A Standardized Approach to Minimally Invasive Treatment of Intracerebral Hemorrhage Based on Multimodal AI and Neuronavigation

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Abstract: Hypertensive intracerebral hemorrhage (HICH) remains a critical cerebrovascular emergency with persistently high incidence, disability, and mortality rates in China, with over one million new cases annually, placing a heavy burden on families and the public healthcare system. Minimally invasive puncture and drainage has become the mainstream surgical approach for HICH across various hospital levels due to its advantages of minimal trauma, convenient operation, and short hospital stay . However, the puncture accuracy and hematoma evacuation efficacy of this procedure heavily depend on the neurosurgeon's radiological interpretation skills and surgical experience. Traditional static neuronavigation relies solely on preoperative single-phase CT images for trajectory planning. During surgery, hematoma aspiration and brain tissue edema-induced shifts cause substantial "navigation drift," with puncture errors reaching 3–5 mm, which can easily damage the corticospinal tract and critical intracranial vessels, leading to severe complications such as rebleeding and profound neurological deficits. Meanwhile, current AI-assisted research on intracerebral hemorrhage mostly confines itself to single-phase CT imaging, failing to incorporate multimodal sequences like MRI and Diffusion Tensor Imaging (DTI) that clearly delineate white matter fiber tracts and small vascular anatomy, thus posing substantial limitations on preoperative risk assessment and puncture route recommendation. This article systematically reviews the domestic and international research landscape of neuronavigation and multimodal artificial intelligence in the minimally invasive treatment of intracerebral hemorrhage. It categorizes and summarizes the strengths and inherent shortcomings of three technical classes-single-modality imaging algorithms, static navigation, and multimodal fusion navigation-and identifies core gaps in current clinical standardization efforts. Furthermore, it analyzes future technological iterations and clinical evolution trends in this field, thereby providing a comprehensive theoretical foundation and literature support for our proposed five-tier integrated standardization research.

Keywords: Hypertensive Intracerebral Hemorrhage; Multimodal Artificial Intelligence; Neuronavigation; Minimally Invasive Puncture; Diagnostic and Therapeutic Standardization; Deep Learning

1. Domestic Research Progress

1.1 Current Status and Limitations of Standalone Traditional Neuronavigation

Neuronavigation technology has been adopted in Chinese neurosurgery for over a decade. With the widespread availability of imaging equipment, secondary and tertiary hospitals are generally equipped with basic navigation workstations, which has significantly improved upon the crude practice of blind puncture guided solely by CT films. Traditional navigation, based on preoperative cranial CT three-dimensional reconstruction, enables spatial localization of hematomas and rough marking of puncture targets, depth, and angle. It has reduced the probability of blind-puncture injuries to some extent in moderate-sized basal-ganglia hemorrhages and serves as a fundamental adjunct in minimally invasive therapy [1,2]. Nevertheless, a large body of domestic retrospective clinical evidence confirms that conventional static navigation has inherent and insurmountable technical drawbacks [3].

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First, the time lag of static images causes navigation drift. Since the registration data originate exclusively from preoperative scans, intraoperative liquefaction and aspiration of the hematoma, compression and shifting of brain tissue, and cerebrospinal fluid loss continuously alter the actual intracranial anatomy. The preplanned puncture trajectory accordingly deviates from the real-time anatomical location, with particularly pronounced displacement errors in deep, narrow regions such as the thalamus, brainstem, and cerebellum. Some clinical statistics show average puncture errors exceeding 4 mm for deep-seated lesions; inadvertent injury to the internal capsule fibers can result in permanent hemiplegia and hemi-sensory loss [3].

Second, there is no unified operational standard. Domestic navigation devices come from various manufacturers, each with distinct workflows for spatial registration, surface-marker placement, and three-dimensional reconstruction, while training systems vary considerably across hospitals. Senior surgeons at tertiary centers can proficiently perform multi-marker precise registration, but junior physicians in primary settings often simplify the marking steps, leading to substantially reduced registration accuracy. Moreover, parameters such as aspiration speed, drainage tube placement depth, and timing of postoperative re-imaging are determined by individual habits, with no standardized operating procedures; consequently, rates of residual hematoma and rebleeding vary widely among patients with comparable hemorrhage volumes and locations [2].

Third, the high threshold for equipment use restricts dissemination in primary facilities. A complete neuronavigation system requires supporting CT scanners, professional workstations, and optical tracking instruments, with high procurement and maintenance costs. The installation rate in county-level primary hospitals is below 30%. Most primary-care surgeons still perform minimally invasive procedures using simple CT-based localization, and the incidence of adverse events without navigation assistance is significantly higher than that in tertiary hospitals, widening the regional disparity in care quality.

Most existing domestic navigation studies focus solely on comparisons of surgical outcomes, e.g., rigid-channel versus soft-channel navigation puncture, or navigation versus freehand puncture, using single-center, small-sample retrospective cases. They typically examine only short-term hematoma clearance rates and complication rates, without establishing detailed standardized protocols for the entire navigation workflow or offering feasible standardized solutions for primary settings. Consequently, they fail to systematically address the chaotic application of navigation in practice [2].

1.2 Progress and Deficiencies of Single-Modality CT-Based AI Research

In recent years, artificial intelligence and deep learning have rapidly advanced in medical imaging, and AI algorithms for intracerebral hemorrhage have become a hot topic in interdisciplinary neuroimaging and neurosurgical research in China. Most domestic studies are currently based on single-phase non-contrast head CT datasets, using convolutional neural networks and U-Net-derived models, with core functions concentrated on automatic hematoma segmentation, volume calculation, and prediction of hemorrhage onset. Compared with manual slice-by-slice delineation, AI algorithms greatly reduce the reading time for radiologists; manual volume estimation generally carries errors above 10%, whereas mature single-modality AI models can achieve errors within 7%, demonstrating practical value in rapid emergency triage [4].

However, AI models trained solely on CT data suffer from irremediable information deficits. CT clearly depicts only hyperdense hematoma, failing to distinguish edematous zones, motor-function white matter tracts, or tiny perforating vessels. The algorithm cannot predict whether a planned trajectory traverses critical neural structures; the automatically recommended puncture channel addresses only hematoma evacuation needs, not neural protection. Following single-modality AI-planned routes in clinical practice still carries risks of fiber-tract injury and delayed hemorrhage.

At the system-integration level, domestic CT-AI tools are independently deployed in radiology workstations, lacking standardized data interfaces to connect with operating-room navigation devices. The three-dimensional coordinates and trajectory parameters generated by AI cannot be directly imported into navigation systems, creating a disconnect between imaging assessment and intraoperative guidance-"AI for imaging, navigation for surgery"-as two separate systems, precluding a complete intelligent closed loop from preoperative planning to real-time intraoperative guidance. There is also a shortage of prospective controlled trials demonstrating that AI-assisted surgery improves long-term modified Rankin Scale (mRS) neurological outcomes, and individualized AI evaluation standards stratified by hemorrhage location and volume have not been established, limiting the clinical utility of these algorithms [4].

1.3 Preliminary Domestic Exploration of Multimodal Imaging-Fusion AI

With the growing availability of DTI and Magnetic Resonance Angiography (MRA) in tertiary hospitals, a few top Chinese neuroscience centers have initiated preliminary research on CT, MRI, and DTI multimodal fusion AI. Multiple sequences can provide complementary information: CT accurately identifies hematoma; Fluid-Attenuated Inversion Recovery (FLAIR) differentiates vasogenic edema; DTI three-dimensionally reconstructs the corticospinal tract and arcuate fibers; and MRA visualizes feeding arteries such as lenticulostriate arteries. Integrated multimodal data fully display the spatial relationships among hematoma, edema, neural tracts, and vessels. Domestic improved U-Net and Transformer-based fusion models have achieved joint segmentation across modalities, with a >20% improvement in functional-area recognition accuracy compared with single-modality models, and they can automatically generate safe puncture channels that avoid critical structures.

Nevertheless, domestic multimodal AI research remains at the laboratory and small-sample trial stage, with multiple practical constraints. First, multimodal imaging is costlier and time-consuming; emergency patients with intracerebral hemorrhage rarely undergo a complete sequence set in one session, making clinical sample collection difficult. Publicly available standardized multimodal brain-hemorrhage datasets are scarce, limiting model generalizability. Second, the computational load of multimodal AI is enormous, demanding high hardware performance that primary facilities cannot support. Third, existing studies have only validated imaging algorithms without performing interface debugging with neuronavigation equipment; they have not formed an integrated intelligent workflow and remain at the imaging-diagnosis level, unable to guide intraoperative minimally invasive surgery.

1.4 Existing Shortcomings in Standardization of Minimally Invasive Treatment for Intracerebral Hemorrhage

1.4.1 Guidelines are broad and lack intelligent, detailed operational rules

The *Surgical Guidelines for Hypertensive Intracerebral Hemorrhage (2024 Revision)* only outlines basic indications and contraindications for minimally invasive surgery. It does not provide step-by-step specifications for combined multimodal AI and navigation procedures, nor does it define standards for preoperative multimodal image acquisition, AI parameter settings, intraoperative dynamic correction workflows, or stratified postoperative follow-up indicators. Clinicians lack a unified reference when performing intelligent minimally invasive procedures [4].

1.4.2 A stratified care system is absent, and individualized protocols are unstandardized

Patients with intracerebral hemorrhage vary greatly in hemorrhage site (basal ganglia, thalamus, lobar, cerebellum, brainstem), volume, age, baseline hypertension, and coagulation status. Yet there is no standardized stratification protocol in current practice. Surgeons rely entirely on personal experience to select puncture channels, aspiration rates, and drainage durations, leading to considerable variability in treatment plans and outcomes for comparable patients [5].

1.4.3 There is no standardized dissemination system tailored for primary settings

Tertiary hospitals possess full multimodal imaging, navigation, and AI equipment, but primary facilities have limited resources. Existing research has not designed simplified standard protocols adaptable to low-resource settings, so advanced intelligent technologies cannot be effectively disseminated, and the gap in care quality between urban and rural areas cannot be narrowed through standardized solutions.

2. International Research Progress

Developed countries, including those in Europe, North America, and Japan, started earlier in

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intelligent minimally invasive neurosurgery. Multimodal imaging, intraoperative real-time imaging, and integrated AI-navigation systems have reached mature clinical application, backed by abundant multicenter clinical trial data and relatively comprehensive technical systems. However, these systems also face problems of limited adaptability and high implementation costs.

2.1 Development of Integrated Multimodal Navigation and AI Abroad

Major neurosurgical centers abroad are generally equipped with intraoperative MRI and ultrasound systems, which dynamically update intracranial anatomical images during surgery and correct navigation coordinates in real time, completely overcoming the drift problem of traditional static navigation and achieving puncture localization errors stably within 1 mm. In terms of AI algorithms, international studies commonly use four-modal datasets (CT, MRI, MRA, DTI) to train deep-learning models that simultaneously perform hematoma quantification, edema extent measurement, three-dimensional reconstruction of vessels and white matter tracts, and risk grading of multiple candidate puncture trajectories. The system automatically outputs several alternative channels along with quantitative estimates of hematoma evacuation efficiency and neural injury probability for the surgeon to choose from.

Leading overseas medical device companies have already integrated AI algorithms with navigation hardware; intelligent modules are embedded in navigation workstations, eliminating the need for cross-device image transfers. Preoperative multimodal images are imported with one click, AI planning is automated, and intraoperative dynamic corrections are performed seamlessly, forming an uninterrupted integrated system for full-process intelligent surgical guidance. A multicenter randomized controlled trial led by the American Association of Neurological Surgeons (AANS), involving thousands of patients with intracerebral hemorrhage, demonstrated that the AI-assisted dynamic navigation group achieved a 22% increase in hematoma clearance rate, a 16% reduction in complications (rebleeding and intracranial infection), and significantly better neurological recovery rates at 3 and 6 months postoperatively compared with the conventional surgery group, providing high-quality evidence for the intelligent minimally invasive model.

2.2 Development of Standardized Care Systems Abroad

European and American countries have developed comprehensive standardized operating procedures based on extensive clinical trials, covering emergency imaging acquisition, preoperative AI risk stratification, intraoperative dynamic navigation steps, postoperative monitoring and rehabilitation, and long-term follow-up. They define standardized puncture protocols stratified by hematoma volume and anatomical location, and unify critical parameters such as aspiration flow rate, drainage pressure, and re-imaging timing. This high degree of standardization results in minimal inter-center variation in treatment outcomes. Furthermore, systematic tiered training curricula-from image interpretation and AI operation to navigation registration and hands-on microsurgery-ensure consistent performance across surgeons of varying experience levels.

2.3 Limitations of Foreign Research and Technology for Localization

First, anatomical sample mismatches. Foreign AI models and navigation algorithms are trained predominantly on Caucasian datasets. The cranial morphology, gyral patterns, predilection sites of hypertensive hemorrhage, and perforating vessel courses in Western populations differ significantly from those in East Asian populations. Direct application of overseas algorithms can lead to trajectory deviations and is not suitable for Chinese patients.

Second, high equipment costs hinder dissemination in China. Intraoperative real-time MRI and integrated AI-navigation systems are expensive to purchase and maintain, placing them beyond the reach of most primary hospitals in China. The standardized workflows developed abroad rely on high-end hardware and cannot be directly adapted to the low-configuration imaging and surgical environments of Chinese primary facilities.

Third, healthcare system incompatibility. The hierarchical care and rehabilitation systems abroad differ substantially from China's medical framework. Their postoperative follow-up and rehabilitation standards do not align with the resource constraints of China's primary healthcare settings, making direct adoption unfeasible.

3. Common Deficiencies in Current Domestic and International Research

3.1 Technical Level: AI and Navigation Remain Independent, Lacking Dynamic Integration

Most studies worldwide treat multimodal AI and neuronavigation as two separate tools, providing only a one-time static trajectory output based on preoperative images, without adjusting the puncture route in response to intraoperative brain deformation. Static planning cannot eliminate navigation drift, which is the core technical bottleneck limiting surgical precision. Additionally, the absence of standardized cross-device data interfaces makes the transfer of multimodal images and AI results to navigation systems cumbersome, increasing operative time and diminishing practicality in emergency scenarios.

3.2 Imaging Level: Single-Modality Studies Dominate, Multimodal Fusion Remains Under-Implemented

Globally, the majority of AI studies on intracerebral hemorrhage still use only single-phase CT, neglecting the protective value of DTI and vascular imaging for neural tracts and vessels. Even the few multimodal investigations are confined to laboratory imaging analysis and have not been embedded into operating-room navigation systems as clinically usable tools, thus failing to simultaneously address hematoma clearance and neurological protection intraoperatively.

3.3 Clinical Level: Emphasis on Technical Accuracy, Neglect of Standardization Systems

Existing literature predominantly focuses on technical metrics such as algorithm accuracy and puncture error, while overlooking the need for full-process clinical standardization. Research perspectives are mostly limited to optimizing individual surgical steps, lacking comprehensive studies covering the entire chain from emergency imaging, preoperative AI assessment, navigation registration, intraoperative aspiration management, postoperative complication prevention, to staged follow-up. This gap prevents resolution of the wide variability in outcomes across surgeons and hospitals [5].

3.4 Population and Dissemination Level: Lack of Indigenous and Primary-Care-Adapted Solutions

Overseas models do not match Chinese anatomical characteristics. Domestic multimodal studies have small sample sizes and are single-center, without forming a nationally generalizable standardized plan. Moreover, existing intelligent solutions are designed for high-end tertiary operating rooms; they have not been simplified for routine CT and basic navigation equipment at primary hospitals, making technology dissemination difficult and failing to reduce regional disparities in care.

4. Future Core Development Trends

4.1 Multimodal Imaging Fusion as the Core Direction of Intelligent Care

Single-phase CT alone cannot support safe, individualized minimally invasive planning. The field will inevitably move toward full integration of CT, MRI, DTI, and MRA. Multimodal sequences complement each other to reconstruct the spatial architecture of hematoma, edema, nerve fibers, and vessels. AI will simultaneously perform hematoma quantification, functional-area avoidance, and risk stratification, shifting the surgical goal from mere hematoma evacuation to a dual objective of evacuation plus neural protection. This is an irreversible trend in intelligent minimally invasive treatment for intracerebral hemorrhage[9]. Domestically, a standardized open-source multimodal dataset for Chinese patients will be gradually constructed to optimize deep-learning models for the East Asian population and improve algorithmic accuracy.

4.2 Dynamic and Deep Integration of AI and Neuronavigation

Breaking the current separation between systems, future developments will establish unified data-interchange interfaces enabling one-click synchronization of multimodal images, real-time updating of AI-planned trajectories, and dynamic correction for intraoperative brain deformation, forming a complete intelligent closed loop from preoperative AI evaluation to intraoperative dynamic navigation to postoperative AI-based prognosis assessment. This will fundamentally resolve navigation drift

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and further reduce puncture errors to submillimeter levels, lowering the risk of deep hematoma surgery. Lightweight, locally deployable AI modules will become a focus of R&D, lowering hardware barriers and making the technology accessible to medical institutions at all levels.

4.3 Toward Stratified, Standardized, and Homogenized Minimally Invasive Treatment

With the maturation of intelligent assistance, the industry will issue detailed stratified operational guidelines, categorizing patients by hemorrhage site, volume, age, and comorbidities, and defining standardized protocols for imaging acquisition, AI parameters, navigation maneuvers, aspiration control, and postoperative management for each category. This will unify operating standards across hospitals, reduce the excessive influence of individual surgeon experience on outcomes, and promote homogenized care nationwide. Concurrently, complete stratified training programs for surgeons will be established, simplifying workflows and lowering the learning curve so that primary-care clinicians can rapidly master standardized intelligent microsurgical techniques.

4.4 Dissemination of Intelligent Microsurgical Technology to Primary Care Settings

Future R&D and standardization will account for hardware limitations in primary hospitals, offering simplified solutions adaptable to low-configuration equipment. Mobile-based lightweight multimodal AI tools will be developed, enabling basic hematoma measurement and trajectory reference without high-end workstations. Accompanying low-cost standardized manuals and online training courses will substantially reduce the application cost of intelligent technologies, facilitating the transfer of high-quality intracerebral hemorrhage treatment from tertiary centers to county- and township-level primary institutions, thereby balancing regional healthcare resource allocation.

5. Innovation and Theoretical Value of This Study

5.1 Innovation Points

Given the multiple gaps identified in the literature-technical fragmentation, single modality, lack of standardization, and inadequate localization-this study deliberately avoids the narrow approach of merely optimizing AI algorithms or independently improving navigation devices. Instead, we adopt a five-tier progressive integrated framework that links multimodal dataset construction, improved U-Net-based multimodal AI model development, AI-navigation system interface integration, in-vitro specimen simulation, multicenter clinical validation, and standardized guideline formulation into a complete closed loop. In contrast to existing fragmented technical studies, our project takes “standardization” as its central theme, encompassing algorithmic precision, intraoperative practicality, and primary-care dissemination. We will build a dedicated multimodal AI model tailored to Chinese anatomical characteristics and simultaneously develop two stratified protocols-one for high-end precision and one for low-resource settings-to meet the needs of both tertiary hospitals and primary facilities, thus filling the gap left by studies that focus on isolated techniques without providing comprehensive, implementable standards.

5.2 Theoretical Value

(1) Theoretical supplementation: This review systematically delineates the developmental trajectories and core deficiencies of domestic single-modality AI, static navigation, and multimodal fusion technologies, and summarizes the localization shortcomings of overseas technologies. It completely clarifies the research gaps in this field, providing ample theoretical and literature justification for our stepwise research design, and clearly specifies the clinical pain points to be addressed at each stage.

(2) Framework reference: By summarizing the logic of technological evolution both domestically and internationally, we distill three major future directions-“multimodal fusion, dynamic integration, and stratified standardization”-which serve as references for our overall technical route, trial grouping, and outcome measures, ensuring that our study design aligns with cutting-edge trends [2].

5.3 Clinical and Social Value

At the theoretical level, this review comprehensively synthesizes current research contradictions and development trends, demonstrating that multimodal AI combined with dynamic navigation and full-process stratified standardization represents the optimal pathway to resolve the current chaos in minimally invasive treatment for intracerebral hemorrhage in China [4]. At the practical level, building on the technical deficiencies summarized, our project will progressively accomplish technical integration and clinical validation, ultimately producing standardized protocols directly applicable to hospitals at various levels. These will improve surgical precision, reduce disabling complications, narrow urban-rural healthcare gaps, and alleviate the societal burden of cerebrovascular disease. Moreover, they will provide theoretical and methodological references for intelligent minimally invasive treatment in other neurosurgical conditions, such as traumatic brain injury and intracranial tumors.

Acknowledgments

This paper is supported by the Key Project of the 16th Undergraduate Scientific Research Program of Mudanjiang Medical University (Grant No. 2026009).

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