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Predictive value of CT imaging features on the risk of hemorrhagic transformation after mechanical thrombectomy for acute ischemic stroke with large vessel obstruction

Linyu Zhou[1†], Hong Yu[1†], Jianbing Bai[1], Yang Wang[1], Yingqiang Zhong[1], Tao Jiang[1] and Yongqing Dai[1*]

†Linyu Zhou and Hong Yu are co-first authors, and they contributed to this work equally.

*Correspondence: Daiyongqing2306@21cn.com

[1] Department of Neurosurgery, Affiliated Hospital 3201, Xi'an Jiaotong University, No. 783, Tianhan Avenue, Hanzhong 723000, Shaanxi, China

Abstract

Objective: To investigate the predictive value of computer tomography (CT) imaging features for the risk of hemorrhagic transformation (HT) after mechanical thrombectomy for acute ischemic stroke with large vessel obstruction (AIS-LVO).

Methods: A total of 135 patients with AIS-LVO diagnosed and treated in our hospital from August 2021 to May 2023 were selected as the research subjects. Their clinical data were retrospectively analyzed. Mechanical thrombectomy was performed in all patients. The patients were divided into the HT group (n = 27) and the non-HT group (n = 108) according to whether HT occurred within 24 h after thrombectomy. CT examination was performed after mechanical thrombectomy in the two groups, and the changes in CT imaging indexes in the two groups were observed. Logistic regression was used to analyze the influencing factors and a prediction model was constructed based on the influencing factors. The receiver operating characteristic (ROC) curve was established to analyze the predictive value. Additionally, ROC curve was used to analyze the diagnostic value of serum CT imaging features.

Results: Compared with the non-HT group, the proportion of atrial fibrillation history in the HT group was significantly increased, and the National Institute of Health Stroke Scale (NIHSS) score and galectin-3 (Gal-3) level were significantly increased before thrombectomy ($P < 0.01$). Compared with the non-HT group, the proportion of exudation of contrast medium and Hyperdense Middle Cerebral Artery Sign (HMCAS) in the HT group was significantly increased, time to peak (TTP) was significantly prolonged, and cerebral blood flow (CBF) was significantly decreased ($P < 0.001$). The history of atrial fibrillation, NIHSS score before thrombectomy, Gal-3, contrast agent exudation, HMCAS, TTP and CBF were the influencing factors of postoperative HT after mechanical thrombectomy in AIS-LVO ($P < 0.05$). Based on the results of multivariate logistic regression analysis, a prediction model was established as follows: Logit (P) = −3.520 + 1.529 × history of atrial fibrillation + 0.968 × NIHSS score before thrombectomy + 0.806 × Gal-3 + 1.134 × contrast agent exudation + 2.146 × HMCAS + 0.684 × TTP—0.725 × CBF. The area under the curve (AUC) of the logistic prediction model for predicting HT after AIS-LVOLVO mechanical thrombectomy was 0.873 (95% CI 0.817–0.929) with a sensitivity of 78.75%

and a specificity of 83.33%, indicating that the prediction model had good prediction efficiency. The AUC of TTP and CBF alone in predicting HT after mechanical thrombectomy in AIS-LVO patients was 0.728 and 0.736, respectively. The AUC of combined detection was 0.783, and the combined detection had a high diagnostic value for HT after mechanical thrombectomy in AIS-LVO patients.

Conclusion: The combined detection of TTP and CBF of CT imaging features had certain diagnostic value for HT in AIS-LVO patients after mechanical thrombectomy. The logistic prediction model based on these influencing factors had a high diagnostic value for HT after mechanical thrombectomy.

Keywords: CT, Acute ischemic stroke with large vessel obstruction, Mechanical thrombolysis, Hemorrhagic transformation

Introduction

Cerebral infarction is a leading cause of death and disability worldwide. Acute ischemic stroke with large vessel obstruction (AIS-LVO) refers to a serious disease caused by the sudden occlusion of anterior circulation large blood vessels (such as internal carotid artery, middle cerebral artery, etc.), which leads to the ischemia and hypoxia of cerebral tissues, and further the necrosis of cerebral tissues. Its etiology mainly includes atherosclerosis, thrombosis, vasculitis, etc. In addition, hypertension, diabetes, hyperlipidemia and other underlying diseases can also increase the risk of this disease [1, 2]. According to statistics, cerebral infarction caused by large vessel occlusion accounts for about 30% of ischemic stroke, which can cause more than half of the patients' life dependence and death after stroke, and has a serious impact on the health and quality of life of patients [3, 4]. Mechanical thrombectomy is a treatment method that directly reaches the thrombus site through a catheter into the blood vessel, and removes the thrombus with a special thrombectomy device to restore vascular patency. Mechanical thrombectomy has the advantages of minimal trauma, rapid recovery and remarkable therapeutic effect. Mechanical thrombectomy has become the standard treatment for AIS-LVO, which can not only prolong the treatment time window, but also improve the vascular patency rate [5, 6].

However, the research has found that compared with drug therapy alone, mechanical thrombectomy is more likely to cause postoperative complications, especially hemorrhagic transformation (HT), which significantly increases the risk of death [7]. HT refers to a complication of hemorrhage in the original infarct area due to vascular recanalization or reperfusion during the treatment on the basis of cerebral infarction, which seriously affects the treatment effect and quality of life of patients [8]. Therefore, accurate prediction of HT risk is of great significance for developing individualized treatment plans and improving patient prognosis. As a common diagnostic method for acute cerebral infarction (ACI), computer tomography (CT) imaging can provide information on the location, size, and shape of the infarction. CT imaging provides an opportunity to evaluate the cerebrovascular status of patients with AIS-LVO, including tissue perfusion, collateral circulation and brain edema [9]. The study has found that CT imaging is beneficial to determine the cerebrovascular condition and evaluate the prognosis of patients with stroke [10]. However, whether CT imaging features can predict the risk of HT after mechanical thrombectomy in AIS-LVO is still unclear.

In this study, patients with AIS-LVO who were diagnosed and treated in our hospital were selected as the research subjects, and were divided into groups based on whether HT occurred within 24 h after mechanical thrombectomy. The purpose of this study was to analyze the influencing factors of HT after mechanical thrombectomy in AIS-LVO, and to determine the predictive value of CT imaging characteristics for the risk of HT after mechanical thrombectomy in AIS-LVO, so as to improve the safety of treatment and provide some reference for clinical diagnosis of HT.

Results

Clinical data analysis of patients with HT after AIS-LVO mechanical thrombectomy

In this study, the clinical data of the patients were compared and analyzed. There was no significant difference in gender, history of hypertension, history of diabetes, smoking history, proportion of thrombectomy times, age, blood pressure, lymphocytes (LY), hemoglobin (Hb), homocysteine (Hcy), creatinine (Cre) levels between HT group and non-HT group ($P>0.05$, Table 1). Compared with the non-HT group, the proportion of atrial fibrillation history in the HT group showed a significantly increased trend ($P<0.01$, Table 1), suggesting that atrial fibrillation may be an important risk factor promoting the occurrence of postoperative HT. In addition, patients in the HT group also had significantly higher National Institutes of Health in the United States score (NIHSS) before thrombectomy than those in the non-HT group ($P<0.01$, Table 1), reflecting the greater pre-stroke neurologic deficits in these patients. At the same time, the level of galectin-3 (Gal-3) in the HT group was also significantly increased ($P<0.01$, Table 1), which may

Table 1 Clinical data analysis of patients with HT after AIS-LVO mechanical thrombectomy [cases (%)], ($\bar{x}\pm s$)

Groups	HT group (n = 27)	Non-HT group (n = 108)	χ^2/t	*P*
Gender (%)			0.275	0.600
Male	17 (62.96)	62 (57.41)		
Female	10 (37.04)	46 (42.59)		
Age (year)	66.88 ± 11.35	65.36 ± 10.14	0.680	0.498
History of hypertension (%)	20 (74.07)	71 (65.74)	0.683	0.409
History of diabetes (%)	9 (33.33)	42 (38.89)	0.284	0.594
Smoking history (%)	11 (40.74)	43 (39.81)	0.008	0.930
History of atrial fibrillation (%)	13 (48.15)	23 (21.30)	7.964	0.005
Pre thrombectomy blood pressure (mmHg)				
SBP	149.85 ± 23.74	145.71 ± 26.87	0.732	0.466
DBP	85.95 ± 14.81	84.69 ± 18.03	0.336	0.738
NIHSS score before thrombectomy (score)	16.14 ± 3.53	11.36 ± 3.96	5.726	< 0.001
Thrombectomy times (times)			1.853	0.173
> 3	6 (22.22)	13 (12.04)		
≤ 3	21 (77.78)	95 (87.96)		
LY ($\times 10^9$/L)	1.04 ± 0.31	1.19 ± 0.44	1.669	0.098
Hb (g/L)	127.82 ± 20.15	125.35 ± 19.73	0.579	0.563
Hcy (μmmol/L)	16.28 ± 7.35	14.89 ± 4.69	1.215	0.226
Gal-3 (μg/L)	8.64 ± 1.65	5.41 ± 1.24	11.286	< 0.001
Cre (μmmol/L)	315.52 ± 86.85	311.30 ± 102.73	0.197	0.845

mean that the inflammatory response in vivo was more severe and further promoted the occurrence of postoperative HT.

CT image analysis of patients with HT and without HT

In order to compare the differences between the two groups more intuitively, CT images of patients with and without HT were analyzed in this study. Compared with the CT images of non-HT patients, the CT images of patients with HT showed high-density shadow, which was in sharp contrast with the surrounding normal brain tissue, showing brain tissue compression, displacement or ventricular deformation (Fig. 1A–D). These results suggested that with CT examination, hemorrhagic transformation could be detected in time to assess its severity and extent.

Analysis of CT imaging features in patients with HT after AIS-LVO mechanical thrombectomy

After understanding the differences in CT images of the patients, this article continued to explore the differences in CT imaging characteristics between the two groups. There was no significant difference in the proportion of CT types and MTT level between the HT group and the non-HT group ($P > 0.05$), which meant that from the perspective of CT imaging and MTT indicators, the two groups of patients did not show significant differences in the structure and blood flow velocity of brain tissue. However, compared with the non-HT group, the patients in the HT group had significantly increased contrast agent exudation and the proportion of hyperdense middle cerebral artery sign (HMCAS) ($P < 0.001$, Table 2), which suggested that the potential damage or increased

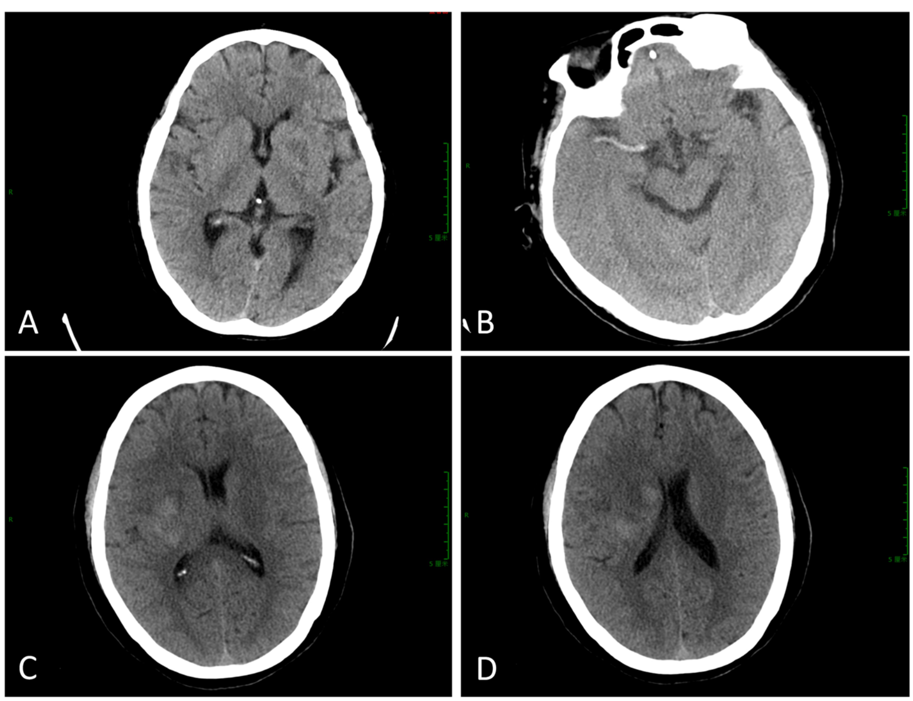

Fig. 1 CT image analysis of patients with combined HT and non-HT. **A** and **B** CT images of patients without HT; **C** and **D** CT images of patients combined with HT

Table 2 CT imaging features in patients with HT after AIS-LVO mechanical thrombectomy [cases (%)], ($\bar{x} \pm s$)

Groups	HT group (n = 27)	Non-HT group (n = 108)	χ^2/t	*P*
CT classification (%)			5.671	0.129
HI-1	9 (33.33)	29 (26.85)		
HI-2	6 (22.22)	43 (39.81)		
PH-1	7 (25.93)	12 (11.11)		
PH-2	5 (18.52)	24 (22.22)		
Contrast agent exudation (%)	22 (81.48)	22 (20.37)	36.717	< 0.001
HMCAS (%)	19 (70.37)	14 (12.96)	38.543	< 0.001
TTP (s)	20.60 ± 2.63	18.20 ± 2.64	4.228	< 0.001
MTT (s)	6.35 ± 1.29	6.82 ± 1.60	1.415	0.160
CBF (mL/100 mL·min)	49.71 ± 7.96	59.18 ± 12.04	3.875	< 0.001

Table 3 Multivariate logistic analysis of the factors contributing to the occurrence of HT after AIS-LVO mechanical thrombectomy

Indicators	β value	SE value	Wald value	P value	OR value	95% CI
History of atrial fibrillation (%)	1.529	0.476	10.318	< 0.001	4.614	1.815 ~ 11.728
Pre thrombectomy NIHSS score (score)	0.968	0.303	10.206	< 0.001	2.633	1.454 ~ 4.768
Gal-3 (μg/L)	0.806	0.284	8.054	0.002	2.239	1.283 ~ 3.908
Contrast agent exudation (%)	1.134	0.358	10.034	< 0.001	3.108	1.540 ~ 6.271
HMCAS (%)	2.146	0.533	16.211	< 0.001	8.551	3.007 ~ 24.313
TTP (s)	0.684	0.227	9.079	< 0.001	1.982	1.270 ~ 3.093
CBF (mL/100 mL·min)	−0.725	0.218	11.060	< 0.001	0.484	0.316 ~ 0.742

permeability of the vessel wall and the obstruction of carotid blood flow may be closely related to the occurrence of HT. At the same time, TTP was significantly prolonged and CBF was significantly decreased in the HT group ($P < 0.001$, Table 2). These findings not only revealed the underlying mechanism of HT, but also provided important clues and basis for clinical intervention.

Multivariate logistic analysis of the factors contributing to the occurrence of HT after AIS-LVO mechanical thrombectomy

Based on the above analysis results of clinical data and CT imaging features, logistic regression analysis was further used to determine the influencing factors. The occurrence of HT after mechanical thrombectomy for AIS-LVO was taken as the dependent variable, and the statistically significant indicators in Tables 1 and 2 were taken as the independent variables, to perform the logistic multivariate analysis. The results showed that the history of atrial fibrillation, NIHSS score before thrombectomy, Gal-3, contrast agent exudation, HMCAS, TTP and CBF were the influencing factors of HT after mechanical thrombectomy for AIS-LVO ($P < 0.01$, Table 3). A history of atrial fibrillation is an important risk factor for postoperative HT, which increases the risk of thrombosis. NIHSS score reflects the neurological deficit before stroke, and high NIHSS score increases the risk of postoperative HT. Gal-3 is an inflammatory marker, and its elevated levels promote postoperative HT. The contrast agent exudation during the operation shows vascular injury or increased permeability, which is the cause of postoperative HT. HMCAS may lead to cerebral hypoperfusion and increase the risk of postoperative HT. Prolonged time from onset to treatment increases brain tissue damage and the risk of postoperative HT, but the effect is complex. The decrease of cerebral blood flow indicates hypoperfusion and increases the risk of postoperative HT, which is related to many factors.

Establishment and validation of predictive models

Furthermore, based on the results of multivariate logistic regression analysis, a predictive model was established as follows: Logit (P) = −3.520 + 1.529 × history of atrial fibrillation + 0.968 × NIHSS score before thrombectomy + 0.806 × Gal-3 + 1.134 × contrast agent exudation + 2.146 × HMCAS + 0.684 × TTP—0.725 × CBF. The receiver operating characteristic (ROC) curve was established. The area under the curve (AUC) of the logistic prediction model for predicting HT after AIS-LVO mechanical thrombectomy was 0.873 (95% CI: 0.817–0.929) (Fig. 2), which was close to 0.9, indicating that the model had high prediction accuracy. At the same time, the sensitivity and specificity of the model were 78.75% and 83.33% (Fig. 2), which were also at a high level, further proving the reliability and effectiveness of the prediction model in practical application.

ROC curve analysis on the diagnostic value of CT imaging features for postoperative complications of HT in AIS-LVO mechanical thrombectomy

Furthermore, the diagnostic value of combined detection of cerebral blood flow (CBF) and time to peak (TTP) was analyzed. ROC curve analysis showed that the AUC of TTP alone was 0.728 (Table 4 and Fig. 3), showing a moderate predictive value. The AUC of CBF detection alone was 0.736 (Table 4 and Fig. 3), which also had moderate prediction efficiency. When the two were combined, the AUC increased to 0.783, indicating that the combined detection could more accurately predict the risk of HT after mechanical thrombectomy for AIS-LVO than single indicator (Table 4 and Fig. 3).

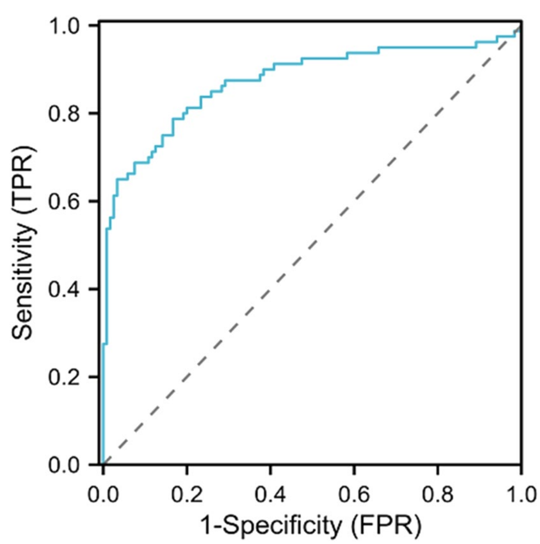

Fig. 2 ROC curve analysis of the multivariate logistic regression analysis prediction model

Table 4 Diagnostic value of CT imaging features for postoperative complications of HT in AIS-LVO mechanical thrombectomy

Indicators	AUC	Sensitivity	Specificity	Youden's index	Cut-off value	*P* value	95% CI
TTP	0.728	39.82	96.30	0.361	17.29 s	< 0.05	0.626–0.831
CBF	0.736	68.52	77.78	0.463	54.02 mL/100 mL·min	< 0.05	0.647–0.825
Combined detection	0.783	68.52	81.48	0.500	–	< 0.05	0.690–0.877

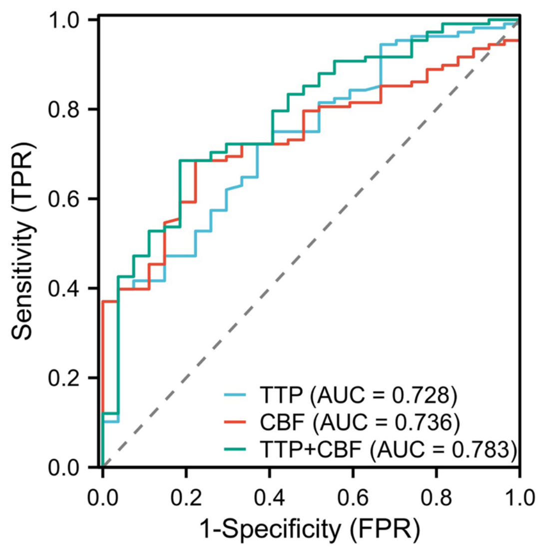

Fig. 3 ROC curve about the diagnostic value of CT imaging features for postoperative complications of HT in AIS-LVO mechanical thrombectomy

Materials and methods

Clinical materials

A total of 135 patients with AIS-LVO treated in our hospital were selected as the research objects, and their clinical data were retrospectively analyzed. The selected period was from August 2021 to May 2023. Inclusion criteria: (1) all patients complied with the diagnostic and treatment guidelines for acute cerebral infarction (ACI) [11]. All patients with concomitant HT were complied with the diagnostic and treatment guidelines for HT after ACI [12]. (2) All patients were confirmed by cranial CT angiography (CTA) or magnetic resonance angiography (MRA) as anterior circulation occlusion of large blood vessels (internal carotid artery, middle cerebral artery M1 or M2 segment). (3) All patients had complete clinical data. (4) All patients admitted to hospital within 6 h of onset. Exclusion criteria: (1) patients with intracranial hemorrhage; (2) patients with a history of cerebral hemorrhage; (3) patients with abnormal liver, kidney or heart function; (4) patients who used thrombolytic drugs for treatment before surgery. Infarction volume exceeded 70 mL; (5) patients who had experienced active bleeding or bleeding in any area within one month of participating in the study.

Research procedure

All patients underwent mechanical thrombectomy, and were divided into the HT group (n = 27) and the non-HT group (n = 108) according to whether HT occurred within 24 h after thrombectomy. The study flow is shown in Fig. 4.

CT imaging features

All patients underwent CT examination with the Ingenuity Core128 CT scanner (Philips Medical Devices Co., Ltd.) after mechanical thrombectomy. CT perfusion scans were performed on the basal ganglia and its upper layers. Contrast agent was injected and the scans were performed after a delay of 6 s. Data were collected once per second and scanned continuously for 40 s. The presence of contrast agent exudation, CBF and TTP

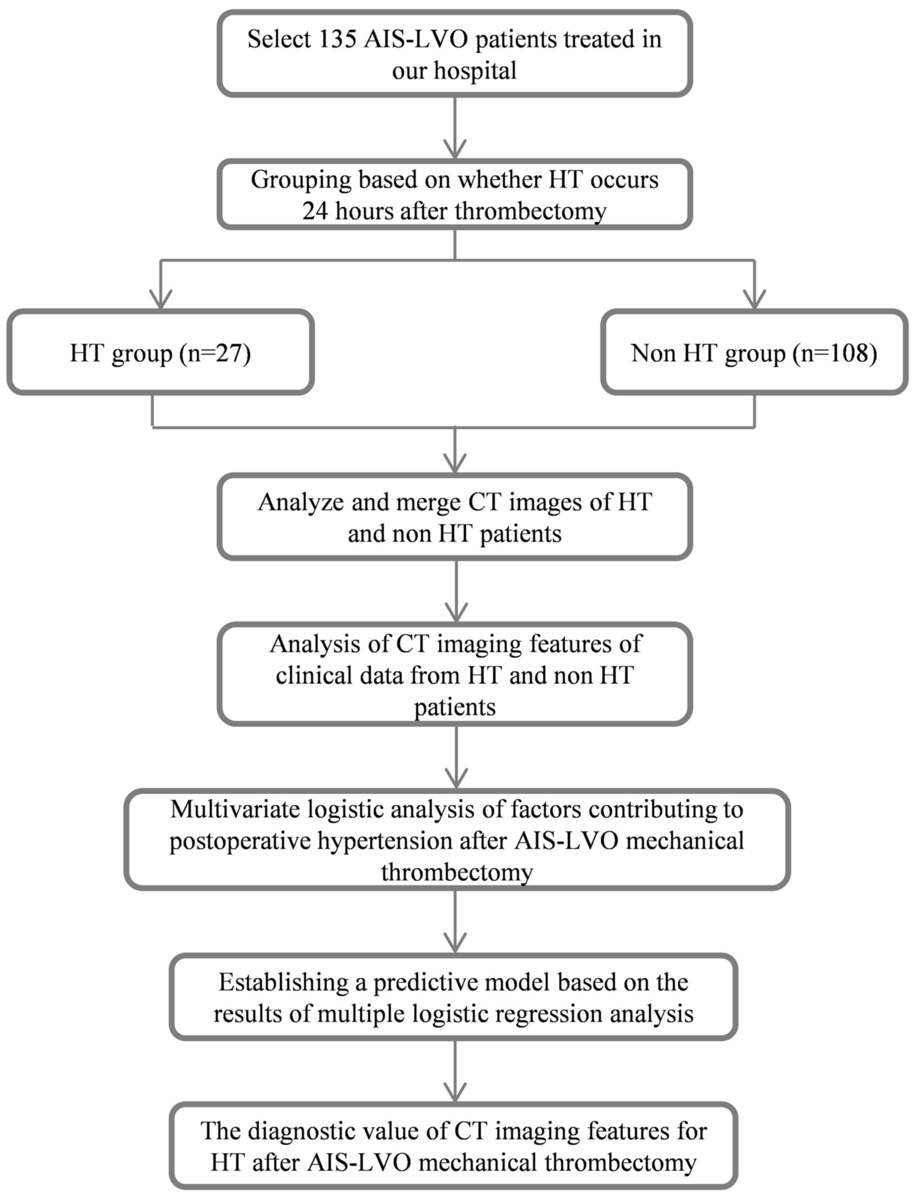

Fig. 4 The research process

were detected. CT classification [hemorrhagic cerebral infarction (HI): punctate hemorrhage at the edge of the infarct (HI-1), multi-spot fusion hemorrhage in the infarct area (HI-2)] and the formation of cerebral hematoma (PH) [hematoma not exceeding 30% infarct area (PH-1), hematoma exceeding 30% infarct area (PH-2)] were observed. The presence of HMCAS (high-density sign at the end of the intracranial segment of the carotid artery to the end of the M1 segment of the middle cerebral artery) was recorded. All CT images were evaluated by at least two experienced radiologists without knowledge of the HT outcome of the patients.

Clinical data collection

The basic clinical data in patients with HT after mechanical thrombectomy for AIS-LVO were collected, including gender, age, hypertension history, diabetes history, smoking history, atrial fibrillation history, blood pressure before thrombectomy [systolic pressure (SBP), diastolic pressure (DBP)], NIHSS score before thrombectomy, thrombectomy times (>3 times, ≤ 3 times), LY, Hb, Hcy, Cre, and Gal-3.

Statistical analysis

SPSS 24.0 statistical software was used to analyze the data. The measurement data, including the level of LY, Hb, Hcy, MTT, TTP, CBF, Cre and Gal-3, were expressed as ($\bar{x} \pm s$) and compared between the two groups by independent sample *t*-test. Enumeration data, such as gender, history of atrial fibrillation and number of thrombectomy, were expressed as [cases (%)], and compared by a Chi-square test between groups. Logistic regression model was used to analyze the influencing factors of HT after mechanical thrombectomy for AIS-LVO. The ROC curve was established to analyze the diagnostic value of serum CT imaging features for AIS-LVO with HT after mechanical thrombectomy. The AUC was [0.85, 0.95], indicating that the effect was very good. The AUC was [0.7, 0.85], indicating that the effect was moderate. The AUC was [0.5, 0.7], indicating that the effect was low. The difference in statistical results with $P < 0.05$ was statistically significant. By using multiple logistic regression, we could obtain regression coefficients corresponding to each independent variable, which reflected the degree to which the independent variable affected the log odds of the probability of occurrence of the dependent variable. Based on these coefficients, we could construct a prediction model that could be used to predict the risk of HT occurrence in new cases.

In logistic regression models, the null hypothesis is usually that there is no significant statistical correlation between the independent variables (such as CTP imaging characteristics, history of atrial fibrillation, NIHSS score before thrombectomy, etc.) and the dependent variable (namely, the occurrence of HT), and the null hypothesis that these independent variables cannot effectively predict the occurrence of HT. However, in ROC curve analysis, the null hypothesis is usually that the evaluated CT imaging features (TTP, CBF, etc.) have no significant diagnostic value for distinguishing the HT group from the non-HT group, that is, AUC is equal to 0.5, indicating that the diagnostic effect is no different from random guess. By comparing the actual statistical results with the null hypothesis, we can determine whether the independent variables have a significant effect on the occurrence of HT and whether the CT imaging features have diagnostic value.

Discussion

ACI is a common clinical cerebrovascular disease caused by cerebral ischemia and hypoxia, which has the characteristics of high incidence rate, high mortality and high disability rate. Timely restoration of blood perfusion in ischemic tissues is the main method for the treatment of ACI [13]. Mechanical thrombectomy can significantly improve the vascular recanalization rate, restore blood flow in time, and rescue ischemic penumbra tissue, which is of great significance in reducing the disability rate of patients [14]. However, HT is a common complication after mechanical thrombectomy. The mechanism may be as follows [15]: after mechanical thrombectomy, when the ischemic tissue is reperfused, the integrity of the blood–brain barrier is destroyed, leading to blood extravasation. This destruction increases vascular permeability and is easy to cause bleeding. In addition, after mechanical thrombectomy, the integrity of the blood–brain barrier is disrupted due to cerebral vascular ischemia or reperfusion injury, which increases the risk of HT. HT not only has a high rate of disability and mortality, but also significantly reduces the therapeutic effect of mechanical thrombectomy [16]. Therefore, it is of great practical significance to analyze the risk factors of HT after mechanical thrombectomy in patients with AIS-LVO to reduce the mortality and improve the therapeutic effect.

The results of this study found that the history of atrial fibrillation, NIHSS score before thrombectomy, and Gal-3 were all influencing factors for HT after mechanical thrombectomy in AIS-LVO. Atrial fibrillation is the most common arrhythmia. The study has found that AIS patients with concomitant atrial fibrillation have poor prognosis and high mortality, which may be related to the higher risk of mural thrombus detachment in patients with atrial fibrillation [17]. It is reported that concomitant atrial fibrillation can increase the risk for parenchymal hematoma-type HT by increasing reperfusion in areas of severe hypoperfusion [18]. A higher NIHSS score may predict a poor prognosis and a larger infarct area, thereby increasing the risk of HT in patients with AIS-LVO after mechanical thrombectomy [19]. Gal-3 is a galectin, which plays an important role in regulating inflammatory responses. It has been reported that when HT occurs, the level of Gal-3 is significantly increased, similar to the results of this study. Analysis of reasons may be that Gal-3 may drive oxidative stress imbalance, enhance inflammatory response, damage the blood–brain barrier, and thus increase the risk of HT [20].

After analyzing the influence of the above clinical related factors on HT, the role of imaging-related indicators on HT was also analyzed. The results of this study also found that contrast agent exudation, HMCAS, TTP, and CBF were the influencing factors of HT after mechanical thrombectomy in AIS-LVO patients, and the combined detection of TTP and CBF was beneficial to the early prediction of HT after mechanical thrombectomy in AIS-LVO patients. CT is an important tool for clinical detection of a variety of diseases. It has high-density resolution and the fault effect of eliminating overlapping structures, and can detect the occurrence of various interventional complications in time after surgery. As a dynamic interface between the peripheral circulation and the central nervous system, the blood–brain barrier controls the entry and exit of substances required for brain metabolic process and nerve function. When acute cerebral infarction occurs, the blood–brain barrier is damaged, and the contrast agent exudates with the increase of blood–brain barrier permeability until the blood–brain barrier is ruptures, causing that the contrast agent and blood exudate in large quantities [21]. HMCAS indicates a significant increase in the density of the middle cerebral artery on one or both sides. CT detection has confirmed that HMCAS is closely related to the risk of HT, and HMCAS can predict the occurrence of HT in patients with ACI [22, 23]. CT perfusion imaging, as a part of the evaluation of AIS, can be quantitatively evaluated through indicators such as TTP and CBF to distinguish between ischemic penumbra and irreversible brain tissue damage, which has certain clinical value in predicting the occurrence of HT [24]. CT imaging, as a commonly used diagnostic method, can provide information about cerebral blood perfusion. CBF is the amount of blood passing through a unit volume of brain tissue per unit time. Decreased CBF has been reported to be a relatively sensitive indicator of tissue ischemia, but there is a possibility of overestimating the final infarct size [25]. After AIS, areas of abnormal CBF usually present as ischemic penumbra, and these areas are prone to reperfusion injury during thrombolytic therapy, resulting in HT [26]. TTP refers to the time from the beginning of enhancement to the peak of enhancement, which indicates that the more serious the cerebral hemodynamic damage is [27]. After ACI, areas of abnormal TTP usually present as ischemic penumbra, and these areas are prone to reperfusion injury during thrombolytic therapy, leading to HT [28]. Based on the above findings, it can be seen that TTP and CBF can reflect the time intensity of contrast enhancement and the degree of hypoperfusion in the infarction area. The results of this this study found that when HT occurred, TTP was significantly prolonged and CBF was significantly reduced, indicating that HT was more likely to occur after mechanical thrombectomy when TTP increased and CBF decreased. This may be because when AIS-LVO occurs, the brain tissue is subjected to ischemia and hypoxia, the blood–brain barrier is damaged, permeability is increased, and local micro-vessels are compressed and narrowed. When blood perfusion is restored after thrombectomy, blood is easy to leak from the necrotic vessel. CBF and TTP are important parameters of CT perfusion imaging, which can reflect the hemodynamic status of brain tissue. Decreased CBF and prolonged TTP usually indicate the aggravation of brain tissue ischemia and increase the risk of hemorrhagic transformation after thrombolytic therapy [29, 30]. Therefore, during thrombolytic therapy for ACI, close monitoring of CBF and TTP changes is of great significance for the prevention and management of HT.

This study further explored the role of imaging-related indicators in this process. The logistic regression model constructed in this study based on the history of atrial fibrillation, NIHSS score before thrombectomy, Gal-3 and CT-related indicators was conducive to early assessment of the risk of HT after mechanical thrombectomy in AIS-LVO patients. The predictive ability of the logistic model was analyzed, and the predictive accuracy of the model was evaluated by ROC curves. The results showed that the AUC of the model was 0.873, indicating that the model had good predictive ability. Yang et al. [31] included 394 patients with intravenous thrombolysis and constructed a nomogram model for the occurrence of HT based on clinical characteristics and imaging indicators, and found that the AUC of the nomogram was 0.859 and 0.839 in the training and validation cohorts, respectively. In contrast to the study by Yang et al., although our prediction model was specific to patients undergoing mechanical thrombectomy and the predictors used were different, both emphasize the importance of combined multivariate prediction. However, only the AUC of the predictive value analysis of CT imaging features was 0.783, and the diagnostic value was moderate. Therefore, it is necessary to combine the clinical data and CT imaging features of patients in clinical practice. The logistic model constructed in this study could effectively predict the risk of HT in patients with AIS-LVO after mechanical thrombectomy, and provide strong support for clinical decision-making. By early identification of high-risk patients, clinicians can take corresponding preventive measures, such as optimizing treatment timing, adjusting antiplatelet and anticoagulant therapy regimens, and controlling the dosage of contrast media, so as to reduce the incidence of HT and improve the prognosis of patients.

In addition, this study found that TTP and CBF, as important parameters of CT perfusion imaging, both showed moderate predictive value when measured separately. The prolonged TTP may reflect the aggravation of brain tissue ischemia, resulting in damage to the blood–brain barrier and increased permeability, thereby increasing the risk of hemorrhagic transformation after thrombolytic therapy. The decrease of CBF may indicate the existence of ischemic penumbra, which is prone to reperfusion injury after restoration of blood flow, and also increases the risk of HT. When TTP and CBF are combined, the predictive value is further improved, which may be because both reflect the hemodynamic state of brain tissue and provide more comprehensive information for predicting HT. However, there was some degree of imbalance between the number of patients in the HT and non-HT groups in this study. Although we used a logistic regression model to deal with this imbalance, it is still possible to affect the predictive power of the model, especially when the model is more likely to predict the majority class (i.e., the non-HT group). Therefore, in future studies, we will consider data with a larger sample size to further validate and optimize the prediction model.

Conclusion

This study found that the history of atrial fibrillation, NIHSS score before thrombectomy, Gal-3 level, contrast medium exudation, HMCAS, prolonged TTP and decreased CBF were all important influencing factors for HT after mechanical thrombectomy in patients with AIS-LVO. By constructing a logistic prediction model, we successfully achieved an effective assessment of the risk of HT after mechanical thrombectomy. In addition, the combined detection of TTP and CBF in CT imaging features shows moderate diagnostic value for HT in patients with AIS-LVO after mechanical thrombectomy, which provides strong support for clinical decision-making. The results of this study are expected to provide new ideas for optimizing the treatment and improving the prognosis of patients with AIS-LVO.

Author contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

Funding

Not applicable.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
This study was approved by The Ethics Committee of Xi'An JiaoTong University, Affiliated Hospital 3201. Informed consent was obtained from participants for the participation in the study and all methods were carried out in accordance with relevant guidelines and regulations.

Competing interests
The authors declare no competing interests.

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References
1. Regenhardt RW, Etherton MR, Das AS, Schirmer MD, Hirsch JA, Stapleton CJ, Patel AB, Leslie-Mazwi TM, Rost NS. White matter acute infarct volume after thrombectomy for anterior circulation large vessel occlusion stroke is associated with long term outcomes. J Stroke Cerebrovasc Dis. 2021;30(3): 105567.
2. Rocha M, Desai S, Son J, Tonetti DA, Jovin T, Jadhav AP. Clinical characteristics of fast and slow progressors of infarct growth in anterior circulation large vessel occlusion stroke. J Cereb Blood Flow Metab. 2021. https://doi.org/10.1177/0271678X211015068.
3. Yu X, Pan J, Zhao X, Hou Q, Liu B. Predicting hemorrhagic transformation after thrombectomy in acute ischemic stroke: a multimodal score of the regional pial collateral. Neuroradiology. 2022;64(3):493–502.
4. Saini V, Guada L, Yavagal DR. Global epidemiology of stroke and access to acute ischemic stroke interventions. Neurology. 2021;97(2):S6–16.
5. Fan H, Li Z, Li Y, Tan Y, Mao Z, Liu Q, Zhu Y. Comparison of a direct aspiration first pass technique vs. stent retriever thrombectomy for the treatment of acute large vessel occlusion stroke in the anterior circulation with atrial fibrillation. Front Neurol. 2023;14:1138993.
6. Kuribara T, Iihoshi S, Tsukagoshi E, Teranishi A, Kinoshita Y, Sugasawa S, Kohyama S, Takahashi S, Kurita H. Thrombectomy for acute large vessel occlusion in posterior and anterior circulation: a single institutional retrospective observational study. Neuroradiology. 2022;64(3):565–74.
7. Sweid A, Hammoud B, Ramesh S, Wong D, Alexander TD, Weinberg JH, Deprince M, Dougherty J, Maamari DJ, Tjoumakaris S, Zarzour H, Gooch MR, Herial N, Romo V, Hasan DM, Rosenwasser RH, Jabbour P. Acute ischaemic stroke interventions: large vessel occlusion and beyond. Stroke Vasc Neurol. 2020;5(1):80–5.
8. Hassan AE, Kotta H, Shariff U, Preston L, Tekle W, Qureshi A. There is no association between the number of stent retriever passes and the incidence of hemorrhagic transformation for patients undergoing mechanical thrombectomy. Front Neurol. 2019;8(10):818.
9. Xin Y, Shi S, Yuan G, Miao Z, Liu Y, Gu Y. Application of CT imaging in the diagnosis of cerebral hemorrhage and cerebral infarction nerve damage. World Neurosurg. 2020;138:714–22.
10. Du J, Guo G, Du W. CT perfusion imaging parameters and serum miR-106a-5p predict short- and long-term prognosis in acute cerebral infarction patients after intravenous thrombolysis. Medicine (Baltimore). 2023;102(31): e34541.
11. Chen Y, Ye M. Risk factors and their correlation with severity of cerebral microbleed in acute large artery atherosclerotic cerebral infarction patients. Clin Neurol Neurosurg. 2022;221: 107380.
12. Kovács KB, Bencs V, Hudák L, Oláh L, Csiba L. Hemorrhagic transformation of ischemic strokes. Int J Mol Sci. 2023;24(18):14067.
13. Volbers B, Gröger R, Engelhorn T, Marsch A, Macha K, Schwab S, Dörfler A, Lang S, Kallmünzer B. Acute stroke with large vessel occlusion and minor clinical deficits: prognostic factors and therapeutic implications. Front Neurol. 2021;12: 736795.
14. Liu F, Shen H, Chen C, Bao H, Zuo L, Xu X, Yang Y, Cochrane A, Xiao Y, Li G. Mechanical thrombectomy for acute stroke due to large-vessel occlusion presenting with mild symptoms. Front Neurol. 2021;12: 739267.
15. Sun A, Cao Y, Jia Z, Zhao L, Shi H, Liu S. Analysis of influencing factors of hemorrhagic transformation in patients with large vessel occlusion stroke after mechanical thrombectomy. Am J Transl Res. 2023;15(10):6304–13.
16. Iwamoto T, Kitano T, Oyama N, Yagita Y. Predicting hemorrhagic transformation after large vessel occlusion stroke in the era of mechanical thrombectomy. PLoS ONE. 2021;16(8): e0256170.
17. Tao A, Wang Z, Chen H, Xu D, Hu H, Wu C, Zhang X, Ma X, Wang Y, Hu H, Lou M. Association of atrial fibrillation with hemorrhagic transformation after intravenous thrombolysis in patients with ischemic stroke. Zhejiang Da Xue Xue Bao Yi Xue Ban. 2019;48(3):254–9.
18. Valentino F, Gentile L, Terruso V, Mastrilli S, Aridon P, Ragonese P, Sarno C, Savettieri G, D'Amelio M. Frequency and determinants for hemorrhagic transformation of posterior cerebral stroke: posterior ischemic stroke and hemorrhagic transformation. BMC Res Notes. 2017;10(1):592.
19. Iancu A, Buleu F, Chita DS, Tutelca A, Tudor R, Brad S. Early hemorrhagic transformation after reperfusion therapy in patients with acute ischemic stroke: analysis of risk factors and predictors. Brain Sci. 2023;13(5):840.
20. Zubair AS, Sheth KN. Hemorrhagic conversion of acute ischemic stroke. Neurotherapeutics. 2023;20(3):705–11.
21. Chen L, Xu Y, Shen R, Sun J, Zhang X, Zhang Q, Wang F. Flat panel CT scanning is helpful in predicting hemorrhagic transformation in acute ischemic stroke patients undergoing endovascular thrombectomy. Biomed Res Int. 2021;2021:5527101.
22. Xu Z, Duan J, Yang B, Huang X, Liang G, Duan Y. Hyperdense middle cerebral artery sign predicts favorable outcome after decompressive craniectomy in patients with malignant middle cerebral artery infarction. Acta Radiol. 2022;63(9):1255–61.

23. Chen Y, Diana F, Mofatteh M, Zhou S, Chen J, Huang Z, Wu W, Yang Y, Zeng Z, Zhang W, Ouyang Z, Nguyen TN, Yang S, Baizabal-Carvallo JF, Liao X. Functional and technical outcomes in acute ischemic stroke patients with hyperdense middle cerebral artery sign treated with endovascular thrombectomy. Front Neurol. 2023;25(14):1150058.
24. Elsaid N, Bigliardi G, Dell'Acqua ML, Vandelli L, Ciolli L, Picchetto L, Borzì G, Ricceri R, Pentore R, Vallone S, Meletti S, Saied A. The role of automated computed topography perfusion in prediction of hemorrhagic transformation after acute ischemic stroke. Neuroradiol J. 2023;36(2):182–8.
25. Kate M, Asdaghi N, Gioia LC, Buck B, Majumdar SR, Jeerakathil T, Shuaib A, Emery D, Beaulieu C, Butcher K. Blood pressure reduction in hypertensive acute ischemic stroke patients does not affect cerebral blood flow. J Cereb Blood Flow Metab. 2019;39(9):1878–87.
26. Feng L, Yu M, Zheng M, Huang W, Yao F, Qiu C, Lin R, Zhou Y, Wu H, Cao G, Kong D, Yang Y, Xu H. Low blood flow ratio is associated with hemorrhagic transformation secondary to mechanical thrombectomy in patients with acute ischemic stroke. J Neuroradiol. 2024;51(4): 101192.
27. Shinoyama M, Nakagawara J, Yoneda H, Suzuki M, Ono H, Kunitsugu I, Kamiyama K, Osato T, Nakamura H. Initial 'TTP Map-Defect' of computed tomography perfusion as a predictor of hemorrhagic transformation of acute ischemic stroke. Cerebrovasc Dis Extra. 2013;3(1):14–25.
28. Duan Y, Yao J, Jiang Y, Sun W, Li F. A retrospective study of non-equidistant interstitial brain CT perfusion scanning and prediction of time to peak. Heliyon. 2024;10(2): e24758.
29. Wu D, Yin L, Zhang Y, Lin Y, Deng W, Zheng C, Liu H, Jiang F, Lan S, Wu Q, Li H, Tang J. Evaluation of microcirculation in asymptomatic cerebral infarction with multi-parameter imaging of spectral CT. Brain Res Bull. 2023;15(203): 110775.
30. Wu C, Jiang B, Sun L, Hu T, Zhang Z, Lu X. A subtle connection between crossed cerebellar diaschisis and supratentorial collateral circulation in subacute and chronic ischemic stroke. J Stroke Cerebrovasc Dis. 2022;31(12): 106856.
31. Yang M, Zhong W, Zou W, Peng J, Tang X. A novel nomogram to predict hemorrhagic transformation in ischemic stroke patients after intravenous thrombolysis. Front Neurol. 2022;8(13): 913442.

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