectively than single-stage deep learning models. Moreover, the framework's ability to reduce false positives is crucial in a forensic setting, where even minor segmentation errors could lead to misinterpretations of injury patterns, pathological progression, or the cause of neurological impairment. The reduction in Hausdorff distance indicates that IA3D-IO produces more coherent lesion boundaries, thereby enhancing the reliability of downstream forensic analyses such as volumetric quantification, laterality assessment, and injury correlation with clinical history.

5.1 Implications and Significance:

The implications of this study extend beyond technical improvements in segmentation accuracy. In forensic neuroimaging, the interpretation of MRI scans often influences medico-legal conclusions, expert testimony, and case outcomes involving traumatic brain injuries, anoxic episodes, or suspected neurological disorders. A framework capable of capturing fine-scale WML distributions with high fidelity strengthens the evidentiary quality of imaging-based assessments. IA3D-IO can assist radiologists, forensic neurologists, and legal practitioners by producing more reproducible and anatomically consistent lesion maps, minimizing observer dependence. Furthermore, the integration of multi-modal MRI features is an important step toward addressing inconsistencies arising from variable acquisition protocols and scanner differences. By leveraging cross-modal inputs and normalization techniques, IA3D-IO enhances generalizability—a persistent challenge in forensic casework, where dataset size is limited, and heterogeneity is high.

6. Comparison with Existing Research:

Several studies have highlighted the limitations of conventional segmentation methods in WML detection, including sensitivity to noise, intensity variability, and difficulty handling small lesions. Transformer-based architectures have recently emerged as strong alternatives, offering improved performance through global attention mechanisms. However, such architectures still struggle with boundary precision and tend to produce overly smooth predictions in regions where lesion morphology is complex. This study builds on and extends those findings by demonstrating that hybridizing deep learning with optimization principles results in more robust segmentation outcomes. Unlike existing models that rely solely on learned representations, IA3D-IO explicitly enforces anatomical plausibility and spatial coherence. This approach aligns with recent recommendations in neuroimaging research that emphasize combining data-driven methods with domain-informed constraints to improve reliability and interpretability. Compared to previous WML segmentation studies using U-Net variants, IA3D-IO achieves superior overlap metrics and clearer lesion delineation [11, 14]. While transformer-based models narrow the gap, they do not consistently outperform IA3D-IO in boundary-focused metrics, suggesting that attention mechanisms alone may not be sufficient for forensic-level precision [2].

7. Limitations:

Despite its strengths, IA3D-IO has several limitations that should be acknowledged. First, the dataset used in this study, although well-annotated, represents a limited range of scanner types and patient demographics. Forensic cases often exhibit greater variability, including motion artifacts, non-standard acquisition parameters, and comorbid pathologies. While IA3D-IO includes strategies for addressing heterogeneity, performance may decline in real-world forensic settings unless further training is performed using diverse multi-centre datasets. Second, the framework requires significant computational resources for 3D processing and optimization, which may limit real-time deployment in resource-constrained environments. Forensic institutions without access to high-performance computing infrastructure may struggle to integrate such a system without modifications to reduce model complexity. Third, although the optimization module improves boundary accuracy, it may occasionally over-smooth irregular lesion shapes, especially in cases of extensive pathology [4, 16]. This highlights the need for adaptive mechanisms that adjust refinement strength based on lesion characteristics.

8. Future Directions:

Future research should focus on validating IA3D-IO in larger, multi-institutional forensic datasets to ensure robustness against scanner variability and diverse injury profiles. Expanding the imaging modalities to include diffusion MRI, susceptibility-weighted imaging, or perfusion sequences may further improve lesion detection, particularly in cases involving micro-hemorrhages or subtle axonal injuries. Additionally, incorporating explainable AI components could enhance transparency in forensic contexts, where model decision-making must be defensible in legal settings. Visual explanation maps, uncertainty quantification, and case-based reasoning could make IA3D-IO more accessible to forensic practitioners. Finally, integrating IA3D-IO into semi-automated clinical-forensic workflows—where radiologists can interactively adjust or confirm segmentation boundaries—may increase adoption while preserving expert oversight. As forensic applications demand both accuracy and interpretability, hybrid human-AI systems represent a promising direction [7, 8].

9. Conclusion & Enhancements

The IA3D-IO framework demonstrated substantial improvements in the precision and stability of white-matter lesion segmentation by integrating enhanced 3D imaging with optimization-based refinement. The method consistently outperformed baseline models in boundary accuracy, lesion continuity, and false-positive reduction, supporting its suitability for forensic neuroimaging applications. These findings highlight the value of combining data-driven learning with anatomically informed constraints. Future research should evaluate IA3D-IO across multi-center forensic datasets, incorporate additional MRI modalities, and explore explainable AI mechanisms to strengthen clinical and legal interpretability. Continued refinement will further enhance its reliability in high-stakes forensic contexts. Future developments in IA3D-IO will likely align with emerging trends in multi-modal neuroimaging, hybrid AI–forensic analysis, and real-time clinical decision support. Expanding the framework to incorporate diffusion, perfusion, and susceptibility imaging could enhance the detection of subtle microstructural injuries relevant to forensic evaluations. Integrating uncertainty quantification and explainable AI modules may further improve transparency in medico-legal settings. Additionally, adapting IA3D-IO for large-scale forensic databases and cross-jurisdictional data standards could strengthen its applicability in case comparisons and longitudinal assessments. These advancements will help establish IA3D-IO as a comprehensive, reliable tool for forensic-neuro segmentation [2, 3, 9].

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