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Research article

Automatic segmentation of hemispheric CSF on MRI using deep learning: Quantifying cerebral edema following large hemispheric infarction

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ABSTRACT

Background and objective: Cerebral edema (CED) is a serious complication of acute ischemic stroke (AIS), especially in patients with large hemispheric infarction (LHI). Herein, a deep learning-based approach is implemented to extract CSF from T2-Weighted Imaging (T2WI) and evaluate the relationship between quantified cerebrospinal fluid and outcomes.

Methods: Patients with acute LHI who underwent magnetic resonance imaging (MRI) were included. We used a deep learning algorithm to segment the CSF from T2WI. The hemispheric CSF ratio was calculated to evaluate its relationship with the degree of brain edema and prognosis in patients with LHI.

Results: For the 93 included patients, the left and right cerebrospinal fluid regions were automatically extracted with a mean Dice similarity coefficient of 0.830. Receiver operating characteristic analysis indicated that hemispheric CSF ratio was an accurate marker for qualitative severe cerebral edema (area under receiver-operating-characteristic curve 0.867 [95% CI, 0.781–0.929]). Multivariate logistic regression analysis of functional prognosis showed that previous stroke (OR = 5.229, 95% CI 1.013–26.984), ASPECT≤6 (OR = 13.208, 95% CI 1.136–153.540) and low hemispheric CSF ratio (OR = 0.966, 95% CI 0.937–0.997) were significantly associated with higher chances for unfavorable functional outcome in patients with LHI.

Conclusions: Automated assessment of CSF volume provides an objective biomarker of cerebral edema that can be leveraged to quantify the degree of cerebral edema and confirm its predictive effect on outcomes after LHI.

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1. Introduction

Large hemispheric infarction (LHI) comprises only less than 10% of all ischemic strokes but has a high mortality due to malignant cerebral edema within 48–72 h of symptom onset, characterized by a midline shift (MLS) on imaging and formation of the life-threatening herniations [1–8]. Stroke researchers evaluate the degree of cerebral edema currently based on a qualitative assessment of sulcal effacement or ventricular compression according to the radiological appearance [9–11]. Based on the SITS-MOST (Safe Implementation of Thrombolysis in Stroke-Monitoring Study) protocol [9], the most widely accepted and commonly used classification assessment for cerebral edema is focal edema comprising <1/3 of the hemisphere (CED-1), focal edema comprising >1/3 of the hemisphere (CED-2), or midline shift (CED-3). However, this qualitative evaluation tool is limited to subjective classification rather than quantifying the entire spectrum of cerebral edema. Furthermore, as cerebral edema may affect these patients in varying degrees after LHI, quantifying this phenomenon would greatly facilitate research in this area.

Displacement of CSF from the sulci, cisterns, and ventricles of the affected hemisphere is the initial compensatory response to cerebral edema after LHI [12]. Once decompensation occurs, midline shift and neurological deterioration will quickly follow. Therefore, CSF volume could serve as a quantitative surrogate of edema severity after cerebral infarction. Recently, Dhar et al. applied a U-Net architecture-based algorithm to quantitatively segment CSF in patients with ischemic stroke and demonstrated that reduction in CSF volume that is measured from baseline to 24 h, using computerized tomography (CT), provides a quantitative biomarker for the degree of brain swelling [12]. However, this study did not consider that the total volume of CSF may be affected by age; younger patients tend to have lower CSF volume regardless of the actual degree of edema. Moreover, accurate measurement of CSF volume can be achieved with magnetic resonance imaging (MRI) rather than with cranial CT. In the present study, we propose that the hemispheric CSF ratio (CSF volume of ischemic ipsilateral hemisphere divided by CSF volume of contralateral hemisphere) may provide a promising imaging biomarker of cerebral edema after LHI, which is performed by a cascade ResU-Net on MRI and associated with clinical outcome.

2. Methods

2.1. Patient selection

We prospectively analyzed the data of patients with acute LHI admitted between January 2020 and October 2022 at the Second Hospital of Hebei Medical University, a Tertiary Care Center. The inclusion criteria were as follows: (1) adult patients (≥18 years); (2) LHI confirmed by diffusion-weighted imaging (DWI) or computed tomography (CT), affecting more than two-thirds of the middle cerebral artery (MCA) territory with or without anterior cerebral artery (ACA) involvement; and (3) acquired T2-Weighted imaging (T2WI), magnetic resonance angiography (MRA), diffusion-weighted imaging (DWI), and susceptibility-weighted imaging (SWI) within the 14 days of stroke symptom onset. Subjects were excluded from this study if they had: (1) AIS of the posterior circulation, (2) AIS of the bilateral cerebral hemispheres, (3) malignant tumor, and (4) severe hepatic and renal dysfunction. Baseline characteristics were collected, including (1) demographic data such as age, sex, and body mass index (BMI); (2) medical history including hypertension, diabetes mellitus, atrial fibrillation, prior stroke, and smoking status; (3) neurological scores regarding stroke severity and functional outcome (NIHSS on admission; DWI-ASPECTS; mRS at 90 days); (4) radiological appearance on SWI (cortical vessel sign, CVS; brush sign; hemorrhagic transformation, HT) and MRA (occluded vessels); and (5) the utilization of intravenous thrombolytic therapy. Poor outcomes were defined as an mRS score of >3 at 90 days. The CVS was categorized using a previously published scheme [13]: prominent - there were more and/or larger veins with a greater signal loss in the affected hemisphere than in the contralateral hemisphere; less - fewer veins in the cortex of the ischemic territory in the affected hemisphere were present compared to those in the contralateral hemisphere; equal - there was no significant difference in the appearance of veins in the bilateral cerebral hemisphere. The brush sign (BS) was defined as enlargement and hypointensity of the deep medullary veins on SWI described in patients with

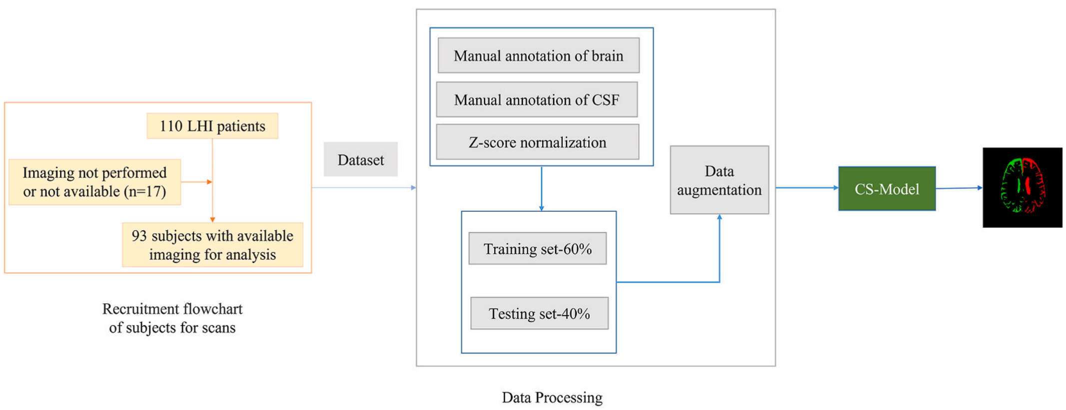

Fig. 1. Flow chart illustrating patient selection and data processing.

ischemic stroke, moyamoya disease, or Sturge-Weber syndrome [14,15].

2.2. Imaging analysis

2.2.1. Imaging assessment of cerebral edema

Each available MRI was evaluated for qualitative CED using established criteria. Edema severity was classified as: without midline shift (CED-2) and with midline shift (CED-3) due to the extent of LHI in over one-third of the hemisphere.

2.2.2. Imaging Preprocessing

The images were acquired at 1.5-T or 3-T with slice thicknesses between 3 and 5 mm and 16 to 24 slices per scan, generating a total of 1709 slices of T2WI from 93 LHI patients, who were divided into training and testing sets at a ratio of 6:4 (Fig. 1). Brain and CSF segmentation was performed on 1709 slices by using a cascade model based on the U-Net and ResNet architecture. CSF regions (sulci, lateral ventricles, third ventricle, perimesencephalic, and suprasellar cisterns) and bilateral brain tissue were manually outlined on T2WI that showed a better characterization of the border of the CSF in ventricles and sulci by two experienced radiologists who were blinded to the clinical information using 3D Slicer software. Next, Digital Imaging and Communications in Medicine (DICOM) files were converted into NPZ format.

2.3. Deep learning model: CS-Net

We proposed a cascade deep learning model named CS-Net (Cascade ResU-Net), which consists of 2 CNN models and morphology operation. The main architecture of the network is shown in Fig. 2. The first block is a U-Net model with Residual Block for the brain segmentation task [16]. After the last layer of the first block, a 1*1 convolution was employed to project the multichannel feature maps into 3 channel to predict whether the probability value of each pixel is left brain, right brain or background.

Although the segmentation results of brain part were relatively accurate, there are still some small holes in the left or right brain, and some small area was recognized as the part of brain. Therefore, the morphology operation was added to the CS-Net to remove small blobs and fill the holes (Fig. 3 a-d). Afterwards, the left and right brain was extracted. In addition, the N4 bias filed correction was used to corrupt the brain images before the CSF segmentation. The last block of the CS-Net was a modified ResU-Net network, which introduced in attention mechanism. The input data included brain image.as well as brain mask. The brain mask was multiplied with the last group layer feature map to play an attention mask role, which can prompt our model will only pay attention at the target region of interest area and discard the irrelevant noisy background [17]. In the connection path of the encoding and decoding, an attention gate was added to suppress irrelevant regions and highlight salient features [18].

2.4. Calculation of hemispheric CSF ratio

CSF volumes in the sulci, ventricles, cisterns, and bilateral brain were automatically segmented from each T2WI using CS-Net, a deep learning-based method, resulting in a hemispheric CSF ratio: CSF volume of ischemic ipsilateral hemisphere divided by CSF volume of contralateral hemisphere. The automatic segmentation processing steps are as follows:1) segmentation of the left and right brain area, 2) segmentation of the total CSF, and 3) identification of CSF volume of the left and right hemispheres based on the results of the first two steps above.

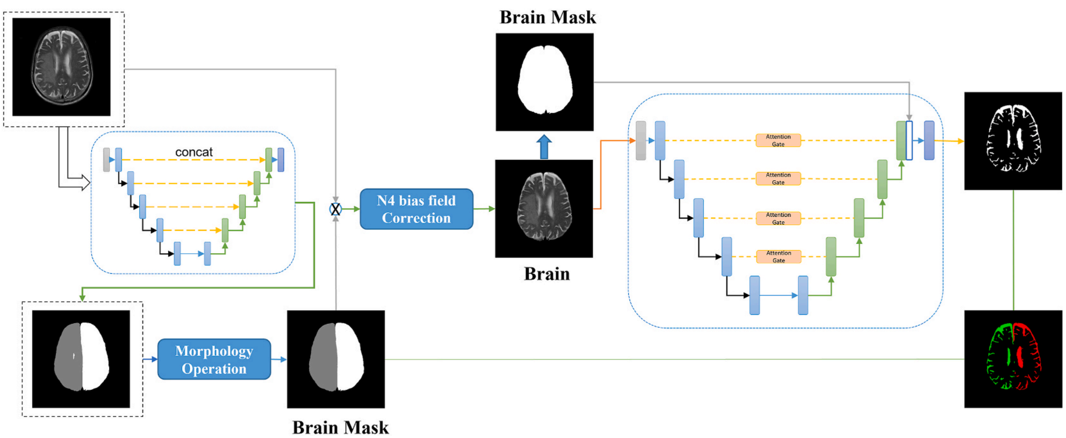

Fig. 2. The architecture of the CS-Net (Cascade ResU-Net for CSF segmentation) .

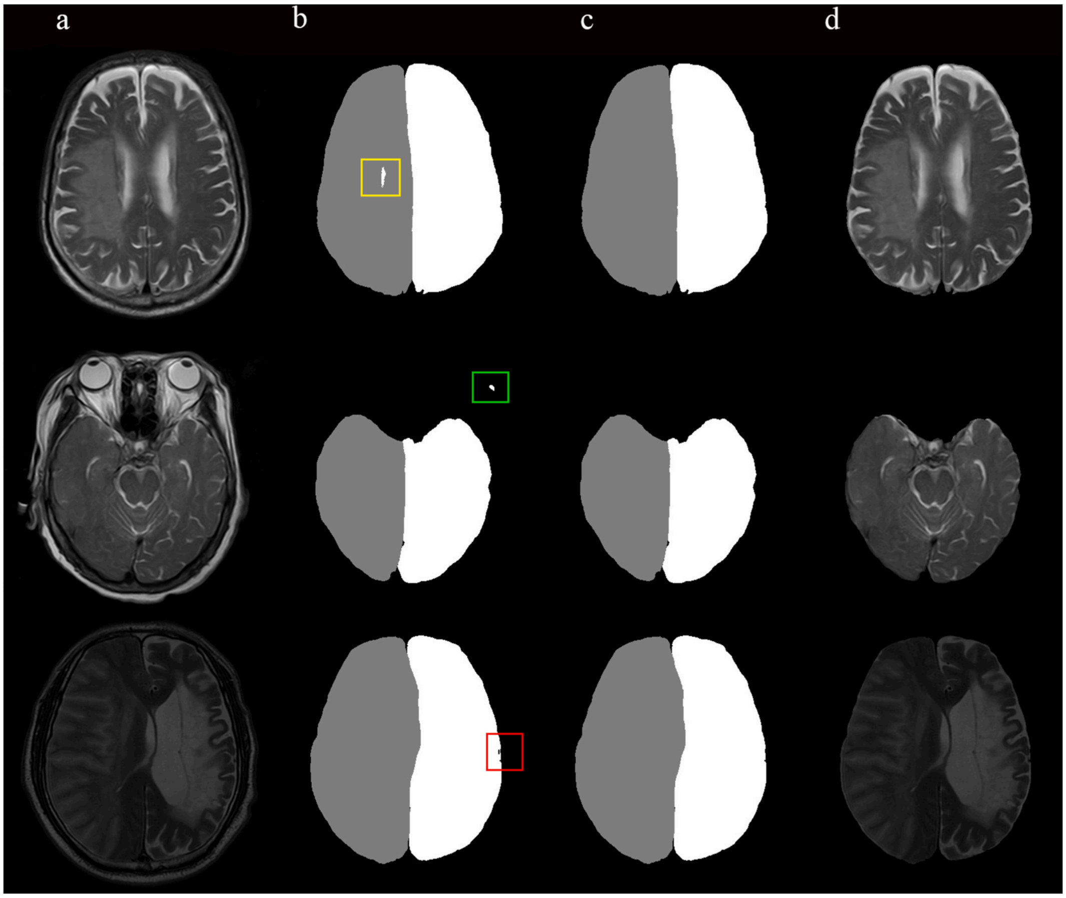

Fig. 3. Results of automated brain segmentation.
a: rawT2 WI; b: examples of automatic brain segmentation with CS-Net; c: morphology operation; d: extracted brain image. Yellow box respected the blob relative to the right brain and the hole relative to the left brain. Green box corresponded to the hole and red box corresponded to the blob. Small blobs were removed and small hole were filled after morphology operation, as shown in the c and finally displayed the extracted brain image as shown in d. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.5. Performance evaluation

The accuracy of automation with manual CSF was assessed using the Dice similarity coefficient (DSC) and correlation. Additionally, DSC reflects the extent of spatial overlap between the prediction and ground truth, ranging from 0 to 1, with higher numbers representing a more significant overlap, as shown in Equation (1):

$$Dice\ Coeff = \frac{2|GT \cap Pred|}{(|GT| + |Pred|)} \tag{1}$$

Ground truth (GT): indicates images were manually marked by experts. Prediction (Pred): represents the predictive value automatically segmented by the model. | GT | and | pred | represent the numbers of pixels for the ground truth and prediction, respectively. | GT ∩ Pred | reflects the number of pixel overlaps between truth and prediction.

2.6. Parameters setting

CS-Net was designed using PyTorch 1.18. There were a total of 100 epochs, with a batch size of 4. The Adam optimizer was used to optimize all trainable parameters. A step learning rate schedule was used with an initial learning rate of 0.001, which was dynamically reduced during the training. The Dice loss (1-Dice score) was used as a loss function in the training process. The training process was performed on a Ubuntu 20.04 workstation with an Nvidia RTX 3060 GPU (16 GB memory, Intel i5-11400F CPU @ 2.60 GHz, 12 GB GPU memory).

2.7. Statistical analyses

Statistical analyses were performed using IBM SPSS version 22. Clinical variables are presented as mean ± *SD* or median with the interquartile range depending on the distribution of the variables. To investigate group differences, continuous variables were compared using the Student's *t*-test, Mann-Whitney *U* test, or one-way analysis of variance (ANOVA), and categorical variables were compared using the $\chi 2$ test or Fisher's exact test. Correlations between age and total CSF volumes were calculated using Pearson correlation. Spearman correlation analysis was used to evaluate the correlation between the hemispheric CSF ratio calculated by automatic segmentation and manual measurements (ground truth). Receiver operating characteristic (ROC) curve analysis was used to evaluate hemispheric CSF ratio as a biomarker for the degree of cerebral edema. We employed logistic regression analysis to examine the association of hemispheric CSF ratio with clinical outcomes, cortical veins, hemorrhagic transformation, ASPECTS and total CSF volume. Results were reported as odds ratios (OR) and 95% CI. Two-sided $P < 0.05$ were considered statistically significant.

3. Result

3.1. Clinical characteristics

Among the 110 original subjects with LHI, 16 had no T2WI and one had a T2WI that was not of sufficient quality to interpret. After the exclusion of ineligible scans, 93 LHI patients were included in the analysis (Fig. 1). Of these, 33 (35.5%) developed midline shift (MLS) with severe CED grade (CED-3), while 60 (64.5%) did not. The characteristics of the patients in relation to qualitative CED are listed in Table 1. Lower ASPECTS was more likely to be associated with MLS. In addition, the proportion of patients with worse 90-day mRS scores was higher in the MLS group.

3.2. Radiographic characteristics for cerebral edema

We obtained the automated CSF volume of the left and right hemispheres on 1709 slices from a subset of 93 LHI T2WI at a median of 4 days after stroke onset (IQR 3–6 day) (Fig. 4 a-c). The accuracy of automated segmentation of CSF volume of the left and right hemispheres was high, with mean DSC of 0.830. The correlation between manually and automatically measured hemispheric CSF ratio was 0.976 ($P < 0.0001$). Considering younger patients with LHI are likely to have lower sulcal volumes, the impact of age on total CSF volume was evaluated. Our results showed that age was positively correlated with the total CSF volume ($r = 0.34$; $P = 0.001$). With age divided into quartiles, patients aged 20–39 years were more likely to have lower total CSF volume compared with patients aged 60–79 years (150.3 ± 43.8 ml vs 228.8 ± 70.0 ml, $P = 0.014$) and 80–99 years (150.3 ± 43.8 ml vs 262.2 ± 50.2 ml, $P = 0.021$) (Fig. 5a).

Table 1
Clinical characteristics and radiographic measurements in LHI patients with and without midline shift.

Characteristics	Without Midline Shift (n = 60)	With Midline Shift (n = 33)	*P* value
Age, years, n (%)			0.584
<60	29 (48.3)	14 (42.4)	
≥60	31 (51.7)	19 (57.6)	
Male, n (%)	44 (73.3)	21 (63.6)	0.329
Admission NIHSS, median (IQR)	15 (6.8)	16 (11.0)	0.103
BMI, kg/m^2, median (IQR)	24.9 (4.3)	26.0 (5.1)	0.275
Thrombolytic therapy, n (%)	14 (23.3)	12 (36.4)	0.180
Medical history, n (%)			
Hypertension	42 (70.0)	24 (72.7)	0.782
Diabetes mellitus	14 (23.3)	12 (36.4)	0.180
Atrial fibrillation	8 (13.3)	7 (21.2)	0.323
Previous stroke	15 (25.0)	12 (36.4)	0.248
Imaging findings			
Brush sing n (%)	15 (25.0)	12 (36.4)	0.248
CVS, n (%)			0.297
prominent	12 (20.0)	5 (15.2)	
less	38 (63.3)	26 (78.8)	
equal	10 (16.7)	2 (6.1)	
Occluded vessels, n (%)			0.518
ICA	5 (8.3)	3 (9.1)	
MCA	27 (45.0)	10 (30.3)	
ICA + MCA	18 (30.0)	14 (42.4)	
None	10 (16.7)	6 (18.2)	
Hemorrhagic transformation, n (%)	23 (38.3)	15 (45.5)	0.504
DWI ASPECTS, median (IQR)	5 (3)	3 (3)	<0.0001****
Follow-up			
mRS>3 at 90d, n (%)	32 (53.3)	25 (75.8)	0.034*

ASPECTS, Alberta Stroke Program Early CT Score; BMI, body mass index; CVS, cortical vessel signs; ICA, internal carotid artery; IQR, interquartile range; MCA, middle cerebral artery; mRS, modified Rankin Scale; NIHSS, National Institutes of Health Stroke Scale. *$P < 0.05$, ****$P < 0.0001$.

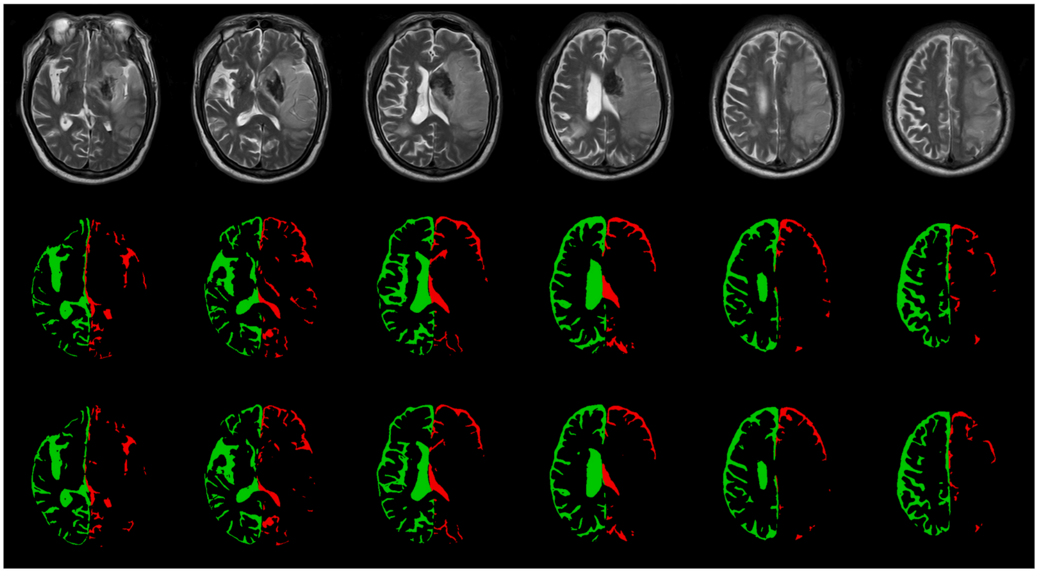

Fig. 4. Example of automated CSF segmentation and calculation of hemispheric CSF ratio on T2 WI after large hemispheric infarction. A patient with a left large hemispheric infarction with midline shift on (a) rawT2 WI, whose CSF in the two hemispheres were manually outlined (b) and automatically segmented (c). CSF volumes in the left hemisphere and right hemisphere were 75.2 ml and 176.4 ml, respectively, with a hemispheric CSF ratio of 0.43.

Hemispheric CSF ratio was used to assess edema severity and eliminate the effect of age on total CSF volume.

Patients with MLS had significantly lower total CSF volume (189.9 ± 70.0 ml vs 233.8 ± 63.0 ml, $p = 0.003$) and lower hemispheric CSF ratio (0.46 vs 0.76, $P < 0.0001$) than those without MLS (Fig. 5b and c). The hemispheric CSF ratio was significantly correlated with midline shift ($r = -0.628$; $P < 0.0001$). ROC analysis indicated that hemispheric CSF ratio was an accurate marker for MLS (AUC = 0.867 [95% CI, 0.781–0.929]; see Fig. 5d). The hemispheric CSF ratio threshold of less than or equal to 0.688 within 14 days provided 93.9% sensitivity and 70.0% specificity in diagnosing severe cerebral edema (CED-3). Using this threshold, 49 (52.7%) of LHI patients would be categorized as CED-3 based on low hemispheric CSF ratio. Variables associated with low hemispheric CSF ratio are shown in Table I in the Data Supplement. DWI ASPECT and total CSF volume were independent factors associated with severe edema, as defined by low hemispheric CSF ratio (the results of multivariable model in Table II in the Data Supplement).

3.3. Prognostic impact of hemispheric CSF ratio on outcome

Out of 93 patients with LHI, 57 (61.3 %) had a poor functional outcome at 90 days. In the univariate analysis, poor outcomes were associated with diabetes mellitus, atrial fibrillation, previous stroke, hemorrhagic transformation, higher admission NIHSS score, lower ASPECTS and hemispheric CSF ratio (Table 2). The multivariable model (Table 3) found that low hemispheric CSF ratio, along with previous stroke and ASPECT≤6, were associated with poor outcomes; for each one percent decrease in hemispheric CSF ratio, the odds for poor outcome increased by 3.4% (OR = 0.966; 95% CI, 0.937–0.997; $P = 0.029$).

4. Discussion

The key findings of our study included the following: (1) hemispheric CSF ratio can be automatically and accurately measured by a deep learning algorithm in a cohort of patients with LHI; (2) a hemispheric CSF ratio cutoff ≤ 0.688 accurately identifies CED-3 after LHI; (3) hemispheric CSF ratio was independent predictor of poor outcome in patients with LHI. These results suggest that the hemispheric CSF ratio obtained by automatic quantification of CSF may provide a quantifiable and reliable biomarker for severity of cerebral edema after LHI.

Cerebral edema is a serious complication of acute ischemic stroke that leads to increased intracranial pressure and tissue displacement, resulting in death in 5% of patients within 2–5 days after stroke onset [19–21]. Currently, there is little evidence for the prevention and treatment of malignant cerebral edema, except for decompressive hemicraniectomy. Therefore, rapid and accurate measurement of the degree of cerebral edema is beneficial for improving the treatment and prognosis of high-risk patients (i.e., those with LHI).

Unlike infarcts or mass, CSF is distributed throughout the brain, which makes the process of directly segmenting the right and left sides of the CSF difficult to achieve. In this study, we propose a cascade deep learning model based on the original U-Net and introduced a residual block and attention mechanism into the automated algorithm for the quantification of CED to enhance feature reuse and suppress irrelevant regions and highlight salient features, producing a satisfactory result with a high mean Dice similarity

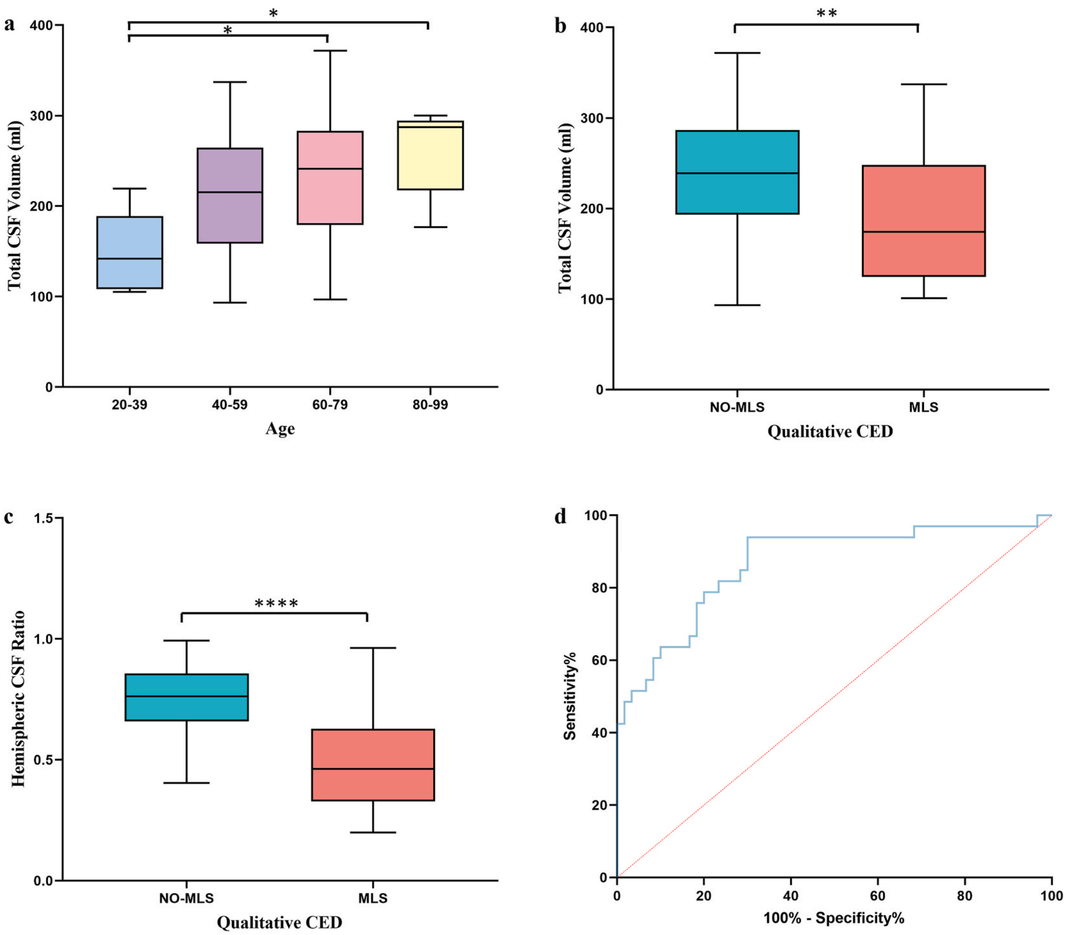

Fig. 5. Relationships of total CSF volume to age and qualitative CED, hemispheric CSF ratio to qualitative CED.
a: The total CSF volume in young subjects with LHI is lower than those in old. b: The total CSF volume is significantly lower in patients with the midline shift. c: Patients with MLS had significantly lower hemispheric CSF ratio than those without MLS. d: Receiver operating characteristic curve for the assessment of edema severity using hemispheric CSF ratio. AUC: area under receiver operating characteristic curve; CED: cerebral edema; MLS: midline shift; ROC: receiver operating characteristic. $^{*}P < 0.05$, $^{**}P < 0.01$, $^{****}P < 0.0001$.

coefficient for CSF segmentation comparing manual to an automated algorithm. Moreover, we found that the total CSF volume in young patients (20–39 years) was significantly lower than that in older patients (60–79 years and 80–99 years), which may be associated with age-related brain atrophy, but this explanation cannot be confirmed due to the absence of baseline CSF measurement. Jane Y. Yuan et al. [22] suggested that younger patients with subarachnoid hemorrhage have less preexisting CSF reserve, which provides greater insights into the underlying mechanisms of our findings. Therefore, hemispheric CSF ratio (CSF volume of ischemic ipsilateral hemisphere divided by CSF volume of contralateral hemisphere) was calculated in this study to eliminate the effect of age on CSF volume.

Midline shift, which is associated with clinical deterioration, has been used as an indicator of the severity of cerebral edema [23]. Previous study has shown that global ΔCSF (reduction in CSF volume between baseline and follow-up computed tomography) is a promising early biomarker for the development of midline shift [12]. An advantage of the hemispheric CSF ratio over ΔCSF is that it can be assessed on a single MRI, without comparison to baseline imaging. We demonstrated that the hemispheric CSF ratio was significantly lower in patients with midline shift. With hemispheric CSF ratio, we may be able to directly quantify edema and capture a broader spectrum of LHI patients than qualitative grading of CED. Low hemispheric CSF ratio was found in 52.7% of subjects, while midline shift accounted for only 35.5% of all LHI patients. Therefore, hemispheric CSF ratio has the potential to be a reliable surrogate indicator of edema severity after LHI.

In this study, we investigated the relationship between cerebral edema assessed by the hemispheric CSF ratio and clinical outcomes in patients with LHI. Our findings suggest that hemispheric CSF ratio is an independent predictor of poor functional outcomes after LHI, with a hemispheric CSF ratio threshold of ≤ 0.688 indicating the greatest sensitivity and specificity for predicting poor outcomes, providing evidence for an association between brain edema and unfavorable neurological outcomes in LHI. A prior study has found that swelling and infarct growth volumes on DWI were associated with worse outcomes in non-lacunar ischemic stroke populations, which was consistent with our results [24].

Table 2
Characteristics associated with 90-day functional outcome in patients with LHI.

Characteristics	Good outcome (n = 36)	Poor outcome (n = 57)	*P* value
Age, years, n (%)			0.152
<60	20 (55.6)	23 (40.4)	
≥60	16 (44.4)	34 (59.6)	
Male, n (%)	26 (72.2)	39 (68.4)	0.697
Admission NIHSS, median (IQR)	12 (6.8)	16 (9)	<0.0001****
BMI, kg/m^2, mean ± SD	25.9 ± 4.0	25.1 ± 4.1	0.387
Thrombolytic therapy, n (%)	9 (25.0)	17 (29.8)	0.614
Medical history, n (%)			
Hypertension	25 (69.4)	41 (71.9)	0.797
Diabetes mellitus	5 (13.9)	21 (36.8)	0.016*
Atrial fibrillation	2 (5.6)	13 (22.8)	0.028*
Previous stroke	4 (11.1)	23 (40.4)	0.002**
Imaging findings			
Brush sing n (%)	10 (27.8)	17 (29.8)	0.832
CVS, n (%)			0.685
prominent	8 (22.2)	9 (15.8)	
less	23 (63.9)	41 (71.9)	
equal	5 (13.9)	7 (12.3)	
Occluded vessels, n (%)			0.409
ICA	5 (13.9)	3 (5.3)	
MCA	14 (38.9)	23 (40.4)	
ICA + MCA	10 (27.8)	22 (38.6)	
None	7 (19.4)	9 (15.8)	
DWI ASPECTS, median (IQR)	5 (2)	3 (2.5)	<0.0001****
Hemorrhagic transformation, n (%)	8 (22.2)	30 (52.6)	0.004**
Total CSF volume, ml, mean ± SD	214.4 ± 68.4	220.6 ± 69.1	0.677
Hemispheric CSF ratio, median (IQR)	0.74 (0.24)	0.64 (0.36)	0.011*

ASPECTS, Alberta Stroke Program Early CT Score; BMI, body mass index; CVS, cortical vessel signs; CSF, cerebrospinal fluid; ICA, internal carotid artery; IQR, interquartile range; MCA, middle cerebral artery; mRS, modified Rankin Scale; NIHSS, National Institutes of Health Stroke Scale; SD, standard deviation. *$P < 0.05$, **$P < 0.01$, ****$P < 0.0001$.

Table 3
Multivariate regression analysis of poor outcome in patients with LHI.

	B value	Odds Ratio (95%CI)	*P* value
Diabetes mellitus	0.814	2.258 (0.526–9.683)	0.273
Atrial fibrillation	1.042	2.835 (0.397–20.232)	0.299
Previous stroke	1.654	5.229 (1.013–26.984)	0.048*
Hemorrhagic transformation	0.657	1.929 (0.487–7.636)	0.349
Admission NIHSS	0.035	1.035 (0.948–1.130)	0.439
ASPECT ≤6	2.581	13.208 (1.136–153.540)	0.039*
Hemispheric CSF ratio (%)	−0.034	0.966 (0.937–0.997)	0.029*

ASPECTS, Alberta Stroke Program Early CT Score; CSF, cerebrospinal fluid; NIHSS, National Institutes of Health Stroke Scale. *$P < 0.05$.

DWI ASPECTS has been shown to correlate with DWI lesion volumes and serve as an useful factor for predicting functional outcome in patients with acute ischemic stroke [25,26]. In present study, ASPECTS was analyzed dichotomized (>6 versus ≤6) based on previous research [27]. As shown in Table 3, ASPECTS≤6 was an independent predictor of poor prognosis and similar to previous prediction result. In addition, previous stroke was found to increased likelihood of poor prognosis in patients with LHI in our study, which we presume may be related to their pre-existing disabilities. In addition, since only 4 patients showed parenchymal hematoma 2 (PH2), hemorrhagic transformation may not have a significant impact on prognosis.

The main strength of this study is the development of valuable imaging marker that could quantify the severity of edema after LHI based on a deep learning approach. Nevertheless, the present study had several limitations. First, our study is limited by the small sample size and single-center investigation, which may introduce bias. Second, further external validation of this algorithm in large prospective cohorts should be performed before this finding can be generalized to a broader population. In addition, hemorrhagic transformation may have an effect on this method of CSF quantification via the mass effect, which could hinder accurate estimation of the hemispheric CSF ratio in patients with severe hemorrhagic transformation. Finally, although the CSF segmentation results produced by this model are able to meet the needs of clinical analysis, the spatial information of cerebrospinal fluid could not be fully utilized due to the fact that it is a two-dimensional network. Moreover, our model is a cascade network composed of two U-Nets with a large number of parameters, which result in a long training time.

5. Conclusion

Hemispheric CSF ratio quantification of cerebral edema is a quantifiable and objective measure that provides an opportunity for recognition and medical intervention for brain edema after LHI.

Ethics Declarations

This study was reviewed and approved by the Research Ethics Committee of the Second Hospital of Hebei Medical University, with the approval number: 2020-P002. All patients (or their proxies/legal guardians) provided informed consent to participate in the study.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Junzhao Cui: Writing – original draft, Formal analysis, Data curation. **Jingyi Yang:** Software, Methodology, Data curation. **Ye Wang:** Data curation. **Meixin Ma:** Software, Methodology, Data curation. **Ning Zhang:** Funding acquisition, Data curation. **Rui Wang:** Data curation. **Biyi Zhou:** Data curation. **Chaoyue Meng:** Data curation. **Peng Yang:** Data curation. **Jianing Yang:** Data curation. **Lei Xu:** Data curation. **Guojun Tan:** Supervision, Data curation. **Lidou Liu:** Visualization, Supervision, Data curation. **Junli Zhen:** Project administration, Data curation. **Li Guo:** Validation, Investigation, Data curation. **Xiaoyun Liu:** Writing – review & editing, Validation, Supervision, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Xiaoyun Liu, Junzhao Cui, Jingyi Yang has patent licensed to Xiaoyun Liu, Junzhao Cui, Jingyi Yang. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e26673.

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